Patterns and Rates of Recent Sedimentation and Intertidal Vegetation Changes in the Kaipara Harbour

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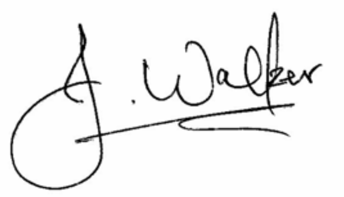

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Patterns and Rates of Recent Sedimentation and Intertidal Vegetation Changes in the Kaipara Harbour

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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, 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 0.1–30̃010–2000 □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 per cent 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 <u>average</u> ^{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) compiled 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).

1.0 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.

1.1 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).

1.2 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).

1.3 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 120m 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.

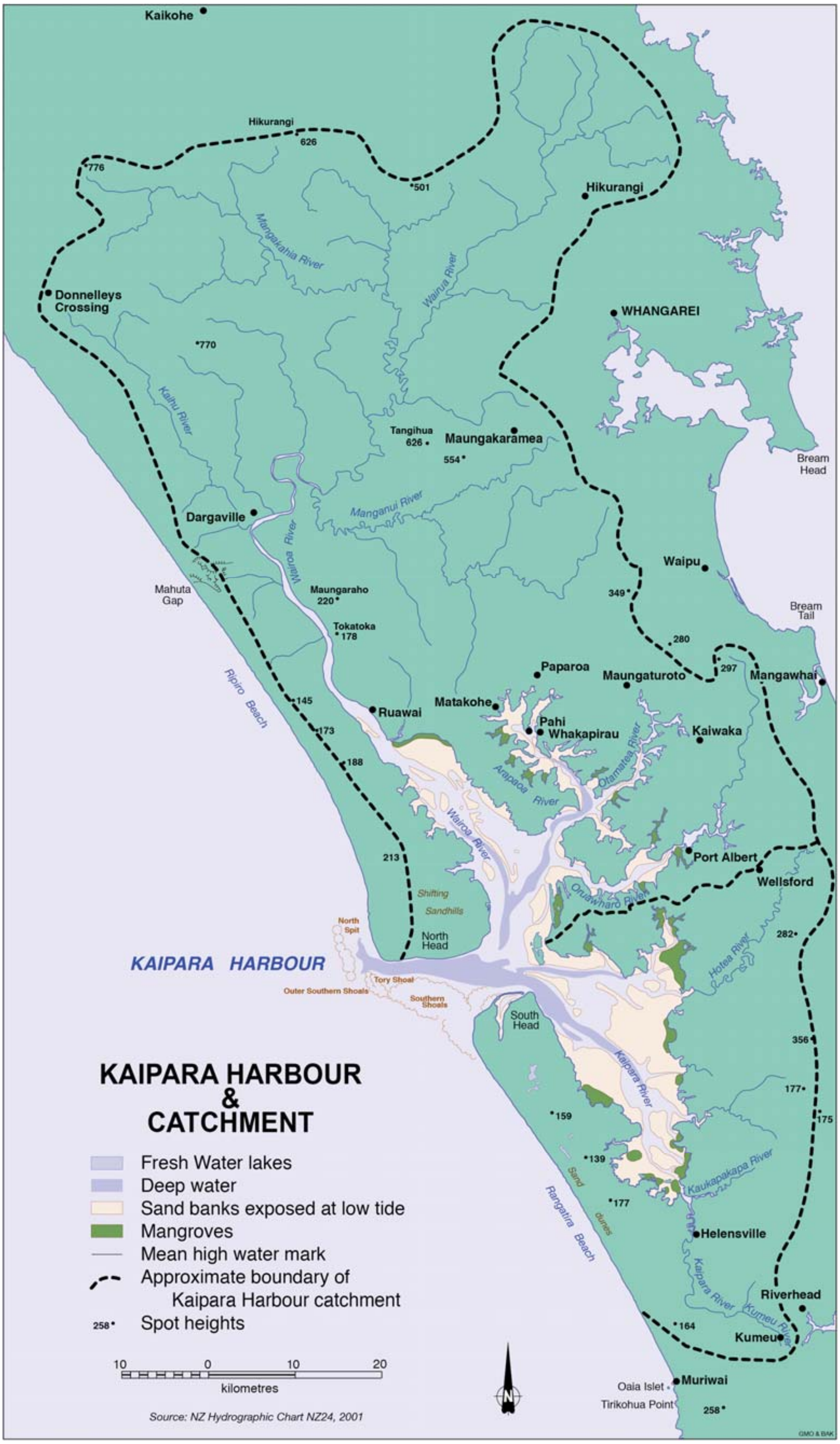


Figure 2.2 Extensive intertidal flats flank the tidal channels. View of the Kaipara River looking south towards Helensville, March 2009 (Photo: A. Swales, NIWA).

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 and 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).

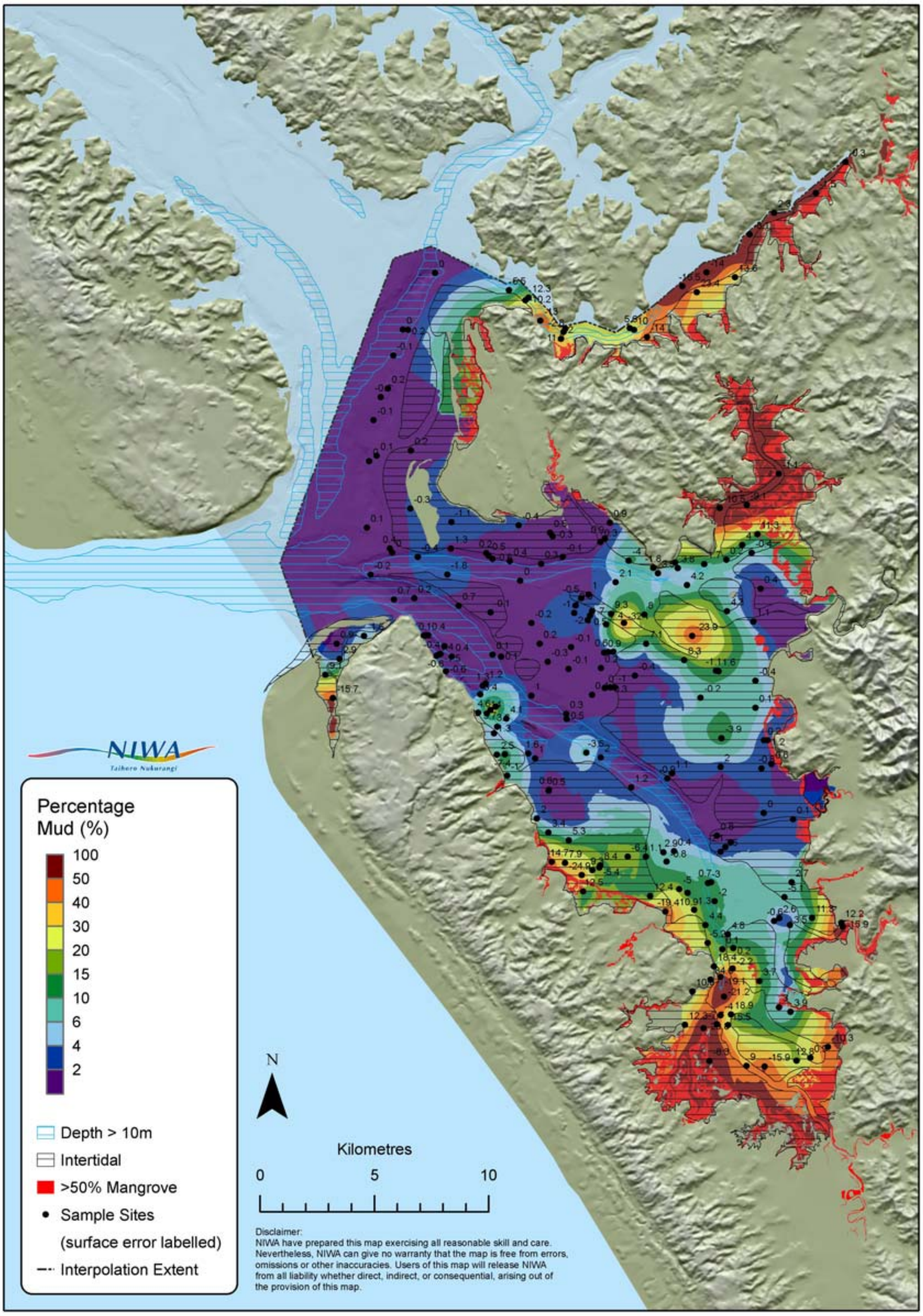


Figure 2.8 Cord-grass (*Spartina* spp.) colonising an upper-intertidal flat immediately seaward of a mangrove stand, south Kaipara Harbour, March 2009 (Photo: A. Swales, NIWA).

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 ≤ 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 ≤ 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).

2.0 Methods

2.1 Sediment-core sampling

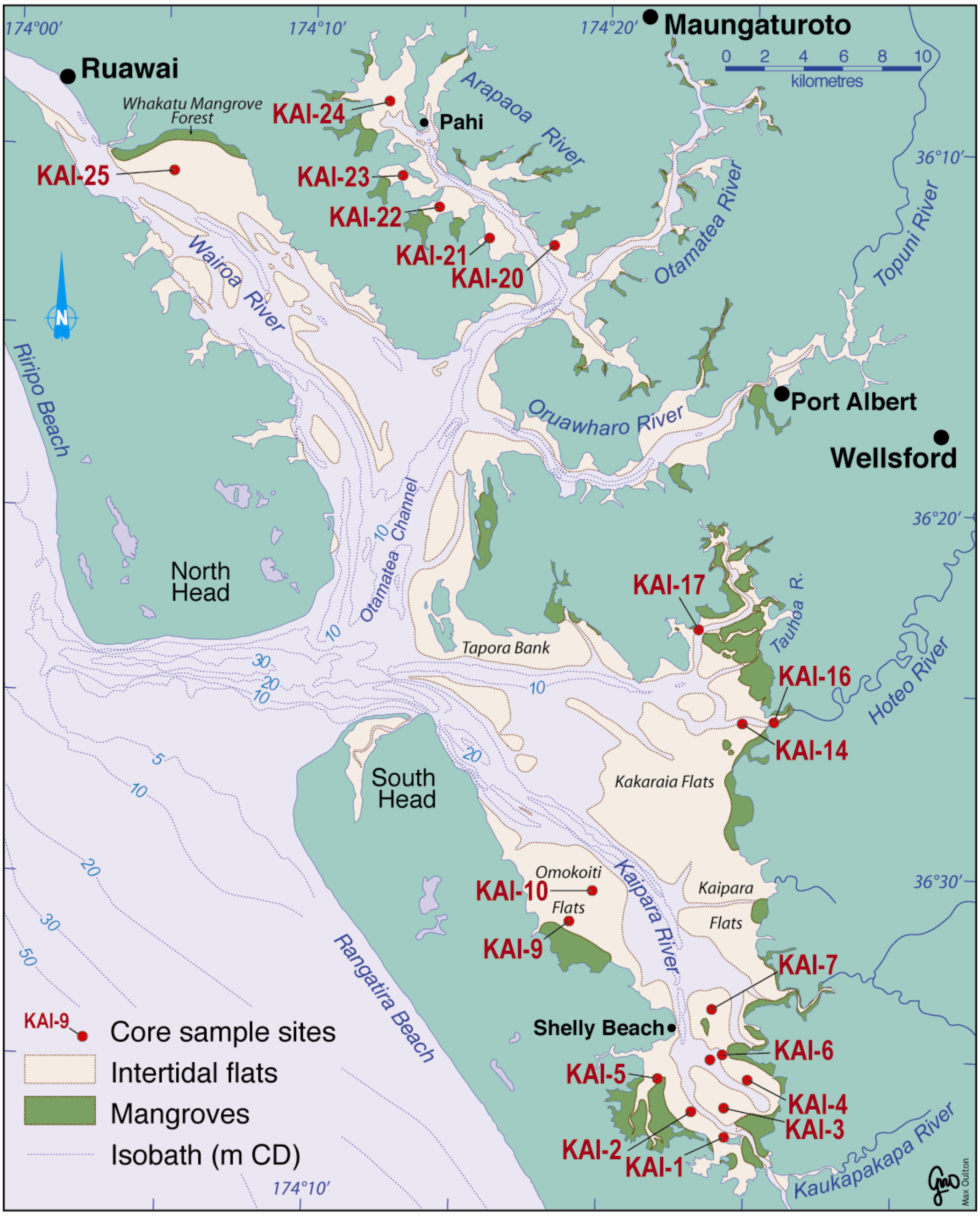
Sediment core sites on intertidal and subtidal flats were selected in consultation with AC and NRC, as well as being informed by existing information. For example, Haggitt et al. (2008) identified areas of the Kaipara Harbour that are likely to be vulnerable to fine-sediment accumulation by mapping peak-tidal 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).

2.2 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.

2.3 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.

2.4 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, μm). With few exceptions most of the sediments analysed were composed of clay and silt particles < 63 μm and fine sand particles < 250 μm 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 μm and 10–2000 μm, 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.

2.5 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).

2.5.1 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*):

$$C_\mathrm{t} = C_0 e^{-kt} \qquad (2)$$

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:

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

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.

2.5.2 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.

2.6 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.

2.6.1 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:

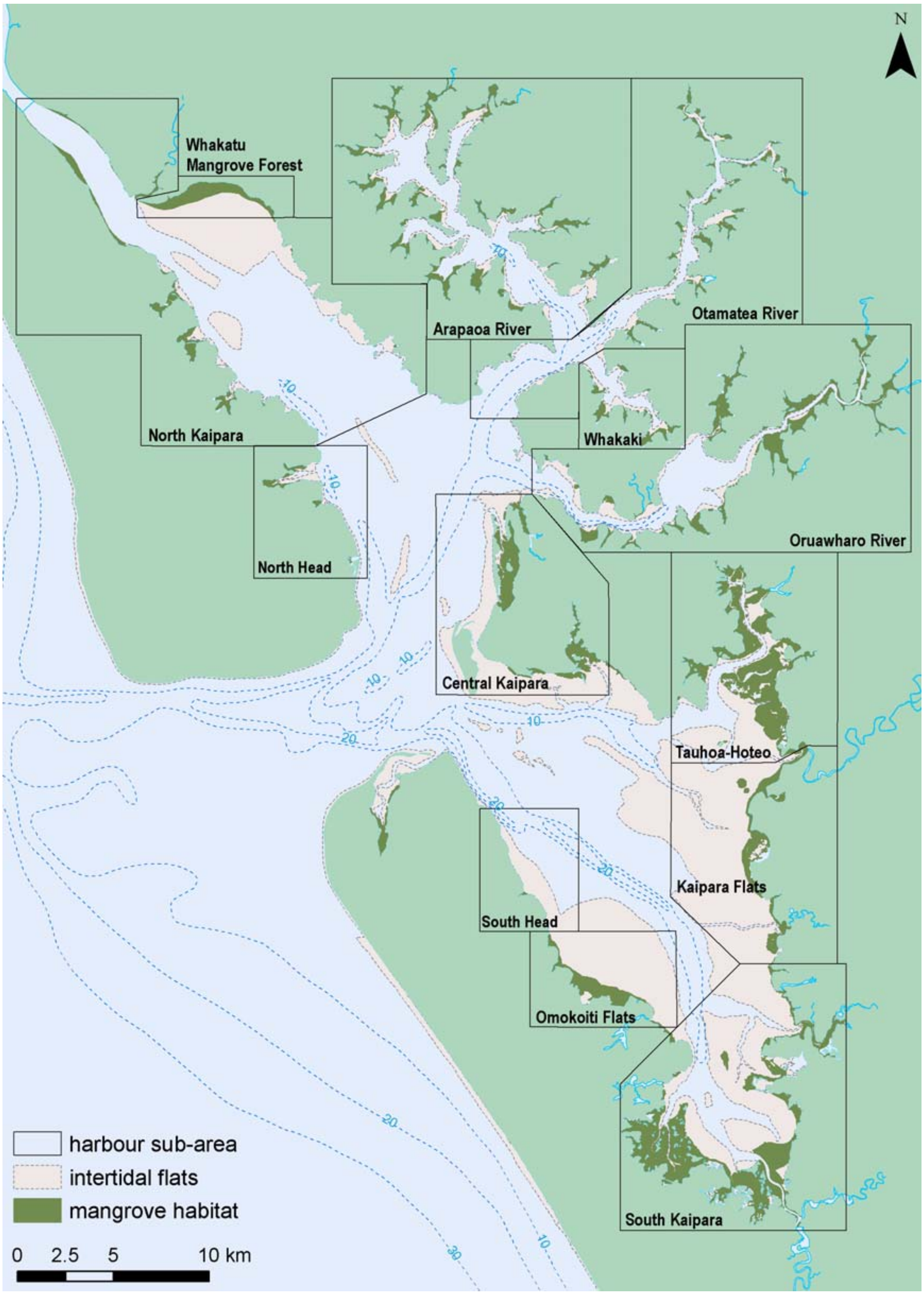
- the smallest vegetation units to be digitised had a long-axis dimension of at least 10 m. This avoided the possibility that vegetation units, with a long-axis dimension of ≥10 m, would be excluded based on a short or intermediate axes < 10 m
- where the boundary between mangrove and salt marsh was 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).



3.0 Results

3.1 Sediment core profiles

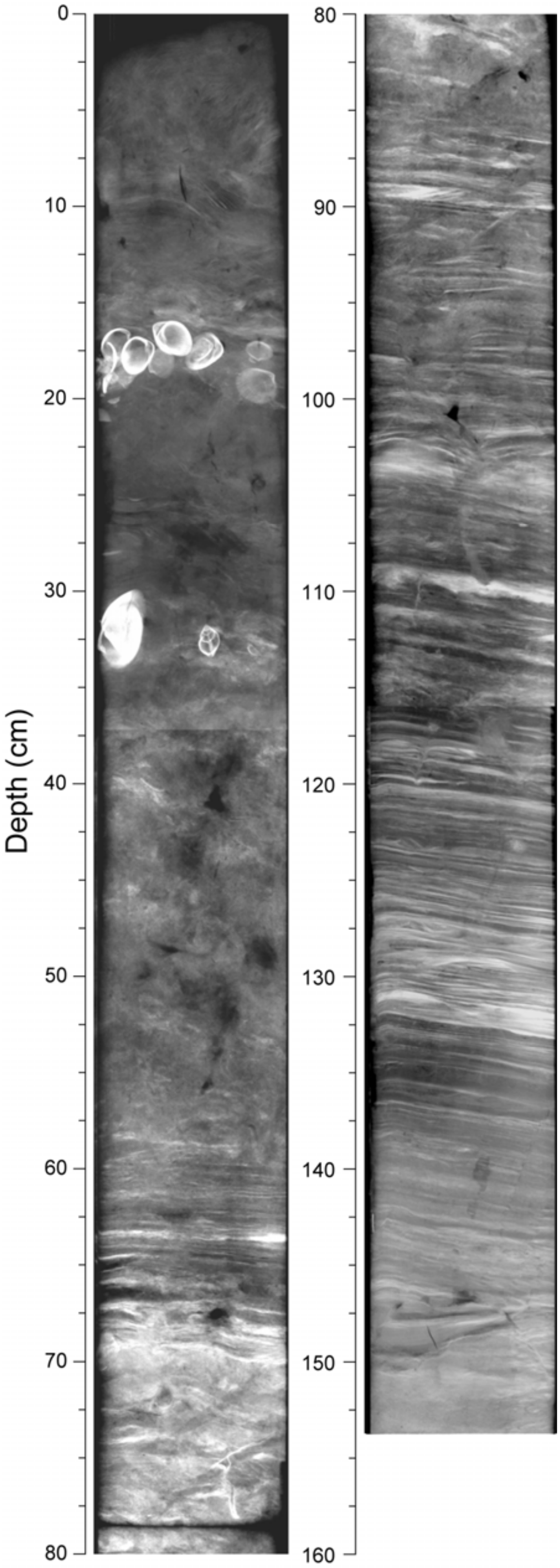
In this section we describe the physical characteristics (i.e., sediment fabric, particle size, bulk density) of each core, SAR and mixing depths estimated from the radioisotope profiles. The principles and application of radioisotope methods to the dating of sediment deposits is described in Appendix 8.2.

3.1.1 Site KAI-1 (southern Kaipara)

Site KAI-1 is located ~2 km north-west of the Kaipara River mouth on the lower-intertidal flat flanking the main navigation channel in the southern Kaipara Harbour (Fig. 3.1). Three sediment cores 95 cm to 152-cm long were collected at this site.

The x-radiographs for core KAI-1B show a range of sediment fabrics, from bioturbated fine-sandy muds and shell layers to sequences of finely laminated silts and sands below 60-cm depth (Fig. 4.1). Note that in these inverted x-ray images, relatively high density objects such as carbonate shells and quartz sands appear white whereas lower-density organic material (e.g., plant fragments) and/or fluid/fine-grained muds are identified as darker grey–black areas.

Figure 4.1 X-radiograph of core KAI-1B, southern Kaipara Harbour.



The top 30-cm or so of the core is composed of partly-mixed fine sands and silts. Discrete areas of intact laminated beds occur (e.g., 10-cm depth), which indicate that sediment mixing by animals and/or physical process has not been sufficient to homogenise these sediments.

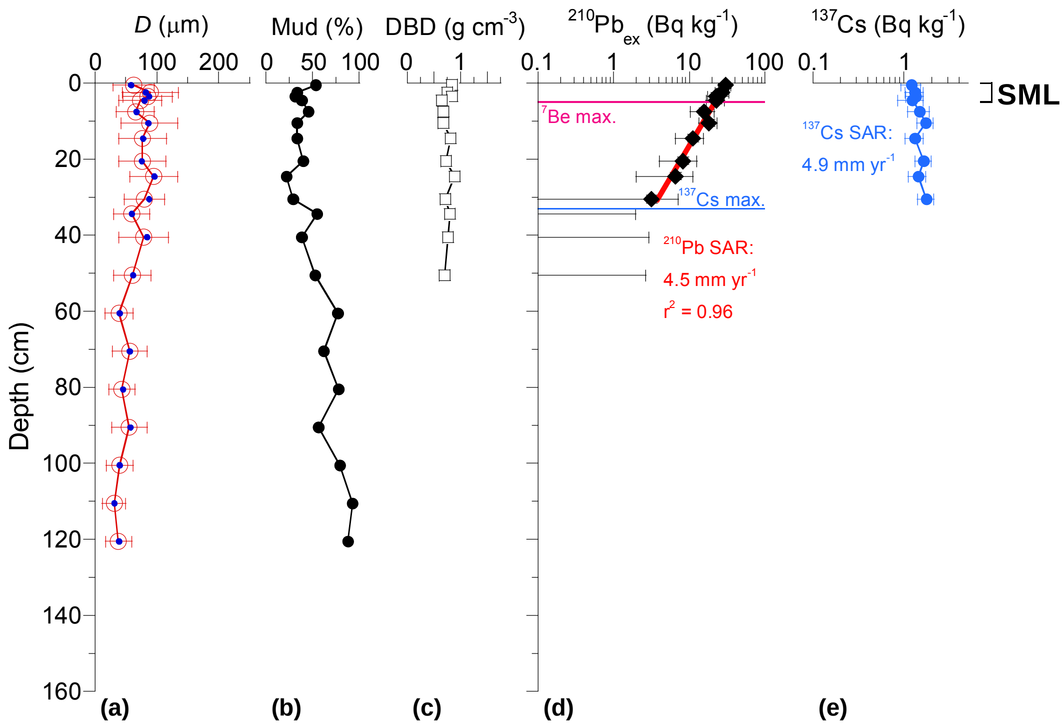
A layer of cockle-shell valves (*Austrovenus stutchburyi*) occurs at 18-20-cm depth. A muddy-sand unit at 68–76-cm depth preserves evidence of cm- diameter animal burrows that have infilled with lower-density muds. These partly-mixed sands and muds are replaced by finely-laminated alternating layers of mud and sand below 60-cm depth, which persist to the bottom of the core at 152-cm depth. Individual mud (grey-black) and sand (white) parallel layers vary in thickness from < 1 mm to ~1 cm. This type of fine-scale, interlayered bedding, otherwise know as rhythmites, can be produced by regular changes in sediment transport rate and/or sediment supply. These changes can occur over short time scales (e.g., tides) or relate to longer-term climatic fluctuations, such as seasonal changes in river sediment loads (Reineck and Singh 1980).

The x-radiographs show that the rhythmites are gradually replaced by partially mixed mud and sand above 70-cm depth. This trend may also reflect a change in local hydrodynamic conditions over time as the intertidal flat has evolved. In particular a local increase in sea-bed elevation due to sedimentation substantially changes tidal inundation and current regimes (i.e., ebb- and flood-tide dominance, reduced peak current speeds) and wave fetch. In this scenario the dominant sediment transport process on the emerging intertidal flat shifts from tidal currents to short-period estuarine waves that become increasingly effective at resuspending/mixing bed sediments (e.g., Green et al. 1997).

These rhythmites may have been formed gradually over hundreds of years or so or they may have been deposited rapidly over the space of several years. Unfortunately, the geochronology of these deposits cannot be ascertained because they are older than the ^{210}Pb and ^{137}Cs-dated sediments. These deposits are too regular and numerous to be the result of episodic flood events (c.f. site KAI-14) and therefore were most likely formed by tidal currents.

The sediment profiles for KAI-1A show how the physical characteristics of the sediments change with depth below the sediment–water interface (Fig 4.2). Mean particle diameter (D_{mean}) gradually increases towards the surface, from ~40 μm (coarse silt) at 120-cm depth to ~80 μm (very-fine sand) in the top 5-cm of the sediment column. Mud content shows a corresponding decrease from 80–90% to 30% (Fig 4.2a and b). The dry bulk sediment density (DBD) profile for the top-50 cm of the core does not display any clear trend with depth, with values varying between 0.64 and 0.89 g cm^{-3} (Fig 4.2c). This is typical for mixed-size estuarine sediments as de-watering and compaction is minimal in the top metre or so of the sediment column. Excess ^{210}Pb ($^{210}Pb_{ex}$) and ^{137}Cs occur to 30-cm depth in core KAI-1A. The surface-mixed layer (SML) is identified by the presence of ^{7}Be in sediments and is detected to 5-cm depth (Fig. 4.2d and e).

Figure 4.2 Core KAI-1A (Intertidal flat, south Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. . Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



The ^{210}Pb SAR estimated for the accumulation zone below the SML is 4.5 mm yr^{-1} (r^2 = 0.96, Fig. 4.2d) and is very similar to the ^{137}Cs SAR of 4.9 mm yr^{-1} (Fig. 4.2e). The close agreement between the two SAR estimates supports the sediment dating for this site.

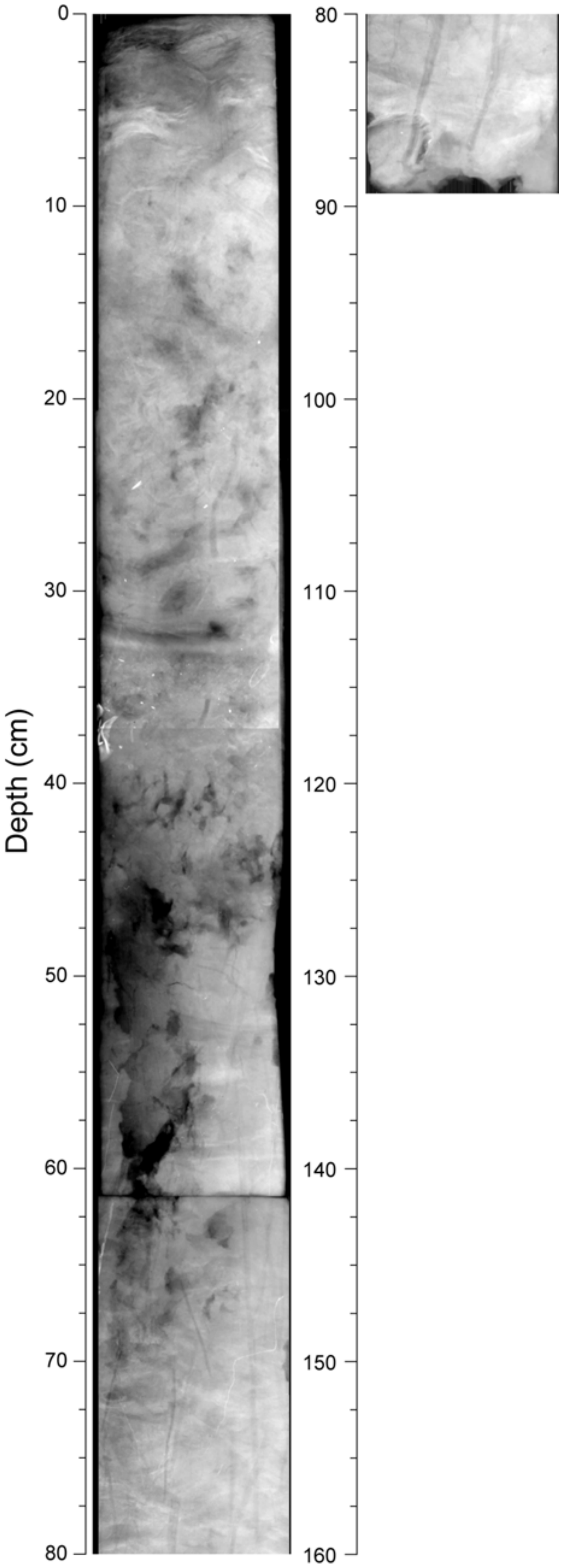
The residence time of sediment in the SML before it is removed by burial can be estimated from the maximum ^{7}Be depth and ^{210}Pb SAR as 50 mm/4.5 mm yr^{-1} = 11 years. In adopting this approach we assume that the sediment mixing depth has been constant over time.

3.1.2 Site KAI-2 (southern Kaipara)

Site KAI-2 is located ~4 km north-west of the Kaipara River mouth on the lower-intertidal flat seaward of Opahekeheke Island in the southern Kaipara Harbour (Fig. 3.1). Three sediment cores 68 cm to 91-cm long were collected at this site.

The x-radiographs for core KAI-2A display a range of sediment fabrics. The top-most 5- cm of the core is composed of mud-rich sediments (Fig 4.3). The sand content of sediment below this surface layer is higher as indicated by the lighter-coloured appearance. There is also a general trend of increasing sand content with depth. Sediments in the upper 50-cm of the core have a mottled appearance, indicative of partial mixing by infauna, although pockets of intact bedding remain. Mud-filled worm burrows up to several mm in diameter and orientated vertically are common in the sand unit below 50 cm depth.

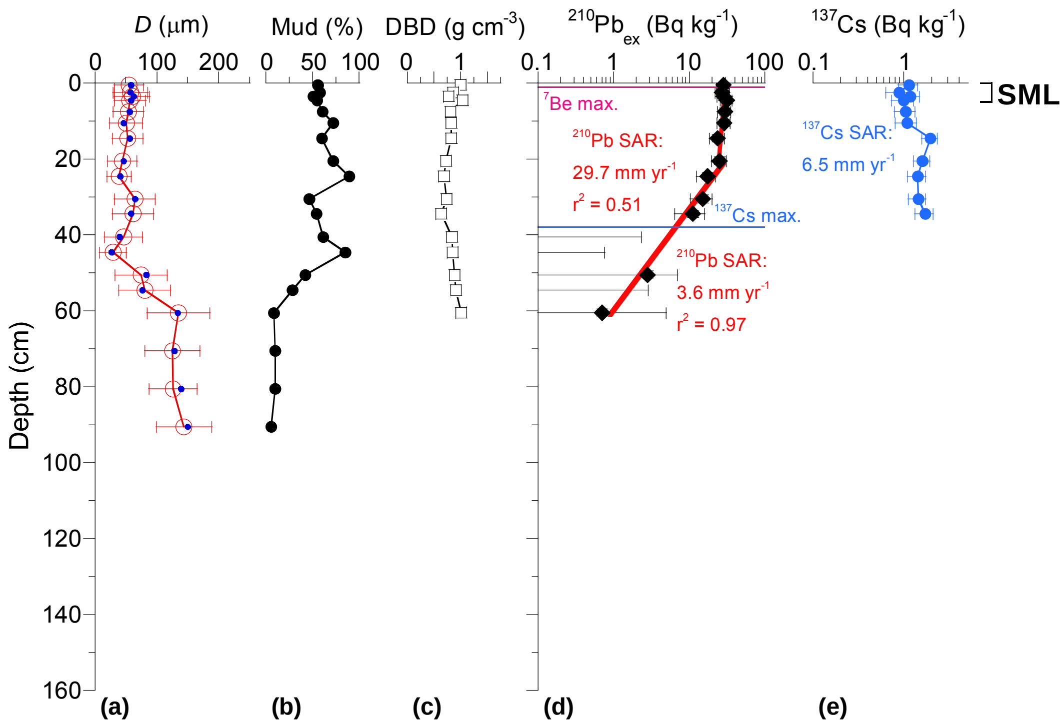
Figure 4.3 X-radiograph of core KAI-2A, southern Kaipara Harbour.



The sediment profiles for KAI-2 indicate a substantial change in type and rate of sedimentation at this site (Fig. 4.4). Mean particle diameter of ~130 m (fine sand) in the lower section of the core rapidly reduces to ~60 m (coarse silt) above 60-cm depth (Fig. 4.4a). Correspondingly, the mud content of sediments increases from less than 10% in the sand layer below 60-cm depth to 60% in the overlying bioturbated sandy mud unit (Fig. 4.4b). The DBD values for sediments to 60-cm depth vary from 0.72 to 1.04 g cm^{-3} (Fig 4.4c).

The $^{210}Pb_{ex}$ profile at site KAI-2 is more complex in form than at site KAI-1, with an apparent ten-fold increase in SAR from 3.6mm yr^{-1} to ~30 mm yr^{-1} occurring during the last decade. This increase in accumulation rate is indicated by an abrupt change in slope of the $^{210}Pb_{ex}$ profile at 20-cm depth (Fig. 4.4d).

Figure 4.4 Core KAI-2B (Intertidal flat, south Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. . Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



The ^{137}Cs profile extends to at least 35-cm depth and spans this apparent increase in $^{210}Pb_{ex}$ SAR. The estimated ^{137}Cs SAR of 6.5 mm yr^{-1} is consistent with a shift to a higher SAR indicated by the $^{210}Pb_{ex}$ profile (Fig. 4.4e). This type of $^{210}Pb_{ex}$ profile can also occur by other means other than increased sediment delivery to an estuary. In particular, downward mixing or younger sediments (with higher $^{210}Pb_{ex}$ concentrations) by bioturbation over years-decades can increase the slope of the $^{210}Pb_{ex}$ profile, indicating an apparent rather than an actual increase in sedimentation rate. The ^{7}Be profile at KAI-2 is relatively shallow, extending to 1-cm depth, which indicates mixing of surficial sediment re-suspension by tides and/or waves rather than bioturbation. The x-radiograph shows also some intact bedding at depth, so that bioturbation alone is unlikely to explain the $^{210}Pb_{ex}$ profile. Alternatively, an increase in SAR can occur due to changes in local conditions such as a change in sediment transport versus deposition rates and the effects of geomorphological adjustments. For example, lateral shifts in tidal- channel position can locally increase sedimentation rates. This type of $^{210}Pb_{ex}$ profile has also been observed in the Mahurangi Harbour, near Hamiltons Landing, where a long term pattern of tidal-channel meandering has been reconstructed from hydrographic charts and sediment-core data (Swales et al. 1997, 2002). On balance, the data for site KAI-2 suggests that the observed increase in $^{210}Pb_{ex}$ SAR more likely reflects a local change in net accumulation rate rather than sediment mixing.

The residence time of sediment in the ^{7}Be SML is relatively short due to the high SAR and is estimated at 10 mm/30 mm yr^{-1} (SML/SAR)= 0.33 years.

3.1.3 Site KAI-3 (southern Kaipara)

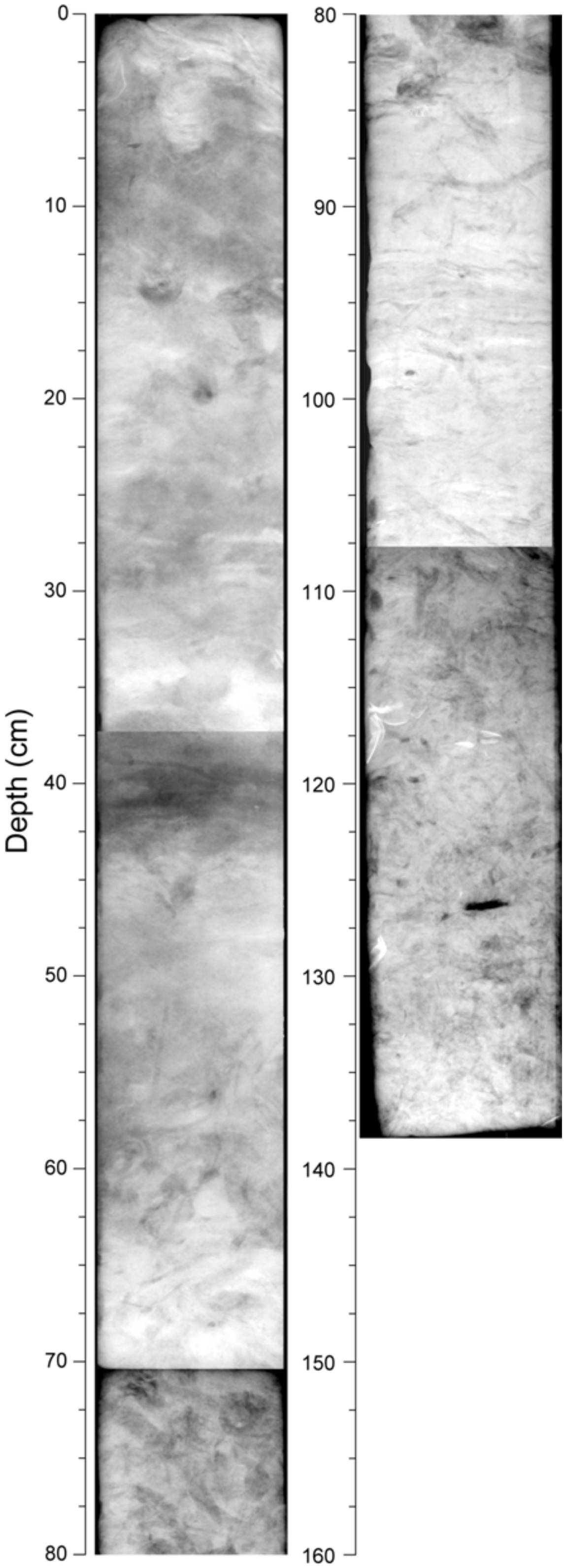
Site KAI-3 is located on a large intertidal bank east of the Kaipara River channel in the in the southern Kaipara Harbour (Fig. 3.1). Three sediment cores 132 cm to 137-cm long were collected at this site.

The x-radiographs for core KAI-3B have a mottled appearance, indicative of partial mixing of denser/coarser sands (light-grey–white) with lower density muds (dark grey–black) (Fig. 4.5). Traces of animal burrows can be seen through-out the core, particularly in sandy sediments where burrows up to 1-cm diameter have filled with lower-density mud (e.g., 70-90 cm depth).

The sediment profiles for KAI-3A show a gradual shift from sand to mud deposition at this site, with D_{mean} reducing from of ~150 m (fine sand) in the bottom of the core to ~110 m (very-fine sand) in near-surface sediments (Fig. 4.6a) and mud content increasing from less than 2% to ~20% (Fig. 4.6b). The DBD values for sediments vary from 0.67 to 1.2 g cm^{-3}, depending on sediment composition (Fig. 4.6c).

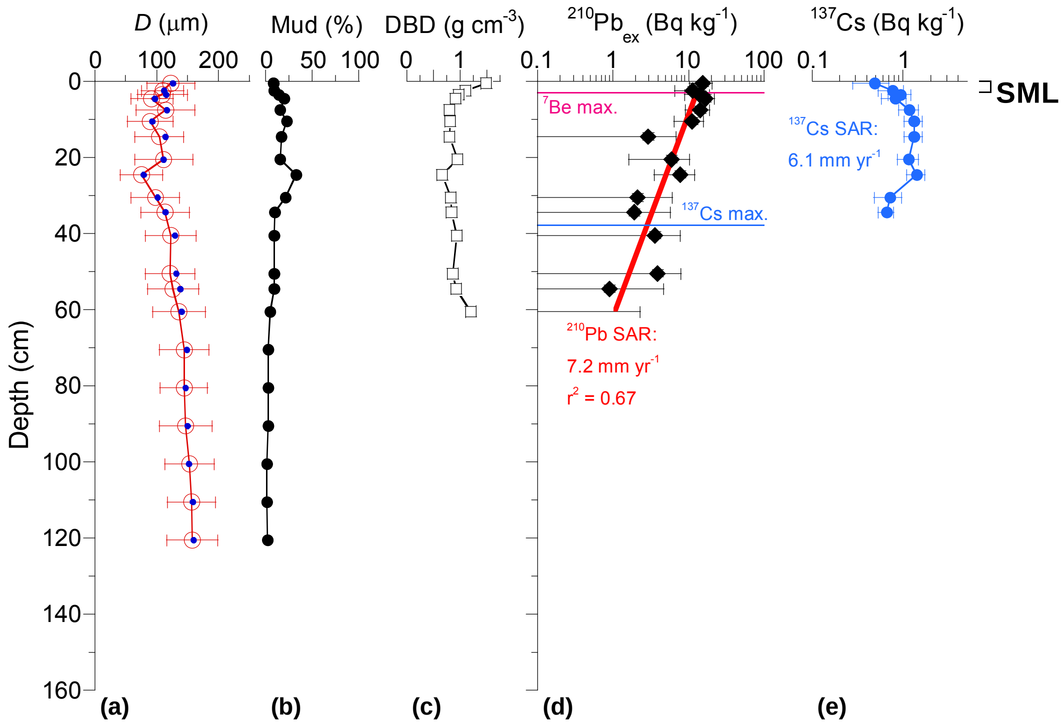
Excess ^{210}Pb occurs to 60-cm depth in core KAI-3A, with an estimated SAR of 7.2 mm yr^{-1}. The data area relatively “noisy” as indicated by the fit of the log-linear regression (r^2 = 0.67, Fig. 4.6d). ^{137}Cs occur to 40-cm depth and labels sediments deposited since the early 1950s. The ^{137}Cs SAR of 6.1 mm yr^{-1} is similar to the ^{210}Pb estimate (Fig. 4.6e). The close agreement between the two SAR estimates supports the sediment dating for this site.

Figure 4.5 X-radiograph of core KAI-3B, southern Kaipara Harbour. Note the uneven exposure of x-ray images between sections due to changes in sediment composition.



The residence time of sediment in the SML before it is removed by burial is estimated from the maximum ^{7}Be depth (i.e., 30 mm) and ^{210}Pb SAR as 30 mm/7.2 mm yr^{-1} = 4.2 years.

Figure 4.6 Core KAI-3A (Intertidal bank, south Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.

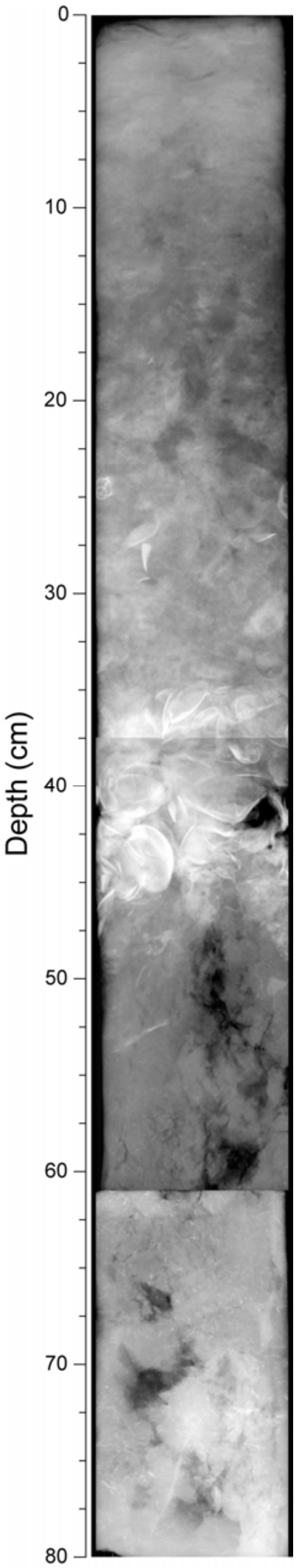


3.1.4 KAI-4 (southern Kaipara)

Site KAI-4 is located ~5 km north of the Kaipara River mouth on the lower intertidal flat flanking the eastern shore of the southern Kaipara Harbour (Fig. 3.1). Two sediment cores 83 cm and 142-cm long were collected at this site.

The x-radiographs for core KAI-4B show discrete changes in sediment composition with depth (Fig 4.7). Mud-rich sediments (0–20 cm depth) overlay more sandy sediments. The base of this sand unit contains densely packed cockle valves (36–46 cm). Mixing at the interface of the mud and sand units (15–24-cm depth), most likely by infauna, is evident. Below the shell layer, the sediments are composed of muds, which extend to the base of the core at 80-cm depth.

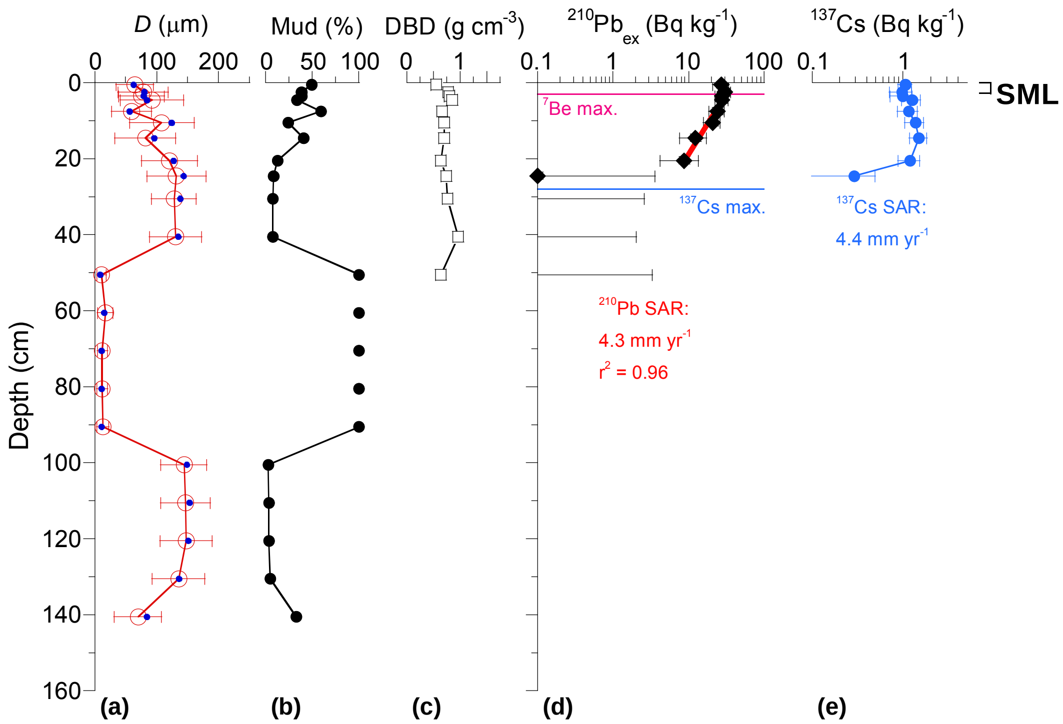
Figure 4.7 X-radiograph of core KAI-4B, southern Kaipara Harbour.



The sediment profiles for KAI-4A further reveal the abrupt changes in sediment composition indicated by the x-radiographs. In fact, core KAI-4A reveals a sequence of mud and sand units: mud

(0-20 cm); sand (20–45 cm); mud (45–95 cm); sand (95–135 cm) and mud (135 cm –) (Fig. 4.8a). The mud content of these sediments varies from less than 4% to as much as 100% (Fig. 4.8b). The DBD values for sediments in the top 50-cm of the core vary from 0.56 to 0.81 g cm^{-3} (Fig 4.8c).

Figure 4.8 Core KAI-4A (Intertidal bank, south Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



Excess ^{210}Pb and ^{137}Cs occur to 25-cm depth in the top-most mud unit (Fig 4.8d). The ^{210}Pb SAR of 4.3 mm yr^{-1} (r^2 = 0.96, Fig. 4.8d) is very similar to the ^{137}Cs SAR value of 4.4 mm yr^{-1} (Fig. 4.8e). The close agreement between the two SAR estimates supports the sediment dating for this site. The residence time of sediment in the SML before it is removed by burial is estimated from the maximum ^{7}Be depth (i.e., 30 mm) and ^{210}Pb SAR as 30 mm/4.3 mm yr^{-1} = 7 years.

3.1.5 Site KAI-5 (southern Kaipara)

Site KAI-5 is located on mid-intertidal flats near the confluence of the Puhareke Creek and Kaipara River channel, southern Kaipara Harbour (Figs. 2.2 and 3.1). Two sediment cores up to 152-cm long were collected at this site.

The x-radiographs for core KAI-5B display a range of sediment fabrics, from small-ripple cross-bedding in surficial sediments (< 5 cm depth), interlayered, finely-laminated muds and sands (12–22 cm depth), low-density muds (88–94 cm depth) and bioturbated sands with worm-burrow traces (125–150 cm depth) (Fig. 4.9).

The sediment profiles for KAI-5A preserve evidence of an abrupt shift from predominantly sand to mud deposition between 70 and 60-cm depth. This is most clearly shown by the particle size and percent mud profiles (Figs. 4.10a–b). Mean particle diameter in the sand unit below 70-cm depth is in the range 164–195 □m (fine sand) with a mud content less than 4%. By comparison, D_{mean} values in the overlying mud layer is in the range 22–65 □m (med–coarse silt) with a mud content of 46–100%. Within the mud layer, there is also a gradual reduction in particle size towards the surface (Figs. 4.10a). Figure 4.10a also shows that median particle diameter exceeds the mean value in some sediment samples where the particle-size distribution is skewed towards the fine tail (i.e., large proportion of small particles). The mud content of the sediments also increases abruptly above 70-cm depth from less than 5% to 70–100% (Fig. 4.10b). The DBD values in the upper 70 cm of the core of 0.48 to 0.68 g cm^{-3} are typical of low-density clay-rich muds (Fig 4.10c).

Excess ^{210}Pb occurs to 70-cm depth in core KAI-5A (Fig 4.10d). A notable feature of the $^{210}Pb_{ex}$ profile is zone of uniform concentration (~18 Bq kg^{-1}) at 12–22 cm depth. This unconformity in the $^{210}Pb_{ex}$ profile can occur due to rapid mixing or deposition of sediment at the sea bed. On an intertidal flat, bed erosion/re-working and re-deposition by waves during an extreme wind-storm event is the most likely mechanism for rapid mixing of bed sediments. For example, $^{210}Pb_{ex}$ data from the southern Firth of Thames indicated that storms during the winter of 1978 eroded the intertidal flat to a depth of 40 cm (Swales et al. 2007). Rapid deposition of terrigenous sediments, delivered during high river discharge (storm) events can also produce this type of unconformity. Both sets of physical drivers (i.e., strong winds and flood runoff) occur simultaneously during storms and in both cases sediments are typically deposited over relatively short time scales (e.g., hours–days). Closer examination of the x-radiograph shows that the unconformity at 12–22 cm depth coincides with finely laminated mud (< 1-cm thick) and sand (< 2 mm thick) layers.

Figure 4.9 X-radiograph of core KAI-5B, Puharekereke Creek mouth, southern Kaipara Harbour.

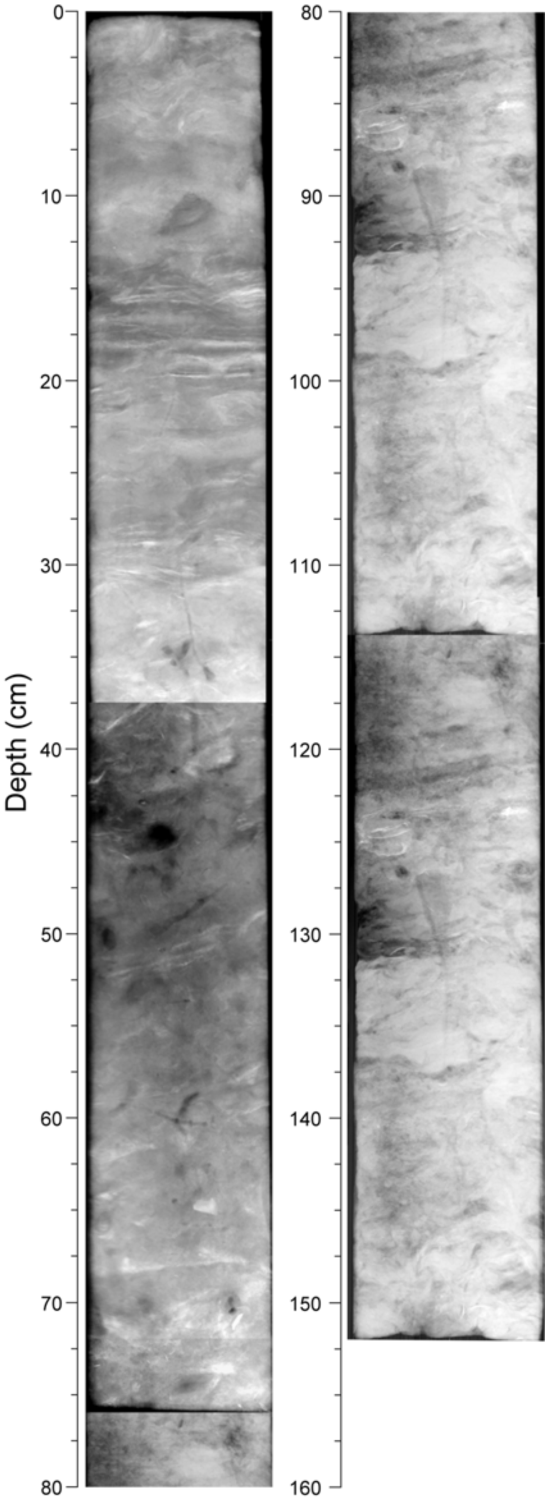
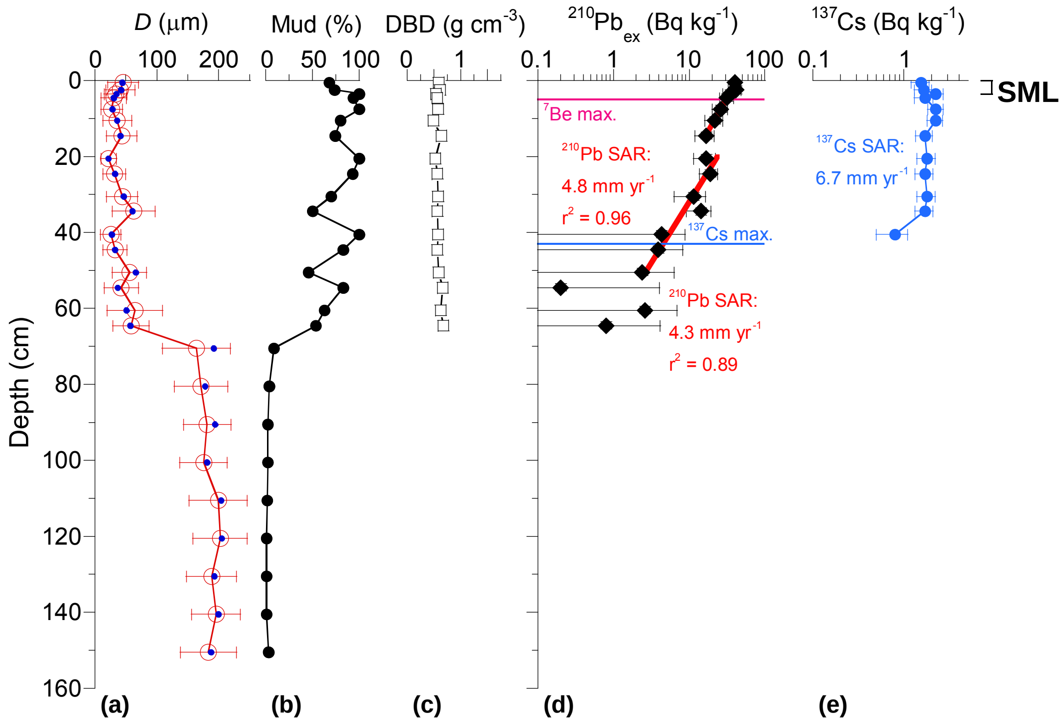


Figure 4.10 Core KAI-5A (Intertidal bank, mouth of Puharakeke Creek, south Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



Sediment accumulation rates estimated above (4.8 mm yr^{-1}) and below (4.3 mm yr^{-1}) the unconformity in the ^{210}Pb$_{ex}$ profile are very similar (Fig. 4.10d). Extrapolation of the ^{210}Pb SAR suggests that the event layer at 12–22 cm depth was deposited in the late 1970s/early 1980s. ^{137}Cs occurs to 41-cm depth, with an estimated SAR of 6.7 mm yr^{-1} being substantially higher than the ^{210}Pb estimate (Fig. 4.10e).

The residence time of sediment in the SML before it is removed by burial is estimated from the maximum ^{7}Be depth (i.e., 30 mm) and ^{210}Pb SAR as 50 mm/4.8 mm yr^{-1} = 10.4 years.

3.1.6 Sites KAI-6 and 6A (southern Kaipara)

Site KAI-6 and 6A are located on the lower-intertidal flats flanking the eastern shore of the southern Kaipara Harbour near Oyster Point and approximately 3 km south east of Shelly Beach (Fig. 3.1). Poor weather on 16 March 2010 necessitated re-sampling the following day at Site KAI-6A, which is located approximately 50 m north east of KAI-6. In total, four sediment cores 84 cm to 170-cm long were collected at these two sites.

The x-radiographs for core KAI-6(B) show that the intertidal sediments at this site are composed of laminated alternating layers of mud and sand (Fig 4.11). Individual mud (grey-black) and sand (white) layers vary in thickness from < 1 mm to as much as 4 cm. This type of interlayered bedding, otherwise know as Rhythmites, can be produced by regular changes in sediment transport rate and/or sediment supply. These changes can occur over short time scales (e.g., tides) or relate to longer-term climatic fluctuations, such as seasonal changes in wave climate and river sediment loads and deposition (Reineck and Singh 1980). The high-degree of stratigraphic preservation in this core, over a long period of time (i.e., hundreds of years) indicates that bioturbation of these sediments has been negligible. Similar, although finer bedding is observed at site KAI-1.

The sediment profiles for KAI-6A, due to the relatively large sampling intervals, do not adequately represent the fine-scale structure revealed by the x-radiographs. Mean particle diameter in the sand layers vary from 110 to 170 μm (very-fine to fine sand), while the mud layers are largely composed of fine-medium silts. The mud content of the sand layers is typically less than 10% (Figs. 4.12a and b). Dry bulk sediment density varies from 0.77 g cm^{-3} (mud layers) to 1.7 g cm^{-3} (sand layers, Fig 4.12c).

Excess ^{210}Pb and ^{137}Cs labelled sediments are limited to the upper 21-cm of core KAI-6A. The ^{210}Pb SAR of 2 mm yr^{-1} (r^2 = 0.98, Fig. 4.12d) is substantially lower than the 4.6 mm yr^{-1} estimated from the ^{137}Cs profile (Fig. 4.12e) so that the geochronology for this site cannot be considered reliable.

The short-lived ^{7}Be was not detected in surficial sediments, which is consistent with their low mud content. This, in addition to the relatively low ^{210}Pb SAR and the thick sequence of well preserved laminated mud and sand beds at this site is consistent with an intertidal flat environment exposed to frequent cycles of sediment resuspension and redeposition by waves.

Figure 4.11 X-radiograph of core KAI-6A(B), lower intertidal flat at Oyster Point, southern Kaipara Harbour. Note, the vertical offset in beds below 80-cm depth down the right-hand side of the core is an artefact of core collection and/or storage.

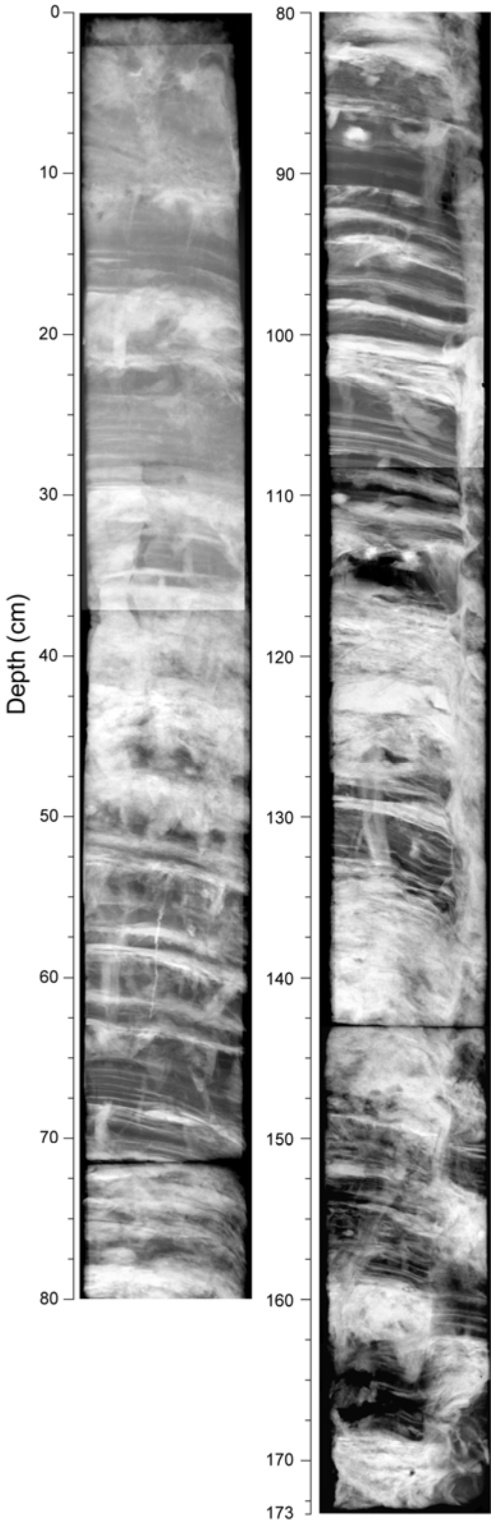
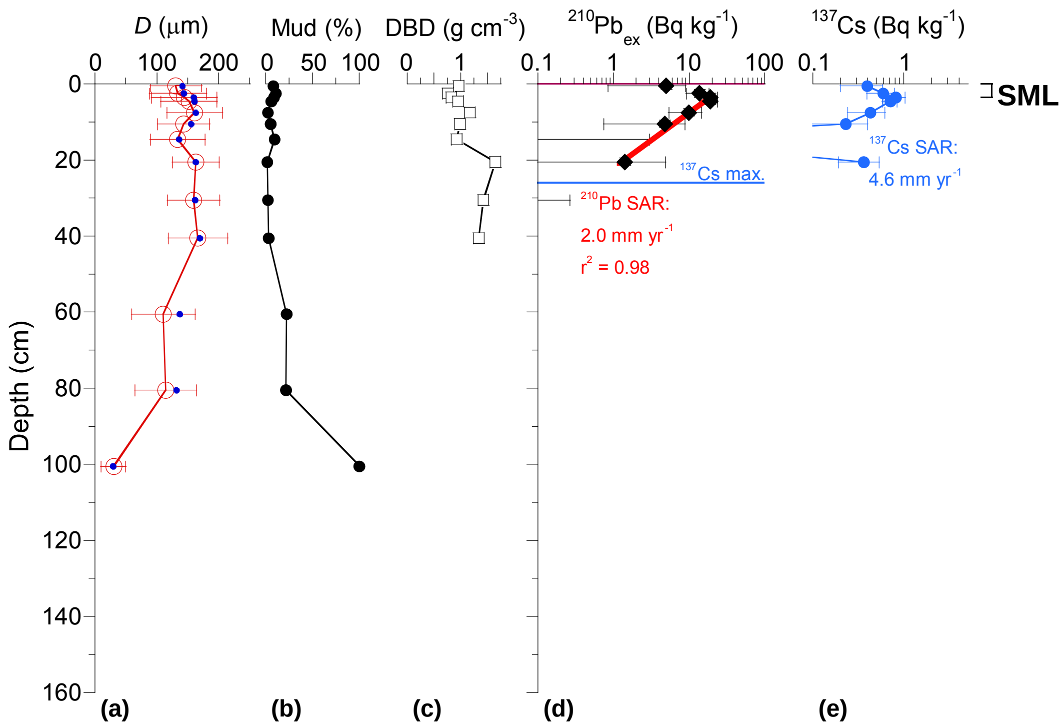


Figure 4.12 Core KAI-6A (Intertidal flat, Oyster Point, south Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by

sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



3.1.7 Site KAI-7 (southern Kaipara)

Site KAI-7 is located on an intertidal bank approximately 2 km east of Shelly Beach an immediately north of a low-lying salt-marsh/mangrove island (Fig. 3.1). Two sediment cores 47 cm and 67-cm long were collected at this site.

The x-radiographs for core KAI-7B show that the intertidal sediments at this site are composed of muddy fine sands. An abrupt change in sediment density occurs at 10-cm depth. A mixture of sand and water (grey–black on x-ray image) occupies the surface layer whereas more compact sands occur below 10-cm depth (Fig. 4.13). A shell layer composed of cockle valves also occurs at 38–42 cm depth.

The sediment profiles for KAI-7A reflect the sediment fabric revealed by the x-radiographs. Particle size and mud content are relatively uniform with depth, with sediments composed of homogenous fine sands. The mud content in the surface layer (5–10%) is higher than in the compact sand (< 2%) below 10-cm depth (Figs. 4.14a–b).

Figure 4.13 X-radiograph of core KAI-7A, intertidal bank east of Shelly Beach, southern Kaipara Harbour.

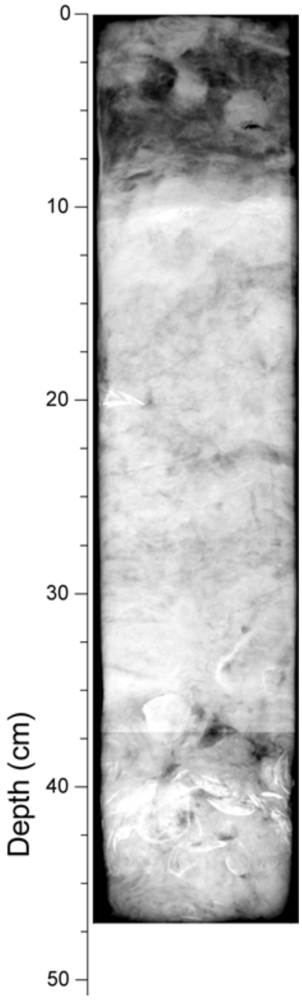
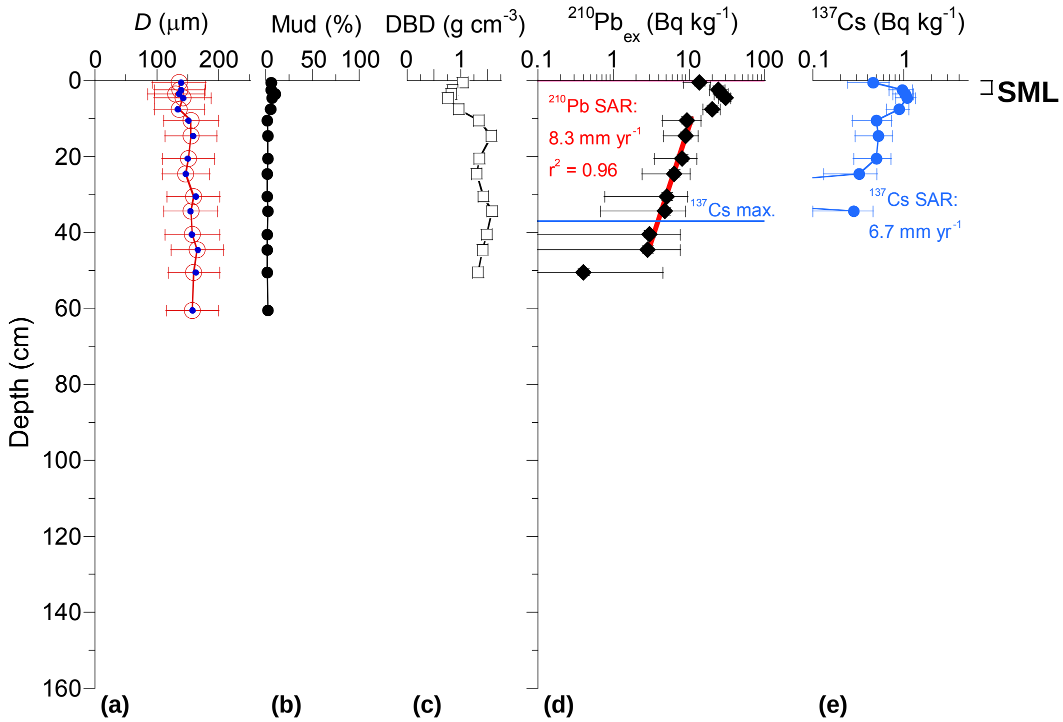


Figure 4.14 Core KAI-7A (Intertidal bank, east of Shelly Beach, south Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



Dry bulk sediment density in the fluid sand surface layer at 0.77–1.0 g cm^{-3} is substantially lower than in the compact sand (1.3–1.59 g cm^{-3}) below 10-cm depth (Fig 4.14c). These sediment data indicate a surface mixed layer (SML) of intensely and frequently reworked sands extending to 10-cm depth.

The effect of the relatively higher mud content in the SML can be seen in the $^{210}Pb_{ex}$ and ^{137}Cs profiles, with concentration peaks occurring at 4–5 cm depth (Figs. 4.14d–e). Below the SML, sediments are rapidly accumulating. The ^{210}Pb SAR of 8.3 mm yr^{-1} (r^2 = 0.96, Fig. 4.14d) is similar to ^{137}Cs SAR (6.7 mm yr^{-1}, Fig. 4.14e). The $^{210}Pb_{ex}$ profile is also deeper (to 50-cm) than the ^{137}Cs profile (to 37 cm). The close agreement between the two SAR estimates supports the sediment dating for this site.

^{7}Be is absent from the fluid/sand SML, however if we assume an SML of 10 cm based on the sediment data then the residence time of sediment in the SML before it is removed by burial is estimated from the ^{210}Pb SAR as 100 mm/8.3 mm yr^{-1} = 12 years.

3.1.8 Site KAI-9 (Omokoiti Flats)

Site KAI-9 is located on the mid-intertidal of the Omokoiti Flats, approximately 1.5 km north east of the Taumata Creek mouth (Fig. 3.1). Three sediment cores 83, 90 and 155-cm long were collected at this site.

The x-radiographs for core KAI-9B show that the intertidal sediments at this site are composed of a diverse range of sediment fabrics (Fig. 4.15). These include a compact fine sand SML (0–12 cm), lenticular bedding with discontinuous pockets of finely laminated muds and sands (i.e., ripples, 12–35 cm depth), shell layer composed of disarticulated shell valves and fragments (35–55 cm depth) and partly mixed muddy sands (55–82 cm).

The sediment profiles (to 50-cm depth) for KAI-9A also reflect the sediment fabric revealed by the x-radiographs. The SML is composed of fine sands (range mean diameter 143–156 μm) with mud content less than 2% (Figs. 4.16a–b). Below the SML, the particle-size data do not adequately describe the fine-scale variations in the laminated mud and sand, however the mud content increases with depth (i.e., < 25 %). Dry bulk sediment density in the SML, composed of compacted sands, is 1.3–1.6 g cm^{-3} , which is higher than in the underlying laminated muddy sands (0.9–1.1 g cm^{-3}) below 12-cm depth (Fig 4.16c).

Excess ^{210}Pb occurs to 11-cm depth in the SML (Fig. 4.16d), although with no systematic decline in concentration with depth so that we were unable to estimate SAR at this site. This is most likely the result of intense and frequent sediment mixing in the surface layer. ^{7}Be was detected to 1-cm depth and reflects recent atmospheric deposition (i.e., days–weeks) of this radioisotope. ^{137}Cs was not detected in the core due to: (1) the low mud content in the SML; and (2) the fact that (unlike the naturally occurring ^{210}Pb and ^{7}Be), atmospheric deposition of ^{137}Cs derived from nuclear weapons tests has not occurred in New Zealand since the mid 1980s (Matthews 1989). Thus, the presence of ^{137}Cs in surface sediments will only occur where ^{137}Cs-labelled muds are deposited at a site. The potential sources of these labelled muds are re-suspension of estuarine deposits and/or eroded catchment topsoil.

The sediment profiles at site KAI-9 are consistent with an intertidal-flat exposed to frequent cycles of sediment resuspension and redeposition by waves.

Figure 4.15 X-radiograph of core KAI-9B, mid-intertidal zone, Omokoiti Flats, Kaipara Harbour.

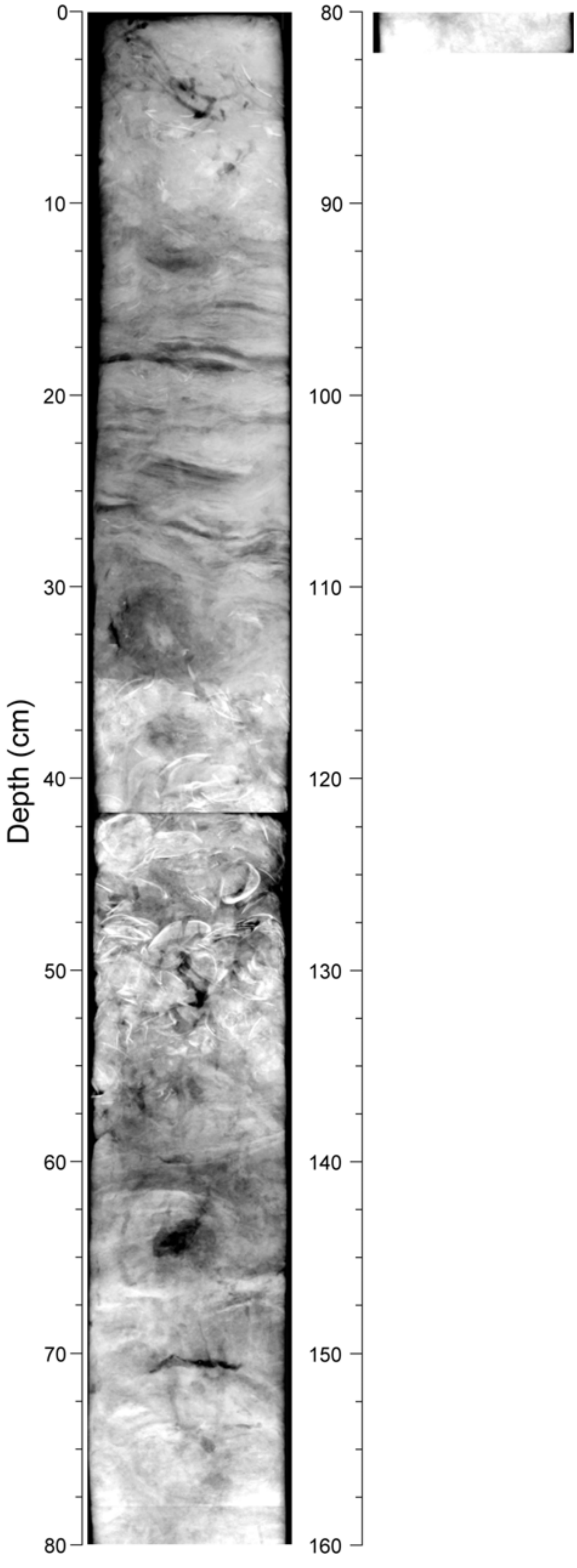
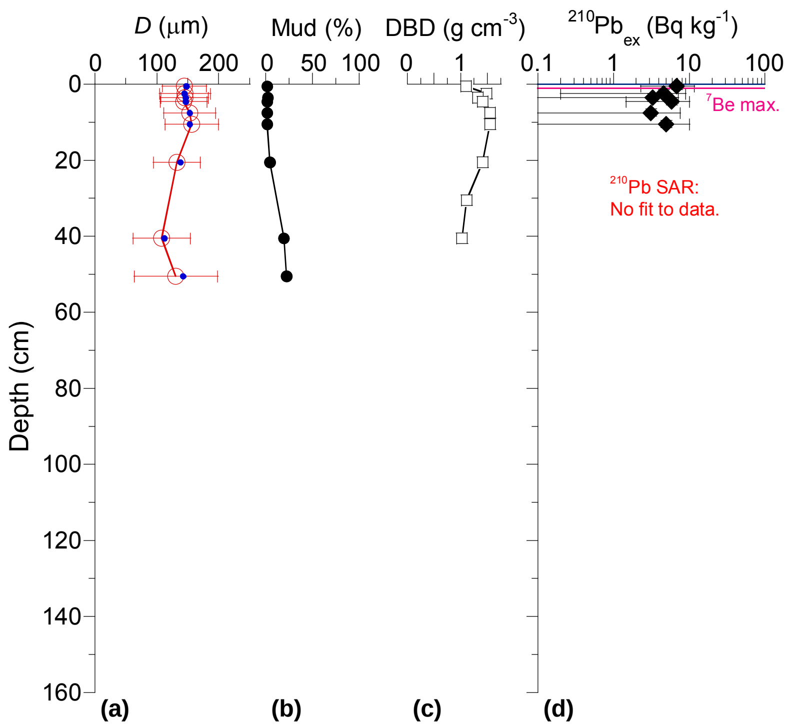


Figure 4.16 Core KAI-9A (Mid-intertidal flat, Omokoiti Flats, Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^7Be depth and maximum ^{137}Cs depth; Note: The surface-mixed layer (SML) is defined by the maximum ^7Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^7Be mixing depth.



3.1.9 Site KAI-10 (Omokoiti Flats)

Site KAI-10 is located on the lower-intertidal zone of the Omokoiti Flats, approximately 3.5 km north east of the Taumata Creek mouth (Fig. 3.1). Two sediment cores 50 and 56-cm long were collected at this site.

The x-radiographs and sediment profiles for core KAI-10B are characteristic of a wave-exposed intertidal flat. Sediments are predominantly fine sands (D_{mean} = 150–170 µm), with discrete layers of disarticulated shell valves and shell fragments (10–20, 25–40 cm depth). Occasional traces of large infauna burrows are also present (20-cm depth) (Figs. 4.17, 4.18a). Mud content is also low, being less than 3% in the top 50 cm of the core (Fig 4.18b). Dry bulk sediment density is in the range 1.1–1.6 g cm^{-3} (Fig 4.18c).

Excess ^{210}Pb occurs to 13-cm depth, with relatively uniform concentrations to 7-cm identifying the depth of the SML (Fig 4.18d). The sediment accumulation rate at this site, estimated from the $^{210}Pb_{ex}$ profile is 1 mm yr^{-1} (r^2 = 0.61), which is substantially lower than the 2.6 mm yr^{-1} estimated from the ^{137}Cs profile (Fig 4.18e). The relatively poor fit of the $^{210}Pb_{ex}$ regression model and the poor agreement between the two dating methods makes the geochronology at this site uncertain.

Figure 4.17 X-radiograph of core KAI-10B, lower-intertidal zone, Omokoiti Flats, Kaipara Harbour.

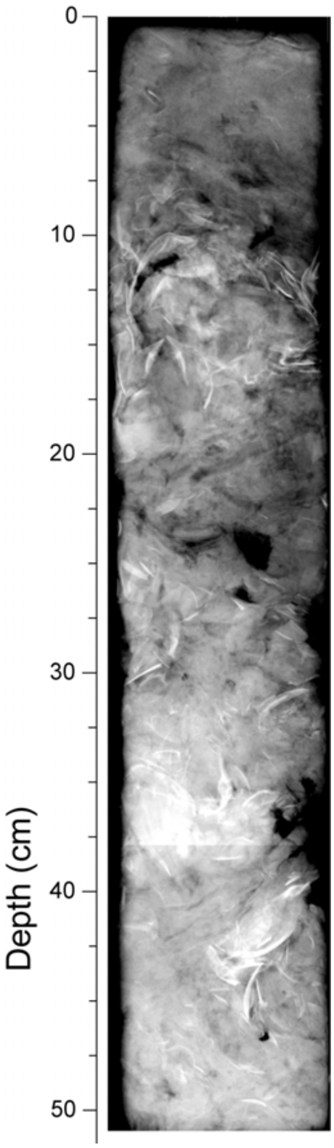
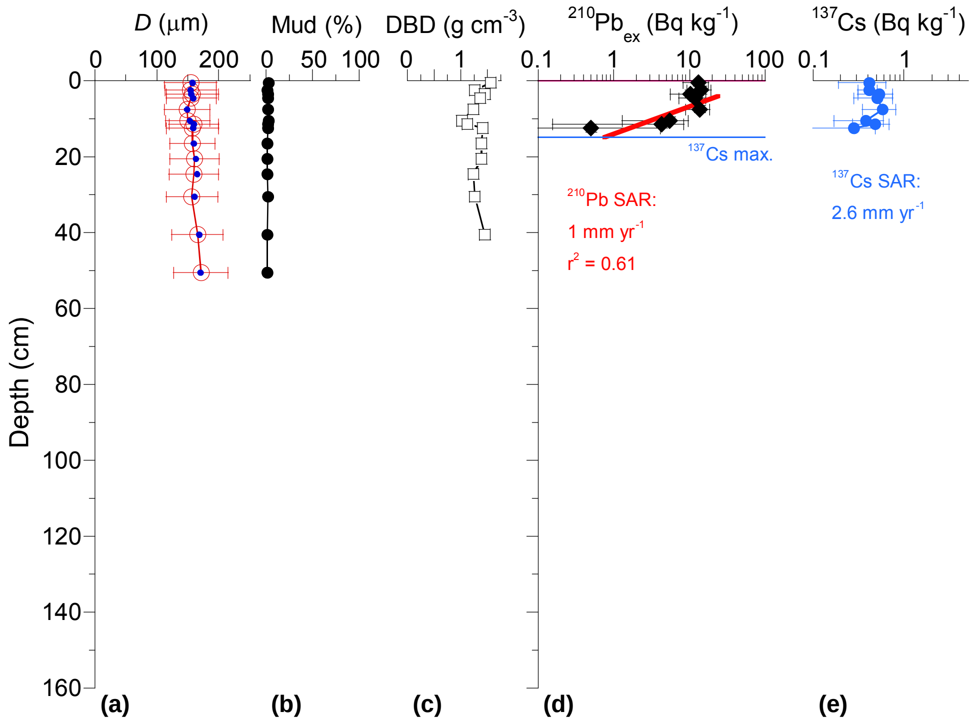


Figure 4.18 Core KAI-10A (Lower intertidal zone, Omokoiti Flats, Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.

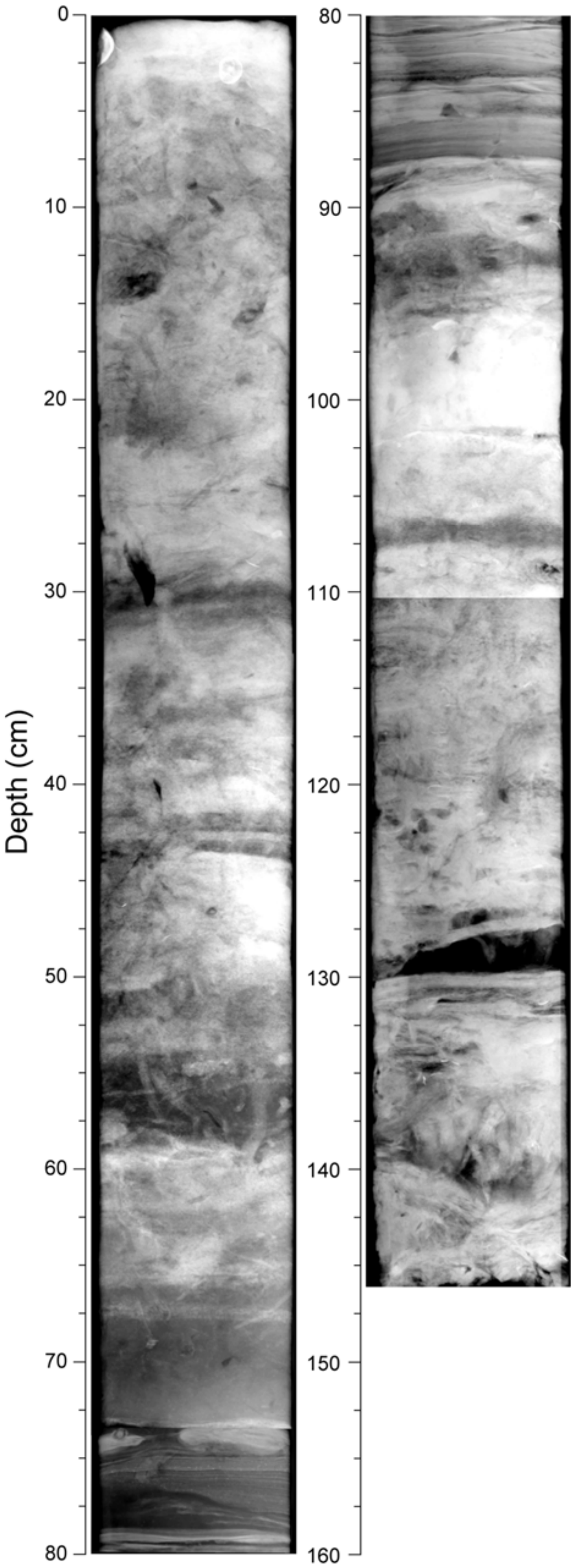


3.1.10 Site KAI-14 (Kakarai Flats, Hoteo)

Site KAI-14 is located on the lower-intertidal zone of the Kakarai Flats, approximately 2 km west of the Hoteo River mouth (Fig. 3.1). Two sediment cores 146 cm and 147-cm long were collected at this site.

The x-radiographs for KAI-14B display a range of estuarine sediment textures as previously described. The bulk of the core is composed of fine sands, although discrete mud layers up to ~6-cm thick occur at frequent intervals down the core: 30–32 cm; 41–43 cm; 50–51 cm; 54–58 cm; 72–88 cm; 91–93 cm; 105–106 cm and 126–128 cm (Fig. 4.19). Some of these mud units consist of two layers separated by a thin sand layer.

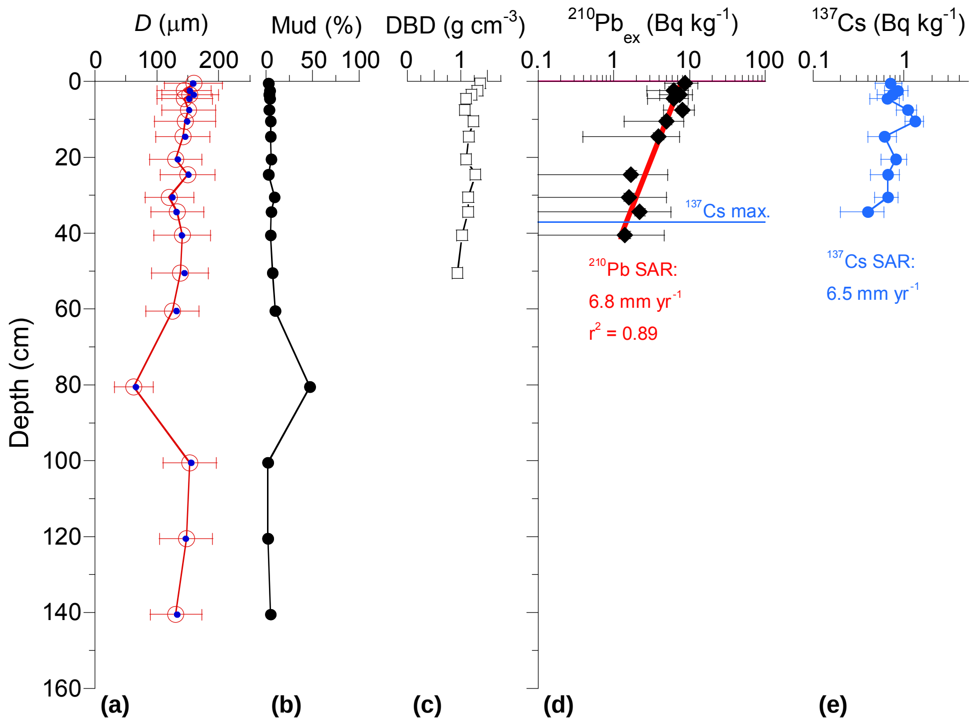
Figure 4.19 X-radiograph of core KAI-14B, lower-intertidal zone, Kakarai Flats, Kaipara Harbour.



The mud unit at 72–88 cm depth actually consists of many very-fine laminated sand and mud layers a millimetre or less thick. Some of these mud units contain the traces of animals burrows filled with denser sands (i.e., lighter coloured) from the under and overlying sediments (e.g., 54–58 cm). Traces of mm-scale worm burrows can also be seen in the sand layers. This sediment fabric is the same as that observed in the x-radiographs at site KAI-1 near the Kaipara River mouth. The high degree of preservation of the mud layers also indicates that sediment mixing by infauna has had a minor effect.

Sediment profiles show that the sand units are composed of slightly-muddy fine sands (D_{mean} = 125–150 □m), with mud content less than 10% (Figs. 4.20a–b). The mud content increases to 50% at 80 cm depth, within in the finely laminated bed at 72–88-cm depth. However, the sampling increment is too coarse to resolve the fine detail shown in the x-radiograph. Dry bulk sediment density in the top 50-cm of the cores is in the range 0.9–1.4 g cm^{-3} (Fig. 4.20c).

Figure 4.20 Core KAI-14B (lower-intertidal zone, Kakarai Flats, Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



The $^{210}Pb_{ex}$ profile extends to 41-cm depth in KAI-14A and is slightly deeper than for the ^{137}Cs profile (to 35 cm). (Figs. 4.20d–e). ^{7}Be was not detected in this core. Below The SML extends to about 2-cm depth, as indicated by the presence of a high-density sand layer in the x-radiograph. Sediments are rapidly accumulating at this site. The ^{210}Pb SAR of 6.8 mm yr^{-1} (r^2 = 0.89, Fig. 4.20d) is also very similar to ^{137}Cs SAR value (6.5 mm yr^{-1}, Fig. 4.20e).

The close agreement between these two SAR estimates as well as the largely intact core stratigraphy provides a high degree of confidence in the dating of this core. The numerous mud layers present at various depths in KAI-14 most likely represent storm layers deposited during flood discharges from the nearby Hoteo River.

3.1.11 Site KAI-16 (Hoteo River mouth)

Site KAI-16 is located on the Hoteo River delta, about 300 m south east of Breach Point (Figs. 3.1 and 4.21). Three sediment cores 152 cm, 154 cm and 175-cm long were collected at this site.

Figure 4.21 Hoteo River delta, March 2009. Core site KAI-16 is located near the bottom right corner of the photo on the north (left) side of the channel (Photo: A. Swales, NIWA).

The x-radiographs for KAI-16B provide a detailed record of mud and fine sand deposition in a deltaic sedimentary environment (Fig. 4.22). Finely-laminated mud and sand layers are common although less distinct than at sites KAI-1 and KAI-14. Crossing bedding and continuous beds inclined from the horizontal, and occasionally in opposite directions (e.g., 60–70 cm), are also evident as occur in channel-bank deposits subject to lateral migration (Reineck and Singh 1980). Traces of mm-scale worm burrows can be seen in the core but these are rare, which suggests that the sediment fabric is the result of physical rather than biological processes. Mud layers can be seen at various depths (10–11, 48–50, 68–70, 83–84, 106–108, 112–114, 131–132 and 138–140 cm) although they are more diffuse than at site KAI-14 on the intertidal-sand flat seaward of the river mouth. The mud units in KAI-16B are less distinct because of the much higher mud content of this delta deposit in comparison to the sand flat (KAI-14). Shell valves and fragments are rare, although a single large pipi (*Paphies australis*) valve occurs at 85–90 cm depth.

The sediments profiles for KAI-16A confirm that these deltaic deposits are composed of muddy very-fine sands. The D_{mean} and mud content of these sediments vary from 43 to 89 μm and 21–69% respectively (Figs. 4.23a–b). The DBD values in the top 110-cm of the core vary from 0.54 to 0.98 g cm^{-3}, with no discernable effects of compaction with depth being apparent (Fig 4.23c).

Excess ^{210}Pb occurs to at least 110-cm depth in core KAI-16A (Fig 4.23d). It is possible that the $^{210}Pb_{ex}$ profile extends tens of cm below this depth, however the estimated SAR of 21 mm yr^{-1} is supported by a comprehensive data set (r^2 = 0.75, n = 22, Fig. 4.23d). ^{137}Cs also occurs to 110-cm depth, so that the estimated SAR of 19 mm yr^{-1} is a minimum value (Fig. 4.23e). As noted for KAI-14, the close agreement between these two independent SAR estimates as well as the largely intact core stratigraphy provides a high degree of confidence in the dating of this core. ^{7}Be occurs to 5-cm depth, which coincides with a set of well-preserved finely-laminated muds and sands. These data indicate that these surficial sediments have been deeply reworked by tidal currents and/or waves.

The residence time of sediment in the SML before it is removed by burial is estimated from the maximum ^{7}Be depth and ^{210}Pb SAR as 50 mm/21 mm yr^{-1} = 2.4 years.

Figure 4.22 X-radiograph of core KAI-16B, Hoteo River mouth/delta, Kaipara Harbour.

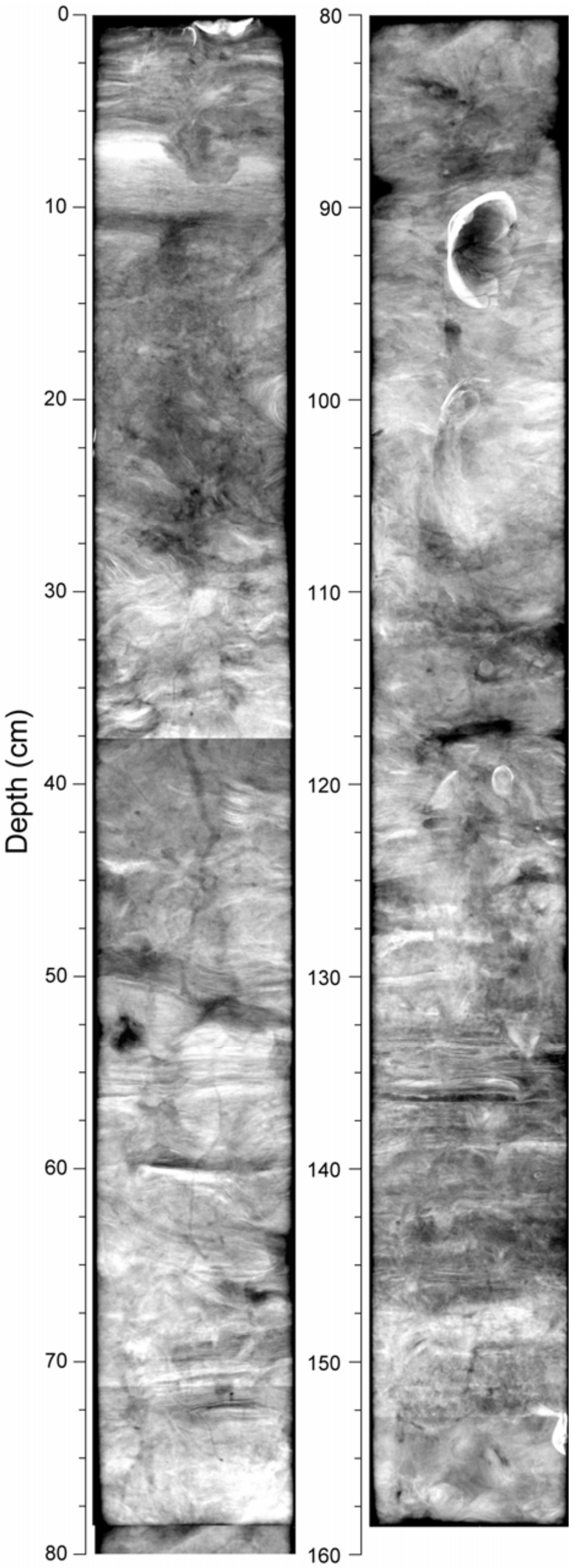
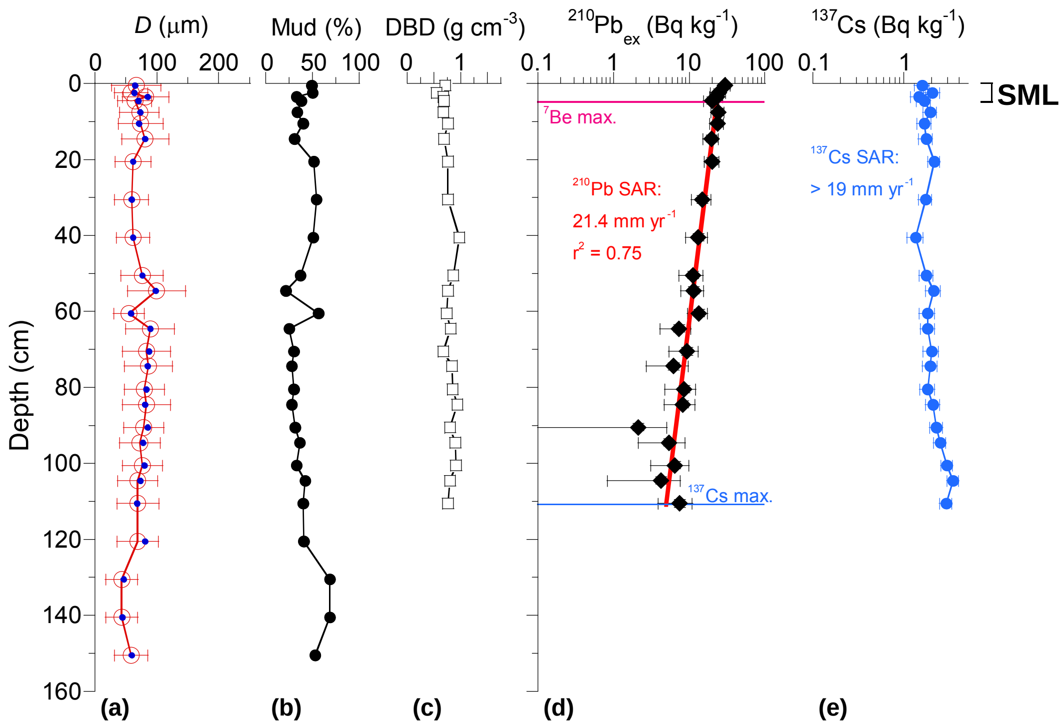


Figure 4.23 Core KAI-16A (delta deposits, Hoteo River mouth, Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.

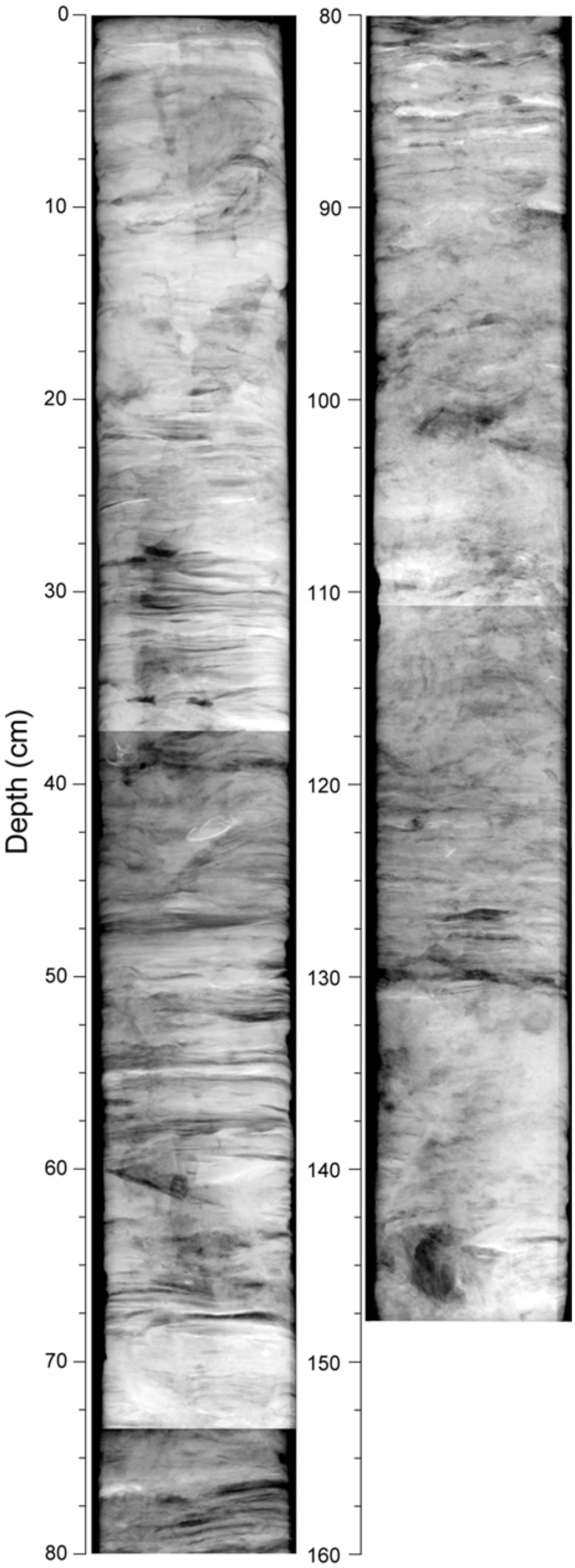


3.1.12 Site KAI-17 (Tauhoa River mouth)

Site KAI-17 is located at Te Raupa Creek, which is on the west bank of the Tauhoa River mouth (Figs. 3.1). Two sediment cores 139 cm and 145-cm long were collected from the lower-intertidal zone at this site.

The x-radiographs for KAI-17B provide a detailed record of deposition at this site (Fig. 4.24). Finely-laminated (i.e., mm scale) mud and sand layers characterise most of the core and is particularly well defined in the top 85-cm. Between 85 and 127 cm, the sediments have a mottled appearance indicative of bioturbated sediments and abundant traces of cm-scale burrows can be seen cross-cutting the bedding at 105–115-cm depth.

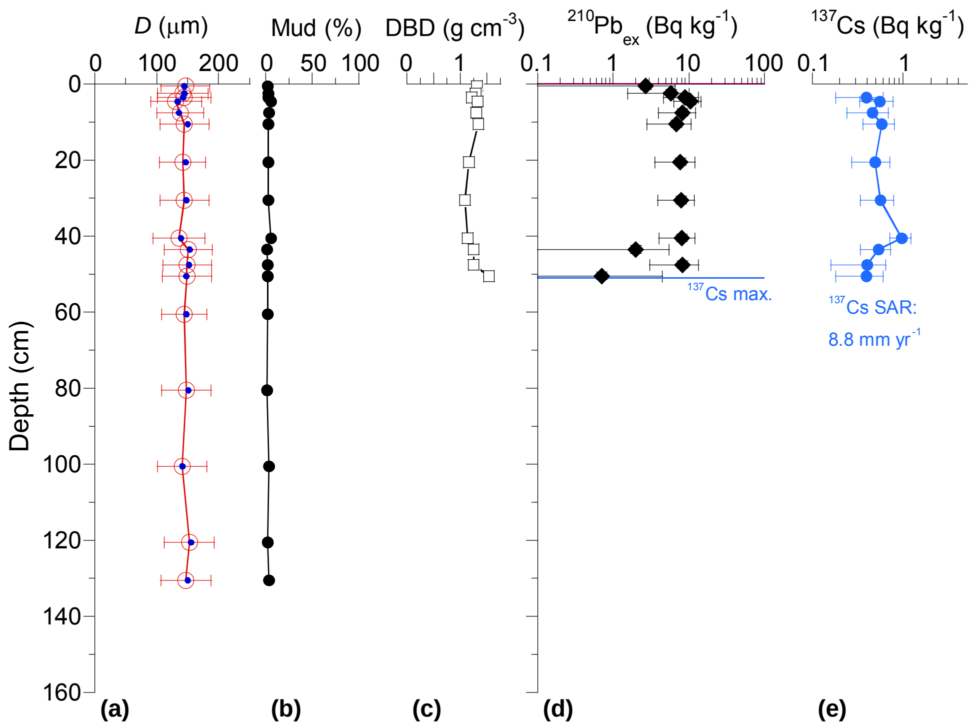
Figure 4.24 X-radiograph of core KAI-17B, Tauhoa River mouth, Kaipara Harbour.



A sharp contact between these bioturbated sediments and a higher-density, homogenous sand occurs at 127-cm depth, which extends to the base of the core at 145-cm.

The sediments profiles for KAI-17A show that the deposits are mainly composed of fine sands, with a relatively narrow range of D_{mean} of 131–151 m (Fig. 4.25a). The mud content of these sediments is also low (1.9–5.7%, Fig. 4.25b). The DBD values for these fine sands vary from 1.1 to 1.5 g cm^{-3} (Fig 4.25c).

Figure 4.25 Core KAI-17A (Tauhoa River mouth, Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



Excess ^{210}Pb and ^{137}Cs occur to at least 51-cm depth in core KAI-17A (Fig 4.25d). The $^{210}Pb_{ex}$ data is unusual, with a uniform concentration profile extending from 3 to 40 cm depth. The presence of a SML to 3-cm depth is indicated by the absence of ^{137}Cs and reduced $^{210}Pb_{ex}$ concentration (Fig 4.25e) and ^{7}Be was not detected at all. In the absence of an exponential decay profile, a ^{210}Pb SAR cannot be determined. Considering the 22-yr half life of ^{210}Pb, this type of uniform concentration profile suggests either very rapid deposition (i.e., over months–year) or complete mixing of the sediment column over a similar time scale. The laminated bedding shown in the x-radiograph points to rapid deposition as the most plausible explanation (Fig 4.24). This could potentially occur on a channel bank where rapid lateral migration of the channel away from the core site has occurred. The ^{137}Cs SAR will therefore be erroneous as we assume that the maximum ^{137}Cs depth represents deposition that occurred in the 1950s.

3.1.13 Site KAI-20 (Arapaoa River)

The Arapaoa River is one of several large tidal-creeks that occur in the Northern Kaipara Harbour (Figs. 3.1). The main channel is ~13 km long and aligned south-east – north-west. The channel is flanked by numerous infilled embayments with extensive intertidal flats. Sediment cores were collected from five sites in these embayments. Site KAI-20 is located near the mouth of the Arapaoa River system in the Hororako Creek and ~200 m east of Whakapirau Point. Three sediment cores 125 cm, 126 cm and 155-cm long were collected from the lower-intertidal zone at this site.

The x-radiographs for KAI-20B display a range of sediment fabrics: shell-rich sands (0–30 cm depth) with a possible SML (0–12 cm depth) consisting of dense sands, low-density muds (30–60 cm depth) and bioturbated muddy sands with numerous worm burrows filed with mud (Fig. 4.26). Shell material includes cockle valves and fragments and occasional gastrpods, such as the turret-shaped screw-shell *Maoriculpus roseus*.

The sediments profiles for KAI-20A mirror the bulk characteristics observed in the x-radiograph. The particle size profiles show that a well-sorted fine-sand occupies the top 12-cm of the core (D_{mean} = 134–150 µm) with a mud content less than 3% (Figs. 4.27a–b). This sand unit grades into a sandy mud at 30–80 cm depth (D_{mean} = 45–90 µm, mud content =27–75%), with the bioturbated muddy sand (D_{mean} = 84–110 µm, mud content =20–28%) below this mud layer to the base of the core at 160 cm. Sediment DBD values decline linearly from the surface (1.4 g cm^{-3}) to 40-cm depth (0.7 g cm^{-3}, Fig 4.27c), mirroring the decline in particle size in this depth range.

Excess ^{210}Pb and ^{137}Cs occurs to 11-cm depth in core KAI-20A (Fig 4.27d). The regression-model fit to the $^{210}Pb_{ex}$ data is poor (r^2= 0.37).The ^{210}Pb SAR value of 12.2 mm yr^{-1} is also several times higher than the ^{137}Cs SAR estimate (1.8 mm yr^{-1}), such that we have a low degree of confidence in the sediment dating at this site. ^{7}Be occurs to 1-cm depth in the core (Figs. 4.27d–e). The $^{210}Pb_{ex}$ coincides with the well-sorted fine-sand unit with low mud content that occupies the top 12-cm of the core. It is possible that these sediments represent a partially mixed surface layer, so that the $^{210}Pb_{ex}$ profile exhibits a steep decay profile due to mixing rather than sedimentation.

Figure 4.26 X-radiograph of core KAI-20B, Tauhoa River mouth, Kaipara Harbour.

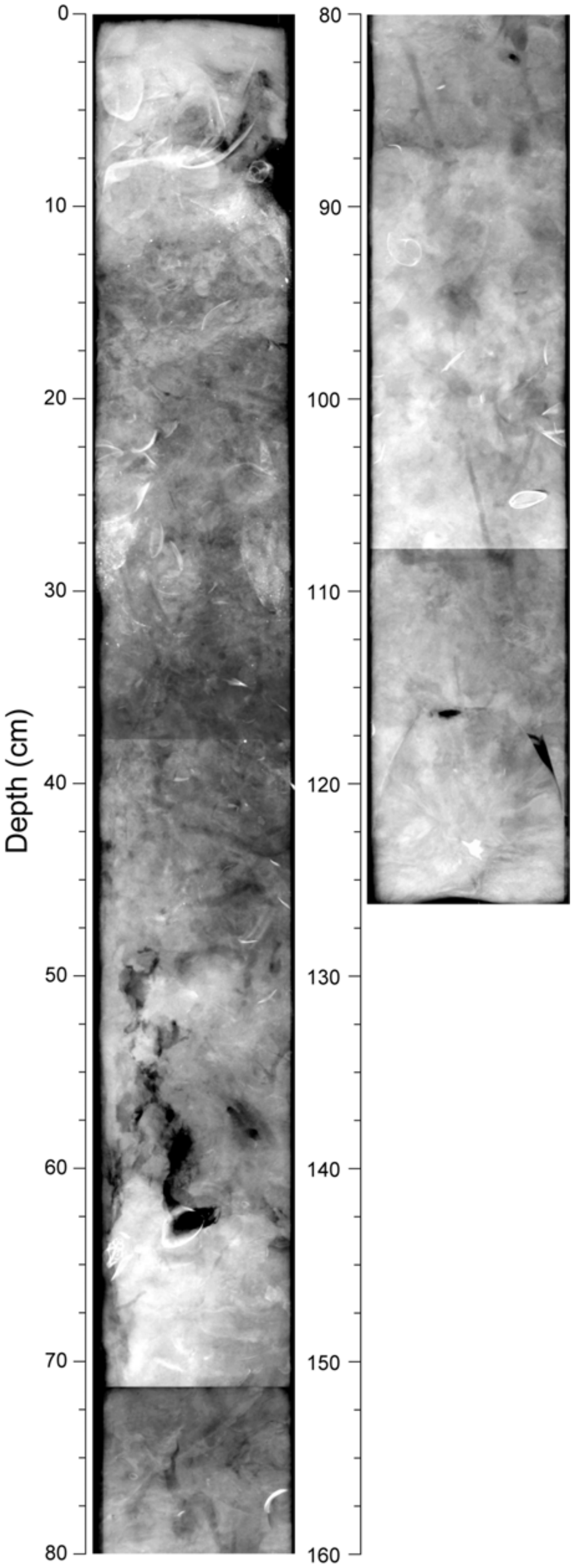
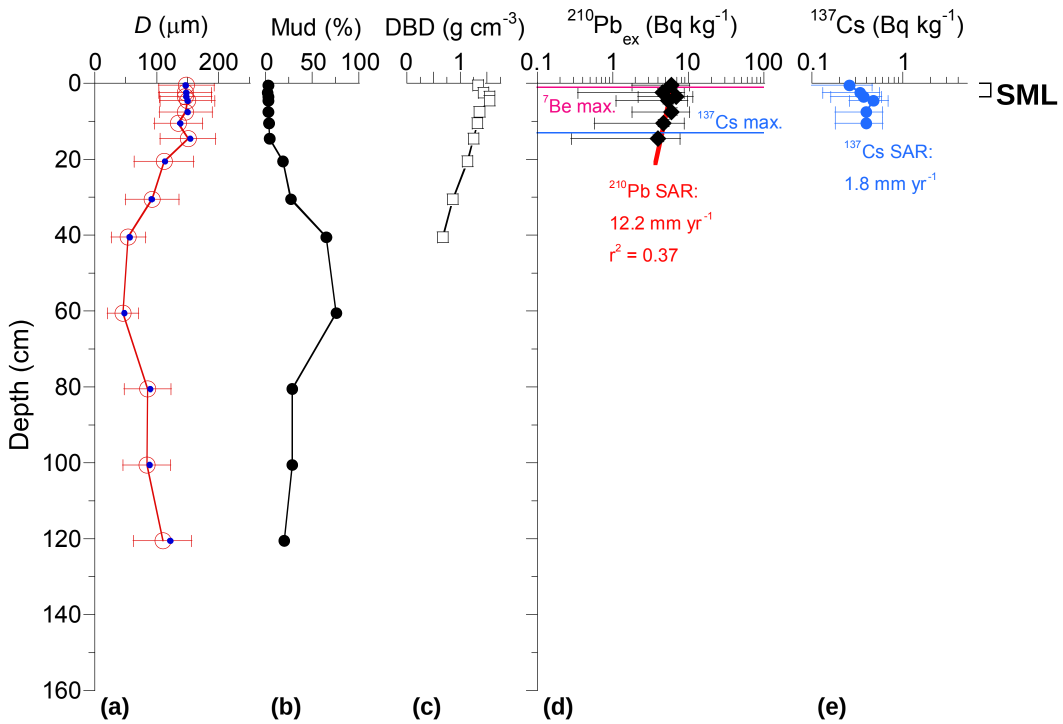


Figure 4.27 Core KAI-20A (Hororako Creek, Arapaoa River, north Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b)

percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.

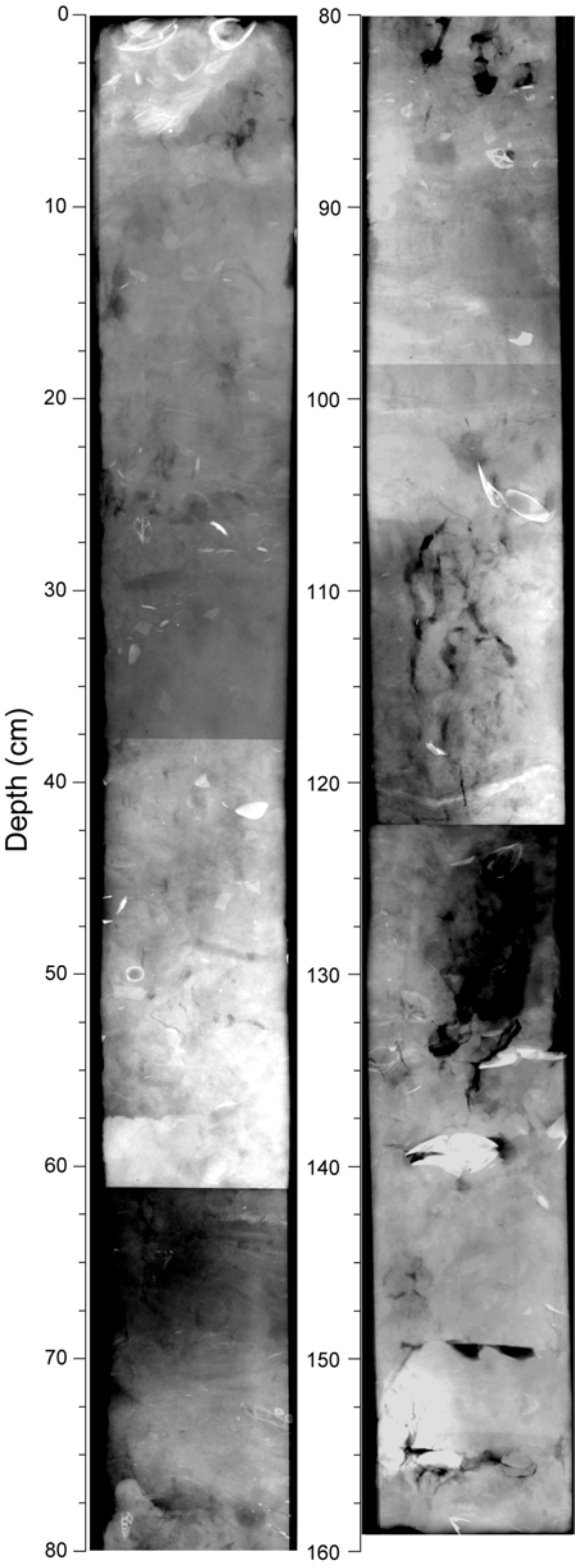


3.1.14 Site KAI-21 (Arapaoa River)

Site KAI-21 is located in an embayment on the west side of the Arapaoa River channel between Puriri and Te Kopua Points (Figs. 3.1). Three sediment cores 91 cm, 157 cm and 165-cm long were collected from the lower-intertidal zone at this site.

The x-radiographs for KAI-21B display a range of sediment fabrics: a shell-lagged (i.e., cockles) surface layer of fine sands (0–6 cm depth) which caps a sandy mud (6–30 cm depth) (Fig. 4.28). Below this depth, the core has a mottled appearance with bedding not well developed, although present as isolated patches. A distinct sand layer (5-mm thick) can be seen at 120-cm depth. However, traces of infauna burrows are rare. Occasional shell valves and fragments are present throughout the core.

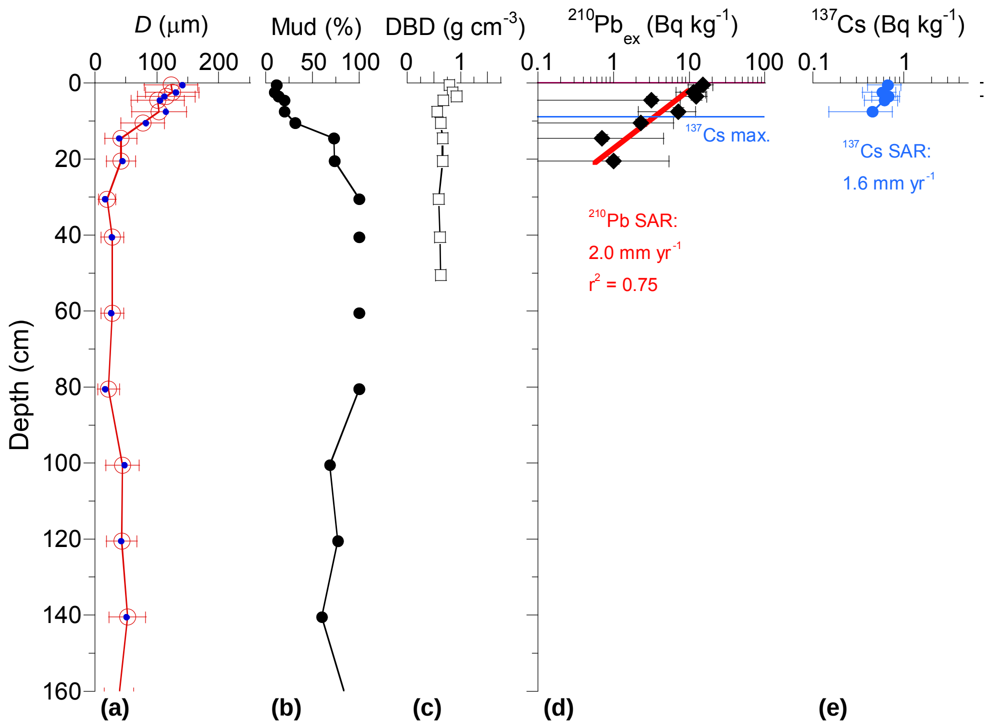
Figure 4.28 X-radiograph of core KAI-21B, Arapaoa River, Kaipara Harbour.



The sediments profiles for KAI-21A show a rapid decline in particle size from the surface to 20-cm depth. The mean particle diameter decreases from 125 □m to 42 □m, while mud content increasing from 10 to 70% (Figs. 4.29a–b). The sediment composition is relatively homogenous below this depth, with D_{mean} varying from 19–52 □m (medium–coarse silt) and mud content of 60–100%. Sediment DBD values gradually decline from the surface (0.85 g cm^{-3}) to 50-cm depth (0.61 g cm^{-3}, Fig. 4.29c).

The $^{210}Pb_{ex}$ profile extends to 21-cm depth in KAI-21A, which is twice the depth of the ^{137}Cs profile (to 9 cm). (Figs. 4.29d–e). ^{7}Be was not detected in the core. The ^{210}Pb SAR of 2 mm yr^{-1} (r^2 = 0.75) is similar to the ^{137}Cs value of 1.6 mm yr^{-1} and this provides some confidence in the sediment dating at this site.

Figure 4.29 Core KAI-21A (Arapaoa River, north Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



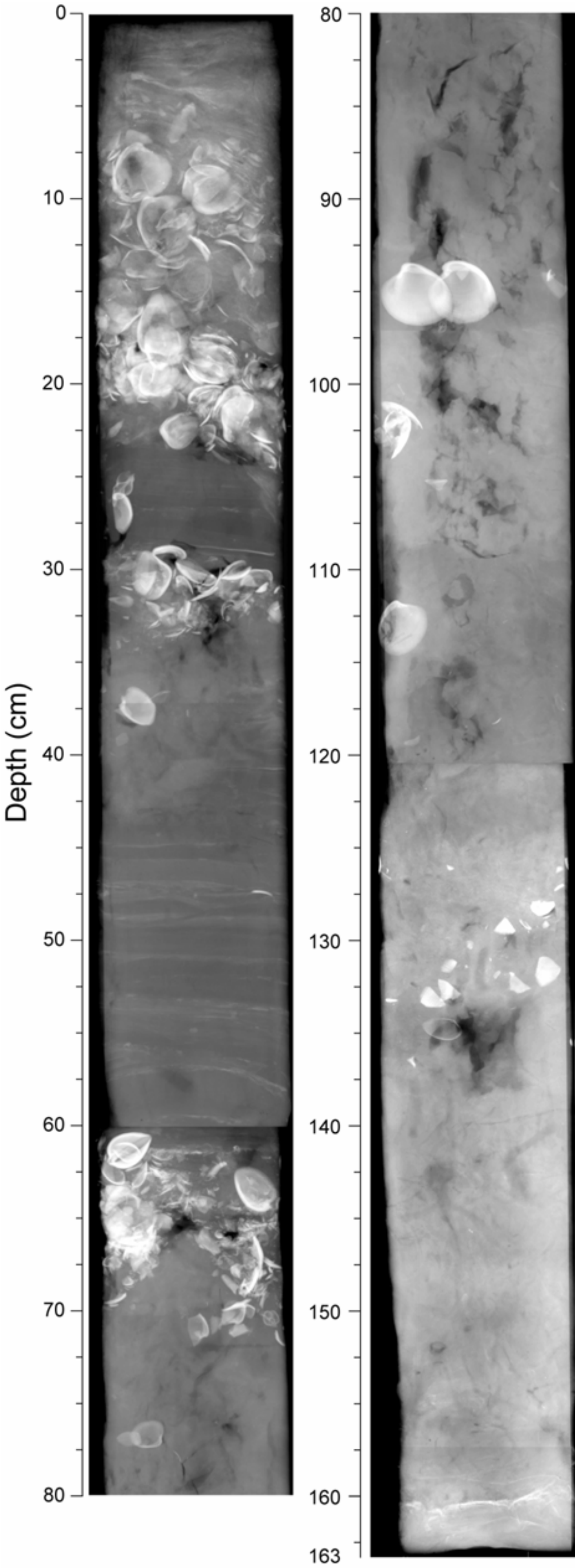
3.1.15 Site KAI-22 (Arapaoa River)

Site KAI-22 is located in the Rapere Creek on the west side of the Arapaoa River channel (Figs. 3.1). Two sediment cores 132 cm and 161-cm long were collected from the mid-intertidal zone at this site.

Core KAI-22B preserves a detailed record of sedimentation at this site. The x-radiographs suggest that the processes of sediment deposition at the site have varied substantially over time (Fig. 4.30). A surface layer of laminated sediments (0–6-cm depth overly cockle-shell valves and fragments (6–

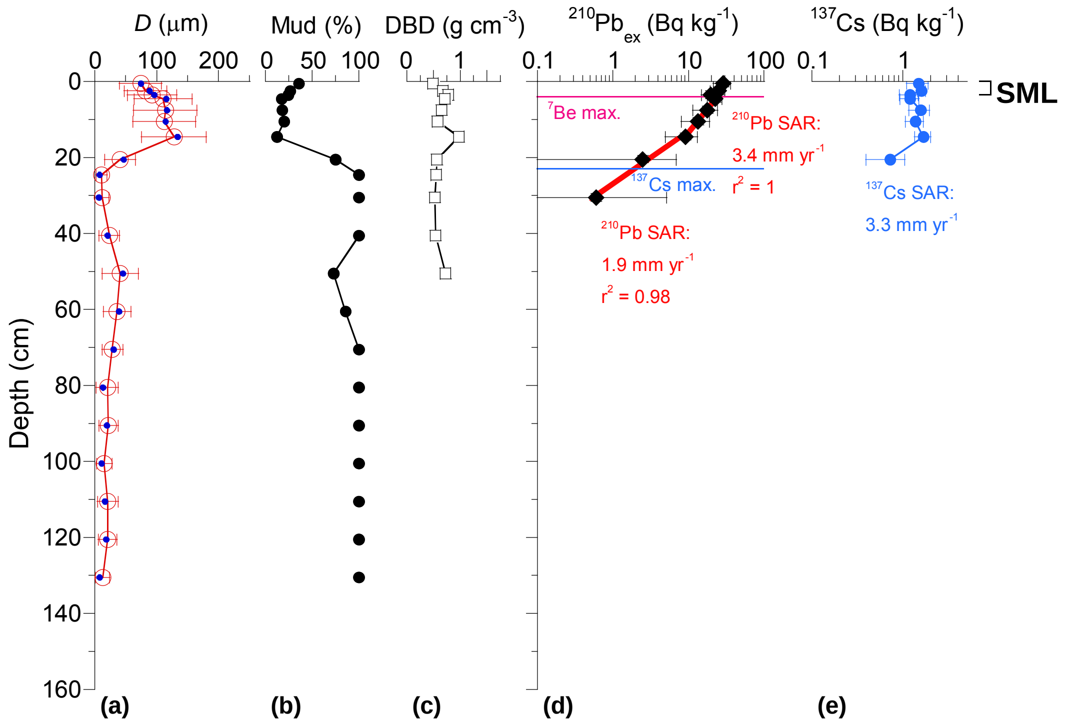
23 cm depth). A sharp contact and transition to very-finely laminated muds (23–30 cm depth) occurs at the base of the shell layer. Differences in grey-scale values are small, which suggests subtle differences in particle size within this laminated mud. Another cockle-shell layer (30–34 cm depth) occurs below the laminated mud and is underlain by a featureless mud (34–42-cm depth). This is replaced by well-preserved laminated sediments (42–60 cm depth). Individual mud layers 1–2 cm thick are separated by mm-thick sand layers, which appear light grey/white in the image. A sharp contact with a cockle shell layer (60–70-cm depth) occurs at the base of these laminated beds. The remainder of the core (70–163-cm depth) is composed of mud with rare cockle-shell valves and fragments. This unit has a mottled appearance that suggests a degree of sediment mixing. With the exception of a thin sand layer at the base of the core, there is little evidence of bedding in this mud and traces of mm-scale worm burrows can be seen.

Figure 4.30 X-radiograph of core KAI-22B, Raepere Creek, Arapaoa River, Kaipara Harbour.



The sediments profiles for KAI-22A show a rapid transition from muddy very-fine sands in near-surface sediments (D_{mean} = 74–127 µm, mud content 12–26%) to mud (D_{mean} = 11–41 µm, mud content 75–100%) below 15-cm depth (Figs. 4.31a–b). Sediment DBD values vary from 0.49 g cm^{-3} to 0.98 g cm^{-3} in the top 50-cm of the core (Fig. 4.31c).

Figure 4.31 Core KAI-22A (Raepere Creek, Arapaoa River, north Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



The excess ^{210}Pb profile extends to 31-cm depth in core KAI-22A. The data indicate an apparent change in SAR at 15-cm depth (Fig 4.31d), which coincides with the transition from mud to fine-sand deposition (Figs. 4.31a–b). The log-linear regression models fitted to these data yield ^{210}Pb SAR of 1.9 mm yr^{-1} (r^2 = 0.98) and 3.4 mm yr^{-1} (r^2 = 1) below and below 15-cm depth. ^{137}Cs occurs to 21-cm depth (Fig. 4.31e) which spans the transition to a higher sedimentation regime indicated by the $^{210}Pb_{ex}$ data. The ^{137}Cs SAR of 3.3 mm yr^{-1} is similar to the ^{210}Pb SAR value above 15-cm depth. ^{7}Be occurs to 4-cm depth and coincides with the finely-laminated muds and sands. These data are consistent with a SML produced by wave re-suspension.

The residence time of sediment in the SML before it is removed by burial is estimated from the maximum ^{7}Be depth and ^{210}Pb SAR as 40 mm/3.4 mm yr^{-1} = 12 years.

3.1.16 Site KAI-23 (Arapaoa River)

Site KAI-23 is located in the Kirikiri Inlet on the west side of the Arapaoa River channel (Figs. 3.1). Two sediment cores 134 cm and 170-cm long were collected from the mid-intertidal zone at this site.

The sediments deposited at site KAI-23 are similar to those described for site KAI-22, with alternating shell and mud layers in the upper ~80-cm of the sediment column. The x-radiographs for KAI-23B show: a surface layer composed of tightly-packed cockle-shell valves and fragments (0–28 cm depth, Fig. 4.32); mud with occasional cockle-shell valves (28–55 cm); a cockle-shell layer (55–62 cm depth); mud with occasional cockle-shell valves (62–74 cm); a cockle-shell layer (74–85 cm depth); homogenous mud with occasional shell valves of cockle and the large wedge shell (*Macomona lilliana*, 116-cm and 156-cm depth).

Particle-size data show that the surface shell layer is mixed with layers of very-fine sand and mud (D_{mean} = 22–144 μm, mud content 17–100%, Fig. 4.33a–b). Below 20-cm depth, sediments are composed entirely of mud (D_{mean} = 10–21 μm, mud content 100%). Sediment DBD values vary from 0.49 g cm^{-3} to 0.98 g cm^{-3} in the top 50-cm of the core (Fig. 4.33c).

Excess ^{210}Pb occurs to 15-cm depth, within the surface shell layer (Fig 4.33d). The SAR estimated from the $^{210}Pb_{ex}$ profile is 1.6 mm yr^{-1} (r^2 = 0.94). ^{137}Cs occurs to 17-cm depth (Fig. 4.33e), with an estimated SAR of 2.6 mm yr^{-1}. This is substantially higher than the ^{210}Pb SAR estimate so that the dating at this site is uncertain. The data do however indicate that the surface shell layer has accumulated over several decades. ^{7}Be occurs to 4-cm depth, which suggests that the shell layer is actively reworked to this depth. Alternatively, ^{7}Be-labelled sediments may be circulated through the upper few cm of the permeable surf ace shell layer by wave-driven flows.

Figure 4.32 X-radiograph of core KAI-23B, Kirikiri Inlet, Arapaoa River, Kaipara Harbour.

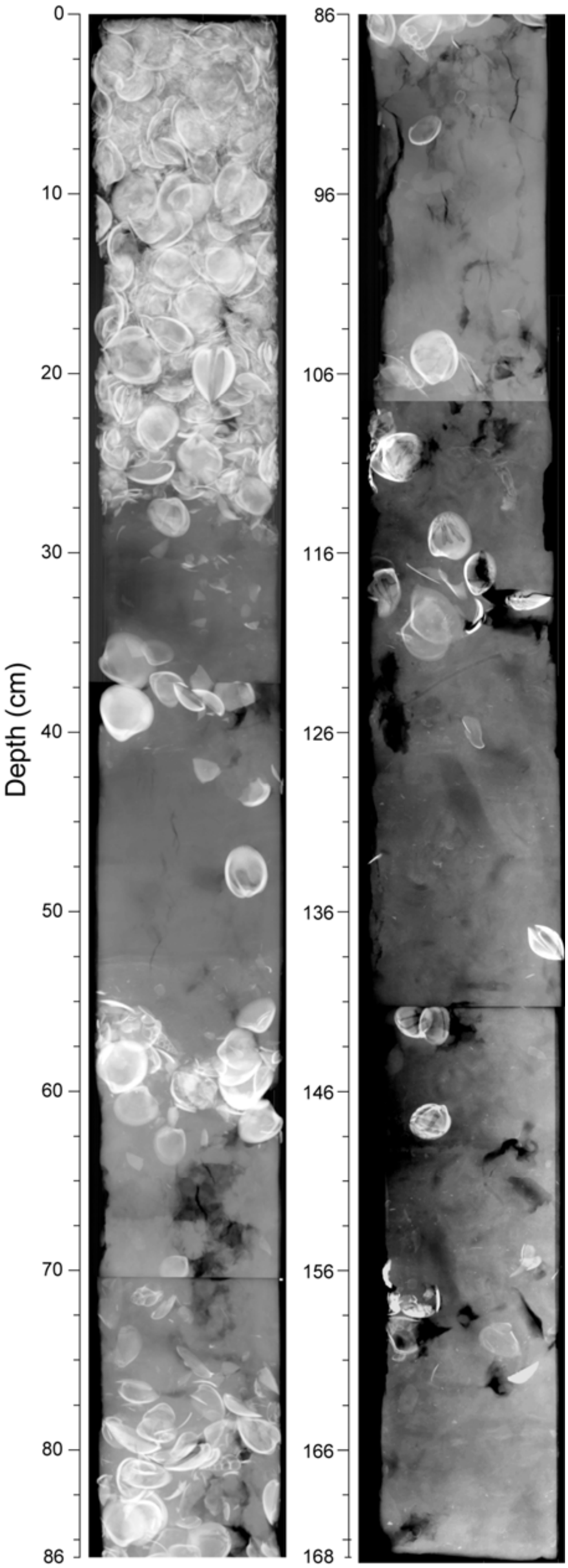
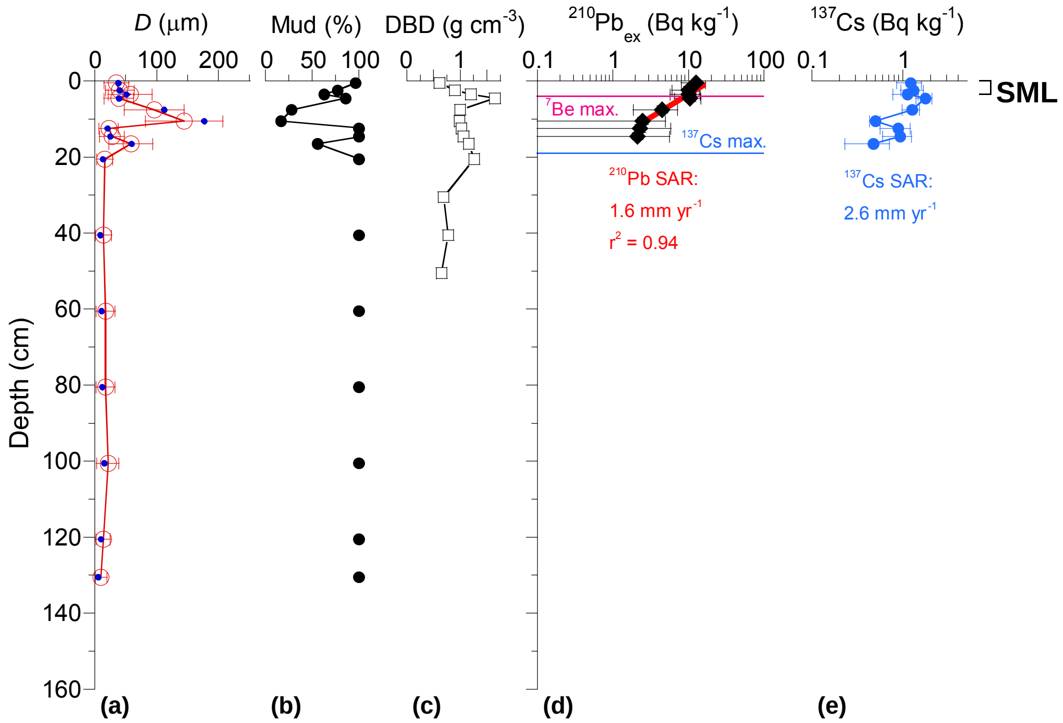


Figure 4.33 Core KAI-23A (Kirikiri Inlet, Arapaoa River, north Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by

sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



3.1.17 Site KAI-24 (Arapaoa River)

Site KAI-24 is located in the basin at the head of the Arapaoa River, west of Pahi township (Figs. 3.1). The basin receives runoff from Paparoa Stream and the Matakohe River. Three sediment cores 106 cm, 145 cm and 170-cm long were collected from the mid-intertidal zone at this site.

The x-radiographs for KAI-24C indicate a general trend of increasing mud content with depth (i.e., time), and a change from light coloured to darker-coloured sediment (Fig. 4.34). The sequence of sediment units are: a surface layer composed of sand with coarse sand particles and cockle-shell valves and fragments (0–10 cm depth); inter-layered cm-thick mud and sand beds (10–30 cm depth); shell layer composed of cockle shell and gastropods (i.e., whelks) at the base (30–50 cm depth). A large inclined burrow ~2-cm diameter occurs at 40-cm depth; mixed muddy-sand (50–60 cm depth); cockle-shell layer (60–64-cm depth); homogenous mud (64–94-cm depth); cockle-shell layer with rare screwshells (*M. roseus*, 94–112-cm depth); and mud with traces of worm burrows (112–166-cm depth) with abundant cockle-shell valves and fragments at 150–160 cm depth.

Particle-size data show that the underlying mud is capped by a 60-cm thick surface layer of fine sands (Fig. 4.35a). The mud content in this sand layer is less than 6% compared to 26–100% below 60-cm depth (Fig. 4.35b). Sediment DBD values vary from 1.1 g cm^{-3} to 1.5 g cm^{-3} in the top 20-cm of the core (Fig. 4.35c).

Excess ^{210}Pb and ^{137}Cs occur to 11-cm depth. The $^{210}Pb_{ex}$ concentrations are uniform to 5-cm depth, which indicates that these sediments are well mixed (Fig 4.35d). There is insufficient data below this depth to estimate a ^{210}Pb SAR. The maximum depth of ^{137}Cs in the sediment is used to estimate a SAR of 2.6 mm yr^{-1} (Fig 4.35e) although this cannot be validated by the ^{210}Pb data. ^{7}Be occurs to 1-cm depth. The difference in the mixing depths indicated by the ^{7}Be (half life = 53 days) and ^{210}Pb (half life = 22 years) profiles may reflect different time scales for mixing (i.e., days–weeks versus years).

Figure 4.34 X-radiograph of core KAI-24C, Pahi, Arapaoa River, Kaipara Harbour.

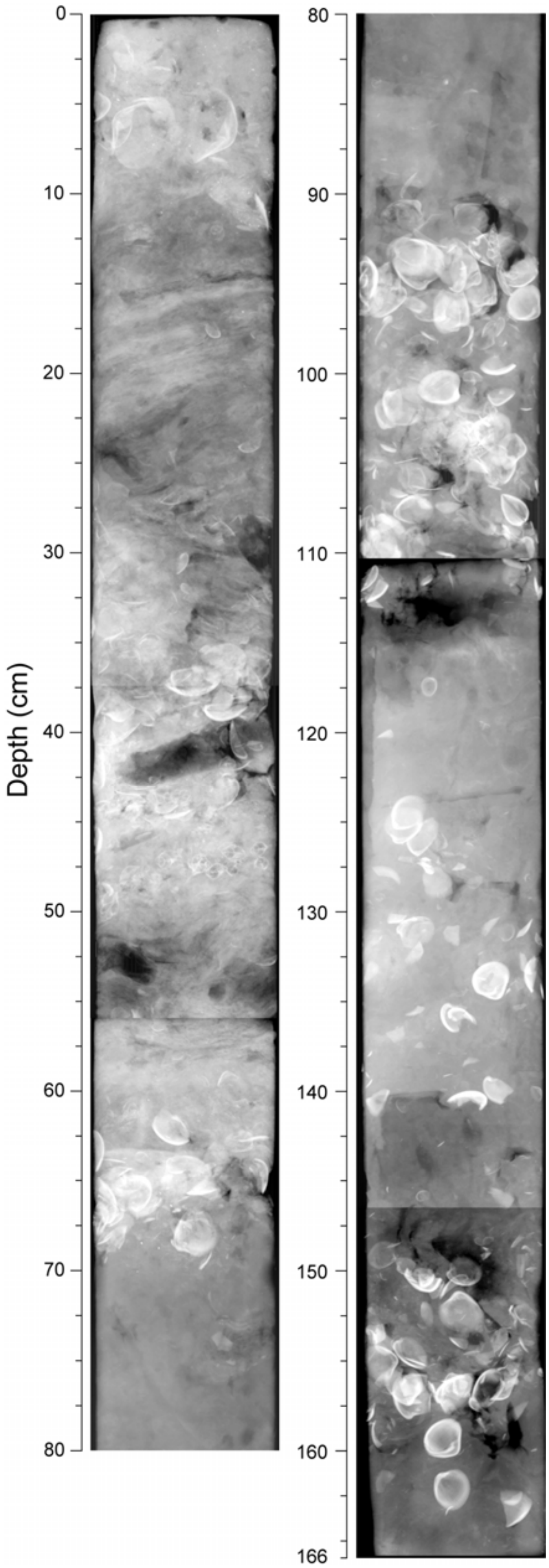
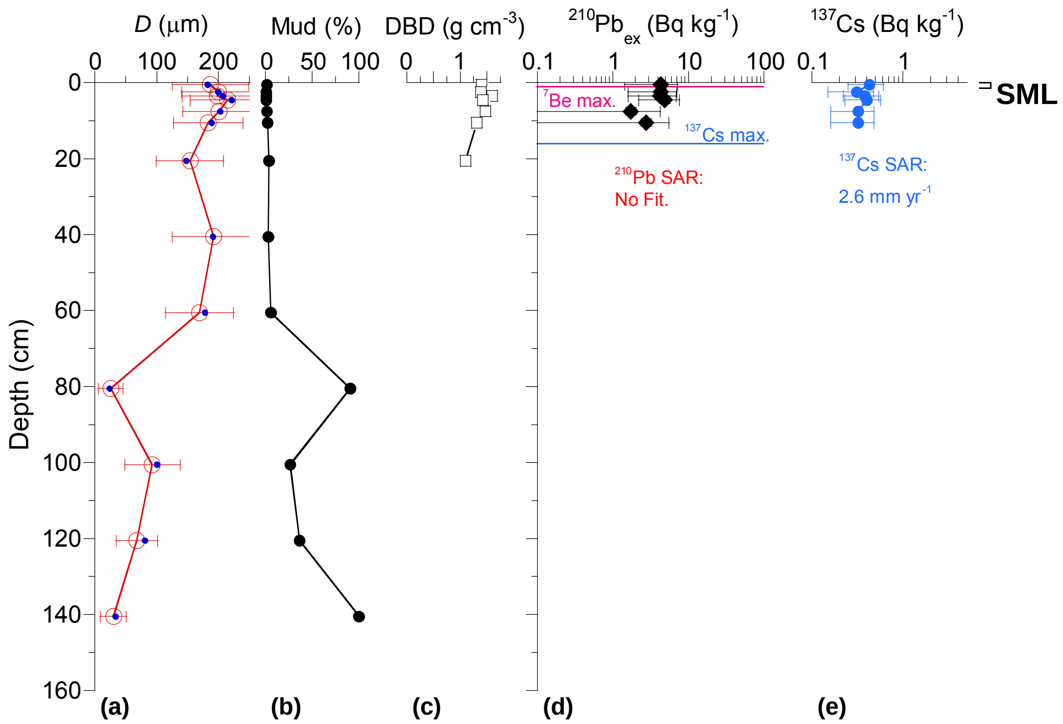


Figure 4.35. Core KAI-24A (Pahi, Arapaoa River, north Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.

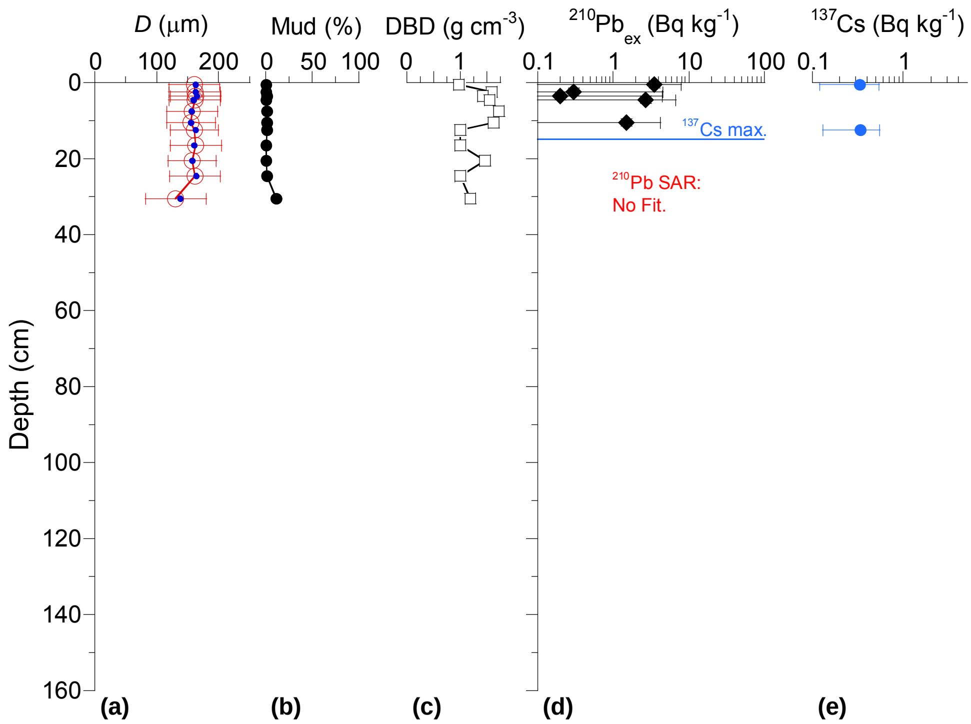


3.1.18 Site KAI-25 (Intertidal flats, Wairoa River mouth)

Site KAI-25 is located on the intertidal flats east of the Wairoa River mouth and south of the Whakatu mangrove forest and oyster reefs previously described in section 2.3 (Figs. 3.1). The site was difficult to sample because the bed was composed of compact sands and the shallow water depth that limited the effectiveness of the gravity corer. Only one sediment core, 34-cm long, was successfully retrieved at this site.

The single core collected at this site was not x-ray imaged, however particle-size analysis was undertaken. Figures 4.36a–b show that the top 30-cm of the sea bed is composed of well-sorted fine sand (D_{mean} =155–162 □m) with mud content less than 2%. Sediments at the base of the core are finer (D_{mean} =131 □m, mud content 12%), which may indicate that these near-surface sand cap muddier sediments at depth. Dry bulk sediment densities vary between 0.9 and 1.7 g cm^{-3} (Fig. 4.36c).

Figure 4.36 Core KAI-25A (Intertidal flats south of Whakatu mangrove forest, north Kaipara Harbour) sediment profiles: (a) particle size statistics – mean (red), median (blue) and standard deviation; (b) percentage mud by sample volume; (c) dry-bulk sediment density; (d) excess ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and coefficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be depth and maximum ^{137}Cs depth; (e) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR shown. Note: The surface-mixed layer (SML) is defined by the maximum ^{7}Be depth. The ^{137}Cs SAR is estimated after subtraction of the ^{7}Be mixing depth.



Excess ^{210}Pb and ^{137}Cs occur to 11 cm and 13-cm depth respectively (Fig. 4.36d–e). The concentrations of both radioisotopes are low and variable, so that we could not reliably estimate the sediment accumulation rate at this site. ^{7}Be was also not detected in the surficial sediments. The low and variable $^{210}Pb_{ex}$ and ^{137}Cs concentrations and low mud content indicate that bed sediments at site KAI-25 are frequently reworked by waves. Although silts and clays may temporarily be deposited at this site after storms, long-term accumulation does not occur.

3.2 Recent changes in vegetated intertidal habitats

3.2.1 Summary

In this section we report on changes in the spatial extent of vegetated intertidal habitats since 1966/1977. These data are derived from GIS analysis of historical aerial photographs for each compartment of the Kaipara Harbour (section 3.6). Table 4.1 summarises the overall changes in the total areas of mangrove forest, salt marsh, mixed mangrove/salt marsh and sea grass (*Zostera* spp.) habitats in the harbour.

Table 4.1 Changes in the area (hectares) of major intertidal vegetation habitats in the Kaipara Harbour: 1977–2002 (Northland Region); 1966/1977–2007 (Auckland Region). Notes: (1) 1966 data for the South Head, Omokoiti Flats and South Kaipara compartments only. Data for the Oruawharo includes AC and NRC regions; (2) Mixed refers to habitat composed of mangrove and saltmarsh; (3) The sea grass per cent change estimate does not include 90.4 ha (2007) in the South Head compartment as no data were available for 1977.

Habitat Type	Auckland			Northland			Harbour - total
	1966/1977	2007	% change	1977	2002	% change	2002/2007
Mangroves	4744.0	4661.0	-1.7	2101.1	2953.8	40.6	7614.8
Salt marsh	445.8	306.9	-31.1	238.5	352.6	47.8	659.5
Mixed	417.0	211.6	-49.3	–	–	–	
Sea grass	–	358.5		–	–	–	

This analysis indicates that the total area of mangrove habitat 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 substantially reduced the area of mangrove habitat in the South Kaipara and Omokoiti compartments. Differences in the years of aerial-photographic coverage between the Auckland and Northland regions makes direct comparisons problematic, however at the regional scale the data are unequivocal. The total area of mangrove in the Auckland region (Kaipara) has not substantially changed since 1966/1977. The apparent 1.7% reduction in mangrove area is likely within the errors of the analysis. This is particularly the case for identification of vegetation types from the small-scale black and white 1966/1977 aerial photography. A substantial increase in mangrove habitat has occurred in the Northland region of the Kaipara Harbour (41%), increasing from an estimated 2101 ha in 1977 to 2954ha in 2002. This estimate includes data from the Auckland Region for the Oruawharo compartment which straddles the regional boundary.

The total area of salt-marsh habitat in the Kaipara Harbour has reduced (-3.6%) from an estimated 684.3 ha (1966/1977) to 659.5 ha in 2002/2007, with all of this apparent reduction occurring in the Auckland region (-31%). By comparison the area of salt marsh in the Northland region has increased by 48% since the mid 1970s. Loss of salt marsh has historically occurred due to reclamation and by the landward expansion of mangrove forests. Displacement of salt-marsh habitat by mangrove (*A. marina* var. *australasica*) is a common mode of mangrove-forest expansion in south-east Australian estuaries. In New Zealand, mangrove forests more typically colonise bare intertidal flats, although landward expansion into salt marsh has been documented (Morrissey et al. 2010).

The area of mixed (mangrove and salt-marsh) habitat has also substantially reduced (-49%) in the Auckland region, from 417 ha (1966/1977) to 212 ha in 2007. The largest reductions in mixed habitat has occurred in the South Kaipara (-86%) and Omokoiti Flats (-78%) compartments and are primarily due to reclamation works. Thus, the reduction in salt-marsh habitat in the Auckland region of the harbour is primarily a result of reclamation rather than mangrove encroachment.

Data on present-day (2007) sea-grass habitat was available for the Auckland region of the harbour. No sea-grass meadows were identified in the northern Kaipara. Almost all of the sea-grass beds occur in the Central Kaipara (41 ha), Omokoiti Flats (227 ha) and South Head (91 ha) compartments.

In the next section, changes in the area of intertidal vegetated habitats are described for each compartment.

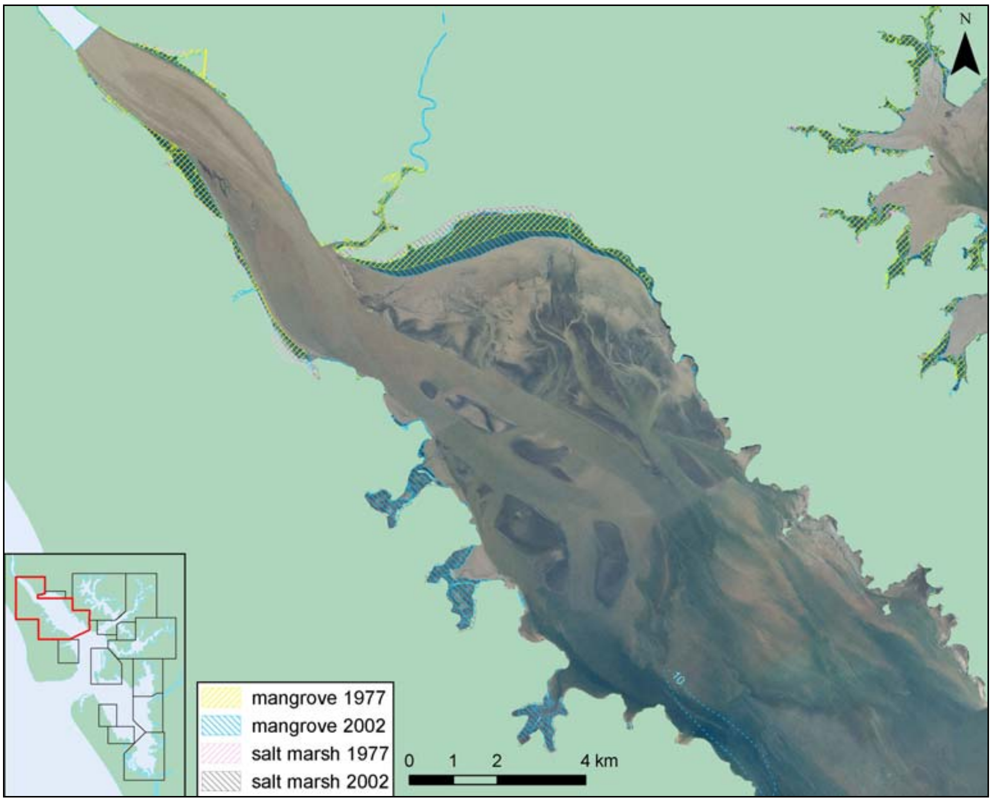
3.2.2 North Kaipara

Table 4.2 and Figure 4.37 summarise the changes in mangrove and salt-marsh habitats that have occurred in North Kaipara compartment during the 25-year period 1977–2002. Mangrove and salt-marsh habitat represents 5.1% and 22% (2002) respectively of the total area of these vegetated habitats in the harbour. The rate of change in the area of mangrove and salt-marsh habitat could not be estimated because aerial photographic coverage for the 1977 survey is incomplete.

Table 4.2 North Kaipara: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2002).

Habitat	1977 (ha)	2002 (ha)	% change	%/yr
Mangrove	161.9	386.7	–	–
Salt marsh	84	145.2	–	–

Figure 4.37 North Kaipara: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2002.



3.2.3 Whakatu mangrove forest

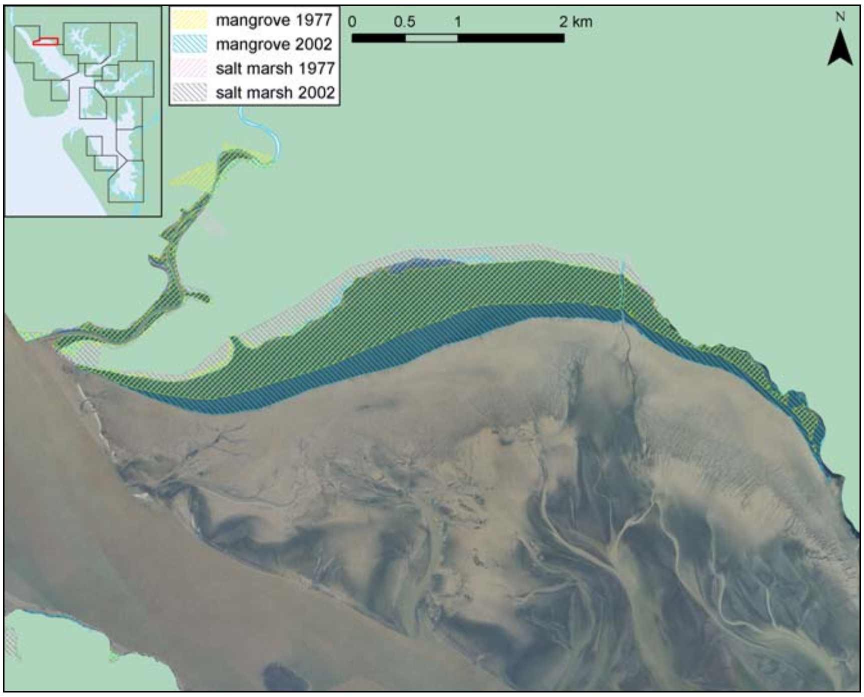
Table 4.3 summarises the changes in mangrove and salt-marsh habitats that have occurred in Whakatu mangrove forest compartment. Mangrove and salt-marsh habitat represent 4.4% and 10.8% (2002) respectively of the total area of these habitats in the harbour. The area of mangrove forest increased by 53% during the period 1977–2002. As described above, most of this increase in mangrove-forest area has occurred due to colonisation of the intertidal mudflats (Fig. 4.38).

Table 4.3 Whakatu mangrove forest: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2002).

Habitat	1977 (ha)	2002 (ha)	% change	%/yr
Mangrove	218.6	334.6	53.1	2.1
Salt marsh	68.8	71.5	3.9	0.15

The Whakatu mangrove forest has a number of similarities with the southern Firth of Thames mangrove forest: close proximity to a large river (i.e., fine-sediment supply); rapidly accreting mud flats; wave-driven onshore mud transport; and a stop bank, which constrains the landward expansion of the forest (Swales and Bentley 2008). Small increases in salt-marsh area (3.9%) have occurred between the stopbank and landward boundary of the mangrove forest. The annual-average rate of increase in mangrove habitat (2.1% yr^{-1}) is ten times higher than for salt marsh.

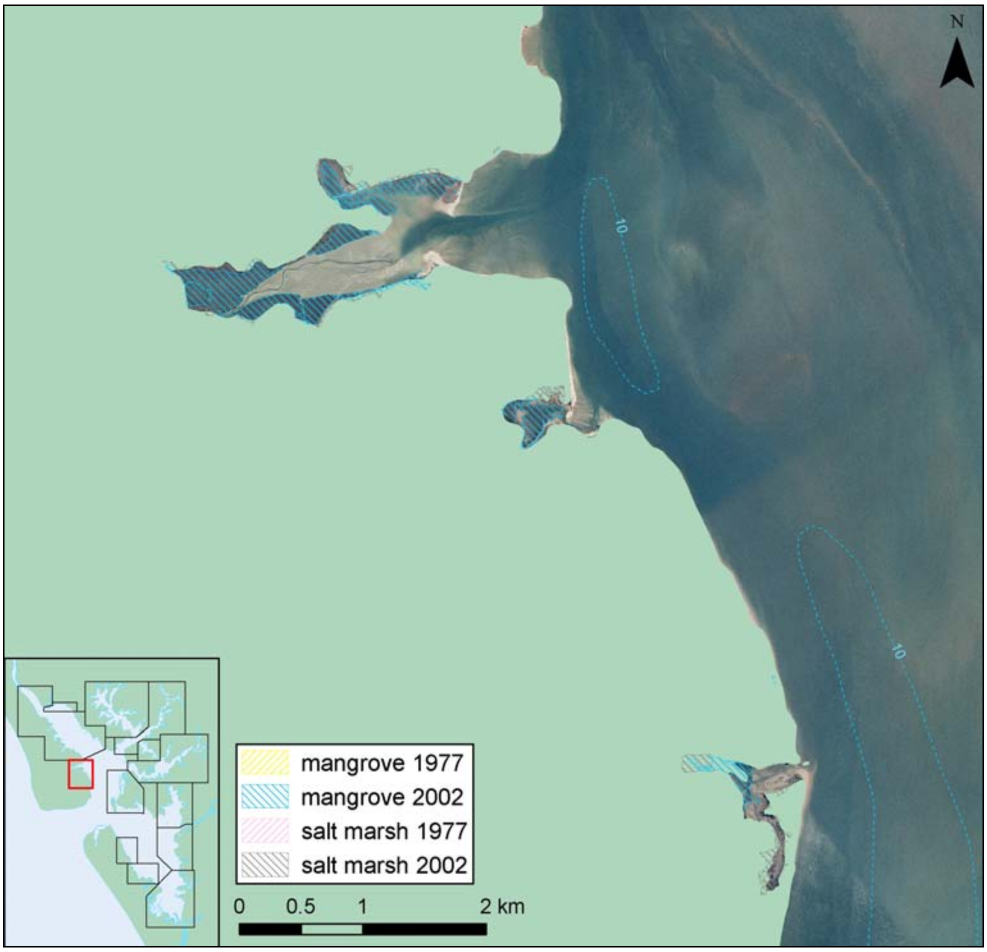
Figure 4.38 Whakatu mangrove forest: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2002.



3.2.4 North Head

North Head compartment includes the shoreline between Ru Point and Pouto Point. The largest inlet with mangrove and salt-marsh habitat is the Okaro Creek (Fig 4.39). Mangrove (64.2 ha) and salt-marsh (24.7 ha) represent 0.8% and 3.7% (2002) respectively of the total area of these habitats in the Kaipara Harbour. No data were available for the 1977 aerial survey so that changes in habitat area cannot be estimated.

Figure 4.39 North Head: spatial distribution of mangrove and salt-marsh habitat (2002).



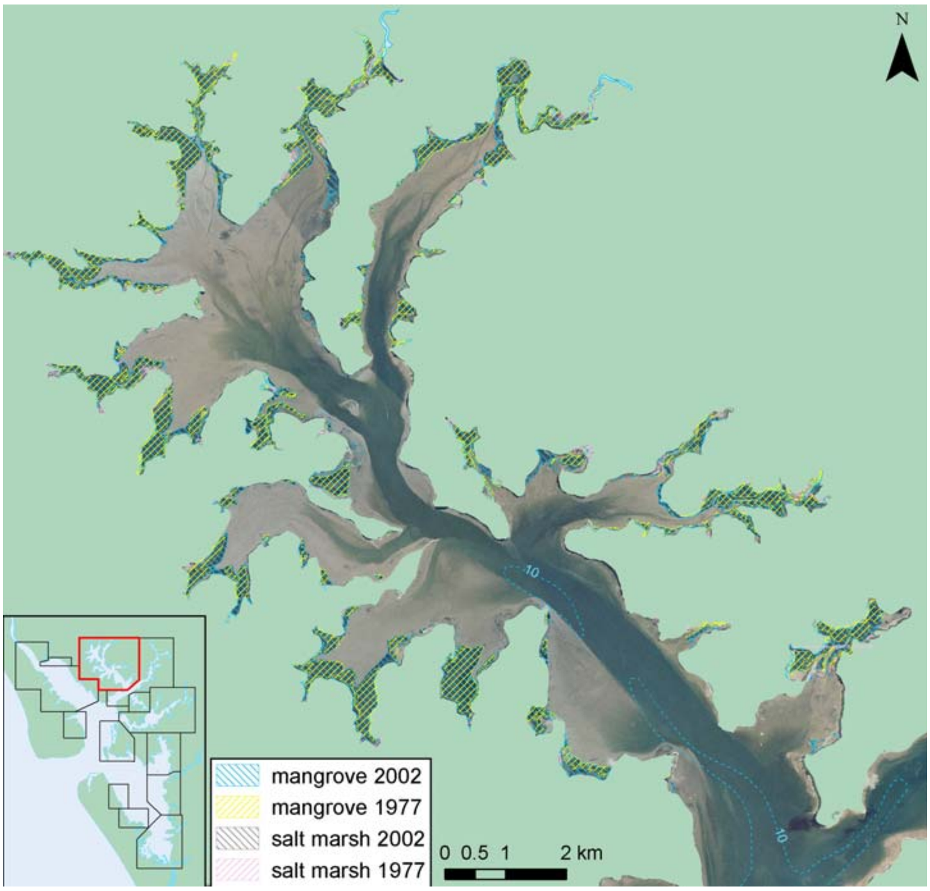
3.2.5 Arapaoa River

Table 4.4 summarises the changes in mangrove and salt-marsh habitats that have occurred in Arapaoa River compartment. Mangrove and salt-marsh habitat represent 11% and 6.4% (2002) respectively of the total area of these habitats in the harbour. The area of mangrove forest increased by 37% during the period 1977–2002. Figure 4.40 shows that mangrove stands occupy the upper-intertidal flats in the numerous creeks and bays that fringe the Arapaoa River. Mangrove-habitat expansion has occurred at most sites by colonisation of bare mud-flat areas immediately seaward of the stands.

Table 4.4 Arapaoa River: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2002).

Habitat	1977 (ha)	2002 (ha)	% change	%/yr
Mangrove	609.7	836.7	37.2	1.5
Salt marsh	42.3	42.2	-0.3	–

Figure 4.40 Arapaoa River: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2002.



The annual-average increase in mangrove habitat between 1977 and 2002 was 1.5% yr^{-1}. The area of salt-marsh habitat in the Arapaoa River compartment did not change during the study period.

3.2.6 Otamatea River

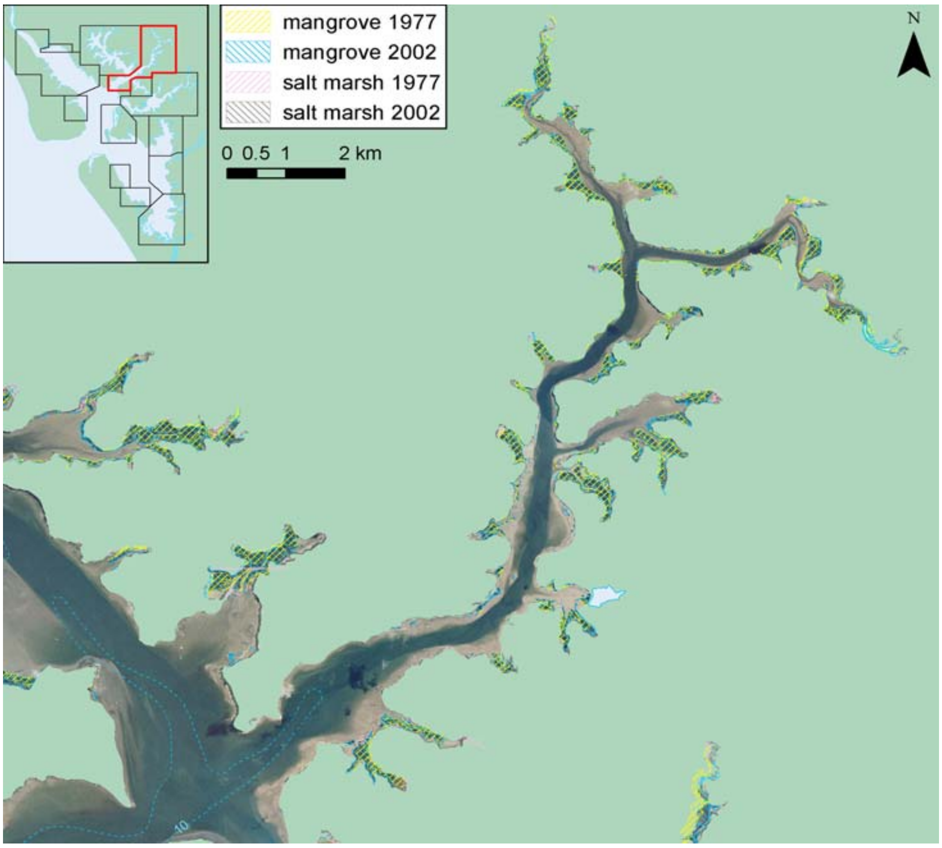
Table 4.5 summarises the changes in mangrove and salt-marsh habitats that have occurred in Otamatea River compartment. Mangrove and salt-marsh habitat represent 4.1% and 4.3% respectively (2002) of the harbour-total areas of these habitats. The area of mangrove forest increased by 34% during the period 1977–2002. Like the Arapaoa, mangrove stands occur on the upper-intertidal flats in the numerous creeks and bays that fringe the Otamatea River, with mangroves colonising the bare mud-flat areas immediately seaward of the pre-existing mangrove stands (Fig. 4.41).

Table 4.5 Otamatea River: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2002).

Habitat	1977 (ha)	2002 (ha)	% change	%/yr
Mangrove	234.9	314.8	34.0	1.4
Salt marsh	13.3	28.0	111.2	4.5

The area of salt marsh doubled during the study period, although the total area in 2002 (28 ha) was only 9% of the area occupied by mangrove. The annual-average rates of increase in mangrove and salt-marsh habitat was 1.4% yr^{-1} and 4.5% yr^{-1} respectively (1977–2002).

Figure 4.41 Otamatea River: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2002.



3.2.7 Oruawharo River

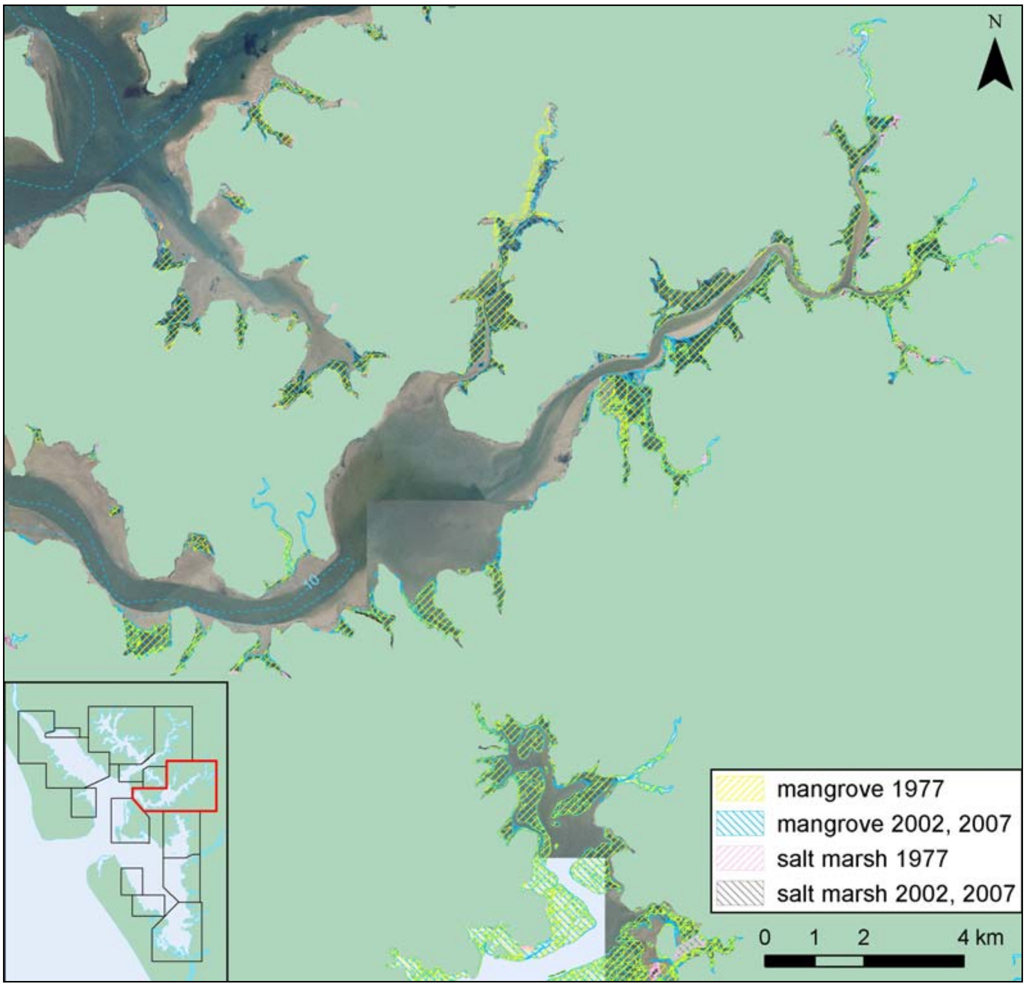
Table 4.6 summarises the changes in mangrove and salt-marsh habitats that have occurred in Oruawharo River compartment. Mangrove and salt-marsh represent 11.8% and 5.4% respectively of the harbour-total area of these habitats. The area of mangrove forest increased by ~15% during the period 1977–2002/2007. Like the Arapaoa, mangrove stands occur on the upper-intertidal flats in the numerous creeks and bays that fringe the Otamatea River, with mangroves colonising the bare mud-flat areas immediately seaward of the pre-existing mangrove stands (Fig. 4.42).

Table 4.6 Oruawharo River: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2002/2007). This compartment includes NRC and AC data, with %/yr calculated based on 27 year time period (i.e., 2005).

Habitat	1977 (ha)	2002/07 (ha)	% change	%/yr
Mangrove	782.9	898.7	14.8	0.6
Salt marsh	26.4	35.3	34.0	1.3

The area of salt marsh increased by 34% during the study period, although the total area in 2002/2007 represented only 3.9% of the area occupied by mangrove habitat. The annual-average rates of increase in mangrove and salt-marsh habitat was 0.6% yr^{-1} and 1.3% yr^{-1} respectively.

Figure 4.42 Oruawharo River: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2002.



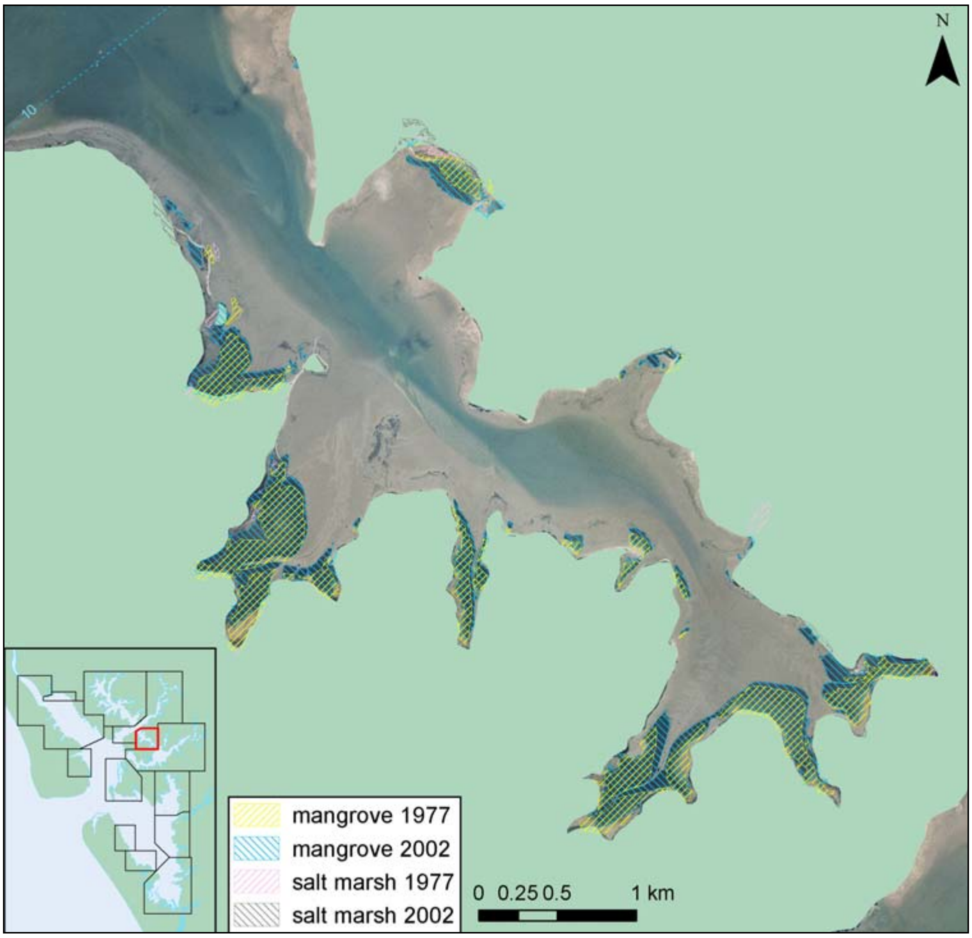
3.2.8 Whakaki River

Table 4.7 summarises the changes in mangrove and salt-marsh habitats that have occurred in the Whakaki River compartment. Mangrove and salt-marsh habitat represent 1.6% and 0.9% (2002) respectively of the harbour-total area of these habitats. The area of mangrove forest increased by 27% during the period 1977–2002 (93.1 to 118.1 ha) primarily by mangroves colonising bare mud-flat areas immediately seaward of the pre-existing stands growing in the creeks and bays that indent the shoreline (Fig. 4.43). The area of salt-marsh habitat is a small fraction of the mangrove area, although the area of salt marsh almost doubled from 3.1 to 5.7 ha. The annual-average rates of increase in mangrove and salt-marsh habitat in the Whakaki River was 1.1% yr^{-1} and 3.4% yr^{-1} respectively (1977–2002).

Table 4.7 Whakaki River: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2002).

Habitat	1977 (ha)	2002 (ha)	% change	%/yr
Mangrove	93.1	118.3	27	1.1
Salt marsh	3.1	5.7	84.4	3.4

Figure 4.43 Whakaki River: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2002.



3.2.9 Central Kaipara

Table 4.8 summarises the changes in each of the intertidal vegetated habitats that have occurred in the Central Kaipara compartment. Mangrove habitat accounts for 7.7% (2007) of the total area of mangrove in the harbour. The data for mangrove habitats includes information on changes in area in each of the four percentage cover classes.

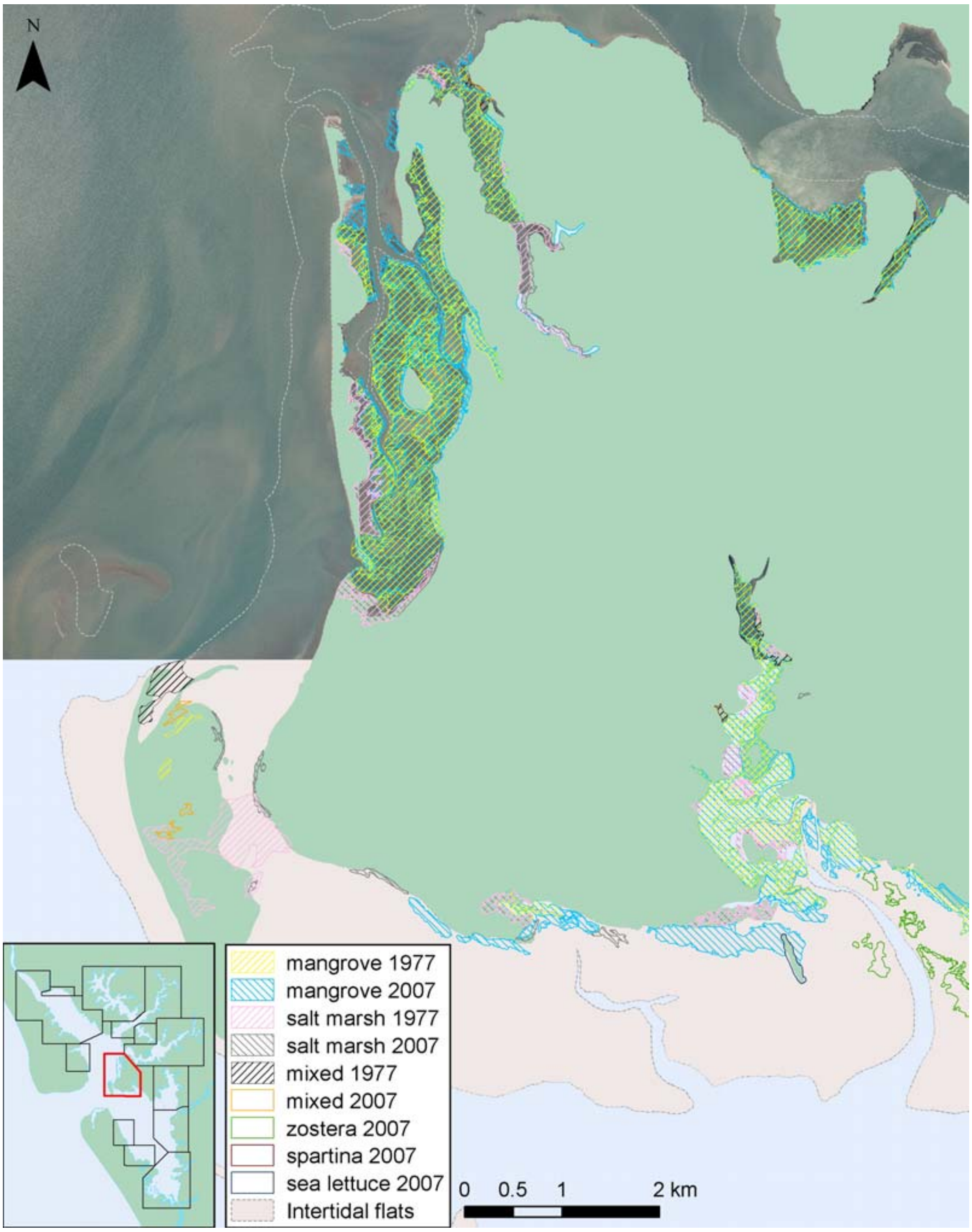
The total increase in mangrove-forest habitat during the period 1977–2002 was 20.8% primarily due to colonisation of bare intertidal flats east and west of Te Ngaio Point on the southern shore of Okahukura Peninsula and, to a lesser extent, expansion of pre-existing mangroves stands in Waikiri and Gum Store Creeks and (Fig. 4.44). The per cent cover data also show this, with 58% of the increase in mangrove habitat occurring in the 0–25% cover class. This also suggests that a large proportion of the increase in mangrove habitat has occurred in recent years because the low per cent cover is usually indicative of young mangrove stands (Table 4.8).

No data was available for salt-marsh habitat in 2007, although the area of mixed mangrove and salt-marsh habitat increase almost four fold to 90 ha (2007). Large areas of sea grass (40.7 ha, 2007) were also mapped on the intertidal flats fringing Gum Store Creek. These sea grass beds were not mapped in the 1977 aerial photos, which may be due to poorer quality of these earlier images (i.e., small-scale and black and white) rather than a complete absence of sea-grass habitat. The annual-average rate of increase in mangrove habitat in the Central Kaipara was relatively modest at 0.7% yr^{-1} (1977–2007).

Table 4.8 Central Kaipara: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2007). The per cent changes (total and per year) in mangrove area by per cent cover class are also shown as well as the per cent contribution of each cover class to the total change in mangrove habitat.

Habitat	1977	2007	% of change in total area	% change	%/yr
Mangrove –total	486.7	588.1		20.8	0.7
0–25%	122.4	181.4	58	48.1	1.6
25–50%	78.05	88.9	10.6	13.9	0.5
50–75%	133.0	153.7	20.4	15.3	0.5
75–100%	153.2	164.4	11.0	7.3	0.2
Mixed	18.6	90.0	–	383.0	12.8
Salt marsh	126.6	–	–	–	–
Sea grass	–	40.7	–	–	–

Figure 4.44 Central Kaipara: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2007.



3.2.10 Tauhoa – Hoteo

Table 4.9 summarises the changes in each of the intertidal vegetated habitats that have occurred in the Tauhoa–Hoteo compartment. Mangrove and salt-marsh habitat represent 17% and 10% (2007) respectively of the total area of these habitats in the harbour. The data for mangrove habitats includes information on changes in area in each of the four percentage cover classes.

Table 4.9 Tauhoa–Hoteo: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2007). The per cent changes (total and per year) in mangrove area by per cent cover class are also shown as well as the per cent contribution of each cover class to the total change in mangrove habitat.

Habitat	1977	2007	% of change in total area	% change	%/yr
Mangrove –total	1230.4	1313.7		6.8	0.2
0–25%	231.0	250.4	23	8.4	0.28
25–50%	270.4	272.6	2.6	0.8	0.03
50–75%	157.2	159.0	2.2	1.1	0.04
75–100%	571.8	631.7	72	10.5	0.4
Mixed	45.6	43.7	–	-4.1	-0.1
Salt marsh	65.9	66.2	–	0.6	0.02

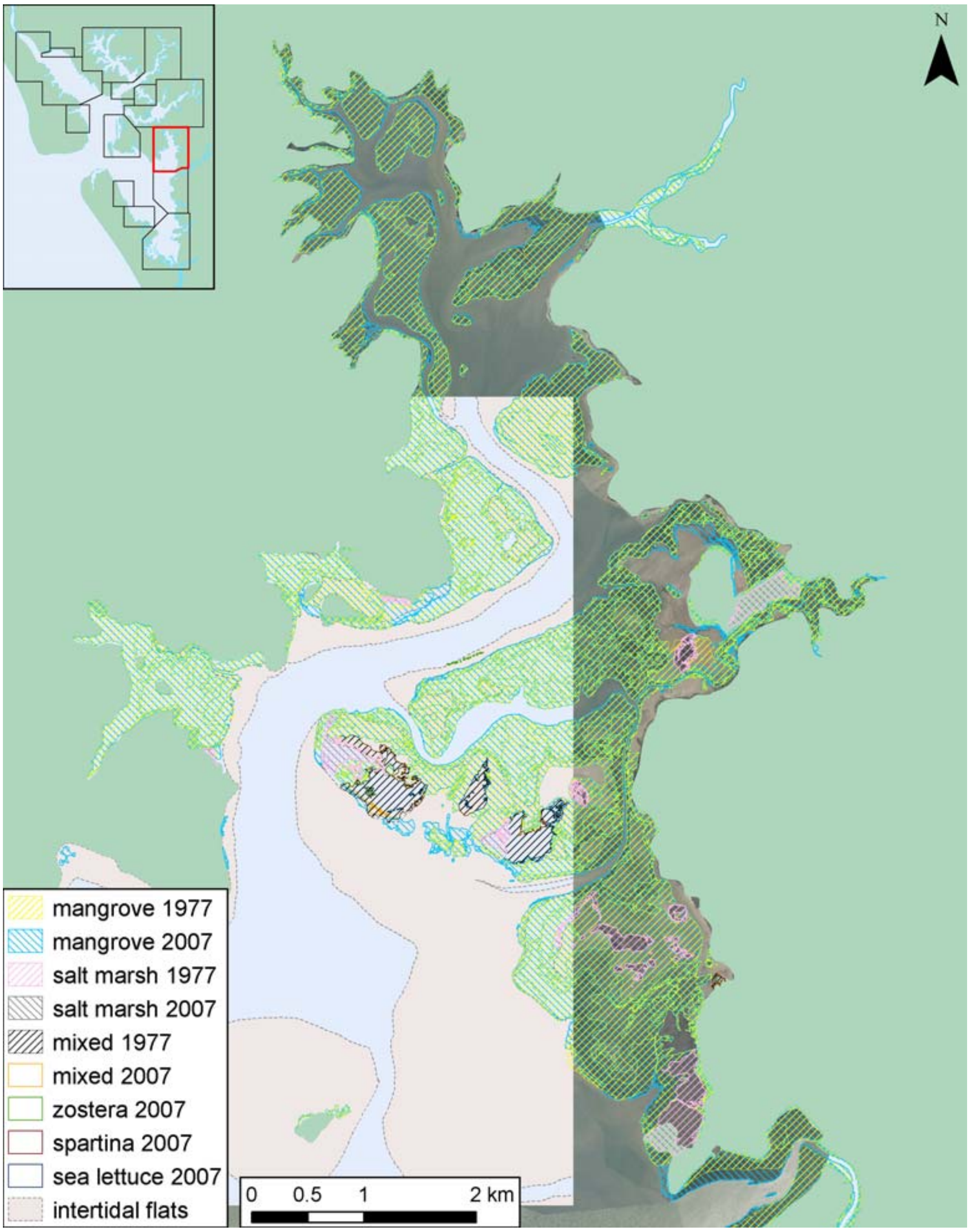
The total increase in mangrove-forest habitat during the period 1977–2007 was 6.8%. In the Tauhoa River, mangroves colonised bare intertidal flats fringing existing stands and new stands were established on intertidal flats at the river mouth (Fig. 4.45). In some areas (e.g., area west of Tauhoa settlement), landward expansion of mangrove stands also occurred. On the northern bank of the Hoteo River mouth, mangroves colonised a substantial area of intertidal flat. The sediment core data show that this is an area of rapid sediment accumulation (~20 mm yr^{-1}, section 4.1.11).

The per cent cover data indicate that most of this increase occurred early in the 1977–2007 period, with the 75–100% cover class (i.e., mature mangrove) accounting for 72% of the total increase in mangrove habitat. Recent colonisation of intertidal flats (i.e., 0–25% canopy class) accounted for 23% of the mangrove-habitat increase (Table 4.9). The assumption that high per cent cover represents mature mangrove generally holds for fringe mangrove forests (e.g., Hoteo River mouth) but is not always the case. For example, canopy cover in old mangrove forests growing landward of the present fringing forests and at the upper limit of the tide can be quite patchy.

Changes in the area of mixed and salt-marsh habitats were negligible (Table 4.9). The mixed vegetation class included an area of salt-tolerant terrestrial plants on a low island/shell bank at the mouth of the Tauhoa River. The total area of mixed and salt-marsh habitat is small relative to mangrove habitat (8.4% in 2007).

The annual-average rate of increase in mangrove habitat in the Tauhoa–Hoteo compartment was low at 0.2% yr^{-1} (1977–2007).

Figure 4.45 Tauhoa–Hoteo: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2007.



3.2.11 Kaipara Flats

Table 4.10 summarises the changes in each of the intertidal vegetated habitats that have occurred in the Kaipara Flats compartment. Mangrove and salt-marsh habitat represent 5.1% and 5.3% (2007) respectively of the total area of these habitats in the harbour. The data for mangrove habitats includes information on changes in area in each of the four percentage cover classes.

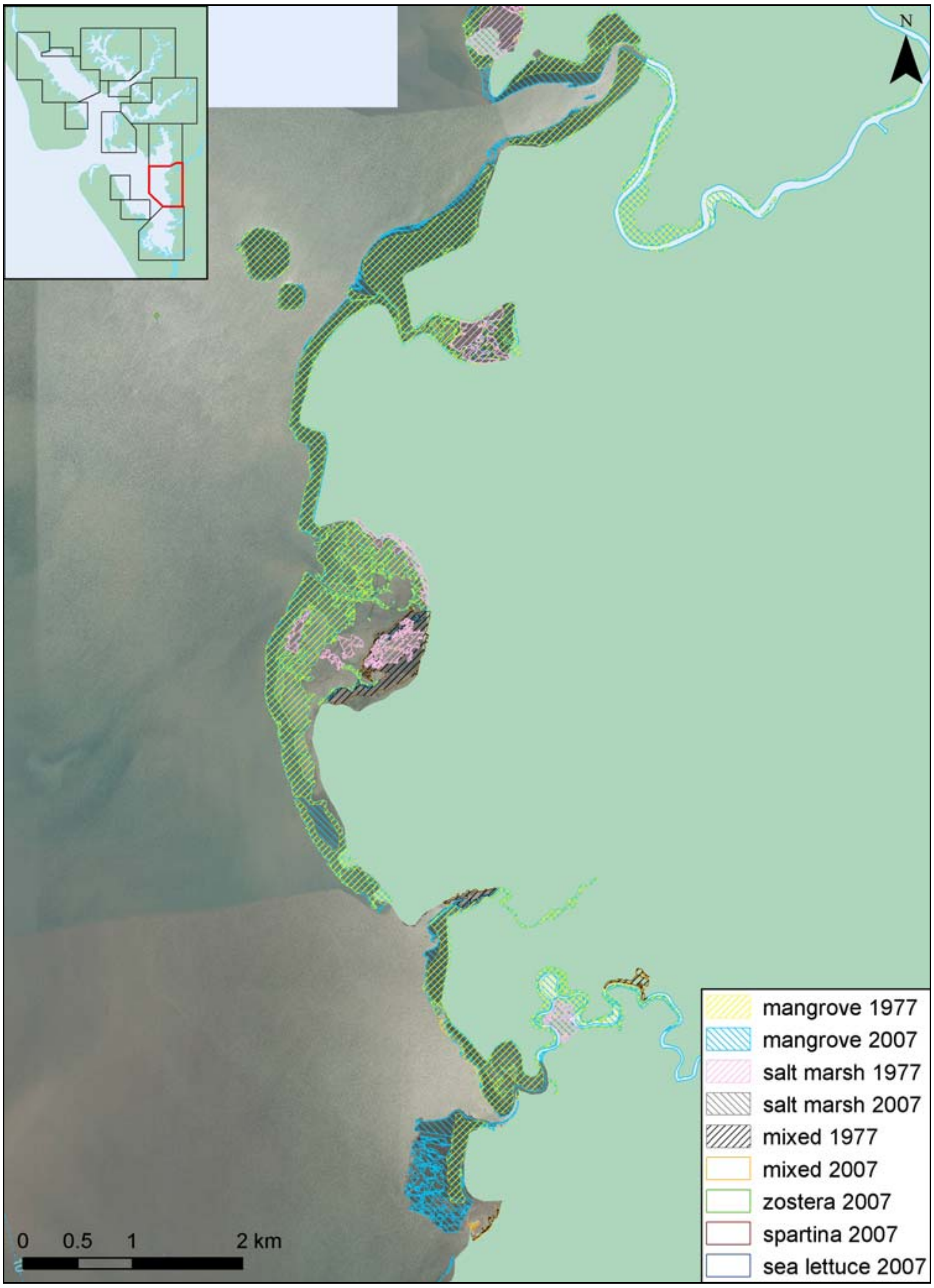
The total increase in mangrove-forest habitat (14.9%) during the period 1977–2007 was mainly due to colonisation of bare intertidal flats fringing mangrove stands south of the Hoteo River and Araparera River mouths (Fig. 4.46). The per cent cover data indicate that two-thirds of this increase occurred in the 75–100% cover class (i.e., mature mangrove), which suggests that this occurred early in the survey period 1977–2007 (Table 4.10).

Table 4.10 Kaipara Flats: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2007). The per cent changes (total and per year) in mangrove area by per cent cover class are also shown as well as the per cent contribution of each cover class to the total change in mangrove habitat.

Habitat	1977	2007	% of change in total area	% change	%/yr
Mangrove –total	340.3	390.9		14.9	0.5
0–25%	40.8	47.9	14.0	17.4	0.04
25–50%	20.9	22.0	2.2	5.3	0.2
50–75%	78.4	87.4	17.8	11.5	0.3
75–100%	200.2	233.6	66.0	16.7	0.3
Mixed	26.2	26.7	–	1.9	0
Salt marsh	34.7	34.7	–	0	0

The annual-average increase in mangrove habitat on the Kaipara Flats was very modest at 0.5% yr^{-1} (1977–2007). This low rate of mangrove-habitat expansion since the mid-1970s is consistent with the exposure of these forests to the prevailing south-west winds. These winds drive sediment re-suspension by waves on the intertidal flats. For example, major phases of mangrove-habitat expansion in the southern Firth of Thames occur infrequently, on average once per decade. These events appear to coincide with rare extended periods of calm summer weather when waves do not excavate mangrove propagules and seedlings from the tidal flats (Swales et al. 2007b).

Figure 4.46 Kaipara Flats: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2007.



3.2.12 South Kaipara

Table 4.11 summarises the changes in each of the intertidal vegetated habitats that have occurred in the South Kaipara compartment. Mangrove and salt-marsh habitat represent 25.9% and 24.3% (2007) respectively of the total area of these habitats in the harbour. The single largest mangrove forest in this compartment is found in the Puharakeke Creek. The data for mangrove habitats includes information on changes in area in each of the four percentage cover classes.

The total area of mangrove habitat decreased (-8.3%) during the period 1966–2007. Much of this mangrove-habitat loss appears to be associated with harbour reclamation along the eastern shore at Kakanui and in the Mairetahi and Parekaea Creeks near Shelly Beach (Fig. 4.47).

Table 4.11 South Kaipara: changes in the area (hectares) of mangrove and salt-marsh habitats (1966–2007). The per cent changes (total and per year) in mangrove area by per cent cover class are also shown as well as the per cent contribution of each cover class to the total change in mangrove habitat.

Habitat	1966	2007	% of change in total area	% change	%/yr
Mangrove –total	2153.8	1974.9		-8.3	-1.2
0–25%	667.2	332.4		-50.2	-1.2
25–50%	233.4	241.2		3.3	0.08
50–75%	366.6	305.5		-16.7	-0.4
75–100%	886.7	1095.8		23.6	0.6
Mixed	283.3	39.3	–	-86.1	-2.1
Salt marsh	178.9	159.9	–	-10.6	-0.3
Spartina spp.	2.36	2.77	–	17.1	0.4
Sea grass		0.24			

Despite these habitat losses, mangrove forests have colonised extensive areas of bare intertidal flat at several locations: Kakanui Point, Makarau River, Ngapuke Creek and south to the Kaipara River mouth. Increases in mangrove habitat have occurred along tidal channels in the Puharakeke Creek albeit on a smaller scale (Fig. 4.47). Historical surveys suggests that this large mangrove forest had reach an advanced stage of maturity by the 1930s (Ferrar 1934) and it has not substantially changed since that time.

The per cent cover data show substantial reductions in the 0–25% (-50%) and 50–75% (-16.7%) classes. The only large increase occurred in the 75–100% cover class (209 ha, 23.6%) with mangrove habitat increasing from 887 to 1096 ha (1966–2007). Thus in the South Kaipara the large-scale loss of mangrove habitat due to reclamation has been largely offset by seaward expansion of forests onto bare intertidal flats.

Figure 4.47 South Kaipara: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2007.

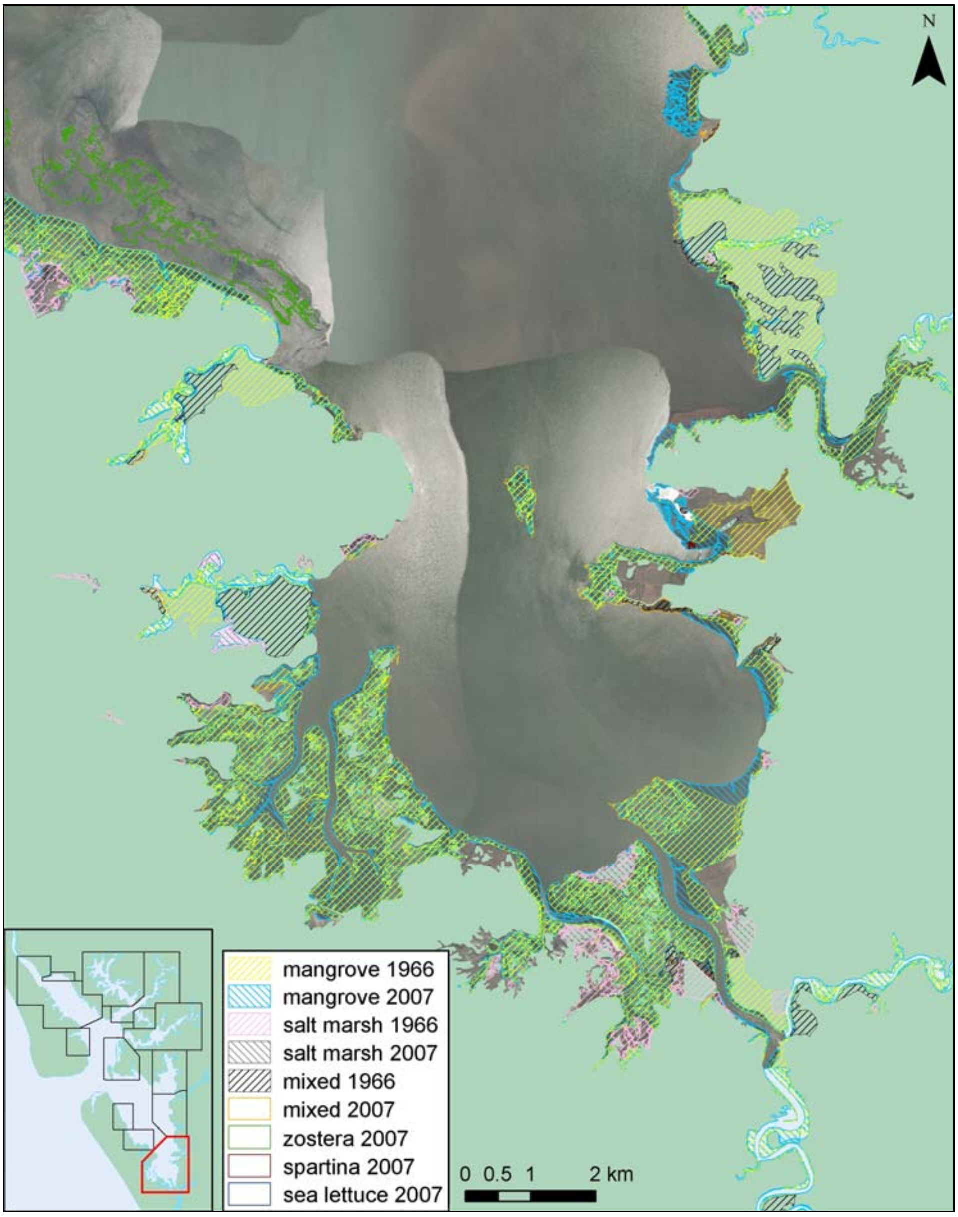


Figure 4.47 and Table 4.11 show that large-scale loss of mixed mangrove and salt-marsh habitats (-86%) has also occurred in the South Kaipara. These data show that human activities have had a major impact on intertidal vegetated habitats in the South Kaipara.

3.2.13 Omokoiti Flats

Table 4.12 summarises the changes in each of the intertidal vegetated habitats that have occurred in the Omokoiti Flats compartment. Mangrove and salt-marsh habitat represent 5% and 6.2% (2007) respectively of the harbour-total area of these habitats. The data for mangrove habitats includes information on changes in area in each of the four percentage cover classes.

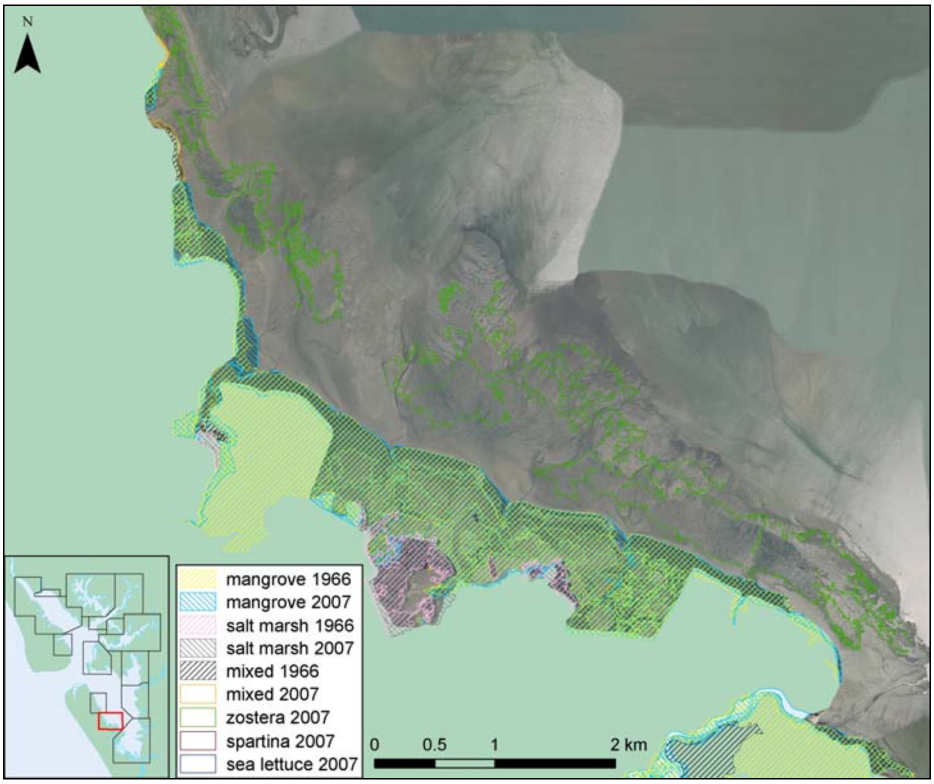
Substantial reclamation of intertidal flats has also occurred in the Omokoiti compartment, which has resulted in substantial loss of mangrove and mixed mangrove and salt-marsh habitat (Fig. 4.48). The largest area of habitat loss due to large-scale reclamation works has occurred between Taumata and Awataha Creeks. Primarily as a result of these reclamations, the total area of mangrove habitat decreased by -26.9%, from 520 ha in 1966 to 380 ha in 2007 (Table. 4.12). The per cent cover data show substantial reductions in the 0–25% (-53%) and 25–50% (-47%) classes, with a total of 150 ha of mangrove habitat loss and similar to the net change in total mangrove habitat of 140 ha.

Substantial loss of mixed mangrove and salt-marsh habitats (-78%) has also occurred in the Omokoiti compartment whereas the net change in salt marsh (+2.8%) since the mid 1960s has been negligible (Table 4.12). As observed in the South Kaipara, reclamation works since the mid 1960s have had a major impact on intertidal vegetated habitats at Omokoiti Flats.

Table 4.12 Omokoiti Flats: changes in the area (hectares) of mangrove and salt-marsh habitats (1966–2007). The per cent changes (total and per year) in mangrove area by per cent cover class are also shown as well as the per cent contribution of each cover class to the total change in mangrove habitat.

Habitat	1966	2007	% of change in total area	% change	%/yr
Mangrove –total	520.2	380.1		-26.9	-0.66
0–25%	178.2	84.5		-52.6	-1.28
25–50%	122.1	65.0		-46.8	-1.14
50–75%	72.4	73.9		2.2	0.05
75–100%	147.5	156.7		6.2	0.15
Mixed	43.3	9.4	–	-78.3	-1.91
Salt marsh	39.7	40.8	–	2.8	0.07
Sea grass	–	226.5			

Figure 4.48 Omokoiti Flats: changes in the spatial distribution of intertidal vegetated habitats between 1966 and 2007.



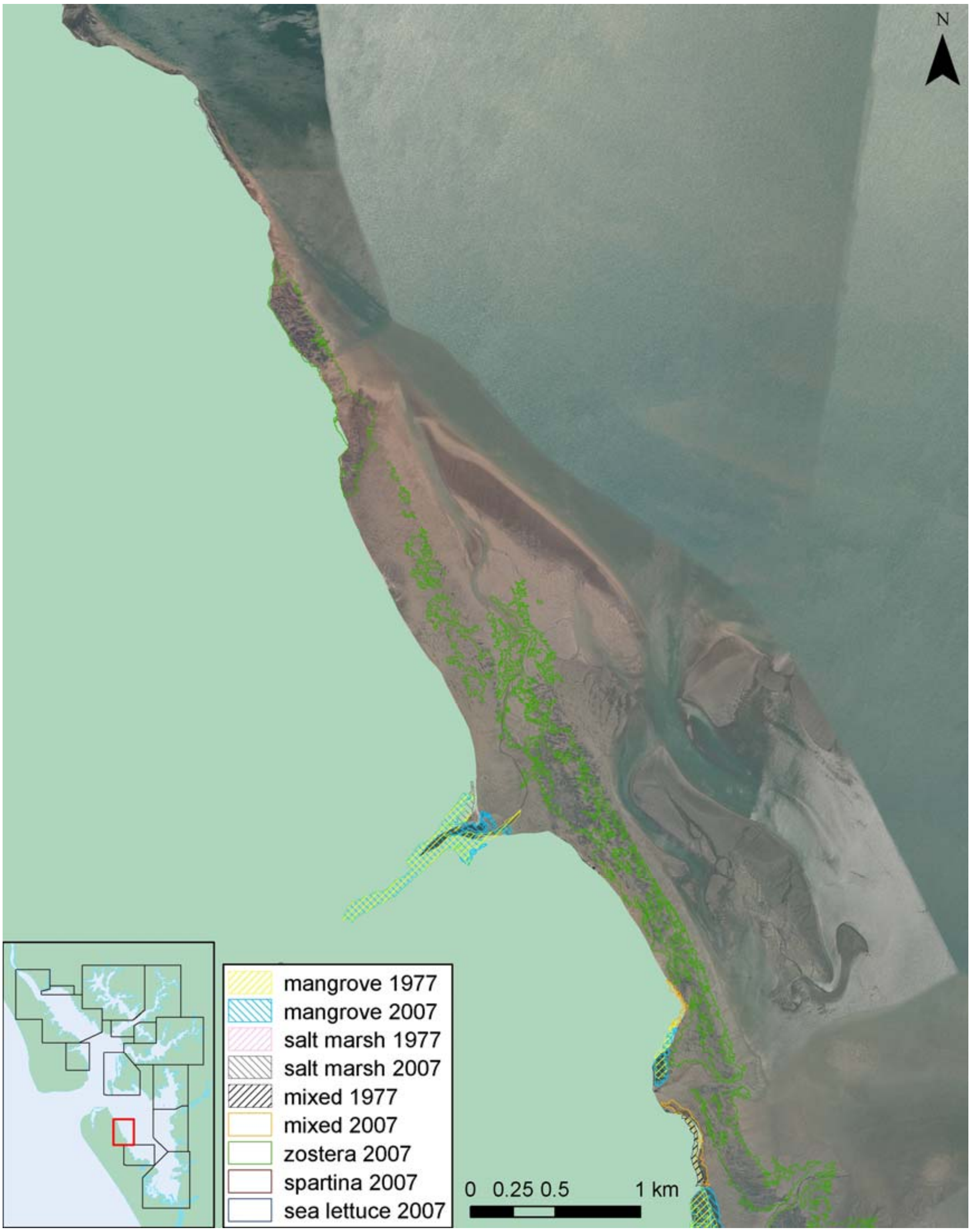
3.2.14 South Head

Table 4.13 summarises the changes in each of the intertidal vegetated habitats that have occurred in the South Head compartment. Mangrove and salt-marsh habitat represent 0.2% and 0.8% (2007) respectively of the harbour-total area of these habitats. The data for mangrove habitats includes information on changes in area in each of the four percentage cover classes. Figure 4.49 shows the distribution of mangrove, salt marsh and sea grass on the mid–upper intertidal flats.

Table 4.13 South Head: changes in the area (hectares) of mangrove and salt-marsh habitats (1977–2007). The per cent changes (total and per year) in mangrove area by per cent cover class are also shown as well as the per cent contribution of each cover class to the total change in mangrove habitat.

Habitat	1977	2007	% of change in total area	% change	%/yr
Mangrove –total	12.4	13.3		7.2	0.2
0–25%	0.13	0.97	93	646	21.5
25–50%	1.3	1.4	11	7.7	0.3
50–75%	0.0	0.0	0.0	–	–
75–100%	11.0	10.9	-0.9	0.0	0.0
Mixed		2.7	–	–	–
Salt marsh		5.3	–	–	–
Sea grass	–	90.9	–	–	–

Figure 4.49 South Head: changes in the spatial distribution of intertidal vegetated habitats between 1977 and 2007.



4.0 Synthesis

4.1 Recent sedimentation in the Kaipara Harbour

4.1.1 Reliability of the sediment dating

An important aspect of sedimentation studies is the validation of sediment accumulation rates (SAR). This is typically achieved by using two or more independent dating methods (section 3.5). In the present study, SAR have been estimated using the radioisotopes ^{210}Pb and ^{137}Cs. These two independent methods can provide accurate “sediment clocks” because they decay exponentially at a known constant rate.

The ^{210}Pb dating method potentially provides the most accurate geochronology. Firstly, ^{210}Pb SAR estimates are based on regression fits to depth profiles of excess ^{210}Pb concentrations. Thus, ^{210}Pb SAR estimates have a statistical basis rather than being solely based on the reliability of a single dated marker horizon (i.e., ^{137}Cs). ^{210}Pb dating can be confounded by sediment mixing (i.e., physical and biological processes). In particular, downward mixing of excess ^{210}Pb from the surface results in a steeper profile and therefore higher apparent SAR value. In the present study, x-radiographs and the short-lived radioisotope ^{7}Be ($t_{1/2}$ = 53 days) provide supporting information to ascertain the validity of the ^{210}Pb geochronology. For example, is sediment bedding present in the x-radiographs? Is there evidence of the burrowing and feeding activities of infauna? The depth of the surface-mixed layer (SML) produced by processes operating over time-scales of days–months can also be determined from the ^{7}Be profile. In most cases the SML is a small fraction of the excess ^{210}Pb profile depth so that this short term-mixing has a minor effect on the ^{210}Pb profile. In the present study the depth of the ^{7}Be SML varied from 1– 5 cm. Secondly, ^{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. The model assumes that ^{210}Pb concentration profiles are primarily the result of radioactive decay rather than variations in the ^{210}Pb supply rate. This assumption is supported by monthly monitoring of the atmospheric ^{210}Pb flux at Auckland (2002 –). These data confirm that the average annual flux (0.0046, range: 0.0036–0.0056 Bq cm^{-2} yr^{-1}) is relatively constant.

Sediments labelled with ^{137}Cs derived from atmospheric nuclear weapons tests indicate deposition since the early 1950s (section 8.2). The following factors should be borne in mind when interpreting ^{137}Cs data: (1) atmospheric ^{137}Cs deposition has not been detected in NZ since the mid 1980s. The activity of ^{137}Cs (i.e., $t_{1/2}$ = 30 years) in recent sediment deposits has substantially reduced since the deposition peak of the early-1960s, which provides the most reliable depth horizon for ^{137}Cs dating. Although this deposition peak has been observed in N.Z. wetland deposits (Gehrels et al. 2008) it does not commonly occur in NZ estuarine and coastal marine sediments primarily due to sediment mixing; (2) consequently, ^{137}Cs activities are likely to be below detectable levels in deeper deposits and the maximum ^{137}Cs depth will be under-estimated. Alternatively, deep mixing by infauna over annual–decadal time scales can mix ^{137}Cs deeper into the sediment column than would otherwise occur due solely to burial, with the result that the ^{137}Cs SAR are over-estimated. The interpretation of ^{137}Cs data is improved by supporting information (e.g., x-radiographs, ^{7}Be).

Reconstructing the recent sedimentation history of estuaries (i.e., last several hundred) is also problematic because there are relatively few alternatives to ^{210}Pb and ^{137}Cs dating or recent sediments. Another commonly used method is based on the analysis of pollen abundance in cores and has been used to date estuarine and swamp sediments in Auckland estuaries (e.g., Hume and McGlone 1986, Swales et al. 2002) and Northland (e.g., Elliot et al. 1997). This method relies on the availability of accurate information on the catchment-landcover history to attribute approximate dates to depth horizons in sediment cores. In this sense it does not provide an absolute dating method, unlike radioisotopes, and is also subject to the uncertainties caused by sediment mixing.

4.1.2 Comparison of ^{210}Pb and ^{137}Cs SAR estimates

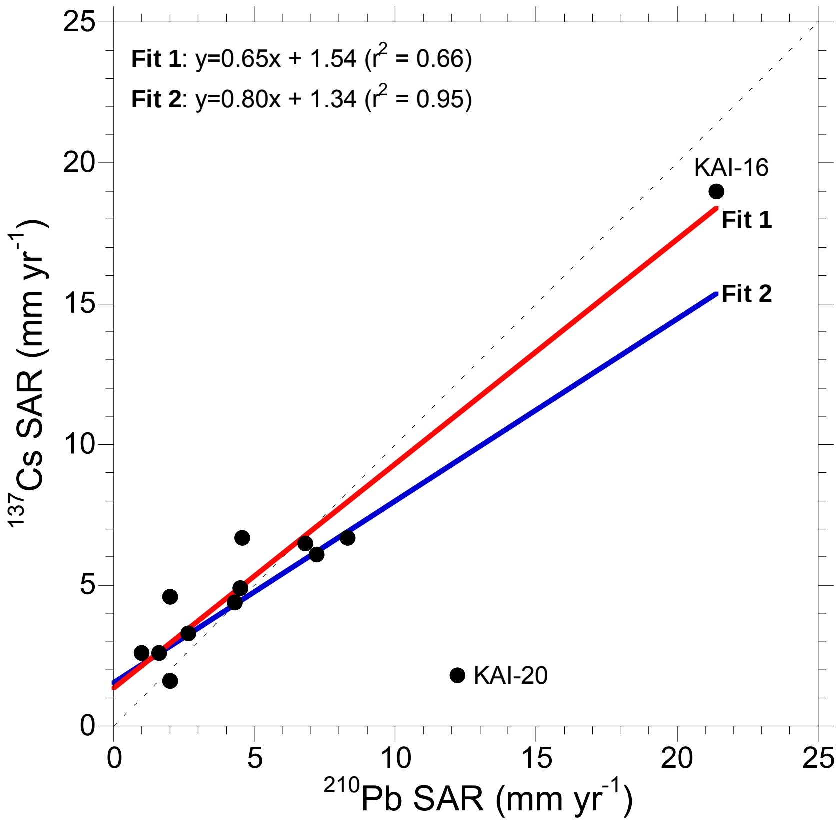
Information on SAR and sediment mixing depths estimated from the ^{210}Pb, ^{137}Cs and ^{7}Be data are listed for each core in Table 5.1. The ^{210}Pb and ^{137}Cs SAR estimated for each core site are also compared in Figure 5.1. It can be seen that (with the exception of KAI-20) the ^{210}Pb and ^{137}Cs SAR estimates are similar, plotting close to and either side of the 1:1 slope line. The linear-regression fits to these data include and exclude the KAI-20 data. Supporting data for KAI-20 indicate that the ^{210}Pb profile at this site results from mixing rather than sedimentation. The ^{137}Cs SAR (1.8 mm yr^{-1}) is also consistent with estimates from other sites in the Arapaoa River.

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 indicate that we can have confidence in the recent geochronology reconstructed from these cores.

Table 5.1 Summary of: time-averaged ^{210}Pb and ^{137}Cs sediment accumulation rates (SAR); and residence time of sediments in the surface-mixed layer (SML) before removal by burial. Note: nd = not detected; nfd = no fit to data.

Core Site	^{210}Pb SAR (mm yr^{-1})	Depth range (cm)	^{210}Cs SAR (mm yr^{-1})	^{7}Be depth (cm)	R (yrs) in SML
KAI-1	4.5	3–31	4.9	5	11
KAI-2	29.7	2–21	6.5	1	0.3
	3.6	20–61			
KAI-3	7.2	3–60	6.1	3	4.2
KAI-4	4.3	3–21	4.4	3	7
KAI-5	4.8	5–15	6.7	5	10.4
	4.3	20–51			
KAI-6A	2	3–21	4.6	nd	–
KAI-7	8.3	10–45	6.7	nd	12
KAI-9	nfd		nd	1	
KAI-10	1	4–15	2.6	nd	
KAI-14	6.8	1–41	6.5	nd	
KAI-16	21.4	5–111	>19	5	2.4
KAI-17	nfd		8.8	nd	
KAI-20	12.2	1–21	1.8	1	0.8
KAI-21	2.0	2–21	1.6	nd	
KAI-22	3.4	4–15	3.3	4	11.8
	1.9	14–31			
KAI-23	1.6		2.6	4	25
KAI-24	nfd		nd	1	
KAI-25	nfd		nd	nd	

Figure 5.1 Comparison of ^{210}Pb and ^{137}Cs sediment accumulation rates (SAR) derived from the radioisotope profiles. Linear regression fits to the data include (Fit 1) and exclude data (Fit 2) for site KAI-20. Note: fit excluding KAI16 and KAI-20 = 0.63x +1.97 (r^2 =0.74).



4.1.3 Comparison of sedimentation rates with other North Island estuaries

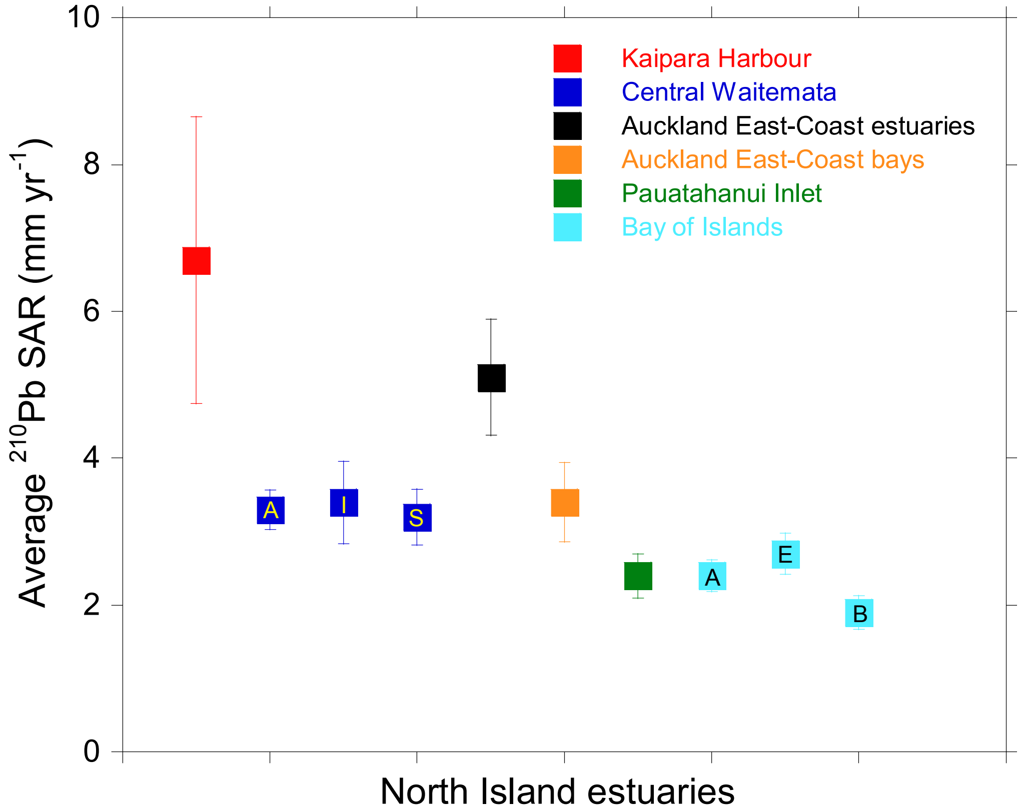
In this section we compare <u>average</u> sediment accumulation rates in the Kaipara Harbour with average rates for other North Island estuaries. This analysis enables the recent sedimentation of the Kaipara Harbour to be considered in a wider context of human impacts on New Zealand estuaries over the last 50–100 years. To ensure that valid comparisons can be made we include ^{210}Pb SAR data that are based on similar sampling and analysis methods. Environments include intertidal and subtidal flats in estuaries and coastal embayments (Swales 2002b, 2005, 2007a, 2008a, 2010). It should also be recognised that these data represent environments where long-term fine-sediment accumulation occurs. There are also environments where this does not occur. In large estuaries with fetches of several km or more waves, and to a lesser extent tidal currents, control fine-sediment transport and fate on intertidal and shallow subtidal flats (e.g., Green et al. 2007).

Figure 5.4 presents the average ^{210}Pb SAR for several North Island estuaries based on data from 85 cores sites. The Auckland east-coast data set includes the Mahurangi, Puhoi, Okura and Te Matuku estuaries and the Karepiro, Whitford and Wairoa embayments. The Bay of Islands data includes the Te Puna, Kerikeri, Kawakawa and Te Rawhiti Inlets as well as data from the Bay in water depths of 1–100 m. Table 5.2 provides additional information.

The average ^{210}Pb SAR estimated for the Kaipara Harbour is 6.7 mm yr^{-1} (SE = 1.9 mm yr^{-1}), which is significantly higher than for most other North Island estuaries. The harbour-average SAR for the Kaipara are skewed by the high SAR values recorded at sites KAI-2 (30 mm yr^{-1}) and KAI-16 (Hoteo, 21 mm yr^{-1}), which also results in the large variability in the estimate. The data for KAI-2 suggests that the recent rapid sedimentation at this site is likely due to local geomorphological adjustment/changing environmental conditions (e.g., lateral shift in channel) rather than due to increased sediment load. Rapid sedimentation at the Hoteo River mouth is consistent with data from Auckland's tidal creeks where SAR have averaged 20–30 mm yr^{-1} over the last ~50 years (Vant et al. 1993, Oldman and Swales 1999, Swales et al. 1997, 2002a). It would be reasonable to exclude the KAI-16 data from the analysis because it is not representative of conditions in the main body of the Harbour. Excluding data for KAI-2 and KAI-16 yields a harbour-average SAR of 4.0 mm yr^{-1} (SE = 0.6 mm yr^{-1}). In either case, the average ^{210}Pb SAR for the Kaipara Harbour is not significantly different from the average value for intertidal flats in Auckland's east-coast estuaries (5.1 mm yr^{-1}, SE = 0.8). Figure 5.4 also shows that average ^{210}Pb SAR are significantly lower in all other estuaries/embayments (range 1.9 –3.4 mm yr^{-1}) for which we have robust data. The lowest rate of sediment infilling occurs in the deep subtidal habitats of the Bay of Islands where the ^{210}Pb SAR has averaged 1.9 mm yr^{-1} (SE = 0.2 mm yr^{-1}).

The high average SAR measured in Auckland east-coast estuaries in comparison to other estuaries (Fig. 5.4) 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. For example, many of the Auckland east-coast estuaries are relatively small and have rapidly infilled with sediments from developing catchments. However, estuarine processes, such as fine-sediment winnowing by waves, appear to play an important role in moderating the rate of estuary infilling. For example, in the Central Waitemata Harbour (CWH), average SAR in intertidal and subtidal habitats is not significantly different (Fig. 5.4). Field measurements and sediment-transport modelling show that this is primarily due to redistribution of sediments within the CWH (Oldman et al. 2007). Silt deposited on the intertidal flats is winnowed from the bed by waves and is subsequently redistributed by currents and deposited on the subtidal flats, which are less frequently reworked by short-period estuarine waves. Thus, over time, this redistribution of fine sediments by estuarine processes has reduced differences in sedimentation rates between intertidal and subtidal environments in the Central Waitemata Harbour.

Figure 5.4 Comparison of average ^{210}Pb sediment accumulation rates (SAR) in North Island estuaries, with standard errors shown. Notes: (1) key - all data (A), intertidal sites (I), subtidal sites (S), estuaries (E), coastal embayments (B); (2) Total number of cores = 85; (3) Data sources: refer to Table 5.2.



Sedimentation rates are also substantially lower in Auckland east-coast embayments (Fig. 5.4). These shallow coastal embayments typically larger than the east-coast estuaries, so that they have more accommodation space for sediments and subject to fine-sediment winnowing by waves. In some cases these embayments are also buffered from catchment sediment loads by receiving estuaries. This appears to be the situation in the Bay of Islands where infilling rates in the bay are significantly lower than in the fringing estuaries (Swales et al. 2010). Further evidence of the key role that waves play in moderating estuary infilling comes from the Pauatahanui Inlet (Porirua), a small (4.6 km^2), shallow subtidal estuary (Swales et al. 2005). Despite the fact that the Inlet receives runoff from a relatively large (109 km^2) steep land catchment, silt plumes during flood are observed to discharge from the inlet. Fine sediment deposited in the Inlet is also frequently resuspended by waves, even in the central basin, so that a substantial proportion of the terrigenous sediment load is exported from the Inlet.

Table 5.2 Summary of average ^{210}Pb sediment accumulation rates (SAR) and standard error (SE) in North Island estuaries and coastal embayments over the last 50—100 years. The total number of cores = 85.

Estuary	n	Habitat	^{210}Pb SAR (mm yr^{-1})	^{210}Pb SAR-SE (mm yr^{-1})	Source
Kaipara	16	intertidal	6.7	1.9	Present study
CWH - all data	18	intertidal and subtidal	3.3	0.3	Swales (2002b, 2007)
CWH - intertidal	10		3.4	0.6	–
CWH - subtidal	8		3.2	0.4	–
Auckland EC estuaries	13	intertidal	5.1	0.8	Swales (2002b, 2007a)
Auckland EC bays	9	subtidal	3.4	0.5	Swales (2002b, 2007a, 2008a)
Pauatahanui	9	subtidal	2.4	0.3	Swales (2005)
BOI – all data	20	subtidal	2.4	0.2	Swales (2010)
BOI – inlets	14	subtidal	2.7	0.3	Swales (2010)
BOI – embayment	6	subtidal	1.9	0.2	Swales (2010)

The average SAR 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. The Kaipara Harbour also receives runoff from large rivers (e.g., Wairoa, Hoteo), however it is also a very large estuary with fetches in excess of 10 km at many locations. On these wave-exposed tidal flats and in tidal channels frequent reworking of the bed by waves and/or strong currents prevent long-term accumulation of fine sediments. Figure 2.7 illustrates the net effect of these physical processes on the distribution of muddy sediments in the Kaipara Harbour. The fate of fine-sediments in the Kaipara Harbour is discussed in the next section.

To conclude: (1) where fine sediments can accumulate in the Kaipara Harbour, sediment accumulation rates are similar to values observed in Auckland's east-coast estuaries; (2) average sedimentation rates over the last 50 years in Auckland estuaries are up to three-times higher than in other North Island estuaries and coastal embayments for which we have robust data.

4.1.4 Fine-sediment fate in the Kaipara Harbour

Estuaries follow similar evolutionary pathways over time: they infill with sediment, subtidal areas and water depths decrease and fluvial processes become increasingly predominant in the estuary as the tidal volume shrinks. As a result hydrodynamic conditions, sediment processes and ecosystems change (Roy et al. 2001). Although terrigenous-sediment input and deposition in estuaries is a natural process, the rate at which this is now occurring globally is higher than before human activities disturbed the natural land cover (Thrush et al. 2004). In New Zealand, increases in sediment loads to estuaries and coastal ecosystems coincide with large-scale deforestation, which followed the arrival of people about 700 years ago (section 2.2). In the Kaipara, the rate of environmental change accelerated with the arrival of the first European settlers in the 1830s.

Sediment-core data collected in the present study show that mud is preferentially depositing on intertidal flats in the southern Kaipara, in the vicinity of the Hoteo River and in the large tidal rivers (e.g., Arapaoa) of the northern Kaipara. Field observations as well as previous studies in other North Island estuaries indicate that mud will be accumulating in the mangrove forests and salt marshes that fringe the Kaipara Harbour (section 2.3) and most likely more rapidly than we have measured on the bare intertidal flats. Most of this terrigenous mud is delivered to the 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 (Fig. 5.2). 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.

Sediment cores from site KAI-14, located ~2km seaward of the Hoteo River mouth, contain the best examples of flood deposits (section 4.1.10). These deposits consist of pure mud layers up to 6-cm thick, which occur at multiple depths between 30 and 128-cm below the present-day seabed. With the exception of the most recent flood deposit at 30–32-cm depth the radioisotope dating show that these mud layers pre-date the 1950s. The excellent preservation of flood deposits at site KAI-14 reflects its close proximity to a large terrigenous sediment source and deposition on a sand flat with rapid post-event burial by sand. The absence of preserved flood deposits above 30-cm depth most likely reflects changes in local hydrodynamic conditions, in particular increased effectiveness of fine-sediment resuspension by waves as the harbour has shoaled.

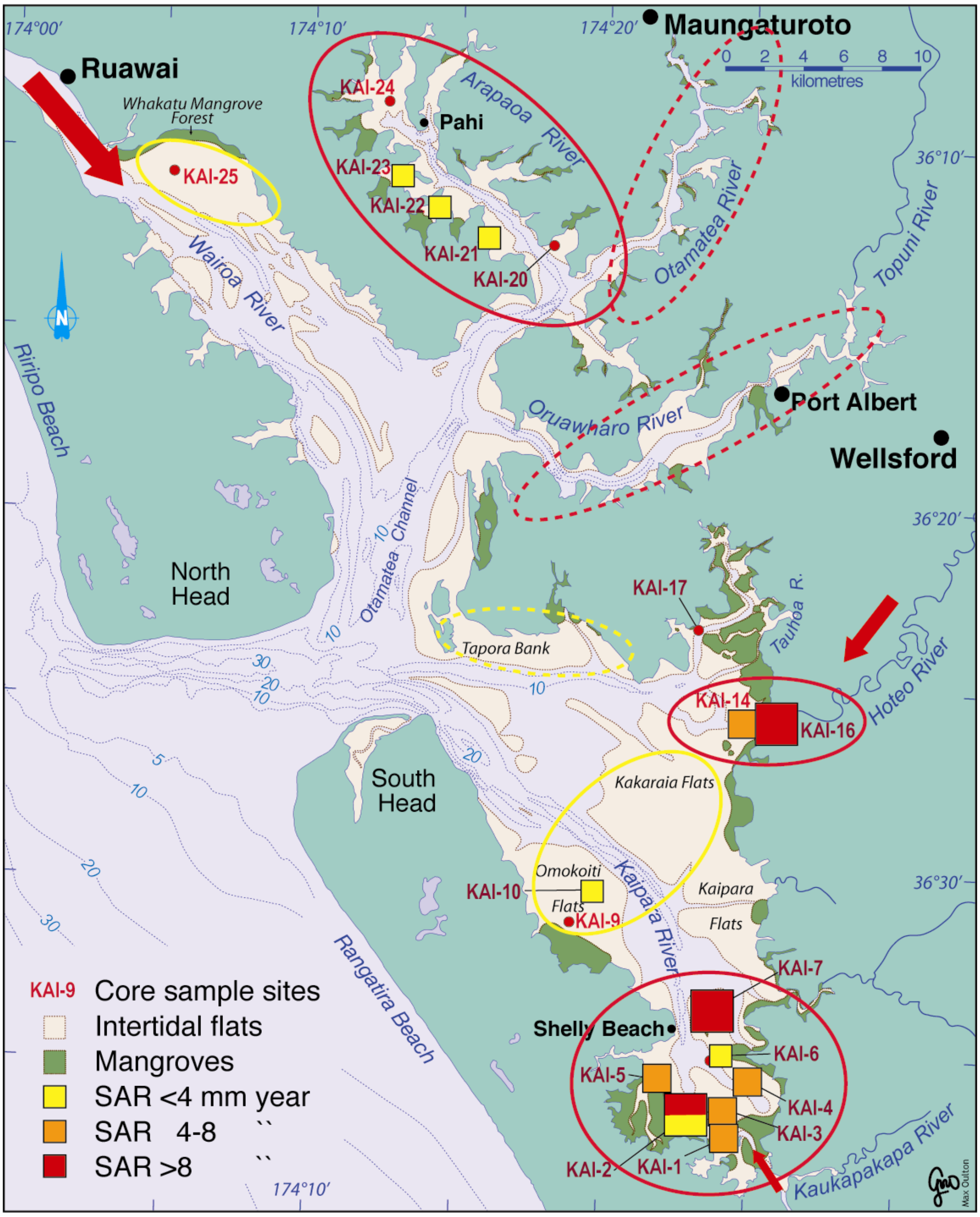
It is notable that mud deposits are absent from the lower-intertidal flats at the mouth of the Wairoa River, which is by far the largest river discharging to the Kaipara Harbour. The rapid pace of seaward expansion of the 335 ha Whakatu mangrove-forest as well as field observations (sections 2.3, 4.2.3) 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, these fine sediments are re-mobilised by waves and transported by currents to eventually accumulate in “low energy” mud sinks. These spatial patterns of mud resuspension and deposition are mirrored in the mud content of surface sediments in the harbour today (Fig 2.7). Particle-size data from the cores (section 4.1) show that sediments on these wave-exposed intertidal flats are composed almost entirely of fine sands. Sediment accumulation rates are also low (i.e., ≤ 1 mm yr^{-1}, KAI-10) or radioisotope concentrations are too low to be detected and/or the profiles show no clear trend with depth (e.g., KAI-9, KAI-15), which indicates that sediments are being reworked to tens of cm depth. Taken together these data indicate that mud has not accumulated on these large intertidal harbour flats for hundreds if not thousands of years.

Figure 5.2 Silt-laden stormwater plume discharging from the Hoteo River mouth on the ebb tide, 22 March 2011 at 2-40 pm (Photos: M. Pritchard, NIWA).

Figure 5.3 summarises the spatial patterns of recent sediment accumulation and inferred sediment sinks and sources of fine sediment in the Kaipara Harbour.

Figure 5.3 Summary of sedimentation and fine-sediment fate in the Kaipara Harbour. Long-term fine-sediment sinks (red ellipses) and temporary sinks (yellow ellipses). Dotted ellipses are inferred sediment sinks. Red arrows represent the relative size of catchment sediment inputs.



Long-term accumulation of fine sediments is occurring 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.

Perhaps the two most important unanswered questions regarding sedimentation in the Kaipara Harbour are:

1) What is the fate of fine-sediments discharged by the Wairoa River to the northern Kaipara harbour. The Wairoa Catchment, at 3,681 km^2, accounts for 63% of the total land catchment.

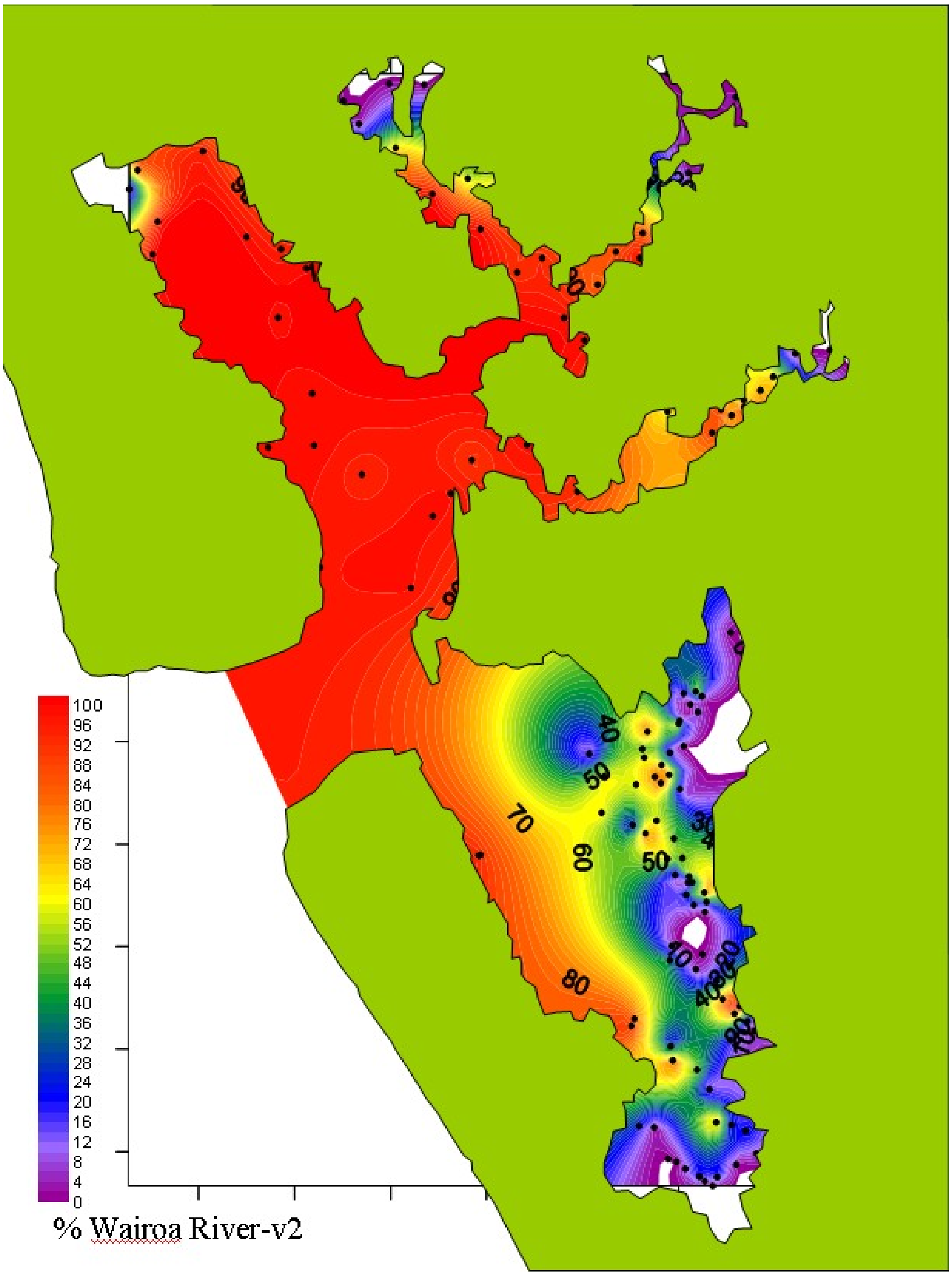
2) What is the degree of fine-sediment connectivity between the northern and southern arms of the harbour? How much of the fine sediment discharged by the Wairoa River accumulates in the southern part of the harbour?

Our observations suggest that fine sediments are accumulating in the mangrove forests and upper intertidal flats that flank the Wairoa River mouth (section 2.3). We have not quantified the amount of mud accumulating in these sub-habitats, however previous work in similar environments (e.g., Swales and Bentley 2008) as well as the rapid expansion of the Whakatu mangrove forest indicates that these areas are major mud sinks in the northern Kaipara. Sediment-core data shows that 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 sediment-source tracking and sediment-transport modelling. Initial results of the NIWA Capability Fund sediment-source tracking study follow.

Extensive field sampling of surface sediments (i.e., top 2 cm) was undertaken in the south and north Kaipara during 2009 and 2010 respectively. Each sampling event was completed during a single low tide to provide a "snap shot" of the spatial distribution of terrigenous sediment from major river sources. Three major river sources were included in this analysis: Wairoa, Kaipara and Hoteo Rivers. The source of sediments deposited at each sampling site was determined using the compound-specific stable isotope (CSSI) technique developed for this purpose (Gibbs 2008). Because of the immense size of the Kaipara Harbour, the sampling density was limited to 60 sites in the north and south Kaipara Harbour. Consequently, the sediment-source dispersion patterns derived from this initial study are indicative rather than definitive and are representative of conditions at the time of sampling. These data also 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.

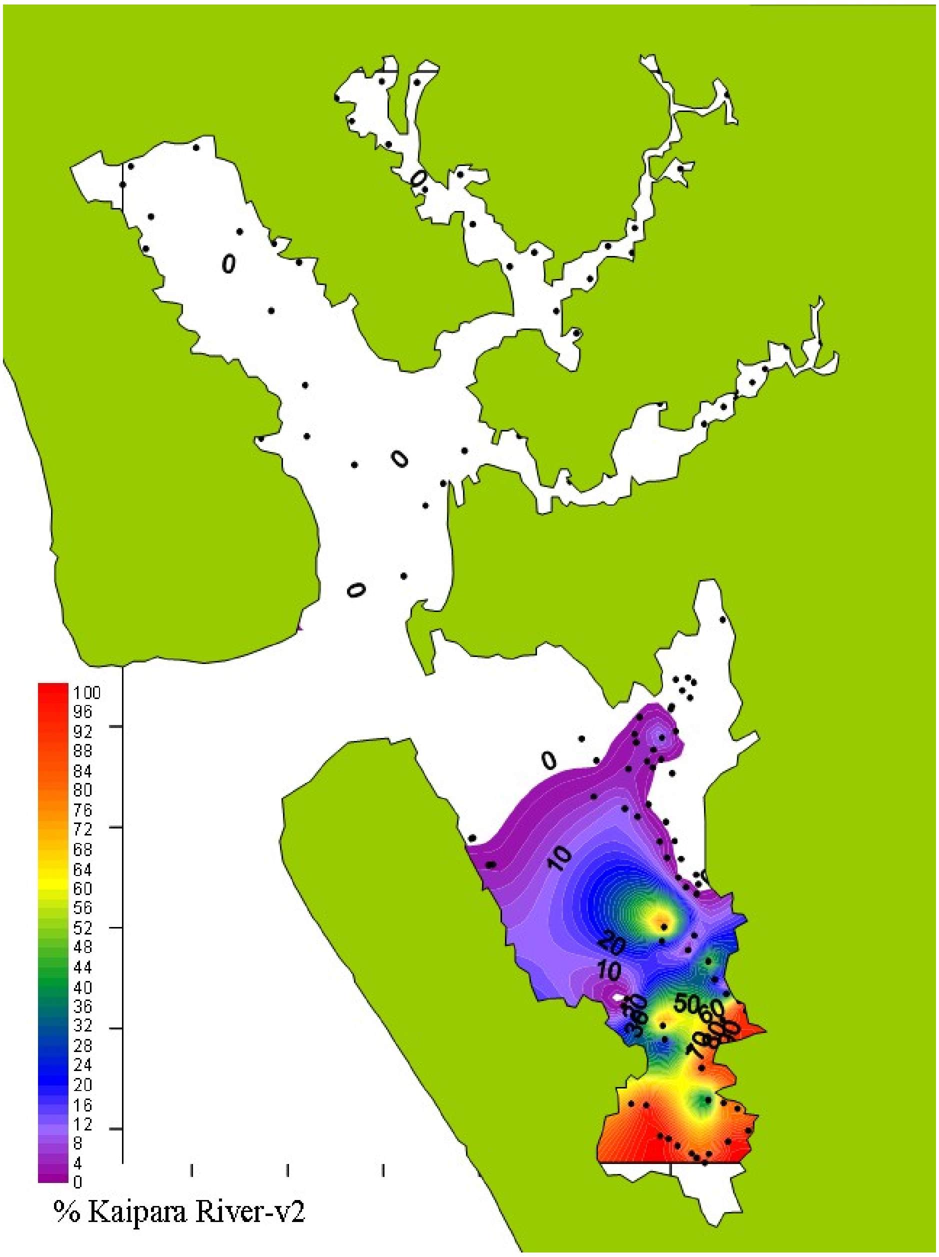
Preliminary results provide clear evidence that sediments from the Wairoa River are widely dispersed across the northern Kaipara, and into the large tidal river systems of the Arapaoa, Otamatea and Oruawharo. Notably, the Wairoa River accounts for most of the contemporary sediment deposited in the Arapaoa River estuary (Fig. 5.4). This result coupled with relatively low sediment accumulation rates (Fig 5.3) indicates that the Arapaoa Catchment is a minor contributor of sediment to the harbour. The Wairoa River is also a major source of sediments deposited in the southern Kaipara, particularly along the western shore of the harbour as far south as Shelly Beach (Fig. 5.4). The Wairoa River source accounts for more than 80% of the sediment sampled at sites within this broad geographical area. Elsewhere in the southern Kaipara Harbour, the Wairoa-River source accounts for typically less than 50% of the surficial sediments deposited at each site. These data suggest a high degree of fine-sediment connectivity between the northern and southern arms of the harbour. A primary mechanism for sediment delivery from the Wairoa River to the southern Kaipara is likely to be tidal advection of silt plumes into both arms of the harbour over successive ebb and flood tides.

Figure 5.4 Deposition pattern of sediment from the Wairoa River based on surficial-sediment sampling (2009–2010). The contribution of the Wairoa River to sediments deposited at each site is expressed as a percentage of all contributing river sources included in the IsoSource sediment-mixing model. Discrimination level set to 2% cut off.



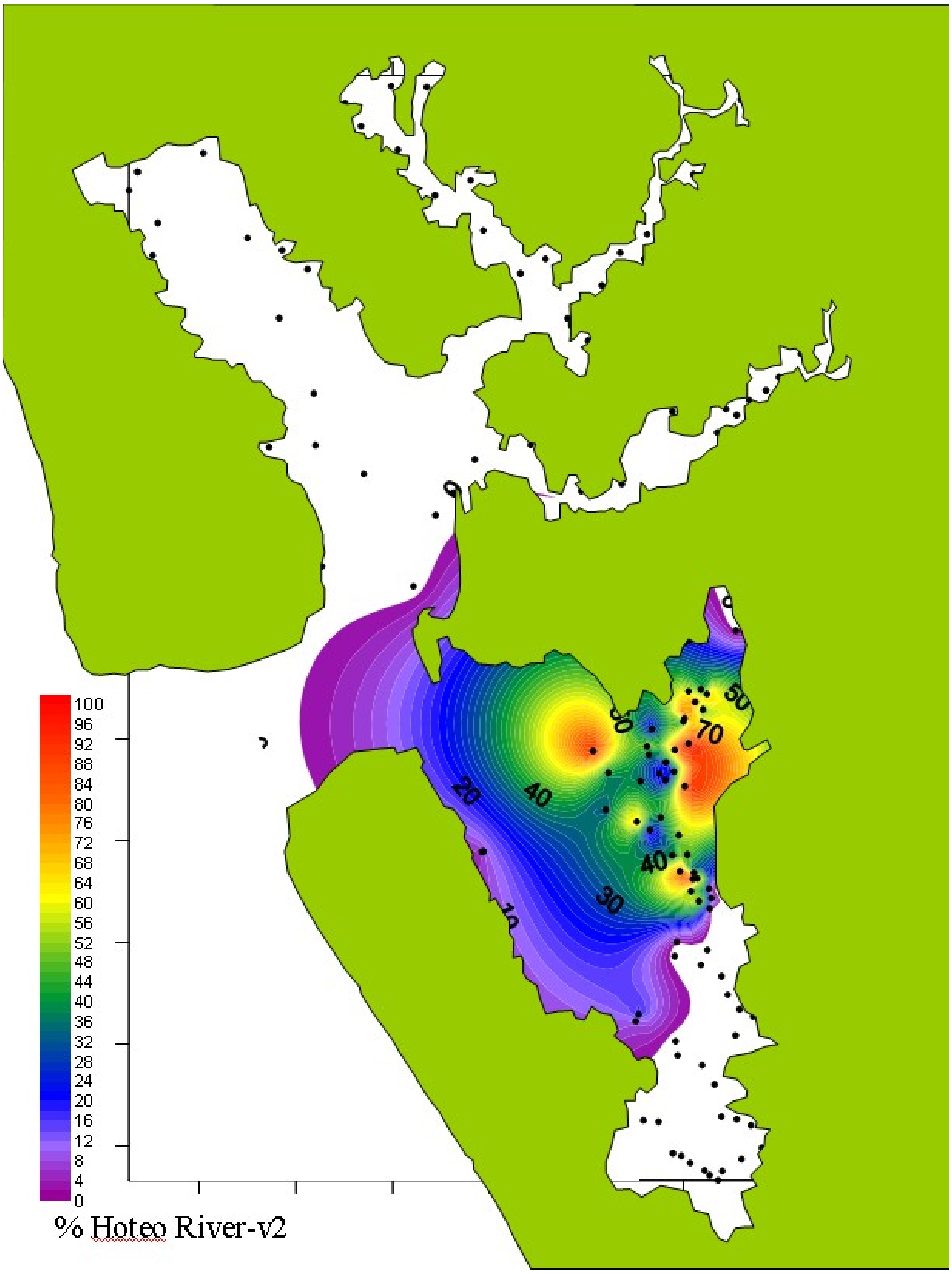
In comparison to the wide-spread dispersal of sediments from the Wairoa River, sediments discharged from the Kaipara River are primarily deposited close to their source, south of Shelly Beach (Fig. 5.5.). Although Kaipara-River sediments are found in deposits north of Shelly Beach, this source typically accounts for less than 20% of surficial-sediment deposits.

Figure 5.5 Deposition pattern of sediment from the Kaipara River based on surficial-sediment sampling (2009–2010). The contribution of the Kaipara River to sediments deposited at each site is expressed as a percentage of all contributing river sources included in the IsoSource sediment-mixing model. Discrimination level set to 2% cut off.



Fine sediment discharged from the Hoteo Catchment is primarily deposited on the Kakaraia Flats, close to the river mouth (Fig. 5.6). South of Okahukura Peninsula, large differences in per cent source contributions at nearby sites indicate that deposition of Hoteo sediments on the lower intertidal flats is patchy. The contribution of the Hoteo River to sediment deposits along the western shoreline at South Kaipara Head is small (i.e., < 10%). This distribution pattern is consistent with local deposition of silt plumes (Fig 5.2) and wave-driven reworking of fine sediments by the prevailing south-west wind that result in fine-sediment deposition on the upper intertidal flats close to the Hoteo River.

Figure 5.6 Deposition pattern of sediment from the Hoteo River based on surficial-sediment sampling (2009–2010). The contribution of the Hoteo River to sediments deposited at each site is expressed as a percentage of all contributing river sources included in the IsoSource sediment-mixing model. Discrimination level set to 2% cut off.



4.2 Recent changes in intertidal vegetated 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 total area of salt-marsh habitat in the Kaipara Harbour has reduced by -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. Data for mixed mangrove and salt-marsh habitat (AC region only) also shows a substantial reduction from 417 ha (1966/1977) to 212 ha in 2007, with most of this habitat loss occurring due to reclamation of the South Kaipara and Omokoiti intertidal flats.

Table 5.3 summarises changes in the areas of mangrove and salt-marsh habitats in the Kaipara Harbour over the last several decades. These data include: present area (ha) and percent contribution to the total area in 2002 (NRC region) and 2007(AC region); and average-annual rate of habitat change (% yr^{-1}) for each compartment. Figures 5.7 and 5.8 present these data on maps.

Table 5.3 Summary of present area and recent historical changes in mangrove and salt-marsh habitat in the Kaipara Harbour. Habitat areas (hectares) are given for the most recent data (2002/2007). The rate of habitat change is given as an average percentage per year: 1977–2002 (Northland Region) and 1966/1977–2007 (Auckland Region). The 1966 photography covers the South Kaipara, Omokoiti and South Head compartments.

Compartment	Mangrove			Salt marsh		
	Area (ha)	Area (% of total)	Habitat change (% yr^{-1})	Area (ha)	Area (% of total)	Habitat change (% yr^{-1})
North Kaipara	386.7	5.1	–	145.2	22.0	–
Whakatu	334.6	4.4	2.1	71.5	10.8	0.2
North Head	64.2	0.8	–	24.7	3.8	–
Arapaoa	836.7	11	1.5	42.2	6.4	0.0
Otamatea	314.8	4.1	1.4	28	4.3	4.5
Oruawharo	898.7	11.8	0.6	35.3	5.4	1.3
Whakaki	118.1	1.6	1.1	5.7	0.9	3.4
Central Kaipara	588.1	7.7	0.7	–		–
Tauhoa – Hoteo	1313.7	17.3	0.2	66.2	10.0	0.0
Kaipara Flats	390.9	5.1	0.5	34.7	5.3	0.0
South Head	13.3	0.2	0.2	5.3	0.8	–
Omokoiti Flats	380.1	5.0	-0.7	40.8	6.2	-0.1
South Kaipara	1974.9	25.9	-1.2	159.9	24.3	-0.3
Total area (ha)	7614.8			659.5		

The South Kaipara compartment contains the largest areas of mangrove (~26%) and salt-marsh habitats (~24%) in the harbour. However, the area of both mangrove (-1.2 % yr^{-1}) and salt-marsh (-0.3 % yr^{-1}) habitat has declined since the mid 1960s, primarily due to reclamation works. The Tauhoa–Hoteo compartment is another major area of mangrove habitat (17% of the harbour total) and has increased at an average rate of 0.2% yr^{-1}. The South Kaipara and Tauhoa–Hoteo compartments together account for 43% of the total mangrove habitat in the Kaipara Harbour.

The rates of change in mangrove habitat in each compartment show a general north to south reduction, from +2.1% yr^{-1} in the Whakatu compartment to -1.2% in the South Kaipara. Although mangrove habitat in the northern (i.e., NRC) Kaipara accounts for only one third of the harbour total (7615 ha), rates of habitat expansion have been higher (1.1–2.1 % yr^{-1}) than in the southern Kaipara where habitat loss has also occurred (-1.2 to +0.7 % yr^{-1}).

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 (Morrisey et al. 2010). 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. A regional study of Auckland east-coast estuaries also showed that the largest increases in mangrove habitat over the last ~50 years have occurred in the smallest (i.e., <5-km^2) estuaries (Swales et al. 2008b). By contrast there were virtually no increases in mangrove habitat in the largest estuaries, such as the Waitemata Harbour, which alone accounts for 30% of the total present-day area of mangrove habitat (2700 ha) in the study estuaries. Furthermore, like the Kaipara Harbour, substantial mangrove-habitat loss has occurred in the Waitemata Harbour due to reclamations associated with motorway construction, industrial development and refuse landfills in the 1950s–1970s (Swales et al. 2008b).

These studies primarily based on analysis of aerial-photography do not encompass the environmental changes, including mangrove-habitat expansion that occurred in many estuaries prior to the 1940s. In the Kaipara Harbour, McShane (2005) compiled 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, such as the Oruawharo, and elsewhere. Although we cannot accurately quantify the extent of these earlier environmental changes in the Kaipara, these historical records (e.g., Ferrar 1934, McShane 2005) show that in some locations major phases of mangrove-habitat expansion occurred prior to the 1940s.

The aerial photographic record also shows similar patterns of salt-marsh habitat change over the last several decades with: (1) a few compartments accounting for most of the area habitat area; and (2) the highest rates of habitat expansion occurring in the northern Kaipara Harbour. The North Kaipara (22% of total) and South Kaipara (25% of total) compartments contain the largest areas of salt-marsh. The northern Kaipara Harbour accounts for 53% of the total salt-marsh habitat. 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}) primarily due to tidal-flat reclamation (1966–2007).

Figure 5.7 Summary of mangrove-habitat in the Kaipara Harbour by compartment: (1) percentage of mangrove-forest habitat in each compartment (2002 – Northland and 2007 – Auckland); and (2) average annual change in mangrove-habitat area (percent per year) since 1966/1977. Note: the 1966 data apply only to the South Kaipara and Omokoiti compartments.

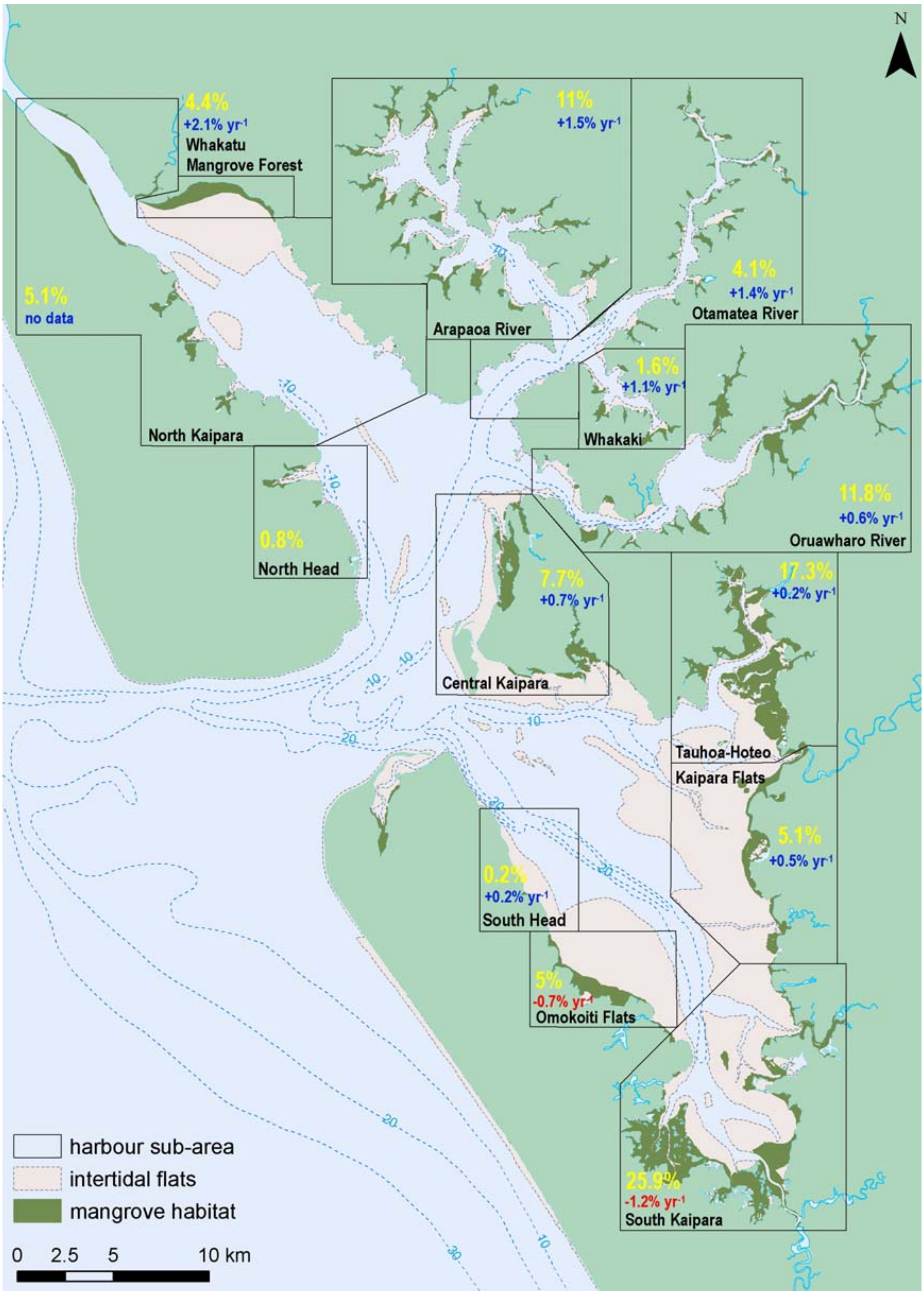
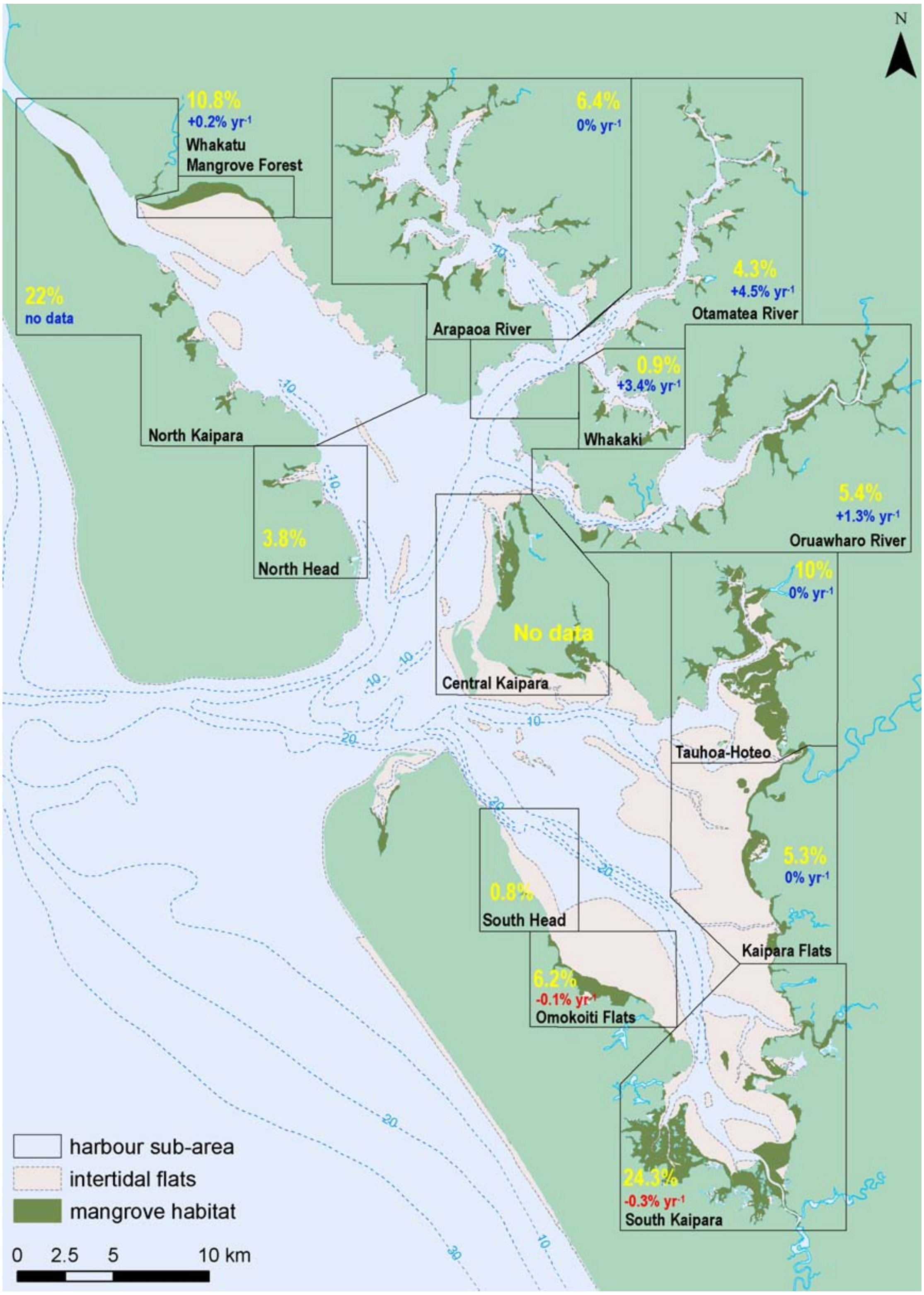


Figure 5.8 Summary of salt-marsh-habitat in the Kaipara Harbour by compartment: (1) percentage of salt-marsh habitat in each compartment (2002 – Northland and 2007 – Auckland); and (2) average annual change in salt-marsh habitat area (percent per year) since 1966/1977. Note: the 1966 data apply only to the South Kaipara and Omokoiti compartments.



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7.0 Appendices

7.1 Location of sampled core sites

Table 8.1 Location and sampling details of sediment cores collected in the Kaipara Harbour, 2010. Location key: South Kaipara Harbour (SKH), Omokoiti Flats (OF); Hoteo River (HR); Arapaoa River (AR); North Kaipara Harbour (NKH).

Core Site	Habitat	Location	Date	Time (NZST)	Water Depth (m)	Latitude	Longitude
Auckland region							
KAI-1	IT	SKH	17/3/10	0935	0.5	36° 37.1808'S	174° 24.3003'E
KAI-2	IT	SKH	17/3/10	1041	1.3	36° 36.3922'S	174° 22.9964'E
KAI-3	IT	SKH	17/3/10	1223	1.8	36° 36.1284'S	174° 24.1116'E
KAI-4	IT	SKH	17/3/10	1123	1.8	36° 35.6146'S	174° 25.5786'E
KAI-5	IT	SKH	17/3/10	1322	1.5	36° 35.103'S	174° 22.241'E
KAI-6	ST	SKH	16/3/10	1346	3.0	36° 35.0039'S	174° 23.6360'E
KAI-6A	ST	SKH	16/3/10	1413	2.3	36° 34.808'S	174° 24.142'E
KAI-7	IT	SKH	16/3/10	0827	1.9	36° 32.5315'S	174° 23.9338'E
KAI-9	IT	OF	16/3/10	1108	1.6	36° 31.4664'S	174° 18.7133'E
KAI-10	IT	OF	16/3/10	1156	3.2	36° 30.4627'S	174° 19.9226'E
KAI-14	IT	HR	15/4/10	1021	2.0	36° 25.7517'S	174° 24.885'E
KAI-16	IT	HR	15/4/10	0923	1.0	36° 25.7721'S	174° 25.9957'E
KAI-17	IT	TR	15/4/10	1208	2.1	36° 23.6604'S	174° 23.446'E
Northland region							
KAI-20	IT	AR	18/3/10	1417	1.1	36° 12.6433'S	174° 18.4408'E
KAI-21	IT	AR	18/3/10	1336	2.3	36° 12.5061'S	174° 16.1397'E
KAI-22	IT	AR	18/3/10	1245	1.8	36° 11.857'S	174° 13.9541'E
KAI-23	IT	AR	18/3/10	1157	0.9	36° 10.8836'S	174° 12.9307'E
KAI-24	IT	AR	18/3/10	1047	1.0	36° 08.805'S	174° 12.4095'E
KAI-25	IT	NKH	19/3/10	1231	1.1	36° 10.755'S	174° 05.158'E

7.2 Appendix: Dating of estuarine sediments

Radioisotopes, such as caesium-137 (^{137}Cs, ½-life 30 years) and lead-210 (^{210}Pb, ½-life 22.3 years), and plant pollen can be used to reconstruct the recent sedimentation history of an estuary.

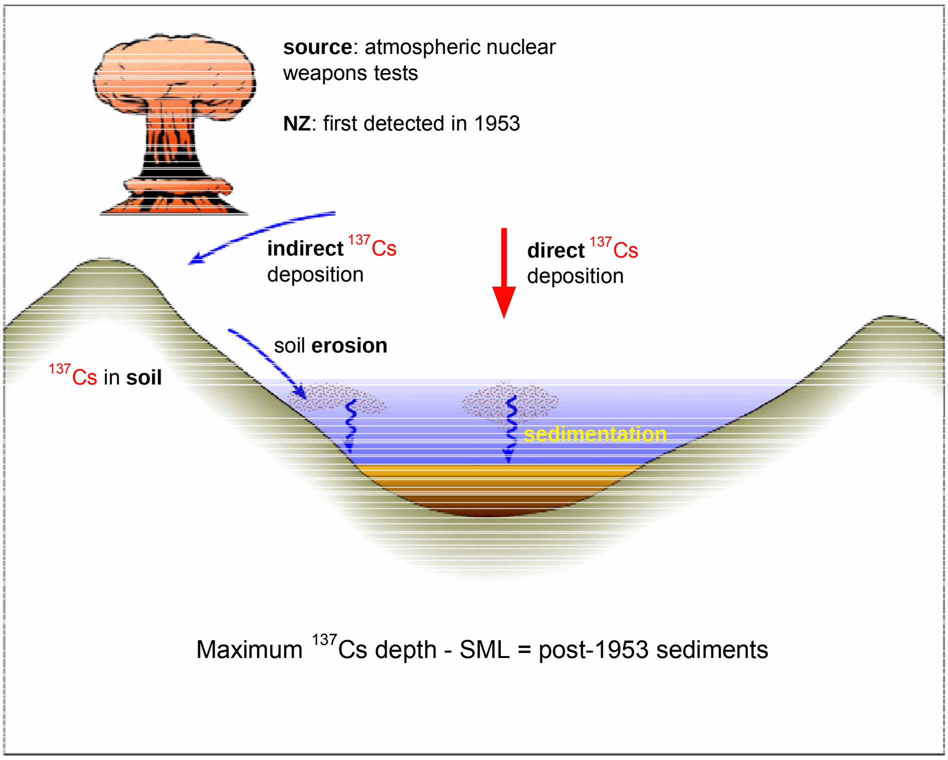
Dating of estuarine sediments using independent methods offsets the limitations of any one approach. This is particularly important when interpreting sediment profiles from lakes and estuaries, given the confounding effects of physical and biological mixing (Robbins and Edgington, 1975; Sharma et al. 1987; Alexander et al. 1993; Valette-Silver, 1993; Benoit et al. 1999). A description of the various methods of dating sediments follows.

The S.I. unit of radioactivity used in this study is the Becquerel (Bq), which is equivalent to one radioactive disintegration per second.

7.2.1 ^{137}Cs dating

^{137}Cs was introduced to the environment by atmospheric nuclear weapons tests in 1953, 1955–1956 and 1963–1964. Peaks in annual ^{137}Cs deposition corresponding to these dates are the usual basis for dating sediments (Wise, 1977; Ritchie and McHenry, 1989). Although direct atmospheric deposition of ^{137}Cs into estuaries is likely to have occurred, ^{137}Cs is also incorporated into catchment soils, which are subsequently eroded and deposited in estuaries (Fig. 8.1). In New Zealand, ^{137}Cs deposition was first detected in 1953 and its annual deposition was been measured at several locations until 1985. Annual ^{137}Cs deposition can be estimated from rainfall using known linear relationships between rainfall and Strontium-90 (^{90}Sr) and measured ^{137}Cs/^{90}Sr deposition ratios (Matthews, 1989). Experience in Auckland estuaries shows that ^{137}Cs profiles measured in estuarine sediments bear no relation to the record of annual ^{137}Cs deposition (i.e., 1955–1956 and 1963–1964 ^{137}Cs-deposition peaks absent), but rather preserve a record of direct and indirect (i.e., soil erosion) atmospheric deposition since 1953 (Swales et al. 2002). The maximum depth of ^{137}Cs occurrence in sediment cores (corrected for sediment mixing) is taken to coincide with the year 1953, when ^{137}Cs deposition was first detected in New Zealand. We assume that there is a negligible delay in initial atmospheric deposition of ^{137}Cs in estuarine sediments (e.g., ^{137}Cs scavenging by suspended particles) whereas there is likely to have been a time-lag (i.e., < 1 yr) in ^{137}Cs inputs to estuaries from topsoil erosion, which would coincide with the occurrence of floods.

Figure 8.1 ^{137}Cs pathways to estuarine sediments.



If a surface mixed layer (SML) is evident in a core, as shown by an x-ray image and/or a tracer profile (e.g., ^{7}Be, ^{210}Pb) then ^{137}Cs is likely to have been rapidly mixed through the SML. Therefore, to calculate time-averaged sedimentation rates, the maximum depth of ^{137}Cs occurrence is reduced by the maximum depth of the SML.

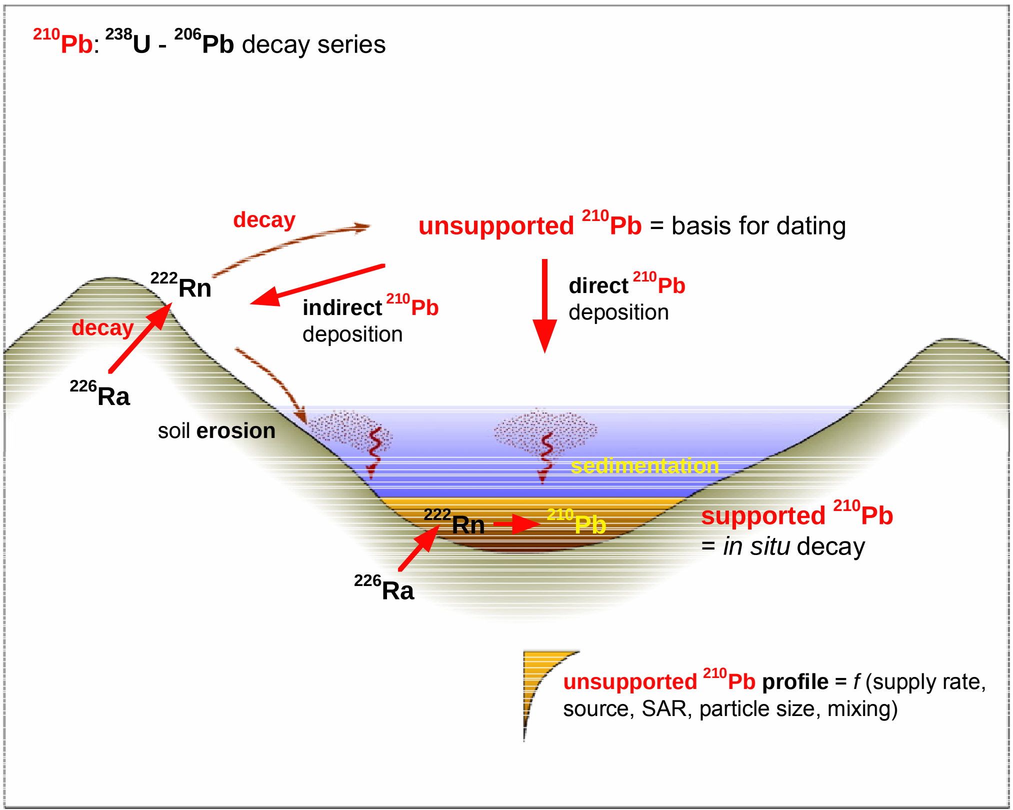
Uncertainty in the maximum depth of ^{137}Cs results from: (1) the depth interval between sediment samples and (2) minimum detectable concentration of ^{137}Cs, which is primarily determined by sample size and counting time. The 1963–1964 ^{137}Cs deposition peak was about five-times than the deposition plateau that occurred between 1953 and 1972. Thus, depending on the sample size, there is uncertainty in the age of the maximum ^{137}Cs depth (i.e., 1953–1963). To reduce this uncertainty, we have maximised the sample mass that is analysed (section 3).

7.2.2 ^{210}Pb dating

^{210}Pb (half-life 22.3 yr) is a naturally occurring radioisotope that has been widely applied to dating recent sedimentation (i.e., last 150 yrs) in lakes, estuaries and the sea (Fig. 8.2). ^{210}Pb is an intermediate decay product in the uranium-238 (^{228}U) decay series and has a radioactive decay constant (k) of 0.03114 yr^{-1}. The intermediate parent radioisotope radium-226 (^{226}Ra, half-life 1622 years) yields the inert gas radon-222 (^{222}Rn, half-life 3.83 days), which decays through several short-lived radioisotopes to produce ^{210}Pb. A proportion of the ^{222}Rn gas formed by ^{226}Ra decay in catchment soils diffuses into the atmosphere where it decays to form ^{210}Pb. This atmospheric ^{210}Pb is deposited at the earth surface by dry deposition or rainfall. The ^{210}Pb in estuarine sediments has two components: supported ^{210}Pb derived from *in situ* ^{222}Rn decay (i.e., within the sediment column) and an unsupported ^{210}Pb component derived from atmospheric fallout. This unsupported ^{210}Pb component of the total ^{210}Pb concentration in excess of the supported ^{210}Pb value is estimated from the ^{226}Ra assay (see below). Some of this atmospheric unsupported ^{210}Pb component is also incorporated into catchment soils and is subsequently eroded and deposited in estuaries. Both the direct and indirect (i.e., soil inputs) atmospheric ^{210}Pb input to receiving environments, such as estuaries, is termed the unsupported or excess ^{210}Pb.

The concentration profile of unsupported ^{210}Pb in sediments is the basis for ^{210}Pb dating. In the absence of atmospheric (unsupported) ^{210}Pb fallout, the ^{226}Ra and ^{210}Pb in estuary sediments would be in radioactive equilibrium, which results from the substantially longer ^{226}Ra half-life. Thus, the ^{210}Pb concentration profile would be uniform with depth. However, what is typically observed is a reduction in ^{210}Pb concentration with depth in the sediment column. This is due to the addition of unsupported ^{210}Pb directly or indirectly from the atmosphere that is deposited with sediment particles on the bed. This unsupported ^{210}Pb component decays with age (k = 0.03114 yr^{-1}) as it is buried through sedimentation. In the absence of sediment mixing, the unsupported ^{210}Pb concentration decays exponentially with depth and time in the sediment column. The validity of ^{210}Pb dating rests on how accurately the ^{210}Pb delivery processes to the estuary are modelled, and in particular the rates of ^{210}Pb and sediment inputs (i.e., constant versus time variable).

Figure 8.2 ^{210}Pb pathways to estuarine sediments.



7.2.3 Sediment accumulation rates (SAR)

Sedimentation rates calculated from cores are **net average sediment accumulation rates (SAR), which are usually expressed as mm yr^{-1}**. These SAR are net values because cores integrate the effects of all processes, which influence sedimentation at a given location. At short time scales (i.e., seconds–months), sediment may be deposited and then subsequently resuspended by tidal currents and/or waves. Thus, over the long term, sedimentation rates derived from cores represent net or cumulative effect of potentially many cycles of sediment deposition and resuspension. However, less disrupted sedimentation histories are found in depositional environments where sediment mixing due to physical processes (e.g., resuspension) and bioturbation is limited. The effects of bioturbation on sediment profiles and dating resolution reduce as SAR increase (Valette-Silver, 1993).

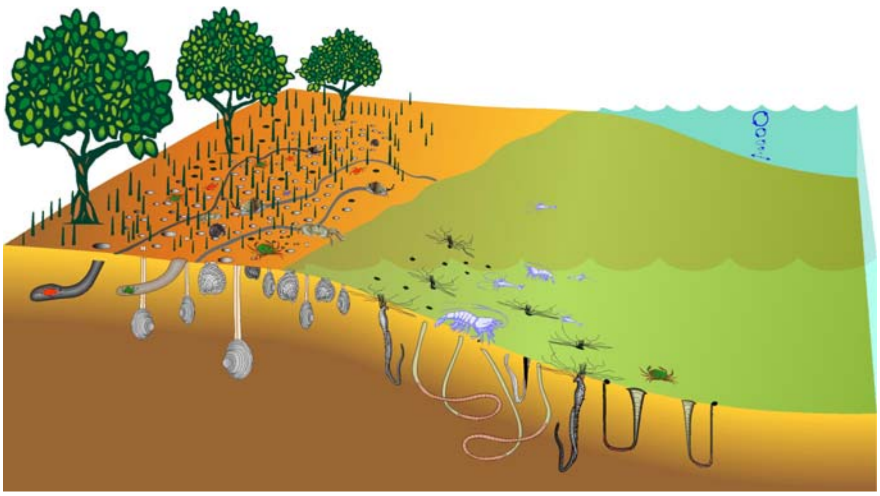
Net sedimentation rates also mask the fact that sedimentation is an episodic process, which largely occurs during catchment floods, rather than the continuous gradual process that is implied. In large estuarine embayments, such as the Firth, mudflat sedimentation is also driven by wave-driven resuspension events. Sediment eroded from the mudflat is subsequently re-deposited elsewhere in the estuary.

Although sedimentation rates are usually expressed as a sediment thickness deposited per unit time (i.e., mm yr^{-1}) this statistic does not account for changes in dry sediment mass with depth in the sediment column due to compaction. Typically, sediment density (ρ = g cm^{-3}) increases with depth and therefore some workers prefer to calculate dry mass accumulation rates per unit area per unit time (g cm^{-2} yr^{-1}). These data can be used to estimate the total mass of sedimentation in an estuary (tonnes yr^{-1}) (e.g., Swales et al. 1997). However, the effects of compaction can be offset by changes in bulk sediment density reflecting layering of low-density mud and higher-density sand deposits. Furthermore, the significance of a SAR expressed as mm yr^{-1} is more readily grasped than a dry-mass sedimentation rate in g cm^{-3} yr^{-1}. For example, the rate of estuary aging due to sedimentation (mm yr^{-1}) can be directly compared with the local rate of sea level rise.

7.2.4 Sediment Mixing

Biological and physical processes, such as the burrowing and feeding activities of animals and/or sediment resuspension by waves (Fig. 8.3), mix the upper sediment column (Bromley, 1996). As a result, sediment profiles are modified and this limits the temporal resolution of dating. Various mathematical models have been proposed to take into account the effects of bioturbation on ^{210}Pb concentration profiles (e.g., Guinasso and Schink, 1975).

Figure 8.3 Biological and physical processes, such as the burrowing and feeding activities of animals and/or sediment resuspension by waves, mix the upper sediment column. As a result, sediment profiles are modified and limit the temporal resolution of dating. The surface mixed layer (SML) is the yellow zone.



Biological mixing has been modelled as a one-dimensional particle-diffusion process (Goldberg and Kiode, 1962) and this approach is based on the assumption that the sum effect of ‘random’ biological mixing is integrated over time. In estuarine sediments exposed to bioturbation, the depth profile of unsupported ^{210}Pb typically shows a two-layer form, with a surface layer of relatively constant unsupported ^{210}Pb concentration overlying a zone of exponential decrease. In applying these types of models, the assumption is made that the mixing rate (i.e., diffusion co-efficient) and mixing depth (i.e., surface-mixed layer, SML) are uniform in time. The validity of this assumption usually cannot be tested, but changes in bioturbation process could be expected to follow changes in benthic community composition.