5 Synthesis

5.1 Recent sedimentation in the Kaipara Harbour

5.1.1 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.

5.1.2 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.

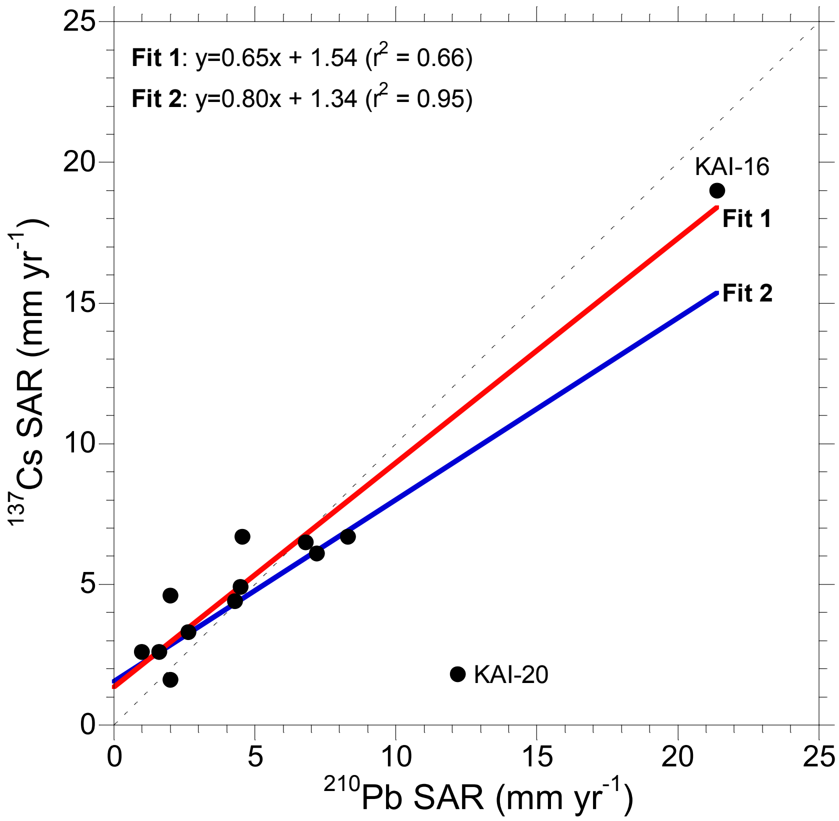
The good agreement between the ^{210}Pb and ^{137}Cs dating as well as the information provided by the x-radiographs, ^{7}Be and sediment composition data indicate that we can have confidence in the recent geochronology reconstructed from these cores.

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	

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-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 (r2 =0.74).



5.1.3 Comparison of sedimentation rates with other North Island estuaries

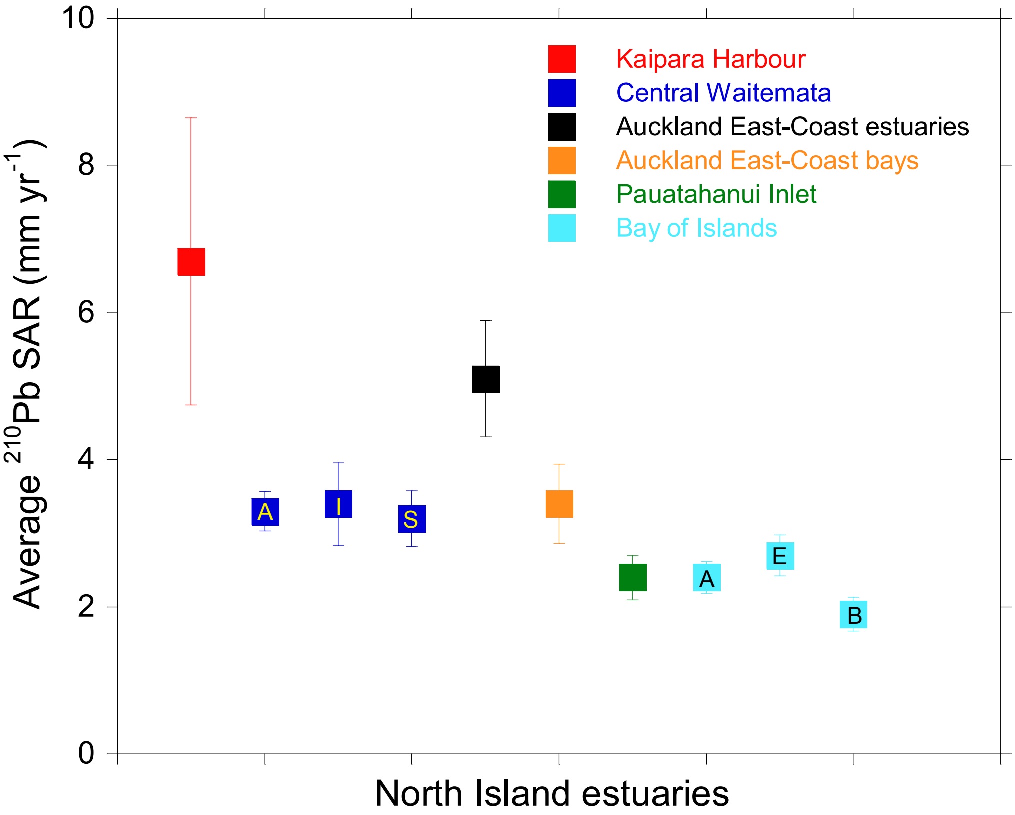
In this section we compare average sediment accumulation rates in the Kaipara Harbour with average rates for other North Island estuaries. This analysis enables the recent sedimentation of the Kaipara Harbour to be considered in a wider context of human impacts on New Zealand estuaries over the last 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.

Table 5-2: 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) steepland 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 5-3: 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 & 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.

5.1.4 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.

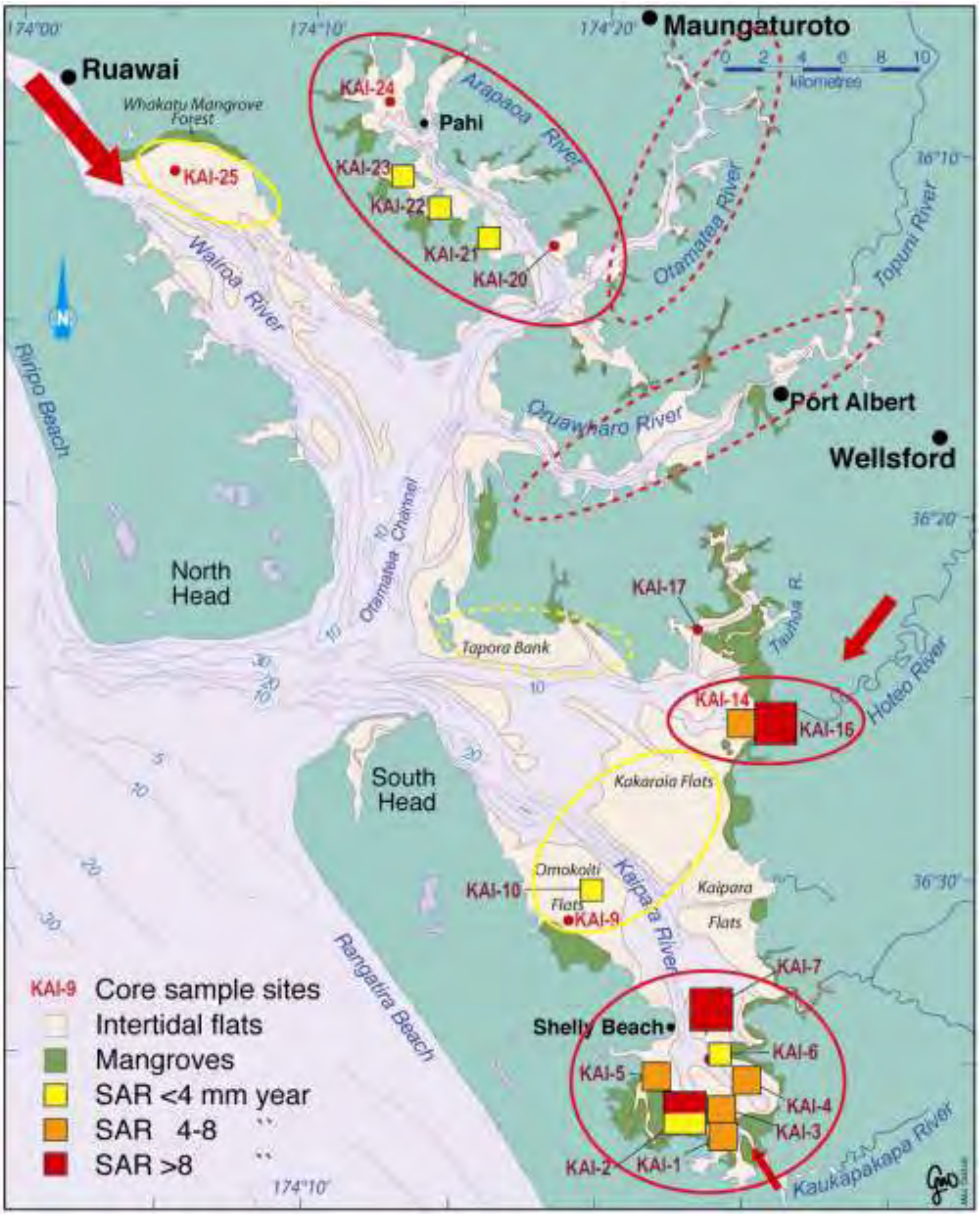
It is notable that mud deposits are absent from the lower-intertidal flats at the mouth of the Wairoa River, which is by far the largest river discharging to the Kaipara Harbour. The rapid pace of seaward expansion of the 335 ha Whakatu mangrove-forest as well as field observations (sections 2.3, 4.2.3) 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.

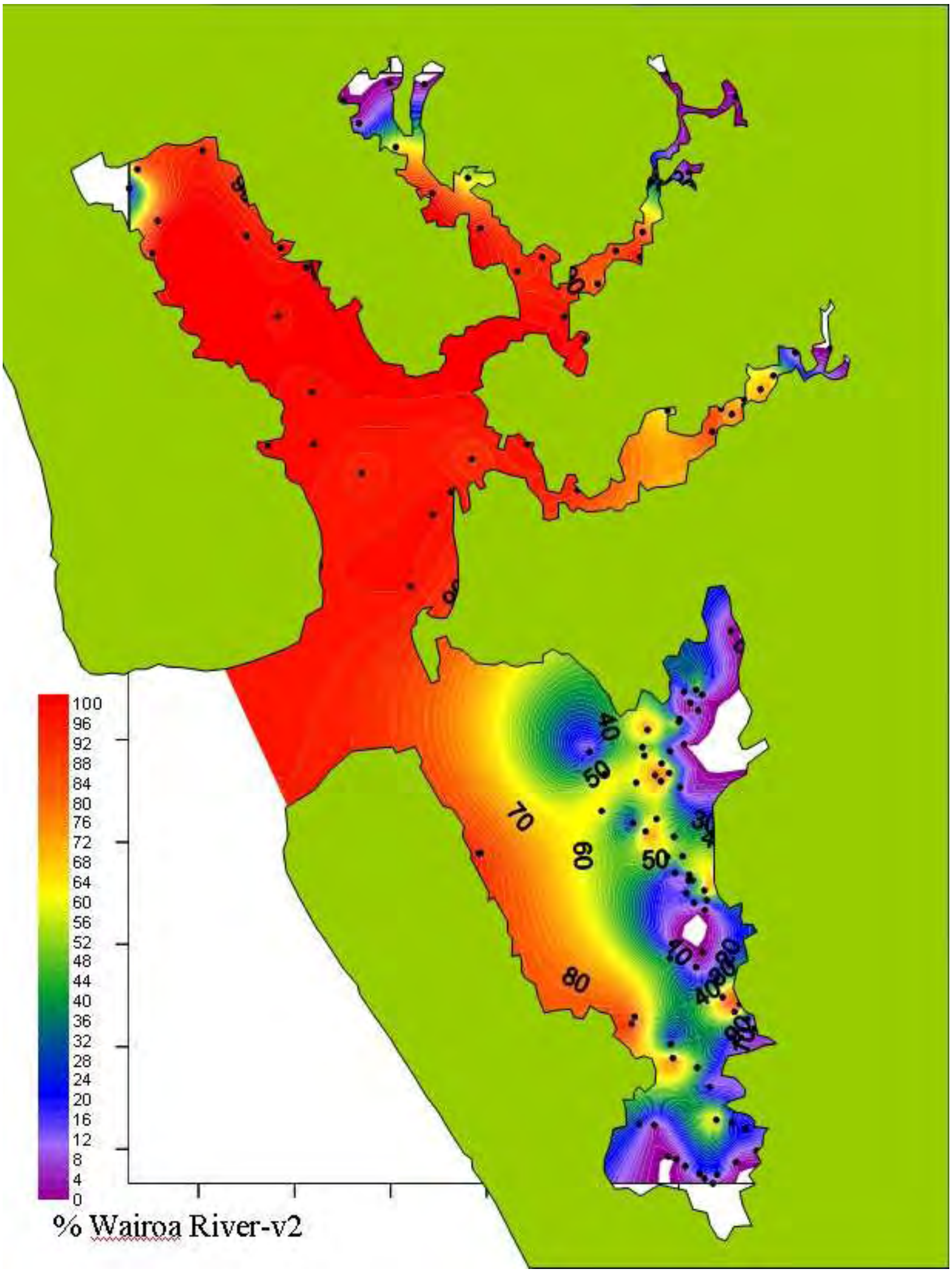
2. What is the degree of fine-sediment connectivity between the northern and southern arms of the harbour? How much of the fine sediment discharged by the Wairoa River accumulates in the southern part of the harbour?

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.

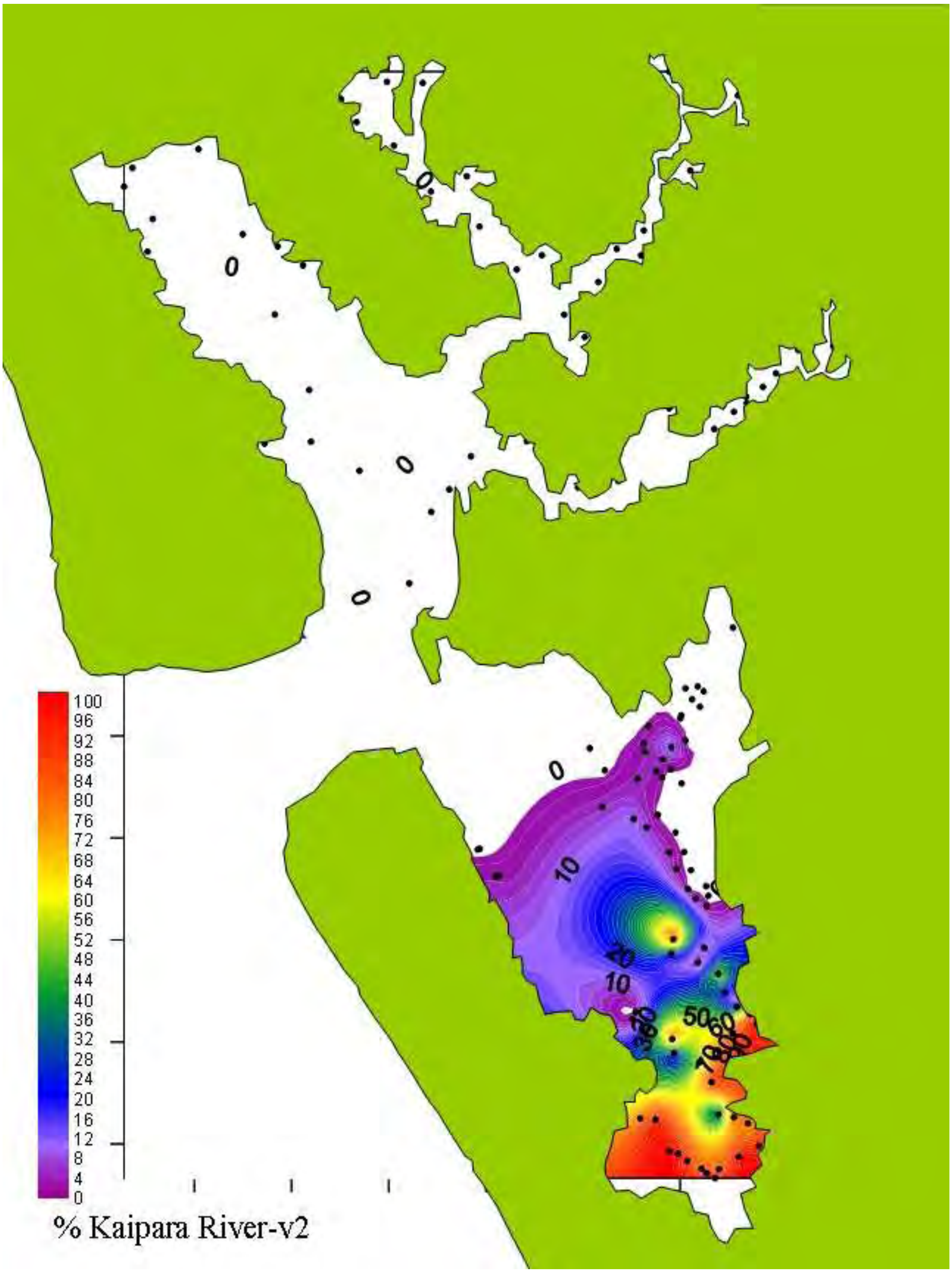
Preliminary results provide clear evidence that sediments from the Wairoa River are widely dispersed across the northern Kaipara, and into the large tidal river systems of the Arapaoa, Otamatea and Oruawharo. Notably, the Wairoa River accounts for most of the contemporary sediment deposited in the Arapaoa 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.



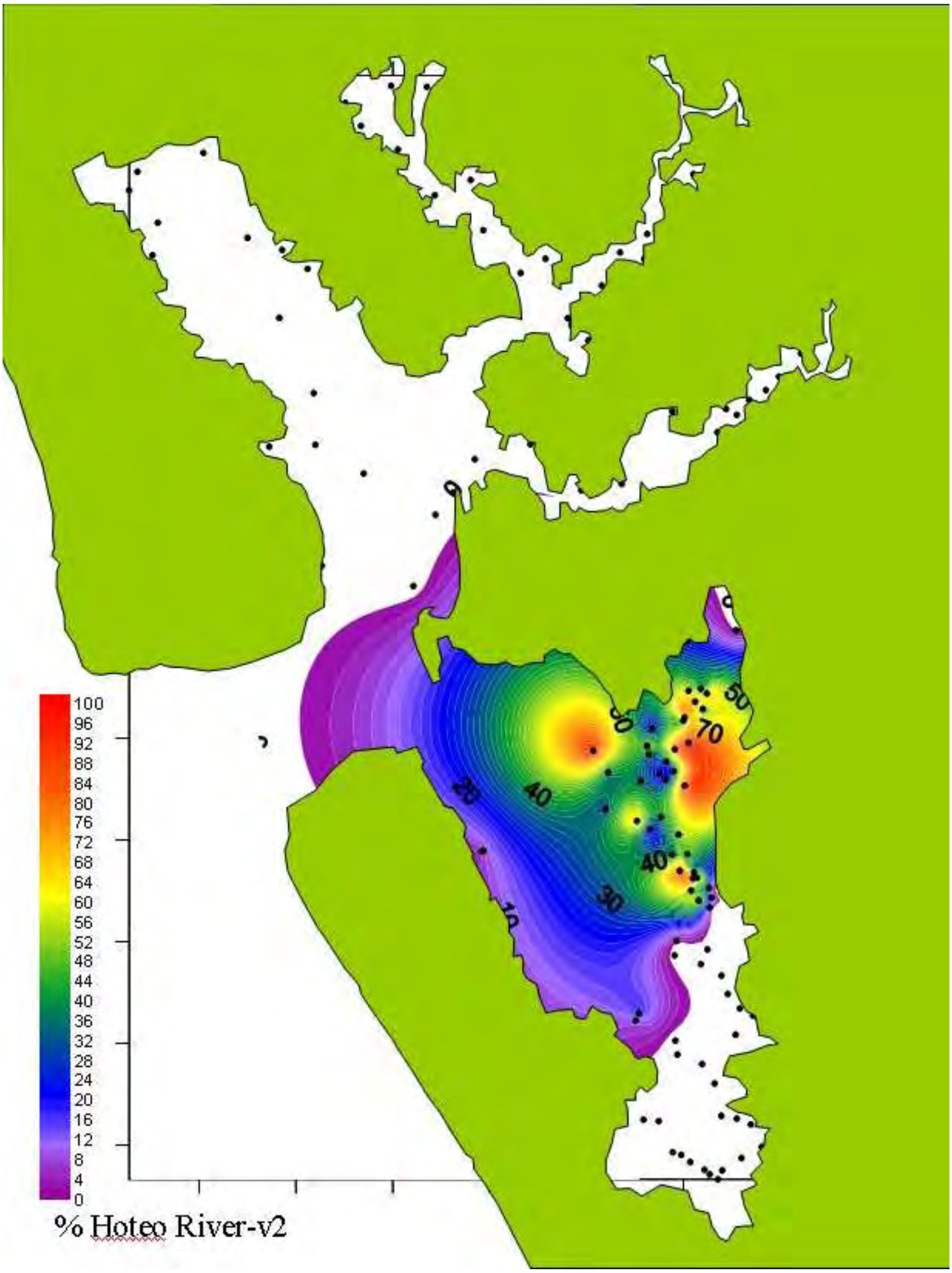
In comparison to the wide-spread dispersal of sediments from the Wairoa River, sediments discharged from the Kaipara River are primarily deposited close to their source, south of Shelly Beach (Fig. 5.5.). Although Kaipara-River sediments are found in deposits north of Shelly Beach, this source typically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



5.2 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 5-4: 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) complied 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 (per cent 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 (per cent per year) since 1966/1977. Note: the 1966 data apply only to the South Kaipara and Omokoiti compartments.

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8 Appendices

8.1 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

8.2 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.

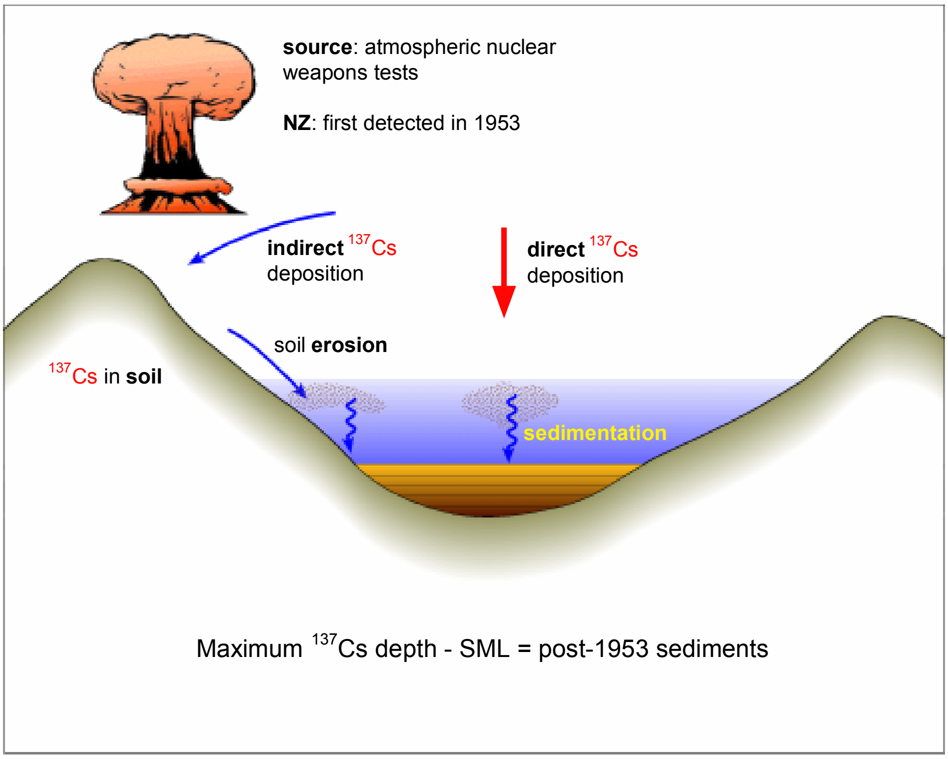
Dating of estuarine sediments using independent methods offsets the limitations of any one approach. This is particularly important when interpreting sediment profiles from lakes and estuaries, given the confounding effects of physical and biological mixing (Robbins and Edgington, 1975; Sharma et al. 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.

8.2.1 ^{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.

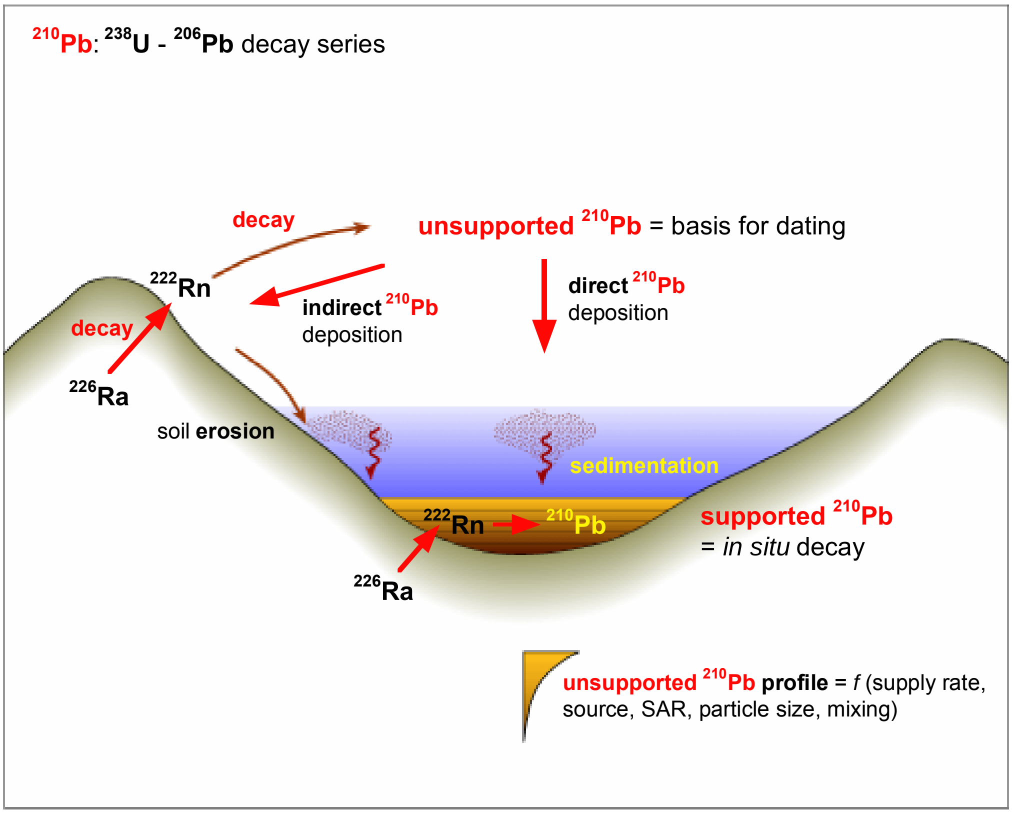
Uncertainty in the maximum depth of ^{137}Cs results from: (1) the depth interval between sediment samples and (2) minimum detectable concentration of ^{137}Cs, which is primarily determined by sample size and counting time. The 1963–1964 ^{137}Cs deposition peak was about five-times than the deposition 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).

8.2.2 ^{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.



8.2.3 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).

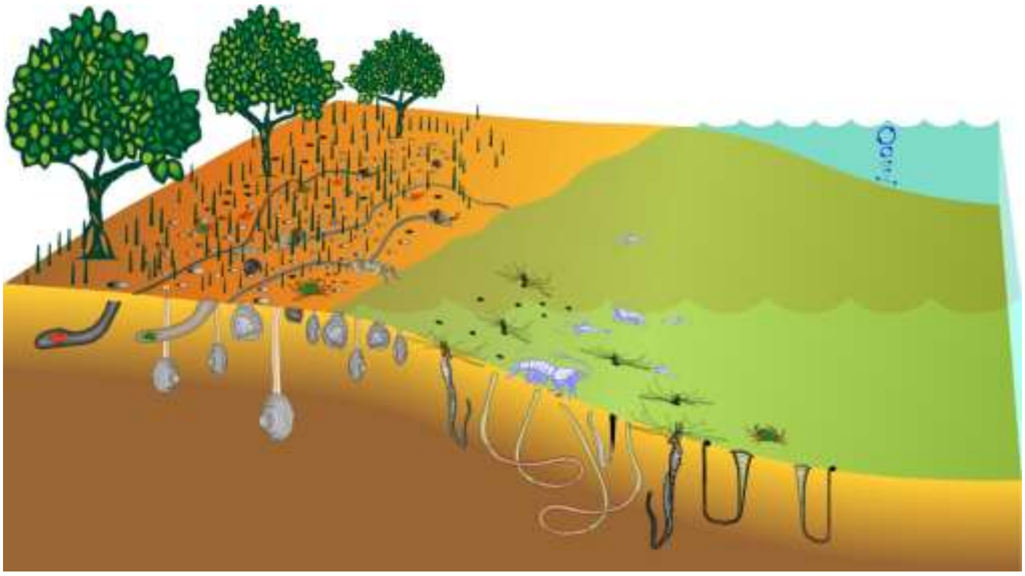
Net sedimentation rates also mask the fact that sedimentation is an episodic process, which largely occurs during catchment floods, rather than the continuous gradual process that is implied. In large estuarine embayments, such as the Firth, mudflat sedimentation is also driven by wave-driven resuspension 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.

8.2.4 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.