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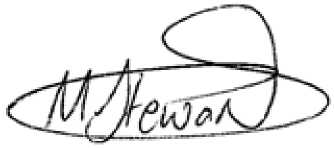
Sedimentation in the Okura-Weiti-Karepiro Bay System

November TR 2008/026

Auckland Regional Council
Technical Report No.026 November 2008
ISSN 1179-0504 (Print)
ISSN 1179-0512 (Online)
ISBN 978-1-877483-68-4

Reviewed by:



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Recommended Citation:
Swales, A., Gibbs, M., Ovenden, R., Budd, R., Hermansphan, N. (2008). Sedimentation in the Okura –Weiti – Karepiro Bay system. Prepared by NIWA for Auckland Regional Council. Auckland Regional Council Technical Report 2008/026.

Sedimentation in the Okura – Weiti – Karepiro Bay system

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Prepared for
Auckland Regional Council
Environmental Research

NIWA Client Report: HAM2008-153
September 2008

NIWA Project: ARC08220

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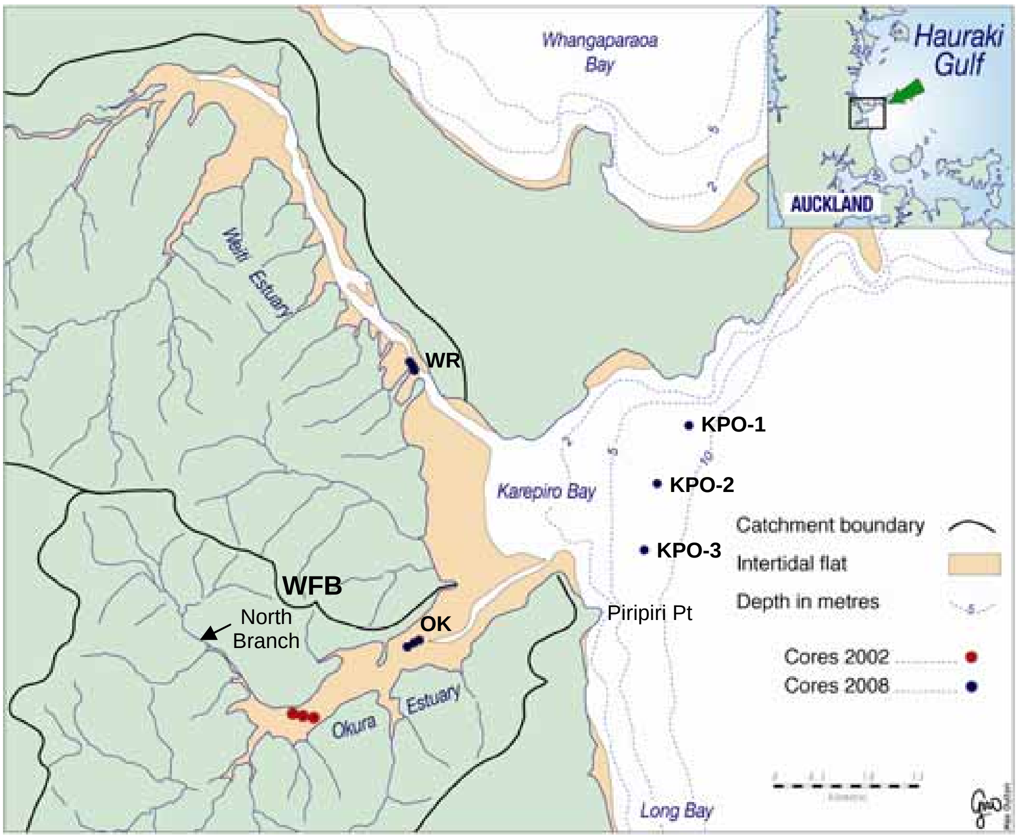
1 Executive Summary

The ARC has identified that future land-use changes in the catchments of the Weiti and Okura estuaries have the potential to have adverse environmental effects on receiving estuarine and coastal environments. Potential land-use changes include the harvesting of the Weiti Forestry Block (WFB), which discharges to both estuaries as well as Karepiro Bay (Fig. 1). As part of a proposed monitoring plan, ARC commissioned NIWA to provide background information on sedimentation and sediment sources to the Okura-Weiti-Karepiro system. The specific objectives of the present study are:

- collect and analyse cores and make an initial assessment of sedimentation in the Okura and Weiti estuaries and adjacent Karepiro Bay over the last 50 years or so; and
- collect catchment and estuary sediment samples for determination of recent sediment sources using the compound specific isotope (CSI) technique.

Figure 1:
Location of study area on Auckland's North Shore. The WFB is the Weiti Forest Block.



Replicate sediment cores were collected at three sites in each of the Okura and Weiti Estuaries and Karepiro Bay. Sediment cores were dated based on concentration profiles of lead-210 (^{210}Pb), caesium-137 (^{137}Cs) and berrylium-7 (^{7}Be). Sediment accumulation rates were determined for the sub-tidal flats of Karepiro Bay along the 8m isobath below chart datum.

There is a low potential for long-term fine-sediment accumulation on the wave-exposed intertidal flats of the lower Okura Estuary. By comparison, the Weiti estuary is sheltered from wave action by its alignment perpendicular to the prevailing southwest/northeast winds and numerous sand and shell ridges, which break the intertidal flats up into smaller compartments with limited wave fetch. Sedimentation is occurring in the lower estuary, as indicated by the $^{210}Pb_{us}$ concentrations, although sediment accumulation rates are likely to vary locally due to the estuary's complex morphology. Because the Okura and Weiti estuaries are largely intertidal and channelised, sediment-laden stormwater is likely to be discharged to Karepiro Bay as buoyant surface plumes thereby bypassing the estuaries.

Karepiro Bay is a long-term sink for fine sediments that have been accumulating in the bay over the last 50 years or so at average rates similar to values measured in the upper Okura Estuary. These results indicate that Karepiro Bay is a major sink for fine sediment eroded from land catchments and intertidal flats in the adjacent estuaries. There is a north to south increase in sediment accumulation rates (2.5 –5.2 mm yr^{-1}) in the bay and highest values occur directly offshore from the Okura-estuary mouth in the lee of Piripiri point. Rapid sediment accumulation here may result from one or a combination of several factors: (1) proximity to the Okura estuary mouth; (2) shelter from the prevailing southwest winds; and (3) hydrodynamic processes that favour deposition of fine sediments, associated with stormwater plumes, in the southern part of the bay.

In Karepiro Bay, ^{210}Pb sediment accumulation rates at sites KPO-1 and KPO-2 (2.5 – 2.6 mm yr^{-1}) are similar to the average 3 mm yr^{-1} measured in the sub-tidal habitats of Auckland's east-coast estuaries over the last 50 years or so. By comparison, the sediment accumulation rate at site KPO-3 (5.2 mm yr^{-1}) is substantially higher than expected. This core site is located on the boundary of the Long Bay – Okura Marine Reserve. Sediment profiles show that the surface mixed layer (SML) extends to $\leq$ 7-cm depth and is composed of low-density fluid mud with a ~60% water content. The residence time of sediments in the SML vary from 10–40 years and vary inversely with SAR. Sediments are eventually removed from this active sediment layer by burial.

A modeling study of silt-plume dispersal and deposition commissioned by the ARC and presently underway will elucidate the patterns of fine-sediment dispersal and sedimentation in Karepiro Bay. Additional sediment-core data in the south bay area would improve confidence in these initial findings and provide validation data for the sediment modeling study. Soils and sediment samples collected at sites in the Okura catchment and estuary have been processed and archived for analysis of sediment sources using the CSI technique.

2 Background

The Auckland Regional Council (ARC) has identified that future land-use changes in the catchments of the Weiti and Okura estuaries have the potential to have adverse environmental effects on receiving estuarine and coastal environments. Potential land-use changes include the harvesting of the Weiti Forestry Block (WFB), which discharges to both estuaries as well as Karepiro Bay (Fig. 2.1).

The ARC commissioned NIWA to develop a monitoring plan for the timely detection of the adverse effects of terrigenous sediments eroded from the WFB on the receiving estuaries and Karepiro Bay (Swales et al. 2007a). As part of this monitoring plan, background information is required on sediment accumulation rates (SAR) in, and sediment sources to the Okura-Weiti-Karepiro system.

2.1 Study objectives

The objectives of the present study are:

- collect and analyse cores and make an initial assessment of sedimentation in the Okura and Weiti estuaries and adjacent Karepiro Bay over the last 50 years or so; and
- collect catchment and estuary sediment samples for determination of the source of recent sediments in the Okura and Weiti estuaries and adjacent Karepiro Bay using the compound specific isotope (CSI) technique (Gibbs, 2008).

2.2 Study area

The Okura and Weiti estuaries are drowned-valley estuaries, with high-tide surface areas of 1.4 km^2 and 2.4 km^2 respectively. The estuaries are small in comparison to their catchment areas and the Okura and Weiti estuaries receive runoff from 22.7 km^2 and 33.3 km^2 catchments respectively. Mean annual suspended sediment loads have been estimated using the USGS SPARROW model calibrated for New Zealand catchments (Elliot et al. 2008). The estimated mean annual loads for the Okura and Weiti Catchments are 1100 tonnes and 2600 tonnes respectively.

The future harvesting of the WFB is a potential source of catchment fine sediment input to the Okura–Weiti–Karepiro System. Some 50% of the WFB discharges to the upper Okura Estuary via the 4.6 km^2 North Branch sub-catchment (Fig. 2.2) and 3 km^2 of the WFB discharges directly to Karepiro Bay. Runoff from the remaining ~1.2 km^2 of the WFB discharges to the Weiti Estuary.

Both estuaries are largely intertidal and exchange almost their entire high-tide volumes each tide. For example, the Okura Estuary is ~80% intertidal, with a single main tidal channel flanked by tidal flats that are submerged to an average depth of one metre at high tide (Swales et al. 2002). Fine suspended sediments that do not settle during the mid–high tide period will be discharged to Karepiro Bay. The Bay has a high-tide surface area of ~4 km^2, of which ~70% is comprised of shallow subtidal flats with a maximum depth of 10 m at its mouth. Surveys of subtidal habitats in the Karepiro – Long Bay area show that mud is being deposited in Karepiro Bay below -5 m Chart Datum (Morrison et al. 1999).

Figure 2.1:
Location of Okura and Weiti estuaries and Karepiro Bay, North Shore. Locations of core collected in the present study (blue symbols) and during an earlier study (red symbols, ARC TP 221) are indicated. WFB is the Weiti Forest Block.

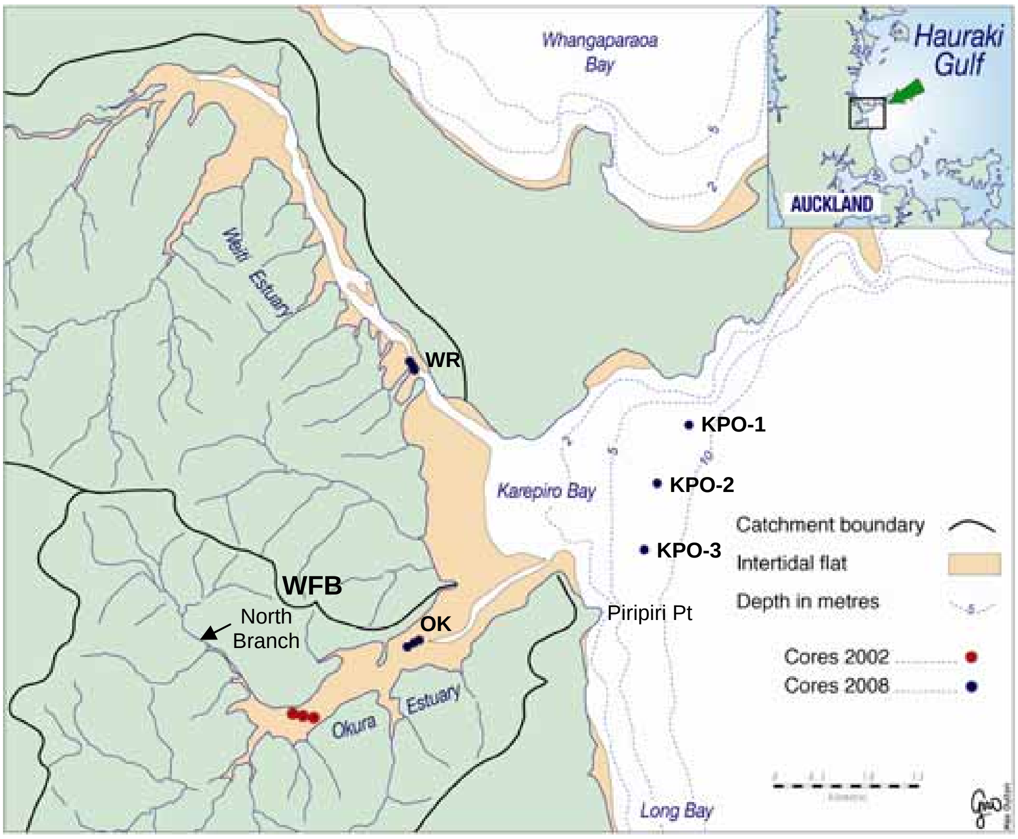


Figure 2.2:

Outlet of the North Branch sub-catchment in the upper reaches of the Okura Estuary. The western boundary of the Weiti Forest Block flanks the tidal creek.

2.3 Estuary sedimentation

Sediments deposited in estuaries integrate and preserve the long-term (i.e., annual–decadal) effects of catchment land use on sediment loads delivered to estuaries. Catchment sediments accumulating in estuaries form tidal flats. These sediments can be sampled in cores and dated using a variety of techniques to determine sediment accumulation rates (SAR). Radioisotope dating has been successfully applied by NIWA to sedimentation studies in Auckland and other North Island estuaries over the last decade (e.g., Swales et al. 1997, 2002, 2005, 2007b). This work includes a regional study of sedimentation in Auckland's east-coast estuaries over the last 50 years (Swales et al. 2002, ARC TP221).

Dated sediment cores have previously been collected in the upper reaches of the Okura Estuary (Swales et al. 2002). However, we have no information on average SAR for the extensive intertidal flats of the middle and lower reaches of the estuary where sediment-sensitive animals occur. These earlier cores also do not include ^{7}Be data so that we have no information on short-term sediment mixing. To address these information gaps, sediment cores were collected from the middle–lower reaches of both the Okura and Weiti estuaries as well as Karepiro Bay.

3 Methods

3.1 Core sampling

Sediments deposited on intertidal and subtidal flats in the Okura-Weiti- Karepiro system were sampled to determine patterns and rates of sediment accumulation in these depositional environments. Confidence in these data is greatly improved by determining SAR at several locations. For example in the TP221 regional sedimentation study, sediment cores were collected at three sites on selected intertidal and subtidal flats. This approach provides a robust estimate of average SAR and provides information on the variability in sedimentation at the tidal-flat scale.

Replicate sediment push cores 10-cm-diameter and ≤ 0.5-m long were collected at three sites in each of the study areas. Core sites were selected to provide information on long-term sediment accumulation in the receiving environments. The radioisotope methods employed in this study require that sediments contain a mud fraction (< 63 μm) for dating. The clays and fine silts in this sediment-size fraction also have the most adverse effects on estuarine biota. Sediment cores were collected during February–March 2008 as follows:

- Karepiro Bay: 27 February 2008.
- Weiti Estuary: 5 March 2008.
- Okura Estuary: 10 March 2008.

Sediment push cores were collected in 10-cm diameter PVC pipe ≤ 0.5 m long. Sediment slabs were also collected using rectangular section Perspex trays for x-ray imaging. In Karepiro Bay, cores were collected by SCUBA divers. Sediment cores were collected by NIWA and ARC staff in the Okura and Weiti Estuaries. Table 3.1 and Figures 2.1 and 3.1 – 3.3 provide details of the core locations.

Information on sedimentation in the upper reaches of the Okura estuary (landward of the shell bank) was provided by ARC TP221 (Swales et al. 2002). This work shows that SAR have averaged 2–6 mm yr^{-1} in the upper estuary over the last 50 –100 years. These sediment deposits contain substantial quantities of mud, averaging ~25% by sample volume). SAR on the extensive intertidal flats seaward of the shell bank were likely to be much lower than in the upper estuary due to the higher wave exposure and potential for re-suspension of bed sediments (Green and Oldman, 1999). Sediment data provided by ARC TP287 (Ford and Anderson, 2005) indicated that the long-term ecological monitoring Site E would be the most suitable area in the lower estuary for radioisotope dating. Field notes from the Okura sediment cores are presented in Appendix 1.

Table 3.1:

Locations of sediment cores. Note: no location recorded for site WR-3.

Estuary	Site	Time (DST)	NZMG (Easting)	NZMG (Northing)
Karepiro	KPO-3	1150	2667220	6503264
	KPO-2	1325	2667378	6503991
	KPO-1	1444	2667761	6504566
Okura	OK-1	–	2664737	6502274
	OK-2	–	2664771	6502283
	OK-3	–	2664806	6502302
Weiti	WR-1	1223	2664774	6505316
	WR-2	1325	2664773	6505290
	WR-3	1437	–	–

The Weiti Estuary has substantially infilled with sediments and large areas of intertidal flats have been colonised by mangroves prior to the 1950s. SAR in mangrove habitats are typically several times or more higher than on tidal flats. Muds accumulate in mangrove habitat and fauna are dominated by mud-tolerant species. The intertidal flats that have not yet been colonised by mangroves are likely to have a more diverse fauna. Accordingly, an intertidal-flat area in the lower estuary for coring was identified from aerial photography.

Figure 3.1:
Karepiro Bay (9 July 2007). Cores collected from sub-tidal flat along the -8 m CD isobath.

A previous habitat assessment in Karepiro Bay by Morrison et al. (1999, Fig. 4) indicates that muds are depositing in the Bay below the -5m CD isobath. Accordingly, core sites were selected to sample bed sediments along an isobath, that would have similar wave exposure. Wave-orbital motions are attenuated in the water column so that the potential for mud re-suspension reduces with increasing water depth. Sediments deposited in the subtidal basin below the -5m CD isobath are more likely to preserve the long-term history of sedimentation in the Bay.

Figure 3.2:

Okura Estuary (9 July 2007). Location of sediment cores collected from the tidal flat immediately seaward of shell bank.

Sediment samples from the top-most 5-cm of each core where first analysed in 1-cm depth increments to capture the short-lived ^{7}Be, as well as ^{210}Pb and ^{137}Cs. These initial results indicated that:

- Long-term fine-sediment accumulation has not occurred in the lower Okura estuary, whereas fine sediments are accumulating in the Weiti Estuary and Karepiro Bay.
- The subtidal flats of Karepiro Bay are a major long-term sink for fine sediments entering the Okura-Weiti-Karepiro system.

The Karepiro Bay cores were subsequently selected, in consultation with the ARC, for full radioisotope dating. A second phase of samples were selected from the Karepiro cores below 5-cm depth to the base of each core to complete the analysis.

Figure 3.3:
Weiti Estuary (9 July 2007). Cores collected from tidal flat in the lower estuary between channel and mangroves.

3.2 X-radiographs

X-radiographs of the sediment cores provide information on the fine-scale sedimentary fabric of deposits. For example, x-radiographs highlight subtle density differences, such as between thin laminae of silt and sand or animal borrows infilled with mud that may not be visible to the naked eye. The 2-cm-thick longitudinal slabs were imaged using a Phillips Model Macrotank 205 X-ray generator with Kodak AA400 film (50 kV, 5 mA, 1.1 min). The x-rays films were digitised as follows. Films were illuminated using a Kaiser Prolite 5000 high-frequency 5000°K lightbox. A Nikon D1x digital SLR camera with 60mm f2.8D microNikkor lens (ISO 125, f6.3 or f7.1 aperture) was used to image the films. File format is black and white RGB-tif files with 3008 x 1960 pixels. The images were cropped and in some cases duplicated and image and contrast adjustments made using the Adobe Photoshop software.

3.3 Radioisotope dating

Sediment cores are dated using the radioisotopes caesium-137 (^{137}Cs, ½ life 30 years) and lead-210 (^{210}Pb, ½ life 22.3 years). SAR are 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 several 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. 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 Appendix 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 ($^{210}Pb_{us}$) 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 $^{210}Pb_{us}$ profiles in cores are used to determine: (1) time-averaged SAR from regression analysis of natural log-transformed data; (2) $^{210}Pb_{us}$ inventory (A, Bq cm^{-2}) and; (3) mean annual supply rate (P, Bq cm^{-2} yr^{-1}) based on the ^{210}Pb decay co-efficient (k, 0.0311 yr^{-1}). These data were compared with the ^{210}Pb atmospheric flux (0.005 Bq cm^{-2} yr^{-1}) measured by NIWA at Auckland. SAR are also estimated from ^{137}Cs profiles based on the maximum depth of ^{137}Cs in each core, which include corrections for sediment mixing in the surface layer indicated by ^{7}Be profiles. In NZ, ^{137}Cs deposition from the atmosphere was first detected in 1953 (Matthews, 1989).

3.3.1 Sediment accumulation rates (SAR)

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

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

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

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

Because $^{210}Pb_{us}$ 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:

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

An advantage of the ^{210}Pb-dating method is that the SAR is based on the entire $^{210}Pb_{us}$ 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:

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

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

3.3.2 ^{210}Pb budget

The quantity of unsupported ^{210}Pb in sediment cores is often referred to as the ^{210}Pb inventory, A(o). This inventory provides important information about the long-term fate of fine-sediments in receiving environments such as estuaries. ^{210}Pb is delivered to the Earth's surface as dry deposition or with rainfall. The latter appears to be more important (Matthews, 1989). ^{210}Pb are delivered to estuaries directly (by atmospheric deposition) and indirectly (attached to eroded soil particles). Once in the estuary, radioisotopes are scavenged by fine-sediment particles suspended in the water column, which then may be deposited on the bed (Swales et al. 2002).

The mean annual ^{210}Pb atmospheric flux (P_{atmos}) can be estimated from the inventory of unsupported ^{210}Pb in the sediment column, which is denoted by A(o) (Bq cm^{-2}). This is estimated from the dry bulk density and unsupported ^{210}Pb concentration in sediment samples. The mean annual supply rate of unsupported ^{210}Pb (P, Bq cm^{-2} yr^{-1}) is then calculated as:

$$P = kA(o) \qquad (6)$$

where k is the decay constant for ^{210}Pb (0.03114 years). Note that unsupported ^{210}Pb is the atmospheric component of ^{210}Pb in sediments, as ^{210}Pb is also produced by in situ decay of parent radioisotopes present in sediments (Appendix 2).

Comparison of the A(o) and P estimates derived from cores with the average annual ^{210}Pb atmospheric flux (P_{atmos}) can be used to evaluate long-term fine-sediment fate at a given core site:

- $P > P_{atmos}$ indicates fine sediment is preferentially being deposited over time scales of decades.
- $P < P_{atmos}$ indicates that fine sediment is being removed from and/or is not accumulating at a site.

The ratio P / P_{atmos} is termed the concentration factor (C).

The atmospheric ^{210}Pb flux has been measured at monthly intervals by NIWA since June 2002 at a rainfall station in Howick. Monthly ^{210}Pb fluxes show substantial variability (0.0001–0.002 Bq cm^{-2} mo^{-1}), whereas annual ^{210}Pb fluxes show much less variability (0.0049–0.0056 Bq cm^{-2} yr^{-1}). This is an important result because constant ^{210}Pb supply at annual–decadal time scales is a key assumption of the ^{210}Pb dating method. The average annual ^{210}Pb flux of 0.0051Bq cm^{-2} yr^{-1} (2003–2007) is used here to calculate C.

3.3.3 Surface mixed layer - sediment residence time

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

3.4 Sediment source sampling

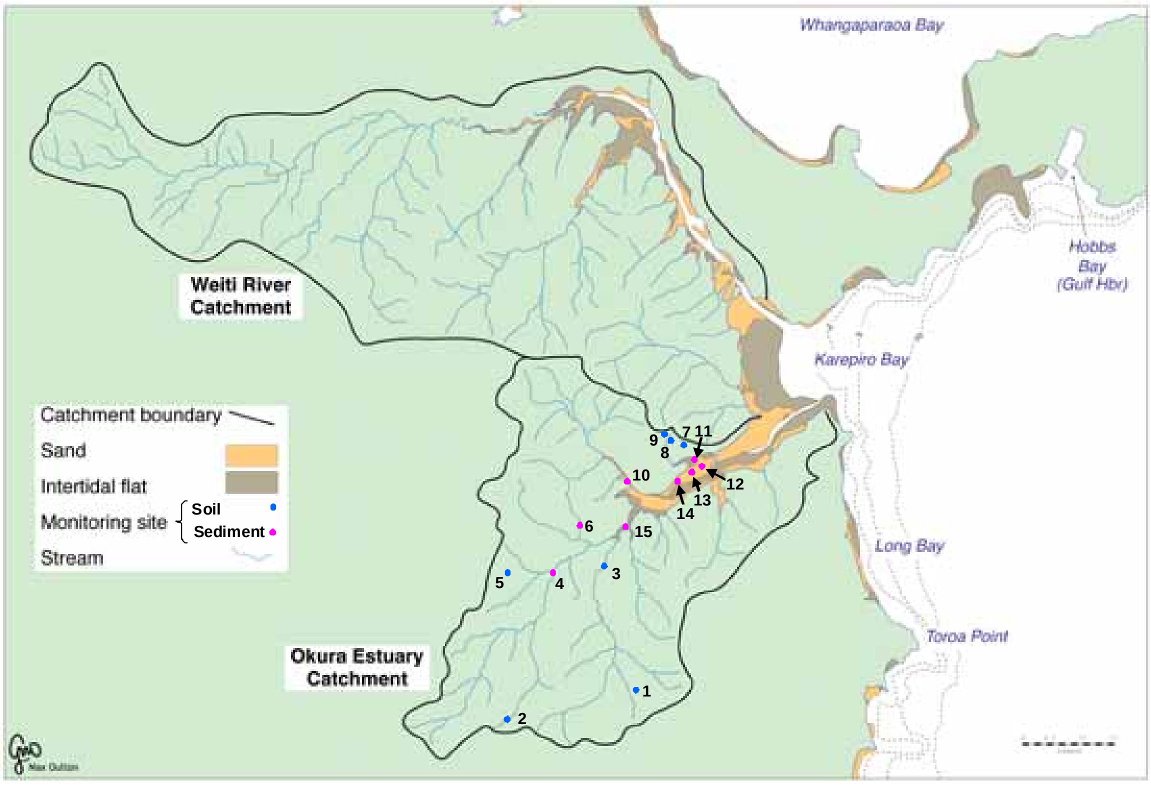
Soil and sediment samples for compound specific isotope analyses were collected a number of sites (Table 3.2) in the Okura catchment and from the intertidal flats in the estuary on 5 June 2008 (Figs. 3.4 & 3.5). Catchment soil samples comprised 20 mm thick scrapings of surface soil from an area of several m^2 for each land-use type. The scrapings were taken with a stainless steel spade after the plant litter had been removed, and combined in a 5-litre clean, sealable, plastic (PVC) bucket, to obtain a total wet weight of about 2 kg. The samples were mixed and a portion (500g) was sieved through a stainless steel 1mm-mesh to remove plant debris, insects, stones, etc. before oven drying at 60ºC. The dried samples were stored in sealed plastic (polyethylene) bags at room temperature pending grinding and extraction for analyses. The remainder of each sample was returned to the plastic bucket, sealed and then stored frozen at -20ºC as backup material.

Table 3.2:

Site locations and sample descriptions referred to in the text and as numbered in Fig. 3.4.

	Weiti-Okura estuary sampling 5 June 2008	NZMG	WGS84
Sample No.	Site description	Easting	Northing
1	Kanuka scrub/pine (152 Lonely Track Rd)	2662947	6498208
2A	Fern/Gleichenia/Manuka (Albany Scenic Reserve) – topsoil	2661895	6497528
2B	Excavation (Albany Heights Rd) – subsoil	2661895	6497528
3	Kikuya grass slope (73 Wright Road)	2662369	6499980
4	Okura River bank (upstream Awanohu Rd culvert)	2661831	6500313
5A	Grass/gorse (top soil)	2661230	6500479
5B	Grass/gorse (sub-soil)	2661230	6500479
6	Stream bank down stream of waterfall (Haigh Access Road)	2662116	6500906
7	Native forest (Nikau dominant)	2664317	6502481
8	Native forest (Kauri dominant)	2664071	6502558
9	Pine forest	2663779	6502743
10	North Branch pine forest stream bed (off foot bridge-Ekman, Fig. 2.2)	2663057	6501852
11	Native Forest stream from reserve (in estuary)	2664178	6502143
13	Estuary upstream for native forest stream (1)	2664186	6502051
14	Estuary upstream for native forest stream (2)	2664063	6501990
15	Estuary upstream for native forest stream (3)	2663956	6501921
16	Okura Stream bank at mouth (Rodeo Rd)	2662964	6501045

Figure 3.4:
Sampling locations in the Okura Estuary catchment. Site descriptions as per numbers in Table 3.2.



The choice of each soil sample location was decided from site inspection for typical land-use types and their potential to produce sediment into the catchment streams. The "native" soil samples include Kanuka + scrub, thick *Gleichenia* sp. + Manuka scrub, Nikau dominant, and Kauri dominant. Each of these "native" types was present in large areas around the head of the sub-catchments (Fig. 3.6). The Nikau and Kauri native samples came from the native reserve on the left bank of the Okura estuary and the Pine forest sample was taken from beneath the *Pinus radiata* stands adjacent to the native reserve, after removing the needle layer. Pasture grass of various types was present in large areas. Samples from the steeper banks where there was erosion allowed collection of surface soils and sub-soils. This area also had evidence of earlier growths of gorse that had been killed with spray. A sample was collected from an area covered with Kikuyu grass by shaking the soil from grass roots. Areas of new urban development had variable amounts of exposed soil but these were constrained within the sediment containment provisions for the development. Recent excavations allowed the collection of a sub-soil sample. Apart from areas of recent excavations, there were no obvious areas of erosion.

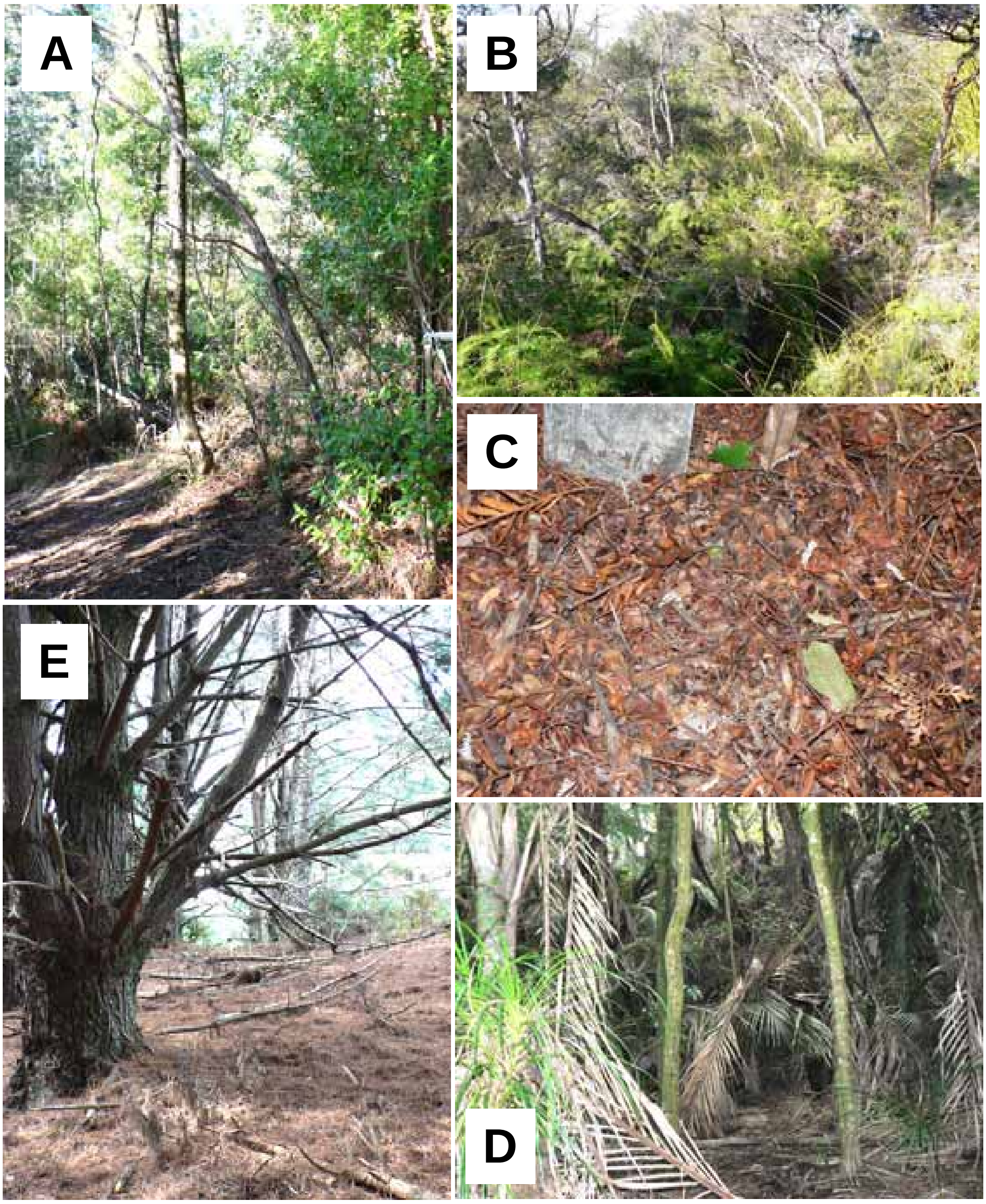
Figure 3.5:

Views of the Okura catchment: (a) looking west of the Albany Heights; (b) looking south, with Site 15 (lower left corner) showing the rural life style blocks and vegetated riparian zone along the Okura River (lower middle) and tributary (upper middle).

Stream samples were taken from sediment fines that had accumulated in niches in the stream bank and on the side of the large pool below the waterfall on the Haigh Access Road. Closer to the estuary, the sediment samples were collected from the exposed stream bed at low tide. Sediment from the North Branch stream was taken from the foot-bridge using an Ekman dredge box corer. The sample collected was sectioned to obtain only the surface 20 mm layer. The sample from the mouth of the Okura Stream was taken with a long-handled corer after wading as far out as was safe in the soft sticky mud. The sample from the native reserve stream was taken by walking up the stream be from the estuary. During this walk it was noted that the stream bed had much shell debris which was being covered by soft silt and fine sand from the estuary.

Figure 3.6:

Soil sampling sites: (a) Kanuka scrub, site 1; (b) *Gleichenia* + Manuka scrub, site 2; (c) Native Kauri leaf litter, site 8; (d) Native Nikau understory, site 7; (e) pine forest needle litter, site 9.



The samples from the open estuary were surface slices of the sediment at each of three locations on the true left side of the estuary, upstream of the native forest stream from the reserve. The sediment at these locations was fine brown silty sand with underlying black sediment, presumably anoxic (by the smell). The samples were taken mid-way between the Okura Stream channel and the shore, as being likely deposition zones. Further inshore, the bed of the estuary had extended areas of hard flat iron-stained clay-sedimentary rock with little sediment accumulation.

4 Results

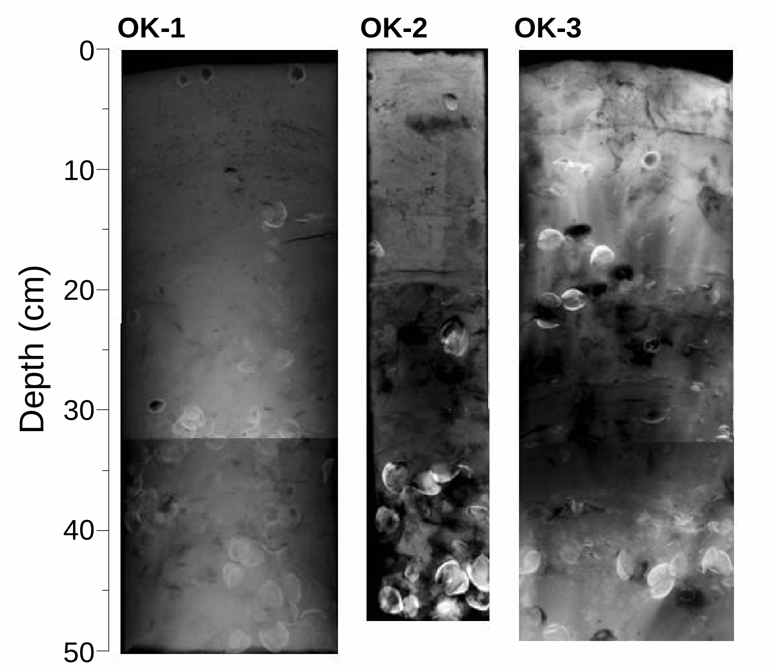
The radioisotope and particle size profiles and x-radiographs provide information on fine-sediment fate in the Okura-Weiti-Karepiro System.

4.1 Okura-estuary cores: intertidal flats

The x-radiographs of the Okura cores, OK-1 – OK-3, are characteristic of the mixed silt and sands deposited on intertidal flats in Auckland estuaries (Fig. 4.1). In these x-ray images, relatively high density objects such as carbonate shells and sands appear white. Lower density organic material (e.g., plant fragments) and/or fine-grained muds are identified as darker grey–black areas.

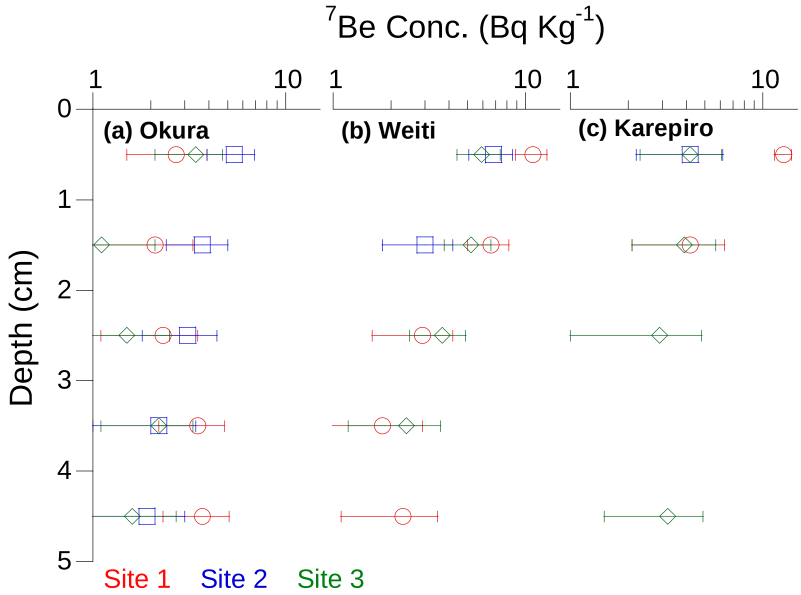
Cockle-shell valves (*Austrovenus stutchburyi*) are abundant in the Okura cores, with shell layers below 35-cm depth in OK-1 and OK-2. Sediments deposited in OK-1 are composed of homogenous silty-sands whereas cores OK-2 and OK-3 are more complex, with fine silt/sand laminations. There is a sharp contact at ~20-cm depth in cores OK-2 and OK-3, with cockle shell valves more common below this level.

Figure 4.1:
Okura Estuary sediment cores x-radiographs. Note: un-even exposure of OK-1.



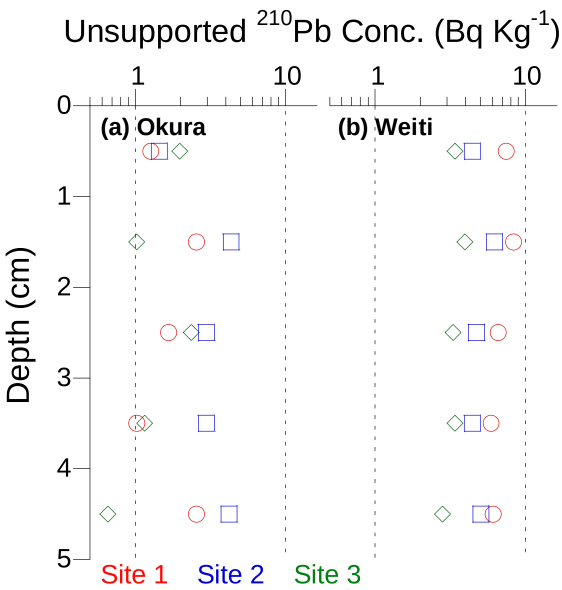
Radioisotope analysis of sediments shows that ^{7}Be was present to at least 5 cm depth in the Okura cores (Fig 4.2a). In the absence of sediment mixing in the surface layer, the maximum ^{7}Be depth due solely to sedimentation would be less than 1–2 mm, based on the short ^{7}Be half-life and a SAR 4 mm yr^{-1}. The presence of ^{7}Be to 5 cm depth indicates that sediments are being rapidly and well mixed over short time scales (i.e., ≤ 100 days) by biological and/or physical processes.

Figure 4.2:
^{7}Be concentrations (log10-scale) in top 5-cm of the Okura, Weiti and Karepiro sediment cores. The 95% confidence intervals for the ^{7}Be concentrations are also shown.



The unsupported ^{210}Pb concentrations ($^{210}Pb_{us}$) in the Okura cores are uniformly low at 0.5–5 Bq Kg^{-1} (Fig. 4.3a) in comparison to $^{210}Pb_{us}$ concentrations of ~10 Bq Kg^{-1} measured in surface sediments in other Auckland estuaries as well as measured in the upper reaches of the Okura Estuary (Swales et al. 2002). These ^{7}Be and $^{210}Pb_{us}$ concentration data indicate that: (1) the surface mixed layer (SML) extends to at least 5-cm depth; and (2) intertidal sediments in the lower Okura estuary are being frequently and intensely reworked. These observations are consistent with physical mixing due to sediment resuspension by waves on an exposed tidal flat.

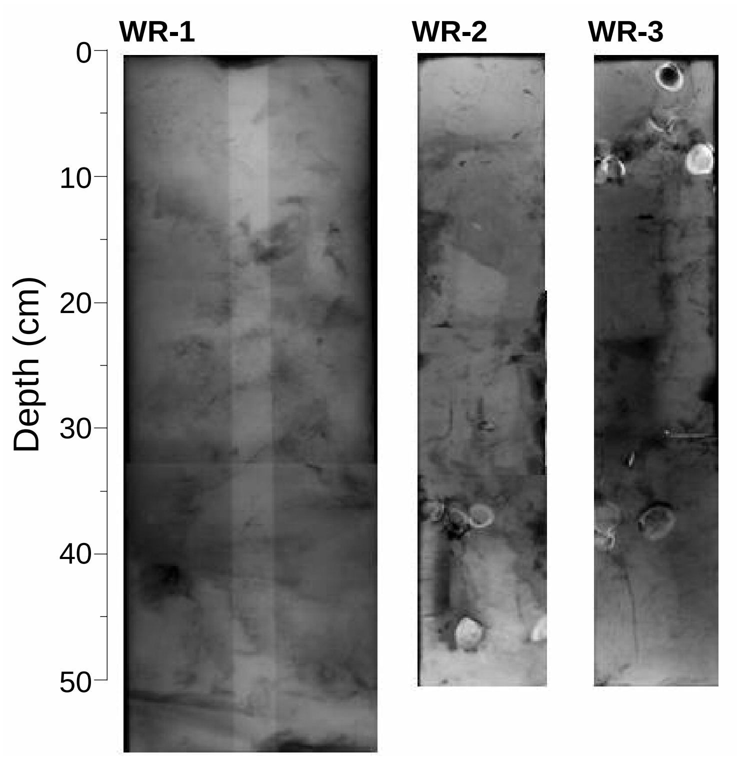
Figure 4.3:
Unsupported ^{210}Pb concentrations (log-scale plot) in the top 5-cm of the Okura and Weiti sediment cores.



4.2 Weiti estuary cores: intertidal flats

The x-radiographs of the Weiti cores (WR-1 – WR-3) indicate that sediments at these sites are composed of silty sands, with rare shell valves (Fig. 4.4). There is evidence of mm-scale animal burrows that have filled with lower-density muds (i.e., darker than surrounding substrate). There is little evidence of layering or fine-scale lamination in the sediments, which is common in estuarine deposits. Sediments in the top ~10-cm of the cores appear to have higher sand content than sediments at depth.

Figure 4.4:
Weiti Estuary sediment cores x-radiographs.



^{7}Be concentrations reduce exponentially with depth in the Weiti cores (Fig. 4.2). Note that these data plot as a straight line on a log scale. This pattern is consistent with a reduction in mixing intensity with depth. The $^{210}Pb_{us}$ concentrations of 3–9 Bq Kg^{-1} are higher than at the Okura sites (Fig. 4.3). These data suggest that: (1) mud is accumulating on the tidal flat; and (2) mixing of the Weiti intertidal sediments is less intense than at the Okura Estuary sites.

4.3 Karepiro Bay (subtidal)

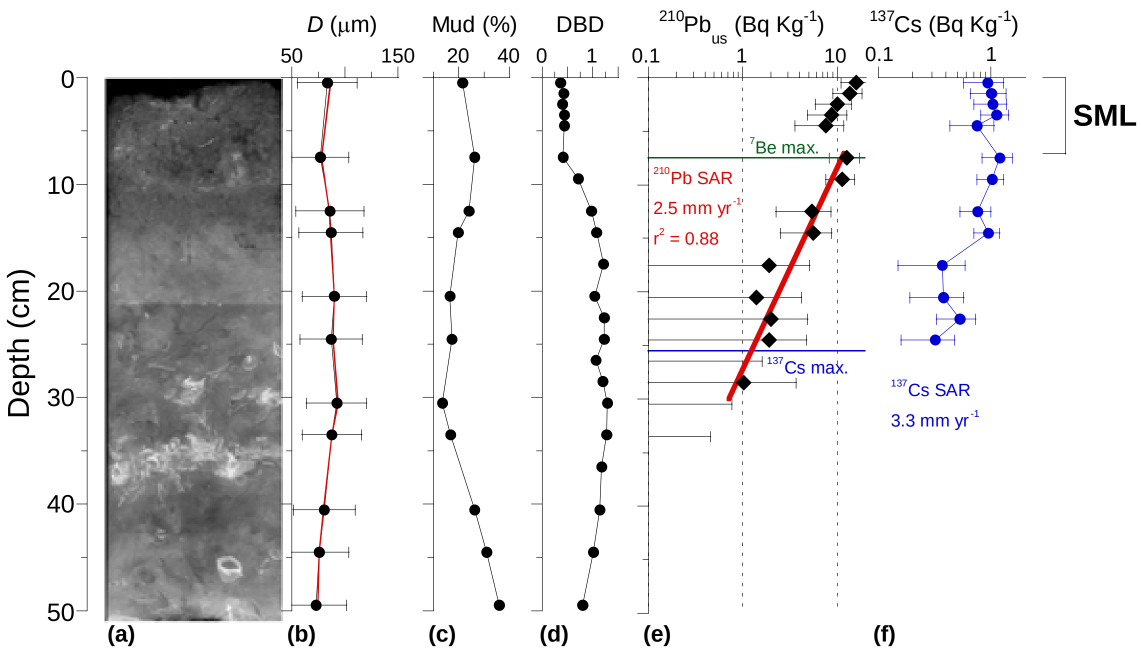
In this section we present interpretations of the Karepiro Bay cores KPO-1, KPO-2 and KPO-3, based on x-radiograph, particle size, bulk density data and radioisotope profiles. SAR and ^{210}Pb concentration factors are also evaluated.

Core KPO-1 was collected at the northern side of Karepiro Bay on the -8 m chart datum (CD) isobath (Fig. 2.1). Figure 4.5 presents the sediment profiles for core KPO-1. Sediments here are composed of a low-density fluid muddy fine-sand extending to 10-cm depth, as shown by the x-radiograph, particle size and bulk density profiles (Figs 4.5a–d). Particle-size distributions are uni-modal, as indicated by the similarity of mean and median diameters (Fig. 4.5b). Dry bulk sediment densities of ~0.4 g cm^{-3} indicate water contents of ~60%. The x-radiograph also shows that the surface fluid-mud layer overlies higher density muddy sand. Mud-filled mm-scale burrows also occur in this silty fine-sand layer. A 3-cm thick layer composed of shell valves and fragments occurs at

~35-cm depth. The mud content of sediment increases linearly with depth below the shell layer to ~35% (by volume) at 50-cm depth.

Figure 4.5:

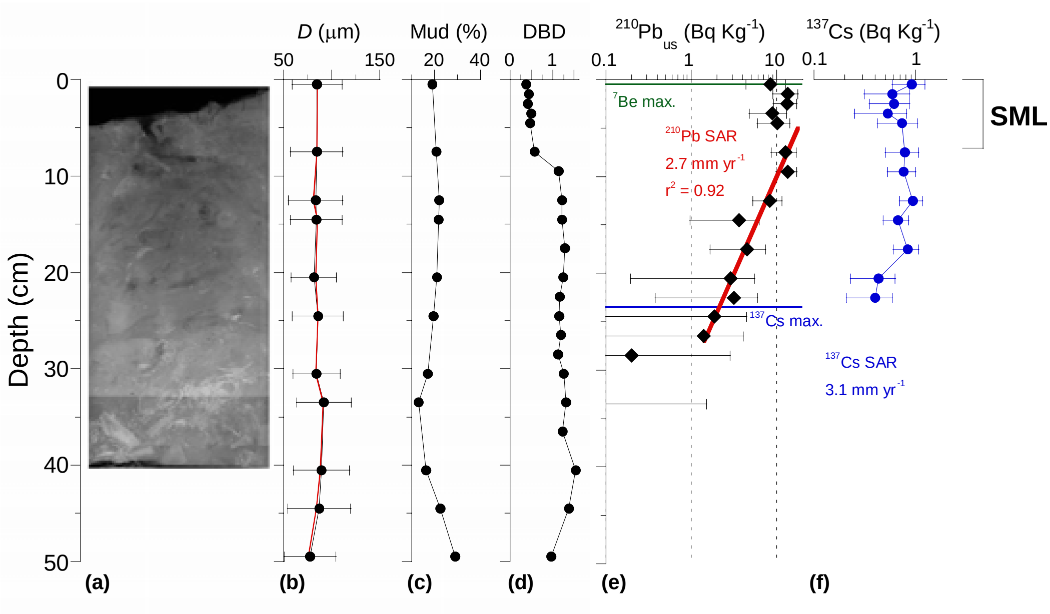
Core KPO-1 (Karepiro Bay sub-tidal) sediment profiles: (a) x-radiograph; (b) mean (black) and median (red) particle diameters, with 1 std dev plotted; (c) Mud content (% volume); (d) dry-bulk sediment density (g cm-); (e) unsupported ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and co-efficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be and ^{137}Cs depths; (f) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR. Note: ^{137}Cs SAR accounts for rapid mixing in the surface mixed layer (SML).



The radioisotope profiles also indicate rapid mixing in the surface fluid –mud layer, with ^{7}Be detected down to 8-cm depth (Fig 4.5e). The unsupported ^{210}Pb profile (^{210}Pb$_{us}$) displays an exponential decay in concentrations above and below 10-cm depth. The concentration decline in the surface fluid-mud layer is notable in that we would expect the ^{210}Pb$_{us}$ concentration in the SML to be uniform. The ^{210}Pb SAR calculated for the accumulation zone below the SML is 2.5 mm yr^{-1} (Fig. 4.5e). The residence time of sediment in the SML before it is removed by burial is then 100 mm/2.5 mm yr^{-1} = 40 years. The maximum ^{137}Cs depth at 25.5 cm is close to the buried shell layer. The ^{137}Cs SAR corrected for the depth of the ^{7}Be SML is estimated as (255 -75 mm)/54 yr or 3.3 mm yr^{-1} (Fig. 4.5f). In adopting this approach we make the assumption that the sediment mixing depth has been constant over time.

Core KPO-2 was collected from the middle of Karepiro Bay on the -8 m CD isobath (Fig. 2.1). Figure 4.6 presents the sediment profiles for core KPO-2. Like KPO-1, sediments at this site are composed of a low-density, fluid, muddy fine-sand extending to ~7-cm depth (Figs 4.6a–d). The x-radiograph shows an L-shaped burrow extending to 5-cm depth below the surface. These types of borrows are constructed by *Thalassinidean* shrimp species, such as *Callianassa*, *Upogebia* and *Alpheus* spp. (Dr Mike Townsend, NIWA, pers comm.).

Figure 4.6:
Core KPO-2 (Karepiro Bay sub-tidal) sediment profiles: (a) x-radiograph; (b) mean (black) and median (red) particle diameters, with 1 std dev plotted; (c) Mud content (% volume); (d) dry-bulk sediment density (g cm-); (e) unsupported ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and co-efficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be and ^{137}Cs depths; (f) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR. Note: ^{137}Cs SAR accounts for rapid mixing in the surface mixed layer (SML).



The x-radiograph also indicates a gradual trend of increasing sediment density with depth due to reduced mud and/or water content. Fine sub-mm scale lamination are evident at 20–25-cm depth and immediately above a silty-fine sand layer with abundant shell fragments, which extends to at least 40-cm depth (Fig 4.6a). The particle-size characteristics are similar to site KPO-1, being uni-modal silty fine-sands (Fig. 4.6b & c). The dry bulk sediment density (DBD) profile again shows very low values at the sediment–water interface of ~ 0.4 g cm^{-3}, indicating a water content of ~60%, and increases to 0.6 g cm^{-3} at the base of the SML (Fig. 4.6d). As for KPO-1, the mud content of the sediment increases linearly with depth below the shell layer to ~30% (by volume) at 50-cm depth.

The radioisotope profiles also indicate rapid mixing in the surface fluid-mud layer, although ^{7}Be is only detected in the top 1-cm of the core (Fig 4.6e). By comparison, the $^{210}Pb_{us}$ profile displays uniform concentrations in the top 7 cm of the sediment column. The absence of ^{7}Be below the surface is likely due to the insufficient mass of sediment in the SML. The ^{210}Pb SAR calculated for the accumulation zone below the SML of 2.7

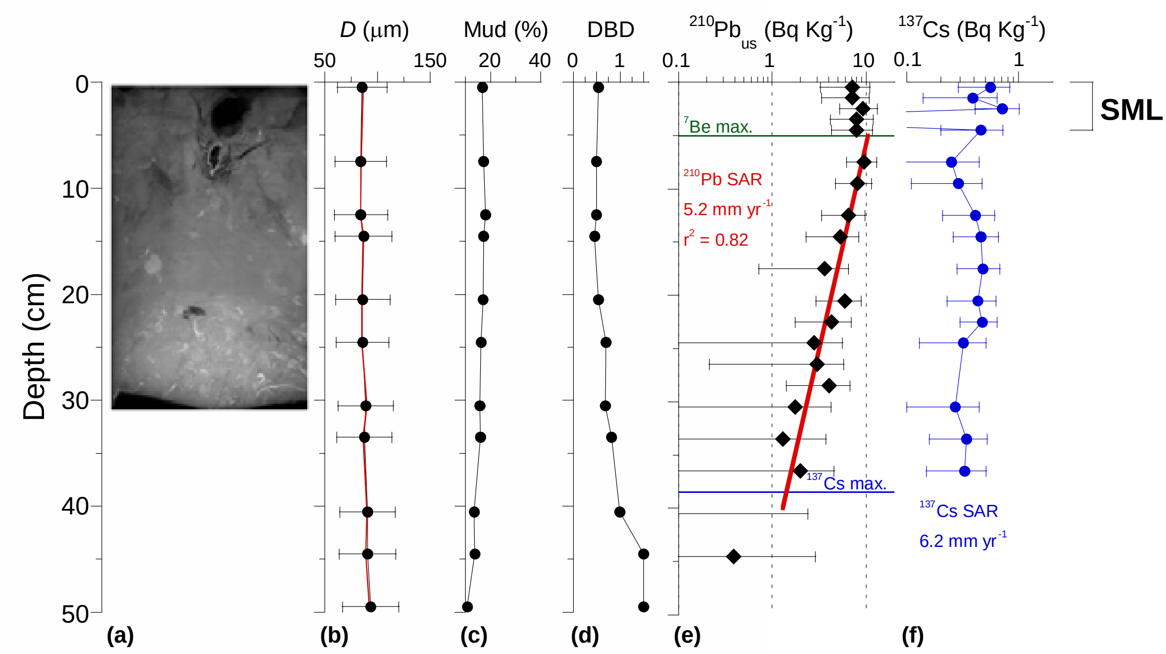
mm yr^{-1} (Fig. 4.6e) is similar to that measured at site KPO-1. The residence time of sediment in the SML before it is removed by burial is then 70 mm/2.7 mm yr^{-1} = 26 years. The maximum ^{137}Cs depth at 23.5 cm coincides with the top of the silty-fine sand layer with abundant shell fragments that occurs below this depth. The ^{137}Cs SAR corrected for the depth of the ^{7}Be SML is estimated as (235 - 70 mm)/54 yr = 3.1 mm yr^{-1} (Fig. 4.6f).

Core KPO-3 was collected from the southern side of Karepiro Bay (-8 m CD) on the boundary of the Long Bay – Okura Marine Reserve (Fig. 2.1). Figure 4.7 presents the sediment profiles for core KPO-3. Unlike sediment deposits at the previous two sites, the sediment deposited at KPO-3 show a clear trend of gradually decreasing mud content with depth. The x-radiograph indicates a gradual decline in mud and/or water content with depth. Like KPO-2, fine sub-mm scale laminations are evident immediately above a silty-fine sand layer with abundant shell fragments, which extends from 20-cm depth to at least 30-cm depth (Fig 4.7a). The particle-size characteristics are similar to site KPO-1 and KPO-2, being uni-modal silty fine-sands (Fig. 4.7b & c). However, the dry bulk sediment density (DBD) profile does not show an abrupt increase in density at 8–10 cm depth. Instead, the DBD gradually increases in the top 40-cm of the core, from 0.5 to 1.0 g cm^{-3} , then abruptly increases to 1.5 g cm^{-3} below this depth (Fig. 4.7d).

The radioisotope profiles indicate rapid mixing in the surface fluid –mud layer, with ^{7}Be detected in the top 5-cm of the core, which is consistent with the uniform $^{210}Pb_{us}$ concentrations in this layer (Fig 4.7e). Notably, the ^{210}Pb SAR calculated for the accumulation zone below the SML of 5.2 mm yr^{-1} (Fig. 4.6e) is two-fold higher than measured at sites KPO-1 and KPO-2. The residence time of sediment in the SML before it is removed by burial is then 50 mm/5.2 mm yr^{-1} = 10 years. The maximum ^{137}Cs depth at 39 cm coincides with the abrupt increase in DBD (Fig. 4.7d & e). The ^{137}Cs SAR corrected for the depth of the ^{7}Be SML is estimated as (385 - 50 mm)/54 yr = 6.2 mm yr^{-1} (Fig. 4.7f), which is two-fold higher than ^{137}Cs SAR measured at the other Karepiro Bay sites.

Figure 4.7:

Core KPO-3 (Karepiro Bay sub-tidal) sediment profiles: (a) x-radiograph; (b) mean (black) and median (red) particle diameters, with 1 std dev plotted; (c) Mud content (% volume); (d) dry-bulk sediment density (g cm-); (e) unsupported ^{210}Pb concentration profile with 95% confidence intervals, time-averaged sediment accumulation rate (SAR) and co-efficient of determination (r^2) derived from fit to data (red line), maximum ^{7}Be and ^{137}Cs depths; (f) ^{137}Cs concentration profile with 95% confidence intervals and time-averaged SAR. Note: ^{137}Cs SAR accounts for rapid mixing in the surface mixed layer (SML).



4.4 Sediment sources

The catchment and estuary samples for determination of sediment sources have been processed and archived for future analysis. A replicate sediment (dating) core from each of the estuaries and Karepiro Bay is also available for subsequent reconstruction of historical sediment sources.

5 Synthesis

5.1 Sediment accumulation rates

Sediment accumulation rates (SAR) have been measured from cores collected in the sub-tidal habitats of several of Auckland's east-coast estuaries, which include the Mahurangi, Waitemata, Whitford and Wairoa systems (Swales et al. 2002, 2007b). These previous studies show that ^{210}Pb SAR have averaged 3 mm yr^{-1} (std dev 1.3 mm yr^{-1}, n = 15) over the last 50 years or so. The ^{210}Pb SAR measured in Karepiro Bay at sites KPO-1 and KPO-2 of 2.5 and 2.6 mm yr^{-1} are within the range of average SAR in sub-tidal habitats. By comparison, the ^{210}Pb SAR at site KPO-3 of 5.2 mm yr^{-1} is substantially higher than expected. Site KPO-3 is located on the boundary of the Long Bay – Okura Marine Reserve. The ^{210}Pb SAR and spatial patterns of sedimentation in Karepiro Bay are also supported by the independent ^{137}Cs dating. These results suggest that fine sediments are preferentially accumulating on subtidal flats in the southern Karepiro Bay.

Table 4.1 summarises the unsupported ^{210}Pb inventory, supply rates and concentration factors for the Karepiro Bay cores. These parameters provide information about the long-term accumulation of fine sediments in the bay. In the absence of sediment transport re-distributing fine sediments in a depositional environment, bed sediments would accumulate ^{210}Pb in direct proportion to the atmospheric flux (i.e., C = 1).

Table 4.1:

Unsupported ^{210}Pb inventories, A(o), mean supply rates (P) estimated from the Karepiro Bay cores. The concentration or (C) is the ratio P/P_{atmos}, where P_{atmos} is the mean annual ^{210}Pb flux from the atmosphere (0.0051Bq cm^{-2}yr^{-1}).

Core	A(o) (Bq cm^{-2})	P (Bq cm^{-2}yr^{-1})	C
KPO-1	0.1154	0.0036	0.71
KPO-2	0.1674	0.0052	1.02
KPO-3	0.1916	0.0060	1.25

The concentration factors for the Karepiro cores indicate that over time-scales of several decades:

- at site KPO-1, C < 1, so that fine sediment is being removed from and/or is not accumulating at the rate predicted by P_{atmos};
- at site KPO-2, C ~ 1, so that fine sediment is accumulating in direct proportion to the atmospheric flux of ^{210}Pb;
- at site KPO-3, C > 1, which indicates that fine sediment is preferentially accumulating at this location.

These concentration factors are in the range measured in subtidal habitats of the Waitemata Harbour and Wairoa Estuary (*C* = 0.3–1.5, Swales et al. 2002, 2007b).

5.2 Sediment mixing

The ^{7}Be and $^{210}Pb_{us}$ radioisotope profiles show that sediments are being rapidly mixed in the surface mixed layer (SML) in the top 5 – 7-cm of the Okura, Weiti and Karepiro cores.

The radioisotope data from the Okura Estuary indicate sediment mixing is likely to be most intense on wave-exposed intertidal flats. The low $^{210}Pb_{us}$ concentrations (0.5–5 Bq kg^{-1}) and uniform ^{7}Be concentrations in the top 5-cm of the Okura cores is indicative of rapid, intense physical mixing of intertidal sediments by waves, as observed in the Waitemata Harbour (Swales et al. 2007b). The presence of ^{7}Be in these sediments also shows that mixing is occurring over time scales < 100 days or so.

The Weiti radioisotope data indicate that sediment mixing does occur but is less intense than occurs at Okura. This is most clearly shown by the exponential decay of ^{7}Be in the SML (Fig. 4.2) and indicates that the SML is intermittently mixed and/or mixing rate decreases with depth so that ^{7}Be concentrations are able to decay. The presence of ^{7}Be to 5-cm depth shows that mixing of sediment down into the bed is still occurring at time scales of < 100 days.

In Karepiro Bay, the maximum ^{7}Be depth in the sediment cores coincides with the SML inferred from the $^{210}Pb_{us}$ profiles. The maximum residence time of sediments in the SML vary from 10 – 40 years and vary inversely with SAR. The SML is characterised by a low-density fluid mud layer, with a water content of ≥ 60%. The presence of ^{7}Be shows that this fluid mud layer is likely to be regularly re-mobilised by wave-orbital motions. Consequently, near-bed suspended-sediment concentrations in the bay are likely to vary from tens of mg l^{-1} during calm conditions to $\sim10^{3}$–10^{4} mg l^{-1} during sediment re-suspension events. Given, the close proximity of site KPO-3 to land and the limited fetch to the west, resuspension events will coincide with strong winds from the north – east quadrant. Thus, fine sediments delivered to the bay will remain mobile for decades before eventually been removed from the "active" sediment system by burial. Notably, a recent ecological baseline survey of Weiti Estuary and Karepiro Bay shows that this dynamic subtidal, muddy-sediment habitat has a relatively high abundance and diversity of benthic fauna in comparison to habitats in the Weiti Estuary (Hewitt, 2008). At the deepest sites in Karepiro Bay (>5m depth), the fluffy (fluid) mud covering the bed was easily disturbed. Mounds of the invasive Asian Date mussel (*Musculista senhousia*) were patchily distributed across the sediment surface. The highest number of taxa and abundance (even discounting *Musculista*) were found here. Many of the taxa found here were either highly mobile or attached epifauna using *Musculista* as a habitat substrate (Hewitt, 2008).

5.3 Fine-sediment fate

Estuaries follow similar evolutionary paths over time as they infill with sediment: subtidal areas and average water depths decrease. As a result, the hydrodynamic and sediment characteristics and biological communities change over time (Roy et al. 2001). The proportion of the catchment sediment load that is trapped in an estuary, the so-called sediment-trapping efficiency, declines over time as the available accommodation space for sediments is reduced. As a result a larger proportion of the catchment sediment load is exported from the estuary to the coastal environment. The Wairoa at Clevedon is an example of an estuary which has completely infilled with sediment, forming intertidal flats that have been colonised by mangroves. This has largely occurred because the land catchment (311 km^2) is large in comparison to the estuary, which has a high-tide surface area < 3 km^2. It is likely that the Wairoa today has a low sediment trapping efficiency and is exporting most of its catchment fine sediment load to the adjacent coastal environment (Swales et al. 2002).

Another important factor controlling fine-sediment fate in intertidal estuaries is waves. These are effective mechanisms for the re-suspension and re-distribution of intertidal sediments (Green et al. 1997). Fine-sediments deposited on wave-exposed intertidal and shallow sub-tidal flats are reworked, re-distributed by currents and eventually deposited in long-term sediment sinks, such as tidal creeks, mangrove stands, saltmarsh and sub-tidal basins. This pattern of initial deposition on intertidal flats, re-suspension and eventual accumulation in longer-term sediment sinks, such as sub-tidal basins is seen in the Central Waitemata Harbour (Swales et al. 2007b).

Today, the Okura and Weiti estuaries have reached advanced stages of infilling, with most of their surface area being intertidal. ^{210}Pb dating shows that fine sediments are accumulating on intertidal flats in the upper Okura Estuary at 3 – 6 mm yr^{-1} (Figs. 2.1 & 2.2, Swales et al. 2002). Long-term sediment accumulation in the upper estuary is favoured by: (1) proximity to the catchment outlet; (2) weak tidal currents on the tidal flats; and (3) limited potential for wave re-suspension due to the short fetch in most wind directions. Seaward of the sand/shell bank, the intertidal flats are exposed to wave action, particularly from the northeasterly quarter (Green and Oldman, 1999). Although slugs of fine sediment are likely to be deposited on the exposed intertidal flats, these deposits do not persist and are eventually re-mobilised by waves and transported from the flat by tidal currents (Green and Oldman, 1999). This type of temporary fine-sediment deposition has sub-lethal and lethal effects on the benthic fauna, particularly on sand flats. These effects include long-term changes in species, communities and habitat, frequently resulting low diversity systems dominated by a few species and one or two habitats. The general exclusion of slow-growing, large species frequently results in lower diversity and reduced ecological functioning of ecosystems (Thrush et al. 2004; Swales et al. 2007a).

The radioisotope data collected in the present study indicate that there is a low potential for long-term fine-sediment accumulation on the intertidal flats of the lower Okura Estuary. By comparison, the Weiti estuary is sheltered from wave action by its alignment perpendicular to the prevailing southwest/northeast winds and numerous sand and shell ridges, which break the intertidal flats up into smaller compartments with limited wave fetch. Sedimentation is occurring in the lower estuary, as indicated by the $^{210}Pb_{us}$ concentrations, although SAR are likely to vary locally due to the complex morphology of the estuary.

Because the Okura and Weiti estuaries are largely intertidal and channelised, sediment-laden stormwater is likely to be discharged to Karepiro Bay as buoyant surface plumes.

Sediment cores show that Karepiro Bay is a long-term sink for fine sediments. Radioisotope data show that sediments have been accumulating in the bay over the last 50 years or so at average rates similar to those measured in the upper Okura Estuary. These data support the hypothesis that Karepiro Bay is a major sink for fine sediment eroded from land catchments and intertidal flats in the adjacent Okura and Weiti Estuaries. The spatial pattern of sedimentation, indicates a north to south trend of increasing sedimentation in the bay. Highest SAR occur directly offshore from the Okura estuary mouth in the lee of Piripiri point. Rapid sediment accumulation here may result from one or a combination of several factors: (1) proximity to the Okura estuary mouth; (2) shelter from the prevailing southwest winds; (3) hydrodynamic processes that favour deposition of fine sediments, associated with stormwater plumes, in the southern part of the bay.

A modeling study of silt-plume dispersal and deposition commissioned by the ARC and presently underway will elucidate the patterns of fine-sediment dispersal and sedimentation in Karepiro Bay. Additional sediment-core data in the southern Karepiro Bay area would improve confidence in these initial findings and provide validation data for the sediment modeling study. Finally, CSI analysis of recent (surface) sediments and the dated sediment cores collected in the present study could provide quantitative information on the contribution of sub-catchments and landuse to sedimentation in the estuaries and coastal environment.

6 Acknowledgements

We would like to thank the following ARC staff who participated in the field work associated with this study: Megan Stewart, Amy Taylor and Mike McMurtry as well as Glen Carbines (Stock Monitoring Services Ltd).

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8 APPENDICIES

8.1 Appendix One: Field notes from Okura estuary

10 March 2008

Mike McMurtry, Megan Stewart, Glen Carbines (ARC), Ron Ovenden (NIWA)

Low tide: 16.18 NZST

Site Okura River (OR)

Reached site at 1330 NZST

<u>Site selection for cores</u>

- Tried up on flat but very sandy.
- Tried slope – some mud content and there was a shell layer but deeper than the core.
- We tried lower down closer to the channel as the tide went out as it was a lot muddier here, but there was a definite bedrock and shell layer.
- It appears there is a bedrock layer all the way out from the coast that has been progressively covered by sand and mud. On the flat the substrate cover is quite deep but there is definitely a barrier below. As the flat slopes away to the channel there is a thick layer of mud but no underlying substrate so the actual layer was too thin to core.

We chose to take the cores as close to the mud as possible, but where we could still get a core in which meant we were on the edge of the slope/flat. So the cores were taken in a line.

Replicate locations (NZ Transverse Mercator).

Okura (cored 10mar08)

1. “050” E 1754260 N 5940568
2. “051” E 1754294 N 5940577
3. “052” E 1754329 N 5940596

Site 3 was closest to the mouth (sea) of the estuary.

OR1

This site was done last. It was a lot drier than when we marked it as the tide had gone out. Took 3 cores OR1/a, OR1/b. OK1/c and a successful slide! We were able to slide the face plate half way in before having to bang it in. This was interesting as it appeared to be the firmest and driest of the sites.

OR2

Got 3 good cores, OR2/a. OR2/b, OR3/c. Two attempts were made at x-ray slides but there was a shell layer that made it impossible to get the face plate in without the slide closing in on itself. We also had problems at this site of the plate not fitting very well in the slide (sloppy) so had to go and find a plate that fitted better. After two attempts and discovering the shell layer we went with an additional core (OR2/d).

OR3

At this site there were quite a lot of riverlets on the surface which were hard to avoid and a lot of shells on the surface. Site was a lot wetter than Weiti, there was a lot of water content in the cores. Took 3 successful cores OR3/a, OR3/b, OR3/c. X-ray slide was not very successful but kept it. Face plate broke as we were almost all the way in. Generally the slide was okay but the face plate had come out of the grove at the bottom. Slide was taped and wrapped in plastic.

8.2 Appendix Two: 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.

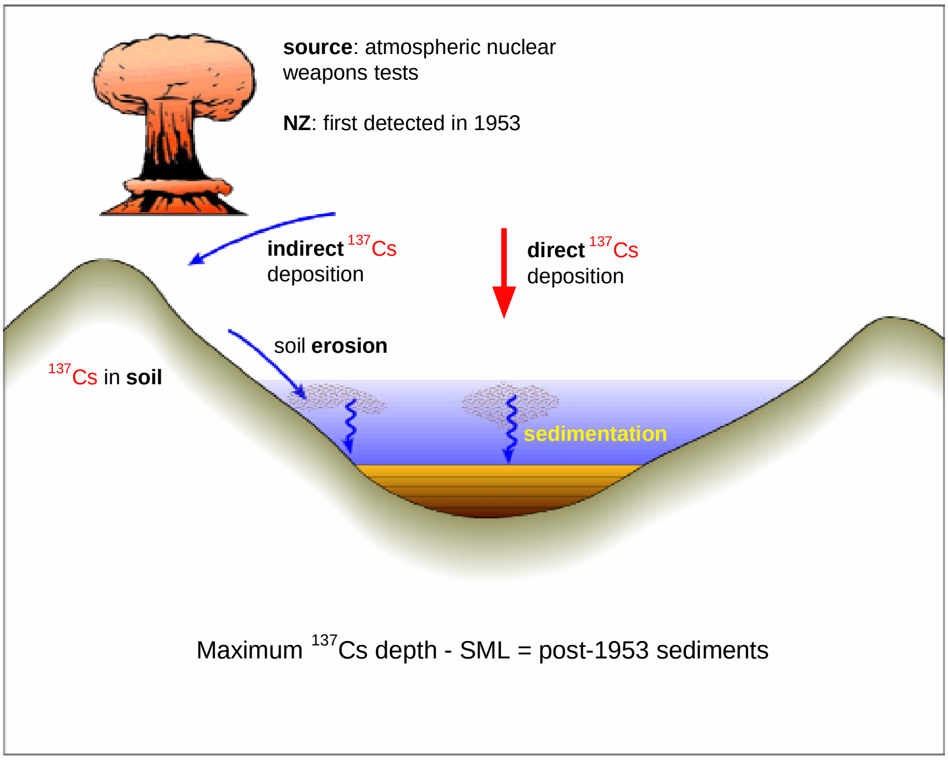
The S.I. unit of radioactivity used in this study is the Becquerel (Bq), which is equivalent to one radioactive disintegration per second.

8.3 ^{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.

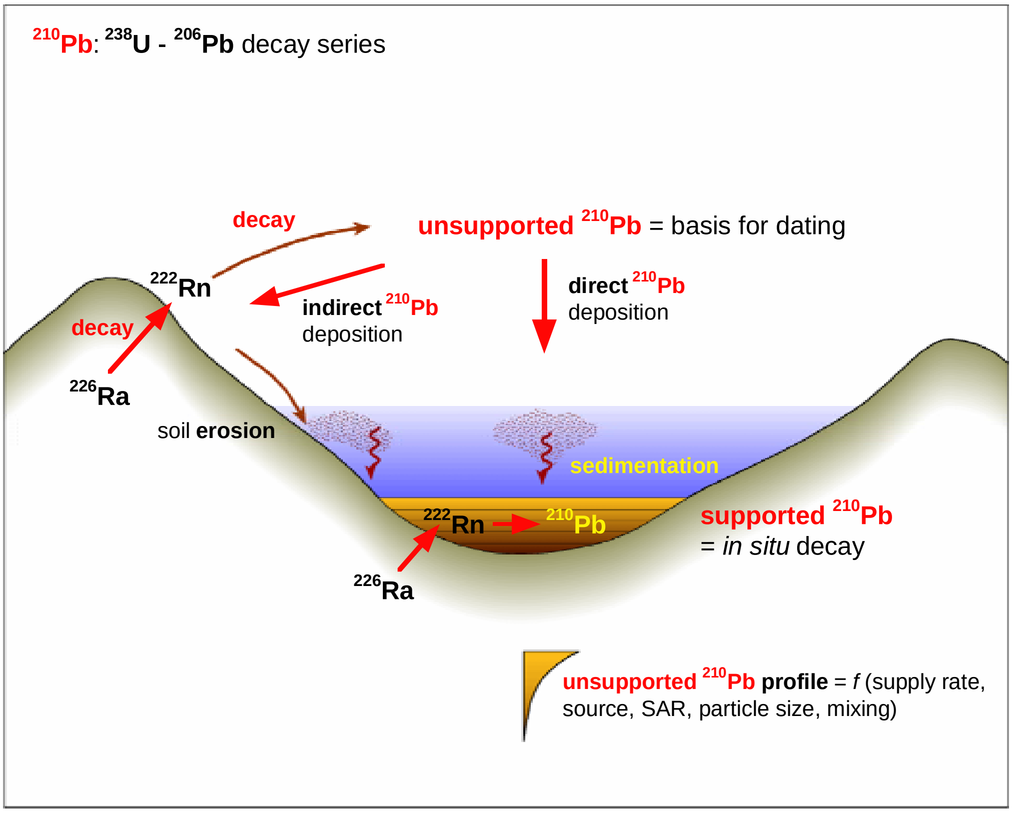
Uncertainty in the maximum depth of ^{137}Cs results from: (1) the depth interval between sediment samples and (2) minimum detectable concentration of ^{137}Cs, which is primarily determined by sample size and counting time. The 1963–1964 ^{137}Cs deposition peak was about five-times than the deposition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

8.4 ^{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.



8.5 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).

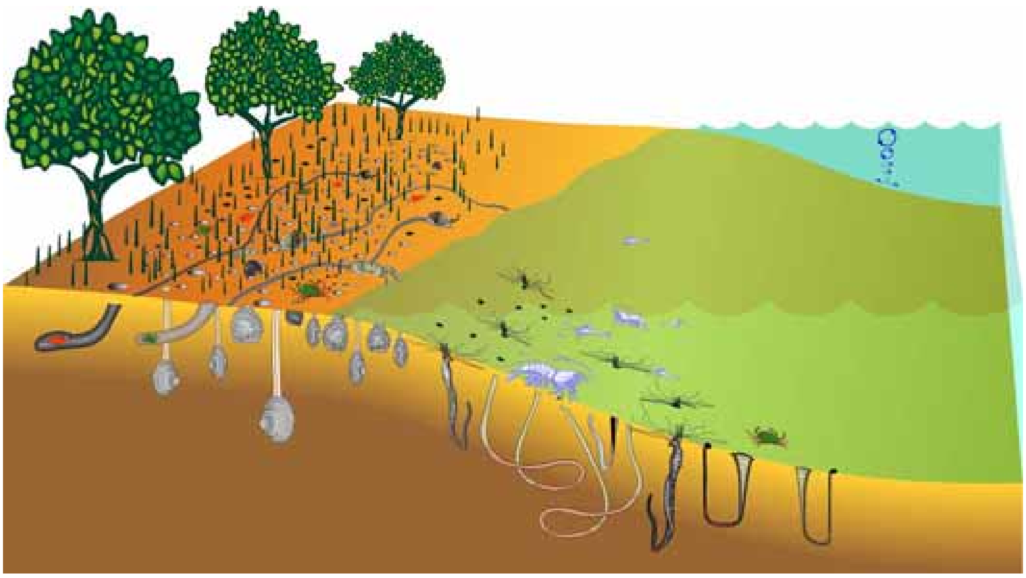
Net sedimentation rates also mask the fact that sedimentation is an episodic process, which largely occurs during catchment floods, rather than the continuous gradual process that is implied. In large estuarine embayments, such as the Firth, mudflat sedimentation is also driven by wave-driven resuspension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

8.6 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.