Kaipara Harbour Sediment Tracing

Sediment dispersion across the harbour

Prepared for Integrated Kaipara Harbour Management Group

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Sandbar near the entrance to the Northern Kaipara Harbour [Photo: Max Gibbs]

Unless otherwise stated, all photographs and diagrams in this report are by Max Gibbs.

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Executive summary

Sediment input, dispersion and accumulation are believed to be responsible for the perceived degradation of water quality, biodiversity and decline in the fishery of the Kaipara Harbour. Landuse intensification and climate change are major causes of erosion, increasing inputs of sediment into estuaries and harbours globally. The location of sediment inputs, sediment dynamics and areas of deposition will determine the scale and severity of impact of the sediment on benthic communities. Effective strategies for managing sediment inputs require accurate information regarding the source, dynamics and fate of sediment. NIWA's compound-specific stable isotope (CSSI) technique allowed sediment sources, dynamics and fate to be assessed. It also allowed the zone of influence of each river sediment input to be estimated. The dispersion and fate of sediment input from various rivers was also assessed.

River sediment dispersion patterns indicate that small inflows generally have a localised influence on the harbour sediments. Beyond that zone of influence, those sediments are increasingly diluted by sediment from larger river inflows and were generally below the level of discrimination of the CSSI technique. While relative river size is important, the amounts of sediment and the extent of the sediment fields is not consistent with mean annual river flows because terrigenous sediment can only deposit on the intertidal flats when they are inundated around high tide, a period of about 3 to 4 hours twice a day. The magnitude of the sediment fields on the intertidal flats could be better explained by the magnitude of mean annual flood flows. This implies that most of the terrigenous sediment on the Kaipara Harbour intertidal flats is deposited during flood events. Furthermore, dispersion patterns indicate that three major river systems contribute most of the terrigenous sediment to the Kaipara Harbour: the Kaipara / Kaukapakapa River system, the Hoteo River and the Wairoa River.

Sediment from the Kaipara / Kaukapakapa River system enters the southern harbour and forms an extensive sediment field across most of the southern Kaipara Harbour. The majority of that sediment deposits around the river mouth and spreads north east across the intertidal flats. This dispersion pattern is probably strongly influenced by prevailing winds from a westerly quarter, which would move buoyant freshwater flood plumes to the eastern side of the harbour.

Sediment from the Hoteo River disperses across the middle reaches of the southern Kaipara Harbour spreading both north and south from the river mouth. This pattern also suggests a strong influence from the westerly winds. The dispersion north and south from the river mouth may result from to the influence of north-westerly and south-westerly winds, but it may also reflect resuspension and lateral transport by wave and tidal action during storm events.

Sediment from the Wairoa River was found in both the northern and southern Kaipara Harbour. This is consistent with mean annual flood flows and associated sediment load being 20 to 40 times greater than those from the Kaipara / Kaukapakapa River system. Sediment from the Wairoa River dispersed across the whole northern Kaipara Harbour and extended well up the narrow fjord-like river channels. Wind effects on this sediment distribution were not obvious and it is likely that the freshwater component is completely mixed into the harbour waters before it leaves the Wairoa River estuary i.e., that 30 km portion of the Wairoa River between Dargaville and the harbour. For sediment from the Wairoa River to enter the southern Kaipara Harbour, it needs to be in suspension when it reaches the mouth

of the harbour, allowing the flood tide to carry it along the deep channels into both halves of the Kaipara Harbour. The relatively high proportions of Wairoa River sediment within the southern Kaipara Harbour (extending as far south as Shelly Beach), supports the hypothesis that this sediment was deposited during flood events.

Both carbon (C) and nitrogen (N) concentrations in the sediments indicate very high organic content in sediment recently deposited near some river inflows. This is consistent with landuse intensification and increasing erosion. This fine material smothers localised areas and is likely to adversely impact on local biodiversity.

Analysis of the isotopic signatures of the sediment from various rivers shows that sediment derived from the Wairoa River has very low carbon content and an enriched bulk ^{13}C signature. This implies a high degree of biological processing, probably within the estuarine portion of the Wairoa River. It also indicates that the intertidal flats affected by this sediment are likely to be depleted in carbon (a food supply for benthic biota). Similar isotopic characteristics were observed in the Hoteo River sediment. Areas subjected to deposition of sediment of this nature are likely to lose sediment sensitive species in favour of species which are more tolerant, resulting in a change in species diversity if not a reduction in biodiversity.

Additional information regarding species distribution obtained by observation during sample collection and following sample processing are included to provide a non-quantitative indication of presence at the sampling locations.

1 Introduction

“Declining biodiversity” and “Increasing sedimentation and poor water quality” were identified as two key issues for the Kaipara Harbour in a recent report by the Integrated Kaipara Harbour Management Group (June 2010). In 2011 it was reported that the environmental state of the harbour was "nearing crisis" and "in significant decline", evidenced by shrinking fish and shellfish stocks, increasing sedimentation and declining water quality. Competition for resource use and development was noted as another issue, with "ninety-nine per cent of the rivers in the catchment polluted" (NZ Herald, 2011).

Globally, sediment is a major pollutant of water and the increased export of fine terrigenous sediments is recognised as a threat to estuarine and coastal marine ecosystems. Although terrigenous sediment input and deposition in these environments is a natural process, the rate at which this is now occurring is higher than occurred before human activities disturbed the natural land cover (Thrush et al. 2004). In New Zealand, increases in sediment loads discharged to estuaries and coastal ecosystems, including the Kaipara Harbour, have coincided with large-scale deforestation, which followed the arrival of people about 700 years ago. Where sediment is deposited in the Kaipara Harbour and its subsequent redistribution by tidal and wave action will in part determine the severity of adverse effects on benthic communities.

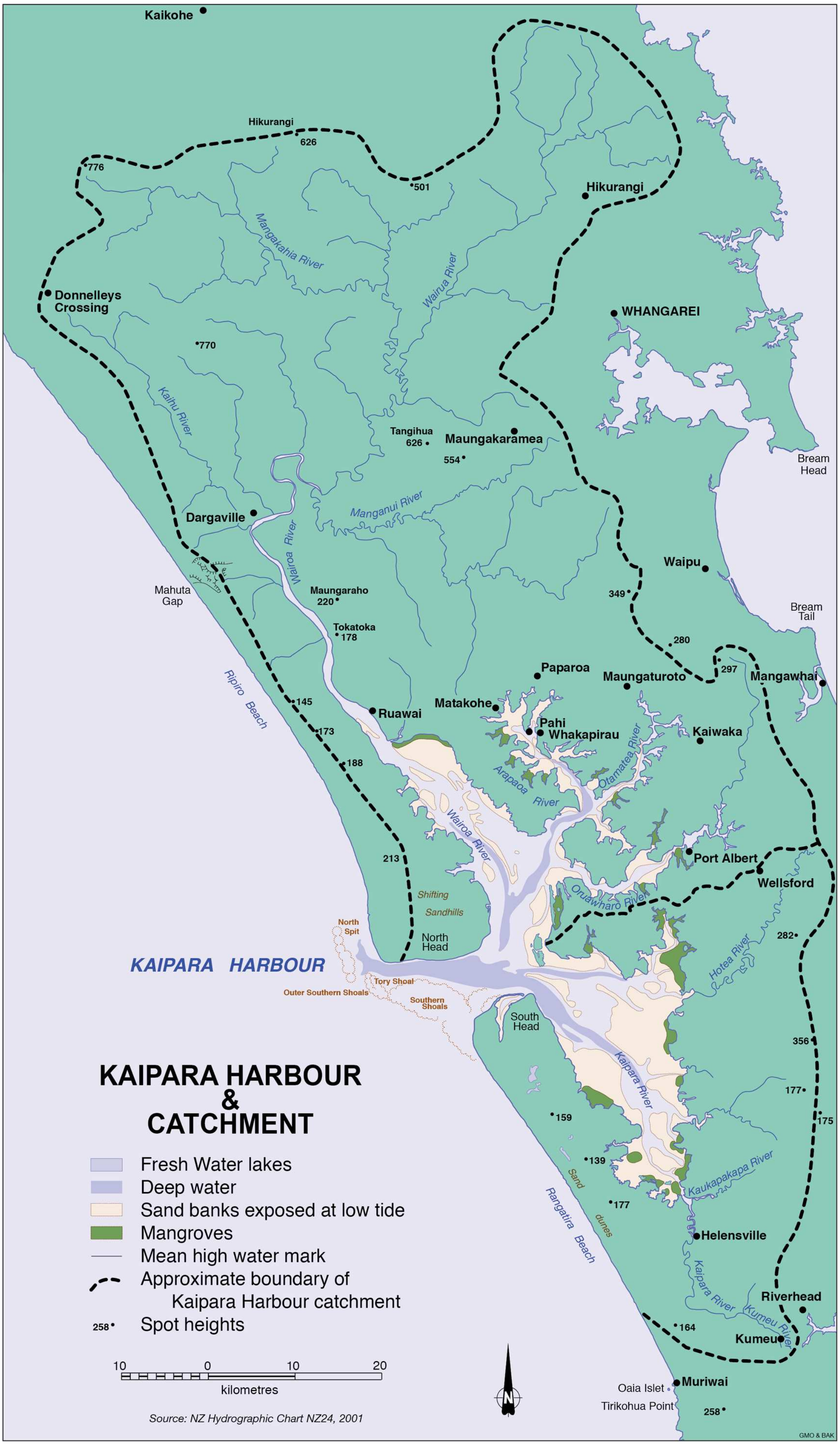
The development of management strategies aimed at reducing or preventing inputs of fine sediment to the harbour requires detailed information regarding the source and fate of this material. The use of the NIWA compound-specific stable isotope (CSSI) technique for identifying sediment sources by landuse and for tracking sediment deposition in estuaries was successfully demonstrated in Mahurangi Harbour (Gibbs 2008) and the Bay of Islands (Gibbs & Olsen, 2010). The present study investigates the sources of sediment entering the Kaipara Harbour and the subsequent dispersion of those sediments within the harbour system. This work complements a NIWA study of the patterns and rates of recent sedimentation in the Kaipara Harbour (Swales et al. 2011).

1.1 Objectives

This study was undertaken to:

- Identify sediment sources and assess sediment dispersion in the Kaipara Harbour using compound-specific stable isotope analysis and related techniques.
- Map the dispersion of the Wairoa River sediment relative to sediment dispersion from other sources within the Kaipara Harbour.

In addition to investigating sediment dispersion, organisms observed in the samples and at each sampling site were recorded to provide crude spatial information regarding benthic biodiversity in the Kaipara Harbour (Appendix A). This information is qualitative and should be regarded as a record of presence, but not necessarily absence, of the species at each site. Some landuse observations are also recorded.



Source: NZ Hydrographic Chart NZ24, 2001

Figure 1-1: Location map of Kaipara Harbour. This shows the overall catchment boundary with the separation between northern and southern catchments and main sub-habitat types.

1.2 Background

The Kaipara Harbour (Figure 1-1) is a complex drowned-valley/barrier-enclosed type estuary (Hume & Herdendorf, 1988), located on the west coast of the Northland Peninsula. The Kaipara Harbour is also one of the largest estuaries in the southern hemisphere, with a high-tide surface area of ~947 km^2, of which 409 km^2 is intertidal (Heath, 1975). The harbour shoreline is convoluted by the entry of many rivers and streams and is about 800 km long (Wo & van Kalken, 2006).

Although most of the harbour is composed of intertidal flat and shallow subtidal habitats, the entrance channel is up to 50 m deep. The deep channels are navigable and between 1875 and 1915 Port Kaipara was visited by between 60 and 160 ships per year (Ryburn, 1999). Despite the depth of the entrance channel, many ships were wrecked attempting to cross the treacherous shifting sand bar.

The sand barriers that form the North and South Heads are composed of late Pliocene and Quaternary dune sand and swamp deposits, as well as the more recent Holocene deposits that form the tidal deltas, beach and dune systems today. The ebb-tide delta alone (to 30 m water depth) contains an estimated 12.3 billion cubic metres of sand (NZ Geological Survey 1972, Hicks & Hume, 1996; Hume et al. 2003). These vast deposits are composed of marine sands that were transported onshore as sea level rose at the end of the last ice age, which was at its peak 16–18,000 years ago. At that time, sea level was 120 m lower than today and the ancestral Kaipara Harbour was most likely a branching system of river valleys that discharged over the present-day continental shelf to an open coast, some 25 km west of its present position (Hume et al. 2003). The harbour that we see today was formed ~6,500 years ago when the sea reached its present level. Subsequent to that time, the ancestral river valleys infilled with marine and terrigenous sediments, which form the present-day sand banks and tidal flats of the inner harbour.

The Kaipara Harbour is an important natural nursery for finfish and is thought to support the snapper fishery along most of the west coast of the North Island of New Zealand (Morrison et al. 2009). The Kaipara Harbour contains a diverse range of estuarine environments, which include extensive wave-exposed intertidal flats (Figure 1-2) and sand barriers (Figure 1-3), extensive mangrove (Figure 1-4) and salt-marsh habitats (Figure 1-5) and large tidal-river systems (Figure 1-6).

The harbour receives runoff from a 6,400 km^2 land catchment. The Wairoa River accounts for 63% of the total catchment area, and discharges to the northern end of the harbour (Figure 1-1). Catchment geology is largely a Cretaceous–Miocene age basement of inter-bedded sandstones and siltstones (NZ Geological Survey, 1972), with areas of volcanic ash in the north west and some limestone deposits to the east of the divide between the northern and southern harbours (GIS database). Landuse is predominantly pastoral agriculture, with production forestry, horticulture and native forest and scrub (Reeve et al. 2009).

As documented elsewhere, landuse changes followed the arrival of Polynesians about 700 years ago. Landuse changes introduced by European settlers from the 1830s increased soil erosion. Kauri gum extraction and timber harvesting preceded the conversion of native forests to pastoral agriculture. Catchment deforestation would have accelerated following the first hydrographic survey of the harbour by H.M.S. Pandora in 1852 and most of the land suitable for pastoral agriculture was cleared by the early 1900s (Ferrar, 1934; Bryne, 1986;

Ryburn, 1999). In recent decades, horticulture, urbanisation and more intensive landuse have increased.

The effects of increased catchment sediment runoff on receiving estuaries following deforestation have been documented for a number of North Island systems. In many cases there has been a shift from sand- to mud-dominated systems due to increased loads of terrigenous fine silts and clays. Order-of-magnitude increases in sediment accumulation rates (SAR) relative to pre-deforestation values have occurred (e.g., Oldman & Swales, 1999, Swales et al. 1997, 2002a, 2002b, 2005, 2007). These changes in sedimentation rate and sediment characteristics affect the ecological "health" of estuarine systems by reducing the abundance of fine-sediment-sensitive species while favouring tolerant species (e.g., mangroves) (Hewitt & Funnell 2005; Thrush et al. 2004). The relative paucity of information regarding changes in sedimentation rates and sediment characteristics in the Kaipara Harbour system means there is a risk that degradation in environmental quality will not be detected in time for an effective management response to be developed and implemented.

Figure 1-2: Extensive intertidal flats flank the tidal channels. View of the Kaipara River looking south towards Helensville, March 2009. (Photo: A. Swales, NIWA).

Figure 1-3: View of the Kaipara Harbour entrance. Marine sands transported onshore since the last ice age have built the large sand barriers and tidal flats that characterise the central harbour. View looking west across Tapora Island, August 2009. (Photo: A. Swales, NIWA).

Figure 1-4: Mangrove forests. Mangrove forests occur at several locations in the Kaipara Harbour, such as this one flanking the Puharakeke Creek at its confluence with southern Kaipara Harbour. View looking north across Shelly Beach headland, March 2009. (Photo: A. Swales, NIWA).

Figure 1-5: Mixed mangrove stand salt-marsh complexes. These are a common feature of the upper-intertidal flats, March 2009. (Photo: A. Swales, NIWA).

Figure 1-6: Numerous tidal rivers indent the Kaipara Harbour shoreline. These environments are characterised by sinuous channels flanked by mud flats and mangrove stands. Very large tidal rivers, extending 10 km or more from the upper reaches to their outlets, occur in the northern Kaipara. View of the upper Oruawharo River, November 2010. (Photo: A. Swales, NIWA).

The Kaipara Harbour may be conveniently divided into two reaches (Figure 1-1):

1. The northern Kaipara (Figure 1-7) has three long, narrow, tidal inlets (Arapaoa, Otamatea, Oruawharo); the main harbour is highly turbid due to sediment inputs from rivers, and sediment suspension by wave action and tidal currents.
2. The southern Kaipara (Figure 1-8) is also turbid due to the sediment inflow from several large rivers (Hoteo, Araparera, Kaipara / Kaukapakapa) and wave resuspension of fine sediment on the wind-swept intertidal flats.

Figure 1-7: Northern Kaipara Harbour. The narrow Otamatea River arm of the northern Kaipara Harbour (upper) contrasts strongly with the wide, highly turbid Wairoa River and the broad mudflats of the main harbour (lower).

The southern Kaipara Harbour has been subject to several ecological surveys (e.g., Hewitt & Funnell, 2005) that have identified a high diversity of habitats including extensive fringing mangroves and salt marshes, *Zostera* (seagrass) meadows and patches, non-vegetated mud and sand intertidal flats, shallow subtidal flats, small areas of steep banks, deep high-flow channels and rocky reefs and cliffs. Despite the high current velocity and potential for wind waves and ocean swell, many areas of the southern Kaipara Harbour display high taxonomic diversity at both species and order level, and a number of organisms living in the harbour are large and long-lived. A number of species are commonly associated with pristine environments (sponges, ascidians, bryozoans, hydroids, echinoderms and pipis) while others are unique (tube building worms *Owenia*, *Macroclymenella*) or rare (subtidal *Zostera*). Pacific oysters (*Crassostera gigas*) are farmed in the southern Kaipara on the sand flats adjacent to the harbour entrance.

Figure 1-8: Southern Kaipara harbour. Broad intertidal sandflats of the southern Kaipara Harbour adjacent to the Hoteo River outlet.

While the northern Kaipara has not been studied to the same extent (e.g., Haggitt et al. 2008), it has similar or higher diversity of habitats as the southern Kaipara. These include vegetated intertidal habitats (mangroves and salt marshes), non-vegetated mud and sand intertidal flats, shallow subtidal flats, small areas of steep banks, deep high-flow channels and rocky reefs and cliffs. Two major differences are the absence of *Zostera* meadows, which are common across the southern Kaipara, and the presence of extensive rack farming of oysters along the shoreline in the tidal river estuaries (e.g., Arapaoa). These tidal river estuaries may also contain habitats not found in the southern Kaipara because of their generally shorter wave fetch.

The Integrated Kaipara Harbour Management Group (2011) noted that, while the decline of the Kaipara biodiversity has not been quantified, "*it has been readily observed by the people of the Kaipara. The Kaipara has been transformed from primeval forest, scrub and wetlands to pasture. It fed the NZ and Australian timber industry from 1860s to 1900s (peak was 1899 and trade ceased about 1939). Supplied kauri gum and flax for building everything and anything in colonial NZ. And today, sand for the entire Auckland region. There is no doubt that the removal of the bush had severe consequences on biodiversity. Soil erosion* *accelerated on the land around the harbour, as did sedimentation in parts of the harbour*[1]*. This has altered the biodiversity of marine habitats substantially*."

These events and environmental effects have been observed elsewhere in Northland. Studies in the adjacent (east coast) Mahurangi Harbour and Okura Estuary have demonstrated the fragility of habitats and benthic biota in the face of increasing turbidity from terrigenous sediment (Ellis et al. 2002; Norkko et al. 2002). The inputs of sediment associated with production forestry on Mahurangi Harbour (Gibbs, 2008) mimic the likely changes in sediment loads that occurred when the timber industry removed most of the native forest around the Kaipara Harbour. Much of the kauri and kahikatea forest, scrub and riparian vegetation, has been replaced with agricultural and urban landuse. Mangrove forests and wetlands have been reclaimed (Swales et al. 2011). In general, soil erosion has increased sedimentation in the harbour (Swales et al. 1997, 2011) and may be causing the apparent decline in abundance of filter-feeding shellfish, especially toheroa, scallops, tuatua, cockles and pipi. Overfishing and the decline in food supply are thought to have reduced the populations of finfish such as mullet, snapper and school shark.

Sediment resuspension, dispersion and re-deposition across the shallow mudflats are likely to cause major ecological effects in some areas. Sedimentation effects that are appearing in the southern Kaipara (Hewitt & Funnell, 2005) are likely to affect the northern Kaipara as well because the Wairoa River inflow at the northern end is much larger, draining over 60% of the total Kaipara Harbour catchment. While the Wairoa River is no more turbid than any of the rivers further south (Hudson, 2010), the mass transport of sediment is much greater. However, the extent to which sediment from the Wairoa River disperses across the Kaipara Harbour and whether it crosses between the northern and southern Kaipara Harbours is largely unknown.

1.3 River inflows

The input of new sediment to the Kaipara Harbour is via river inflows but there are only a few rivers where there are sufficient inflow data from which to construct a sediment budget. The only long-term inflow data available are for the Hoteo River at SH1 at a site known as "Gubbs" (NIWA National Rivers Water Quality Network). This site is well inland from the river mouth because of tidal influence in the lower reaches. Similarly, the Kaipara River flowing into the southern Kaipara Harbour is measured at Waimauku, which is well upstream of the mouth and upstream of the confluence with the Kaukapakapa River, its largest tributary.

In contrast, no single point exists where flows in the Wairoa River are measured. Instead, the Wairoa River inflow is estimated as a composite of flows in four rivers (Kaihu, Mangakahia, Manganui and Wairua Rivers) that combine to form the Wairoa upstream of Dargaville, 30 km from its point of discharge into the Kaipara Harbour. These four rivers account for around 76% of the 3650 km^2 Wairoa River catchment area.

River flow information is rarely reported (e.g., Scarsbrook, 2007) but, for this report, some flow estimates have been provided by Regional Councils. For the purposes of developing a simple water budget for the Kaipara Harbour, these estimates have been combined with flow estimates from NIWA's Water Resources Explorer NZ model (WRENZ 2007). A list of inflows

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[1] Not quantified until now (Swales et al. 2011).

to the Kaipara Harbour has been produced showing mean annual flow, mean annual flood flow, and maximum flood flows (Table 1-1). Specific land discharge values calculated from these data indicate higher runoff from the steeper catchments draining the hill country headwaters than the coastal lands. It must be noted that while the WRNEZ flow estimates are consistent with Regional Council estimates, allowing them to be used to compare the relative magnitudes of the main inflows, they are not absolute values and should be used for any other purpose with caution.

The mean annual flow in the Wairoa River is more than 10 times greater than the combined mean annual flows in the Kaipara and Kaukapakapa Rivers. This means that although the sediment concentrations in the mean annual flow for these rivers may be similar (Hudson, 2010), the Wairoa River delivers at least 10 times more sediment into the Kaipara Harbour than the largest river system in the southern Kaipara Harbour. The Wairoa River also carries more than 20 times the volume of the Kaipara and Kaukapakapa Rivers in the mean annual flood events and more than 40 times the maximum flood flow (Table 1-1). Putting the Wairoa River inflow into perspective, 9 days of mean annual flood flow is equivalent to a year of mean annual flow. This indicates that a large portion of the sediment entering the harbour arrives during flood events.

Table 1-1: River flow estimates. These values are from NIWA's Water Explorer NZ model (WRENZ 2007) and should be used with caution. Note: Unless otherwise stated, catchment areas are upstream of the hydrometric stations, which do not coincide with the coastline indicated as "Mouth".

River	**Tributaries**	**Flow** ($m^3 s^{-1}$)			**Catchment Area**	**Specific land discharge** ($L s^{-1} km^{-2}$)		
		Mean annual flow	Mean annual flood	Maximum flood	(km^2)	Mean annual flow	Mean annual flood	Maximum flood
Northern inflows								
Wairoa	Kaihu River	10.6	228	469	325	0.033	0.702	1.443
	Mangakahia River	22.3	1240	2758	838	0.027	1.480	3.291
	Manganui River	15.5	519	1067	790	0.020	0.657	1.351
	Wairua River	22.3	354	885	749	0.030	0.473	1.182
	@ Ruawai	88.5	3716	8006	3554	0.025	1.046	2.253
Arapaoa	@ Mouth	1.5	53	109	72	0.021	0.736	1.514
Otamatea	@ Mouth	0.65	40	88	37	0.018	1.081	2.378
Oruawharo	Topuni	1.5	102	234	94	0.016	1.085	2.489
Oruawharo	total	2.25	144	330	133	0.017	1.083	2.481
Southern inflows								
Tauhoa	@ Mouth	0.47	12	27	23.7	0.020	0.506	1.139
Hoteo	@ Gubbs	4.35	181	465	270	0.016	0.670	1.722
Hoteo	@ Mouth	8.2	221	550	405	0.020	0.546	1.358
Araparera	@ Mouth	1.5	38	96	69	0.022	0.551	1.391
Makarau	@ Mouth	1.6	48	129	74	0.022	0.649	1.743
Kaipara	@ Mouth	4.8	93	277	267	0.018	0.348	1.037
Kaukapakapa	@ Mouth	2.4	64	181	120	0.020	0.533	1.508

2 Methods

2.1 Sampling

The size of the Kaipara Harbour and the requirement to obtain surface (0 to 2 cm depth) sediments over a large area of exposed mud and sand flats in a short time necessitated sampling from a helicopter. Sampling was done in two three-hour periods over spring low tides on 8 December 2009 for the southern Kaipara (64 samples), and on 1 November 2010 in the northern Kaipara (57 samples). Sample locations were recorded by GPS in New Zealand Map Grid (NZMG) coordinates (Figure 2-1). Although collected a year apart, it is valid to combine the datasets for the whole Kaipara Harbour because SAR for the harbour is 4 to 5 mm y^{-1} (Swales et al. 2011), indicating that the 0 to 2 cm surface sediment layer integrates the sediments derived from all sources over a period of 4-5 years.

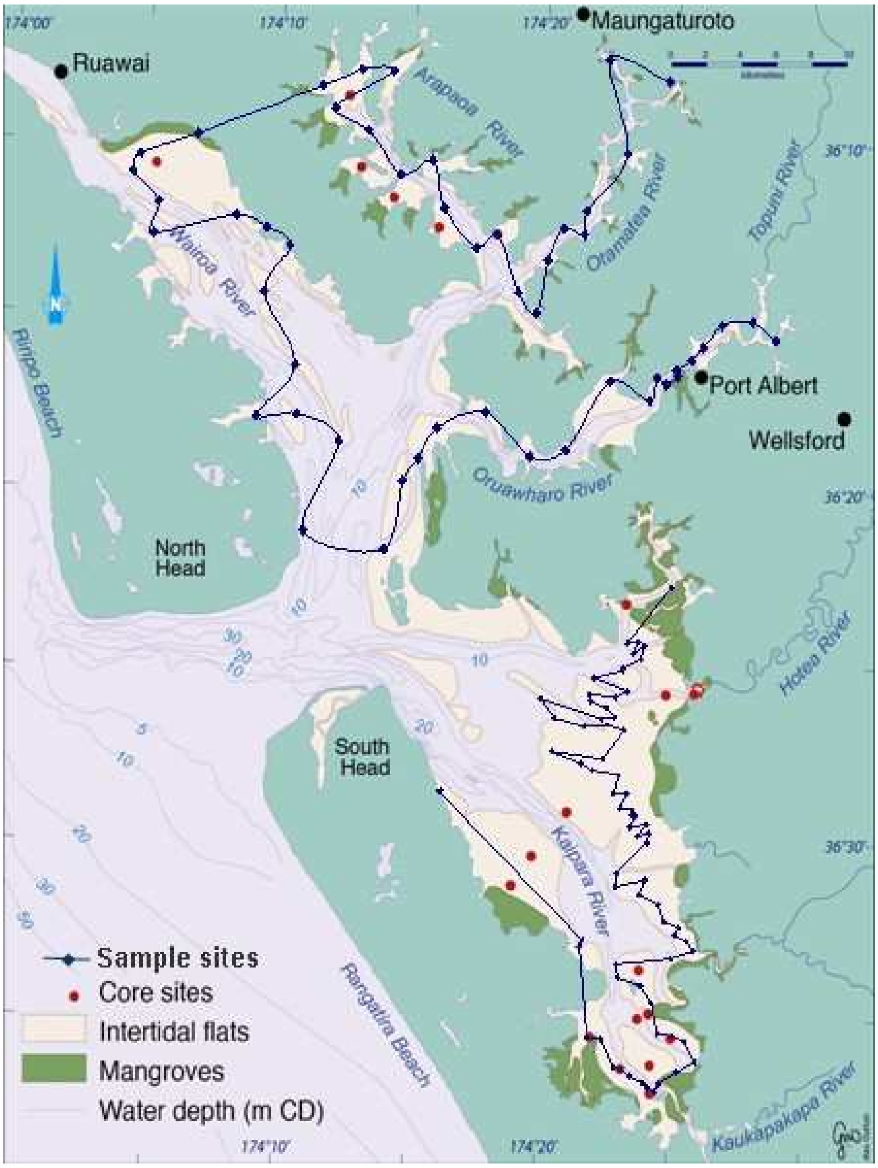

Figure 2-1: Sediment sampling sites. Fight paths across the northern (2010) and southern (2009) Kaipara Harbour relative to sediment core sites (red dots) from a study by Swales et al. (2011).

At each sample location, oblique and vertical photographs of the sediment surface were taken before a sample of the 0 to 2 cm surface layer was scooped from several locations with a plastic trowel (Figure 2-2). In the northern Kaipara, a 0.5 m square quadrat was dropped onto the sediment to assist later interpretation of the vertical photos. Large debris was removed before the sample (~500 g) was placed in a zip seal plastic bag, which was stored upright in a large fish bin. The site code was written in pencil on a waterproof paper label which was placed in the bag before the bag was sealed. The bag was also labelled.

Figure 2-2: Sediment sampling. Plastic sampling scoop was 150 mm wide with a 20 mm high back. Multiple divots were placed in the plastic bag. The sample shown is an Asian mussel mat (*Musculista senhousia*). [Subject: Max Gibbs; Photo: Luca Chiaroni, NIWA].

The wet samples were sieved (1 mm mesh) into pre-weighed aluminium trays and freeze dried to determine moisture content and to allow preparation for subsequent analyses. Biota and flora retained in the sieve were recorded for each location. Where sections of the Asian mussel (*Musculista senhousia*) mat were collected, the mud was separated from the mat by hand and a subsample retained for moisture content before the remainder was washed into the sample tray with tap water. These washed samples were allowed to settle and the excess water was decanted before freeze drying. The dried samples were reweighed to estimate moisture content before being ground to a fine powder (<0.1 mm) and sealed in air-tight plastic bags at room temperature in the dark, pending analysis of carbon (C) and nitrogen (N) content (%) and the stable isotopes values of C (^{12}C & ^{13}C) and N (^{14}N & ^{15}N).

2.2 Stable isotopes

The techniques used for identifying sediment sources in sediment samples from the harbour rely on the fundamental principles of stable isotopes. This section provides a brief introduction to stable isotopes and how the isotopic data are interpreted. Stable isotopes are not radioactive and are a natural phenomenon in many elements. Carbon (C) stable isotopes are used to determine the provenance of sediments.

About 98.9% of all carbon has the atomic weight (mass) 12. The remaining ~1.1% of C has an extra neutron in the atomic structure giving it an atomic weight (mass) of 13. These are the two stable isotopes of carbon. To distinguish between them, they are written as ^{12}C and ^{13}C. They are also referred to as light (^{12}C) and heavy (^{13}C) isotopes. Both isotopes of carbon have the same chemical properties and react in the same way. However, because ^{13}C has the extra neutron in its atom, it is slightly larger than the ^{12}C atom. This causes molecules with the ^{13}C atoms in their structure to react slightly slower than those with ^{12}C atoms, and to pass through cell walls in plants or animals at a slower rate than molecules with ^{12}C atoms. Consequently, more of the ^{12}C isotope passes through the cell wall than the ^{13}C isotope, which results in more ^{12}C on one side of the cell wall than the other. This effect is called isotopic fractionation and the difference can be measured using a mass spectrometer. Because the fractionation due to passage through one cell-wall step is constant, the amount of fractionation can be used to determine chemical and biological pathways and processes in the ecosystem. Each cell wall transfer or "step" is positive and results in enrichment of the ^{13}C content.

The amount of fractionation is very small (about one thousandth of a percent of the total molecules for each step) and the numbers become very cumbersome to use. A convention has been developed where the difference in mass is reported as a ratio of heavy-to-light isotope. This ratio is called "delta notation" and uses the symbol "δ" before the heavy isotope symbol to indicate the ratio i.e., δ^{13}C. The units are expressed as "per mil" which uses the symbol "‰". The delta value of a sample is calculated using the equation:

$$\delta^{13}C = [(R_{sample} / R_{standard}) - 1] \times 1000 \text{ ‰}$$

where R is the molar ratio of the heavy to light isotope ^{13}C/^{12}C. The international reference standard for carbon is a limestone, Pee Dee Belemnite (PDB), which had a δ^{13}C value of 0 ‰. As all of this primary standard has been used, secondary standards calibrated to the PDB standard are used.

The instruments used to measure stable isotopes are called "isotope ratio mass spectrometers" (IRMS) and they report delta values directly. However, because they have to measure the amount of ^{12}C in the sample, and the bulk of the sample C will be ^{12}C, the instrument also gives the percent C (%C) in the sample.

When analysing a sample for stable isotopes, the δ^{13}C value obtained is referred to as the bulk δ^{13}C value. This value indicates the type of organic material in the sample and the level of biological processing that has occurred. (Biological processing requires passage through a cell wall, such as in digestion and excretion processes and bacterial decomposition.) The bulk δ^{13}C value can be used as an indicator of the likely source landuse of the sediment. For example, fresh soil from forests has a high organic content with %C in the range 5% to 20% and a low bulk δ^{13}C value in the range -28‰ to -40‰. As biological processing occurs, bacterial decomposition converts some of the organic carbon to carbon dioxide (CO_2) gas which is lost to the atmosphere. This reduces the %C value and, because microbial decomposition has many steps, the bulk $\delta^{13}C$ value increases by ~1‰ for each step. Pasture landuse and marine sediments typically have bulk $\delta^{13}C$ values in the range -24‰ to -26‰ and -20‰ to -22‰, respectively. Waste water and dairy farm effluent have bulk $\delta^{13}C$ values more enriched than -20‰. Consequently, dairy farm landuse, where animal waste has been spread on the ground as fertilizer, will have bulk $\delta^{13}C$ values higher (more enriched) than pasture used for sheep and beef grazing.

In addition to the bulk $\delta^{13}C$ value, organic carbon compounds in the sediment can be extracted and the $\delta^{13}C$ values of each different compound can be measured. These values are referred to as compound-specific stable isotope (CSSI) values. A forensic technique recently developed to determine the provenance of sediment uses both bulk $\delta^{13}C$ values and CSSI values from each sediment sample for comparison with a range of landuse samples as reference materials. This method is called the CSSI technique (Gibbs, 2008).

The CSSI technique is based on the concepts that:

1. landuse is primarily defined by the plant community growing on the land, and
2. all plants produce the same range of organic compounds but with slightly different CSSI values because of differences in the way each plant species grows.

The compounds targeted for CSSI analysis are natural plant fatty acids which bind to the soil particles as labels called biomarkers. While the amount of a biomarker may decline over time, the CSSI value of the biomarker does not change. The CSSI values for the range of biomarkers in a soil provides positive identification of the source of the soil by landuse.

The sediment at any location in an estuary or harbour can be derived from many sources including river inflows, coastal sediments and harbour sediment deposits that have been mobilised by tidal currents and wind-waves. The contribution of each sediment source to the sediment mixture at the sampling location will be different. To separate and apportion the contribution of each source to the sample, a mixing model is used. The CSSI technique uses the mixing model IsoSource (Phillips & Gregg, 2003).

IsoSource is not a conventional mixing model. The model input data required are the isotopic values of bulk and compound-specific stable isotopes of all possible sources and the sediment sample. IsoSource constructs a list of all possible combinations of isotopic values and compares these with isotopic values in the sample. It then selects those combinations of sources that combine to produce isotopic values closest to the isotopic values in the sample. Those combinations have an isotopic balance that matches the sample and are called feasible solutions.

The number of feasible solutions, n, is a measure of the confidence in the result. High values of n indicate many feasible solutions and hence there is low confidence in the result. As the value of n reduces towards 1 the level of confidence increases until n = 1, which is a unique solution. It is rare to have an exact match or unique solution. In most cases there will be many feasible solutions and these can be statistically evaluated to assess the most likely combination of sources in the sediment sample. These feasible solutions are expressed as isotopic feasible proportions (%) with an uncertainty value equivalent to the standard deviation (SD) about the mean.

Because less than 5% of most sediment samples is carbon, and the isotopic balance only applies to the carbon content of each source, the isotopic feasible proportions are scaled up by the ratio of the %C in the source material to obtain percent-source contributions. A complete description of the method and protocols are provided in Gibbs (2008).

While the information on stable isotopes above has focused on carbon, these descriptions also apply to nitrogen (N), which also has two stable isotopes, ^{14}N and ^{15}N. The bulk N content (%N) and bulk isotopic values of N, $\delta^{15}N$, also provide information on landuse in the catchment but, because the microbial processes of nitrification and denitrification can cause additional fractionation after the sediment has been deposited, bulk $\delta^{15}N$ cannot be used to identify sediment sources. The fractionation step for N is ~3.5‰ with bulk $\delta^{15}N$ values for forest soils in the range 2‰ to 5‰. Microbial decomposition processes result in bulk $\delta^{15}N$ values in the range 6‰ to 12‰ while waste water and dairy effluent can produce bulk $\delta^{15}N$ values up to 20‰. However, the use of synthetic fertilizers such as urea, which has $\delta^{15}N$ values of -5‰, can result in bulk $\delta^{15}N$ values <0‰.

2.3 Analyses

An aliquot of each dry sediment sample was acidified with 1 N hydrochloric acid to remove inorganic carbonate before analysing for bulk organic C and N stable isotopes. About 50 mg of each acidified sample was combusted in a helium gas stream in a Fisons N1500 Elemental Analyser coupled via a ConFlo-II interface to a Thermo-Finnegan Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS).

For $\delta^{13}C$, CF-IRMS measurements typically have a precision of ± 0.1 ‰ or better and the instrument also provides the proportion of organic C and N (%) in each sample.

Aliquots (20 to 40 g) of the non-acidified dry sediment were extracted with dichloromethane (100 ºC) under high pressure (2000 psi) in a Dionex Accelerated Solvent Extractor (ASE 2000) to extract the fatty acids bound to the sediment particles. The fatty acids were methylated using 5% boron trifluoride catalyst in methanol to produce fatty acid methyl esters (FAMEs). These FAMEs were analysed by gas chromatography (GC)-combustion-IRMS to produce compound-specific stable isotope $\delta^{13}C$ values i.e., CSSI values. Method details and data interpretation protocols were described previously by Gibbs (2008).

2.4 Data processing and presentation

The bulk $\delta^{13}C$ values, %C and suite of CSSI values for the extracted FAMEs were assembled into a matrix table and modelled using IsoSource to estimate isotopically feasible proportions of the main sediment sources at each sampling location. In successive model iterations, potential sources were added or removed to find an isotopic balance where the confidence level was high (lowest n value) and uncertainty was low. In general, soil proportions less than 5% were considered possible but potentially not present. Soil proportions >5% were considered to be present within the range of the mean ± SD.

The per cent-soil proportions for the major river inflows were then plotted as spatial distribution maps across the Kaipara Harbour using the contouring programme “Surfer-V8”

(Golden Software), using linear kriging. Non-isotopic data describing the presence of mud, seagrass, Asian mussels, Pacific oysters and cockles were also mapped using this software.

Because of the paucity of data across such a large harbour area, the contour plots produced by linear kriging are indicative rather than definitive.

2.5 Sedimentation process assumptions for modelling

For sediment arising from a river source to be present on an intertidal mud or sand flat, we assume:

- deposition occurs around high tide i.e., when there is water over the intertidal flats, and
- because freshwater is less dense than seawater, it will float as a thin layer on the surface of the sea until wind and wave action mix it into the estuarine water.

Terrigenous soil in freshwater will travel with the freshwater plume while sedimenting out. As a buoyant plume, the path of the freshwater layer will be influenced by the wind. Consequently, a river inflow from the eastern shores of the Kaipara Harbour is more likely to deposit sediment closer inshore than offshore due to the prevailing westerly wind.

At low tide, more than 43% of the area of the Kaipara Harbour comprises exposed sand- and mud-flats. On the ebb tide, the freshwater inflows follow deep channels through these intertidal flats (Figure 2-3), causing the open water mixing phase to occur well away from the point of freshwater discharge, and the sediment to be carried toward or out of the harbour entrance.

On the rising tide, the freshwater and fine sediment plumes will be forced back up the channels. The fine sediment will comprise a mixture of materials derived from all possible sediment sources. This means that theoretically it is possible for material from any source to be found at any location in the Kaipara Harbour.

However, because some sources are larger than others (Table 1-1), and the mixing of freshwater and estuarine water occurs in proportion to the size of the inflows, small river inflows are likely to be diluted below the level of discrimination of the CSSI technique, unless sampling coincided with a flood event. Tidal flow, localised circulation patterns and prolonged wind stress from one direction will also strongly influence the fate of sediment.

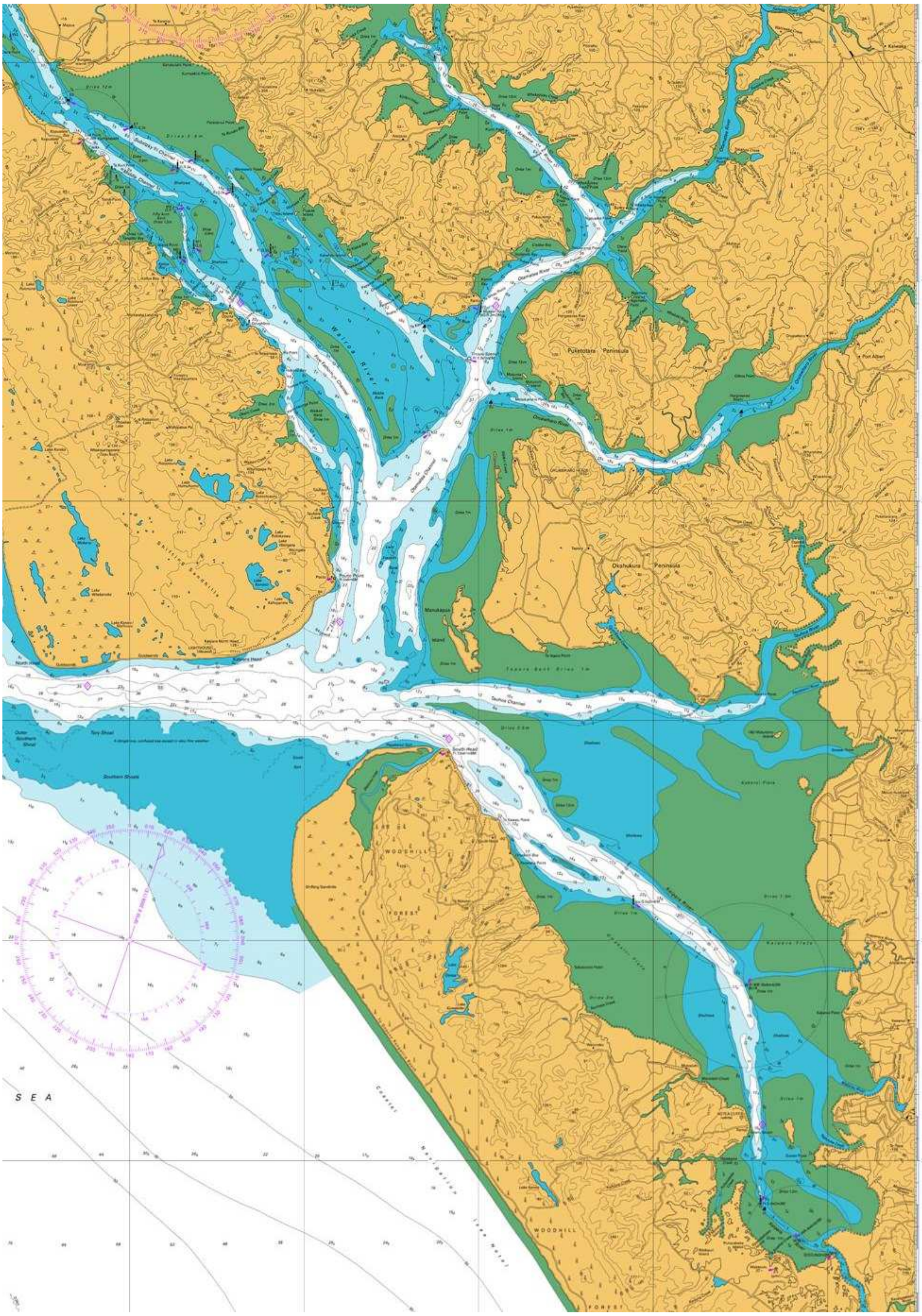

Figure 2-3: Bathymetric chart of the Kaipara Harbour. The deeply incised channels are shown in white between the intertidal mud- and sand-flats (green). Permanent water is shown in shades of blue. (Bathymetric chart from Land Information New Zealand (LINZ) Chart No. NZ4265).

3 Results

In the following figures, modelled results are presented as contour plots to identify large-scale spatial distribution patterns in the Kaipara Harbour. The distribution patterns are indicative not absolute.

3.1 Bulk nitrogen and carbon

The bulk N and C content of the sediment was extremely low with means of 0.07% and 0.6% respectively. The %C data (Figure 3-1) show very low organic carbon content through the main body of the Kaipara Harbour extending from the Wairoa River inflow in the north almost as far south as the Kaipara River. These low %C values suggest substantial reworking of sediments over time in processes involving microbial, bioturbation and wave and tidal action. Higher %C concentrations close to each river inflow (and especially in the narrow estuarine arms in the northern Kaipara) indicate more recent input of organically enriched sediment from those catchments (Figure 3-1). This pattern is consistent with the presence of fine mud which has recently settled near the river inflows during the high water stage of the tide (Figure 3-2).

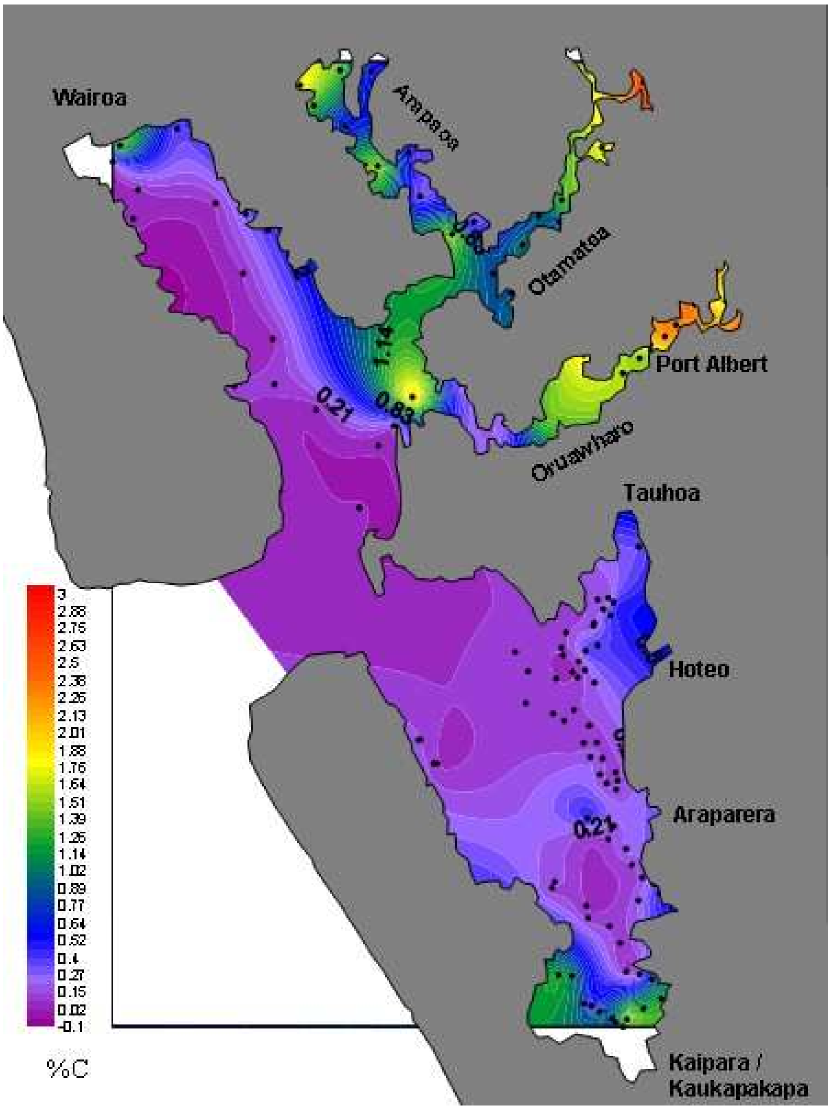

Figure 3-1: Carbon (%C) spatial distribution.

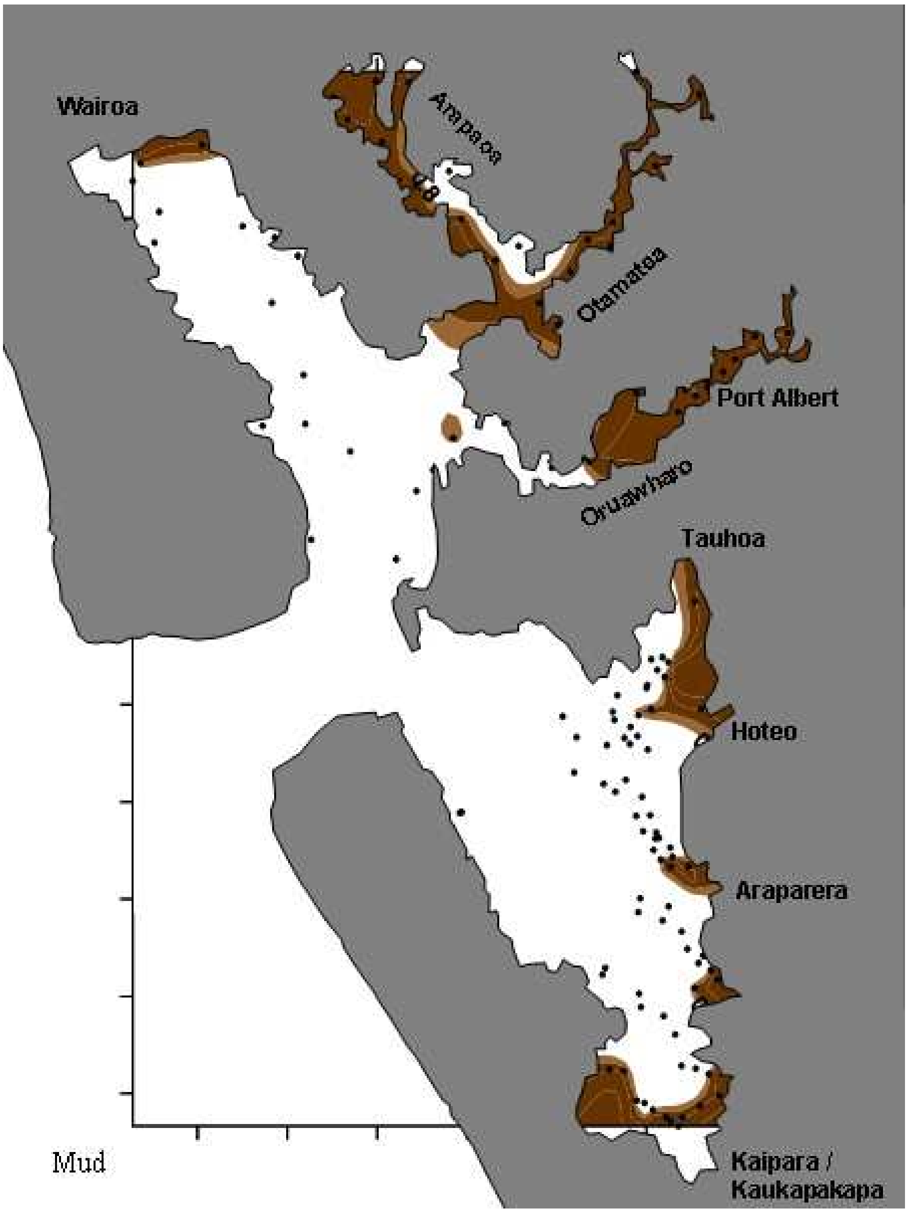

Figure 3-2: Spatial distribution of fine mud. These qualitative data are based on the texture of the sediment samples collected when sieved. Arbitrary scale: dark is high, pale is low and white is sand. The limited number of samples, especially near the river mouths in the southern Kaipara Harbour, means that the distribution pattern is not complete and not mapped.

The very low organic C content of the sediment at the mouth of the Wairoa River (mid-channel sandbar) contrasts strongly with the higher organic C found near the mouths of other river inflows. A possible explanation is that much of the sediment at the mouth of the Wairoa River may be from older sediment eroded from the banks and bed in the lower reaches of the river/estuarine channel. It is also consistent with recent, more organically enriched sediment being deposited further upstream and subsequently being biologically processed within the river/estuarine channel before it reaches the Kaipara Harbour.

A localised area of higher %C near the mouth of the Wairoa River is associated with two small streams draining low-lying farmland behind the mangrove forest at the head of the harbour (Figure 3-3), but may also include recent sediment derived from the Wairoa River.

Figure 3-3: Northern end of Kaipara Harbour. One of two streams draining low-lying farmland behind the mangrove forest at the northern end of the Kaipara Harbour. Pale areas in the mid-regions of the farm land were bare cultivated land. The Wairoa River at top left flows toward the reader.

While the high %C data (Figure 3-1) shows where new carbon is entering the Kaipara Harbour, the bulk $\delta^{13}C$ (Figure 3-4) and $\delta^{15}N$ (Figure 3-5) values of the sediments show the degree of natural abundance enrichment, which indicates the likely source of sediment (refer to section 2.2 for an explanation of stable isotopes). In general, marine sediment $\delta^{13}C$ values are typically around -20‰ to -22‰, pasture grasses around -24‰ to -26‰, and forests around -28‰ to -40‰. Bulk $\delta^{13}C$ values more enriched than -20‰ are typically associated with waste water, including runoff from dairy farming. The main body of the Kaipara Harbour has $\delta^{13}C$ values of -19‰ to -18‰ suggesting sediment input from terrigenous sources rather than from purely marine sources. The signature indicating enrichment is also found along the shoreline around the Hoteo and Araparera Rivers (Figure 3-4) and may be associated with land drainage and the development of dairy farms on the low-land farms along this area of the eastern shores of the southern Kaipara Harbour (Figure 3-6).

In contrast, the sediments in the Arapaoa, Otamatea and Oruawharo River channels in the northern Kaipara, as well as around the Tauhoa and the Kaipara Rivers in the southern Kaipara, have $\delta^{13}C$ values of -23‰ to -24‰, consistent with accumulation of sediment from rolling pasture used for sheep and beef farming, and less intensive dairy farming. At the head of the Otamatea and Oruawharo River channels, highly depleted $\delta^{13}C$ values of -25‰ to -28‰ indicate runoff from forestry, consistent with the production forestry landuse on the high country to the east of these rivers. There are also blocks of pine forest behind the mangrove forest at the head of the northern Kaipara Harbour and along the eastern shores, which may have contributed to the relatively more depleted $\delta^{13}C$ values in that location.

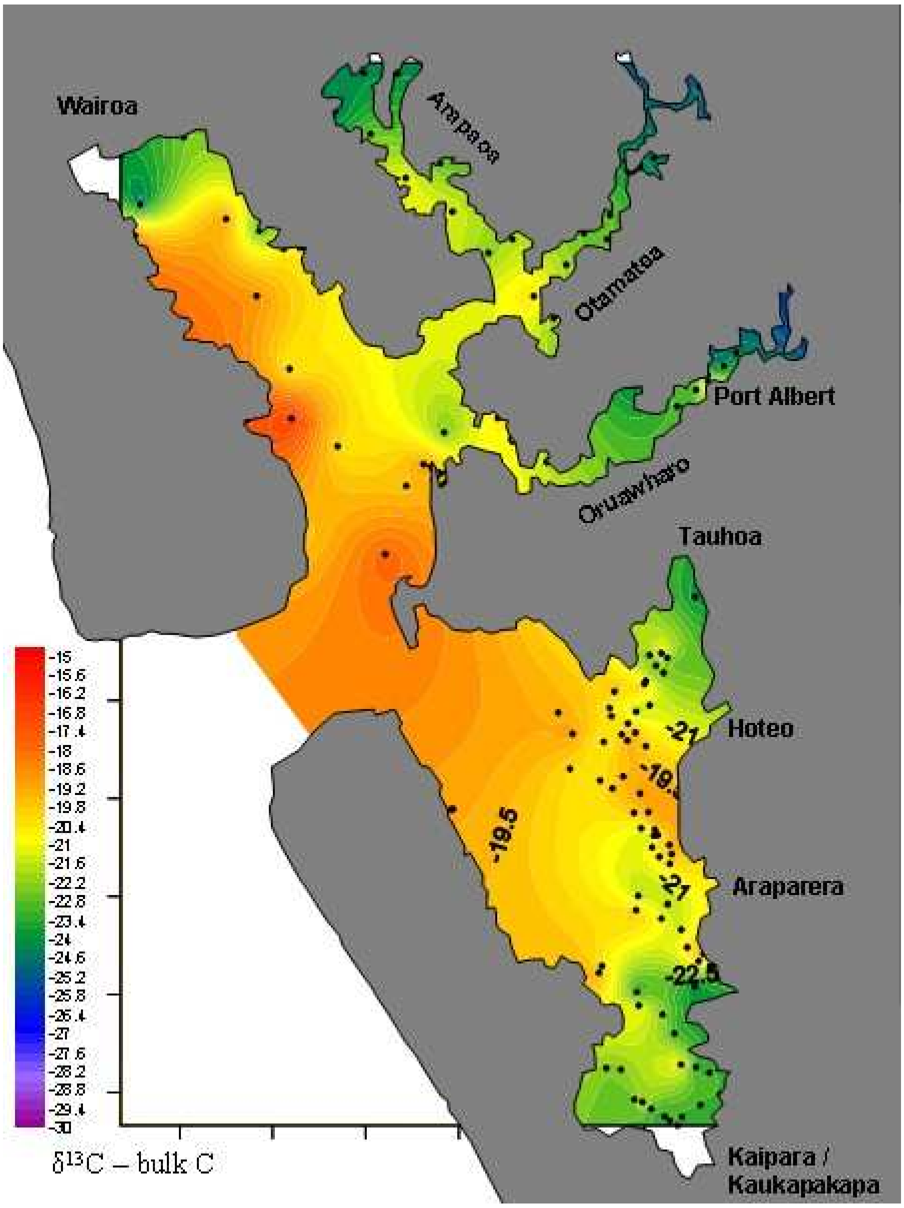

Figure 3-4: Bulk δ^{13}C spatial distribution.

As with the bulk δ^{13}C values, bulk δ^{15}N values also provide information regarding the landuse in the catchment. However, because N can be reprocessed via decomposition in the sediments and subsequently by nitrifying and denitrifying bacteria at the sediment—water interface, δ^{15}N values experience additional isotopic fractionation after deposition and cannot be used to identify sources. The use of synthetic fertilizers such as urea can result in very depleted δ^{15}N values (<0‰) but there is little indication of the use of this fertilizer in the Kaipara Harbour sediments. In general, natural abundance δ^{15}N values would be expected to be around 4‰; enrichment associated with decomposition processes are likely to produce δ^{15}N values >5‰. The spatial distribution plot shows large areas of the Kaipara Harbour with δ^{15}N values of >6‰ (Figure 3-5), especially around the Kaipara / Kaukapakapa, Araparera and Hoteo Rivers in the southern Kaipara and throughout most of the northern Kaipara including the narrow river channels. This distribution pattern is consistent with sediment being derived from agricultural / farm land, as indicated by the bulk δ^{13}C values (Figure 3-4).

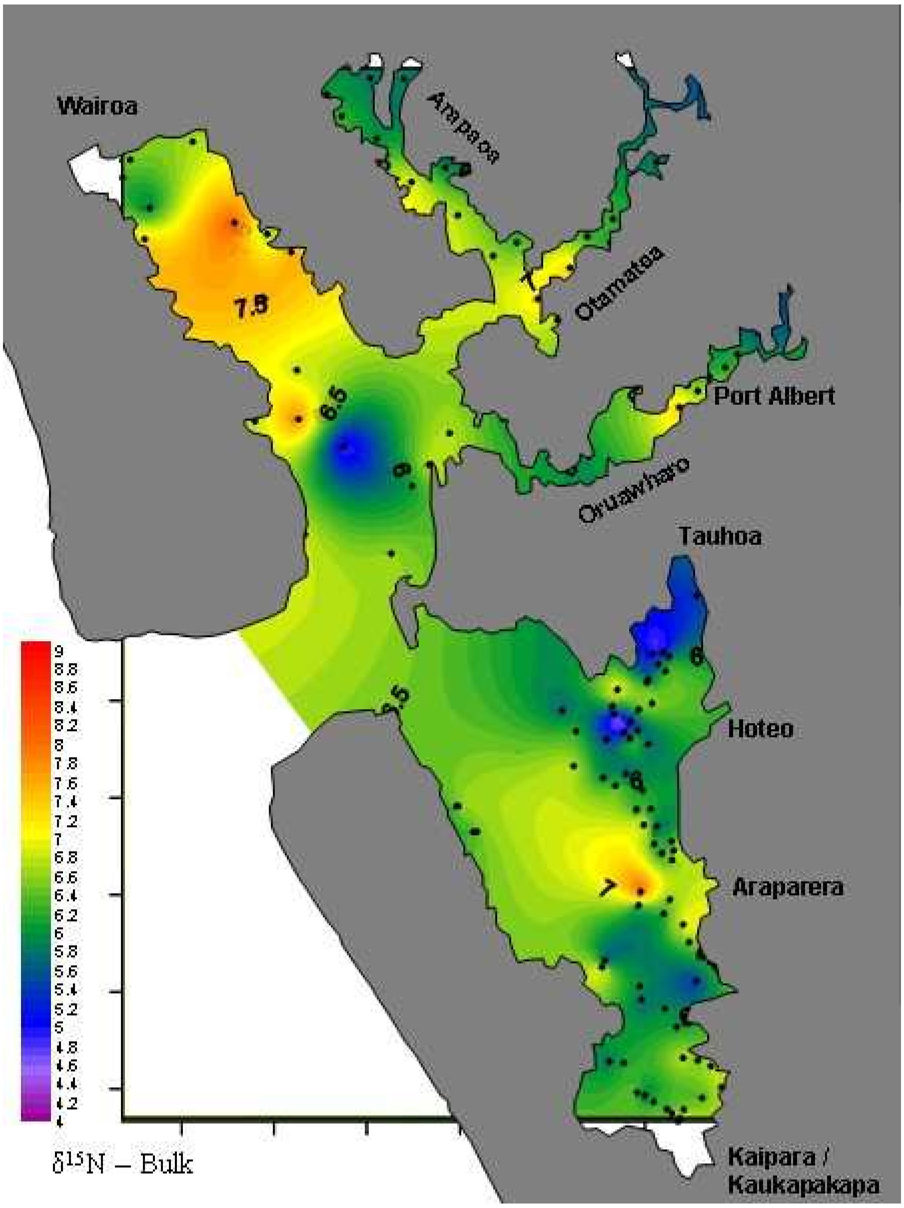

Figure 3-5: Bulk δ^{15}N spatial distribution.

Figure 3-6: Drainage and dairy intensification. This low-land farm adjacent to the Hoteo River is one of several on the eastern shores of the southern Kaipara Harbour.

3.2 Compound-specific stable isotopes (CSSI)

Whereas the bulk C and N stable isotope signatures provide an indication of likely sediment sources according to landuse type, the CSSI signatures of the fatty acids attached to the sediment particles provide an unambiguous link to each source (refer to section 2.2 for details). The CSSI technique provides estimates of the proportion of soil contributed by specified sources at each location, enabling the dispersion of sediment from each source to be mapped spatially across the whole Kaipara Harbour.

The major sediment sources mapped using this technique were the Wairoa, Arapaoa and Otamatea Rivers in the northern Kaipara, and the Hoteo and Kaipara/Kaukapakapa Rivers in the southern Kaipara Harbour. The similarity between the Otamatea and Oruawharo Rivers, and the Araparera and Kaipara/Kaukapakapa Rivers in the preliminary modelling results suggest that the sediment in the minor rivers i.e., the Oruawharo and Araparera Rivers, was from very similar landuse to the major river. Without more detailed sampling, it is not possible to distinguish between sediment derived from these pairs of sources. Consequently, only the major inflow of the paired source has been mapped in this report.

3.2.1 Wairoa River

The estimated mean annual flow and mean annual flood flow in the Wairoa River at Ruawai is 88.5 m^3 s^{-1} and about 3700 m^3 s^{-1}, respectively (Table 1-1). The spatial distribution of sediment from the Wairoa River encompasses almost the entire Kaipara Harbour (Figure 3-7). While high proportions of Wairoa sediment in the main northern Kaipara were expected, the presence of Wairoa sediments (Figure 3-7) in the Arapaoa, Otamatea and Oruawharo River arms as well as in the southern Kaipara Harbour, shows that fine sediments from the Wairoa catchment are being widely dispersed.

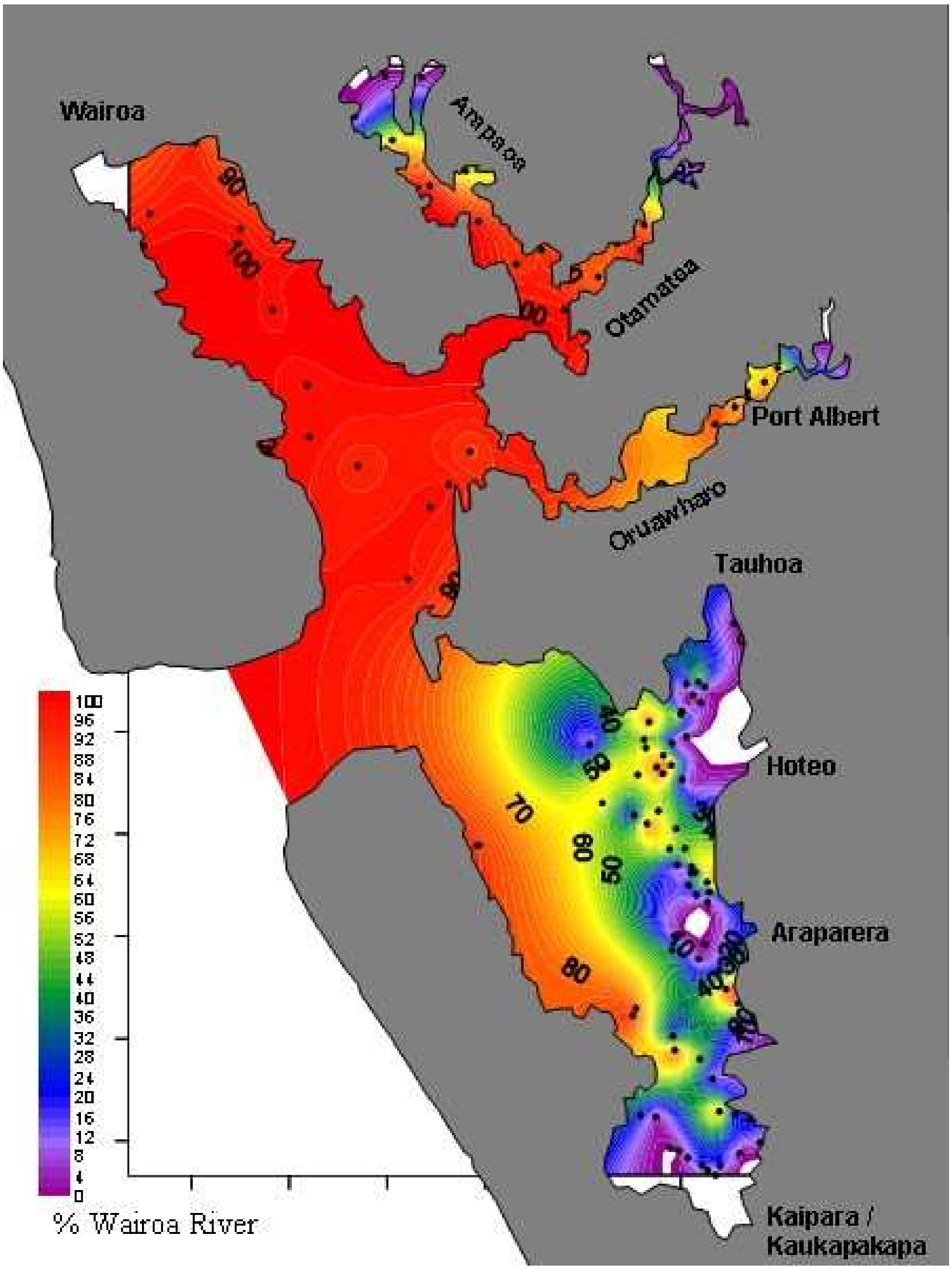

Figure 3-7: Dispersion of sediment derived from the Wairoa River across the Kaipara Harbour. The pattern is indicative rather than absolute and is subject to the plotting software package interpolation between the limited number of data points. Uncertainty is typically < ± 5% on each sample point.

A closer look at the dispersion of Wairoa sediment in the Arapaoa River channel indicates that Wairoa sediment tends to settle along the western side of this inlet with higher proportions of Arapaoa River sediment along the eastern side and in the eastern embayments. This pattern may be due to Wairoa River sediment being mixed throughout the water advected into the river channel on the rising tide, with the new sediment in the Arapaoa River water being initially confined to the surface low-salinity buoyant layer which can be held against the eastern shores by the prevailing westerly winds. This would cause a bias in sedimentation of material from the Arapaoa River towards the eastern side of the river channel as indicated by the CSSI data. This pattern of sedimentation is based on 10 samples and thus has high uncertainty.

A similar effect may be occurring in the southern Kaipara where, again, Wairoa sediment occurs mainly on the western side of the harbour, while sediment from the main southern river inflows is more likely to deposit along the eastern shores. The intrusion of Wairoa sediment into the southern Kaipara is probably enhanced by the bathymetry of the harbour, with a deep channel extending from the harbour entrance to Shelly Beach (Figure 2-3). This would favour rapid advection up-harbour (i.e., to the south) of the sediment-rich water derived from the harbour entrance on the rising tide, before overtopping of the intertidal flats allows water to spread east. However, unlike in the northern Kaipara where the deep channels may have guided Wairoa sediments into the narrow side arms, Wairoa sediments do not appear as a major component along the deep channel near the Hoteo River inflow. This is consistent with the freshwater surface layer being held into that corner of the harbour by the prevailing westerly wind.

Wairoa sediments did not reach the head of each river channel and the sediment in these areas was dominated by mud (Figure 3-2) derived from the local river inflows. The mud was particularly obvious when sampling, although relatively few samples were collected in the river mouths.

These data suggest a high degree of fine-sediment connectivity between the northern and southern basins of the Kaipara Harbour. A primary mechanism for sediment delivery from the Wairoa River in the northern harbour to the southern harbour is likely to be tidal transport of silt plumes into both basins of the harbour over successive ebb and flood tides, modified by prevailing wind flows.

3.2.2 Arapaoa River

The estimated mean annual flow and mean annual flood flow in the Arapaoa River system is 2.5 m^3 s^{-1} and about 50 m^3 s^{-1}, respectively. Sediment from the Arapaoa River tends to spread along the eastern side of the northern harbour, extending into the Otamatea River channel (Figure 3-8). Although the spatial pattern indicates a high proportion of Arapaoa River sediment in the headwaters of the Otamatea River, this is probably a reflection of the similarity between these two sources. A point to note is that sediment from the Arapaoa River was not detected above the 5% threshold on intertidal flats in the main harbour or in the Oruawharo River arm. This most likely reflects the relatively small contribution of sediments from this source and dilution of sediment in the main body of the harbour. Although the sediment will be present, it will be there at very low proportions. This dispersion pattern is also consistent with the mud distribution patterns (Figure 3-2).

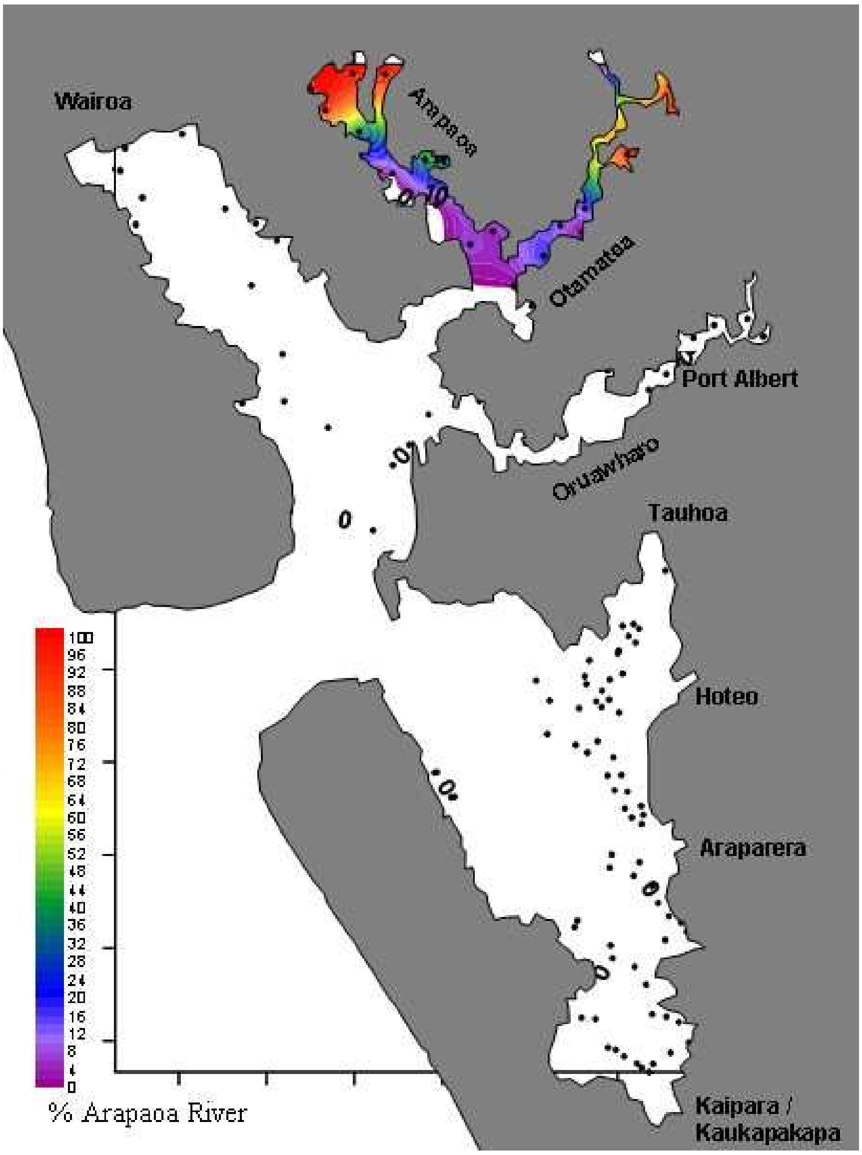

Figure 3-8: Dispersion of sediment derived from the Arapaoa River within the Kaipara Harbour. The pattern is indicative rather than absolute and is subject to the plotting software package interpolation between the limited number of data points. Uncertainty is typically <±5% on each sample point.

3.2.3 Otamatea River

The estimated mean annual flow and mean annual flood flow in the Otamatea River system is 0.65 $m^3 s^{-1}$ and about 40 $m^3 s^{-1}$, respectively. Sediment from the Otamatea River was confined mostly to the Otamatea and Oruawharo River channels with a small possibility of some entering the Arapaoa River channel (Figure 3-9). The apparent dispersion of the Otamatea River sediment into the Arapaoa River channel is analogous to dispersion of the Arapaoa sediment into the Otamatea channel. This may reflect the similar landuse in the headwaters of these three rivers. Consequently, it is most likely that the sediment deposited around the mouths of these inflows was derived from their respective upstream catchments.

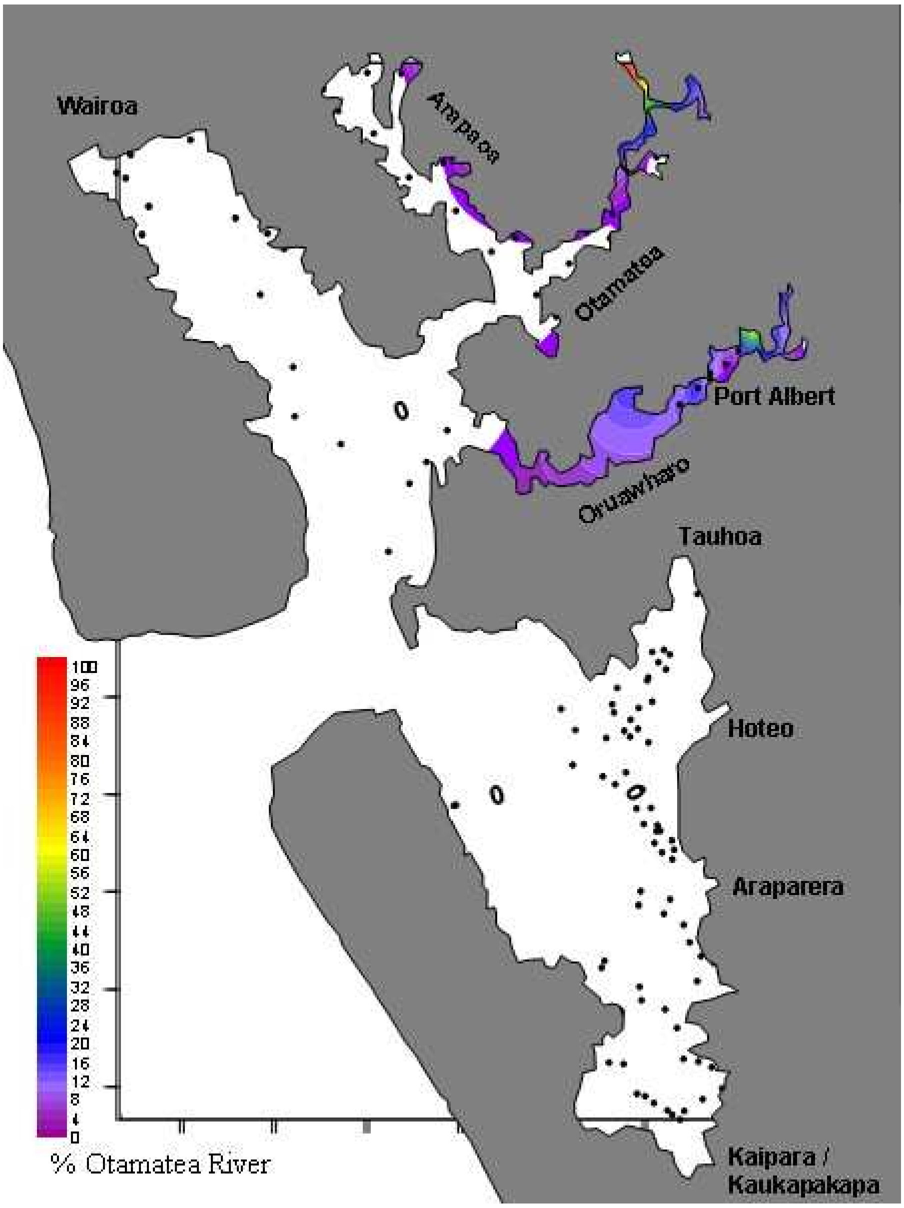

Figure 3-9: Dispersion of sediment derived from the Otamatea River within the Kaipara Harbour. The pattern is indicative rather than absolute and is subject to the plotting software package interpolation between the limited number of data points. Uncertainty is typically <±5% on each sample point.

3.2.4 Hoteo River

The estimated mean annual flow and mean annual flood flow in the Hoteo River system is 8.2 $m^3 s^{-1}$ and about 140 $m^3 s^{-1}$, respectively. In contrast to the river flows in the northern Kaipara side arms, the Hoteo River has a larger flow and higher sediment load. This is reflected by both the spatial distribution of mud (Figure 3-2) and the CSSI sediment distribution pattern (Figure 3-10). The dispersion pattern of sediment from the Hoteo River extends north and south across the eastern sandflats of the southern harbour. Although there is a single data point anomaly (with higher proportions of Hoteo River sediment further offshore from the river mouth), the general pattern is consistent with the channelization of the river water between the local sand banks on the ebb tide (e.g., Figure 2-3), and subsequent deposition in the slower flow further off shore (see assumptions, section 2.4). It is also likely that some sediment from the Hoteo River leaves the harbour on the ebb tide.

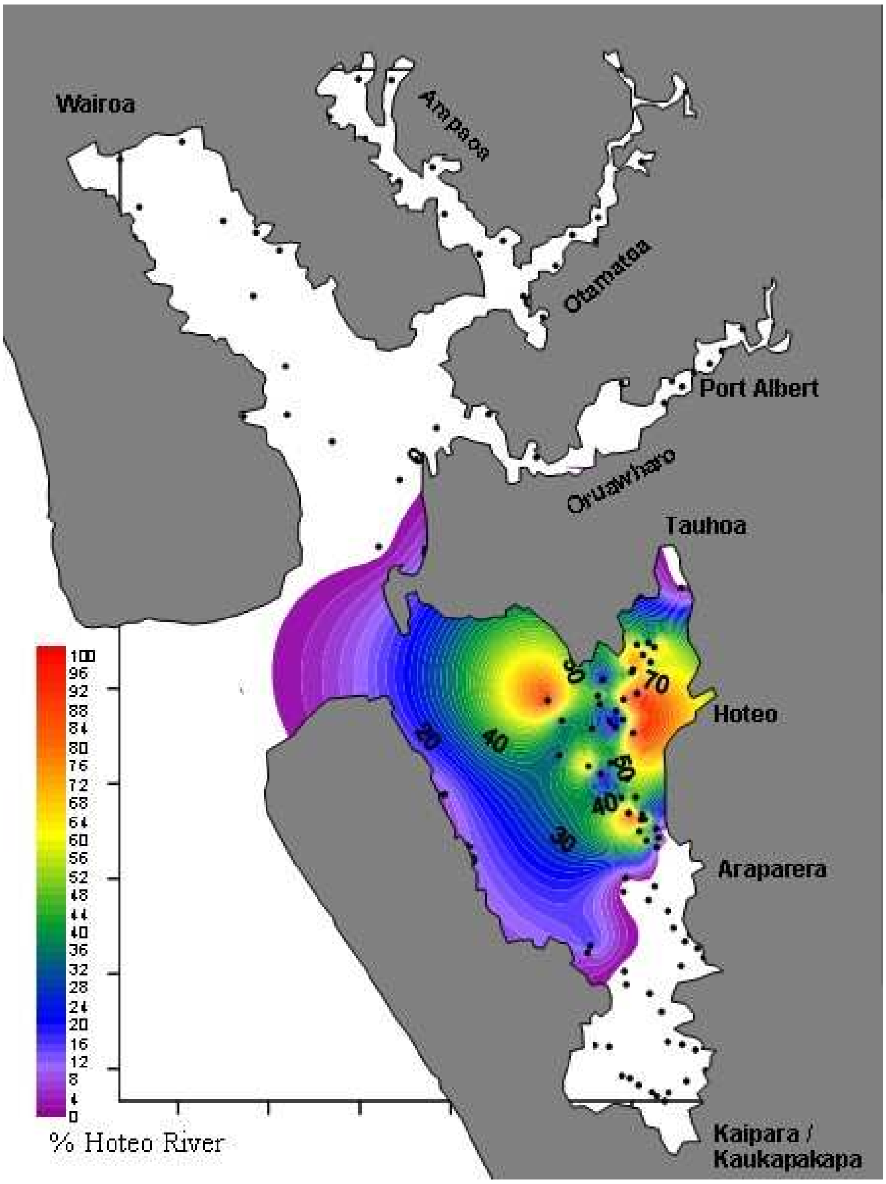

Figure 3-10: Dispersion of sediment derived from the Hoteo River across the Kaipara Harbour. The pattern is indicative rather than absolute and is subject to the plotting software package interpolation between the limited number of data points. Uncertainty is typically <±5% on each sample point.

Aerial photos taken after a flood event (22nd March 2011) show a sediment plume dispersing widely from the Hoteo River (Figure 3-11). The leading edge of the plume appears to be being held up by the outflow of water from further up harbour on the ebb tide.

Figure 3-11: Plume of silt-laden flood water dispersing widely from the Hoteo River mouth on the ebb tide, 22nd March 2011, at 2:40 pm. **Upper photo** looking northwest towards the entrance to the Kaipara Harbour; **Lower photo** looking northeast across the southern Kaipara Harbour to the Hoteo River mouth. (Photos: Mark Pritchard, NIWA).

3.2.5 Kaipara and Kaukapakapa River system

The estimated mean annual flow and mean annual flood flow in the Kaipara River is 4.8 $m^3 s^{-1}$ and about 90 $m^3 s^{-1}$, respectively. The estimated mean annual flow and mean annual flood flow in the Kaukapakapa River is 2.4 $m^3 s^{-1}$ and about 70 $m^3 s^{-1}$, respectively. Together, this river system is the main local river source of sediment to the southern Kaipara Harbour (Figure 3-12). The dispersion pattern indicates that Kaipara / Kaukapakapa sediment extends north up the harbour towards the harbour mouth. However, the pattern also suggests that sediment from this river system is generally deposited close to source on the intertidal flats within the southern Kaipara.

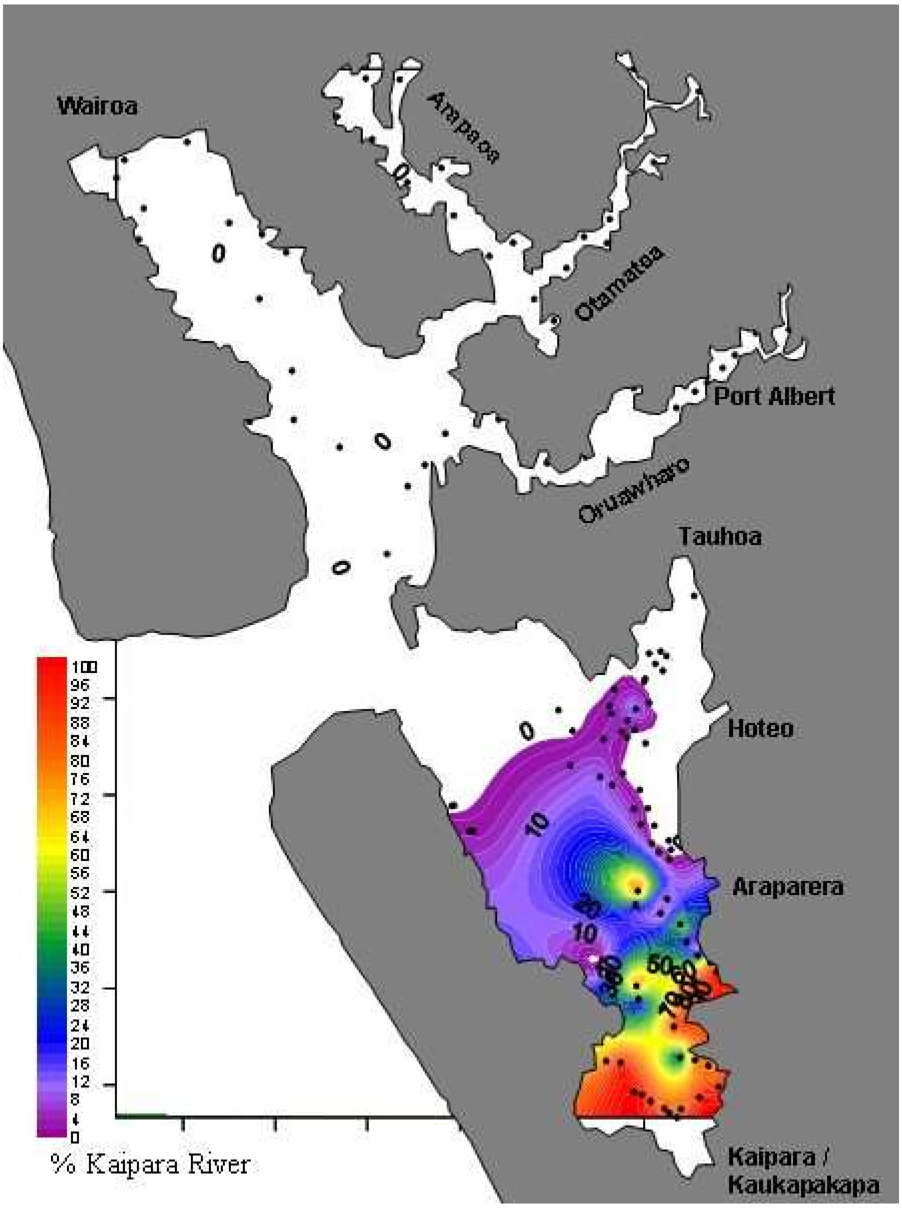

Figure 3-12: Dispersion of sediment derived from the Kaipara and Kaukapakapa River system across the Kaipara Harbour. The pattern is indicative rather than absolute and is subject to the plotting software package interpolation between the limited number of data points. Uncertainty is typically <±5% on each sample point.

4 Conclusions

Kaipara Harbour is a large and complex system. Freshwater inflows are minor compared to the tidal prism. Reworking of the harbour floor by tidal currents and wave action has winnowed and removed fines, leaving extensive sandy intertidal flats. As fines are normally associated with organic carbon, this process gradually depletes the carbon available as “food’ in the harbour.

River inflows are important, replenishing the stock of carbon that supports the diverse communities in the harbour. However, as landuse changes and soil erosion increases, the proportion of organic matter in the sediment decreases and the inorganic components impact on the benthic biota and seagrass communities by smothering and, especially for filter feeders, by interfering with feeding. Elevated levels of fine sediment occlude light and reduce the growth of both benthic and pelagic algae.

The CSSI technique has been used to map spatial patterns of sediment dispersal across the harbour from major river sources.

Sediment discharged from the Hoteo River spreads both north and south from the river mouth (Figure 3-10), possibly driven by currents forced by winds from the southwest (currents flow to the north) and the northwest (currents flow to the south). Flow data (Table 1-1) show that the majority of the sediment discharged by the Hoteo River is delivered to the harbour by flood flows rather than by the mean annual flow.

Sediment discharged from the Kaipara / Kaukapakapa River disperses across the intertidal flats in the southern part of the harbour (Figure 3-12). Buoyant freshwater plumes may reach the middle of the southern harbour on an ebb tide, to be pushed back to the south by the next flood tide. Westerly winds could account for the dispersion of sediment along the eastern side of the harbour beyond Shelly Beach headland.

Sediment discharged from the Wairoa River spreads across both the northern and southern basins of the harbour (Figure 3-7). Such widespread dispersal is likely to be related to the relatively large freshwater discharge from the Wairoa (mean annual flow more than 10 times greater and mean annual flood flows 20 to 40 times greater than the combined Kaipara / Kaukapakapa River [Table 1-1]).

Heath (1976b) estimated the residence time of water in the Kaipara Harbour as five tidal cycles or 2.6 days. This is consistent with the depletion of the %C content (Figure 3-1) and enrichment of the isotopic signatures for the bulk $\delta^{13}C$ of the sediment (Figure 3-4), both of which require time to allow biological processes to consume C and cause isotopic enrichment.

Sediments deposited at the mouths of the smaller streams on the eastern sides of the harbour and sediments discharged from the Kaipara / Kaukapakapa River have much higher %C content but more isotopically depleted bulk $\delta^{13}C$ values. This is consistent with the deposition of relatively new soil from the respective subcatchments, all of which contain pasture and forested land.

Where the Wairoa River opens into the wider harbour, %C is depleted and the bulk $\delta^{13}C$ values are enriched, indicating that considerable biological processing has occurred before sediment discharged from the Wairoa River reaches this point. This would most likely have occurred up-river, in the 30-km of stretch of water between Dargaville and the wider harbour.

5 Acknowledgments

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Appendix A Species distribution patterns

Observations made while sampling and recorded subsequently during sediment sample processing provided a coarse estimate of the spatial distribution of seagrass meadows and cockle beds, and the extent of Pacific oyster (*Crassostera gigas*) and Asian mussel (*Musculista senhousia*) invasion within the Kaipara Harbour. The sample site photos provided information regarding the presence of other species such as *Macomona liliana* beds, rocky reef communities, patches of red filamentous seaweeds, small polychaetes, large sand worms and areas where there were high numbers of snails such as *Zeacumantus lutulentus*. Much of this information has yet to be processed but photos showing examples of some of these occurrences are included in this appendix.

At best, this information should be regarded as evidence of presence of the species at a location, rather than their absence at other locations. For a more complete description of the benthic biodiversity in the Kaipara Harbour, refer to the detailed study of Hewitt & Funnell (2005) and water quality data reviews such as Hudson (2010).

Seagrass (*Zostera*)

Seagrass meadows were mostly found in the southern Kaipara Harbour although two small patches were located in the northern Kaipara (Figure A-1).

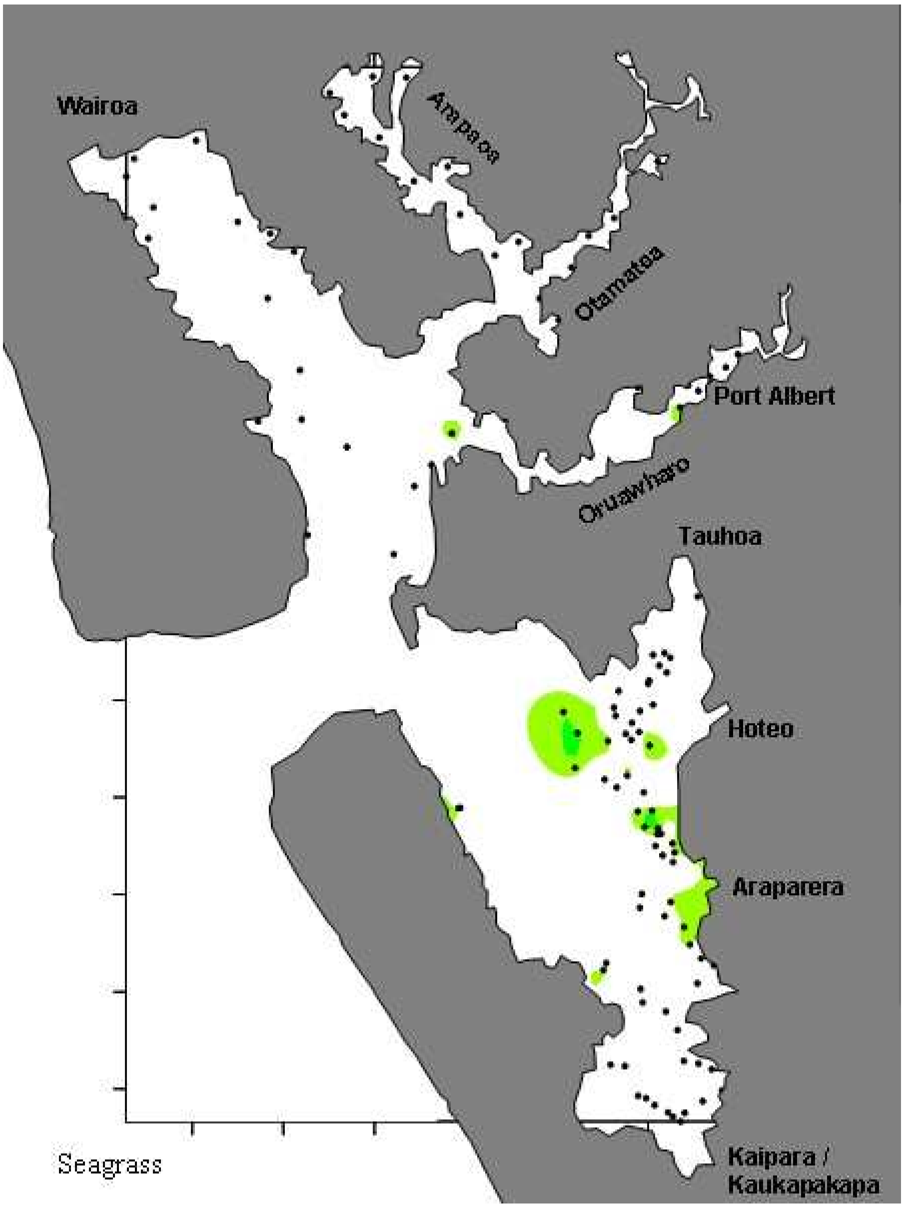

Figure A-1: Seagrass (*Zostera*) beds in the Kaipara Harbour. Large areas of seagrass were observed inshore to the Hoteo River mouth.

The seagrass meadows covered much of the sand flats between the Hoteo and Araparera Rivers and, at the time of sampling, these were being grazed by numerous black swan (Figure A-2).

Figure A-2: Seagrass meadows. These were located between the Hoteo and Araparera Rivers in December 2009. The seagrass was being grazed by numerous swan. [Photo: Luca Chiaroni, NIWA].

Closer to the Hoteo River, the healthy seagrass meadows had large areas coated with mud (Figure A-3, A) and further out on the sand flats the meadows ended where they had been buried beneath sandy mud (Figure A-3, B). This damage was attributed to recent (2009) storm events.

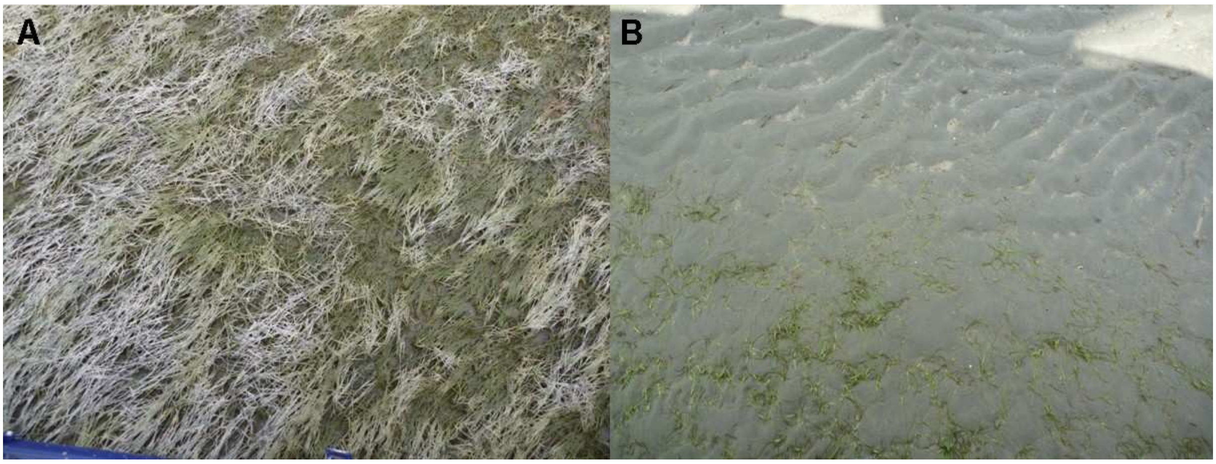

Figure A-3: (A) Seagrass near the Hoteo River coated with fine silty mud; (B) Seagrass buried beneath sandy mud suspended by wave action across the sand flats.

The two patches of seagrass in the northern Kaipara were small and in poor condition, as a result of being coated with fine silt or partially buried.

Cockles (*Austrovenus stutchburyi*)

Cockle beds were present throughout the Kaipara Harbour, often associated with seagrass beds in the southern Kaipara but also in sand flats in areas protected from wave action in the northern Kaipara (Figure A-4). Most of the cockles found were small and often occurred in large numbers in the seagrass meadows (Figure A-5). Cockle spat also were recovered from sieved mud at the head of the northern Kaipara side arms and from the large sand flats in the middle of the main northern Kaipara Harbour. These sand flats also had lots of pipi spat and possibly tuatua spat.

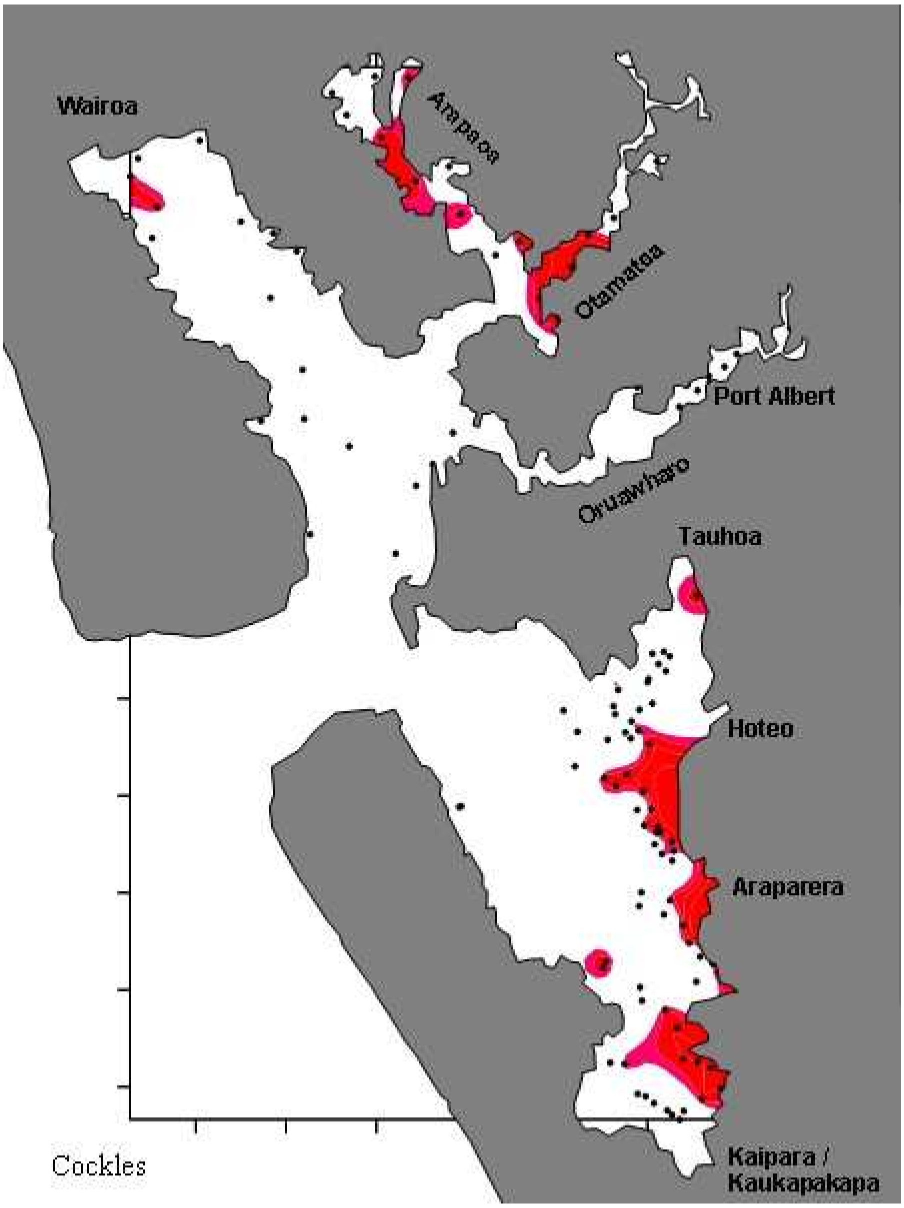

Figure A-4: Cockle (*Austrovenus stutchburyi*) distribution as identified by live cockles in the samples and at the sampling site.

Figure A-5: Cockles in seagrass meadows. Cockles tended to be highly abundant in the fringes of the seagrass meadows along with other gastropods and crabs. Generally these were small (1 to 2 cm across).

Pacific oyster (*Crassostera gigas*)

Photographic observations from the sampling flights (Figure 2-1) found no obvious areas of Pacific oyster in the southern Kaipara apart from the oyster farm adjacent to the Hoteo River sand flats, but indicated the presence of 'wild' oysters in the northern Kaipara (Figure A-6). The main areas of infestation were in the Arapaoa River channel, where oyster farming occurs (Figure A-7), and the soft muddy headwater areas of the northern Kaipara (Figure A-8). This distribution pattern is consistent with the results of a 2008 spatial survey (Kelly 2008).

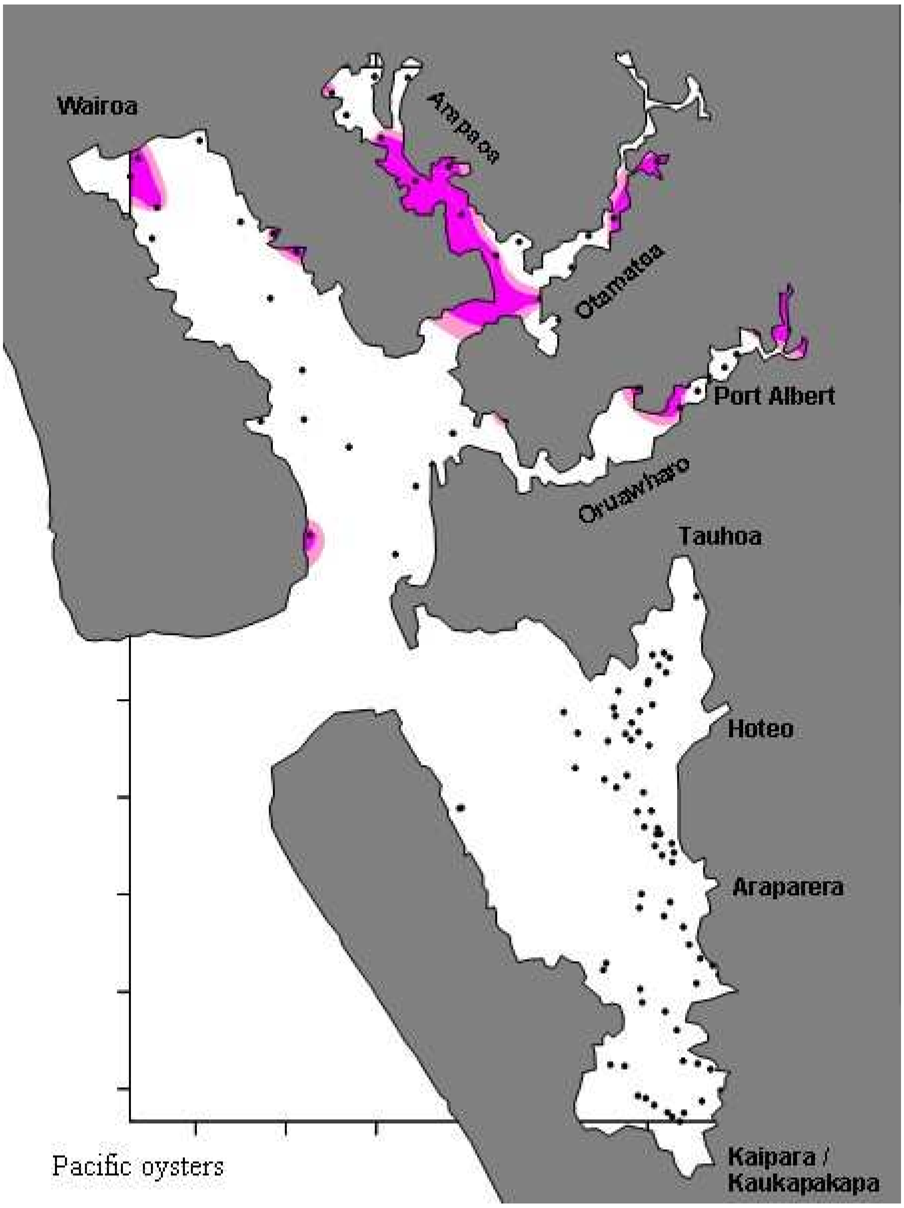

Figure A-6: Distribution of the wild population of Pacific oyster (*Crassostera gigas*) as observed from the sampling flights. The oyster farm in the southern Kaipara Harbour was not in the sampling sites and does not feature in this distribution plot.

Figure A-7: Oyster farming along the Arapaoa River channel.

Figure A-8: Reefs of wild Pacific oyster near the mouth of the Wairoa River.

Asian mussel (*Musculista senhousia*)

The presence of Asian mussel was only detected at the time of sampling when the mats prevented easy surficial sediment sampling. These mussels occurred in both the northern and southern Kaipara (Figure A-9) but mostly in the southern Kaipara.

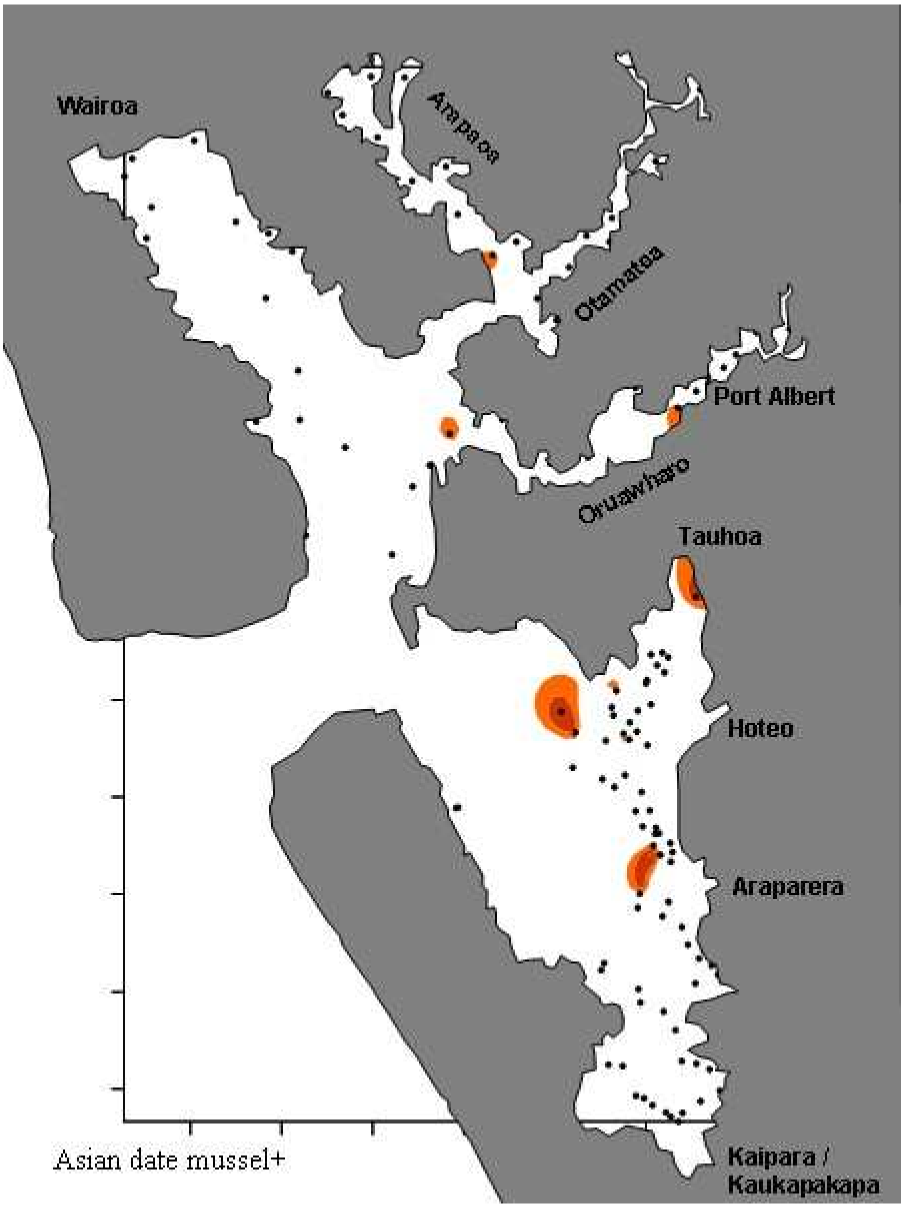

Figure A-9: Distribution of the wild population of Asian mussel (*Musculista senhousia*) as determined from the sediment samples.

Other species

The southern Kaipara had a broad range of species including many polychaetes (unidentified) and gastropods, including localised areas with high numbers of *Zeacumantus lutulentus* (Figure A-10) apparently feeding on fresh sediment. Small mud crabs were abundant in the headwater mudflats in both harbours and large unidentified worms occurred on the sandbars in the middle of the northern Kaipara (Figure A-11).

Figure A-10: Localised areas with high numbers of gastropods (*Zeacumantus lutulentus*).

Figure A-11: Unidentified mud worm deposits and gastropods on a sandbar in the middle of the northern Kaipara. The brown colour is recent sediment deposited from the Wairoa River.

Less obvious were the wedge clams, *Macomona liliana*. Their presence was detected from the characteristic “bird footprint” feeding tracks on the sediment surface (Figure A-12) and the occasional specimen in the sample. While this species is likely to be present in the northern Kaipara, it was only found at some sampling sites in the southern Kaipara.

Figure A-12: Characteristic feeding tracks of *Macomona liliana* on the sediment surface.

Seaweeds and algae

Plant species other than *Zostera* included a range of seaweeds which were attached to areas of Asian mussel and harder substrates in the southern Kaipara (e.g., Figure A-13). The sampling sites in the northern Kaipara did not coincide with areas of these macrophytes although the presence of subtidal macrophyte beds was obvious from the air in the narrow river channels.

Elsewhere in the Kaipara Harbour, algal mats (benthic microphytes) were found on the sediment surface. In the southern Kaipara these occurred on the mudflats between the Araparera and Kaipara River mouths (Figure A-14). In the affected areas, the benthic microphytes formed a thin layer on the soft mud and were apparent as a bright green colour contrasting with the grey-brown of the non-affected areas. The areas of benthic microphytes were adjacent to seepages from low-lying dairy farm land and the mud samples were smelly. In the northern Kaipara, filamentous algal mats were found on the mudflats in the Arapaoa River channel attached to mounds (Figure A-15).

Figure A-13: Red and brown filamentous seaweeds on hard substrates in the southern Kaipara.

Figure A-14: Algal growth on mud surface. These were associated with smelly areas adjacent to low-land dairy farming at the south end of the southern Kaipara Harbour.

Figure A-15: Filamentous algal mats. These mats were attached to hard substrates in the Arapaoa River channel.

Catchment features

Aerial views of the catchment indicate that much of the land is farmed, with dairy intensification evident in some low-land areas (e.g., Figure 3-6). The steeper land used for sheep and beef grazing often showed signs of erosion (Figure A-16). Very steep land was mostly in native forest or production pine forest with the latter also occurring at several locations close to the shoreline of the harbour (Figure A-17; Figure A-18). In one area a quarry appeared to be releasing sediment into the harbour (Figure A-19), although the linkage is not certain.

Figure A-16: (A) Sheep and (B) beef on steep land. Stock grazing on steep land was often associated with localised erosion.

Figure A-17: Exotic pine forest behind the fringing mangroves in the northern Kaipara Harbour.

Figure A-18: Infrastructure along the shoreline of the northern Kaipara Harbour. Unsealed roads, quarries and the loading facilities for the barge represent potential sources of localised sediment erosion.

Figure A-19: This quarry is on the shores of the southern Kaipara. While the quarry appears to be a local source of sediment adjacent to the harbour, the linkage is not certain.