Whangarei Harbour sedimentation

Sediment accumulation rates and present-day sediment sources

Prepared for Northland Regional Council

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Contents

Tables

Figures

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Executive summary

Northland Regional Council (NRC) commissioned NIWA to determine historical sediment accumulation rates (SAR) and contemporary sources of catchment sediments depositing in the Whangarei Harbour system. The results of this study will provide information to make informed management decisions, prioritise land management initiatives that reduce sediment erosion and runoff to estuaries. NRC is also working with the Whangarei District Council and the community to develop a catchment management plan, including objectives relating to sediment load limits, intended to protect and restore the Harbour environment.

This report provides information on sedimentation in the Whangarei Harbour system over the last~150 years derived from dated sediment cores as well as identifying contemporary sources of catchment sediments that are depositing in the harbour. Sediment accumulation rates are derived from lead-210 (^{210}Pb) and caesium-137 (^{137}Cs) dating of sediment cores. Information on present-day sediment sources is derived using a Compound Specific Stable Isotope (CSSI) sediment-source tracking method. The specific objectives of this study are:

- Quantify sediment accumulation rates based on radioisotope dating of sediment cores collected from nine sites in Whangarei Harbour.
- Identify contemporary sources of catchment sediments deposited in the harbour from CSSI analysis and modelling of catchment soils (sources) and harbour surficial sediment deposits.
- Interpret spatial patterns in historical SAR derived from cores and where possible relate to rates prior to catchment deforestation.
- Compare sedimentation rates in Whangarei Harbour with rates measured in other North Island estuaries.

Study area

Whangarei Harbour is a complex barrier-enclosed lagoon (lower harbour) and drowned-valley (upper harbour) estuary located on the north-east coast of the North Island. The harbour has a high-tide surface area of 104 km^2 and is relatively shallow due to extensive intertidal flats, which account for 58% of the high-tide area. The upper harbour is dominated by the sheltered tidal arms of the Mangapai and Hātea Rivers. The Onerahi Peninsula and Limestone Island form a natural constriction through which sediments transported by river plumes and tidal currents are exported to the lower harbour. Several bays indent the northern shoreline of the lower harbour, the largest of which is Parua Bay. The harbour receives runoff from a 295 km^2 land catchment, with 70% of the catchment discharging to the upper harbour west of Limestone Island.

Catchment landcover has been substantially modified as a result of deforestation. The indigenous forest was composed of broadleaf community dominated by tararire, puriri, kohekohe and kahikatea close to the harbour and river flats, with kauri and podocarps on steeplands. Today, indigenous forest accounts for about 20% of the total catchment area and occurs as isolated forest remnants and Pukenui forest, which borders the western boundary of Whangarei City. High producing exotic grassland, for cattle and dairy farming accounts for 50% of the total catchment area, with plantation forestry (10%) and urban areas (10%) being significant secondary land uses.

Sedimentation

The sources of soil from different land uses contributing to the sediment depositing in an estuary are not necessarily directly proportional to area of each land use in the catchment. Some land-use practices produce very little sediment while others may produce disproportionately large amounts. Consequently, sediment accumulation rates in the harbour provide an estimate of the amount of sediment that is being deposited per unit time but not its source. In order to determine where the soil is coming from, a forensic technique, comparing the compound-specific stable isotope (CSSI) signatures of organic compounds in the soil, is used.

The recent sedimentation history of the harbour was reconstructed from dated sediment cores collected from eight intertidal and one sub-tidal site. ^{210}Pb and ^{137}Cs dating have been used to determine time-averaged SAR. The approximate residence time of sediments in the surface-mixed layer (SML) of the seabed has also been evaluated at each core site using the maximum penetration depth of the short-lived berylium-7 (^{7}Be, half-life 53 days) and ^{210}Pb SAR. The interpretation of these data has been informed by the results of the sediment-transport modelling, sediment-source evaluation (described below) and the previous work of Millar (1980). The key results of the sediment core analysis are:

- The upper harbour has substantially infilled with eroded catchment soils. Mud is exported from the upper to the lower harbour where it has been accumulating in the bays and inlets that indent the northern shoreline.
- In the Mangapai arm, ^{210}Pb SAR have averaged 3–4.9 mm/yr over the last 40–100 years. Apparent declines in SAR during the early–mid 20th century are most likely due to reduced sediment delivery associated with a reduction in tidal inundation as the intertidal flats have accreted over time.
- In the Hātea arm, muds are accumulating on intertidal flats in the lee of the Onerahi Peninsula. ^{210}Pb SAR at core sites WHG-6 and WHG-14 were 2.8 and 6.5 mm/yr respectively. By contrast, long-term mud accumulation is not occurring on the intertidal flats west of Limestone Island most likely due to their exposure to 5 km+ east–west wave fetch.
- In Parua Bay, rapid vertical accretion of the intertidal flats occurred until the early 1950s when reduced tidal inundation sediment delivery. Today, the intertidal flat is accumulating sediment (2.9 mm/yr) at a similar rate to the central sub-tidal basin (2.2 mm/yr).
- The sediment-core record at Munro Bay (east of Parua Bay) suggests that mud exported from rivers discharging to the upper harbour began impacting habitats in the lower harbour in the mid-1950s. This also coincides with the development of the Port of Whangarei and the realignment of the Waiarohia Stream. At Munro Bay, mud has accumulated at a rate averaging 3.1 mm/yr since that time so that today a 15-cm-thick layer of mud has buried the previous shell-rich sand.
- The effects of catchment deforestation (mid-1800s–) on harbour-sedimentation rates has cannot be quantified. However, recent work in the Bay of Island's

system suggests a ten-fold increase in SAR following deforestation (Swales et al. 2012), as found in a number of North Island estuaries. The export of mud from infilled estuaries and deposition in environments remote from major river sources during the last century is also a feature of the Bay of Islands system.

- The average sediment accumulation rate in Whangarei harbour (^{210}Pb SAR of 3.4 mm/yr) within the range observed in other North Island estuaries (1.9–6.7 mm/yr) over the last century.

Catchment sediment yield

The long-term specific sediment yield from the ~220 km^2 upper-harbour catchment has been estimated from sedimentation data as 138 ±28 t/km^2/yr (30,400 ±6040 t/yr) over the last 50 years (1962–2012). This is within the range of values estimated by NIWA's WRENZ model for the major sub-catchments (60–355 t/km^2/yr). The total sediment mass retained in the upper harbour is estimated at 1.5 million tonnes (1962–2012). This assessment is complicated by the fact that 2.1 million tonnes (dry weight) of clay washings were discharged to the harbour from the Portland cement works, averaging 87,000 t/yr between 1958 and 1982 when discharges ceased. Evidence presented in the present study as well as the previous work of Millar (1980) suggest that a large fraction of the Portland clay washings were exported from the upper to the lower harbour and deposited.

This assessment suggests that the estimated specific sediment yield of 138 ±28 t/km^2/yr for the upper-harbour catchment includes a historical contribution from the Portland Cement Plant. Information on the clay mineralogy and/or stable-isotope (FAME) signatures of these dated cores would enable the relative contributions of Portland versus catchment fine-sediments to be determined.

Future sedimentation

The vertical accretion of the intertidal flats due to progressive sedimentation ultimately results in a reduction in sediment accumulation rates. This occurs due to reduced frequency and duration of tidal submergence so that sediment delivery declines. The short-period waves generated in fetch-limited estuaries, such as Whangarei Harbour, also become more effective at winnowing fine sediments from intertidal flats as water depth progressively declines due to sedimentation. Subtidal environments are continuously submerged so that sedimentation rates are primarily limited by sediment supply rather than sediment delivery.

Sedimentation rates on intertidal flats could increase in the future due to accelerated sea-level rise (SLR) depending on the rate of sediment-supply from land and marine sources. Rates of sea-level rise may reach up to about 9 mm/yr by the 2090s (MfE 2008). This represents a likely maximum SLR value at Whangarei Harbour, due to its relative tectonic stability, so that local SLR rates are not augmented by subsidence. There is substantial uncertainty in any estimates of future sediment supply rates as they are coupled with future climate change (e.g., rainfall, wind, storm intensity and duration).

Sediment sources

Contemporary sources of terrigenous sediments depositing in Whangarei Harbour were determined from analysis and modelling of the stable isotope signatures of Fatty Acid soil biomarkers. The results of this work indicate that:

- Sediments derived from the Hātea sub-catchment are the most widely dispersed and have accumulated in the upper and middle-reaches of Whangarei Harbour. The spatial distribution pattern indicates that sediment from the Hātea River system has also dispersed east along the northern shores beyond the Onerahi Peninsula.
- Sediments derived from Otaika and the Mangapai sub-catchments and Portland cement works have accumulated near these sources. It is notable that Portland sediments were present in the surficial sediments of Parua Bay and elsewhere in the middle reaches of the harbour in the late 1970s (Millar 1980). This indicates that these montmorillonite-clay rich sediments were more widely dispersed during the 74 years (1918–1982) that the cement plant discharged reject washings to the upper harbour. The present-day distribution of the Portland sediments reflects the large quantities of material deposited in the Mangapai arm close to the source.

Evaluation of surficial sediments deposited at the outlets of the major river sources enables the likely present-day contribution of various land uses to harbour sedimentation to be identified. The proportional soil contributions from the various land-use sources evaluated from the CSSI data are reported here to the nearest whole percent.

It should be noted that the analysis of the stable-isotope data show a substantial change in the sources of sediment deposited in the tidal reach of the Hātea River south of Mair Park. There are several potential reasons for this “isotopic disconnect” between the upper Hātea catchment soils and the harbour sediments: (1) The sediment-source modelling may not have included all potential sources, e.g., the harbour sediments Hātea-arm are likely to include “urban sediments” eroded during the development of the city; (2) historical sediment deposits are also likely to have been reworked and mixed with more recent sediments by dredging and reclamation works associated with the extensive port development that occurred from the 1950s onwards. These older sediment deposits are isotopically enriched relative to contemporary sediments. Therefore, this reworking of sediment deposits will result in a blended stable-isotope signature, a mixture of old and new. The data presented in this report suggests that upper-harbour sediments were exported to the lower harbour from the 1950s onwards. These exported sediments would have included reworked sediments with a blended stable-isotope signature from the tidal reach of the Hātea River. The results of the analysis of the Hātea River sediment sources are interpreted in line with these considerations.

The major sources of sediment by land use and sub-catchment have been evaluated for the Hātea, Otaika and Mangapai catchments. The results of this work indicate that:

- Sub soils derived from stream-bank erosion, gullying and slips are major sources of sediments deposited in stream beds and at river deltas in the upper harbour. Native forest and pasture are the other primary sources of sediment. The contributions from pasture and subsoil are likely to reflect bank erosion by stock direct access to streams rather than erosion from flat paddocks.

Hātea River

- Almost all (>90%) of the recent sediment in the Hātea River at Mair Park came from the catchment upstream of Tikipunga with <10% coming from the Otangarei Stream system and the steep forest land on the eastern side of the river. That sediment is composed of soils from pine forest (24%), pasture of all types (11%), pasture sub-soil (7%) and native forest including totara (59%). It should be noted that the soils under pasture that has recently been established following deforestation will retain the stable-isotope signature of the original forest for several years or more.
- Assessment of the sediment sources to the Hātea River Delta site showed that a maximum of 9% of these delta sediments came from the upper Hātea River. The Awaroa and Waioneone Creeks contributed up to 3%, Limeburners Creek contributed up to 31% and the Raumanga Stream system contributed up to 56%.
- The disproportionately low proportion of upper Hātea River sediment in the river delta sample is most likely due to the blending of stable-isotope signatures associated with the disturbance of delta sediment deposits resulting from the extensive dredging and reclamation works at the Port of Whangarei since the 1950s. The few mm of recent Hātea sediment would be diluted by this blended sediment in the 20-mm thick surficial sediment samples that were analysed.
- In the Raumanga Stream, most (90%) of the stream sediment were composed of sub-soils most likely derived from bank erosion and slips in the Maunu Road tributary. This source potentially includes the Waiarohia Stream although the latter was not sampled. The main Raumanga Stream contributed up to 5% as subsoil with up to 4% native forest including totara. Pasture signature was present but at <1 %.
- In Limeburners Creek up to 90% of steam sediments was composed of subsoil of the type found along the Maunu Road tributary (45%) and the main Raumanga Stream (44%) with up to 10% as native forest including Totara.

Otaika River

- The Otaika River delta receives sediment from the main Otaika River system (80%) and the Puwera Stream system (20%). Modelling of the CSSI data shows that 65% of the sediment comes from the upper catchment (above the Puwera Stream confluence), including the Otakaranga Stream catchment and the Otaika Valley streams. The remaining sediment is contributed from pasture (25%) and native forest (8%) from the steeper northern hills.
- The Otaika Valley river catchment above the confluence with the Otakaranga Stream produces 12% of the upper catchment sediment, mostly from pasture with an underlying native forest (totara) signature. The Otakaranga Stream catchment contributes 86% of the sediment. The Otakaranga Stream sediment is composed of sediments eroded from pasture (11%), bank erosion (19%) and

native-forest soils (69%). The large native-forest soil contribution most likely reflects the relatively recent clearing of native forest and conversion to pasture.

Deconstruction of the Puwera Stream sediment sources showed that 94% were subsoils which may have been derived from bank erosion or recent slips. There was a small proportion of pine (4%) and traces of pasture and native forest soils present.

Mangapai River

- Sediment in the Mangapai River delta was collected at core site WHG-1. The catchment sediment source contributions were evaluated using the land-use soil (stable-isotope) signatures. The results indicate that around 75% of the sediment was derived from bank erosion, which includes dirt roads and road cuttings. The rest of the sediment came from pine forestry (10%), pasture (7%) and native forest (8%).

1 Introduction

1.1 Background

The Northland Regional Council (NRC) commissioned NIWA to determine historical rates of sediment accumulation and contemporary sources of catchment sediments depositing in the Whangarei Harbour system.

The results of this study will provide resource planners, politicians and the public with valuable information regarding sediment accumulation rates (SAR) and the present-day sources of sediment accumulating in the Whangarei Harbour system. This together with previous studies of sedimentation in the Kaipara Harbour and the Bay of Islands system will help NRC to make informed management decisions on activities that contribute to sediment erosion and prioritise land management initiatives to reduce sediment erosion and runoff to estuaries. In addition, NRC is working with the Whangarei District Council and the community to develop a catchment management plan for the Whangarei Harbour. The information from this report will be valuable for the development of water management objectives, limits, and targets for the harbour catchment.

Globally, the increased loading of fine terrigenous sediments is recognised as a threat to estuarine and coastal marine ecosystems. Although terrigenous sediment input and deposition in these receiving environments is a natural process, the rate at which this is now occurring is higher than before human activities disturbed the natural land cover (Thrush et al. 2004). In New Zealand, increases in sediment loads to estuaries and coastal ecosystems coincide with large-scale deforestation, which followed the arrival of people about 700 years ago (Wilmshurst et al. 2008).

1.2 Study objectives

This report provides information on sediment accumulation rates (SAR) in the Whangarei Harbour system over the last~150 years as well as identifying present-day sources of catchment sediments that are depositing in the harbour. The SAR are derived from lead-210 (^{210}Pb) and caesium-137 (^{137}Cs) dating of sediment cores. Information on present-day sediment sources is derived using the Compound Specific Stable Isotope (CSSI) sediment-source tracking method. Both of these methods are described in detail in the Appendices.

The specific objectives of the study are:

- Undertake radioisotope dating of sediment cores collected from nine sites in Whangarei Harbour.
- Determine sediment accumulation rates from the dated cores.
- Identify contemporary sources of catchment sediments deposited in the harbour from CSSI analysis and modelling of catchment soils (sources) and harbour surficial sediment deposits.
- Interpret spatial patterns in historical SAR derived from cores and where possible relate to rates prior to catchment deforestation.
- Relate sedimentation rates to historical land use change and practices.

- Compare historical SAR in Whangarei Harbour with rates measured in other North Island estuaries.

1.3 Recent sedimentation in NZ estuaries and coastal marine environments

Sediments deposited in estuaries and coastal marine areas can provide detailed information about how these receiving environments have changed over time, which include the effects of human activities on the land. In New Zealand, major changes have occurred in estuaries and coastal ecosystems over the last several hundred years due to large-scale removal of native forests by people. This deforestation began shortly after initial colonisation by Polynesians in ~1300 A.D. (Wilmshurst et al. 2008) and accelerated following the arrival of European settlers in the early–mid 1800s. Forest clearance associated with slash and burn agriculture by early Māori, and subsequent timber extraction, mining and land conversion to pastoral agriculture by European settlers triggered large increases in fine-sediment loads from catchments. During the peak period of deforestation in the mid-1800s to early 1900s, sediment loads increased by a factor of ten or more. In many estuaries, this influx of fine sediment resulted in a shift from sandy to more shallow, turbid and muddy environments and large increases in sediment accumulation rates (SAR). Studies mainly in North Island estuaries indicate that in pre-Polynesian times (i.e., before 1300 A.D.) SAR averaged 0.1–1 millimetres per year (mm/yr). In comparison the rates have increased to 2–5 mm/yr in these same systems today. Sedimentation rates in tidal creeks, mangrove forests and in estuaries near large catchment outlets are even higher and typically in the range of 10–30 mm/yr (e.g., Hume and McGlone, 1986; Sheffield et al. 1995; Swales et al. 1997; 2002a).

A number of studies conducted by NIWA have quantified sediment accumulation rates (SAR) in North Island estuaries and coastal marine environments (Swales et al. 1997, 2002a, 2002b, 2007a, 2007b, 2008a, 2008b, 2011, 2012). This work has also documented the environmental changes that have resulted from increased sediment loads discharged from catchments following large-scale catchment deforestation that began in the mid-1800s. Effects include accelerated rates of infilling, shifts in sediment type from sand to mud and former subtidal habitats have become intertidal. In the upper North Island, many of these intertidal habitats have been colonised by mangroves that have further accelerated estuary infilling (Swales et al. 2007b). Today, many NZ estuaries have infilled with eroded catchment soils to the extent that much of the estuary area is intertidal flat composed of muds or muddy sands.

In this report we estimate the quantity (i.e., rate) and sources of sediment accumulating in the Whangarei Harbour system. The recent sedimentation history of Whangarei Harbour over the last ~150 years is reconstructed from dated sediment cores using radioisotope methods. Contemporary sources of catchment sediments accumulating in Whangarei Harbour are identified using the CSSI forensic technique that has been developed by NIWA (Gibbs, 2008) and successfully applied to several North Island estuaries (Gibbs 2006a, 2006b, Gibbs & Bremner, 2007, Gibbs et al. 2012, Swales et al. 2012), as well as a large river system (Gibbs et al. 2008b). These CSSI data also provide information for the implementation, validation and interpretation of sediment-transport model predictions of deposition.

1.4 Study area

1.4.1 The harbour

Whangarei Harbour is a mesotidal barrier-enclosed lagoon (lower harbour) and drowned-valley (upper harbour) estuarine system located on the north-east coast of the North Island (Fig. 1-1). The harbour has a high-tide surface area of 104 km^2 and is relatively shallow (i.e., mean high-tide depth 4.4 m) due to extensive intertidal flats (Fig. 1-1), particularly in the lower harbour, which account for 58% of the high-tide area (NIWA Coastal Explorer). The harbour has a mean tidal range of 1.7 m (neap tides) to 2.3 m (spring tides). The average residence times for water masses in Whangarei Harbour range from 24 days in winter to 120 days in summer (Millar 1980). Residence times typically decrease with increasing freshwater input into the harbour system, although freshwater inputs are generally low due to the small size of the surrounding catchment. The Hātea River is the main source of freshwater to the harbour, with a mean annual flow of 1 m^3/s. The Waiarohia and Raumahanga streams have mean annual flows of 0.35 m^3/s and 0.34 m^3/s respectively (Reeve et al. 2010).

The upper harbour is dominated by the sheltered tidal arms of the Mangapai and Hātea Rivers, which have substantially infilled with sediment. The Onerahi Peninsula and Limestone Island form a natural constriction through which sediments transported by river plumes and ebb-tidal currents are exported to the middle and lower reaches of the harbour. Several bays indent the northern shoreline of the lower harbour, the largest of which is Parua Bay (Fig. 1-1). Snake bank, a large sand body located inside the harbour mouth, is the harbour's flood-tide delta. The bathymetry of the lower harbour is relatively stable. Although tidal currents are strong enough to entrain sand on the delta, they are not competent to entrain the shell-lagged channel beds (Black et al. 1989).

Extensive mangrove forests fringe the upper intertidal flats of the upper harbour and southern shore of the middle harbour to One Tree Point (Fig. 1-3). The large mangrove stands between Hewlett Point and Rat Island and in the upper reaches of the Mangapai arm developed prior to the 1920s (Ferrar 1925). The relationship between estuary sedimentation and mangrove forest development was recognised at that time:

"*Mangrove flats, covered by sea-water at high tide, appear in every creek and sheltered inlet… The area covered by the growing mangroves depends on the extent to which each has been insilted* (Ferrar 1925).

More recently, analysis of aerial photography (1942, 1966, and 1979) indicates that increases in mangrove habitat have occurred largely due to colonisation of tidal flats landward of mangrove stands fringing tidal channels and intertidal flats between Hewlett Point and Takahiwai. Mangrove colonisation has also occurred in the Mangapai arm near the Portland cement works. Discharge of Portland sediments resulted in rapid vertical accretion of the intertidal flats in this vicinity, with mangroves colonising 47 hectares of intertidal flat adjacent to the cement works between 1966 and 1979 (Northland Regional Council 1989). Today, surface elevations within these mangrove forests are close to the upper limit of the tide (Millar 1980), so that present-day sedimentation rates in these mature forests are likely to mirror the rate of relative sea-level rise (RSLR). At the Port of Whangarei, RSLR has averaged 2.2 ± 0.6 mm/yr (1999–2007) and 1.5 ± 0.1 mm/yr at the Port of Auckland over the last century (Hannah & Bell 2012). Seagrass meadows also occupy the intertidal sandflats from Rat Island to One Tree Point (Fig. 1-4).

Whangarei Harbour receives runoff from a 295 km^2 land catchment. Some 74% of the catchment (composed of the Puwera, Otaika, Hātea and Mangapai sub-catchments) discharges to the upper harbour west of Limestone Island (Millar 1980). Annual average rainfall at Whangarei Airport is 1309 mm (range: 847–1763 mm/yr, 1991–2011).

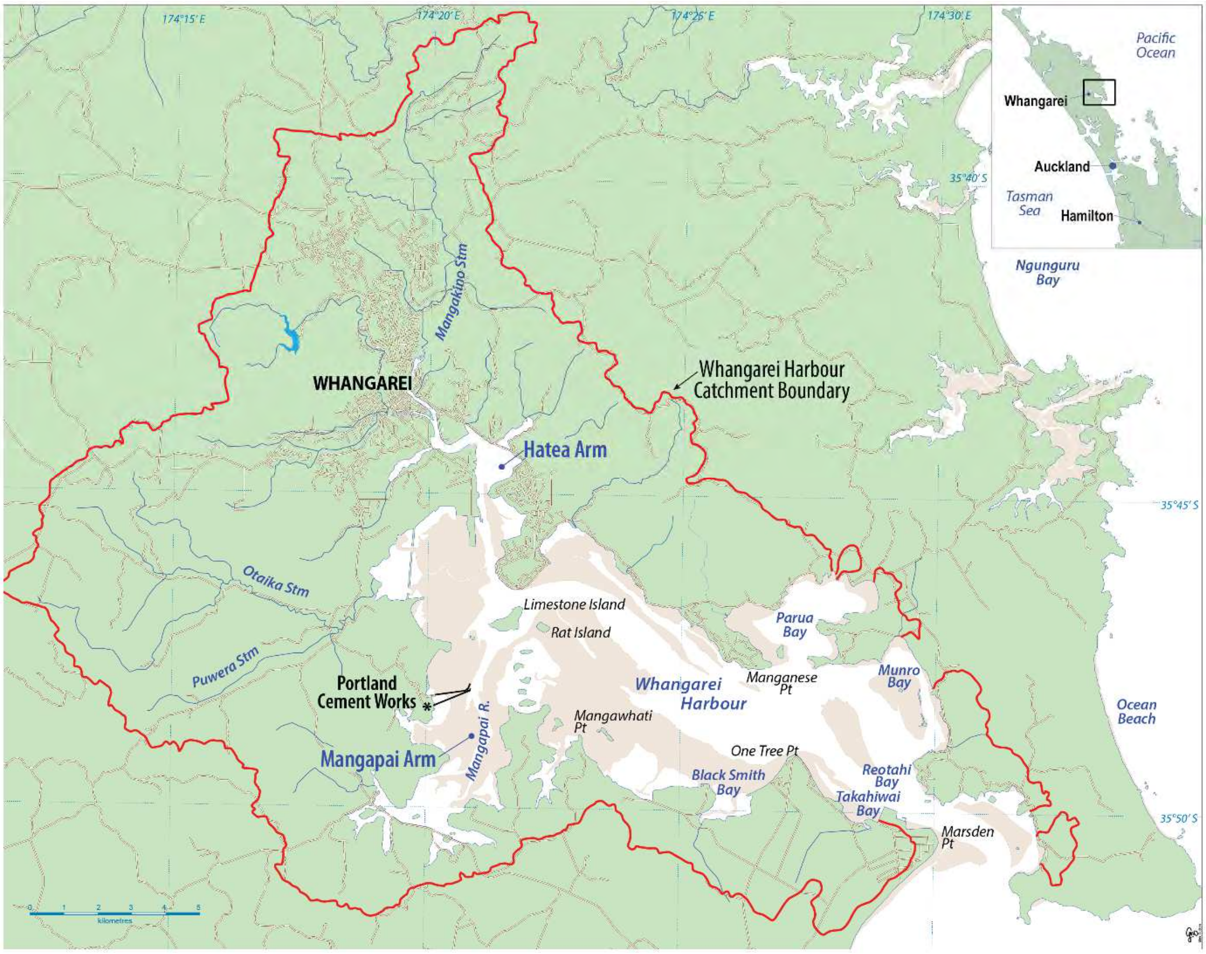

Figure 1-1: Location of Whangarei Harbour and catchment, Northland, New Zealand.

Figure 1-2: View of Parua Bay, Whangarei Harbour. (Photo credit: M. Gibbs, NIWA, 2 February 2012).

Figure 1-3: Mangrove forest, southern shore of Whangarei Harbour. View of mangroves and fringing sea grass near Mangawhati Point (Photo credit: M. Gibbs, NIWA, 21 February 2012).

Figure 1-4: Extensive intertidal seagrass meadows fringe the southern shore of Whangarei Harbour. View of seagrass and mangrove forest, looking south-west from Mangawhati Point towards the Mangapai arm of the harbour (Photo credit: M. Gibbs, NIWA, 21 February 2012).

1.4.2 Catchment history, land use and sediment loads

Catchment landcover has been substantially modified as a result of deforestation since the mid-1800s. Prior to arrival of people, the indigenous forest was composed of broadleaf community dominated by tararire, puriri, kohekohe and kahikatea close to the harbour and river flats, with kauri and podocarps on steeplands (New Zealand Soil Bureau 1968). Catchment deforestation and conversion for pastoral agriculture was largely completed prior to the 1920s, with most native forest remnants being in State Forest reserves. Saw mills did continue to operate at that time and logs were exported to Auckland from Parua Bay (Ferrar 1925). Today, indigenous forest accounts for ~20% of the total catchment area and is limited to isolated forest remnants in small sub-catchments north of the harbour and the Pukenui forest, which borders the western boundary of Whangarei City (Fig. 1-5, Fig. 1-6). High producing exotic grassland, for cattle and dairy farming accounts for 50% of the total catchment area, with plantation forestry (10%) and urban areas (10%) being significant secondary land uses.

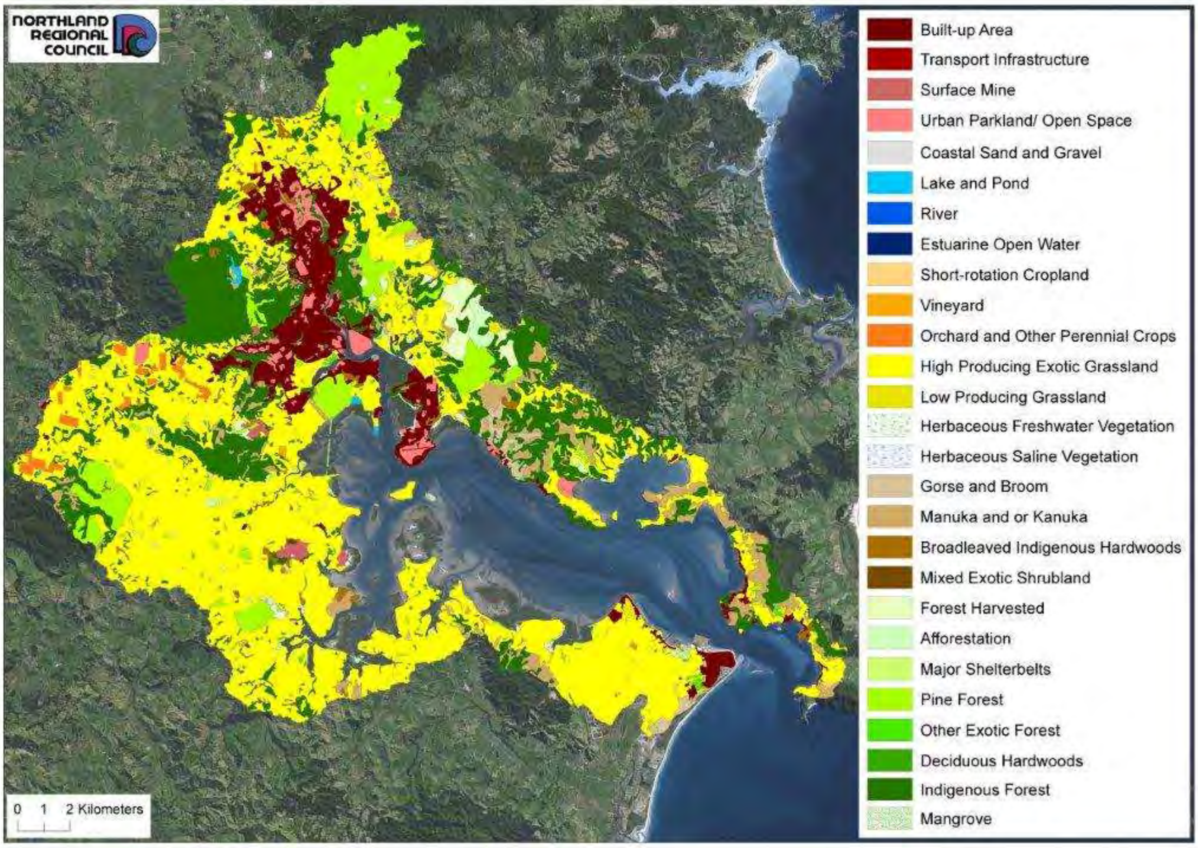

Figure 1-5: Present-day land use in the Whangarei Harbour catchment. Source: New Zealand Land Cover Database (LCDB2, 2001) and Northland Regional Council.

The city of Whangarei, located on the banks of the Hātea River is the regional capital of Northland and had an estimated population of 51,100 in June 2008 (Statistics New Zealand 2008). This has grown from a population of 8,156 recorded at the 1921 census (Ferrar 1925).

The 117 km^2 Hātea sub-catchment accounts for 40% of the harbour's land catchment. Land-use in the Hātea sub-catchment remains predominantly rural, being comprised of indigenous forest (26%), high-producing exotic grassland (32%) and production forestry (15%). Urban land use accounts for 19% of the Hātea sub catchment.

The sediment loads of the major sub-catchments are not routinely monitored at NRC hydrometric stations. Specific sediment yields for major sub-catchments are estimated using NIWA's Water Resources Explorer NZ (WRENZ 2007) tool: 122 t/km^2/yr (Hātea), 355 t/km^2/yr (Otaika) and 60 t/km^2/yr (Mangapai). Records of sediment dredging from navigation channels by the former Northland Harbour Board provide historical information on sediment inputs to the harbour (Fig. 1-7). On average, 155,000 m^3 of sediment was dredged between 1976 and 1982 (Whangarei Harbour Study, 1989). This is equivalent to an estimated 190,000 tonnes of sediment per year, using a characteristic wet bulk density for estuarine sediments (~1.2 t/m^3).

Figure 1-6: Native bush and pasture sub-catchment, Whangarei Harbour. Tamaterau sub-catchment, characteristic of those along the northern shore of the harbour (Photo credit: A. Swales, NIWA, 30 November 2012).

Figure 1-7: Hātea arm of Whangarei Harbour. View looking north-east across the Hatea channel to the Port of Whangarei and the City. Core site WHG-14 is located on the intertidal flats north of the isolated mangroves in the middle distance (Photo credit: M. Gibbs, NIWA, 21 February 2012).

Historically, the Wilsons (N.Z.) Portland cement works was a major source of fine sediment discharged to the harbour (Fig. 1-8). Limestone quarried from Limestone Island was first exported to Auckland in 1850 for the production of cement, with this activity gradually increasing over the following fifty years or so. In 1916 the cement works on the present-day site at Mangapai were established by the Dominion Cement Company, which was subsequently acquired by the Wilsons (N.Z.) Portland Cement Company in 1919 (Ferrar 1925). Between 1918 and 1982 the plant discharged clay washing onto the intertidal flats in the upper harbour at Portland.

The cement plant was a major source of fine sediment to Whangarei Harbour, with an estimated two million tonnes (dry weight) of clay-rich mud discharged between 1958 and 1978 alone. A large proportion of this material (60%) was discharged between 1966 and 1972, averaging 200,000 tonnes/year (Wilsons (N.Z.) Portland Cement Ltd, 1978 – in Millar (1980)). Between 1979 and 1982 when discharges ceased an additional ~100,000 tonnes of clay washing had entered the harbour. This material is largely composed (75%) of montmorillonite clay whereas the clay mineralogy of suspended sediments discharged by streams is dominated by kaolinite and illite (Millar 1980). The distinctive clay mineralogy of the Portland sediments provides a useful tracer to consider the dispersal of fine sediments from the upper harbour (Section 2.1).

Figure 1-8: Mangapai arm of Whangarei Harbour. View from the air looking west across the Mangapai arm of the harbour, with the Wilsons (Portland) cement works in the middle distance (Photo credit: M. Gibbs, NIWA, 21 February 2012).

2 Methods

2.1 Strategy

The approach taken in this study is to quantify sedimentation rates along effects gradients, from catchment outlets in the upper reaches of the harbour (Figure 2-1). Sediment cores were selected for dating in consultation with NRC, with the priority being to identify the physical effects of catchment-derived fine sediments on the Whangarei Harbour system. Radioisotopes are also strongly bound to fine sediments and dating of cores with low/negligible mud content was unlikely to be successful, as observed at sites WHG-4 and WHG-5. Consequently, cores at some sites remote from the major catchment outlets and/or were fine sediments have not accumulated were not dated.

The results of previous work were used to identify potential sediment-transport pathways and areas where long-term deposition of catchment fine sediments has occurred in the harbour. In particular, x-ray diffraction analysis of clay minerals by Millar (1980) found that the ratio of montmorillonite to kaolinite and illite (M/K+I) clays in sediments discharged from the Portland cement works was greater than two. Sampling of surficial sediments throughout the harbour identified where Portland clays (i.e., M/K+I >2) had accumulated (Figure 4-4). This distinctive clay mineralogy provides a useful tracer to consider the dispersal of fine sediments within the harbour over several decades.

In the present study, a 3-dimensional hydrodynamic HD and particle-tracking model was used to simulate fine-sediment transport from the major rivers and subsequent dispersal and deposition. The DHI MIKE3-FM HD model had used in an earlier water quality study of the harbor (Reeve et al. 2010), with the MT (mud) transport module implement in the present study.

These model predictions of mud deposition patterns were compared with Millar's (1980) observations of Portland-clay dispersal and disposition in the harbour.

2.2 Mud-transport modelling

The coupled HD-mud transport model was used to predict sedimentation patterns of fine suspended sediments (20 micron diameter) discharged from the three largest rivers into the upper harbor: Hātea; Otaika; and Mangapai.

2.2.1 Freshwater and sediment input

Discharge records supplied by Northland Regional Council were available for the Hātea and Otaika Rivers. For the purpose of this modeling study, the discharge record for the Mangapai was assumed to be the same as for the Otaika. This is acceptable given: (1) the dearth of sediment-load data in particular; (2) the primary aim of this modelling is to gain a qualitative understanding of fine-sediment fate in the harbor; and (3) to inform the selection of sediment cores and surficial-sediment samples for source determination.

Three discharge scenarios were selected for simulation: average, one-year and ten year return period storms. Suspended sediment concentrations (SSC) were estimated from expert opinion drawn from observations made in other North Island catchment–estuarine systems. The intention of the sediment modeling is to determine the relative spatial differences in sedimentation depth to inform the selection of sampling sites rather than to estimate actual storm-event deposition depths.

The peak flood discharges and SSC values used in the sediment model are presented in Table 2-1.

Table 2-1: Peak flood discharges and suspended sediment concentration scenarios used in the sedimentation modeling, Whangarei Harbour.

River	Scenario	Peak Discharge (m^3/s)	SSC (mg/l)	CSA of outflow (m^2)
Hātea	Average flow	2.5	500	81
	1-year	54	1500	81
	10-year	138	1500	126
Otaika	Average flow	2	500	126
	1-year	106	1500	126
	10-year	138	1500	126
Mangapai	Average flow	2	500	126
	1-year	106	1500	126
	10-year	138	1500	126

2.2.2 Model implementation

A five-layer three-dimensional HD model was implemented and forced at the outer boundaries using the mean (M_2) tidal range for a duration of 20-days (Reeve et al. 2010). No wind or wave effects were included in the setup in the simulations. The transport, Stokes-settling and deposition of fine-silt particles (20 micron diameter) was considered, including re-suspension and final deposition within the time period of simulation. Erosion of the pre-existing bed sediments was excluded so that only the fate of the newly introduced flood sediments from the three rivers could be determined. Each river source included in the model was initially run at average flow and SSC for 7.5-days then subsequently linearly increased up and down to peak flood discharge and SSC over 0.75-days respectively. The mud-transport model was then run for further 11-days to simulate post-event sediment transport/re-suspension/deposition by tidal currents. The key outputs from the modeling wee maps of net sediment accumulation for the baseline, one-year and ten-year return period flood events.

2.3 Sediment accumulation rates

2.3.1 Coring

Sediment cores were collected from Whangarei Harbour at a total of 13 sites in water depths ranging from 1 m above to 3 m below chart datum (CD) (Figure 2-1).

Sediment cores were collected during 14–16 February 2012 using a Gravity Corer deployed from the R.V. Rangitahi III (Figure 2-2). Replicate cores up to 1.74 m long and 10-cm internal diameter were collected from intertidal and shallow subtidal flats using this method at sites in the Mangapai and Hātea arms of the upper harbour, Parua, Munro and Marsden Bays, and at Takahiwai, immediately west of One Tree Point.

Figure 2-1: Location of sediment cores collected from Whangarei Harbour.

Duplicate one-metre long cores were also collected from an additional site (WHG-14) in the Hātea Arm of the Harbour by Northland Regional Council on 5 October 2012 (Figure 2-4). This followed initial radioisotope analysis of near-surface sediments in the cores, which indicated that fine sediments are not accumulating in the middle reaches of the Hātea arm of the harbour (i.e., core sites WHG-4, WHG-5). Data from WHG-6 and subsequent field observations suggest mud deposition is constrained to the more sheltered reaches of the Hātea arm north of the airport.

Gravity corers provide a simple but effective way to collect long cores in muddy sediments. The corer, loaded with up to 160 kg of lead weight, was slowly lowered to within a few metres of the seabed and then released in free fall to penetrate the seabed. A one-way valve at the top of the corer provides suction to hold the sediment in the PVC plastic core barrel as it is winched back up to the boat. A core catcher attached to the bottom end of the core barrel provides an additional means to prevent sediment loss. Immediately after penetrating the seabed, the gravity corer was extracted using an electric winch and davit. The PVC barrel containing the sediment was separated from the corer on the boat, sealed at both ends, labelled and secured in racks for shipment (Figure 2-2). Typically two replicate cores were collected at each site, with one used for radioisotope dating, particle size and bulk density analyses and the second core prepared for x-ray imaging. A third replicate core was collected at some of the sites for determination of historical changes in sediment sources using stable isotopes.

Figure 2-2: Sediment coring from R.V. Rangitahi III. Retrieving a Gravity Corer as used to collect sediment cores from Whangarei Harbour (photo: Rod Budd, NIWA, Hamilton).

Table 2-2 provides details of the sediment-core sites collected from Whangarei Harbour during February and October 2012.

Table 2-2: Sediment cores collected in Whangarei Harbour, February and October 2012. Lengths of each core indicated. Note: original co-ordinates recorded in Lat./Long. (Appendix A).

Site	Location description	Date	Time (NZST)	Water depth (m)	NZTM-N	NZTM-E	Core lengths (cm)
WHG-1	Mangapai arm	15/02/12	1222	1.7	6034450	1721536	163,155
WHG-2	Mangapai arm	15/02/12	1255	1.5	6035986	1721365	174,153
WHG-3	Mangapai arm	15/02/12	1117	0.6	6037498	1721598	57, 59
WHG-4	Hātea arm	14/02/12	1238	1.3	6039099	1721573	66,185, 65
WHG-5	Hātea arm	14/02/12	1157	1.2	6040061	1721087	30,32
WHG-6	Hātea arm	14/02/12	1126	1.5	6041424	1721203	168,137
WHG-7	Munro Bay	16/02/12	1335	3.5	6038434	1734371	46,55
WHG-8	Takahiwai	02/12	low tide	0.0	6034564	1730526	54
WHG-10	Parua Bay	14/02/12	1002	3.4	6039677	1731785	110,105
WHG-11	Parua Bay	16/02/12	1227	–	6039179	17301156	110,160
WHG-12	Marsden Bay	16/02/12	–	LT	6033425N	1733453E	60,60
WHG-13	Parua Bay	14/02/12	1452	–	6038969	1730706	63,85,85
WHG-14	Hātea arm	05/10/12	–	LT	6041641	1722598	100,100

Sediment cores selected for radioisotope dating were cut open length-wise using a skill saw with a 125-mm diameter blade. After cutting the core barrels along their entire lengths on both sides, thin stainless steel sheets were pushed through the sediment to split the core into two separate halves. The cores was first logged, including description of any obvious sediment layers before sub-sampling for radioisotope, particle size and bulk density.

2.3.2 Radioisotope dating and sediment accumulation rates

Sediment accumulation rates (SAR) were estimated from radioisotope activities measured in each core. Radioisotopes are strongly attracted to the surfaces of clays and silt particles and this makes them particularly useful as "mud meters" (Sommerfield et al. 1999). In the present study, historical SAR over the last 50–150 years was quantified based on caesium-137 (^{137}Cs) and lead-210 (^{210}Pb) dating. The short-lived radioisotope beryllium-7 (^{7}Be) also provided information on the depth of the surface mixed layer (SML) The SML is the surface layer in which seabed sediments are mixed by the activities of benthic animals and current- and/or wave-driven sediment transport. These radioisotope dating techniques are described in detail in the Appendices and briefly summarised here.

Radioisotopes are unstable atoms that release excess energy in the form of radiation (i.e., gamma rays, alpha particles) in the process of radioactive decay. The radioactive-decay rate can be considered fixed for each type of radioisotope and it is this property that makes them very useful as geological clocks. The half-life ($t_{1/2}$) of a radioisotope is one measure of the radioactive decay rate and is defined as the period of time taken for the quantity of a substance to reduce by exactly half. Therefore after two half-lives only 25% of the original quantity remains. The $t_{1/2}$ value of radioisotopes also defines the time-scale over which they are useful for dating. For example, ^{210}Pb has a half-life of 22 years and can be used to date sediments up to seven half-lives old or about 150 years (Appendix B). Dating by ^{210}Pb is based on the rate of decrease in unsupported or <u>excess</u> ^{210}Pb activity with depth in the sediment. Excess ^{210}Pb is produced in the atmosphere and is deposited continuously on the earth's surface, where it falls directly into the sea or on land. Like other radioisotopes, ^{210}Pb is strongly attracted to fine sediment particles (e.g., clay and silt), which settle out of the water column and are deposited on the sea bed. ^{210}Pb also falls directly on land and is attached to soil particles. When soils are eroded they may eventually by carried into estuaries and the sea and provide another source of excess ^{210}Pb. As these fine sediments accumulate on the sea bed and bury older sediments over time, the excess ^{210}Pb decays at a constant rate (i.e., the half-life). The rate of decline in excess ^{210}Pb activity with depth also depends on the local SAR. Slow declines in ^{210}Pb activity with depth indicate rapid sedimentation whereas rapid declines indicate that sedimentation is occurring more slowly.

Radioisotopes can occur naturally, such as ^{210}Pb, whereas others are artificially produced. Caesium-137 ($t_{1/2}$ = 30 yrs) is an artificial radioisotope that is produced by the detonation of nuclear weapon or by nuclear reactors. In New Zealand, the fallout of caesium-137 associated with atmospheric nuclear weapons tests was first detected in 1953, with peak deposition occurring during the mid-1960s. Therefore, caesium-137 occurs in sediments deposited since the early 1950s. The feeding and burrowing activities of benthic animals (e.g., worms and shellfish) can complicate matters due to downward mixing of younger sediments into older sediments. Repeated reworking of sea bed sediments by waves also mixes younger sediment down into older sediments. X-ray images and short-lived radioisotopes such as ^{7}Be ($t_{1/2}$ = 53 days) can provide information on sediment mixing processes.

Radioisotope activity in each core was determined by gamma spectrometry of 40–60 g dry samples (1-cm slices) of sediment taken at increasing depths in each core. The radioisotope activity of a sediment sample is expressed in the S.I. units of Becquerel (number of disintegrations per second) per kilogram (Bq kg^{-1}). The radioactivity of samples was counted at the ESR National Radiation Laboratory for 23 hours using a Canberra Model BE5030 hyper-pure germanium detector. The excess ^{210}Pb activity was determined from the (^{226}Ra, $t_{1/2}$ 1622 yr) assay. The excess ^{210}Pb profiles in each core were used to determine time-averaged SAR from regression analysis of natural-log transformed data. The maximum depth of ^{137}Cs in the cores was used to estimate time-averaged SAR since the early 1950s. This included a correction for downward mixing of ^{137}Cs, based on the maximum depth of ^{7}Be. In New Zealand, ^{137}Cs deposition from the atmosphere was first detected in 1953 (Matthews, 1989).

2.3.3 Sediment composition

Information on the composition and stratigraphy of the sediment cores was provided by x-ray imaging. An x-ray image or x-radiograph provides information on the fine-scale sedimentary fabric of sediment deposits. Density differences (due to particle size and composition, porosity) between layers of silt and sand or animal burrows that are infilled with mud make these often subtle features easily recognisable in the x-ray image even though they may not be visible to the naked eye.

X-radiographs were made of each sediment core prior to dating. To do this, each core was first split lengthways and sectioned into 40-cm long and 2-cm thick longitudinal slabs. These slabs were then imaged using a Varian PaxScan 4030E amorphous silicon digital detector panel. X-rays were generated using an Ultra EPX-F2800 portable x-ray source with a typical exposure of 25 mAs (milliamp seconds) and 45–55 kV (Figure 2-4). The raw x-ray images were post-processed using the Image-J software package.

Figure 2-3: NIWA digital x-ray system, with a sediment slab mounted on the detector plate ready for imaging. (Photo: Ron Ovenden, NIWA Hamilton).

2.3.4 Sediment bulk density

The dry-bulk density (ρ_b) of a sediment is the dry mass per unit volume of a sediment deposit and was determined for each 1-cm thick core slice prepared for radioisotope dating. The slice volume was 78 cm^3 for the 10-cm diameter cores. Samples were processed by first weighing on a chemical balance to the nearest 0.01 g, dried at 70°C for 24 hours and reweighed to obtain the dry-sample weight. The ρ_b is expressed in units of grams per cubic centimetre (g cm^3) and was calculated from the dry sample weight and sample volume.

The ρ_b reflects the bulk characteristics of the sediment deposit, in particular sediment porosity (i.e, proportion of pore-space volume) and particle characteristics, such as size distribution and mineralogy. For example the ρ_b of an estuarine sand deposit is of the order of 1.5–1.7 g/cm^3, whereas a mud deposit with high water content can typically have a ρ_b of ~ 0.5 g/cm^3.

2.4 Long-term catchment sediment yield

The long-term average annual sediment yield from catchments draining to the upper harbour (i.e., west of Limestone Island) was estimated from the dated sediment cores, historical rates of sea-level rise and areas of major intertidal habitats (i.e., mangrove, saltmarsh, unvegetated intertidal flat) and catchment area.

The sediment mass deposited per year in each upper harbour intertidal habitat (D_T, tonnes/yr) was estimated as:

$D_T = A \times S \times \rho_b$

Where A is the plan area of each intertidal habitat (m^2), S is the average sediment accumulation rate (m/yr) and ρ_b is the dry-bulk density of sediments deposited within the last 50 years (1.18 ±0.08 t/m^3, 95% confidence interval, C.I.). The total sediment mass ($\sum D_T$) deposited in the upper harbour was estimated by summing the quantity of sediment deposited in each habitat.

The average SAR on the un-vegetated intertidal flats was estimated from ^{210}Pb dating of upper-harbour cores as 4 ±1.4 mm/yr (95% C.I.) (Fig. 2-1). Average SAR in the mangrove and saltmarsh habitats of the mid–upper intertidal flats is assumed to be equivalent to the long-term rate of relative sea-level rise (RSLR) at the Port of Auckland (1.5 ±0.1 mm/yr, section 1.4.1) and is used in preference to the short record for the Port of Whangarei (1999–2007, 2.2 ± 0.6 mm/yr). This assumption is reasonable given that most of these fringing vegetated habitats developed at an early stage following catchment deforestation (mid–late1800s). Progressive deposition of catchment-derived sediments would have increased surface elevations to close to the upper-tidal limit by the early 1900s (section 1.4.1). Subsequently SAR could not exceed the rate of increase in sediment accommodation space resulting from progressive sea-level rise. The total sediment mass deposited in the upper harbour was estimated from the combined total for each intertidal habitat.

The 2.3 km^2 area of intertidal flat west of and between Knight Point (south of Limestone Island) and the Onerahi Peninsula was excluded from the estimates as radioisotope data from cores shows that long-term sediment accumulation does not occur in this area.

The cumulative error (95% confidence interval) for the total sediment mass deposited per year in each intertidal habitat was estimated as

$$D_{T\text{-}ERR} = \pm A[(d^2S^2) + (s^2\rho_b^2)]^{0.5}$$

Where *s* and *d* are respectively the upper or lower 95% confidence limits of the average SAR and dry-bulk sediment density estimated as $1.96(sd/(n)^{0.5}$, with sd = 1 standard deviation.

Table 2-3: Estimation of average annual sediment deposition in the upper harbour. Calculated for intertidal flats, mangrove and saltmarsh habitats based on Lead-210 SAR from cores, rate of sea level rise and dry-bulk sediment density.

Habitat	Area (m^2)	Average SAR (m/yr)	Average SAR (m^3/yr)	Average SAR (D_T t/yr)	Average SAR error ($D_{T\text{-}ERR}$, ± t/yr)
Intertidal flat	2,660,000	0.004	10,640	12,558	4,389
Mangrove	9,870,000	0.0015	14,805	17,469	1,638
Saltmarsh	210,000	0.0015	315	372	35
Total			**25,760**	**30,396**	**6,062**

The average annual catchment sediment yield (S_y, t/km^2/yr) for the upper harbour was calculated as:

$$S_y = (\sum D_T)/A_C$$

where A_C is the catchment area draining to the upper harbour (219.6 km^2), which includes:

- Hatea sub-catchment (116.8 km^2)
- Otaika sub-catchment (61.6 km^2)
- Mangapai sub-catchment (28.1 km^2)
- Small catchment areas (13.1 km^2)

Although there are uncertainties in the annual average catchment sediment-yield estimate, the method has the significant advantage that the estimate is based on measured long-term sediment accumulation rates and sediment bulk density. The estimate is also likely to be conservative given that a proportion of the catchment sediment delivered to the upper harbour has been exported to the lower harbour (section 4).

2.5 Sediment source determination

2.5.1 Background

The sources of soil from different land uses contributing to the sediment depositing in an estuary or harbour are not necessarily directly proportional to area of each landuse in the catchment. Some landuse practices produce very little sediment while others may produce disproportionately large amounts. Consequently, sediment accumulation rates in Whangarei Harbour provide an estimate of how much sediment is being deposited but not where it is coming from. In order to determine where the soil is coming from, a forensic technique, comparing the compound-specific stable isotope (CSSI) signatures of organic compounds in the soil, is used.

Present-day sources of terrigenous sediments deposited in the Whangarei Harbour system were determined using the CSSI method (Gibbs 2008). An introduction to stable isotopes, including a description of the CSSI method are provided in Appendix D. The CSSI method was applied to contemporary/present-day (i.e., surface 2-cm) deposits as well as to the analysis of long-cores that preserve the history of sedimentation over the last several thousand years.

The CSSI method is based on the principle that organic (carbon) compounds exuded primarily by the roots of plants bind to the soil particles around them and thereby impart a unique isotopic signature to soils. Because we define land-use by the type of vegetation growing on the land, the isotopic signatures of these compounds (biomarkers) can be used to link the soil to a specific land-cover (Blake et al. 2012). While plants exude a range of compounds that can be used as biomarkers, the fatty acids (FA) have been demonstrated to be particularly suitable as soil tracers, being bound to fine-sediment particles and long lived (i.e., decades–centuries) (Gibbs 2008). Estuarine and coastal sediments are typically mixtures of soils and marine sediments from various sources. To identify the sources of sediment in a deposit, the isotopic signatures of individual sources are first determined by sampling soils for each major vegetation type (e.g., native forest, pine, pasture etc.). The feasible soil sources in each sediment mixture are then evaluated using an isotopic mixing model. The IsoSource mixing model (Phillip & Gregg, 2003) was used in the present study, with the feasible proportions of each source expressed as percentages (i.e., mean and standard deviation). While it is recommended to use the range of feasible proportions, those data do not relate to soil proportions and have not been reported.

2.5.2 Deconstruction of the sediment mixture to identify soil sources

This section provides details of the isotopic-mixing model method and its outputs as an aid to interpretation of the results presented in section 3.4. Appendix D provides a detailed description of the CSSI method, including sediment-source modelling.

The sources of terrigenous sediments deposited on the present-day seabed were determined from analysis of the CSSI signatures of potential sources (i.e., soils) and mixtures (i.e., marine-sediment deposits). This method requires a library of the isotopic signatures of potential soil sources, which was provided by sampling of catchment soils from major catchment land-cover types.

The IsoSource model identifies the feasible proportions of each source in a mixture using the isotopic signatures of the FA biomarkers. The model firstly calculates all the possible combinations from 0% to 100% present of the isotopic values for each FA from the sources to create a matrix table of mixtures. It then selects those combinations that have an isotopic balance which is within a specified tolerance expressed as “per mil” (‰).

To constrain the number of feasible solutions, the tolerance value is minimised by iteration. A small tolerance value, say <0.5 ‰, although being at or less than the analytical precision of the analyses, is valid because it indicates that mathematically all of the feasible solutions were very close to the isotopic balance in the sediment mixture from the sampling site. Occasionally, the tolerance value can be large, say >2 ‰, but is still valid. The large value means that the isotopic balance may be missing a source component or that the isotopic signature of the FA in one or more of the sources has a high variance. Consequently, tolerance can give an indication of uncertainty in the results. The large tolerance is not wrong and can still produce a unique solution.

The feasible solutions are presented as a histogram which is typically a bell-shaped curve where number of feasible solutions (*n*) for the proportional contribution of each source has a finite upper and lower limit. By definition, each feasible solution is possible which means, for a finite range of proportional contributions, that specific source is present in the sediment mixture in a proportion somewhere between the upper and lower limit of the range. However, where the range of proportions includes zero, it is possible that that source is not present within the uncertainty of the method.

The primary indicators of uncertainty are *n*, the tolerance and the range of proportions. Because *n* is the number of feasible solutions, when *n* is large there are that number of solutions and the uncertainty is high as to which is correct. As *n* decreases towards 1, a unique solution, the uncertainty decreases. If the range of proportions is small and excludes zero as a valid solution, the uncertainty is low. For convenience with subsequent data manipulations, the mean of the range of proportions can be used as the most probable solution (usually matches the most common feasible solution in the bell curve) and the standard deviation (SD) of the range of proportions can be used to define the level of uncertainty.

The modelling yielded estimates of the isotopic proportional contributions of each soil by land-cover type in each marine sample. The level of uncertainty for each estimate was taken as the standard deviation of the IsoSource model solution and was typically less than 5%.

The IsoSource model provides results in terms of isotopic proportions of the source soils required to produce an isotopic balance that best matches the isotopic signatures in the sediment sample/mixture. These isotopic proportions are not the same as the proportions of soil from each source. Typically less than 5% of most soils are composed of carbon, and the isotopic balance evaluated by IsoSource is only applicable to the carbon content (%C) of each source. These isotopically feasible proportions must therefore be converted to soil proportions using a linear scaling factor based on the %C in each source to estimate the percent contribution of each feasible soil source. For example, if one soil has 1% carbon and another has 10% carbon but the isotopic proportions indicate that both sources are contributing the same amount (e.g., 50% each) of isotope to the mixture, it would require 10 times as much of the 1% carbon soil to provide the same amount of isotope as the 10% carbon soil. When the isotopic proportions are converted to soil proportions, the uncertainty defined by the standard deviation of the isotopic proportions is unchanged. This conversion of feasible isotopic source proportions to soil source proportions is described in Appendix D.

2.5.3 Sample collection and processing

Present-day catchment soils, estuarine and marine sediment samples for sediment-source determination were collected during February 2012. Catchment soils were collected at a total of 39 sites mostly in the Hātea River, Otaika Stream and Raumanga Stream sub-catchments on the 20th and 21st February, with additional samples being subsequently collected from around the remainder of the harbour by Northland Regional Council personnel. Vegetation types sampled included pasture (dairying and dry stock), pine forest (mature, clear-felled, surface and sub-soil), and native forest (i.e., mixed broadleaf and totara). Samples included surface and some sub-soils, the latter being taken from slip faces active erosion zones and bank erosion. Sediment samples were also collected from deposition zones in the streams as representative of catchment sources upstream of that location. Surficial sediments in the harbour were sampled at a total of 50 sites including river deltas in estuaries and long-core sites in the inlets and central Bay (Figure 2-9). One core site from Calliope Bay was used as the ocean end member to establish whether and how much coastal sediment was being transported into the harbour. With the exception of the 15 core sites, 32 harbour samples were collected by helicopter in a 1.5 hour period over low tide. The sample was collected using a flat-bottomed plastic scoop while standing on the helicopter skid as it hovered or rested on the mud surface. Figure 2-4 shows the relative positions of all terrestrial and harbour sediment samples. Appendix B provides full details of sampling locations and tabulated stable-isotope data.

These contemporary soil and sediment samples were taken from the top-most 2-cm layer of the substrate.

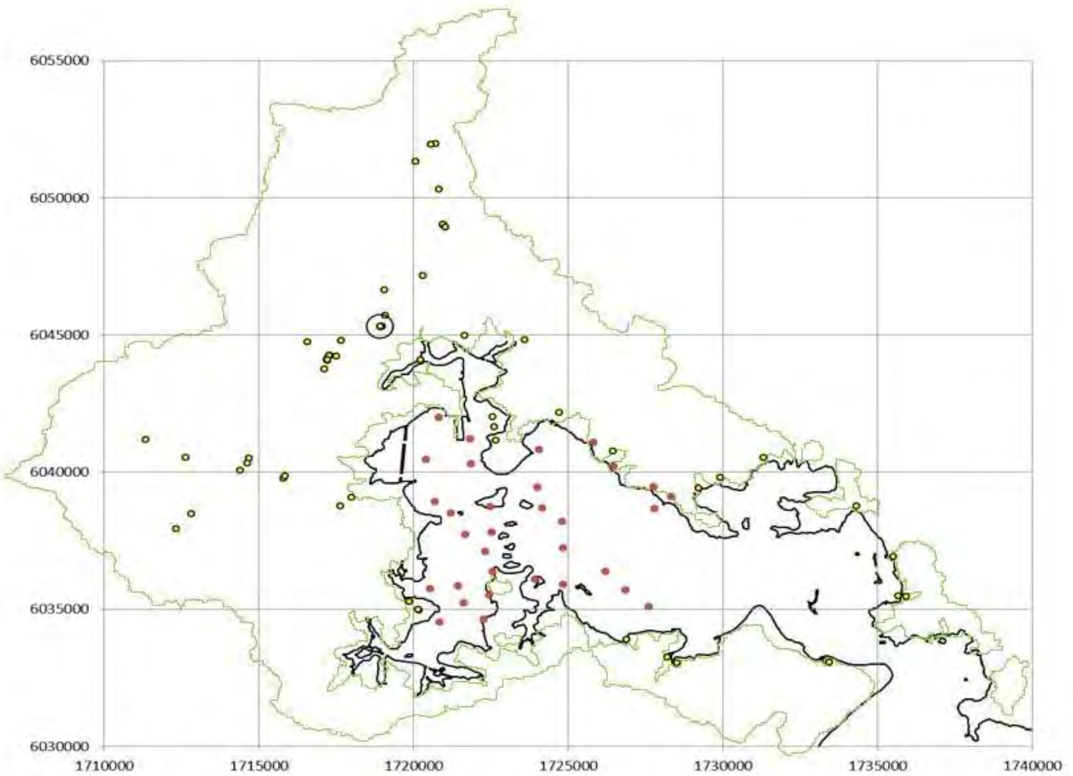

Figure 2-4: Schematic map showing relative positions of samples collected for CSSI analysis. Red dots are harbour samples, yellow dots are terrestrial samples and the black circle identifies the Whangarei CBD. Map co-ordinate system: NZTM2000.

The soil and sediment samples were sieved to remove shells, stones, leaves, roots, woody debris, and insects. The sieving process ensured the samples were completely mixed so that subsequent sub-samples would be representative of the whole sample. The samples were freeze-dried to remove all moisture before being ground to a fine powder (<100 μm) prior to analysis.

For bulk stable isotope analysis of each sample, an aliquot (~5 g) was acidified with 5 ml of 10% hydrochloric acid in a 50 ml plastic centrifuge tube to remove inorganic carbonate. When effervescence ceased, an additional 2 ml of fresh acid was added to ensure complete removal. To remove the acid, the mixture in the centrifuge tube was diluted to 50 ml with distilled water, shaken vigorously for 1 minute and then centrifuged at 3000 rpm for 10 minutes. The supernatant liquid (diluted acid) was decanted and discarded. This rinsing process was repeated and then the sediment was dried in the centrifuge tube in a fan oven at 60°C for 12 hours. The dry sample was ground in a pestle and mortar to a fine powder in preparation for organic carbon analysis as percent carbon (%C) and bulk isotopic carbon as $\delta^{13}C$ by continuous flow, isotope ratio mass spectrometry (IRMS) after combustion at 1060°C in an elemental analyser.

For compound-specific stable isotope analysis of fatty acids, an aliquot (10 g to 40 g) of dry sample mixture was extracted with two sequences of hot (100°C) solvent (dichloromethane) at high pressure (2000 psi) for 5 minutes in an accelerated sample extractor (Dionex ASE 200). Following extraction the solvent was removed by evaporation under low pressure at 35°C, finally concentrating the fatty acids into a 20 ml screw-cap glass reaction tube. The fatty acids where then dissolved in 2 ml of 5% boron trifluoride in ultra-pure methanol. The reaction tube was sealed and heated in a fan oven at 70°C for 20 minutes. The reaction was stopped by cooling the tube in cold water. This reaction converts the fatty acids in the sample to fatty acid methyl esters (FAME), which allows them to be analysed on a gas chromatography-combustion-IRMS (GC-C-IRMS). The output from this instrument gives the $\delta^{13}C$ value of the carbon molecules in each fatty acid.

Fatty acids consist of the elements carbon (C), hydrogen (H) and oxygen (O) arranged as a carbon chain skeleton with a carboxyl group (-COOH) at one end. There are up to 24 possible fatty acids in each sample each defined by the number of carbons in the chain ranging 12 (C12:0) to 26 (C26:0). Saturated fatty acids (SFAs) have all the hydrogen atoms that the carbon atoms can hold, and therefore, have no double bonds between the carbons. This is indicated by the :0 in the simple descriptor (i.e., C16:0). Unsaturated fatty acids have one or two carbon-to-carbon links with double bonds, which is indicated by: 1 or :2 in the simple descriptor (i.e., C16:1). Where there are several unsaturated fatty acids with the same chain length, the simple descriptor also includes the position of the double bond relative to the carboxyl group in the molecule. For example a very useful fatty acid biomarker used in the CSSI technique is oleic acid, (C18:1w9), which has one double bond on the 9th carbon in the chain from the carboxyl group and is present in varying abundance in most plants. A similar unsaturated fatty acid is C18:1w7, which is less common and is not used in the CSSI technique. For the CSSI technique, only the most common fatty acids are used i.e., palmitic acid (C16:0), stearic acid (C18:0), oleic acid (C18:1w9) and occasionally other fatty acids, as required for better separations. These are used together with the bulk organic carbon $\delta^{13}C$ value in the mixing model during the disaggregation process.

All model isotopic proportion outputs were converted to percent soil proportions before interpretation. Spatial patterns of soil contributions have used the mean values in contour plots produced using Surfer32 (Golden Software). The contouring graphics package connects between adjacent points at any distance and therefore connects points across open water in the outer harbour where there are no data. Consequently the contour plots provide indicative distribution patterns rather than absolute concentration gradients. For example, Figure 2-5 shows the spatial distribution of the isotopic signature of oleic acid in the sediments across the Whangarei Harbour.

Estimates apportioning of landuse contributions to sediments in the river systems at specific points uses the mean soil values with the standard deviation (SD) in parentheses after the percent contribution as the indication of uncertainty.

Isotopic enrichment refers to the isotopic signature in per mil (‰). In the natural environment, the isotopic signatures of organic carbon compounds lie in a range from about -40‰ to -8‰. The less negative values are said to be more enriched than the lower end of the range while the more negative values are more depleted than the upper end of the range. The isotopic signature of a compound from one source can have a different isotopic signature, which are more enriched or depleted, than the same compound from another source. Terrestrial sources are typically more isotopically depleted than estuarine sediments (Figure 2-5).

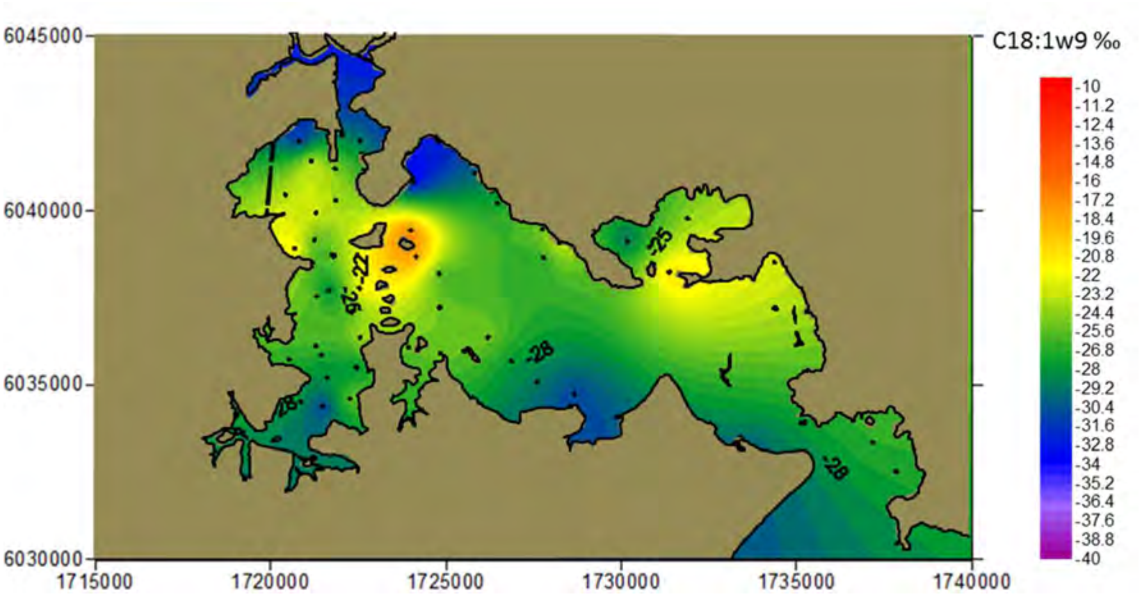

Figure 2-5: Spatial distribution pattern of oleic acid (C18:1w9) in the sediments across the harbour. Dots indicate the sampling points, Map co-ordinate system: NZTM2000.

2.5.4 Isotopic disconnect

Initial examination of the CSSI data indicated that there was an “isotopic disconnect” between terrigenous sources in the Hātea River system and the sediment in the harbour. This was seen as the harbour sediments having more enriched isotopic signatures than could be explained by the isotopic signatures of any of the terrigenous sources in the catchments, except some sub-soils. This implies a missing source of sediment or other major factor that has resulted in the wide-spread enrichment of harbour sediments.

Although present to a small degree with the Otaika River, the enrichment effect was most noticeable in the Hātea River where the isotopic disconnect occurred between the Hātea River at Mair Park and the river delta in the harbour. Between these two locations are the confluences of the Raumanga Stream, Lime Burners Creek, the Awaroa Stream and the William Frazer Memorial Park landfill (Figure 2-6). Of these possible sources, there was no sample representing the William Frazer Memorial Park landfill and it is assumed that material used in this reclamation is from local quarries. It is also assumed that the landfill construction was designed for minimum loss of fill material and, as it has been in existence for a long time without washing away, it is not likely to be a significant sediment source.

A historical reference to the issue of erosion in the Whangarei Harbour Catchment is annexed from the Northland Catchment Commission and Regional Water Board 1984 report in the Whangarei Harbour Study (Northland Regional Council, 1989) as section 2.2.5. Included in this section is a schematic map indicating that there are areas of moderate erosion around the Raumanga Stream subcatchment, which were observed (Figure 2-7), as well as further south in the Otaika River catchment. Further information from NRC (Ben Tait, pers. comm.) indicate that "urban development" of Whangarei City may have been a major contributor of sediment to the harbour. For example, "a considerable proportion of the Hātea River delta was reclaimed for development (i.e., the old port, the town basin, re-routing of the Waiarohia Stream, and the railway causeway adjacent to the river at Onerahi)." It is thought "that these changes have significantly changed the harbour hydrodynamics and reduced natural deposition zones." NRC indicate "that a lot of these changes happened in the early-middle part of the 20th century and may explain why sediment began depositing from the mid 1950's". The dredging and reclamation works associated with port development since the 1950s would also have reworked older (more isotopically enriched) sediment deposits. This information is consistent with the CSSI results which indicate a large change in the sources of sediment below Mair Park.

Subsoils are almost always more isotopically enriched than contemporary surface soils. Older sediment deposits composed of topsoils will also be more enriched than sediments composed of more recently eroded topsoils. Conversely, more recently deposited sediments composed of topsoils will be isotopically depleted relative to older deposits. This isotopic depletion primarily occurs due to the so called Suess Effect, whereby the release of old carbon associated with the burning of isotopically-depleted fossil fuels since the early 1700s has resulted in a decline in $\delta^{13}C$ in atmospheric CO_2 ($\delta^{13}CO_2$). The $\delta^{13}C$ signatures of plant biomarkers in soils, such as Fatty Acids have also changed due to the Suess effect. Consequently, the isotopic signatures of estuarine sediments (i.e., the mixture) deposited in the past must be corrected to match the isotopic signatures of present-day source soils. This applies down the temporal continuum of a sediment core and these isotopic corrections were applied to dated sediment cores in a study of sedimentation in the Bay of Islands (BOI) system (Swales et al. 2012). In contrast to long term deposition in the BOI system, port development and realignment of stream channels in the city will have released older sediments (more enriched) which have been deposited and mixed with more recent sediments from the Hātea River arm of the upper harbour. This has caused an isotopic disconnect between the recent catchment sediments and the harbour sediments and it will take time before these isotopically-mixed harbour sediments are removed from the present-day surface mixed layer by deposition of new sediment deposits from the upper Hātea River. This reworking of sediment deposits in the tidal-reach of the Hātea River will have resulted in a blended stable-isotope signature, a mixture of old and new, that is distinct from present-day sediments delivered by the Hātea River.

The modelling of the Hātea River will be separated into above and below Mair Park and will assess the relative importance of the streams flowing into the lower reaches of the Hātea River. One of these streams, Limeburners Creek, receives the discharge of treated effluent water from the wastewater treatment plant. Because this is a liquid with few solids, it is unlikely to influence the fatty acid content of sediments or the CSSI results in the Hātea River.

Figure 2-6: Map of the lower Hātea River and the tributaries that could provide sediment to the lower river. With the exception of the Otaika River, all named sources have the potential to contribute sediment to the Hātea River delta sampling point. Base image from Google Earth, flown in 2008.

Figure 2-7: Bank erosion on the Raumanga Stream showing the thickness of the historical sediment deposits relative to buried logs that are now becoming exposed. (Photo credit: M. Gibbs, NIWA, 21 February 2012).

As a result of this isotopic disconnect, sources of soil contributing to the rivers were modelled for the Hātea and Otaika River systems above the tidal influence and the harbour was modelled using river delta sediments as the source material from these inflows. Consequently, the estimation of a catchment specific landuse source contribution at any location in the harbour is difficult.

Because we used the top-most 20 mm of surficial sediment, and sedimentation rates in the Hātea arm are relatively low at 2.8 to 6 mm yr^{-1} (section 3.3.2:Hātea), the 20 mm surface layer represents an integration over 3 to 6+ years. This suggests the sediment causing the isotopic disconnect has been entering the harbour for an extended period of years rather than being a recent event.

3 Results

3.1 Modelled sedimentation patterns

The results of the mud-transport modelling indicate where fine sediment is likely to accumulate in the harbour under the influence of freshwater inflows, tidal currents and settling for the average inflow, one-year and ten-year return period flood discharges. Figures 3-1 to 3-3 show the net mass sediment deposition (kg/m^2) from which the sedimentation depth can be estimated assuming a typical wet-bulk density for estuarine sediments of ~1.2 t/m^3 (e.g., 2.5–5 kg/m^2 ~ 2–4 mm sediment depth, orange zone).

Figure 3-1 (average inflow) indicates that most of the fine silt discharged by the Hātea, Otaika and Mangapai Rivers is deposited close to source on intertidal flats in the Upper Harbour, west of Onerahi–Limestone Island.

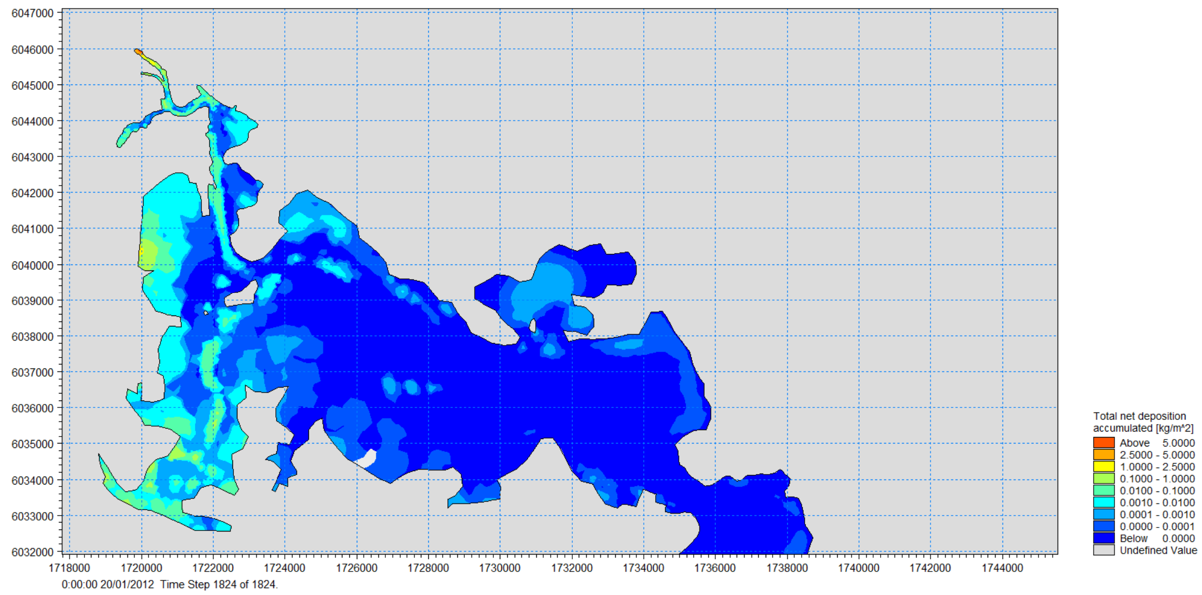

Figure 3-1: Average stream inflows - net sediment deposition pattern (kg/m^2) in Whangarei Harbour.

The predicted pattern of sediment-mass deposition associated with an annual flood (one-year return period) also indicates that a large proportion of fine-sediment deposition occurs in the upper harbour (Fig 3-2). However, flood sediments are also predicted to deposit on intertidal flats in the middle reaches of the harbour particularly along the harbour's northern shoreline east of Onerahi to Munro Bay and in the subtidal compartment of Parua Bay. A similar mass-deposition pattern is predicted for the ten-year return period flood event. (Fig 3-3).

We can compare these event-based model predictions for catchment fine sediments discharged to the upper harbour with Millar's (1980) clay-mineral data for harbour sediments. The montmorillonite-rich "Portland" clays (i.e., M/K+I >2) were primarily deposited throughout the Mangapai Arm close to the outfall. Portland clays were also found in channel-bed sediments east of Limestone Island and in Parua Bay (Millar 1980, p 148). Thus, model predictions and sedimentary data suggest preferential deposition of fine suspended sediments from upper-harbour catchments along the northern shoreline and tidal flats of the main harbour east of Limestone Island.

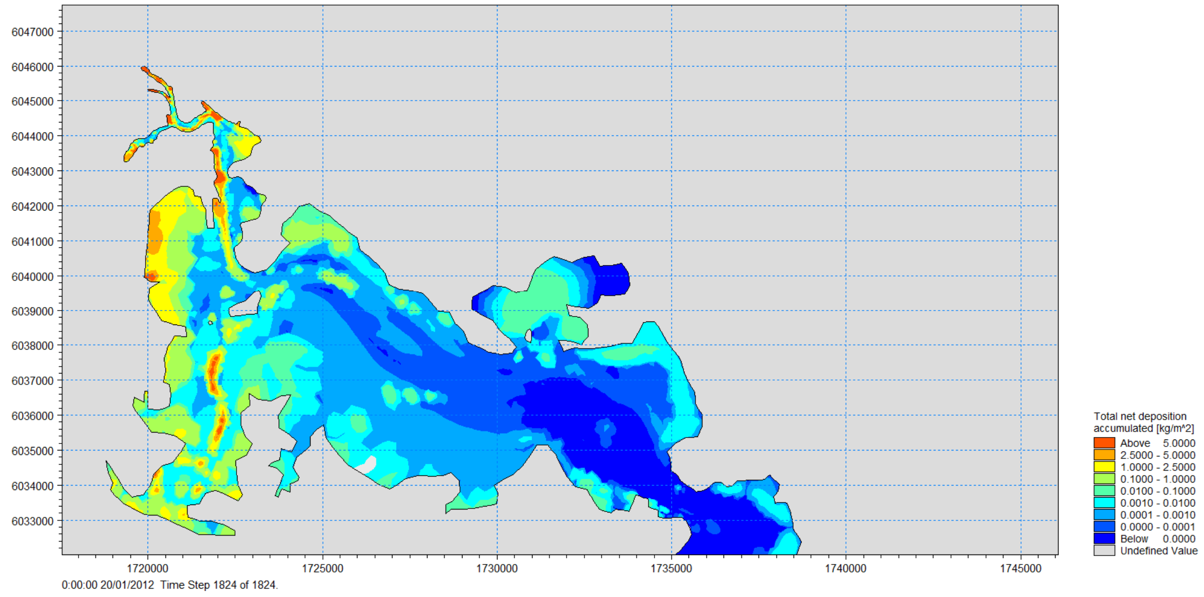

Figure 3-2: Flood flows (1-year return period) - net sediment deposition pattern (kg/m^2) in Whangarei Harbour.

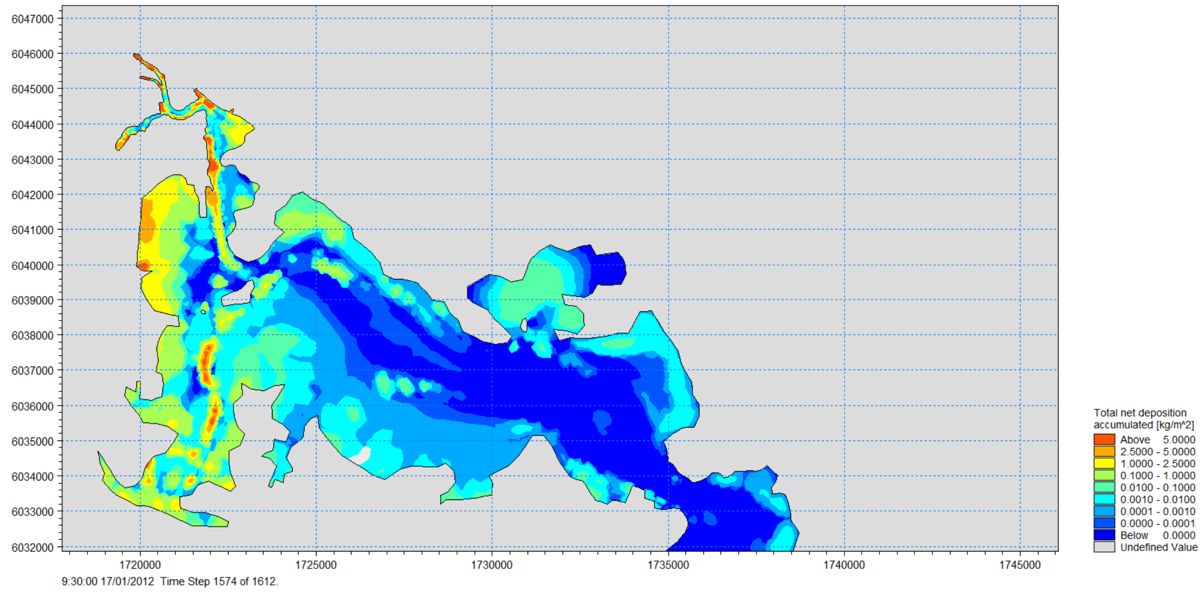

Figure 3-3: Flood flows (10-year return period) - net sediment deposition pattern (kg/m^2) in Whangarei Harbour.