Sediment sources and accumulation rates in the Bay of Islands and implications for macro-benthic fauna, mangrove and saltmarsh habitats

Prepared for Northland Regional Council

May 2012

Authors/Contributors:
Andrew Swales
Max Gibbs
Judi Hewitt
Sarah Hailes
Richard Griffiths1
Greg Olsen
Ron Ovenden
Sanjay Wadhwa

1. Northland Regional Council

For any information regarding this report please contact:
Andrew Swales

+64-7-856 1761
andrew.swales@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone +64-7-856 7026
Fax +64-7-856 0151

NIWA Client Report No:	HAM2012-048
Report date:	May 2012
NIWA Project:	NRC12202

Contents

Tables

Figures

Reviewed by

Dr Terry Hume

Approved for release by

Dr David Roper

Executive summary

The Northland Regional Council (NRC) commissioned NIWA to analyse and report on sediment and benthic ecological data collected as part of the 2010 LINZ Oceans 20/20 Bay of Islands (BOI) survey. These data provide: 1) detailed and robust information on the state of the environment; and 2) an opportunity to inform the future management of the catchment and the receiving coastal marine environment of the BOI system. This report provides a detailed account of how the BOI system has been impacted by catchment land-use changes over the last ~700 years following the arrival of people.

Globally, the increased loading of fine terrigenous sediments is recognised as a threat to estuarine and coastal marine ecosystems. Although terrigenous sediment erosion and deposition in 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 estuarine and coastal ecosystems coincide with large-scale deforestation, which followed the arrival of people about 700 years ago. This process began at an early stage after the arrival of people in the Bay of Islands, although the environmental effects of these increased fine-sediment inputs on this highly-valued marine environment were largely unknown prior to this study.

The specific objectives of the study are:

- Analysis and interpretation of marine sediment cores. Relate sediment accumulation rates (SAR) to historical land use changes and compare sediment accumulation rates (SAR) in the BOI system with rates in other North Island estuaries.
- Determine the sediment capacity of BOI estuaries based on measured SAR and historical rates of sea level rise and consideration of estuarine processes.
- Analysis and interpretation of the Compound Specific Stable Isotope (CSSI) data to identify present-day and past sources of catchment soils deposited in the BOI system.
- Identify possible linkages between the composition of soft-sediment benthic communities (SSBC) and sedimentation patterns, SSBC at risk from sedimentation, and the sources of sediments impacting these habitats.
- Interpretation of changes in the recent extent of mangrove and saltmarsh habitats (1978–2009) and relate these to relevant environmental factors (e.g., sedimentation) and evaluate potential future changes in mangrove habitat extent.

The data sources drawn on in this study include: (1) historical records and published accounts of early Europeans; (2) sedimentology, radioisotope and stable-isotope data derived from sediment cores; (3) stable-isotope signatures of potential soil sources derived from samples collected from the BOI catchment and other upper North Island sites; (4) composition of soft-sediment benthic communities at intertidal and subtidal sites (LINZ Oceans 20/20 and NRC monitoring); and (5) GIS analysis of aerial photography (1978 & 2009) to quantify temporal changes in the spatial extent of mangrove and saltmarsh habitats.

Catchment history

The original native-forest landcover of the Bay of Islands catchment was dominated by rimu, totara, tanekaha and kauri. Natural erosion of native-forest catchment soils occurred for thousands of years before people arrived in the Bay of Islands, as indicated by compound-specific stable-isotope (CSSI) analysis of dated sediment cores (section 3.9). Previous paleoenvironmental studies and historical accounts show that large-scale catchment deforestation began in the Bay of Islands soon after Polynesian arrival (mid-1300s) and several centuries before European settlement began in the1820s. Catchment deforestation appears to have occurred earlier than in many other locations in the North Island due to the relatively high pre-European population density. Although large native-forest remnants are found in the Waikare and Kawakawa catchments, large-scale deforestation continued following European settlement. By the early 1900s a substantial proportion of the BOI catchment was dominated by pastoral agriculture. Citrus orchards were first planted in the late-1920s in the Kerikeri sub-catchment. Citrus production increased after World War Two as well as the introduction of other crops (e.g., kiwi fruit) from the early 1970s.

Present-day landcover of the 1294 km^2 BOI catchment is dominated by pasture (46%), with smaller areas of native forest (20%) and scrub (10%), pine forest (11%) and orchards (3%).

Sedimentation

The sedimentation history of the BOI system was reconstructed from historical records and dated sediment cores collected at twenty-three sites in water depths ranging from 1 m in estuaries to 100 m on the inner continental shelf. The radioisotopes lead-210 (^{210}Pb), caesium-137 (^{137}Cs) and radiocarbon (^{14}C) have been used to determine time-averaged SAR and to reconstruct the sedimentation history of the BOI system over the last several thousand years. Geophysical data from the Oceans 20/20 survey also provided information on seabed type and the thickness of sediment layers deposited over the last ~12,000 years (Bostock et al. 2010). The 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 berrylium-7 (^{7}Be, half-life 53 days) and ^{210}Pb SAR.

The key results of the radioisotope analyses of the sediment cores are:

- The thickness of the active seabed layer or surface-mixed layer (SML) identified by ^{7}Be is 1–5 cm. Sediments in SML are reworked by waves, currents, and/or benthic fauna and are eventually removed by progressive burial. The average residence time of sediments in the SML is 16 ±4.3 years (95% Confidence Interval, CI).
- ^{210}Pb dating of sediment cores yields time-averaged SAR of 1–5 mm/yr over the last 80–200 years in the BOI system. Fringing estuaries close to major rivers are accumulating sediment more rapidly (<5 mm/yr) than the central Bay and inner shelf (<2.5 mm/yr). A notable exception to this general pattern is the high ^{210}Pb SAR (2.3–4.9 mm/yr) observed in Te Rawhiti Inlet. Stable-isotope data indicate that present-day sediments depositing in Te Rawhiti Inlet are most-likely derived from the Kawakawa and Waitangi Rivers. This suggests that silt discharged from these rivers during floods are transported and dispersed widely by freshwater runoff and tidal currents into the central Bay, before being transported by the tide into Te Rawhiti Inlet.

- The BOI system is infilling more slowly with sediment than other North Island estuaries for which we have comparative data. The average ^{210}Pb SAR for the entire BOI system is 2.4 mm/yr in comparison to 2.4–6.7 mm/yr in other North Island estuaries (section 3.6). This is primarily a result of the large sediment accommodation capacity of the system relative to the sediment-supply rate.

- Sediment accumulation rates in the BOI system have increased by an order of magnitude following catchment deforestation. Radiocarbon dating of shell material preserved deep in the sediment cores provides an average ^{14}C SAR of 0.23 ±0.1 mm/yr (95% CI) over the last ten thousand years that is an order of magnitude lower than ^{210}Pb SAR over the last 80–200 years. This is consistent with data from other North Island estuaries.

- Comparison of the Holocene and recent sedimentation budgets indicate a major shift towards sedimentation and infilling in the BOI system. Annual sediment deposition in the BOI system has averaged 509,000 ±210,000 tonnes per year (t/yr, 95% CI) over the last ~150 years. This is far greater than the average of 20,000–50,000 t/yr over the last several thousand years.

- Present-day sediment deposition in the BOI system is similar to the estimated ~430,000 tonnes/yr of suspended sediment that is discharged to the BOI system by the largest sub-catchments. This suggests that a large proportion of the catchment sediment input is trapped in the Bay.

- The capacity of the BOI estuaries to accommodate sediment inputs over the next century was evaluated based on measured ^{210}Pb SAR and historical rates of sea-level rise (SLR) at the Port of Auckland (1.5 mm ±0.1 mm/yr), which is the closest tide-gauge with a reliable long-term record. The most rapid loss of accommodation space has occurred in the Waikare, Veronica and Te Rawhiti Inlets. These areas are most likely to experience large-scale environmental changes in the future.

Sediment sources

Present-day and past sources of terrigenous sediments deposited in the estuarine and coastal waters of the BOI system were determined by applying the CSSI method (Gibbs 2008) to surficial marine sediments and dated sediment cores. The CSSI method is based on the principle that organic (carbon) compounds exuded by the roots of plants impart a unique isotopic signature to soils. Fatty acids (FA) have been demonstrated to be particularly suitable soil tracers, being bound to fine-sediment particles and long lived (i.e., decades–centuries). The feasible soil sources in each marine-sediment mixture were evaluated using the IsoSource model (Phillip & Gregg, 2003). The output from this model is statistical information about the feasible isotopic proportion of each soil source (i.e., % average, standard deviation and range).

The CSSI method was extended for the first time to the analysis of dated sediment cores (up to 2,700 years ago) by incorporating a time-dependent correction factor that accounts for changes in the isotopic signatures of organic compounds due to deforestation and burning of fossil fuels since the early 1700s. The key results of the CSSI analysis of catchment sediment sources are:

- Soil eroded from pasture (cattle and sheep) accounts for more than 60% of the present-day sediment delivery to the BOI system. In the Kerikeri and Waitangi sub-catchments a large proportion of these eroded pasture soils are composed of subsoils. This suggests deep erosion of hillslope pasture in these sub-catchments. Production forestry (pine) also accounts for a substantial proportion of the soil deposited in the Te Puna (36%) and Kawakawa (27%) Inlets. In the Waikare sub-catchment most of the soil was eroded from kanuka scrub (70%) and native forest (26%), which reflects the large proportion of native landcover that remains in this sub-catchment today.

- Bracken-labelled sediments are present in cores occur hundreds–thousands of years before the arrival of people (1300s) and subsequent catchment deforestation. These results indicate that natural disturbance of the landscape was a feature of this environment. Likely causes of forest disturbance include landslides during high-intensity rainstorms and/or fires.

- The effects of Māori on catchment soil erosion are not well represented in the sediment cores that were analysed. This partly reflects the coarse sampling interval of the cores and relatively thin <20-cm thick sediment layer representing the Māori period (~1300–1800 AD).

- The effects of land-use practices on soil erosion over the last century is major and clearly evident due to the introduction of exotic plants, whose isotopic signatures are also evident in soils preserved in the cores. The signatures of dry-stock pasture and potato cultivation enter the sedimentary record from the mid-1800s. In the Kerikeri Inlet, soils eroded from citrus orchards occur in the estuarine sediments from the late 1940s onwards.

- The long-term impact of soil erosion from pastoral agriculture on the BOI system is clearly shown in a core collected from 30-m water depth in the inner Bay (site KAH S-20). This core contains sediments deposited since the early 1960s and pasture soils have accounted for most of the sediment deposited at this site since the early 1980s at a rate averaging 2.4 mm/yr.

Macro-benthic fauna

The soft-sediment macro-benthic fauna of the BOI system are highly diverse and contain many taxa that are expected to be sensitive to increased terrigenous-sediment inputs. The known and predicted tolerance of key habitat-forming taxa, together with information on biodiversity, have been used in this study to determine areas that have already begun to be impacted by sedimentation and those that would be expected to be sensitive to future deposition. The key results of this analysis of soft-sediment macro-faunal data are:

- Sensitive intertidal areas are dispersed around the Bay. Those areas with low sensitivity are mainly concentrated in the Inlets close to major catchment sediment sources (e.g., Kawakawa, Waikare Inlets) and in the upper reaches of the Te Puna and Kerikeri Inlets. Communities in these areas are dominated by mud-tolerant species including the mud crab *Austrohelice crassa*, annelids including *Nereidae* and the shellfish *Theora lubrica*.

- Sensitive subtidal macro-faunal communities are mainly found within Te Rawhiti inlet and the outer deeper areas of the Bay. Te Rawhiti Inlet and the sandy areas around Waitangi and in Veronica Channel are most vulnerable, mainly driven by the greater likelihood of sedimentation occurring. Stable-isotope analysis of sediment deposits indicates that sediments in the Te Rawhiti Inlet are primarily derived from pasture and clear-felled pine forests in the Kawakawa catchment.

- The influence of SAR as well as sediment mud and organic matter content (%) on soft-sediment benthic community composition was evaluated by regression analysis using a ranked value of SAR, which was also used to define the relative risk for each site. Although these analyses suggest that SAR is an important factor, the variability explained by this variable alone for several measures of community structure was generally low.

Changes in mangrove and saltmarsh habitat extent

Recent changes in the spatial extent of mangrove and saltmarsh-habitats (1978–2009) were evaluated for each compartment of the BOI system. The key results of this analysis are:

- Mangrove and saltmarsh habitats presently occupy 1181 hectares (ha) and 280 ha respectively of intertidal flat in the BOI system (2009). Most of the mangrove habitat (77%) occurs in the Waikare and Veronica Inlets. The large areas of mangrove habitat present in these two inlets in 1978 suggests that these forests had established decades earlier. These spatial patterns are consistent with more rapid infilling of estuaries near major river outlets and the consequent development of intertidal flats suitable for colonisation by mangroves.

- The total area of mangrove habitat increased by 10.8% (127 ha) between 1978 and 2009, while saltmarsh habitat declined by 12.3% (39 ha). Some 40% (51 ha) of the increase in mangrove-habitat and 61% (-24 ha) decrease in saltmarsh habitat have occurred in the Waikare Inlet. This loss of saltmarsh-habitat is consistent with landward expansion of mangrove into saltmarsh habitat and/or reclamations along the foreshore.

- Rates of mangrove-habitat expansion in the BOI system of 0.3–1.4% yr^{-1} are in the range observed in other North Island estuaries (0.2–20 % yr^{-1}) although substantially less than the average rate of 4 % yr^{-1} since the 1940s (Morrisey et al. 2010).

- Increases in mangrove habitat (1978–2009) has occurred most rapidly in the Te Rawhiti Inlet (1.4%), although mangrove habitat in this compartment accounts for less than 5% of the total.

- The potential for future mangrove-habitat expansion in BOI estuaries is likely to be limited based on the low historical rate of forest expansion, deep reworking of intertidal sediments by waves (as indicated by ^{7}Be mixing depths) that restricts seedling recruitment and the future effects of sea-level rise (SLR), which are likely to outpace tidal-flat accretion due to sedimentation.

- Large-scale loss of mangrove habitat is predicted to occur under the most likely scenarios for accelerated SLR over the next century of 5.5–8.8 mm yr^{-1}. Under these scenarios, tidal creeks would provide refuges for mangroves assuming that rapid sedimentation observed in these environments over the past ~50 years continues in the future.

In summary, the Bay of Islands system is accumulating fine terrigenous sediments more rapidly than prior to the catchment deforestation and consequent soil erosion that occurred following the arrival of people ~700 years ago. The average ^{210}Pb SAR of 2.4 mm/yr over the last ~100 years is, however, lower than for most other North Island estuaries for which we have comparative data. The Bay traps most sediment that is eroded from the catchment. Muds, which have a more adverse ecological effect on benthic habitat (compared to sands), are accumulating most rapidly in sheltered bays and inlets and close to the major catchment outlets of Te Rawhiti; Veronica; Waikare and Kawakawa Inlets. The 20-fold increase in annual average sedimentation in the BOI system in the last 100 years is consistent with increased soil erosion following large-scale deforestation that began with the arrival of Polynesians about 700 years ago. While such changes are a global phenomenon they appear to be particularly pronounced in New Zealand where human colonisation has occurred in just a few hundred years.

1 Introduction

1.1 Background

The Northland Regional Council (NRC) commissioned NIWA to analyse and report on sediment and benthic ecological data collected as part of the 2010 Land Information New Zealand (LINZ) Oceans 20/20 Bay of Islands (BOI) survey. These data provide: (1) detailed and robust information on the state of the environment; and (2) an opportunity to inform the future management of the catchment and the receiving coastal marine environment of the BOI system.

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. This process began at an early stage in the Bay of Islands (section 1.5); however prior to the Oceans 20/20 study the physical and ecological effects of these increased fine-sediment inputs on this highly-valued marine environment were largely unknown.

In relation to the issue of sediments, the Bay of Islands (BOI) Oceans 20/20 Phase One Study identified that:

> *"the origins of sediments, the transport pathways and rates within the Bay of Islands are poorly known. Similarly, the age and accumulation rates of sediments of sediments are unknown"* (MacDiarmid et al. 2009, p 149).

Sedimentation was also identified as a serious environmental issue by the local community, as identified by during public meetings held in October 2008 as part of phase one of the Oceans 20/20 project. To address these issues, data on sediment accumulation rates (SAR) and terrigenous sediment sources were collected and partly analysed during phase two of the Oceans 20/20 project. These data are analysed in detail and our findings reported here as part of the present study for the Northland Regional Council.

1.2 Study objectives

This report provides a detailed account of how the Bay of Islands (BOI) system has been impacted by catchment land-use changes over the last ~700 years following the arrival of people.

The specific objectives of the study are:

- Analyse and interpret sediment cores collected as part of Oceans 20/20.
- Relate sedimentation rates to historical land use change and practices.
- Compare sedimentation accumulation rates (SAR) in the BOI system with those in the Kaipara Harbour and other North Island estuaries.

- Determine the sediment capacity for Kawakawa River, Waikare Inlet, Kerikeri Inlet, Te Puna and other estuaries. This will be based on likely scenarios for infilling of these estuarine systems based on current sedimentation rates at core sites, measured rates of sea level rise over the last ~100 years and consideration of the effects of estuarine processes on infilling.
- Identify possible linkages between soft sediment benthic communities data collected as part of Oceans 20/20 and NRC's estuarine monitoring data and sedimentation deposition patterns.
- Identify soft sediment benthic communities at risk from sediment deposition and identify sediment sources impacting these habitats.
- Interpret the historical extent of mangrove habitat in relation to catchment land use and sedimentation rates.
- Predict future mangrove habitat extent based on sedimentation rates.
- Analyse and interpret the Compound Specific Stable Isotope (CSSI) data collected as part of Oceans 20/20 used to identify catchment sediment sources.
- Determine whether sediment currently being deposited in the Bay of Islands is 'new' sediment entering the system from the catchment or reworking of historical sediment previously deposited in the Bay.

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; 2002).

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). 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 muddy intertidal flats can be seen at low tide.

In this report we estimate the quantity, type and sources of sediment accumulating in the BOI system. The sedimentation history of the BOI system is reconstructed from dated sediment cores using radioisotope methods that span monthly, annual, decadal and millennial time scales. Past and present-day sources of catchment sediments accumulating in the BOI system over the last 100–150 years 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), as well as a large river system (Gibbs et al. 2008). Information on how sediment is exchanged between different parts of the BOI system must rely on measurements and/or simulation of sediment-transport processes. An uncalibrated sediment-transport model was developed as part of the Phase Two Oceans 20/20 BOI study.

1.4 Study area

The Bay of Islands is a system of drowned river valleys and coastal plains, covering some 290 km^2 that was formed between 12,000 and 7,000 years ago as the sea rose to its present level at the end of the last (Otira) ice age. Since that time the BOI system has accumulated sediments derived from catchment runoff (terrigenous sediment) and marine sources. The coastline of the BOI is indented with numerous bays, inlets and estuaries and contains numerous small islands. The islands shelter some areas from ocean swells that would otherwise rework seabed sediments. This geomorphology has produced a variety of coastal and estuarine environments characterised by differences in tidal flows, wave exposure, water depth, salinity, sediment type and ecology. Marine habitats within the BOI range from sheltered estuaries and bays that are accumulating fine muds to wave-exposed rocky headlands and reefs, where fine sediments are temporarily deposited after storms.

In the BOI system, muddy intertidal flats occur close to the river and steam mouths in bays and inlets such as Waikare Inlet, Parekura and Orongo Bays and Kerikeri Inlet. How quickly the bays and estuaries fill with sediment mainly depends on rate of sediment input and the original volume of the estuary or bay when they were flooded by the sea. This flooding was completed about 6,500 years ago after the sea had reached its present level. The rate of sediment input in turn mainly depends on the size of the land catchment and the rate of soil erosion, which is a function of the geology, topography, soil, vegetation cover and climate. The volume of a bay or estuary (i.e., area x mean depth) is an important measure of estuary size and is what marine geologists often refer to as the sediment accommodation space. The Bay of Islands today remains largely subtidal owing to its relatively large accommodation space, with most marine habitats remaining submerged and “out of sight” even at low tide.

Sediments deposited in the BOI system have progressively accumulated so that the oldest sediments are buried by progressively younger sediments. By collecting and dating sediment cores from the seabed we can reconstruct the history of sedimentation in the BOI system.

1.5 History of the Bay of Islands: deforestation and settlement

There is good evidence that, as in other parts of New Zealand, deforestation by Māori and European settlers in the Bay of Islands resulted in soil erosion and increased sedimentation. Pollen and sediments deposited in a wetland near the Hauparua arm of the Kerikeri Inlet preserve the vegetation history of the northern Bay of Islands over the last 4300 years (Elliot et al. 1997). These deposits show that the original forest landcover of the Bay of Islands was dominated by rimu, with totara, tānekaha and kauri. A sharp decline in the pollen abundance of all tree and shrub species occurs 600 years before present (B.P. = 1950 A.D.), with a coincident sharp rise in bracken and charcoal content. These changes are characteristic signatures of catchment deforestation by humans. Changes in the types and rates of sediments accumulating in the wetland also indicate that this large-scale deforestation resulted in substantial soil erosion and sedimentation.

Sediment accumulation rates (SAR) in the wetland averaged ~0.6 mm/yr over several thousand years prior to 600 years B.P. (i.e., before Polynesian arrival), increasing to 2 mm/yr after that time. An abrupt increase in coarse silt input to the wetland after deforestation began is also indicative of soil erosion (Elliot et al. 1997). These sediment-core records build a picture of large-scale catchment deforestation in the Bay of Islands by Māori, a process which began several centuries before European settlement began in the 1820s.

Captain James Cook visited the eastern Bay of Islands in 1769 and noted that:

> *"the habitants of the Bay are far more numerous than at any other place we have yet been in" (Beaglehole, 1955).*

Settlements were numerous on both the mainland and on the islands, with large areas cleared of forest. Some 40-50 acres on Moturua Island were under cultivation with root crops (Hayward, 1980). Between the time of Cook's visit and the arrival of European settlers kauri trees were logged by Māori to supply visiting Man-o-War and whaling ships with spars in exchange for trade items (Ferrar, 1925).

Aspects of the vegetation cover of the catchment hinterland were also recorded some 60 years later by Charles Darwin, who visited the Bay of Islands with H.M.S. Beagle in December 1835 (Armstrong, 1992). At this time the shoreline around Paihia had a dense cover of tree ferns and scrub. Darwin walked the 24 km inland to Waimate (North) along the Waitangi River. At Waimate he visited a kauri-forest remnant close to the farmstead and by this time it appears that large areas of the catchment had been converted to grassland. Darwin's records in his diary:

> *"I think with much probability that all this extensive open country was once covered by forests and that it had been cleared in past ages by the aid of fire. It is said that frequently digging in the barest spots, lumps of resin, which flows from the Kauri pine, are found. The natives had an evident motive in thus clearing the country, for in such parts of the fern, formerly so staple an article of food best flourishes".*

The high pre-European population density is also inferred from Darwin's observation that "every hill" had evidence of past occupation or fortification, as observed by Captain Cook (Beaglehole, 1955; Armstrong, 1992). It is also apparent that within one–two decades of European settlement, further forest clearance by fire had occurred for conversion to pasture. By the 1920s, the largest forest remnants were mainly restricted to state forests. However, removal of remnant Kauri trees was revived, with saw mills in operation at Opua and Moerewa and Whangaruru to the south (Ferrar, 1925). The population of the Bay of Islands County, as recorded in the 1921 census was only 7094 of which 60% were European (Ferrar, 1920).

Catchment land cover changes that have occurred in each of the major estuaries of the BOI system are described in section 2.8 as part of the analysis of historical sediment-source changes reconstructed from sediment cores.

2 Methods

2.1 Strategy

The general approach taken in this study is to quantify sedimentation rates along effects gradients, from catchment outlets in the upper reaches of estuaries fringing the BOI system to the inner continental shelf at the 100-m isobaths (Figure 2-1). Historical information as well as the results of previous studies indicates that that terrigenous (i.e., catchment derived) sediments are the major source of sediments accumulating in the BOI system (section 1.5).

Figure 2-1: Location of sediment cores used to estimate sediment accumulation rates. The pre-fixes KAH and RAN denote cores collected from R.V. Kaharoa and R.V. Rangitahi lll, August-September 2009.

Information on present-day catchment sediment loads delivered to the BOI system is sparse, with relatively short river-flow records only available at a few sites. Estimates based on catchment models indicate that ~430,000 tonnes per year of suspended sediment is delivered from a 916 km^2 area comprising the largest sub-catchments discharging to the Bay (i.e., Kawakawa, Waitangi, Kerikeri, Waipapa and Waikare, MacDiarmid et al. 2009). The total catchment area draining to the Bay of Islands is 1,294 km^2 (source: Northland Regional Council). The 443 km^2 Kawakawa sub-catchment delivers about 80% of this combined annual total so that this sub-catchment is the primary source of terrigenous sediments delivered to the BOI system. A large fraction of the annual sediment load will be composed of silt and clay and delivered by river runoff during storms.

Some of these fine sediments will be deposited in the Waikare Inlet, due to proximity to catchment outlets and physical processes that favour sedimentation (e.g., flocculation and settling). However, a proportion of the suspended storm loads will be dispersed as plumes to the central bay and other fringing estuaries and inlets due to the low settling velocities of fine silts. Based on previous studies, these fine-terrigenous sediments will accumulate in sheltered estuaries and bays on intertidal and shallow subtidal flats, in mangrove forests and saltmarsh and in the deep-water habitats of the central and outer Bay of Islands.

In the present study, sediment accumulation rates (SAR) over tens to thousands of years have been determined at discrete locations using dated sediment cores. These sediment cores also provide information on sediments types (i.e., mud, sand, gravel) and bulk densities. A longer-term picture of sediment accumulation within the Bay, over thousands of years, is provided by geophysical surveys undertaken from R.V. Tangaroa during the Oceans 20/20 study (Bostock et al. 2010). This acoustic data is used to quantify the thickness of mud layers that have been deposited in the BOI system over the last 12,000 years or more. These various information strands are also used to estimate past and present-day rates of sediment deposition (tonnes/year) in the BOI system.

2.2 Sediment core collection

Sediment cores were collected at twenty-three sites in water depths ranging from 1 to 100 m in the sheltered estuaries that fringe the Bay and out to the inner Continental Shelf at site KAH-2 (Figure 2-1).

Deep-water sites (i.e., depth >30 m) were sampled using an Ocean Instruments Multicorer MC-800 deployed from the R.V. Kaharoa during August 2009 (Figure 2-2). The MC-800 collects eight cores up to 0.9 m long in muddy sediments. In this method, clear plastic core barrels are mechanically pushed into the seabed. Sediments are retained in the core by bottom caps that swing into position as the plastic barrels emerge from the seabed.

In the present study, cores up to 0.5 m long (9.5-cm internal diameter, ID) were collected and cores from six of these deep-water sites were included in the present study. Sediment cores for radioisotopic dating and particle-size analysis were extruded from the core barrels and sub-sampled at 1-cm depth intervals from top to bottom and stored in plastic bags. A replicate core from each site was also sectioned to provide a ~2-cm thick longitudinal slab for x-ray imaging.

Sediment cores from shallow-water sites (≤ 30-m water depth) were collected during September 2009 using a Gravity Corer deployed from the R.V. Rangitahi III (Figure 2-3). Replicate cores up to 1.7 m long (10-cm ID) were collected using this method at sites in the Te Puna, Kerikeri, Te Rawhiti, Kawakawa and Waikare Inlets and Parekura, Manawaora, Onewhero, Pomare and Orongo Bays, in addition to the inner Bay. 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 provide 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 2-4). 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: R.V. Kaharoa, Bay of Islands, August 2009. Retrieving the Multicorer tripod used to collect short cores at deep-water sites (photo: Lisa Northcote, NIWA Greta Point).

Figure 2-3: R.V. Rangitahi III, Bay of Islands, September 2009. Retrieving the Gravity Corer used to collect long cores at shallow-water sites (photo: Rod Budd, NIWA, Hamilton).

Figure 2-4: R.V. Rangitahi III, Bay of Islands, September 2009. Sealing a sediment core ready for shipment to NIWA Hamilton (photo: Rod Budd, NIWA Hamilton).

Tables 2-1 and 2-2 below provides details of the sediment-core sites sampled by the R.V. Kaharoa and R.V. Rangitahi III during August–September 2009.

Table 2-1: Details of sediment short cores collected by R.V Kaharoa for the BOI oceans 2020 study, August 2009.

Site	Location description	Date	Time (NZST)	Water depth (m)	Latitude	Longitude	Core lengths (cm)
KAH S-2	Inner Continental Shelf	29/08/09	1200	101	35° 06.480'S	174° 12.600'E	46
KAH S-6	Outer Bay of Islands	23/08/09	1732	72	35° 09.790'S	174° 12.550'E	38
KAH S-11	North of Moturoa Island	21/08/09	1054	25	35° 11.510'S	174° 05.810'E	19
KAH S-12	Central Bay of Islands	22/08/09	1610	36	35° 11.700'S	174° 07.780'E	23
KAH S-13	Central Bay of Islands	20/08/09	1650	43	35° 11.710'S	174° 09.400'E	12
KAH S-20	Inner Bay of Islands	22/08/09	1247	30	35° 13.450'S	174° 08.110'E	20

Table 2-2: Details of sediment long cores collected by R.V. Rangitahi III for the BOI Oceans 2020 study, September 2009. Note: the replicate core used for dating indicated by bold lettering in the last column.

Site	Location description	Date	Time (NZST)	Water depth (m)	Latitude	Longitude	Core lengths (cm)
RAN S-1	Kawakawa Inlet	15/09/09	1523	1.4	35° 19.599'S	174° 07.073'E	A:86, **B:129**
RAN S-2	Kawakawa Inlet at Opua	15/09/09	1634	2.2	35° 19.205'S	174° 07.244'E	A:50, **B:128**, C:130
RAN S-3	Waikare Inlet - west	15/9/09	0935	1.2	35° 18.939'S	174° 08.588'E	**A:135**,B:153
RAN S-4	Waikare Inlet - central	16/9/09	1745	2.5	35° 18.404'S	174° 10.940'E	**A:133**,B:162
RAN S-5	Waikare Inlet - east	16/9/09	1653	1.8	35° 18.9621'S	174° 12.0582'E	**A:154**, B:83
RAN S-7	Orongo Bay	15/9/09	1300	2.7	35° 17.101'S	174° 08.199'E	**A:97**, B:86
RAN S-8	Porare Bay	15/9/09	1150	3.9	35° 16.704'S	174° 07.822'E	**A:146**,B:122
RAN S-9	Kororareka Pt, Russell	16/9/09	0839	11.5	35° 15.571'S	174° 06.468'E	**A:140**,B:134 C:146
RAN S-14	Onewhero Bay, nth of Brampton Shoals	17/9/09	0854	18.2	35° 13.5036'S	174° 05.610'E	A:128,**B:125**
RAN S-15	Central BOI, north east of Roberton Island	17/9/09	0953	31.5	35° 13.4804'S	174° 08.0567'E	A:19,B:43, **C:65**
RAN S-15	Central BOI, north east of Roberton Island	17/9/09	0953	31.5	35° 13.4804'S	174° 08.0567'E	A:19,B:43, **C:65**
RAN S-18	Rahui Isles, Kerikeri Inlet	16/9/09	1411	4.4	35° 12.1785'S	174° 01.6256'E	**A:138**,B:167
RAN S-19	Kerikeri Inlet	16/9/09	1457	1.7	35° 12.0985'S	174° 00.7052'E	A:105,**B:147**
RAN S-20	Te Puna Inlet - North	16/9/09	1057	2.5	35° 09.2806'S	174° 00.6043'E	A:103,**B:112**
RAN S-21	Te Puna Inlet - South	16/9/09	1327	7.4	35° 10.8057'S	174° 02.6703'E	**A:162**,B:169
RAN S-27	Manawaroa Bay	17/9/09	1536	6.4	35° 16.207'S	174° 12.0907'E	**A:127**,B:163

2.3 Radioisotope dating and sediment accumulation rates

Sediment cores (RAN series) 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.

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 were 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. Information on pre-historic SAR (i.e., last several thousand years) was derived from radiocarbon dating (^{14}C) of carbonate-shell material collected from the lower parts of sediment cores.

2.3.1 Lead-210 and Caesium-137 dating

Radioisotopes are unstable atoms that release excess energy in the form of radiation (e.g., 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 A). 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 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).

2.3.2 Radiocarbon dating

Radiocarbon dating has been widely applied to date fossil (carbonate) shell and plant material preserved in marine and estuarine sediments. Samples from marine sediments younger than about 500 yr B.P. cannot be dated using ^{14}C, which largely coincides with the arrival of people in New Zealand and the large-scale environmental changes that have occurred. In this study, ^{14}C dating is used to estimate long-term SAR during the period mainly before the arrival of Polynesian settlers in the Bay of Islands around 1300 years before present (B.P.).

Samples of shell material from gravity cores were selected for ^{14}C dating. Filter-feeding species were selected where possible from the lower sections of the cores and well below the maximum depth of the excess ^{210}Pb profiles. In all cases, samples were $\leq$ 10 g so that dating was undertaken by the Atomic Mass Spectrometry (AMS) method to minimise the uncertainty in the calibrated ^{14}C ages. Table 2-3 provides details of samples submitted to the Waikato Radiocarbon Dating Laboratory.

2.4 Sediment core composition

2.4.1 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 taken of replicate cores from the RAN- and KAH-series sites. These cores were split and sectioned into 40-cm long and 2-cm thick longitudinal slabs and 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.

An example of an x-ray image is included in this report.

Table 2-3: Bay of Islands sediment cores. Details of shell samples submitted for AMS dating. Notes: Wk = Waikato Radiocarbon Laboratory number; FF = filter feeder; DF = deposit feeder.

Wk number	NIWA Sample ID (Location)	Core	Sample depth (cm)	Description
28224	BOI_5A 118-120cm_sample1 [Waikare Inlet]	RAN S-5A	118–120	1 x cockle-shell valve (*Austrovenus stuchburyi*), FF (~10 g).
28225	BOI_5A 118-120cm_sample2 [Waikare Inlet]	RAN S-5A	118–120	1 x cockle-shell valve (*Austrovenus stuchburyi*), FF (~10 g).
28226	BOI_5A 118-120cm_sample3 [Waikare Inlet]	RAN S-5A	118–120	1 x cockle-shell valve (*Austrovenus stuchburyi*), FF (~10 g).
28227	BOI_S13C_130-132cm [Te Rawhiti Inlet]	RAN S-13C	130–132	1 x shell valve (*Satellina nitida*), DF (0.42 g)
28228	BOI_19B_141-143cm [Kerikeri Inlet]	RAN S-19B	141–143	2 x articulated shell valves (*Dosina subrosa*), FF, (1.7 g)
28229	BOI_20B_101-103cm [Te Puna Inlet]	RAN S-20B	101–103	1 x shell valve (*Serratina charlottae*), DF (~0.2 g)
28230	BOI_27A_114cm [Manawaroa Bay]	RAN S-27A	114	2 x articulated cockle-shell valves (*Austrovenus stuchburyi*), FF (4.8 g)
28231	BOI_KAH-129_114-115cm [Central BOI]	KAH S-129	114–115	1 x shell valve (*Tawera spissa*), DF (<0.2 g)
28232	BOI_KAH-132_190-193cm [outside Te Puna Inlet]	KAH S-132	190–193	1 x Turret Shell (*Maoriculpus roseus*), DF (<1 g)
28233	BOI_KAH-141_159-161cm [Central BOI]	KAH S-141	159–161	1 x shell valve of clam (*Talochlamys zelandiae*), FF (<1 g)
	BOI_14_135–141cm [South of Motoroa Island]	RAN S-14	135–141	1 x large scallop shell (*Pecten novaezelandiae*)

Figure 2-5: NIWA digital x-ray system, with a sediment slab mounted on the detector plate ready for imaging. (Photo: Ron Ovenden, NIWA Hamilton).

2.4.2 Sediment particle size

The particle-size distributions (PSD) of sediment samples were determined using a CIS-100 time of transition (TOT) stream-scanning laser sizer (e.g., Jantschik et al. 1992). Sediment samples of ~0.5 cm^3 were first wet-sieved to remove vegetation and shell fragments greater than 2 mm diameter (i.e., 2000 microns, μm). With few exceptions most of the sediments analysed were composed of clay and silt particles $\leq$63 μm and fine sand particles <250 μm diameter. A representative sub-sample was taken from a homogenised one-litre suspension. Samples were disaggregated by ultra-sonic dispersion for 4 minutes before analysis and then continuously re-circulated through the measurement cell by a peristaltic pump. Particle diameters were individually measured in the range 0.5–600 μm using the TOT method, with 10^5–10^6 particles analysed per sample. The spherical volumes calculated from the measured particle diameters were used to determine a volume-based PSD for each sample.

Particle size data from core sites RAN S-3 and RAN S-13 are included in this report.

2.4.3 Sediment bulk density

Sediment dry-bulk densities (DBD) were determined for each of the 1-cm thick sediment samples prepared for radioisotope analysis. The sample volume of 78 cm^3 was taken from the cross-section area of the core (10 cm ID) minus the ~0.5 cm^3 PSD sub-sample. Each sample was weighed on a chemical balance to the nearest 0.01 g then dried at 70°C for 24 hours and reweighed to obtain the dry-sample weight. Sediment DBD expressed as grams per cubic cm (g cm^3) were calculated from the dry sample weight and sample volume. These DBD data are used to estimate the annual sediment-mass deposition rate in the BOI system.

2.5 Sediment deposition in the BOI system

2.5.1 Historical sediment deposition

The annual rate of sediment deposition in the BOI system during the last ~150 years was estimated from the dated sediment cores (SAR, bulk density, particle size) and the detailed seabed mapping of habitat types undertaken as part of the LINZ Oceans 20/20 study.

The BOI system was classified into seven compartments, which reflect the various sedimentary settings in the Bay. These include the sheltered estuaries/inlets near catchment outlets and the more exposed inner, central and outer Bay (Figure 2-6).

The first step in building the sedimentation budget was to "ground truth" the seabed map products derived from the Oceans 20/20 sea-bed mapping backscatter data with particle-size distribution (PSD) information from the RAN and KAH series cores and surface sampling sites. The PSD data were compared to seabed textures identified through: (1) segmentation; and (2) Hill Shade analysis. The segmentation analysis identified five habitat classes based on backscatter properties and these habitat classes are plotted with the PSD (percentage mud and sand) data in Figure 2-7. The PSD data did not support differentiation of the five habitat classes based on sediment type.

The PSD was also plotted with the seabed Hill Shade map derived from the backscatter data, which clearly identified areas of rocky reef in each compartment (Figure 2-8). The Hill Shade map accentuates differences in the elevation of adjacent grid cells in a Digital

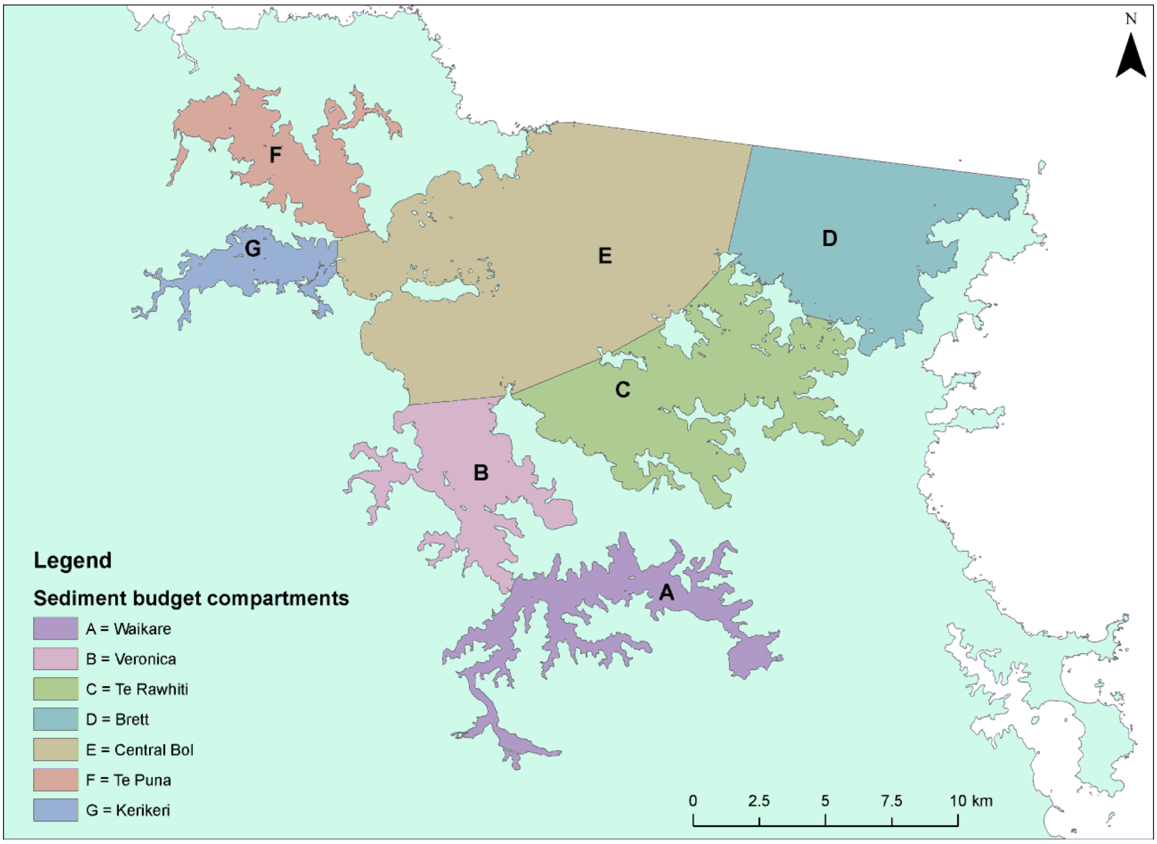

Figure 2-6: Sedimentation compartments defined for the Bay of Islands system.

Elevation Model (DTM). The DTM was illuminated from a single light source (direction 315° and azimuth 45°) thereby creating a pseudo-light and -shadow image. This method was particularly effective for identification of the complex topography of rocky-reef habitats. In total, rocky-reef habitat accounts for 53.6 km^2 of the 287.6 km^2 BOI system.

The sedimentation budget was constructed for each compartment as follows. The area of rocky reef in each compartment was digitised and excluded from the sediment-budget calculations. Typically, the backscatter data were not available for much of the shoreline, in the inlets and immediately around islands. In these areas, information on rocky-reef extent was extracted from the RNZN Chart N.Z. 5122 Bay of Islands. The remaining soft sediment habitats in each compartment therefore represent areas where long-term sediment accumulation has occurred in the BOI system. The compartment average ^{210}Pb SAR and sediment dry-bulk density (DBD) were calculated from cores located in each compartment (Table 2-4). The annual sedimentation budget for the BOI system was estimated as described below.

The total sediment mass (D_T, tonnes) deposited per year in each compartment was estimated as:

$$D_T = \text{ASS } (m^2) \times \text{SAR } (m/yr) \times \text{DBD } (t/m^3)$$

The total mud (D_M) and sand (D_S) mass deposited per year in each compartment was estimated as:

$$D_M, D_S = D_T \times F$$

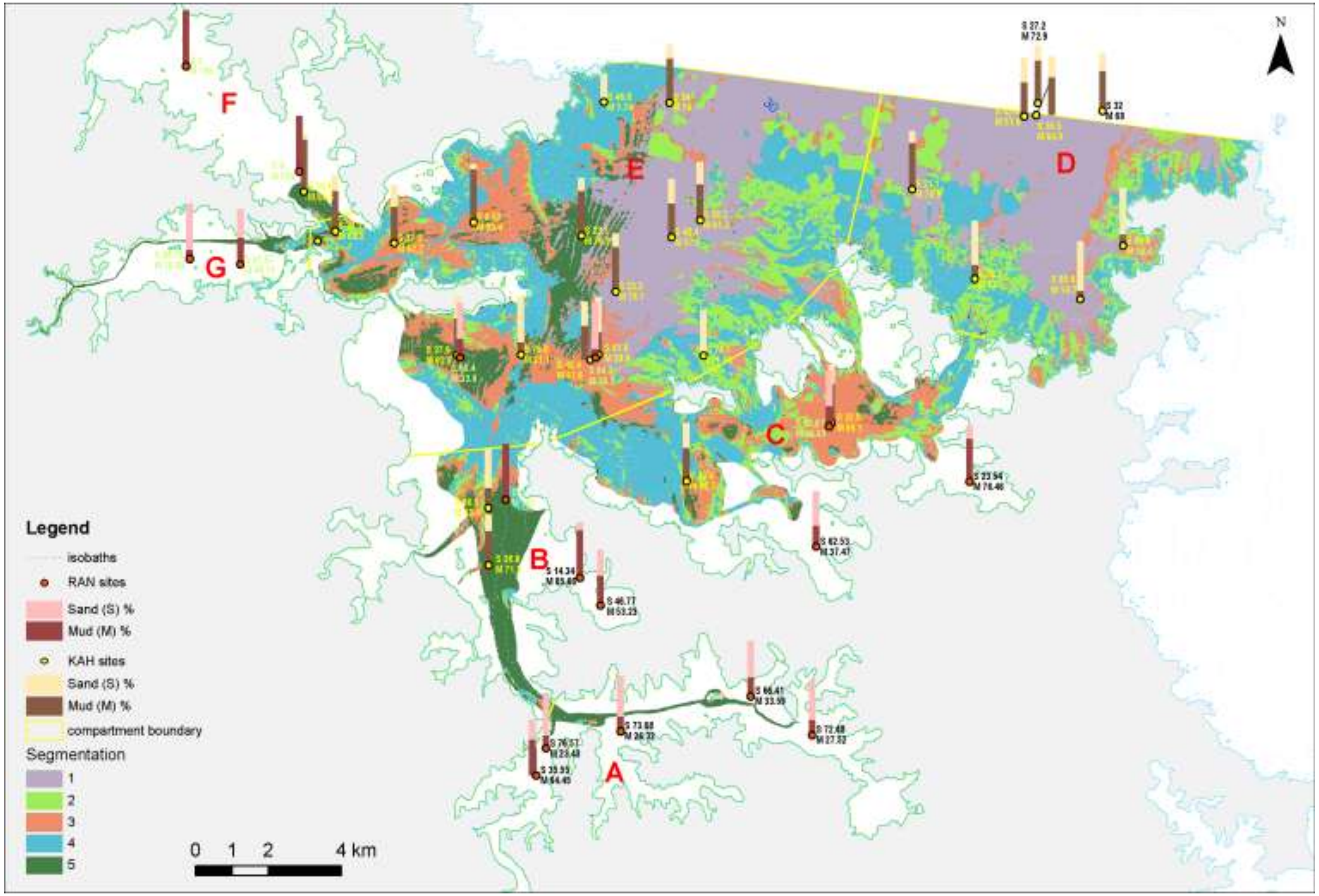

Figure 2-7: Bay of Islands system. Seabed texture classes defined by segmentation analysis of backscatter data with percentage mud and sand content of surface samples (0-1 cm depth) at core sites shown.

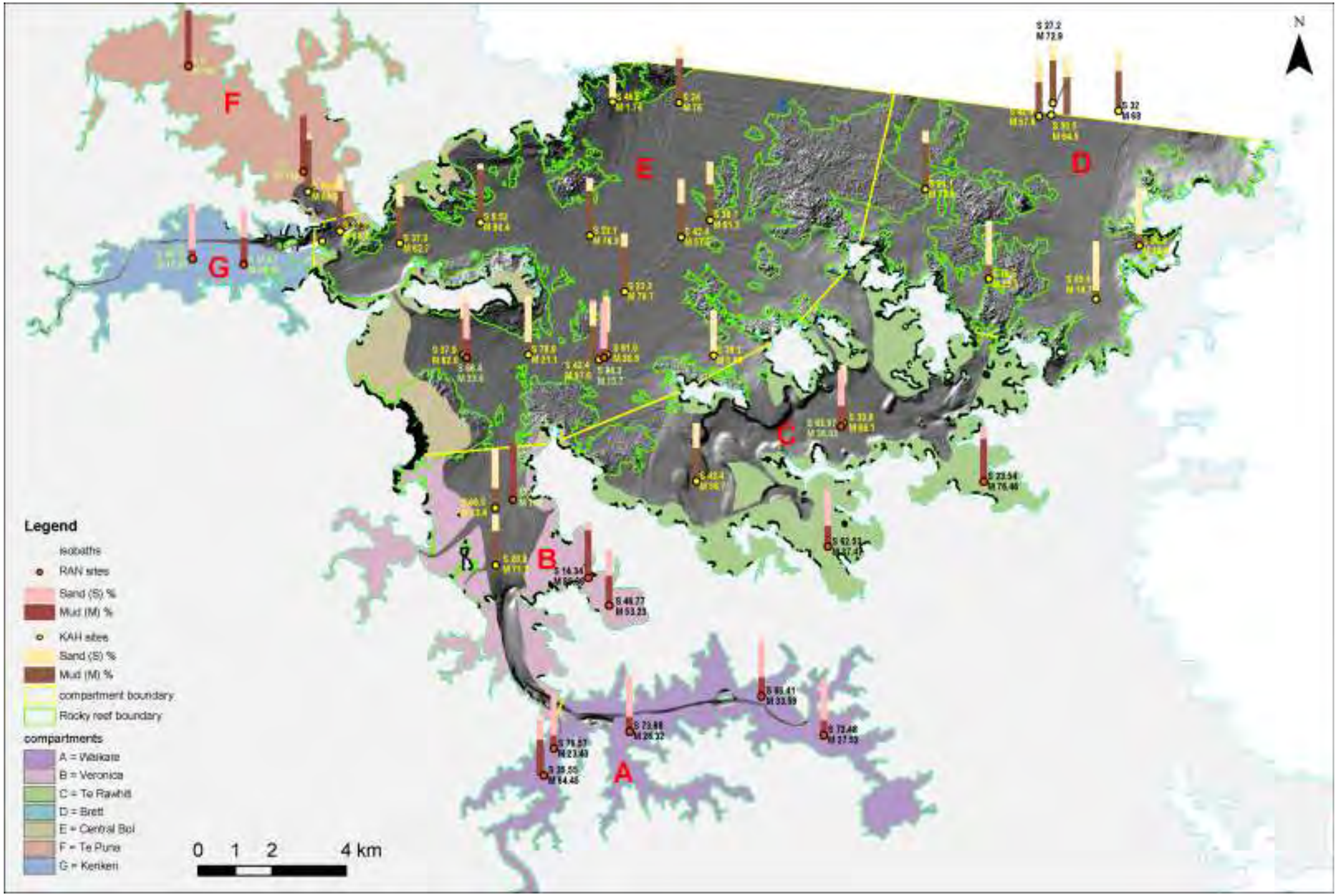

Figure 2-8: Bay of Islands system. Seabed type and areas of complex rocky reef defined by Hill Shade analysis of backscatter data with percentage mud and sand content of surface samples (0-1 cm depth) at core sites shown.

Table 2-4: Data used to calculate annual sedimentation mass for each sedimentary compartment, BOI system.

Compartment	Total area (km^2)	ASS (10^6 m^2)	Cores	SAR (mm/yr) [s, n]	Mud & Sand content (% vol) [s, n]	DBD (t/m^3) [s, n]
Waikare	25.0	25.0	RAN S-1, 2, 3, 4 ,5	2.4 [1.0, 5]	M: 27.7 [4.3, 5] S: 72.3	0.843 [0.145, 71]
Veronica	24.6	23.3	RAN S-7, 8, 9	3.2 [1.2, 3]	M: 68.7 [26.3, 3] S: 31.3	0.909 [0.173, 49]
Te Rawhiti	50.4	46.0	RAN S-11, 13, 27,	3.2 [1.5, 3]	M: 54.6 [17.7, 5] S: 45.4	0.843 [0.305, 41]
Brett	49.2	33.9	KAH S-2, 6	1.9 [0.3, 2]	M: 49.9 [4.3, 8] S: 50.1	0.843 [0.179, 32]
Central BOI	107.0	74.6	RAN S-14, 15 KAH S-11, 12	1.8 [0.7, 4]	M: 55.1 [20, 14] S: 42.6	1.015 [0.299, 49]
Te Puna	20.3	20.3	RAN S-20, 21	1.7 [0.4, 2]	M: 100 [-, 2] S: 0	0.697 [0.111, 35]
Kerikeri	11.1	10.9	RAN S-18, 19	2.1 [0.4, 2]	M: 32.0 [22.8, 2] S: 68.0	0.911 [0.177, 26]

Key: (1) Area of soft sediment (ASS); (2) Average lead-210 sediment accumulation rate in the compartment, standard deviation (s) and sample size (n); (3) Average mud and sand content of seabed sediment (depth: 0–1 cm); (4) Sediment dry bulk density (DBD) from RAN-series cores.

Where ASS, SAR, DBD are define in Table 2.4 and F is the mud or sand fraction in the surface (0–1 cm) sediment sample. The cumulative error (95% Confidence Interval, C.I.) for total annual sediment deposition, $D_{T\text{-}ERR}$ in each compartment was calculated as:

$$D_{T\text{-}ERR} = ASS \times ((s^2 DBD^2) + (SAR^2 d^2))^{0.5}$$

Where s and d are respectively the upper or lower 95% confidence limit of the ^{210}Pb SAR and the sediment dry-bulk density estimated as $1.96(sd/(n)^{0.5})$, with sd = 1 standard deviation.

2.5.2 Pre-historic sediment deposition

The annual rate of mud deposition was also estimated for the last several thousand years, which largely reflects sediment delivery from an undisturbed native-forest catchment along with sediment from marine sources. This long-term pre-deforestation annual deposition rate was estimate using two methods:

- Total volume of sediment deposited in the BOI system over the last 10,000 ±3,000 years based on geophysical surveys of the thickness of unconsolidated Holocene sediments deposited on the underlying bedrock erosion surface. The volume estimate is converted to an annual mass deposition using an estimated dry-bulk sediment density of 0.9 t/m^3 (Bostock et al. 2010). This method has the advantage of estimating the total sediment volume from tens of kilometres of geophysical survey transects, although the deposition time scale will vary with location in the BOI system.
- Total volume of sediment deposited in the BOI system over the last ≤9,400 years based on long-term average ^{14}C SAR derived from sediment cores collected at eight sites (section 3.7). The average ^{14}C SAR and dry-bulk densities (DBD) used in this analysis are respectively 0.23 ±0.1 mm/yr and 0.98 t/m^3 ±0.08 t/m^3 (95% Confidence

Interval, CI). The DBD 95% CI was estimated from the dated cores for sediments deposited prior to the mid-1800s, based on ^{210}Pb dating. The total area of seabed included in the sediment budget calculation excluded areas of present-day rocky reef exposed at the seabed. The area of exposed reef in the BOI system was derived from LINZ Oceans 20/20 sea-bed mapping data as described in the previous section. The main advantage of this method is that sediment accumulation rates are directly measured, although only at a few sites.

2.6 Sediment accommodation capacity of fringing estuaries

The capacity of the estuaries fringing the Bay to accommodate terrigenous sediments over the next century is assessed based on: (1) measured SAR over the last ~100 years; (2) historical data on rates of sea level rise; and (3) understanding of estuarine physical processes. Estuaries with large sub-tidal volumes have the capacity to accommodate future sediment inputs for centuries–millennia without experiencing obvious large-scale environmental changes due to infilling. Potential large-scale changes include the development and/or increase in intertidal area and resulting development of salt marsh and/or mangrove forest.

The rate of estuary infilling depends on several key factors, namely: (1) the volume of the receiving basin; (2) the rate of sediment delivery to the estuary; (3) the sediment trapping efficiency of the estuary; and (4) the rate of sea-level rise (SLR). As estuaries infill the accommodation space available to accumulate sediments reduces and as water depth decreases to a few metres or less, short-period waves become increasingly effective at re-suspending sediments (e.g., Green et al. 1997; Swales et al. 2004). As a consequence, the sediment trapping efficiency of an estuary declines as it infills and more of the sediment input is exported to adjacent estuarine and marine environments. The sediment accumulation rate integrates the long-term effects of all these factors acting over seasonal–millennial time-scales.

To a first approximation, a direct comparison of SAR with SLR can therefore be used to assess the long-term fate of an estuarine system. For example, where SAR <SLR, the average depth of the estuary is increasing over time, more than offsetting the effects of sedimentation. In the opposite case, with SAR >SLR, the sediment accommodation space of the estuary declines over time. This simple approach assumes: (1) steady-state conditions; and (2) SAR approximates increases in seabed elevation due to sediment deposition. This is a reasonable assumption for near-surface (i.e., top few m of sediment column) muddy sediments. Estuarine muds typically have low permeability so that compaction due to dewatering is negligible in the top few metres of the sediment column. Mixed sediments, composed of mud and sand will display more compaction so that increases in seabed elevation will be less than the SAR.

In this assessment ^{210}Pb SAR from the Oceans 20/20 core sites were used to infer increases in seabed elevation. The long-term annual average rate of sea-level rise measured at the Port of Auckland (1.5 ± 0.1 mm yr^{-1}, Hannah et al. 2010) provides the most reliable SLR estimate.

2.7 Sediment source determination

2.7.1 Background

Present-day and past sources of terrigenous sediments deposited in the coastal and estuarine waters of the Bay of Islands system were determined using the Compound Specific Stable Isotope (CSSI) method (Gibbs 2008). An introduction to stable isotopes, including a description of the CSSI method are provided in Appendix B. The CSSI method was applied to present-day (i.e., surface) 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 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. 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., average, standard deviation and range).

The CSSI method has not previously been applied to reconstruct historical changes in the sources of terrigenous sediment using sediment cores. This has been achieved in the present study by incorporating a time-dependent correction factor that accounts for changes in the isotopic signature of organic compounds due to the burning of fossil fuels (1700 AD–present). The method used to correct for this so-called “Suess effect” is described in Appendix B.

2.7.2 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 sections 3.8 and 3.9. Appendix B provides a detailed description of the CSSI method, including sediment-source modelling.

The sources of terrigenous sediments deposited on the present-day seabed and at various times in the past 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. Data from other North Island locations were also included where local (i.e., Bay of Islands) soils were not available because: (1) they could not be accessed or (2) no longer occur in the catchment (e.g., kumara gardens).

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 are within a specified tolerance (i.e., ± ‰).

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 (*s*) of the range of proportions can be used to define the level of uncertainty. An example result from the analysis of a sample from RAN S-5B (Waikare Inlet) is shown in Table 2.5 below.

Table 2-5: Example of IsoSource model results, Core RAN-5B (Waikare Inlet), 30-31 cm depth (1914 AD). The results are mean isotopic proportions in the range 0 to 1. The tolerance (*n*), median and standard deviation (*s*) values are shown.

Tolerance	n	Nikau			Kauri			Bracken		
		mean	median	s	mean	median	s	mean	median	s
0.9	3	0.317	0.32	0.006	0.55	0.55	0.01	0.133	0.13	0.006

The Waikare catchment today remains largely under native forest and scrub land cover so that sediments deposited in the inlet should reflect these land cover signatures. The sample was taken from 30–31-cm depth in the core, with radioisotope dating indicating that it was deposited in the early 1900s.

Table 2-5 shows that the sediment sample at 30–31-cm depth is largely derived from native forest (kauri and nikau associations), with a small contribution from bracken. The presence of bracken is a key indicator of catchment disturbance/forest clearing. The presence of bracken pollen in sediment deposits has long been used in historical reconstructions of the New

Zealand environment (e.g., McGlone 1983). The tolerance at 0.9 ‰ is a mid-range value, with values as low as 0.01 ‰ occurring in some of the samples that were analysed. The number of feasible solutions (n = 3) is low, which also provides confidence in these results.

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 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 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 B.

2.7.3 Sample collection and processing

Present-day catchment soils, estuarine and marine sediment samples for sediment-source determination were collected during December 2009. Catchment soils were collected at a total of 22 sites in the Kerikeri, Waitangi and Kawakawa catchments. Vegetation types sampled included pasture (dairying and dry stock), pine forest (mature, clear-felled, surface and sub-soil), native forest and scrub (i.e., Kanuka and fern) and citrus orchards. In addition to these BOI soils, the CSSI reference library of potential sediment sources also included data from other vegetation types that are not present today and/or not sampled in the catchment. These include native vegetation types such as Kauri forest, Nikau-dominated forest and bracken as well as introduced plants such as maize, potato and corn. The stable-isotope signatures for potato are used in this study as a surrogate for kumara (sweet potato) because data for the latter is not yet available in the CSSI reference library. We assume that the signatures for these plants will be similar.

Marine surficial sediments were sampled at a total of 35 sites including river deltas in estuaries and long-core sites in the inlets and central Bay (Figure 2-9). These contemporary soil and sediment samples were taken from the top-most 2-cm layer of the substrate.

A sub-set of dated long cores collected from five sites were also selected for CSSI analysis and used to reconstruct historical changes in the sources of terrigenous sediment deposited in the Bay of Islands system (Fig. 2.1). These core sites include:

- Waikare Inlet (RAN S-5)
- Russell (RAN S-9)
- Kerikeri Inlet (RAN S-18)

- Inner BOI at ~30-m isobath (KAH S-20)
- Inner continental shelf at ~100-m isobath (KAH S-2).

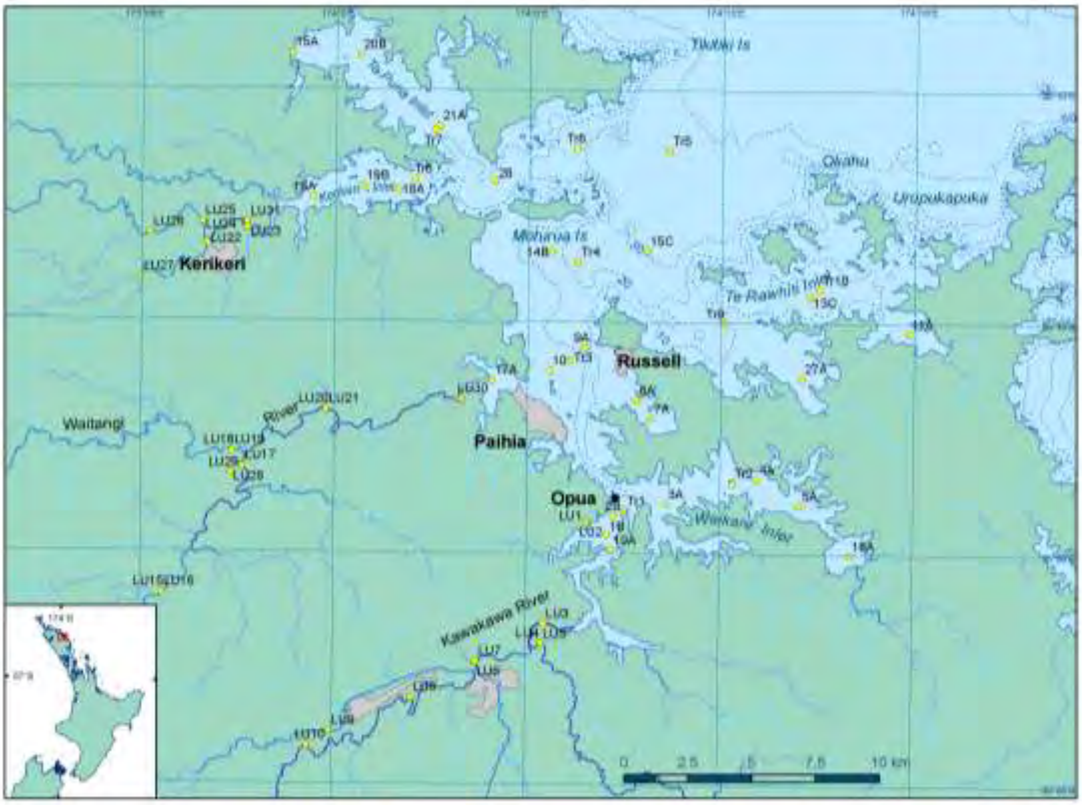

Figure 2-9: Location of sample sites for determination of catchment sources of present-day estuarine and marine sediment deposits, Bay of Islands system.

The dated sediment cores were sub-sampled in 1-cm thick layers at 1-cm intervals down to 5-cm depth, 7-8 cm, 10-11-cm then at 10-cm intervals to a maximum depth of 140 cm. These sediment samples were sieved through a 2-mm mesh to remove shell hash, benthic animals, gravel and plant fragments before drying at 60ºC. The dry samples were ground to a fine powder (less than 100 μm) and stored in clean zip-lock plastic bags in the dark prior to isotopic analysis.

The CSSI method, including the chemical analysis of the samples, is described in detail in the appendices.

2.8 Landcover history for sediment-source modelling

Historical records of catchment land-cover changes were used to constrain the analysis of likely sediment-sources. This approach minimises the risk of unrealistic interpretations of potentially feasible (isotopic) solutions of soil sources derived from the mixing model.

New Zealand was the last major land mass to be colonised by people. Detailed work by Wilmshurst et al. (2008) confirms that Polynesians arrived in New Zealand in ~1280 AD. In the Bay of Islands, paleo-environmental reconstruction of swamp deposits at Kerikeri Inlet (Elliot et al. 1997) indicates that Polynesians also arrived here at about the same time. Terrigenous sediments deposited in a swamp preserve a detailed record of vegetation changes over the last 4300 years. These sedimentary records show a sharp decline in native-forest species, with a coincident increase in bracken and charcoal content occurred 600 years BP (~1350 AD). The accounts of Early European explorers, such as Captain Cook, indicate that large areas had been cleared of native forest and under cultivation (Beaglehole 1955). By the early 1800s extensive gardens of potatoes, kumara and other vegetable were cultivated by Māori (Richie, 1990). It is likely that introduced vegetables, such as potatoes, would have been obtained through trade with early European visitors, such as Whalers. These accounts do not, however, generally provide detailed land-cover information for specific sub-catchments.

In the following section we describe the land-cover history of major sub-catchments draining to the BOI System.

2.8.1 Waikare sub-catchment

The Waikare sub-catchment covers 81.4 km^2 (6.3%) of the total land catchment draining to the BOI system. Present-day land cover is dominated by native forest (56%), manuka/kanuka scrub (34%) and pasture (8%). Pine forest accounts for ~0.4% of the catchment area (NZ Land Cover Database- LCDB2, 2001).

Historical accounts suggest that the Waikare and Kawakawa areas were much less densely populated by Māori prior to the arrival of Europeans and large areas of native forest remained intact as they are today. From the early 1800s these forests supplied timber for construction of European settlements at Kerikeri and Waitangi where native timber was already scarce by the early 1800s. Although some forest clearance has occurred this was limited to areas along the Karetu River and along the shoreline (Lee, 1983; Richie, 1990).

2.8.2 Kawakawa sub-catchment

The Kawakawa sub-catchment covers 508.7 km^2 (39.3%) of the total land catchment draining to the BOI system. Present-day land cover is dominated by pasture (35%) native forest (25%), pine forest (18%) and manuka/kanuka scrub (10%) (NZ Land Cover Database- LCDB2, 2001).

Large-scale forest clearance occurred latter than in the Kerikeri and Waitangi sub-catchments following European settlement. Much of this forest clearance within the sub-catchment at Whangae and Pakarau, north and south of Kawakawa township occurred from the 1860s. Access tracks were still being cut through native forest as late as 1892. The Ruapekapeka area, on the southern boundary of the sub-catchment was also developed for homestead settlement and gum digging from the 1860s (Ritchie, 1990).

2.8.3 Waitangi sub-catchment

The Waitangi sub-catchment covers 316.3 km^2 (24.4%) of the total land catchment draining to the BOI system. Present-day land cover is dominated by pasture (66%) native forest (14%), manuka/kanuka scrub (7%) and pine forest (6%) (NZ Land Cover Database- LCDB2, 2001).

The Waitangi sub-catchment was a major population centre from the early Māori period due to fertile volcanic soils that were suitable for gardening of kumara and taro. This “food bowl” was centred on the area between Waimate North, Ohaeawai to the south and Puketona to the east. Evidence of networks of tracks, which criss-crossed garden areas and continued through the standing forest all over the district remain (Ritchie, 1990). This archaeological evidence is consistent with Darwin's account of Waimate North in 1835, which indicated that large areas of the catchment had been deforested prior to European settlement (Armstrong, 1992). These records suggest that in pre-European times the Waitangi catchment was a patchwork of gardens, native-forest remnants and scrub. The slash and burn agriculture that was practice also implies large areas of manuka/kanuka scrub and bracken, although the highly fertile soils of the area imply that gardens were likely to be occupied for relatively long periods.

Large areas of native-forest remnants (puriri, taraire & tawa), were cleared by European settlers from the late 1850s at locations such as Okaihau (north of Lake Omapere) where 5000 acres purchased from Māori were cleared for farmland (Ritchie, 1990). The first wheat crops at Okaihau were sown in 1869, but were short lived as the warm and humid climate was not suitable for wheat growing. Following these attempts to grow wheat & maize, dairying was established on smaller farms whereas dry-stock (i.e., sheep and cattle) farming occurred on larger farms. Extensive kauri-gum fields were also worked in the Lake Omapere area during the 1880s to early 1900s. A dairy factory opened at Ohaeawai in 1902 but was relocated to Moerewa in 1929 when the railway was completed. Although pastoral agriculture has dominated catchment landcover since the early 1900s, extensive orchards of citrus, kiwi fruit and avocado were established in the Waimate North & Ohaeawai area from the 1970s onwards (Ritchie, 1990).

2.8.4 Kerikeri sub-catchment

The Kerikeri sub-catchment covers 211.2 km^2 (16.3%) of the total land catchment draining to the BOI system. Present-day land cover is dominated by pasture (52%), orchards (18.3%, primarily citrus), native forest (6.4%), manuka/kanuka scrub (4.5%) and pine forest (9.5%) (NZ Land Cover Database - LCDB2, 2001).

Historical accounts and paleo-sedimentogical evidence indicate that deforestation of the Kerikeri sub-catchment occurred at an early stage after Polynesian arrival (Elliot et al. 1997). These sedimentary records show that the original catchment landcover in the Kerikeri area was composed of native forest dominated by rimu, with totara, tānekaha and kauri. A sharp decline in native-forest species, with a coincident increase in bracken and charcoal content occurred 600 years BP shortly after Polynesian arrival.

It appears likely that the Kerikeri area had large populations of Māori and that it was intensively cultivated for root crops. By the time of European settlement at Kerikeri (1819), deforestation was largely complete and timber for construction was obtained from native-forest stands in the Kawakawa and Waikare sub-catchments. Dry-stock pastoral agriculture (sheep and cattle) developed as a major land-use activity from the early 1800s.

Citrus was first introduced to Kerikeri in 1928 by George Alderton, who planted 10,000 trees purchased from Australia. By the late 1930s large orchards were producing citrus fruit, which was interrupted by the Second World War and droughts in 1945–1946. Citrus production subsequently increased in subsequent decades as well as the introduction of other fruit varieties, such as kiwi fruit in 1973–1974.

2.8.5 Te Puna sub-catchment

The Te Puna sub-catchment covers 47.6 km^2 (3.7%) of the total land catchment draining to the BOI system. Present-day land cover is dominated by pasture (73%), manuka/kanuka scrub (12%), native forest (5%) and pine forest (4%) (NZ Land Cover Database - LCDB2, 2001).

Like Kerikeri, Te Puna was settled by Māori at an early stage following the arrival of people about 700 years BP. At Wairoa Bay, east of Te Puna inlet, radiocarbon dating of shell from midden yield calibrated ^{14}C ages of 712 years ±39 years BP (Middleton 2003). Following the arrival of Europeans in the early 1800s, potatoes became an important stable crop for local Māori. Historical information on landcover changes in the Te Puna catchment itself is scant. The early settlement of this area by Māori, indicates that deforestation would have occurred at an early stage following the arrival of people.

2.9 Benthic ecology and sensitivity and vulnerability to sedimentation

The sensitivity and vulnerability of soft-sediment macro-benthic communities in the BOI system to the effects of sedimentation were evaluated using several datasets: two intertidal benthic infauna datasets collected by Northland Regional Council (NRC) and NIWA, under Oceans 20/20 funding, respectively; one shallow sub-tidal dataset containing both epifaunal and infaunal data, collected by NIWA under Oceans 20/20 funding; and one deeper subtidal dataset containing epifaunal data only, collected by NIWA under Oceans 20/20 funding.

The sensitivity of a macro-benthic community to sedimentation is defined as the response of individual taxa to sedimentation, based on their biological traits.

The vulnerability of a site's macro-benthic community to sedimentation is defined as the product of the likelihood of sedimentation occurring and the sensitivity of the macro-benthic community at that site.

2.9.1 Intertidal sampling

Intertidal sampling is undertaken annually by NRC at three sites located within the western flank of Kerikeri Inlet (Kerikeri River: KR; Pickmere Channel: PC and Waipapa River: WR) (Griffiths 2011) (Figure 2-10). The sites were selected to capture inputs from the inlets main sub-catchments which could then be related to changes in community structure. Each site is approximately 1800 m^2 and is a homogenous, un-vegetated intertidal area that is characteristic of the surrounding area. Sampling protocol described in Robertson et al. (2002) is replicated at each site and includes the collection of 10 macrofauna core samples (12.5 cm diameter and 15 cm deep; sieved across a 500 µm mesh and material fixed with 90% ethanol) and 10 amalgamated smaller sediment samples (2-cm deep) for the analysis of sediment grain size, organic content and heavy metals.

Intertidal sites 1–25 (Figure 2-10) were sampled in 2009 as part of the Oceans 20/20 programme and were selected to represent a variety of different habitats, hydrodynamic gradients and their potential for anthropogenic impacts (Hewitt et al. 2010). At each site (approximately 200 m^2), an assessment of visual habitat characteristics was made to assign the sites to habitat types (generally biogenic). Following this, 3-5 (depending on the heterogeneity of the site) samples were collected for macrofauna (13-cm diameter, 15 cm deep cores) and the analysis of sediment grain size and organic content (3-5 amalgamated 2 cm diameter and 2 cm deep cores). Macrofaunal samples were sieved across a 1 mm mesh and all material retained was preserved in 50% isopropyl alcohol. A full description of the sampling protocol is given in Chapter 11 (Hewitt et al. 2010).

These two datasets differ in timing of sampling, mesh size used to sieve (and thus the size range of the fauna collected) and taxonomic resolution. Problems posed by differences in taxonomic resolution were removed by amalgamating taxonomic groups in each dataset to match each other. For example, Nereididae species had to be amalgamated to the family level. The potential for sampling dates and mesh sizes to affect results was assessed by comparing community data collected from similar sites in each dataset using log transformed data to calculate Bray-Curtis dissimilarities between sites. These potential differences were then displayed using non-metric multidimensional scaling ordination (MDS, PrimerE, Clarke & Gorley, 2006).

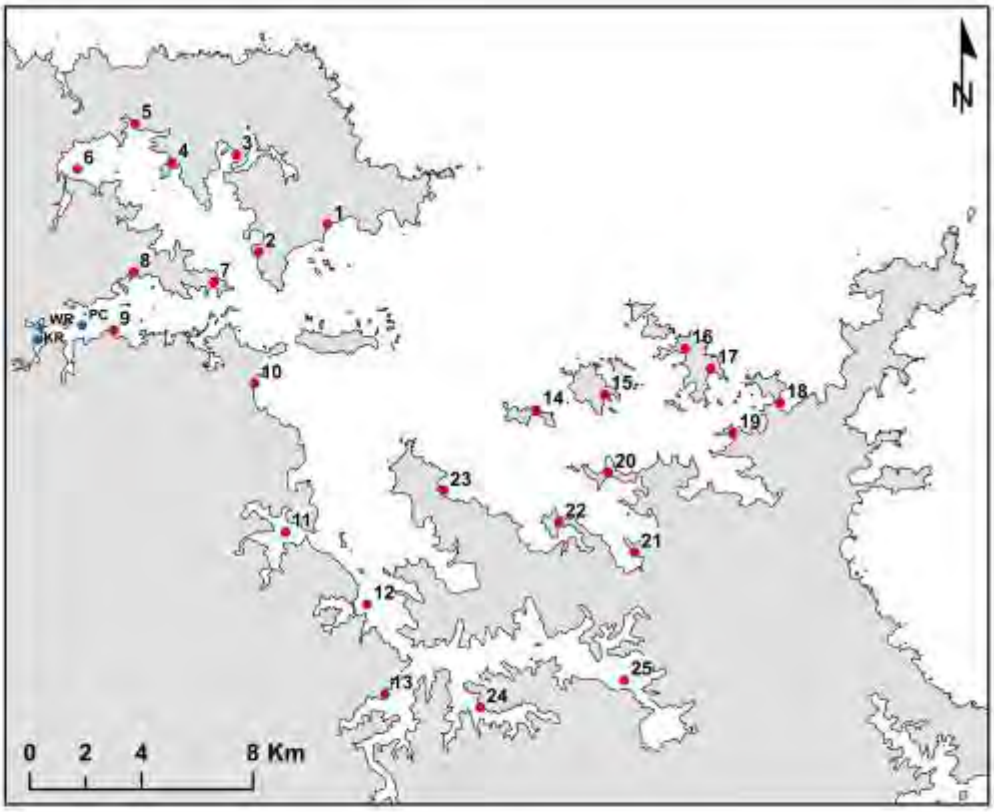

Figure 2-10: Intertidal sites sampled across the Bay of Islands as part of NRC's annual monitoring programme (KR, WR and PC denoted by blue circles) and the Oceans 2020 programme (sites 1-25 denoted by red circles).

2.9.2 Shallow subtidal sampling

Twenty eight shallow subtidal sites (<20 m) were sampled as part of the Ocean 20/20 research programme (Hewitt et al. 2010) (Figure 2-11). They were chosen based on geographical location, hydrodynamic gradients, and bathymetry.

Most sites were placed offshore from the mouths of inlets or within bays, as these were areas identified by MacDiarmid et al. (2009) as lacking previous sampling, with the remainder sampling near reefs or channel areas.

At each site, two 20 m transect tapes were deployed at right angles by divers and videoed. Sites were assigned to habitats based on video counts of the epifauna and flora along the transects.

Macrofauna cores (5–12 per site; 10-cm diameter, 15-cm deep) were collected along each transect in such a way as to sample the maximum apparent heterogeneity in habitat features. Cores were sieved across a 1 mm mesh, the material retained was preserved in 70% isopropyl alcohol and macrofauna were sorted and identified to lowest practical taxonomic level.

In addition, four syringe cores (2-cm diameter, 5-cm deep) were collected; the top 2 cm of sediment was sectioned and amalgamated for analysis of chlorophyll a, sediment grain size and organic content.

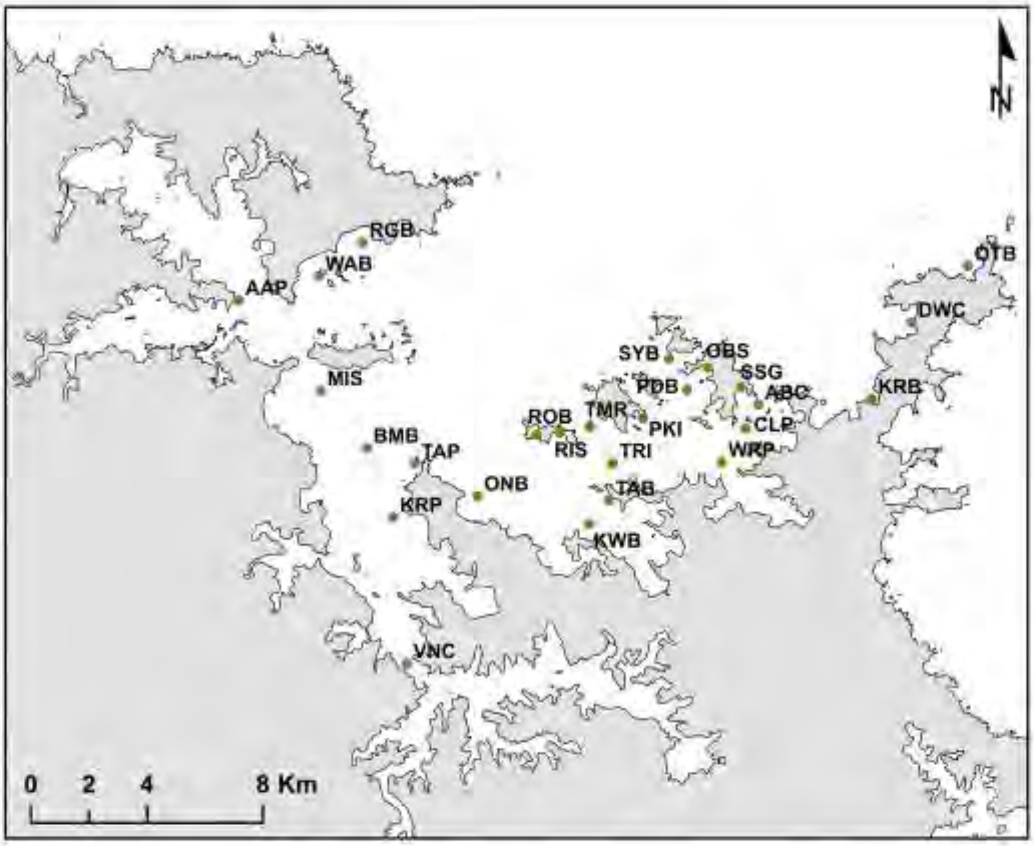

Figure 2-11: DTIS transect sites across the Bay of Islands, as part of the Oceans 20/20 programme.

2.9.3 Deeper sub-tidal sampling (DTIS)

Forty-four subtidal sites were sampled at night using NIWA's Deep Towed Imaging System (DTIS) to record data on seabed substrates, demersal and benthic fish, benthic invertebrates and algae (Bowden et al. 2010). Most of the sites were deeper than 20 m although some shallower sites were sampled to allow for comparisons between the shallow and deep sampling methods. Transects at each site (Figure 2-12) were run for approximately 30 minutes, with a target speed of approximately 0.5 m/s. Video footage and still images obtained were viewed and flora and fauna present were identified to the lowest practical level. In this study we utilise data from the video counts only.

2.10 Estimation of benthic community vulnerability to sedimentation

2.10.1 Determining SAR sub-areas

The sediment accumulation rates (SAR) determined at 22 subtidal sites in the present study were used in this assessment of the vulnerability of benthic communities at sampling sites. For the purposes of this analysis, the SAR data were interpolated and the Bay of Islands was divided up into six zones, based on knowledge of the catchment and sediment deposition (Table 2-6, Figure 2-13). Both intertidal and subtidal sites located within each of the six zones were then given an SAR rank based on the midpoint of the range.

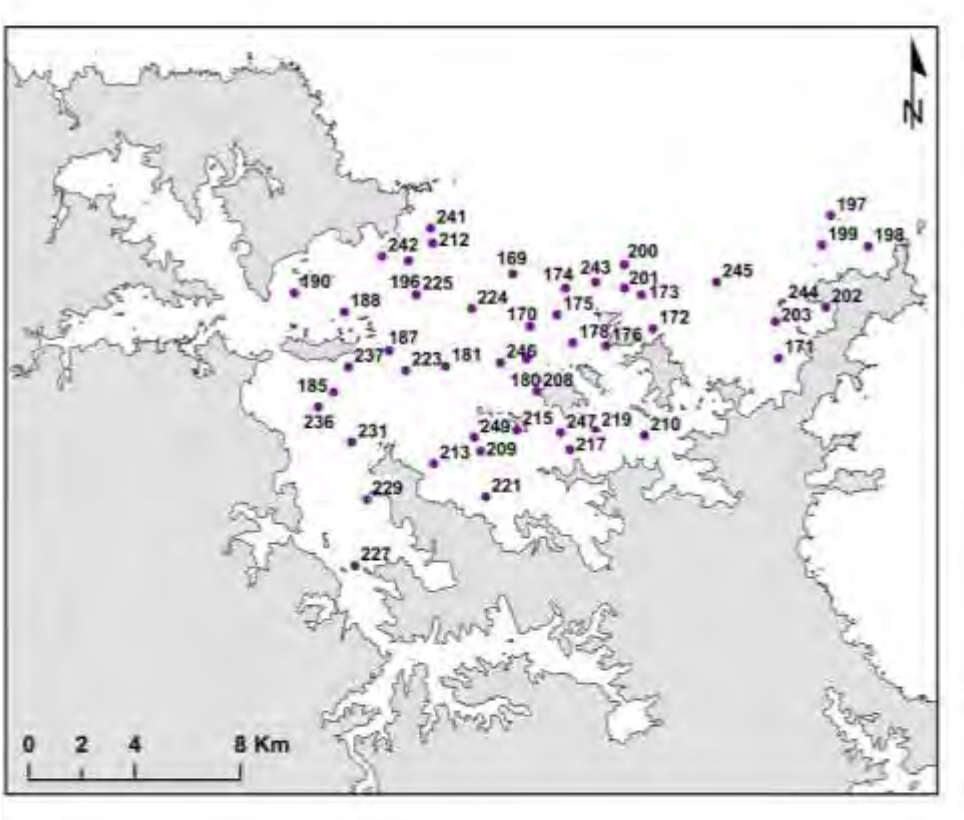

Figure 2-12:DTIS transect sites across the Bay of Islands, as part of the Oceans 20/20 programme.

Table 2-6: Sedimentation zones with estimated similar SAR levels, the SAR range for each zone and a justification as to why each zone was chosen. Note: number of core sites in brackets.

Zone	Description	Justification for zonation	SAR Range ($mmyr^{-1}$)	SAR ranking
1	Kawakawa to Russell	Largest Catchment	2.4–10+ (5)	6
2	Waikare Inlet	Proximity to Zone 1	1.1–3.2 (3)	4
3	Te Rawhiti Inlet	Small catchment and is also the deposition zone for Zone 1	2.3–4.9 (3)	5
4	Kerikeri and Te Puna Inlets	Smaller catchments and is remote from Zone 1. Similar SAR levels detected	1.8–2.4 (4)	3
5	Outer Bay of Islands	>30 m depth and is below the wave base	1.7–2.4 (3)	2
6	Inner Bay of Islands	<30 m depth and is subject to intense wave exposure which promotes resuspension	<1.5 (2)	1

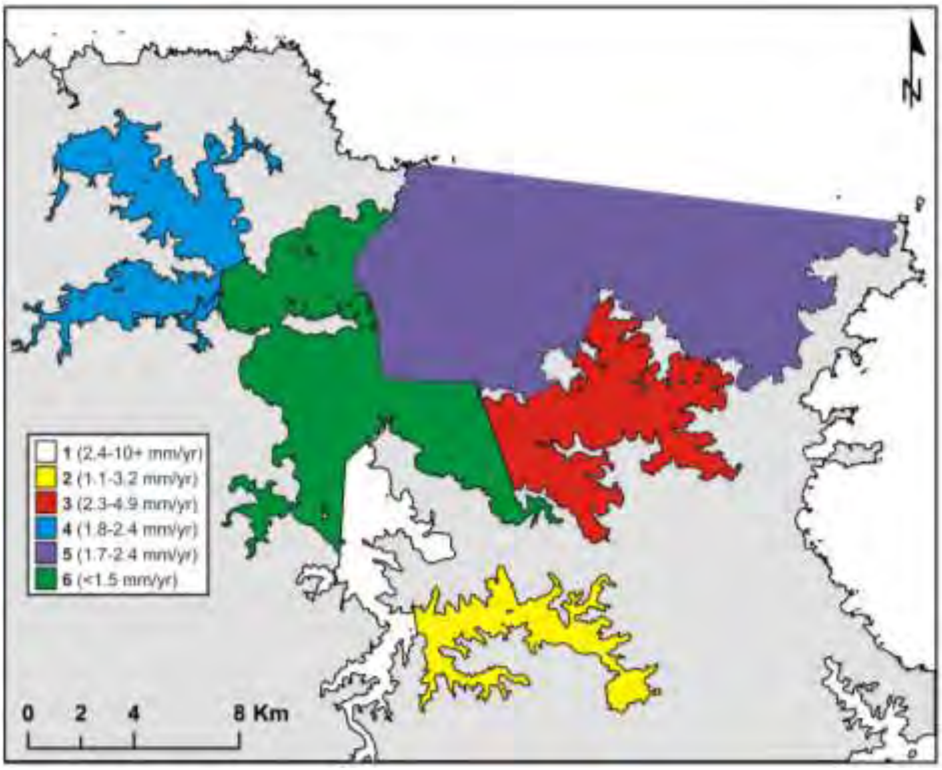

Figure 2-13: Estimated time-average sediment accumulation rate (SAR; mm/yr) zones of the Bay of Islands. SAR based on ^{210}Pb and ^{137}Cs dating of sediment cores.

2.10.2 Estimation of sensitivity

Information on species sensitivity to sediment deposition is not always available. There is information available for intertidal soft-sediment species (Gibbs & Hewitt, 2004), although mostly limited to the genera or family level. For subtidal species, there is much less species-specific information (but see (Ellis et al. 2002; Lohrer et al. 2003). For this reason, we determined species sensitivity using a simple ranking system consisting of three levels of sensitivity, namely: very sensitive (3); slightly sensitive to sediment deposition or preferring some mud content (2); and tolerant of moderate to high sediment mud content (1), rather than a more quantitative procedure.

Individual taxa sensitivities were determined at two levels: the dominant habitat forming species, for Oceans 2020 intertidal and subtidal datasets; and the ten most abundant taxa, for all datasets. Finally, beyond effects on individual taxa, increased sediment deposition can also be expected to decrease biodiversity measures (refs). For each site, number of taxa and the Shannon-Weiner diversity index were calculated and used to assign each site to one of three rankings (High (3), medium (2) and low (1)).

Overall site sensitivity to sediment deposition was defined, using the following hierarchical method:

- Very sensitive, if one of the dominant habitat-forming taxa was very sensitive, or if there was high diversity associated with one of the dominant habitat-forming taxa being sensitive or one of the ten most abundant taxa were highly sensitive.
- Sensitive, if one of the dominant habitat-forming taxa, or if one of the ten most abundant taxa was sensitive.
- Tolerant otherwise.

Again this results in a qualitative assessment.

2.10.3 Estimation of vulnerability at a location

Moving from sensitivity to vulnerability involves incorporating some assessment of risk. Here, we used the SAR ranks as the relative risk and, for each site, the sensitivity rank was then multiplied by a rank variable representing expected relative SAR at each site.

We used regression analysis to check that the SAR ranks were reasonable and that the SAR was an important driver of the benthic community composition and diversity. For the communities this was done using a distance based multivariate analysis communities (DSTLIM within PERMANOVA+ for PRIMER (Anderson et al. 2008). This was conducted with square root transformation of community data and a Bray-Curtis dissimilarity measure and utilized sediment properties (% mud and % organic content) as well as SAR as potential environmental drivers. For number of taxa, evenness and Shannon-Weiner diversity, this was done using Generalised linear modelling. The potential for some non-linearity was included by using $\log_{10}$ transformations of organic content and mud. Note that per cent explained by multivariate techniques should be expected to generally be lower than would be the case for univariate regression modelling (e.g., number of taxa), due mainly to problems in collapsing the multivariate dataset to the few dimensions able to be modelled with the environmental variables.

2.11 Recent changes in mangrove and saltmarsh-habitat extent

Changes in the spatial extent of mangrove and salt marsh habitat in the BOI system were determined based on analysis of aerial photography for a 31-year period (1978–2009). This analysis was undertaken by the Northland Regional Council as described here.

The 1978 aerial photography (NZ aerial mapping, S/N 5006, scale, 1:12,500) were scanned at 600dpi and georectified using a minimum of six ground control points. In all cases the residuals generated by this georectification were less than 10 metres. The 2009 aerial images were those flown for NIWA as part of the LINZ Oceans 20/20 BOI survey.

The areas of mangrove and saltmarsh habitats within each sediment compartment were hand digitised at a scale of 1:2000. Several protocols for digitising the vegetated habitat areas were adopted as applied in the Kaipara Harbour sedimentation study (Swales et al. 2011):

- Minimum polygon size has a maximum axis length of at least 10 m.
- Where habitat boundaries are obscured by shadow, either between habitat types or at the landward boundary, then the shadow is taken as the habitat boundary.
- Mangrove stands separated by small geomorphological features (e.g., channels) are digitised as separate polygons, even if the distance between the stands is less than 10 m.
- Single mangrove trees separated from mangrove stands were not included in the polygon area as this results in an over-estimate of the mangrove stand area.

Comparison of the 1978 and 2009 photography also provided a means to check the location of the land boundary when this was obscured in a particular survey.

Note that coverage for parts of the Veronica and Kerikeri compartments was not available for the 1978 survey. To calculate meaningful statistics of habitat change theses same areas were discarded from the 2009 survey. The actual habitat areas in 2009 within these two compartments are reported.

3 Results

3.1 Sedimentation patterns

The results of the radioisotope analysis of sediment cores are described in this section and summarised in Figure 3-1 and Table 3-1. They provide an estimate of time-averaged sediment accumulation rates in the BOI system over the last 100–150 years based on ^{137}Cs and ^{210}Pb dating.

The depth of the ^{7}Be surface mixed layer (SML) in bed sediments varies between 1–5 cm, which is consistent with observations in other North Island estuaries and coastal marine environments. The presence of the short-lived ^{7}Be ($t_{1/2}$ = 53 days) indicates that these surface sediments are being mixed over time scales of weeks to months by physical and/or biological processes. Long-term accumulation of sediments occurs once they are removed from the SML by burial as sediments continue to deposit.

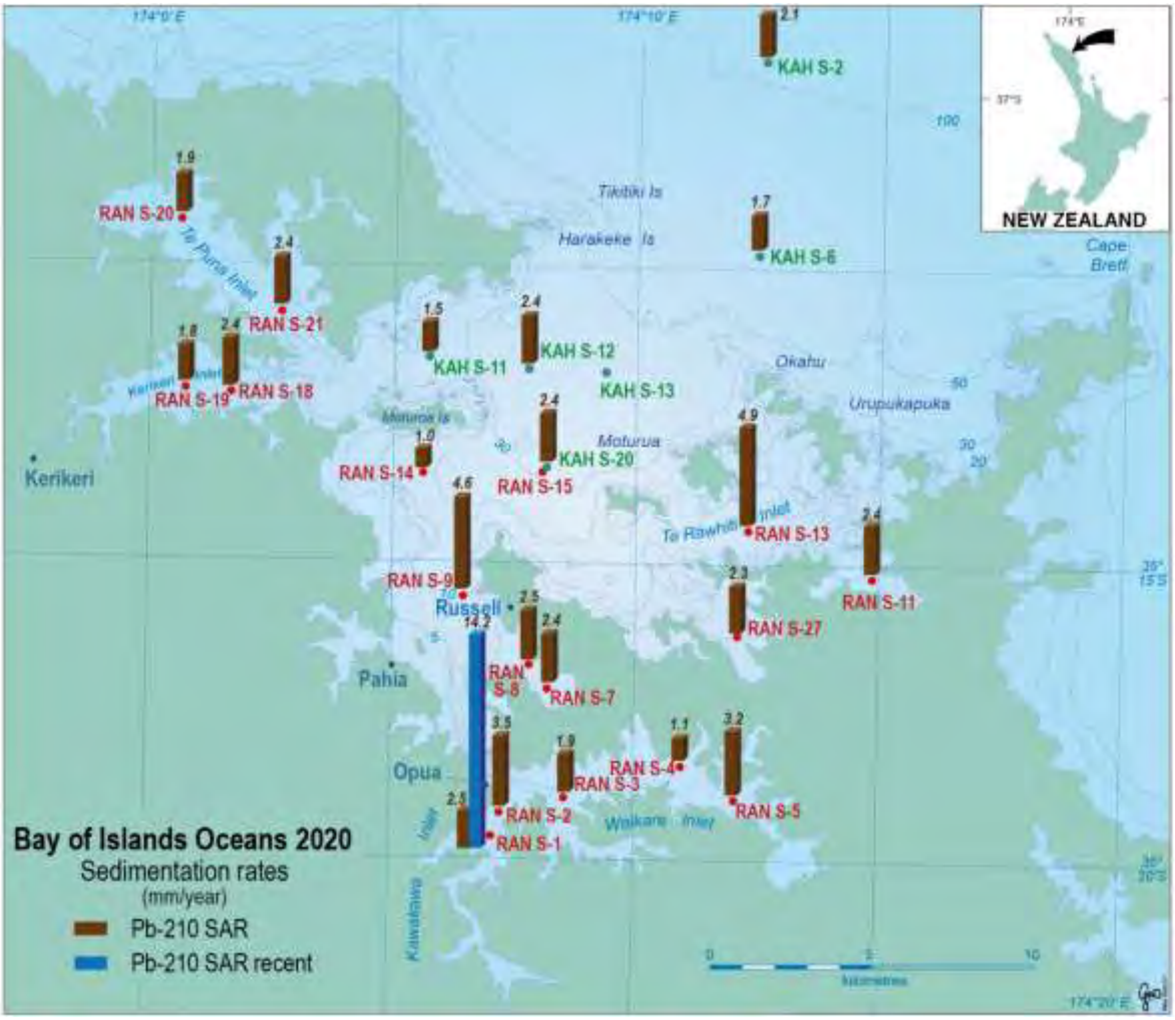

Figure 3-1: Time-averaged sediment accumulation rates in the Bay of Islands system estimated from excess ^{210}Pb profiles measured in RAN and KAH series sediment cores.

Table 3-1: Summary of sedimentation data from RAN and KAH series cores, Bay of Islands system.

Compartment	Core Site	^{7}Be SML (cm)	^{137}Cs max depth (cm)	^{137}Cs SAR (mm/yr)	^{210}Pb SAR (mm/yr)	r^2	n
Waikare	RAN S-1B	5	38	5.9	14.2 2.5	0.97 0.98	6 6
	RAN S-2B	4	28	4.3	3.5	0.91	7
	RAN S-3A	5	26	3.8	1.9	0.91	8
	RAN S-4A	5	17	2.1	1.1	0.65	5
	RAN S-5A	4	43	6.9	3.2	0.97	6
Veronica	RAN S-7A	4	23	3.4	2.4	0.98	9
	RAN S-8A	4	13	1.6	2.5	0.85	6
	RAN S-9A	4	38	6.1	4.6	0.96	16
Te Rawhiti	RAN S-11A	3	20	3.0	2.4	0.80	9
	RAN S-13C	1	28	4.8	4.9	0.97	11
	RAN S-27A	2	23	3.8	2.3	0.94	9
Brett	KAH S-2	3	17	2.5	2.1	0.97	13
	KAH S-6	2	14	2.1	1.7	0.94	12
Central BOI	RAN S-14B	2	14	2.1	1.0	0.95	8
	RAN S-15C	2	14	2.1	2.4	0.98	12
	KAH S-11	5	17	2.1	1.5	0.97	5
	KAH S-12	4	17	2.3	2.4	0.95	7
Te Puna	RAN S-20B	3	22	3.4	1.9	0.95	7
	RAN S-21A	4	23	3.4	2.4	0.85	13
Kerikeri	RAN S-18A	5	23	3.2	2.4	0.95	7
	RAN S-19B	3	23	3.6	1.8	0.93	6

Key: (1) surface mixed layer (SML) based on maximum depth of Berrylium-7 (^{7}Be SML); (2) maximum depth of caesium-137 (^{137}Cs); (3) time-averaged sediment accumulation rate based on regression fit to natural-log transformed excess lead-210 data (^{210}Pb SAR); (4) co-efficient of determination of fit in (3) (r^2); (5) sample size (n).

3.2 Estimating the surface mixed layer and recent sediment accumulation rates

The Bay of Islands has accumulated terrigenous sediments delivered to the system by rivers and streams over the last ~12,000 years (Bostock et al. 2010). These sediment deposits have been progressively buried by more recent inputs. In some locations, such as the central Bay and some of the inlets, these Holocene deposits are more than 30 metres thick. At any point in time, remobilisation of surficial sediments by currents, wave action and/or by benthic fauna is possible within the surface mixed layer (SML). Only when sediments are removed from the SML by progressive burial are they no longer part of the active sedimentary system.

3.2.1 Residence time of sediments in the surface mixed layer

The depth of the SML in seabed sediments can be evaluated using the maximum depth of the short-lived berrylium-7 (^{7}Be, $t_{1/2}$ = 53 days) profile. In the BOI system, the maximum depth of the SML varies between 1 and 5 cm depth, which is consistent with observations in other North Island estuaries and coastal marine environments. The presence of ^{7}Be indicates that these surface sediments are being mixed over time scales of weeks to months by physical and/or biological processes (Appendices). Long-term accumulation of sediments occurs once they have been removed from the SML by burial as sediments continue to deposit. A first order estimate of the residence time (R) of sediments within the SML can estimated from radioisotope data as:

$$R = T/S$$

where T is the thickness of the SML (mm) given by the maximum depth of ^{7}Bein the sediment column and S is the ^{210}Pb SAR (mm/yr) (Table 3-2). This analysis indicates that the average residence time of sediments in the SML is 16 ±4.3 years (95% CI), with a range of 2 to 45 years. The residence time can be used to define the age of recent sediment deposits as sediments, deposited (on average) over the previous 16 years. Thus sediments within the SML are composed of:

- Soils eroded by seasonal–annual storms and discharged by rivers draining the present-day catchment.
- Soils that were eroded from the catchment within the past two decades and are presently being reworked on the seabed by physical and/or biological processes within the SML.
- Older sediment deposits mixed upwards within the SML with ages typically $<R$.

An implicit assumption in this type of analysis is that the SML characteristics are constant over time. In reality, infrequent natural events, such as large-magnitude storms can erode older deposits and mix these with more recent near-surface sediments. For example, evidence of storm deposits is preserved as unconformities in the ^{210}Pb profiles of cores from the central BOI (RAN S-15, 30-m water depth, Figure 3-6) and on the inner shelf in 70–100 m water depth (KAH S-2 and KAH S-6, Figure 3-5). These cores show ~10-cm thick layers with uniform excess ^{210}Pb activities between 18 and 30 cm below the present-day seabed. Radioisotope dating indicates that these deposits were formed by an event that occurred in the early 1900s. This unconformity most likely represents deep erosion/mixing and subsequent re-deposition of bed sediments by large storm waves. These data are described in more detail in section 3.3.

3.2.2 Recent sediment accumulation rates in the BOI system

Recent sediment accumulation rates (SAR) have been estimated from ^{137}Cs and excess ^{210}Pb profiles, dating sediments deposited over the last ~150 years. Rates of sediment accumulation in the Bay of Island system before Polynesians arrived in New Zealand are presented in section 3.4.

Time-averaged SAR have been estimated from the maximum depth of the ^{137}Cs in each core, corrected for the ^{7}Be SML depth as described in the methods section. Sediments labelled with ^{137}Cs indicate deposition since the early 1950s. The ^{137}Cs SAR vary between 1.6 and 6.9 mm/yr (Table 3-1). Several factors suggest that the ^{137}Cs data should be used with caution: (1) ^{137}Cs activity has substantially reduced even since the early-1960s ^{137}Cs deposition peak (i.e., $t_{1/2}$ = 30 years) so that ^{137}Cs activities are below detectable levels in

Table 3-2: Residence time (R) of recent sediments in the surface mixed layer (SML) at core sites derived from ^{210}Pb and ^{7}Be data.

Core sites	Max. ^{7}Be depth (mm)	^{210}Pb SAR (mm/yr)	R (years)
Waikare			
RAN S-1B	50	14.2	3.5
RAN S-2B	40	3.5	11.4
RAN S-3A	50	1.9	26.3
RAN S-4A	50	1.1	45.5
RAN S-5A	40	3.2	12.5
Veronica			
RAN S-7A	40	2.4	16.7
RAN S-8A	40	2.5	16.0
RAN S-9A	40	4.6	8.7
Te Rawhiti			
RAN S-11A	30	2.4	12.5
RAN S-13C	10	4.9	2.0
RAN S-27A	20	2.3	8.7
Brett			
KAH S-2	30	2.1	14.3
KAH S-6	20	1.7	11.8
Central BOI			
RAN S-14B	20	1.0	20
RAN S-15C	20	2.4	8.3
KAH S-11	50	1.5	33.3
KAH S-12	40	2.4	16.7
Kerikeri			
RAN S-18A	30	2.4	12.5
RAN S-19B	40	1.8	22.2
Te Puna			
RAN S-20B	50	1.9	26.3
RAN S-21A	30	2.4	12.5
average	35.2	3.0	16.3
std deviation	12.1	2.7	10.1
std error	2.6	0.59	2.2

deeper deposits and the maximum ^{137}Cs is under-estimated; (2) we assume that the ^{7}Be SML has been constant over time. In fact, deeper mixing over annual–decadal time scales is indicated by some of the ^{137}Pb profiles (e.g., RAN S-5 and S-20) so that mixing maybe deeper, with the result that the maximum ^{137}Cs is over-estimated; (3) the early-1960s ^{137}Cs deposition peak observed in New Zealand wetland deposits (Gehrels et al. 2008), and the most reliable ^{137}Cs markers for dating, are absent in NZ estuarine and coastal marine sediments (Appendix A).

The ^{210}Pb profiles provide time-averaged SAR (i.e., most sites 1–4.9 mm/yr) that are generally lower than ^{137}Cs estimates. The ^{210}Pb estimates are considered more reliable as the dating is based on regression fits to the excess ^{210}Pb data and therefore have a statistical basis rather than purely relying on the reliability of a marker horizon as is the case for ^{137}Cs. In some situations the ^{210}Pb SAR estimate may overestimate the "true" value if recent (i.e., high activity) ^{210}Pb is mixed deeply into the seabed. This results in a steeper profile and therefore higher apparent SAR value. In most cases the SML is a small fraction of the excess ^{210}Pb profile depth so that we consider that the ^{210}Pb SAR are reliable estimates. Figures 3.2–3.7 present the sediment-core radioisotope data for each sedimentary compartment that is used to develop the recent sedimentation budget of the entire BOI system.

3.3 Spatial variations in recent sediment accumulation rates

3.3.1 Waikare Inlet

The Waikare Inlet includes cores RAN S-1 and S-2 collected near the Kawakawa River mouth as well as three sites along the main axis of the Waikare Inlet (RAN S-3 to S-5). The ^{210}Pb data for RAN S-1, close to the river mouth is unusual in that it indicates a large increase in sedimentation from 2.5 to 14.2 mm/yr in the recent past. This is clearly shown by the upward inflection in the ^{210}Pb profile at 20-cm depth (Figure 3-2), which dates to the mid-1990s.

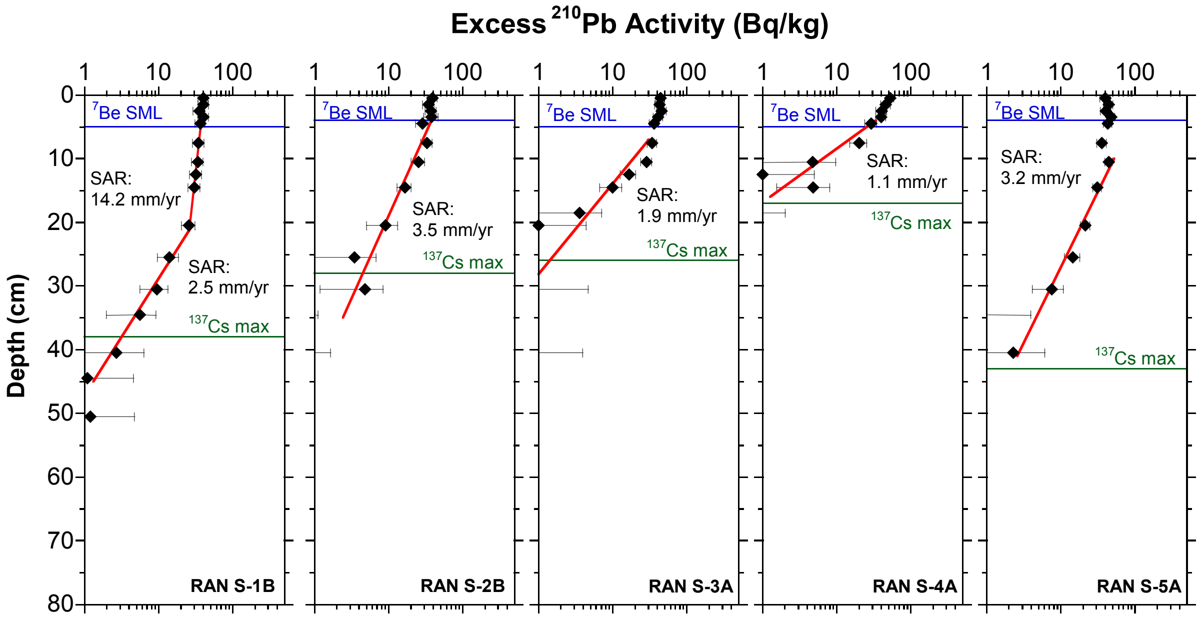

Figure 3-2: Waikare Inlet: sediment accumulation rates (SAR) for core sites RAN S-1 to S-5. Excess ^{210}Pb activity profiles with **95%** confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum depth of caesium-137 (^{137}Cs max) in each sediment core is also shown. Sediments below the ^{137}Cs max depth were deposited before the 1950s. Radioisotope activities are expressed in S.I. units of Becquerel's (Bq), which is equivalent to one radioactive disintegration per second.

An apparent reduction in ^{210}Pb SAR occurs from west to east along the main axis of the Waikare Inlet (S-2 to S-4, 3.5–1.1 mm/yr). Closer to the head of the Inlet, sediments accumulate more rapidly (RAN S-5, 3.2 mm/yr). Sediment-trap data and sediment-transport modelling undertaken as part of the Oceans 20/20 study suggests that this sedimentation pattern is a result of sediment resuspension in the Waikare Inlet by tidal currents and/or fetch-limited waves (Gibbs & Olsen, 2010).

3.3.2 Veronica Channel

Sediment cores from 3 sites located on the eastern side of Veronica Channel near Russell show excess ^{210}Pb profiles indicating uniform rates of sediment accumulation over the last 120 years in Orongo and Pomare Bays (Figure 3-3), with SAR averaging 2.4-2.5 mm/yr (RAN S-7 & S-8). Further north near Kororareka Point, muds have accumulated much more rapidly at site RAN S-9 on the subtidal flat flanking Veronica Channel. Here the excess ^{210}Pb profile extends to 70-cm depth, with SAR averaging 4.6 mm/yr. Core RAN S-9 provides one of the most reliable and extensive records of recent sedimentation records in the BOI system.

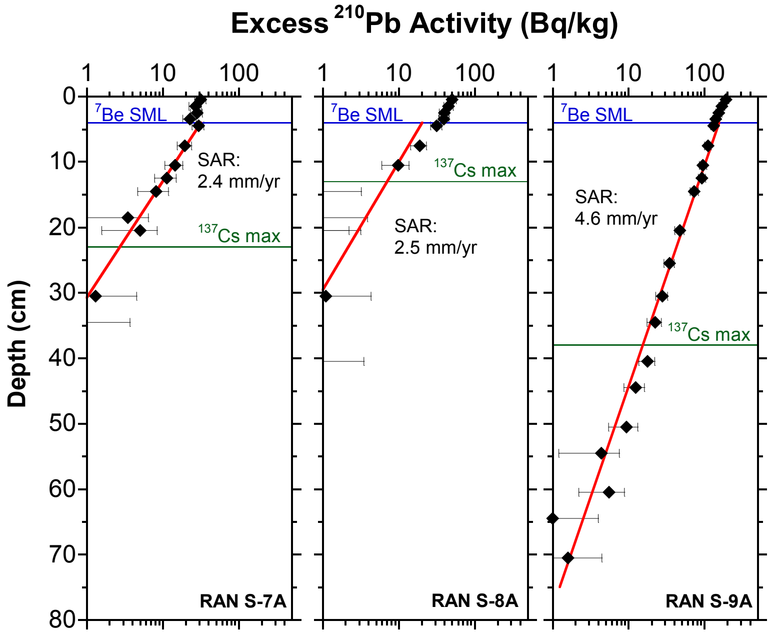

Figure 3-3: Veronica Inlet: sediment accumulation rates (SAR) for core sites RAN S-1 to S-5. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum depth of caesium-137 (^{137}Cs max) in each sediment core is also shown. Sediments below the ^{137}Cs max depth were deposited before the 1950s. Radioisotope activities are expressed in S.I. units of Becquerel's (Bq), which is equivalent to one radioactive disintegration per second.

3.3.3 Te Rawhiti

Sediment cores were collected from Te Rawhiti Inlet (RAN S-13) and the Parekura (RAN S-11) and Manawaora Bays (RAN S-27), which flank the inlet's southern shore. The excess ^{210}Pb profiles preserved in these cores indicate that the Te Rawhiti Inlet is a depocentre for fine sediment. The SAR of 4.9 mm/yr in the central Te Rawhiti Inlet at 4.9 mm/yr is two-times higher than in the bays over the last 80–120 years (2.3-2.4 mm/yr) (Figure 3-4). These data are consistent with rapid mud accumulation in a relatively deep fetch-limited basin, with lower SAR values in the flanking bays due to increased sediment resuspension by waves on shallow subtidal flats.

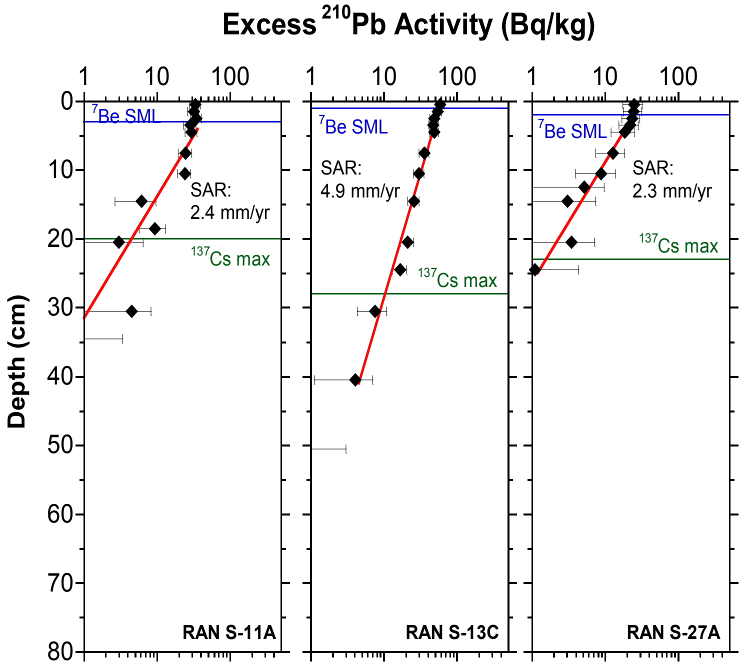

Figure 3-4: Te Rawhiti Inlet: sediment accumulation rates (SAR) for core sites RAN S-11, S-13 and to S-27. Excess ^{210}Pb activity profiles with 95% confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum depth of caesium-137 (^{137}Cs max) in each sediment core is also shown. Sediments below the ^{137}Cs max depth were deposited before the 1950s. Radioisotope activities are expressed in S.I. units of Becquerel's (Bq), which is equivalent to one radioactive disintegration per second.

3.3.4 Brett/Inner shelf

Sediment cores from the inner continental shelf (70–100 m water depth) at sites KAH S-2 and S-6 preserve a record of sedimentation over the last ~150 years (Fig. 3.5). These cores show that sediments are accumulating at a rate averaging ~2-mm/yr on the inner shelf. However, due to its relative large area the inner shelf environment is a major sink for mud.

A layer of sediments with uniform ^{210}Pb activities at 18–30 cm depth is indicative of deep reworking of the seabed to ~10-cm depth at a time in the past when this sediment layer was at the surface. This ^{210}Pb unconformity is more pronounced at the shallower KAH S-6. Closer scrutiny of the ^{210}Pb profiles also indicates lower accumulation rates below this unconformity than above it. For example, apparent SAR above and below the unconformity increase from 0.5 to 1.7 mm/yr and 1.2 to 2.1 mm/yr in KAH S-2 and S-6 respectively.

The most likely explanation for the unconformities in these sediment profiles is deep bed erosion by strong bi-directional currents generated by large, long-period storm waves. A similar ^{210}Pb profile unconformity is observed in a sediment core collected from the southern Firth of Thames, where storm waves eroded the intertidal mud flat to ~40-cm depth in July 1978 (Swales et al. 2007b).

The outer Bay of Islands and inner shelf are exposed to waves generated by north to north-easterly winds. ^{210}Pb dating of the upper surface of these unconformities provides a consistent age of 108 years (i.e., 1902 A.D.) for both core sites. Uncertainty in this age estimate arises from: (1) the fit of the regression line to the ^{210}Pb data, which determines the

SAR estimate and hence the age of sediments at any given depth; and (2) subsequent vertical mixing of the upper surface of this storm layer within the "fair-weather" surface mixed layer (SML) by waves and/or the activities of benthic animals. Figure 3-5 shows that the ^{210}Pb activities have relatively small errors, such that mixing of the storm-layer is a more likely source of uncertainty in the event age. At KAH S-2 and KAH S-6 sediments within the 20–30 mm thick SML have a residence time of 12–14 years before being removed from the active sedimentary environment by progressive burial (section 3.2.1). This process would have mixed the upper surface of the storm layer into younger post-storm sediments over the following decade so that the storm may have occurred as much as a ~decade later than 1902.

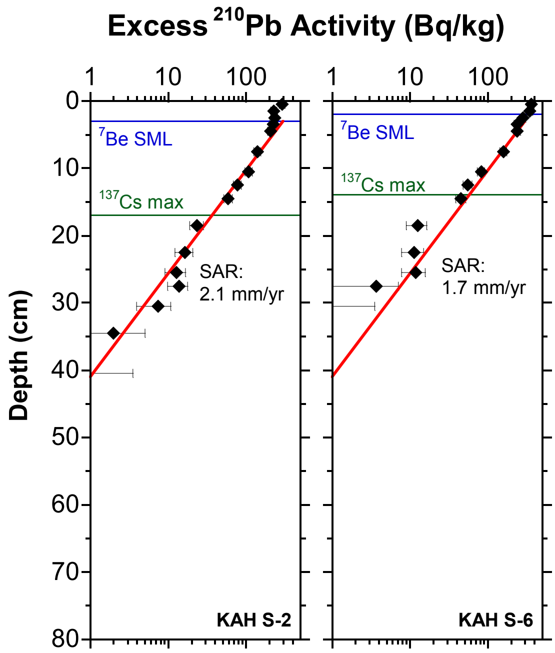

Figure 3-5: Brett: sediment accumulation rates (SAR) for core sites KAH S-2 and S-6. Excess ^{210}Pb activity profiles with 95% confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum depth of caesium-137 (^{137}Cs max) in each sediment core is also shown. Sediments below the ^{137}Cs max depth were deposited before the 1950s. Radioisotope activities are expressed in S.I. units of Becquerel's (Bq), which is equivalent to one radioactive disintegration per second.

Potential candidate storms have been identified from the New Zealand Historic Weather Events Catalogue (http://hwe.niwa.co.nz/):

- **June 1898:** upper North Island flooding and high winds. "Heaviest gale experienced in years" and "a severe storm on the night of 22nd June, winds from due east and it blew with hurricane force, the rain falling in sheets during 30 hours".
- **August 1905:** North Island storm. High wind at Russell. The "old British residency has suffered very severely, trees have been torn up by the roots, all the chimneys of the house blown down" and "veranda has been blown clean away".
- **March 1908:** Upper North Island storm. At Whangarei, "an easterly gale (3 days) accompanied by a tremendous downpour of rain, raged from the evening of the 7th to

the 9th". Heavy seas also resulted in the loss of many small boats in the Waitemata Harbour.

- **July 1909:** New Zealand storm. High winds in Northland and Auckland. At Auckland, the wind speed over 24 hours to 9 am on the 3rd July averaged 64 km/h, "but at time was much greater than this". The north-east gale averaged 53 km/h over 3–4 July. At Ruakaka (Northland) the wind blew the roof off a house.

3.3.5 Central Bay of Islands

In the central BOI sediment cores, radioisotope data indicate an offshore increase in SAR, from the inshore sites (1-1.5 mm/yr) to 2.4 mm/yr in the deeper waters of the central Bay (Figure 3-6). These sedimentation patterns are consistent with a wave-exposed sedimentary environment. The swell waves that penetrate the central Bay are likely have the capacity to rework the seabed in these intermediate water depths (18–40 m). In general this sediment reworking will occur more frequently as water depth decreases closer to shore.

Core RAN S-15 also contains evidence of an unconformity in the ^{210}Pb profile between 18 and 28-cm depth, similar to those preserved in deeper water at sites KAH S-2 and KAH S-6. The ^{210}Pb profile above 18-cm depth indicates a time-averaged SAR of 2.1 mm/yr, which dates the upper surface of the unconformity to the mid-1920s, which is substantially latter than estimated for the ~1902 event at KAH S-2 and KAH S-6. This unconformity may represent a more recent storm event.

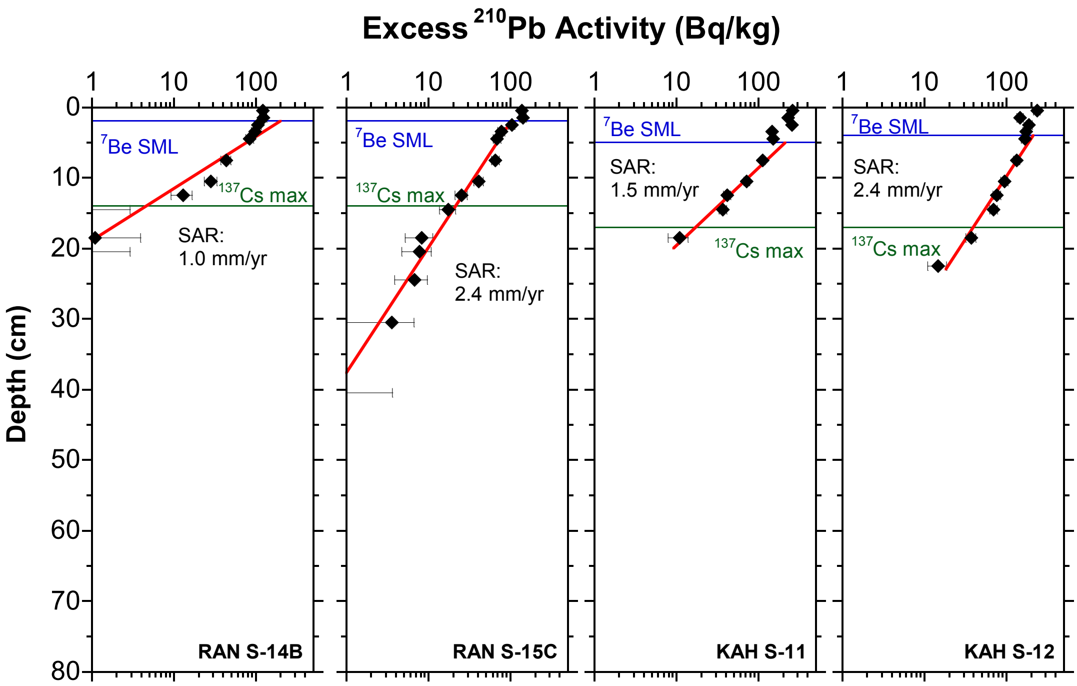

Figure 3-6: Central Bay of Islands: sediment accumulation rates (SAR) for core sites RAN S-14B and S-15C, and KAH S-11 and S-12. Excess 210Pb activity profiles with 95% confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum depth of caesium-137 (^{137}Cs max) in each sediment core is also shown. Sediments below the ^{137}Cs max depth were deposited before the 1950s. Radioisotope activities are expressed in S.I. units of Becquerel's (Bq), which is equivalent to one radioactive disintegration per second.

3.3.6 Kerikeri and Te Puna Inlets

Sediment cores from the Kerikeri and Te Puna Inlets which discharge to the north-west corner of the central BOI show similar patterns to each other with ^{210}Pb SAR of 1.8–2.4 mm/yr indicating relatively uniform rates of sedimentation in these inlets over the last ~100 years (Figure 3-7). An example of the fine-scale sedimentary fabric preserved in the sediment cores is shown by an x-ray image of core RAN S-18 sampled from the Kerikeri Inlet (Figure 3-8). The low-density muds (dark colour) in the top ~5 cm of the core coincide with the ^{7}Be surface mixed layer.

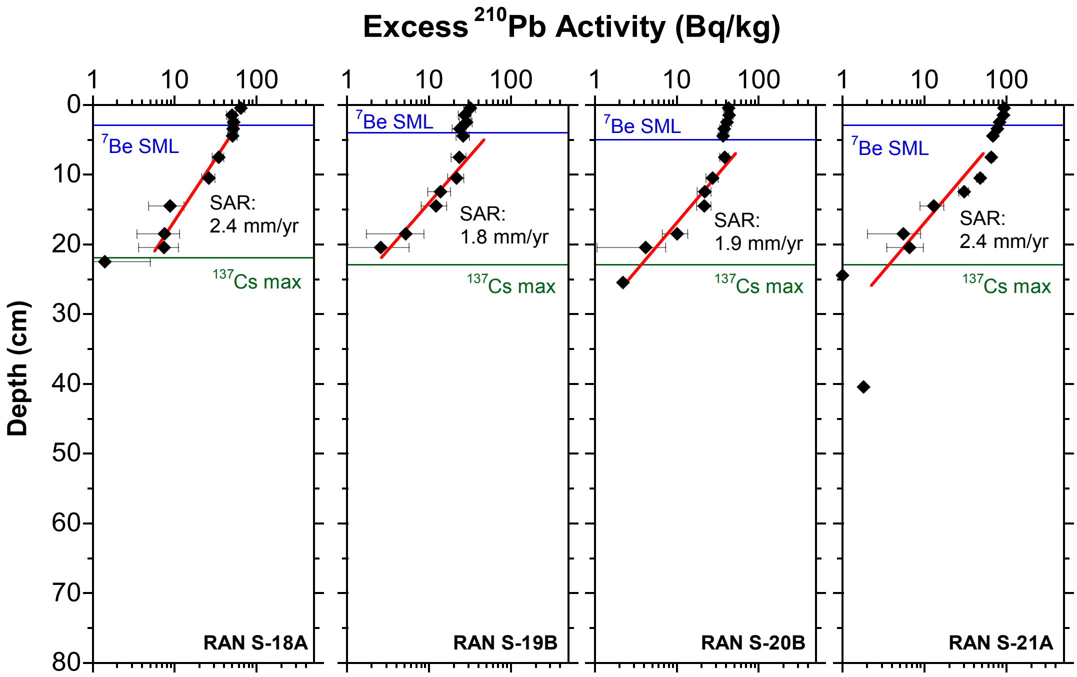

Figure 3-7: Kerikeri and Te Puna Inlets: sediment accumulation rates (SAR) for core sites RAN S-18A to S-21A. Excess ^{210}Pb activity profiles with 95% confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum depth of caesium-137 (^{137}Cs max) in each sediment core is also shown. Sediments below the ^{137}Cs max depth were deposited before the 1950s. Radioisotope activities are expressed in S.I. units of Becquerel's (Bq), which is equivalent to one radioactive disintegration per second.

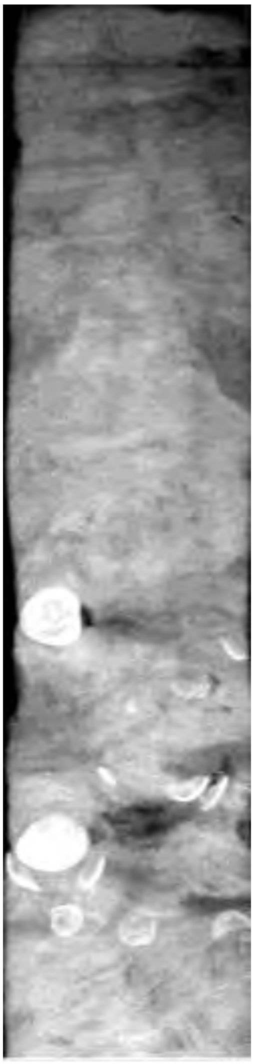

Figure 3-8: X-radiograph of the top 40 cm of core RAN S-18 collected in the Kerikeri Inlet (Exposure 25 mAs, 55 kV). The image has been inverted so that higher-density sediments appear white (e.g., quartz sand, shell, DBD ~2.7 g/cm^3) and low density and/or high-porosity sediments (e.g., saturated mud DBD <1 g/cm^3) appear dark. Cross-bedded, thin laminated layers of muds and fine sand are characteristic of estuarine sediments that have been reworked by waves and/or tidal currents. Cockle-shell valves can also be clearly seen in the core.

3.4 Long-term sediment accumulation rates

Radiocarbon dating of shell material preserved at depth in sediment cores has been used to estimated time-average SAR in the BOI system over the last several thousand years. Table 3-3 presents the calibrated ^{14}C ages estimated from Atomic Mass Spectrometry. The calibrated ages are in terms of years Before Present (BP, 1950 AD).

Long-term sedimentation rates below the recent (i.e., ^{210}Pb, last 150 yr) sediment layer are estimated from the sample depth and age. Sediments deposited below the ^{210}Pb-labelled layer include the period of human occupation since 1300 AD (i.e., ~650 yr B.P.). The period of human occupation represents a varying fraction (0.07–0.29) of the total sedimentation history represented by the ^{14}C-dated cores.

Table 3-3: Calibrated ^{14}C ages of shell samples and estimated long-term SAR for sediments deposited below the recent sediment layer, as indicated by the maximum depth of excess ^{210}Pb. Details of shell samples submitted for AMS dating. Notes: FF = filter feeder; DF = deposit feeder, Wk = Waikato Radiocarbon Laboratory number.

Location [Core]	Sample depth (mm)	Description	Age (yr BP)	Max ^{210}Pb depth (mm)	SAR (mm/yr)
Waikare Inlet [RAN S-5A]	1180–1200	1 x cockle-shell valve ((*Austrovenus stuchburyi*)), FF ~10 g [Wk-28224]	3,428 ±30	405	0.23
Waikare Inlet [RAN S-5A]	1180–1200	1 x cockle-shell valve (*Austrovenus stuchburyi*), FF ~10 g [Wk-28225]	2,584 ±30	405	0.30
Waikare Inlet [RAN S-5A]	1180–1200	1 x cockle-shell valve (*Austrovenus stuchburyi*), FF ~10 g [Wk-28226]	3,852 ±30	405	0.20
Te Rawhiti Inlet [RAN S-13C]	1300–1320	1 x shell valve (*Satellina nitida*), DF (0.42 g [Wk-28227]	7,633 ±31	505	0.11
Kerikeri Inlet [RAN S-19B]	1410–1430	2 x articulated shell valves (*Dosina subrosa*), FF 1.7 g [Wk-28228]	2,842 ±30	205	0.43
Te Puna Inlet [RAN S-20B]	1010–1030	1 x shell valve (*Serratina charlottae*), DF ~0.2 g [Wk-28229]	2,170 ±34	255	0.35
Manawaroa Bay [RAN S-27A]	1140	2 x articulated cockle-shell valves (*Austrovenus stuchburyi*), FF 4.8 g [Wk-28230]	7,781 ±30	245	0.12
Central BOI [KAH S-129]	1140–1150	1 x shell valve (*Tawera spissa*), DF <0.2 g [Wk-28231]	9,409 ±30	410	0.08
outside Te Puna Inlet [KAH S-132]	1900–1930	1 x Turret Shell (*Maoriculpus roseus*), DF <1 g [Wk-28232]	4,440 ±30	~235	0.38
Central BOI [KAH S-141]	1590–1610	1 x shell valve of clam (*Talochlamys zelandiae*), FF <1 g [Wk-28233]	6,581 ±30	~200 (KAH S-12/13	~0.21
South of Motoroa Island [RAN S-14]	1350–1410	1 x large scallop shell (*Pecten novaezelandiae*), FF [Wk-28491]	7,479 ±46	210	0.16

The ages of shell samples deposited 1.1–1.9 m below the present seabed surface varied in age from 2170 to 9409 years B.P. The associated dating uncertainty was ±30–46 years at the 95% confidence interval.

A limitation of ^{14}C dating is the potential for reworking of shell material after death of the shellfish that is subsequently re-deposited at another location and/or in younger or older sediments. In these situations, the sediment layer containing the sample is erroneously dated as an older deposit. This situation could arise during storm events where large-scale erosion of the floor occurs. In situations where shells of varying ages are remobilised and re-deposited, varying ages for the associated sediment layer would be inferred. The most reliable ^{14}C dates for sediment deposits are generally provided by articulated shells (i.e., both valves still attached) and oriented as they would have been when living.

Three disarticulated cockle-shell valves dated in core RAN S-5A (Waikare Inlet) illustrates this potential source of error. Table 3.3 shows that two of the shell valves have similar ages (i.e., 3428 and 3852 yr B.P.), whereas the third shell valve is significantly younger at 2584 yr

B.P. This ~1000 year age difference represents a 0.1 mm yr^{-1} (~30%) difference in the estimated long-term SAR.

The long-term ^{14}C SAR values display a similar spatial pattern to more recent sedimentation indicated by the ^{210}Pb dating. Sediment accumulation prior to catchment deforestation was most rapid in the estuaries close to the larger rivers. The ^{14}C SAR have averaged 0.2–0.43 mm/ yr in Waikare, Kerikeri and Te Puna Inlets, whereas accumulation rates at more remote sites in the inner and central Bay have been substantially lower (0.08–0.21 mm yr^{-1}). A major exception to this general sedimentation gradient is that SAR over the last ~100 years in the Te Rawhiti Inlet are among the highest measured in the entire BOI system. This is in sharp contrast to low ^{14}C SAR values over the last ~7,500 years (0.11–0.12 mm yr^{-1}) prior to large-scale human disturbance of catchments. These results indicate that fine sediments are being preferentially transported to and deposited in the Te Rawhiti Inlet.

3.5 Influence of land-use changes on sedimentation

Comparison of SAR estimated for time periods before and after the arrival of people in the Bay of Islands provides information on how large-scale catchment deforestation from the mid-1300s onwards (section 1.3) has impacted on the marine environment. The ^{14}C ages for the dated shell material range from 2170 to 9409 years B.P. (i.e., 1950 A.D). Post-European sedimentation, as defined by ^{210}Pb dating, span the last 82–200 years. It should be noted that the time-average ^{14}C SAR estimates for the pre-European period include the effects of Māori land-use practices since the mid-1300s. Consequently, the ^{14}C SAR values are probably higher than the actual pre-human values. Table 3-4 presents the results of this analysis.

Table 3-4: Comparison of long-term pre-human and recent sediment accumulation rates (SAR) based on radiocarbon and ^{210}Pb dating of sediment cores, Bay of Islands.

Core site	Location	^{14}C SAR (mm/yr)	^{210}Pb SAR (mm/yr)	^{210}Pb time period	SAR increase	Comment
RAN S-5A	Waikare	0.24	3.2	post 1885	x13	
RAN S-13C	Te Rawhiti	0.11	4.9	post 1928	x45	
RAN S-19B	Kerikeri	0.43	1.8	post 1899	x4.2	
RAN S-20B	Te Puna	0.35	1.9	post 1879	x5.4	
RAN S-27A	Te Rawhiti	0.12	2.3	post 1901	x19	
KAH S-129	Central BOI	0.08	2.4	post 1865	x30	near RAN S-15
KAH S-132	Te Puna	0.38	2.4	post 1906	x6.3	near RAN S-18 & S-21
RAN S-14B	Inner BOI	0.16	1.0	Post 1810	x6.3	
average		0.23	2.49			
std error		0.05	0.41			

Radioisotope dating of the sediment cores indicates that SAR have increased by an order of magnitude following large-scale deforestation of the Bay of Islands catchment. Average ^{14}C and ^{210}Pb SAR are 0.23 ±0.1 mm yr^{-1} and 2.5 ±0.8 mm yr^{-1} (95% CI) respectively. Although the variations in the pre-/post-deforestation periods for each core make detailed comparisons problematic, the data do suggest spatial variations in the impacts of catchment disturbance on sedimentation in the BOI system.

Increases in SAR vary 4–13 fold in the estuaries to 19–45 fold in the Central Bay and Te Rawhiti Inlet. These results indicate that: (1) pre-human SAR were lower at sites remote from river outlets; and (2) remote environments have been relatively more adversely impacted by fine-sediment deposition over the last ~150 years following European settlement. These observed order-of-magnitude increases in SAR following deforestation of the BOI catchment are consistent with data from other North Island estuaries (Goff 1997; Hume & McGlone, 1986; Hume & Dahm, 1992; Oldman & Swales, 1999; Swales & Hume, 1995; Swales et al. 1997, 2002a, 2002b, 2007a).

3.6 Particle size

Figure 3-9 presents particle-size information for the Waikare (RAN S-3) and Te Rawhiti (RAN S-13) Inlets. These data are for volume-based particle size distributions (PSD) as described in the methods section. Depth profiles of key particle-size statistics are shown: mean; median; D10 and D90. The D10 and D90 statistics are the particle diameters corresponding to the 10th and 90th percentile of the particle-size distribution.

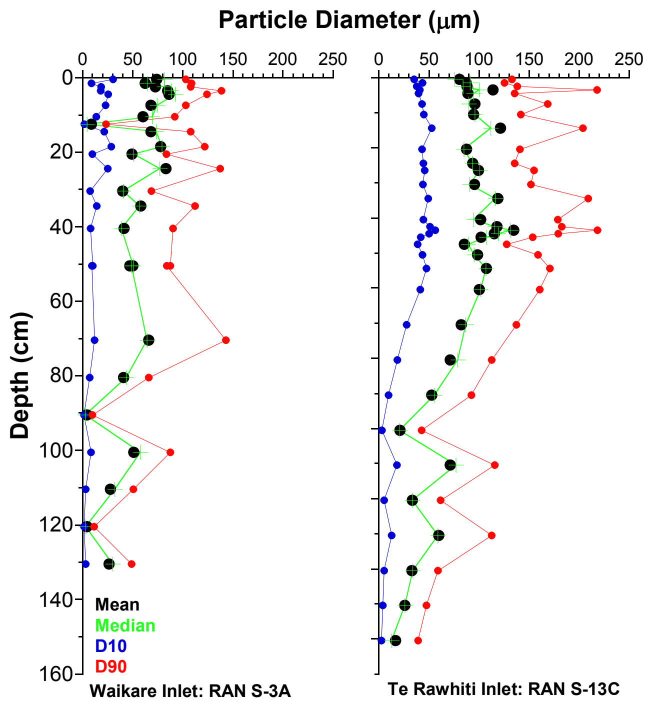

Figure 3-9: Depth profiles of key particle size statistics for cores from the Waikare (RAN S-3) and Te Rawhiti (RAN S-13) Inlets, Bay of Islands.

Particle size at both core sites display small-scale variability with an overall weak trend of decreasing particle size with depth in the sediment column. Thus, more recent sediments near the top of the core contain more fine sand than older deposits at depth. The particle size distribution of the Waikare Inlet sediments are noticeably finer than in the Te Rawhiti Inlet, the former being composed almost entirely of mud.

3.7 Recent sedimentation in the BOI system

Sediment accumulation in the BOI system over the last ~150 years reconstructed from dated cores and seabed mapping is summarised in Table 3-5 and presented as bar charts in Figures 3-10 and 3-11. The annual deposition rates in tonnes/year are normalised to a unit-area sedimentation flux in kg/m^2/yr to take into account the different sizes (i.e., areas) of each compartment (Figure 2-6).

Table 3-5: Annual sediment deposition in each sedimentary compartment estimated from sediment core and seabed mapping data, Bay of Islands system.

Compartment	Total area (km^2)	ASS (km^2)	D_V (m^3/yr)	D_T (t/yr)	$D_{T\text{-}ERR}$ 95% C.I.	D_M (t/yr)	D_S (t/yr)	$D_{M/A}$ (kg/m^2 yr)	$D_{S/A}$ (kg/m^2 yr)
Waikare	25.0	25.02	60,054	50,629	18,602	14,176	36,453	0.57	1.46
Veronica	24.6	23.26	74,438	67,640	28,929	46,672	20,968	2.01	0.90
Te Rawhiti	50.4	46.0	147,185	154,710	83,204	85,090	69,619	1.85	1.51
Brett	49.2	33.92	64,444	54,634	12,609	27,317	27,317	0.81	0.81
Central BOI	107.0	74.6	134,335	136,326	53,157	74,979	58,620	1.00	0.79
Te Puna	20.3	20.3	34,506	24,050	7,944	24,050	0	1.18	0.0
Kerikeri	11.1	10.9	22,880	20,849	5,720	6,672	14,177	0.61	1.3
Total	287.6	234.0	537,841	508,837	210,164	278,955	227,155		

Key: (1) area of soft sediment (ASS); (2) sediment dry bulk density (DBD) from RAN-series cores; (3) annual total sediment volume deposited (D_V); (5) annual total sediment mass (D_T), mud (D_M) and sand (D_S) deposited (t/year); (6) annual mass of mud and sand deposited in tonnes per square metre per year ($D_{M/A}$ and $D_{S/A}$).

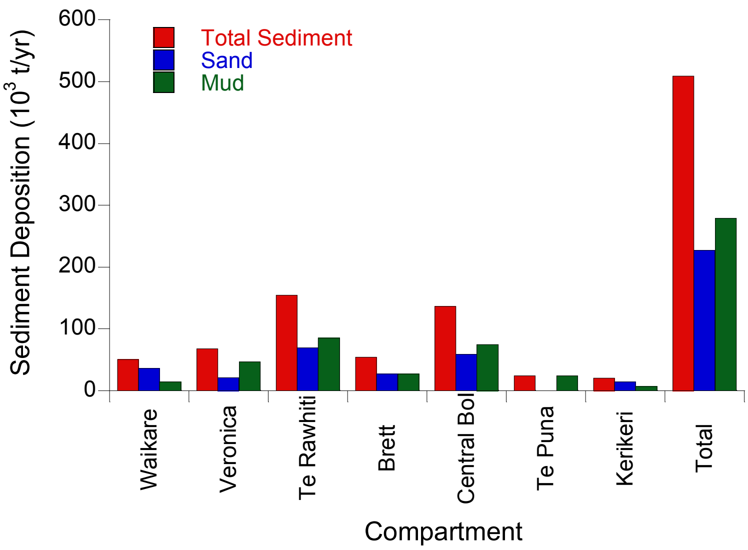

Figure 3-10: Annual sediment deposition rates (tonnes per year) in each compartment for total sediment mud and sand fractions.

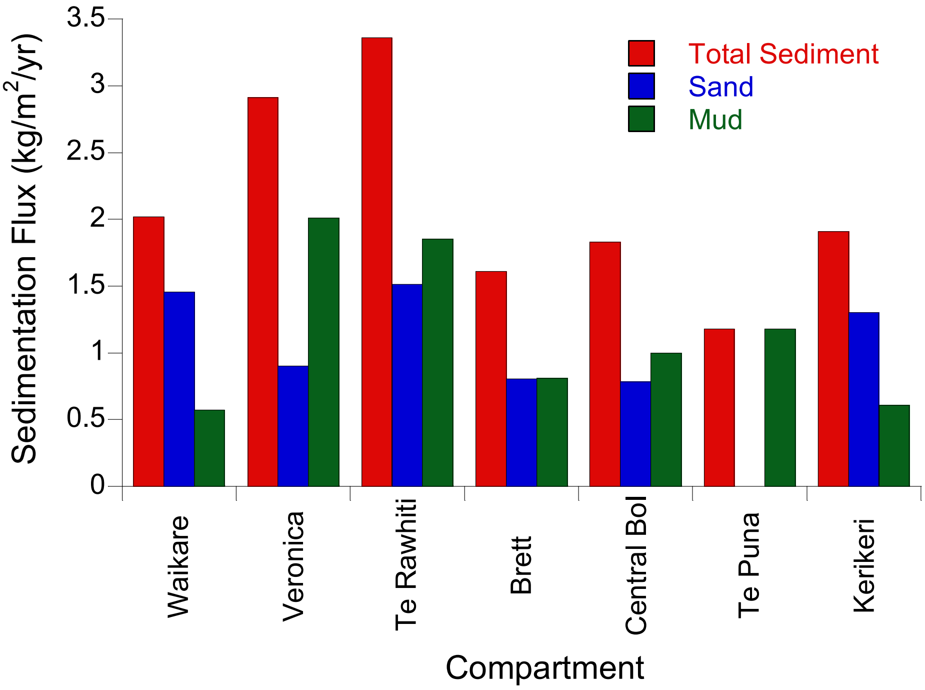

Figure 3-11: Annual sediment deposition rates in each sedimentary compartment expressed as unit-area sedimentation flux (kg/m^2/yr) for total sediment, mud and sand.

The key results of this analysis are:

- The average annual sediment deposition in the BOI system over the last ~150 years has totalled 509,000 tonnes per year (t/yr), with a 95% confidence interval (C.I.) of 299,000–719,000 t/yr. This 95% C.I. is based on ^{210}Pb SAR and DBD data for each compartment.
- Overall, 55% of this annual sediment deposition is composed of mud and 45% is fine sand.
- The Te Rawhiti Inlet, with a depositional area of ~46 km^2 and a relatively high average SAR of 3.2 mm/yr is presently the single largest sediment sink in the BOI system, and accounts for 30% of the annual sedimentation deposition.
- The annual average sediment deposition in the BOI system is similar to the estimated present-day annual suspended load of ~430,000 t/yr of the largest sub-catchments that discharge to the BOI system, suggesting that a large proportion of the catchment sediment input is trapped in the bay.

3.8 Comparison of recent and prehistoric sediment budgets

The long-term sediment budget of the BOI system has been estimated for the Holocene period before and after European settlement. This analysis indicates average sediment deposition of 509,000 ±210,000 tonnes per year (t/yr, 95% CI) over the last ~150 years.

This long-term pre-deforestation annual deposition rate was estimated using two methods:

- Total volume of sediment deposited in the BOI system over the last 10,000 ±3000 years based on geophysical surveys of the Holocene unconsolidated marine sediments deposited on the underlying bedrock erosion surface (Bostock et al. 2010). This method has the advantage of estimating the total sediment volume from tens of kilometres of geophysical survey transects.
- Total volume of sediment deposited in the BOI system over the last ≤ 9,400 years based on ^{14}C dating of sediment cores (section 3.4). The average ^{14}C SAR and dry-bulk densities (DBD) used in this analysis are respectively 0.23 ±0.1 mm/yr and 0.98 t/m^3 ±0.08 t/m^3 (95% CI). The total area of seabed included in the sediment budget calculation excluded areas of present-day rocky reef exposed at the seabed. The main advantage of this method is that sediment accumulation rates are directly measured, although at relatively few sites.

This analysis provides estimates of average sediment deposition rates over the last several thousand years prior to European settlement:

- 23,000 ±9,000 t/yr (95% CI) based on the estimated volume of Holocene sediment deposits and an assumed time-scale.
- 53,000 ±23,000 t/yr (95% CI) based on ^{14}C dating of sediment cores.

The variation in these sediment-budget estimates reflects uncertainties in the two approaches used. The pre-European period includes the effects of partial catchment deforestation by Māori over several hundred years prior to the mid-1800s so that actual background sediment inputs would likely have been lower than estimated here. It is reasonable to conclude that background sediment inputs to the BOI from a native-forest catchment were of the order of tens of thousands of tonnes per year.

Comparison of the Holocene and recent sedimentation budgets indicate a major shift in the sedimentary regime of the BOI system. The annual average rate of sediment deposition in the BOI system over the last ~150 years of 509,000 ±210,000 t/yr is 10-20 times higher than during the preceding Holocene period and before European settlement. This order of magnitude increase in sedimentation is consistent with increased soil erosion following large-scale deforestation by people. This is a global phenomenon (Thrush et al. 2004), although the timing of this deforestation varies with location. New Zealand was the last major land mass to be colonised by people, so that these major environmental changes have occurred in only the last few hundred years.

3.9 Comparison with sedimentation rates in other North Island estuaries

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

Figure 3-12 presents the average ^{210}Pb SAR for several North Island estuaries based on data from 85 cores sites. The Auckland east-coast data set includes the Mahurangi, Puhoi, Okura and Te Matuku estuaries and the Karepiro, Whitford and Wairoa embayments. The Bay of Islands data includes the Te Puna, Kerikeri, Kawakawa and Te Rawhiti Inlets as well as data from the Bay in water depths of 1–100 m. Table 3-6 provides additional information.

The average ^{210}Pb SAR in the BOI system is 2.4 mm yr^{-1} (SE = 0.2 mm yr^{-1}), which is lower than for most other North Island estuaries included in this comparison. The lowest sedimentation rates occur in the central Bay of Islands where ^{210}Pb SAR have averaged 1.9 mm yr^{-1} (SE = 0.2 mm yr^{-1}) over the last century.

Sediment accumulation rates in the Kaipara Harbour are substantially higher than in the BOI system. The harbour-average SAR for the Kaipara Harbour is 6.7 mm yr^{-1}, although this is skewed by high SAR values recorded at two sites, with SAR of 20–30 mm yr^{-1}. This also results in the large variability in the harbour-average SAR estimate. It is likely that these high SAR values reflect local environmental conditions (e.g., lateral shift in channel position, proximity to river mouth) rather than due to increased catchment sediment load. Excluding data for these two outliers yields a harbour-average SAR of 4.0 mm yr^{-1} (SE = 0.6 mm yr^{-1}) for the Kaipara Harbour. In either case, the average ^{210}Pb SAR for the Kaipara Harbour is not significantly different from the average value for intertidal environments in Auckland east-coast estuaries (5.1 mm yr^{-1}, SE = 0.8). Figure 3.11 also shows that average ^{210}Pb SAR are significantly lower in all other North Island estuaries and embayments (range 1.9–3.4 mm yr^{-1}) for which we have reliable data.

The relatively low SAR measured in the BOI system reflects the overall large capacity (i.e., accommodation space) of the receiving environment relative to the catchment sediment load. This is not to say that rapid sediment accumulation does not occur in the smaller fringing estuaries close to river sources. Land-use intensification has not occurred to the same extent as that in Auckland, where progressive urbanisation and land-use intensification over several decades has increased sediment delivery to estuarine receiving environments.

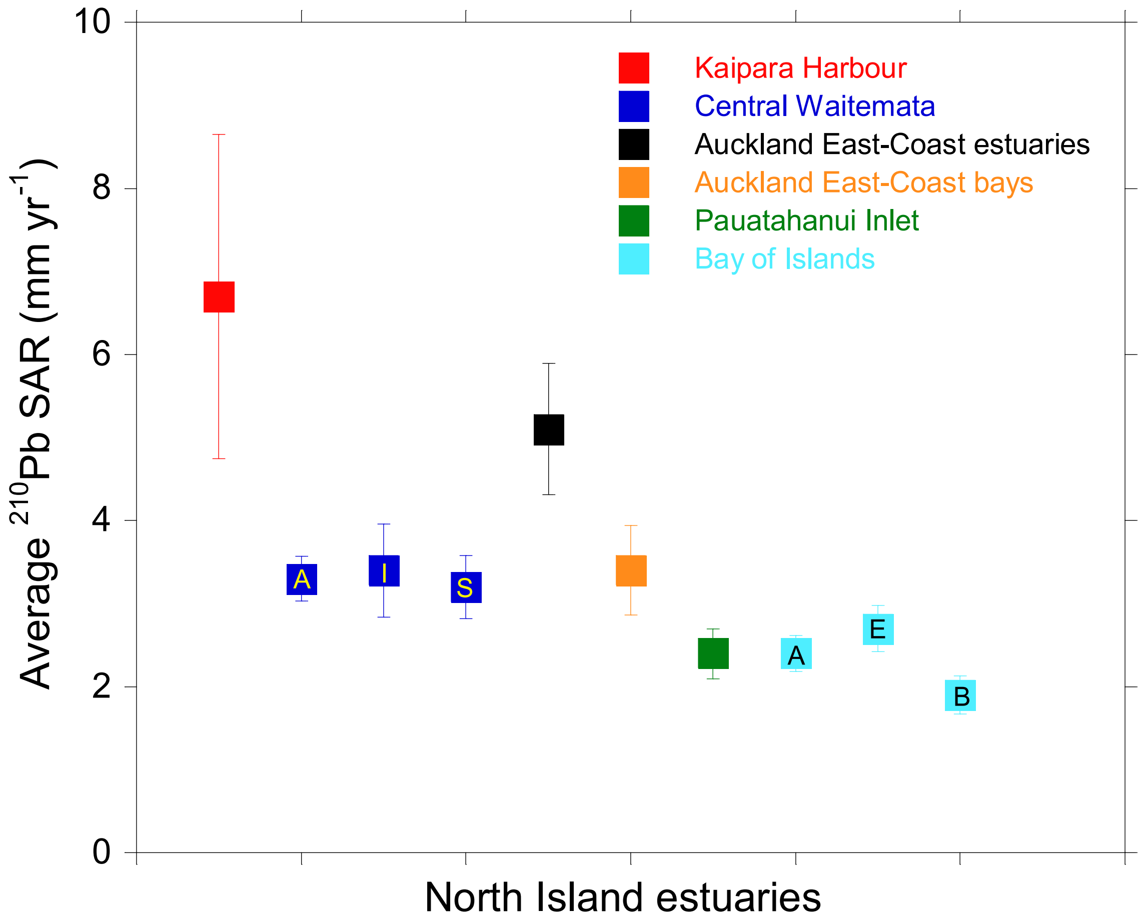

Figure 3-12: Comparison of average ^{210}Pb sediment accumulation rates (SAR) in North Island estuaries with standard errors shown. Notes: (1) key - all data (A), intertidal sites (I), subtidal sites (S), estuaries (E), coastal embayments (B); (2) Total number of cores = 85; (3) Data sources: Table 3-6.

Table 3-6: Summary of average ^{210}Pb sediment accumulation rates (SAR) and standard error (SE) in North Island estuaries and coastal embayments over the last 50-100 years. The total number of cores = 85.

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

The small size (i.e., area and volume) of many of these Auckland estuaries relative to the sediment-supply rate, as well as estuarine processes and basin size and shape interact to influence sediment trapping. For example, many of the Auckland east-coast estuaries are relatively small and have rapidly infilled with sediments from developing catchments. However, estuarine processes, such as fine-sediment winnowing by waves, appear to play an important role in moderating the rate of estuary infilling. For example, in the Central Waitemata Harbour (CWH), average SAR in intertidal and subtidal habitats is not significantly different (Figure 3-12). Field measurements and sediment-transport modelling show that this is primarily due to redistribution of sediments within the CWH (Oldman et al. 2007). Silt deposited on the intertidal flats is winnowed from the bed by waves and is subsequently redistributed by currents and deposited on the subtidal flats, which are less frequently reworked by short-period estuarine waves. Thus, over time, this redistribution of fine sediments by estuarine processes has reduced differences in sedimentation rates between intertidal and subtidal environments in the Central Waitemata Harbour.

Further evidence of the key role that waves play in moderating estuary infilling comes from the Pauatahanui Inlet (Porirua), a small (4.6 km^2), shallow subtidal estuary (Swales et al. 2005). Despite the fact that the Inlet receives runoff from a relatively large (109 km^2) steepland catchment, silt plumes during floods are observed to discharge from the inlet. Fine sediment deposited in the Inlet is also frequently resuspended by waves, even in the central basin, so that a substantial proportion of the terrigenous sediment load is exported from the Pauatahanui Inlet to the open sea.

Sedimentation accumulation rates are also low in Auckland east-coast bays (Figure 3-12). These shallow coastal embayments are typically larger than the estuaries, so that they have more accommodation space for sediments and are subject to fine-sediment winnowing by waves. In some cases these embayments are also buffered from catchment sediment runoff which must pass through estuaries, where a proportion of this terrigenous sediment is deposited. This appears to be the general situation in the Bay of Islands where infilling rates in the bay are significantly lower than in the fringing estuaries. The Te Rawhiti Inlet is a notable exception to this pattern, with fine terrigenous sediments rapidly accumulating in this sheltered basin. Stable-isotope data suggest that sediments depositing in the Te Rawhiti Inlet are derived from the large rivers, such as the Kawakawa and Waitangi that discharge to the southern part of the BOI system. This sediment is dispersed by river plumes and tidal currents into the Bay. The relatively high SAR in the Te Rawhiti Inlet suggests that a substantial fraction of these river-borne sediments are being deposited at Te Rawhiti.

To conclude, the BOI system is infilling more slowly than in other North Island estuaries for which comparative data are available. This is primarily a result of the large sediment accommodation capacity of the system relative to the sediment supply rate. In the small estuaries fringing the Bay, sediment accumulation rates are higher due to their close proximity to large rivers, limited sediment accommodation space and estuarine processes that favour mud trapping.

3.10 Sediment accommodation capacity of fringing estuaries

The capacity of the estuaries fringing the Bay to accommodate terrigenous sediments over the next century was assessed based on: (1) measured ^{210}Pb SAR over the last ~100 years;

(2) historical data on rates of sea level rise (1.5 ±0.1 mm yr^{-1}, Hannah et al. 2010); (3) and understanding of estuarine physical processes.

Figure 3-13 presents the results of this simple analysis for each core site, which are grouped into the various sedimentary sub-compartments that have been defined for the BOI system. This analysis indicates that all of the estuaries fringing the bay as well as the bay itself have been infilling more rapidly than can be offset by sea-level rise over the last ~100 years. Long-term net changes in sediment accommodation space are in the range +0.5 to -3.4 mm yr^{-1}, with negative values indicating infilling. The most rapid losses in sediment accommodation space, in excess of -1 mm yr^{-1} have occurred in the Waikare, Veronica and Te Rawhiti compartments (Figure 3-13). It is notable that the Waikare and Veronica compartments receive runoff from the largest catchments (i.e., Kawakawa, Waitangi), whereas Te Rawhiti Inlet is remote from these large river sources.

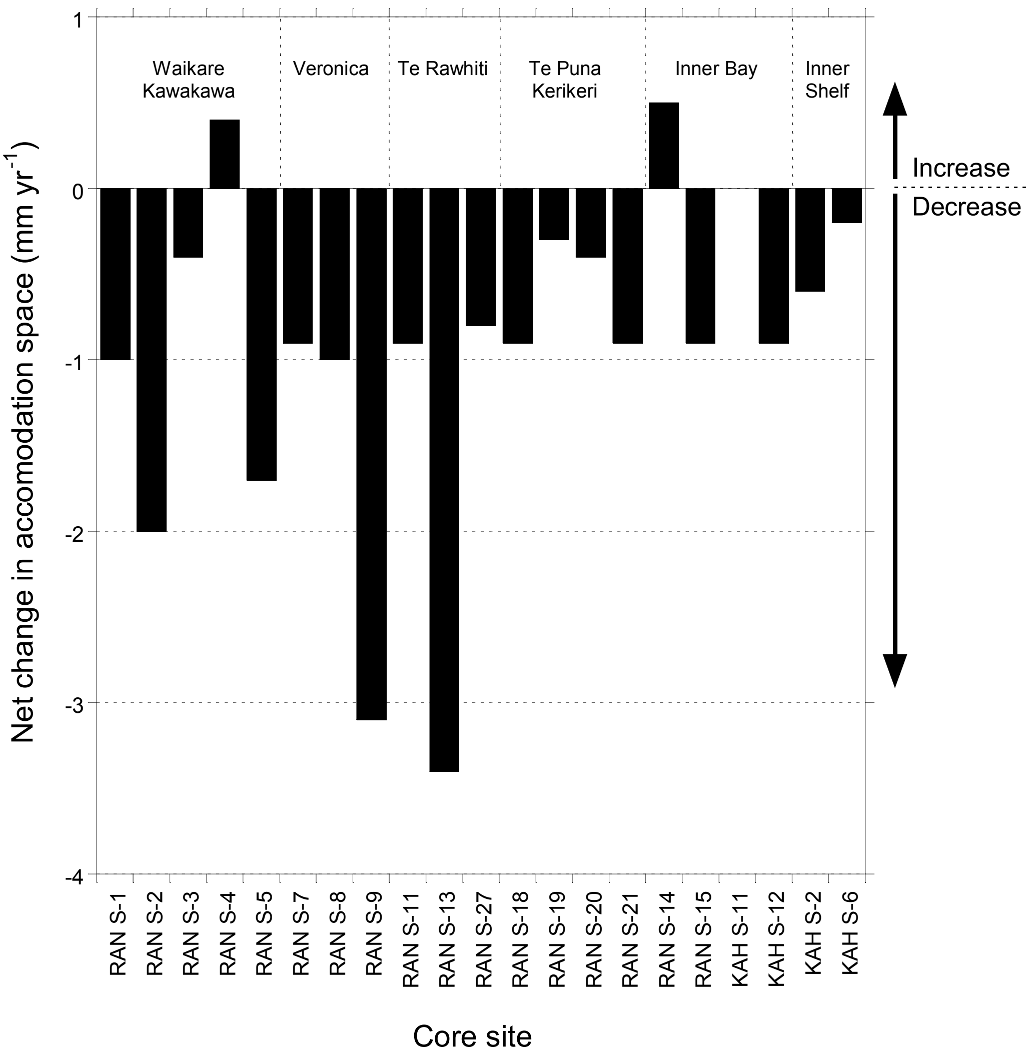

Figure 3-13: Net change in sediment accommodation space (mm/yr) in sedimentary compartments based on ^{210}Pb SAR measured at core sites and the historical rate of sea level rise at the Port of Auckland.

The most obvious physical effects of sediment infilling will occur in the shallow estuaries fringing the Bay that are infilling relatively quickly and where average high-tide water depths are no more than metres. In these environments, loss of tidal-prism volume (i.e., volume between low and high tide) will occur as intertidal flats replace shallow subtidal habitats. In turn, mean tidal-current speeds are reduced, further exacerbating sedimentation. As intertidal-flat elevations increase in estuaries, two key processes ultimately limit sediment accumulation rates, namely: (1) wave-driven resuspension of muds; and (2) progressive reduction in sediment delivery due to reduced duration and frequency of tidal inundation as tidal-flat elevation increases. Both increased wave resuspension and reduced sediment delivery operate as negative feedbacks that reduce sediment trapping in estuaries, so that increasingly large proportions of the catchment sediment load are discharged to adjacent coastal and continental shelf environments. Only in sedimentary environments where wave resuspension is negligible (e.g., tidal creeks, mangrove forests and salt marshes) do tidal-flat elevations approach the upper limit of the tide. Under these conditions, SAR are ultimately limited to the rate at which new sediment accommodation space is created either by progressive sea-level rise and/or subsidence.

The Kawakawa, Waikare and Veronica compartments are most vulnerable to environmental changes associated with sediment infilling such as loss of subtidal habitat and transition to intertidal mud flats. The largest mangrove forests in the BOI system also occur on the extensive intertidal flats that characterise the Waikare and Veronica compartments.

In Te Rawhiti Inlet, the ^{210}Pb SAR measured at site RAN-13 is relatively high, although the capacity to accommodate sediments is substantially higher than in the fringing estuaries. Habitats within the Te Rawhiti Inlet does contain more benthic communities that are sensitive to fine-sediment deposition in comparison to the estuaries (section 3.14) so that rapid mud sedimentation is of concern.

3.11 Present-day sources of Bay of Islands sediments

3.11.1 Spatial patterns

The spatial patterns of the stable-isotopes, $\delta^{13}C$ and $\delta^{15}N$, signatures of surficial sediments at the sampling sites provide information about the likely sources of terrigenous sediments deposited in the BOI system.

The stable isotope data from weakly acidified samples showed $\delta^{13}C$ enrichment in the surface sediments increasing with depth and distance off shore. This is consistent with the increasing concentrations of carbonate in the sediments from deeper waters off shore (Maas & Nodder, 2010). Increasing carbonate is an indication of low sedimentation rates and high turnover rates by organisms that can precipitate aragonite or form calcite sheaths. High sedimentation rates would dilute the carbonate with fresh organic terrestrial sediment. The pattern of $\delta^{13}C$ enrichment remained after re-acidification to remove this carbonate consistent with high bacterial lipase activity in these sediments (Maas & Nodder, 2010).

The surficial sediment $\delta^{15}N$ values also showed a pattern of enrichment away from the shore (Figure 3-14). In this case the enrichment was expected as ^{15}N enrichment is a natural part of biological processing of nitrogen in the environment. Each biological process or “trophic step” can cause the isotopic value of $\delta^{15}N$ to increase by about 3.5 ‰. The spatial pattern shows less enriched $\delta^{15}N$ values in the inlets with lowest values in the Kerikeri Inlet. While this spatial pattern is consistent with terrigenous material entering the estuaries, the values in the Kerikeri Inlet may reflect wastewater sources or the use of artificial fertilisers associated with horticulture and/or urban gardening in this river catchment. Urea fertiliser has a typically depleted $\delta^{15}N$ value of about -1 ‰.

The $\delta^{13}C$ values of selected biomarkers showed consistent patterns that indicate dispersal of sediment from specific estuarine inlets. For example, the spatial distribution of the $\delta^{13}C$ values of the fatty acid biomarker stearic acid (C18:0) drawn as a contour plot (Figure 3-15), shows distinct differences between sediments in the Kerikeri/Te Puna and Kawakawa/ Waikare Inlets compared with the Waitangi Inlet. These data indicate that sediment was mostly coming from these three groups of inlets which also represent the three major river inflows to the Bay of Islands – Kerekeri River, Waitangi River, and Kawakawa River (Figure 3-15).

The slightly isotopically depleted stearic acid pattern observed in the Kerikeri Inlet is confined to the channel on the northern side of Moturoa Island and then extends offshore. This indicates that sediment from the Kerikeri River moves through this channel to get to the open ocean. The isotopic pattern suggests that only a small amount of sediment from the Kerikeri River moves south towards the Te Rawhiti Inlet. Conversely, it is likely that sediment from the Kerikeri River enters the Te Puna Inlet, which has no large river discharge, and may be the major source of sediment in that Inlet. Note also that there is more isotopically enriched stearic acid at the inner end of the Kerikeri Inlet which indicates possible wastewater contamination of those sediments.

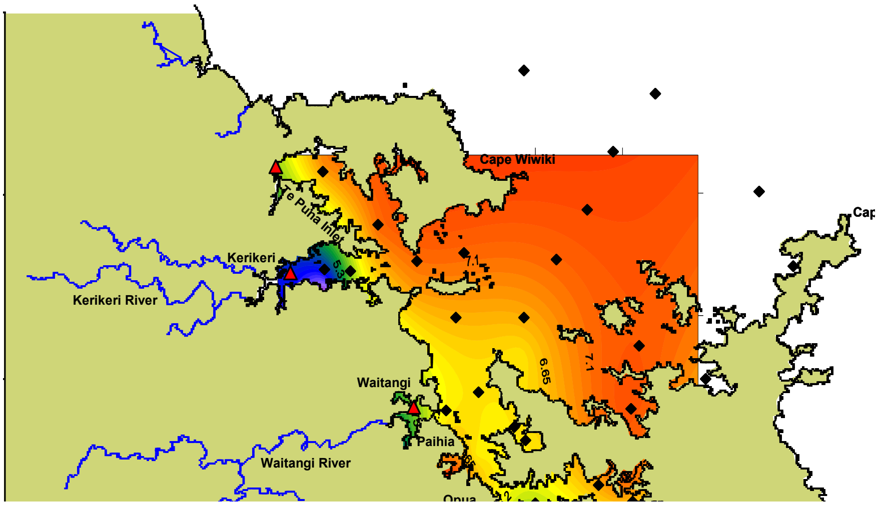

Figure 3-14: Spatial contour plot of ^{15}N stable isotope values in the surficial sediment of the Bay of Islands. The contour plot used linear krigging to interpolate between adjacent data points and is indicative rather than absolute.

.

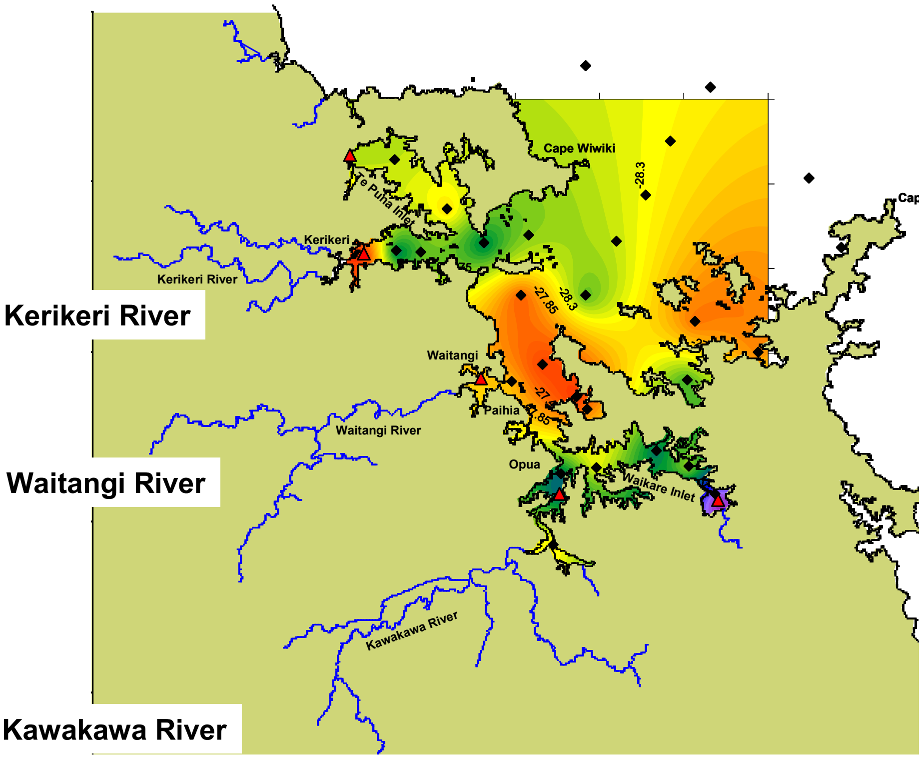

Figure 3-15: Spatial contour plot of the distribution of the compound-specific stable isotope $\delta^{13}C$ values of stearic acid (C18:0) in surficial sediments of the Bay of Islands. The contour plot used linear krigging to interpolate between adjacent data points and is indicative rather than absolute.

In the Waikare/Kawakawa Inlet system, slightly isotopically depleted stearic acid extends throughout both arms, consistent with observations from sediment trap data (Gibbs & Olsen, 2010) that sediment is moving back and forth along these channels with the tidal cycle, rather than being exchanged into the open waters of the Bay under the no-rainfall conditions. Because there is no large river inflow into the Waikare Inlet, it is likely that sediment from the Kawakawa River is dispersed into the Waikare Inlet, which may act as a natural sediment trap to the Kawakawa River. The more isotopically depleted stearic acid at the head of the Waikare Inlet may reflect localised sediment inputs from the small headwater stream, and is consistent with the more isotopically depleted CSSI values from native forest.

The Waitangi Inlet lies between the Kerikeri and Kawakawa Inlets and has a slightly isotopically enriched stearic acid signature which is also found in the surficial sediment in the Veronica Channel outside the Inlet. The presence of this enriched stearic acid signature in the sediment between the areas of depleted stearic acid signatures associated with the other inlets indicates that water from the Kerikeri and Kawakawa Rivers is unlikely to mix during a rainfall event until well out in the Bay. The cause of the enriched stearic acid signature is probably related to the land-use in the Waitangi River catchment, but may also reflect the presence of geothermally influenced soils from around the Ngawha Springs at the head of the Waiaruhe River tributary of the Waitangi River.

The spatial patterns in these contour plots are a snapshot in time and may represent only the most recent sedimentation event prior to sampling, within the limitations of the high levels of sediment resuspension in the inlets (Gibbs & Olsen, 2010). These patterns may change following a rainfall event and will be strongly influenced by where the rain falls in the Bay of Islands catchment and the subsequent flows in these three rivers.

3.11.2 Present-day sediment sources

The slight differences in isotopic enrichment of most of the fatty acid biomarkers in the delta sediment attributable to the river inflows, typically reflects differences in erosion from specific land-uses in the catchments. While it was possible to detect the presence of most land-use soils, many were at very low levels (below 1%) and hence only the six most common soil sources have been modelled for each river delta (Table 3-7). There were three different types of pasture: (1) cattle (dairy and beef) on the lowlands adjacent to the river channels; (2) sheep and beef on rolling hill pasture which was mostly being used for hay production at the time of sampling (late November 2009); and (3) sub-soils which include floodplain and bank erosion material. This latter material from earlier flood events lines the river channels and would be remobilised during high flows and gradually move down the river to the sea.

Table 3-7: Land-use source contributions (%) to the sediment deposited in the river delta in each estuary. Main land-use types are shown. Sources with <1% are unlikely to be present, sources with <5% may be present, sources with >5% are present. level of uncertainty of values are <5%.

Source soil	Pasture (cattle)	Pasture (sheep)	Pasture (sub-soil)	Native (broadleaf)	Pine (clear-fell)	Kanuka (scrub)
Te Puna Inlet	27.0	32.4	<1	3.5	36.7	<1
Kerikeri Inlet	13.6	44.7	34.8	6.8	<1	<1
Waitangi Inlet	37.7	17.2	42.4	2.6	<1	<1
Kawakawa Inlet	68.3	<1	<1	2.7	27.5	1.2
Waikare Inlet	<1	<1	<1	26.6	<1	72.4

In total, the erosion of soil from pasture produces more than 60% of the sediment entering the Bay of Islands (Table 3-7) from all rivers except the Waikare. This is consistent with observations in the river catchments where much of the land (40-60%) is in pasture, although there are large areas of production pine forest in the upper reaches of the Kawakawa River (22%) and Te Puna sub-catchments. There are also numerous citrus orchards in the lower reaches of the Kerikeri sub-catchment. While the Waikare sub-catchment is almost entirely in native forest (81%) and kanuka scrub (15%) (MacDiarmid et al. 2009), the kanuka scrub land-use was contributing more than 70% of the sediment to the Waikare River delta, which may reflect clearing of scrub land in the catchment. Undisturbed native forest would not be expected to contribute much sediment to the Waikare River even though it is the main land-use in that catchment.

The high proportion of sediment from pasture is also consistent with other studies which have found that pasture farming can produce about four times more sediment than mature pine forests (Eyles & Fahey, 2006). Observations in these sub-catchments also suggest that stock access to stream banks may be exacerbating sediment erosion by causing soil instability which would be carried into the stream with quick-flow at the beginning of a rainfall event or eroded by the river over-topping the bank (Figure 3-16).

Figure 3-16: Stock damage to stream banks exposes bare soil which is then vulnerable to erosion during rainfall events.

In general, the CSSI technique results show that the main sources of sediment are consistent with the main land-uses. The relationship was not 1:1, indicating that there is less sediment from some land-uses and more from others which means that land-use practices vary across similar land-uses. For example, there was a lack of material linked to citrus orchards and mature pine forest in the delta sediment, which suggests these areas have little bare ground while the trees have sufficient leaf canopy to reduce soil erosion during rainfall events. Conversely, the CSSI model output indicates there was sediment from areas of recently clear-felled pine forest present in the delta sediments from the Te Puna and Kawakawa Inlets. Recently clear-felled pine forest (Figure 3-17) leaves the steep slopes highly vulnerable to erosion for up to 6 years until replanting and canopy closure is re-established (Phillips et al. 2005). The high proportion of kanuka scrub signature in the Waikare River sediment suggests clearance of scrub land in that catchment.

Figure 3-17: Recently clear-felled production pine forest on steep slopes leaves soils vulnerable.

While the CSSI model identifies the presence of soil from these land-uses in the sediment as a proportion of the total sediment, it does not provide a quantitative estimate of how much sediment was deposited or when. That information comes from other data such as flow and suspended sediment monitoring or from the use of sediment accumulation rates derived from radioisotope dating (section 2.3).

The proportions of source soils listed in Table 3-7 are presented as a percentage of the total sediment in each river delta sample. The values are best estimates within defined limits of the modelling (±SD) and require sediment transport data to provide quantified estimates of the rate of erosion from each land-use. These soil source proportions were converted into mean annual sediment loads by land use for the whole Bay of Islands (Figure 3-18), by using the estimated mean annual river sediment yields for the four major river inflows from Pritchard et al. (2010, Table 1). A value 50% of the Waikare River sediment yield was used for the mean annual sediment yield from the Te Puna River in this calculation.

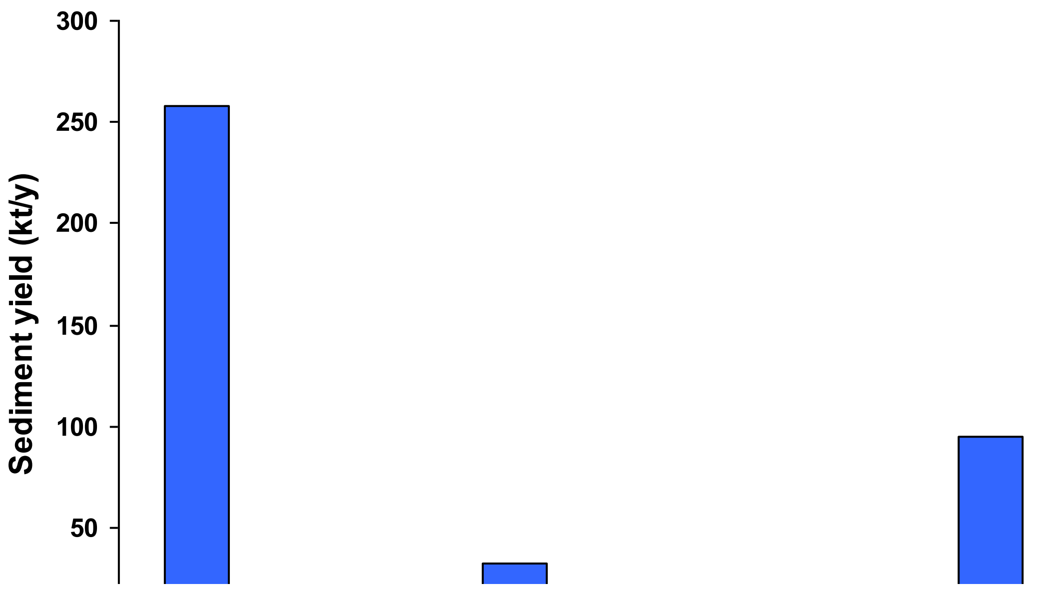

Figure 3-18: Estimated mean annual sediment loads (kt/y) on the Bay of Islands by present day land-use. (Sediment yield data: Pritchard et al. 2010).

These estimates show that most of the sediment entering the Bay of Islands comes from two main sources, pasture used for cattle farming (dairy and beef) and pine forest which has recently been clear-felled.

3.12 Past sources of Bay of Islands sediments

Stable isotopes of Fatty Acids have been used to reconstruct the sources of terrigenous sediments deposited in the coastal and estuarine waters of the Bay of Islands system over the last several thousand years. These sedimentation records were reconstructed for five core sites:

- Waikare Inlet (RAN S-5)
- Russell (RAN S-9)
- Kerikeri Inlet (RAN S-18)
- Inner Bay at 30-m isobath (KAH S-20)
- Inner continental shelf at ~100-m isobath (KAH S-2).

The IsoSource model was used to determine the feasible isotopic proportions of each soil source in a mixture using the Fatty Acid biomarkers. The plots below show: (1) how the isotopic proportions of the soil sources has changed over time, with depth in the sediment column; (2) the minimum tolerance value (i.e., ± $^{0}/_{00}$, per mil) for which isotopically feasible solutions could be determined; and (3) number of feasible solutions (*n*). While it is possible for the isotopic proportions of present day sources to be converted to soil proportions, because we can measure the carbon content in those source soils, we do not have reliable data on the carbon content of the historical source soils. Conversion could be made using the carbon content of present day sources but this would introduce an unknown error term. Consequently, only the isotopic proportions of source soils are presented in this section

In interpreting these results it is important to bear in mind that the suite of soil type detected in the sediment at a given time does not imply that these were the only vegetation types present in the catchment. What these results do indicate is the major sources of sediment that were eroded and deposited in the Bay of Islands system at that time. The results of this retrospective analysis of long-term changes in soil sources over time preserved in each of the sediment cores are presented here.

3.12.1 Waikare Inlet

Figure 3-19 present the results of the CSSI analysis of core RAN S-5 collected from the upper reaches of the Waikare Inlet. The upper 80-cm of this sediment core records the sedimentation history and environmental changes over the last 1,800 years.

Prior to Polynesian arrival around 1300 AD, sediments deposited in Waikare Inlet were derived from erosion of soils vegetated by native forest, with Nikau and kauri-forest isotopic signatures. At 50-cm depth (mid-1400s AD), the isotopic signature is dominated by bracken, with lesser proportions of native-forest soils. Bracken is a characteristic indicator of deforestation, a plant-type that rapidly colonises areas when forest-cover is removed. Bracken is subsequently present in all samples to the top of the core. Soils derived from dry-stock pasture enter the sediment record in the mid-1940s.

As a guide to the reliability of these results minimum tolerances were typically ≤1$^{0}/_{00}$. Unique solutions (*n*=1) were obtained for 5 of the 15 samples, with the remaining samples typically having 2-3 solutions.

3.12.2 Veronica channel at Russell

Figure 3-20 present the results of the CSSI analysis of core RAN S-9 collected from subtidal flats in the Veronica channel and ~2 km north-west of Russell township. The upper 130-cm of this sediment core records the sedimentation history and environmental changes over the last ~2600 years.

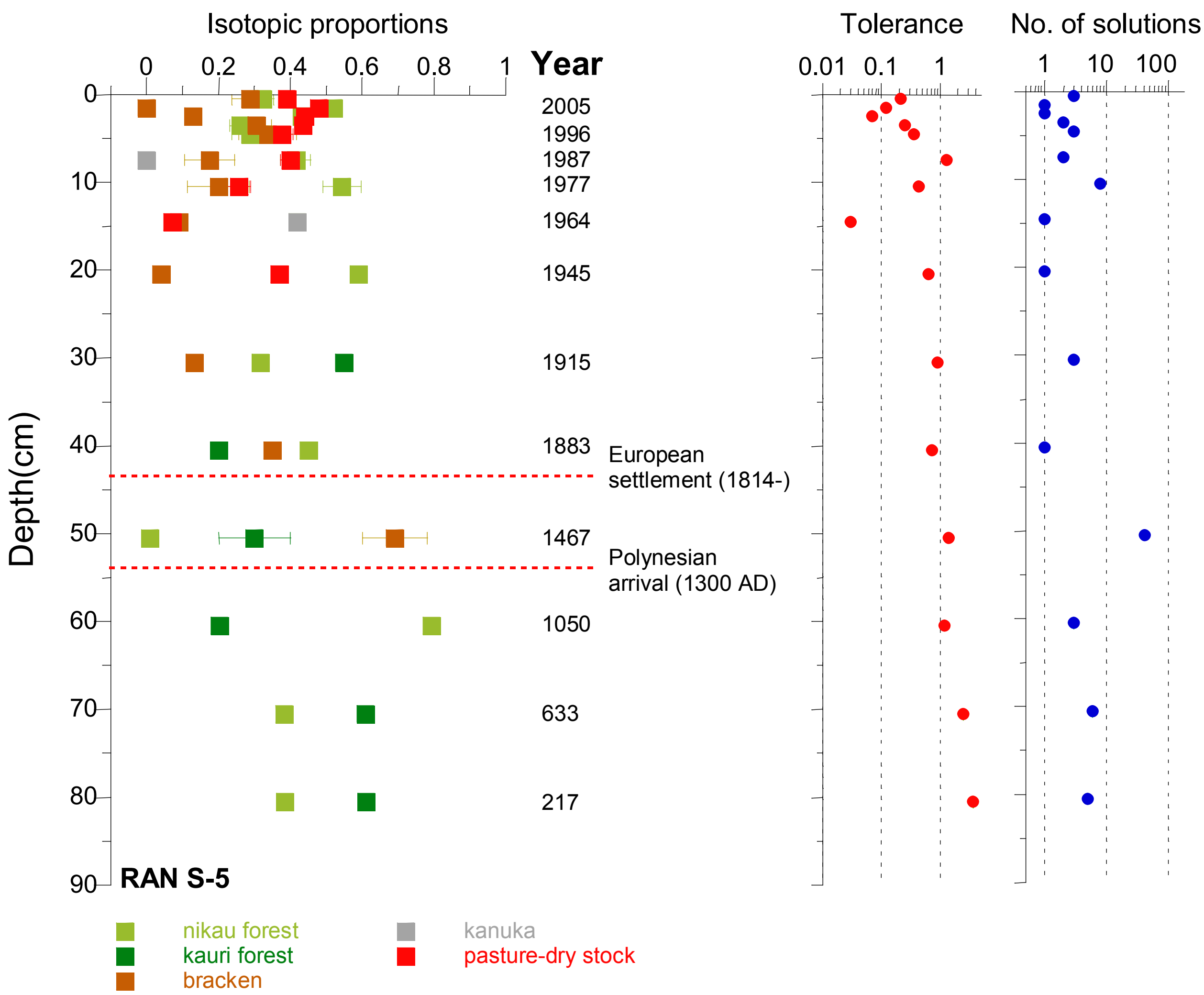

Figure 3-19: Waikare Inlet (RAN-S5): (a) feasible isotopic proportions (average and standard deviation) of soil courses in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modelling of sources; and (c) number of feasible solutions.

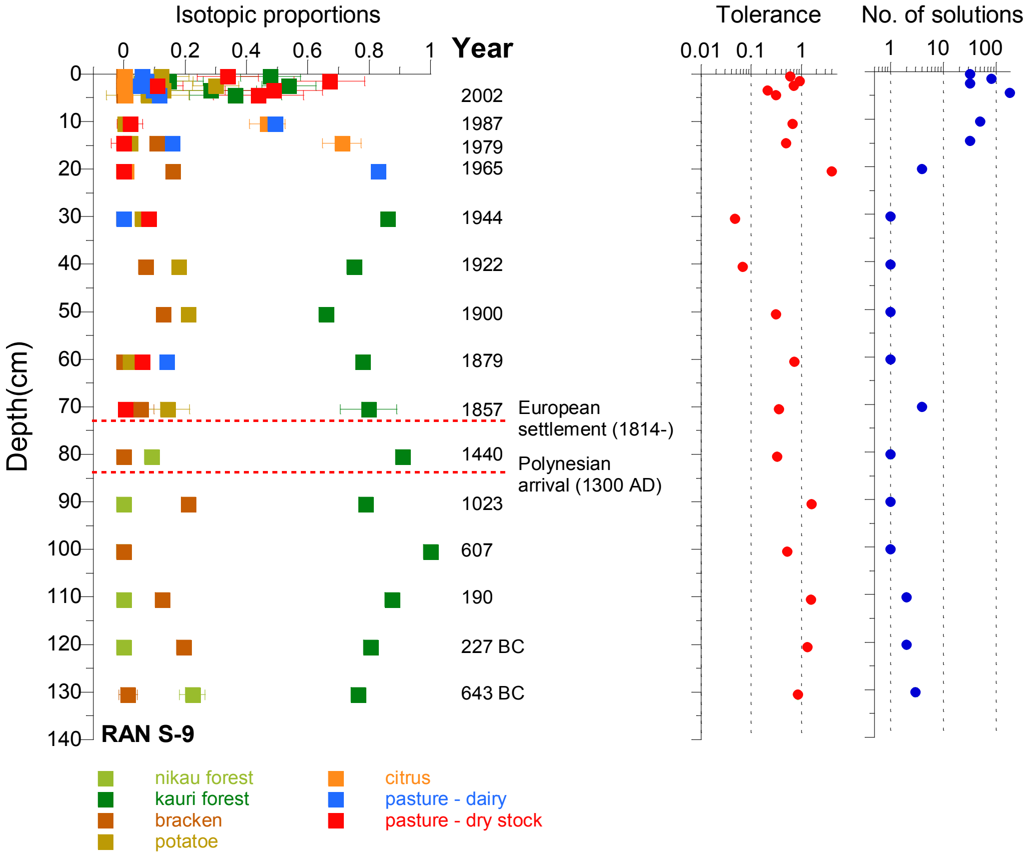

Figure 3-20: Veronica channel at Russell (RAN-S9): (a) feasible isotopic proportions of soil sources in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modelling of sources; and (c) number of feasible solutions.

Pre-Polynesian sediment deposits at this site are composed of soils derived from erosion of native forest soils as well as bracken. The presence of bracken over the ~2000 years prior to human arrival is notable and indicates that natural disturbance of the landscape was of feature of this environment. Likely causes of forest disturbance include landslides during high-intensity rainfall events and/or fires triggered by lightning storms. The presence of kauri-forest soils in the estuarine deposits until the mid-1940s indicates that soils eroded from this source persisted long after most of the native-forest landcover had been removed. By the 1850s (70-cm depth) soils derived from potatoes and dry-stock pasture are detected. This is consistent with historical records, with potatoes introduced by European whalers from the late 1700s onwards. Soils derived from dairying appear in the 1870s (60-cm depth). The kauri forest signature declines from the mid-1940s. Soils derived from citrus orchards appear in the late 1970s (15-cm depth).

As a guide to the reliability of these results minimum tolerances were typically ≤1.2 ‰ and the number of feasible solutions was typically <3 below. Unique solutions (*n*=1) were obtained for 7 of the 19 samples, with the remaining samples having 2–195 solutions. A large number of feasible solutions were generate for two samples in the top 5-cm of the core, which primarily reflects an increase in the number of potential soil sources.

3.12.3 Kerikeri Inlet

Figure 3-21 present the results of the CSSI analysis of core RAN S-18 collected from the lower reaches of the Kerikeri Inlet. The upper 140-cm of this sediment core records the sedimentation history and environmental changes in the Kerikeri Inlet over the last ~2700 years.

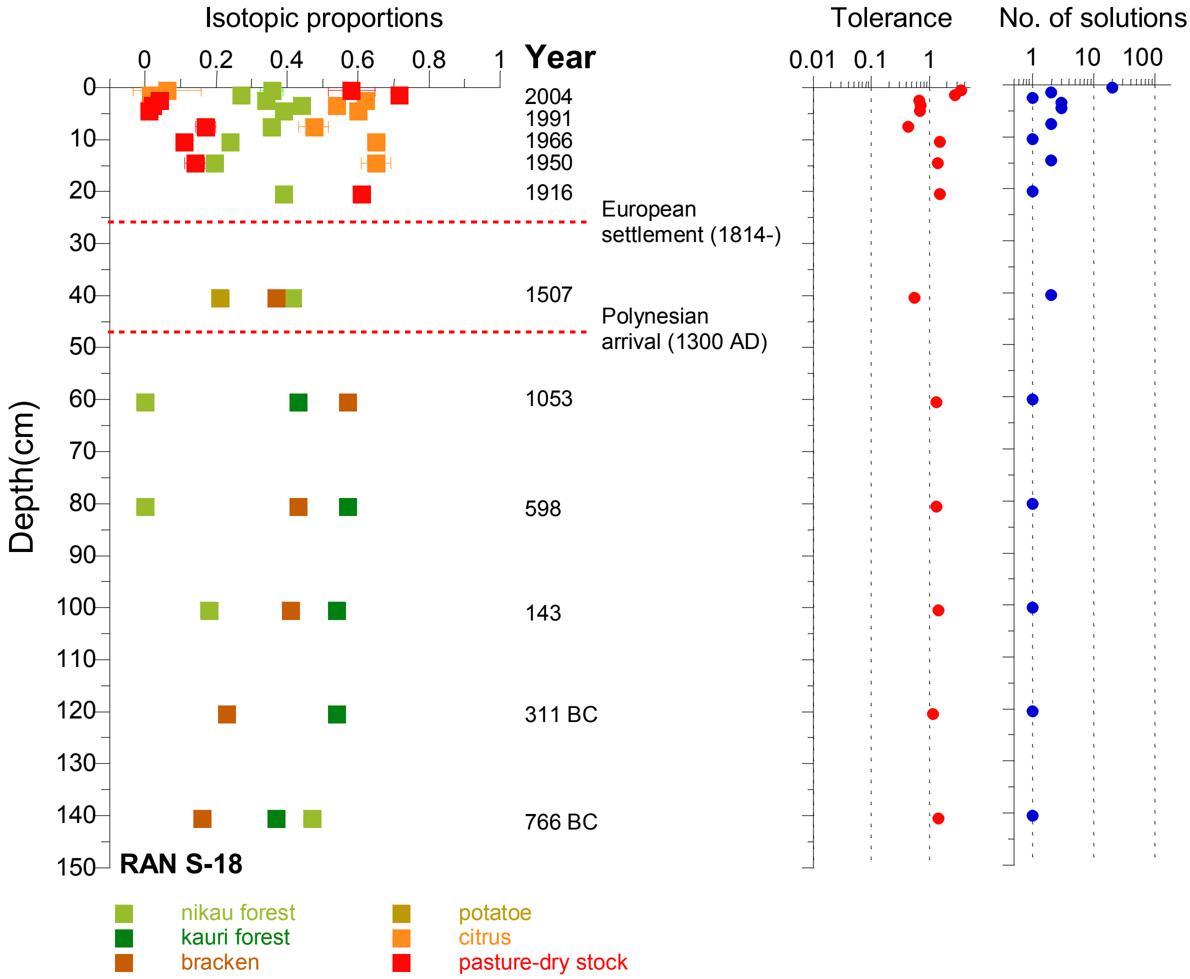

Figure 3-21: Kerikeri (RAN-S18): (a) feasible isotopic proportions of soil sources in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modelling of sources; and (c) number of feasible solutions.

As also observed at Russell, pre-Polynesian sediment deposits at this site are composed of soils derived from erosion of native forest soils as well as bracken. The presence of bracken over the ~2000 years prior to human arrival also at this site indicates that natural disturbance of the landscape was a large-scale feature of the Bay of Islands system. The Fatty Acid signature for potatoes appears after Polynesian arrival, in the early 1500s. This most likely represents the cultivation of kumara, as the signature for both plants is likely to be similar (section 2.6.2).

The European period at this site is contained in the top 25-cm of the core, with dry-stock pasture sediments appearing in the early 1900s (21-cm depth) and soils from citrus orchards deposited from the late 1940s onwards. The deposition of a native forest (Nikau type) soils persist to the present day.

As a guide to the reliability of these results minimum tolerances were typically ≤1.5 ‰, with the exception of surface sediments (tol. ~3.5). Unique solutions (n=1) were obtained for 8 of the 15 samples, with the remaining samples having 2–20 solutions.

3.12.4 Inner Bay of Islands

Figure 3-22 present the results of the CSSI analysis of core KAH S-20 collected from the inner Bay south-east of Motoroa Island at ~30 m isobath. This short core preserve the recent sedimentation history of the bay, dating back to the early 1960s (12-cm depth).

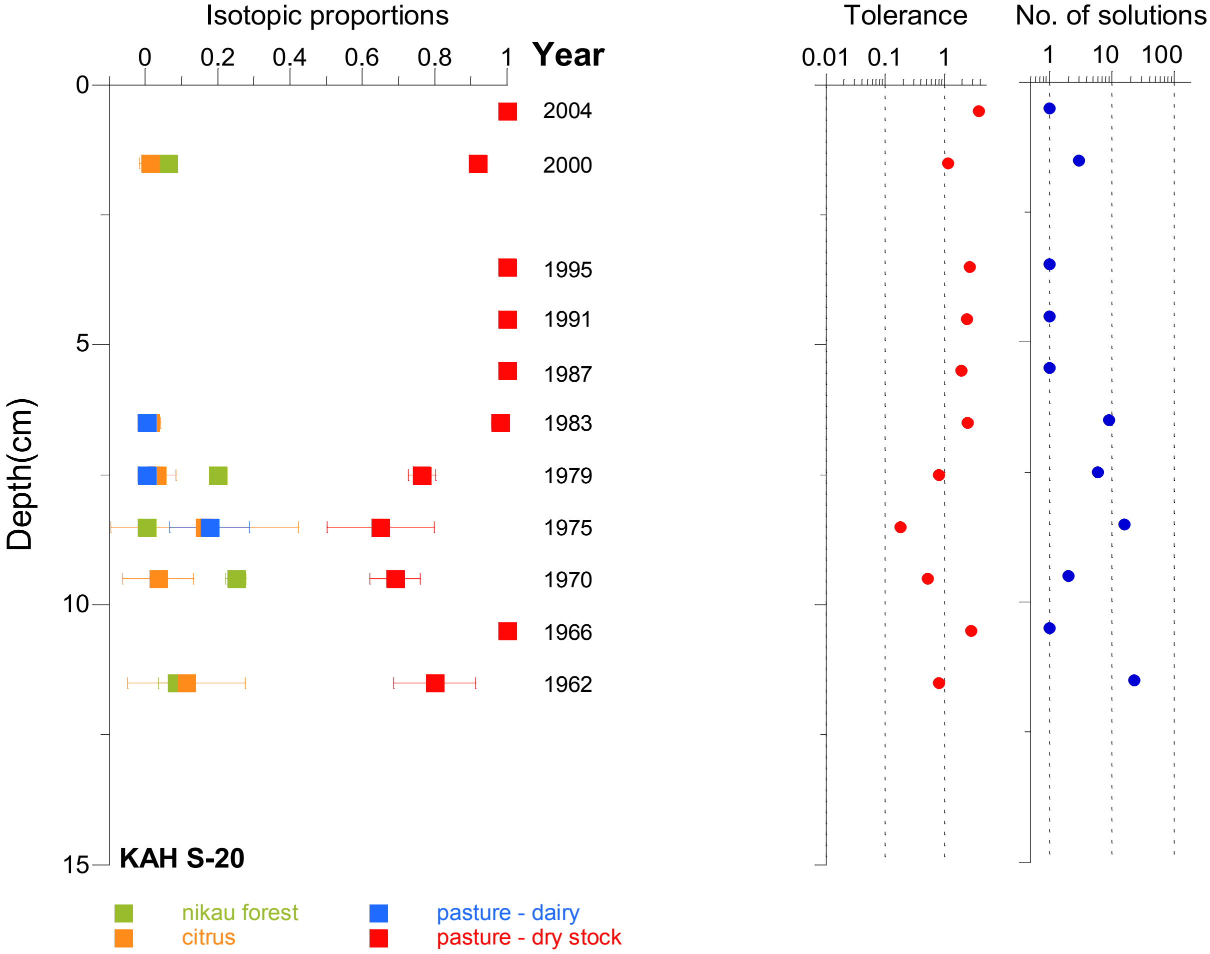

Figure 3-22: Inner Bay of Islands at ~30-m isobath (KAH-S20): (a) feasible isotopic proportions of soil sources in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modeling of sources; and (c) number of feasible solutions.

These sediments are composed of soils from native forest (nikau type), citrus, dairying and dry-stock pasture. In most of the samples above 7-cm depth the sediments are composed entirely of soils eroded from dry-stock pasture.

As a guide to the reliability of these results minimum tolerances were typically ≤2 ‰, with the exception of surface sediments (tol. ~3.5). Unique solutions (n=1) were obtained for 5 of the 11 samples, with the remaining samples having ≤23 solutions.

3.12.5 Inner shelf

Figure 3-23 present the results of the CSSI analysis of core KAH S-2 collected from the inner continental shelf at the ~100 m isobath. This short core preserves the last 200 years of sedimentation on the inner shelf, dating back to the early 1800s (40-cm depth).

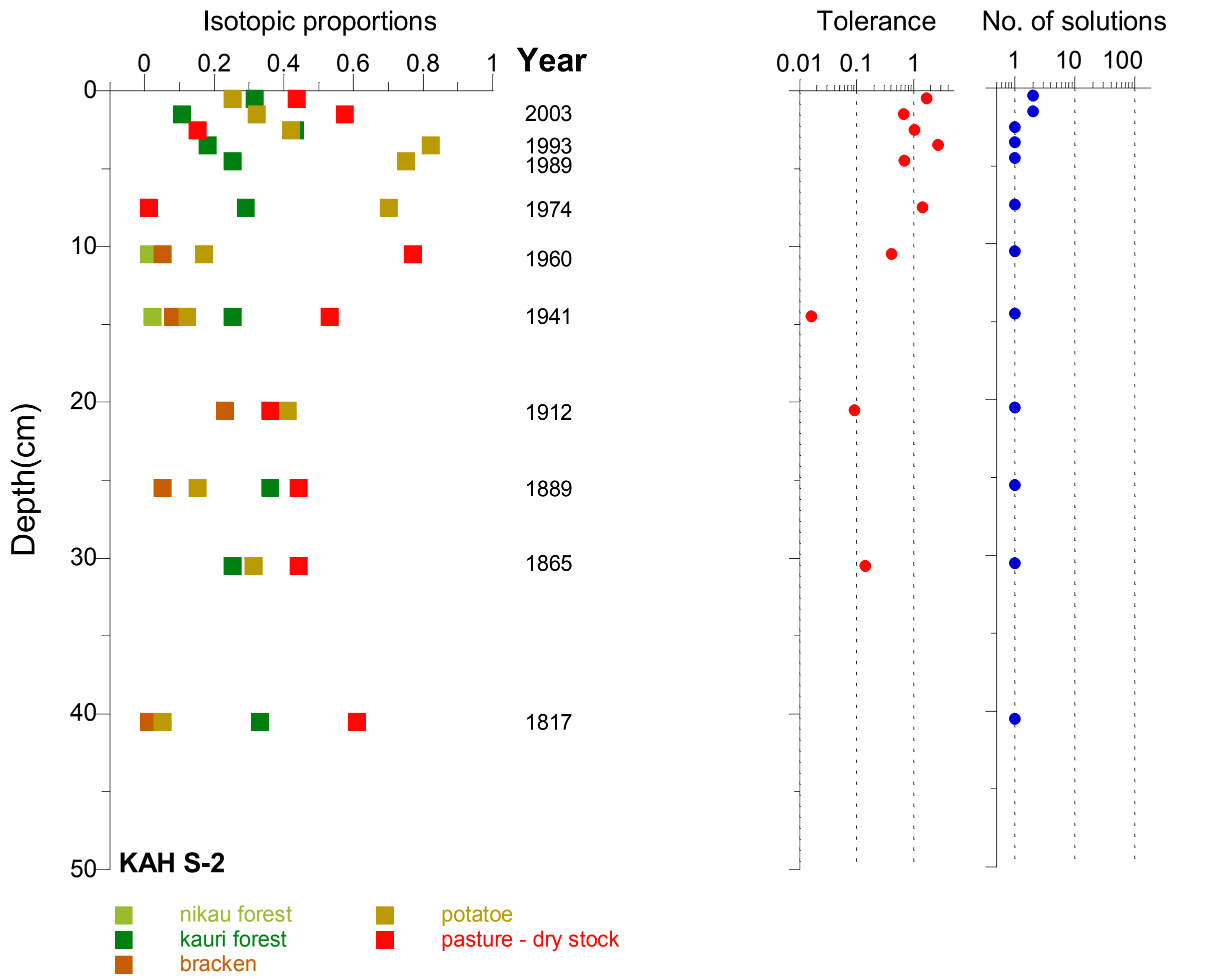

Figure 3-23: Inner shelf at 100 m isobath (KAH-S2): (a) feasible isotopic proportions of soil sources in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modelling of sources; and (c) number of feasible solutions.

Catchment soil sources are dominated by exotic plants (dry-stock pasture, potato/kumara) and bracken. An interesting feature is that kauri-forest soils occur throughout this record. This may reflect mixing of older kauri-labelled sediments into more recent deposits, given that native-forest landcover dominated for most of the Holocene. These data also suggest that large quantities of more recently eroded soils are accumulating on the inner shelf, remote from their catchment sources.

As a guide to the reliability of these results minimum tolerances were typically ≤2 ‰, with the exception of surface sediments (tol. ~3.5). Unique solutions (*n*=1) were obtained for 5 of the 11 samples, with the remaining samples having ≤23 solutions.

3.13 Present-day deposits – recent or historical sediments?

A key issue regarding the potential to mitigate the adverse environmental effects of terrigenous sediment inputs on the BOI system relates to the age of sediments in the active sedimentary system. There are two aspects to this issue:

1. The lag time between soil erosion at a site and sediment delivery and deposition in the BOI system. This is evaluated using a sediment-core record from the Kerikeri Inlet.

2. Potential for sediment remobilisation (mixing and/or resuspension) of near-surface sediment deposits. It is in this surface mixed layer (SML) that plants and animals live and sediments are frequently or episodically reworked by physical processes, such as waves and currents. The depth of the SML and the sediment accumulation rate determines the residence time of sediments in the active sedimentary system. This SML is evaluated for all cores sites in section 3.2.1.

3.13.1 Time-scale for sediment delivery to the BOI system

Sediment tracers have been widely used to elucidate the dynamics of sedimentary systems, these include radioisotopes, geochemical properties and biological markers. The CSSI signatures of exotic plant species with well know chronologies in both the catchment and sedimentary record of the receiving environment can potentially be used as sediment tracers. To detect the CSSI signatures of plant tracers in estuarine sediments, however, the plants must have been introduced on a large scale so that large quantities of top soil were labelled and subsequently eroded and deposited in the estuarine receiving environment. This constraint indicates that plantation/orchard scale (i.e., hectares) areas of plantings would be required.

The requirements for this analysis include:

1. availability of a suitable plant tracer

2. reliable history of plant introduction to the catchment

3. the degree of preservation of the original sediment record, which depends on the degree of sediment mixing subsequent to initial sediment deposition

4. down-core sampling frequency. The ability to detect the initial appearance of a tracer in the sediment record depends on the sampling frequency. For example a core sampled at 1-cm intervals will provide a more detailed record than a core sampled at 10-cm intervals, and

5. the temporal resolution of the sediment record, which depends on the sediment sample increment, sediment accumulation rate and residence time in the SML. For example, the time increment represented by a 10-mm thick sediment sample extracted from a core with SAR = 2 mm yr^{-1} is 10 mm/2 mm yr^{-1} = 5 years. The uncertainty in sediment dating or recent sediments is also increased by mixing within the SML, which is discussed in the next section.

The introduction of citrus to the Kerikeri catchment arguably provides the most reliable CSSI tracer to evaluate the time-scale for recent soil deposition in the BOI system. Although citrus was first introduced to Kerikeri on a large scale in 1928 (i.e., 10,000 trees planted) we assume that sufficiently large quantities of soil were not labelled, eroded or deposited in the Kerikeri estuary until the late 1930s at the earliest. Citrus production continued to increase in the decades after World War Two.

Figure 3.20 shows the isotopic profiles of soils from major vegetation types deposited in the dated RAN S-18 core collected from the Kerikeri Inlet. Lead-210 dating of this core indicates that soils eroded from citrus orchards were deposited from the late 1940s onwards and are first detected at 14-15 cm depth.

Citrus-labelled soils are not detected in the next sample down core (20-21-cm depth, *circa* 1924). It is conceivable that citrus-labelled soils were initially deposited before the late 1940s but this cannot be determined because the sampling of the core is not sufficiently detailed.

Furthermore, as described in the next section, the mixing of sediments in the SML increases the uncertainty in dating. ^{7}Be data for core RAN S-18A indicates a present- SML to at least 30 mm depth. This implies that recently deposited sediments are mixed down to this depth over time scales of days-months. Given a ^{210}Pb SAR of 2.4 mm yr^{-1} then the residence time (*R*) of “recent” sediment in the SML is ~12 years. Assuming that the depth of the SML is uniform over time, recent sediments at this site can be defined as those deposited within the previous decade.

The implication of this surface-mixing process is that tracers, such as citrus-labelled soil or ^{137}Cs appear earlier in the sediment record than they would do otherwise. Therefore, initial deposition of citrus-labelled soils at site RAN S-18 may not have occurred until the late 1950s.

The time lag between soil erosion and deposition will also depend on: (1) catchment size; (2) location of the soil-erosion site in the catchment; and (3) the magnitude and frequency of floods sufficiently large to erode citrus soils. The residence time of eroded soils in the river network are influenced by all of these factors.

This analysis enables the potential time-lag between initial erosion of citrus-labelled soils and deposition in the Kerikeri inlet at RAN S-18A:

- minimum time-lag of ~10 years (i.e., late 1930s to late 1940s)
- maximum time-lag of ~20 years (i.e., late 1930s to late 1950s)

3.14 Benthic ecology

3.14.1 Comparison of NRC and Oceans 20/20 Intertidal data

A non-metric multi-dimensional scaling ordination suggested that the intertidal benthic communities at NRC sites (KR, PC and WR) are similar to Oceans 20/20 sites located in similarly muddy areas (Figure 3-24). Sites 24 and 25 are situated in the upper reaches of Waikare Inlet and are approximately 36% and 47% similar to sites KR and PC, respectively.

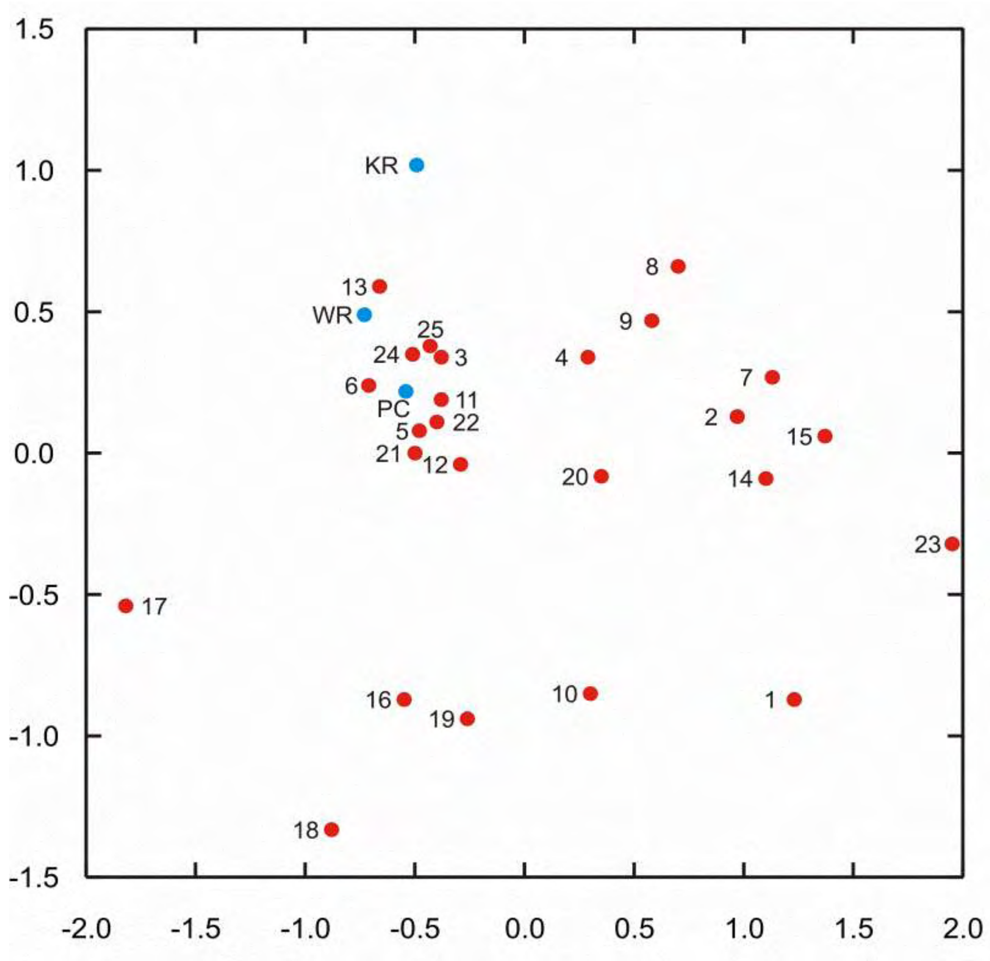

Figure 3-24: Multi-dimensional Scaling (MDS) plot of the dissimilarity in macrofaunal communities at NRC monitoring sites (blue circle) Kerikeri River (KR), Waipapa River (WR) and Pickmere Channel (PC) and Oceans 20/20 sites (red circles) labelled 1-25 (Log transformed data). The further away the points are in the ordination space, the more dissimilar the sites. Stress = 0.14.

3.14.2 Estimation of site sensitivity

Application of the available sensitivity information for macro-benthic species resulted in the sites being allocated to the 3 sensitivity rankings as per Table 3-8. The application of the hierarchical method for assigning sensitivity resulted in some exposed intertidal sites being assigned a middle ranking due to low diversity and lack of information about the sensitivity of the infauna.

The spatial distribution of sensitivity of macro-benthic communities to terrigenous-sediment inputs at sites in the BOI system are mapped in Figures 3-25 to 3-27. All areas of the Bay had some intertidal sites with sensitive communities, however, sensitive communities were found further up the Te Puna and Kerikeri Inlets than they were in Kawakawa and Waikare Inlets (Figure 3-25). Conversely, shallow subtidal sites with the most sensitive communities were mainly observed in Te Rawhiti Inlet (Figure 3-26). Sites with the lowest sensitivity rankings were found in all areas. For the deeper subtidal sites, surveyed by DTIS, (Figure 3-27), very sensitive communities were mainly found in the outer Bay of Islands and Te Rawhiti Inlet.

Table 3-8: Site sensitivity rankings. Bolded site numbers indicate exposed gravelly beaches.

	Sites	Sensitivity Ranking	Description
Intertidal	2, 4, 7, 8, 12, 15, 18, 17, 19, 9, 22	3	High species diversity or dominant taxa are very sensitive to mud (i.e., Pipi, Macomona)
	1, 3, 6, 10, **14, 16,** 20, 21, **23,** PC, 11	2	Site is dominated by taxa sensitive to or tolerant of low amounts of mud (i.e., cockles, dense tube-worm mats, *Prionopsio aucklandica*)
	5, 13, 24, 25, KR, WR	1	Low diversity and dominated by taxa with a preference for mud (i.e., Oligochaeta & *Scolecolepides benhami*)
Shallow subtidal	TMR, KWB, OBS, ROB, PKI, SSG, CLP PDB, WRP	3	Dominated by seagrass, macroalgae, rhodoliths sponges or atrina. Regarded as a “pristine habitat” with high species diversity
	TRI, RIS,TAB, WAB, BMB, TAP, AAP, SYB	2	Dominated by sparse patchy algae or atrina beds or tubeworms with high infaunal diversity
	RGB, ONB **ABC,** KRB, VNC, MIS, **OTB, DWC**, KRP	1	Dominated by mobile epifauna (i.e., starfish and gastropods) or infauna, with low diversity
DTIS subtidal	169, 171, 172, 196, 197, 198, 199, 200, 203, 242, 244, 245	3	Dominated by structuring organisms and suspension-feeders (e.g., sponges, anthozoa or atrina), with high species diversity
	170, 173, 175, 176, 178, 180, 185, 190, 201, 202, 208, 212, 215, 223, 229, 231, 236, 237, 241, 243, 246, 249	2	Medium diversity, lower numbers or patchy distributions of sponges, atrina and anthozoa.
	174, 181, 187, 188, 209, 210, 213, 217, 219, 221, 224, 225, 227, 247	1	Dominated by mobile epifauna (e.g., crustaceans, echinoderms, polychaetes) with low diversity

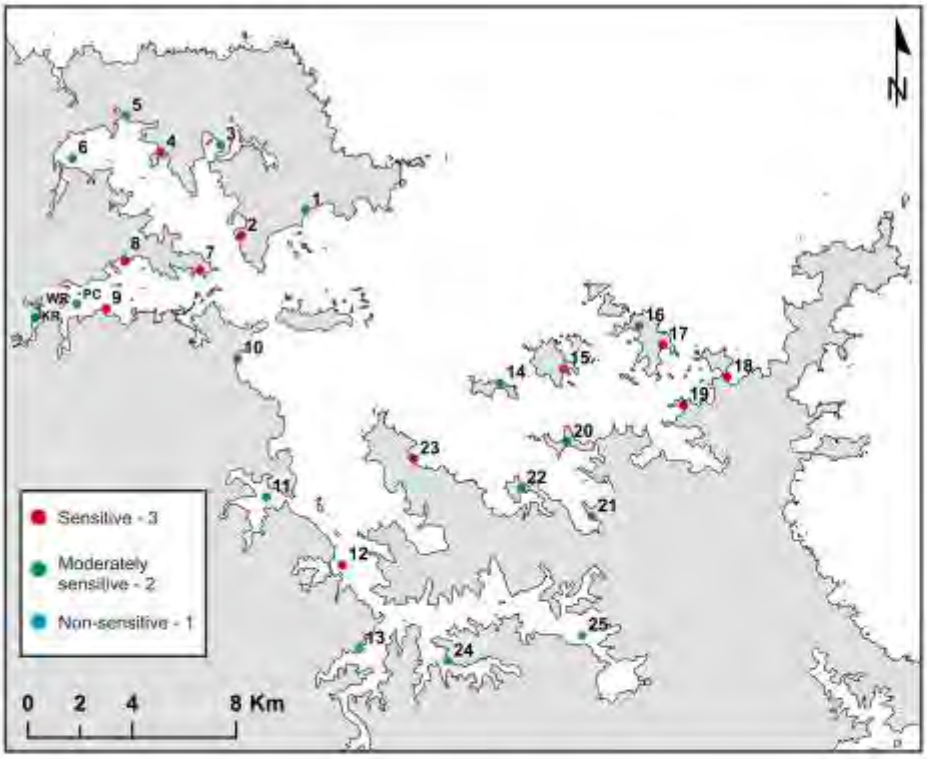

Figure 3-25: Spatial distribution of intertidal macrobenthic communities in the Bay of Islands with varying sensitivity to terrestrial sediment inputs.

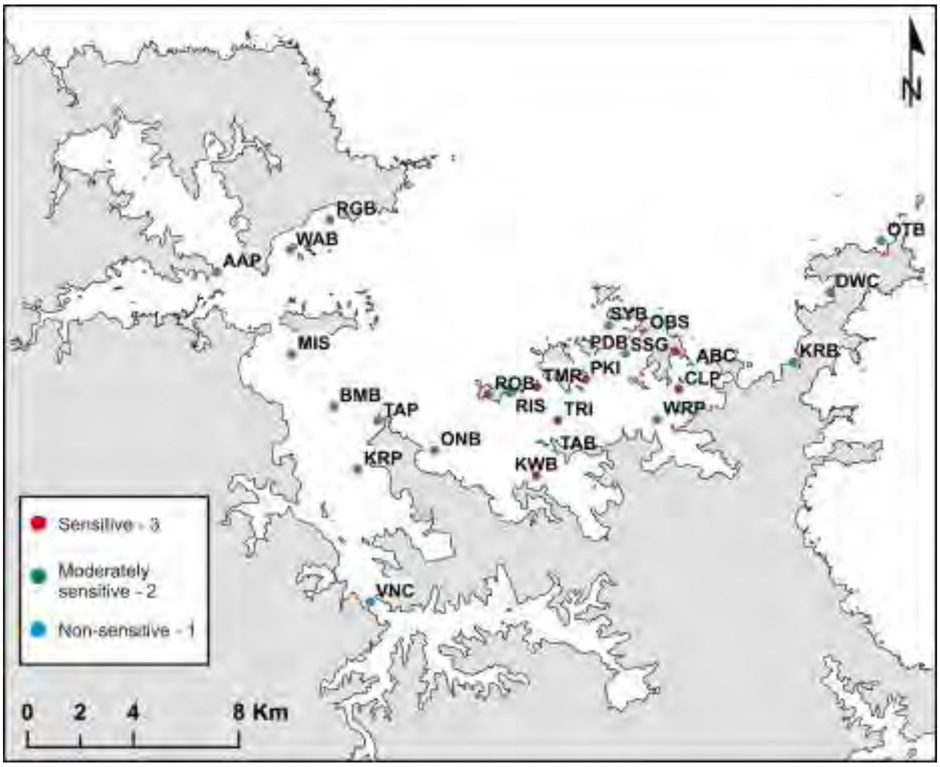

Figure 3-26: Spatial distribution of shallow subtidal macrobenthic communities in the Bay of Islands with varying sensitivity to terrestrial sediment inputs.

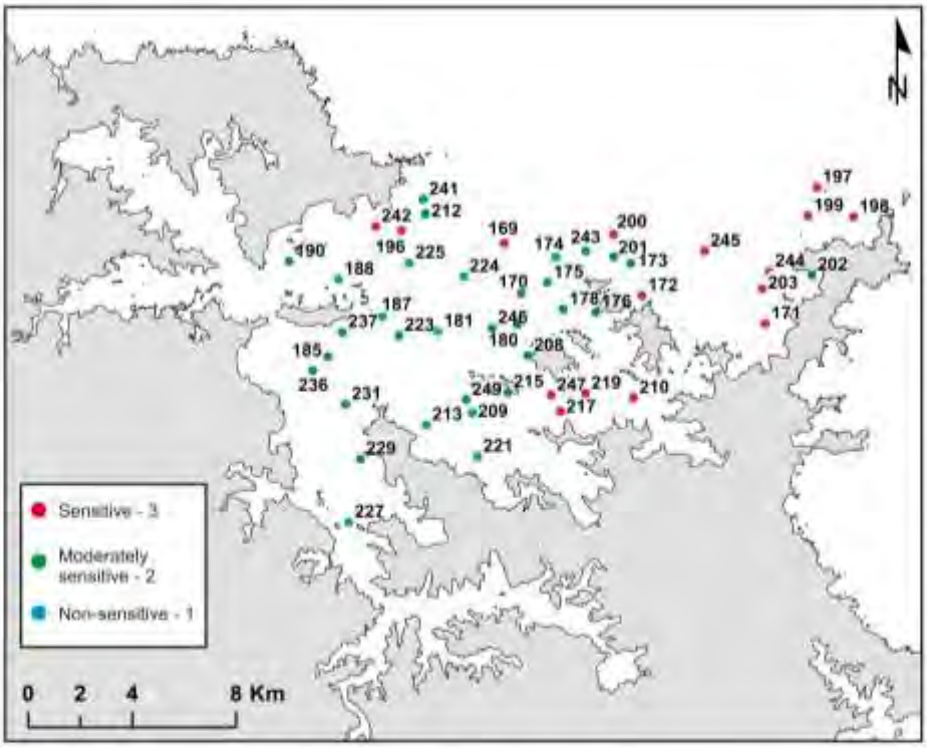

Figure 3-27: Spatial distribution of DTIS macrobenthic communities in the Bay of Islands with varying sensitivity to terrestrial sediment inputs.

3.14.3 Estimation of vulnerability at site locations

The rank value of SAR was selected as an important predictor of community data, for all three datasets (Table 3-9, Figure 3-28). These analyses suggests that, while SAR was an important predictor, the amount of variability explained by this variable alone was generally <5%. Interestingly, the amount explained was not significantly less for the intertidal sites at the community level. However, SAR explained a larger percentage or variation in both the shallow and deeper subtidal sites for Pielou's evenness (10–13%) and in the deeper subtidal sites for number of taxa (15%).

Table 3-9: Percent of overall variation (R2) explained by regression analysis for intertidal, subtidal and DTIS data sets. NB $\log_{10}$ transformations were used to mud and organic content in the intertidal and subtidal data sets.

Data Set	Variable	Important variables	R^2
Intertidal	Community	Mud, OC, SAR	0.25
	Number of taxa	Mud, OC	0.47
	Evenness		<0.10
	Shannon-Weiner	Mud	0.25
Subtidal	Community	Mud, SAR	0.12
	Number of taxa		<0.10
	Evenness	SAR	0.13
	Shannon-Weiner		<0.10
DTIS	Community	Mud, SAR	0.17
	Number of taxa	Mud, SAR	0.35
	Evenness	Mud, SAR	0.20
	Shannon-Weiner	Mud	0.26

As the SAR ranks did provide some predictive ability for the data, we used them to calculate vulnerability.

The spatial distribution of vulnerability of macro-benthic communities to SAR at sites in the BOI system is mapped in Figures 3-29 to 3-31. Across intertidal sites, site 12, located adjacent to Victoria Channel and the Haumi River mouth was the most vulnerable (Figure 3-29). The site was ranked as high sensitivity (sandy habitat; with *Paphies australis*, *Aonides trifida*, and *Notoacmea scapha)* and occurred on the edge of the zone with the highest SAR rank. Highly sensitive sites located in SAR zone 3 (Te Rawhiti Inlet: average SAR rates between 2.3 and 4.9 mmyr^{-1}) were the next most vulnerable, due to the high SAR rank allocated to this zone. As no sites in this zone had been allocated low sensitivity, Te Rawhiti Inlet is the intertidal area most vulnerable.

Similar to the intertidal situation, most of the vulnerable shallow subtidal sites are found in Te Rawhiti Inlet, a combination of their sensitivity and the high SAR ranking assigned to this area (Figure 3-29). Conversely, sites in Veronica Channel have lower vulnerability, due to the predicted lower sensitivity of the communities observed there.

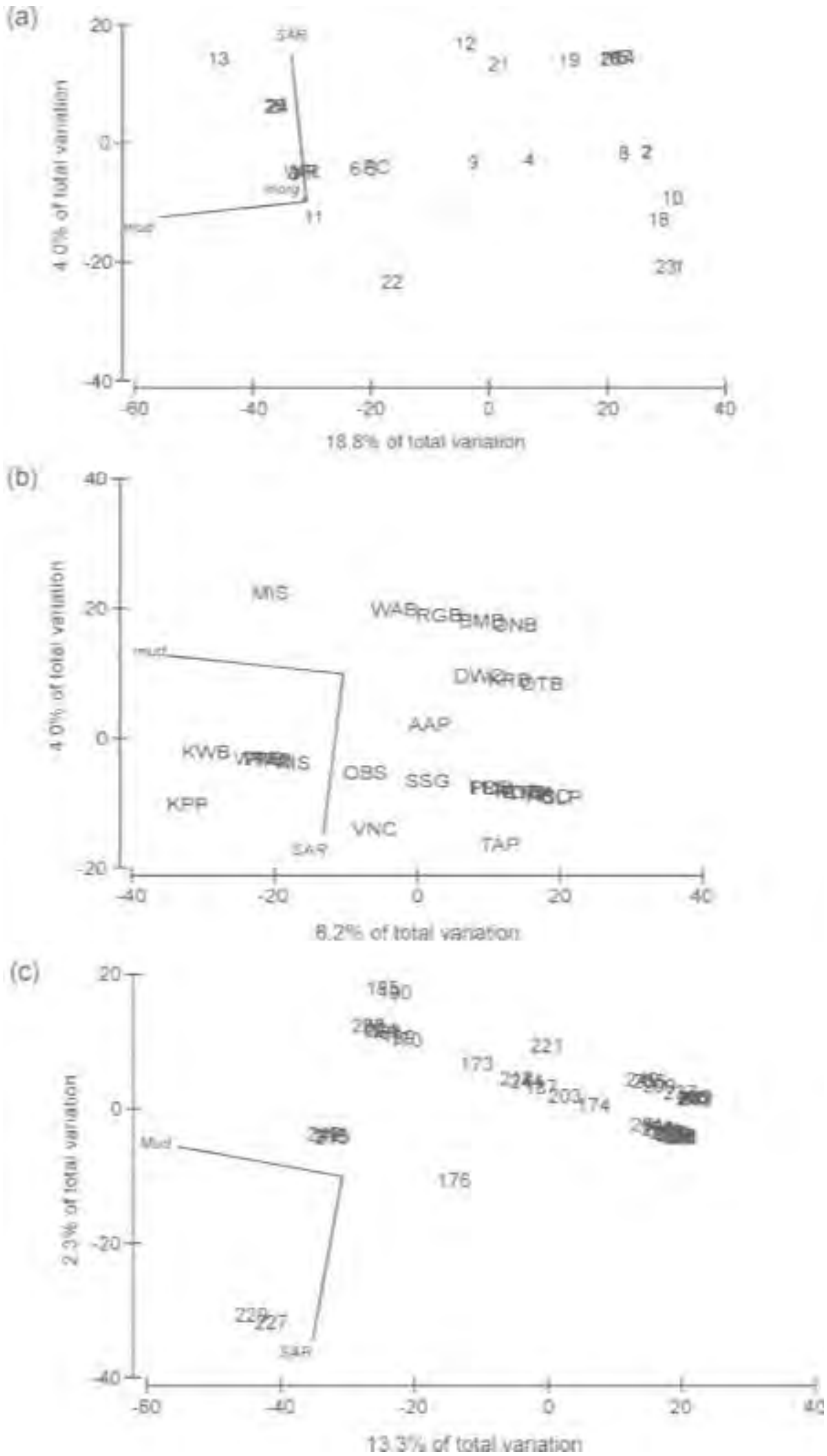

Figure 3-28: Distance-based redundancy analysis of the communities observed in (a) intertidal, (b) shallow subtidal and (c) deeper subtidal areas. Sites that are closest together are most similar, and the length and direction of arrows relative to the amount explained by the horizontal and vertical axis gives an indication of the relative importance of different environmental variables.

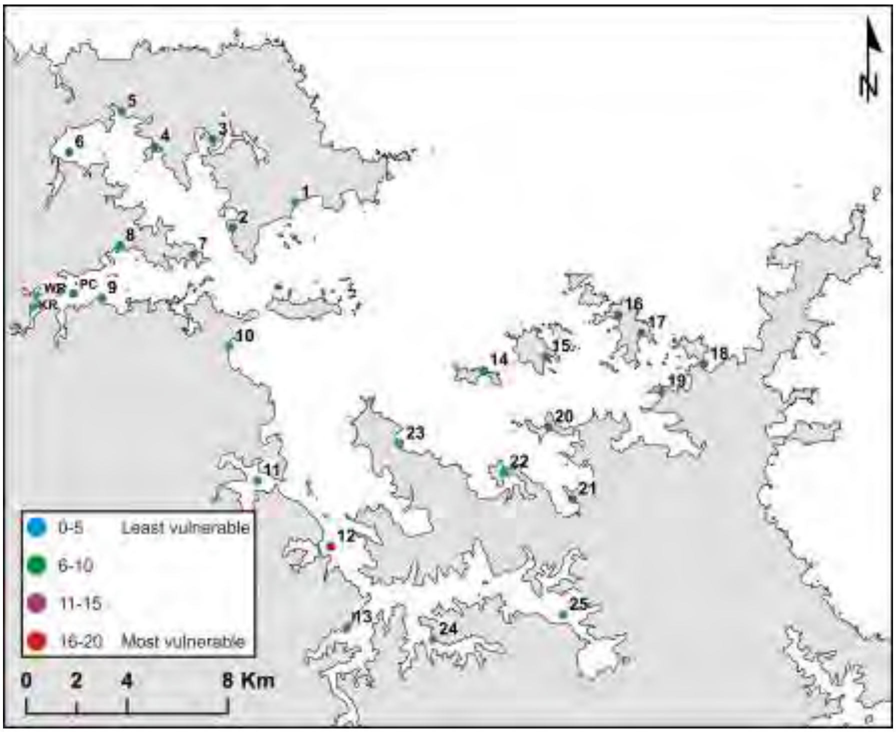

Figure 3-29: Vulnerability of intertidal communities in the Bay of Islands to potential sediment deposition. The larger the value, the more vulnerable the community is to sediment deposition, at estimated rates described from interpolated SAR values calculated in the present study.

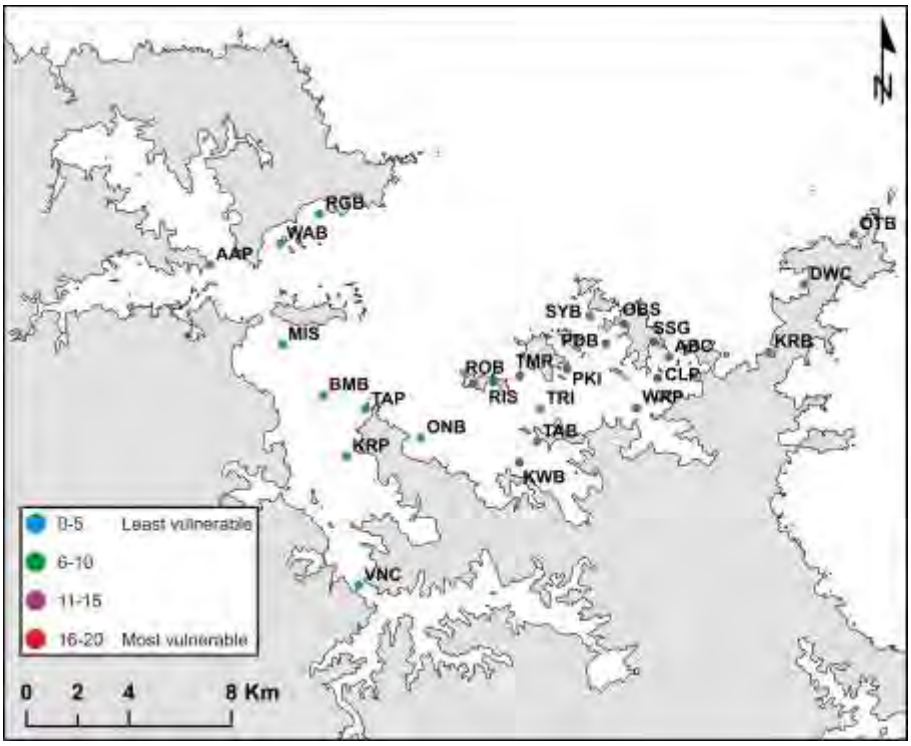

Figure 3-30: Vulnerability of subtidal communities in the Bay of Islands to potential sediment deposition. The larger the value, the more vulnerable the community is to sediment deposition, at estimated rates described from interpolated SAR values calculated in the present study.

Deeper subtidal sampling showed vulnerable communities were found throughout the Bay (Figure 3-31), however, Te Rawhiti Inlet was least likely to lack highly vulnerable sites. A single site sampled in Veronica Channel was the most vulnerable due to the presence of relatively dense beds of *Atrina*.

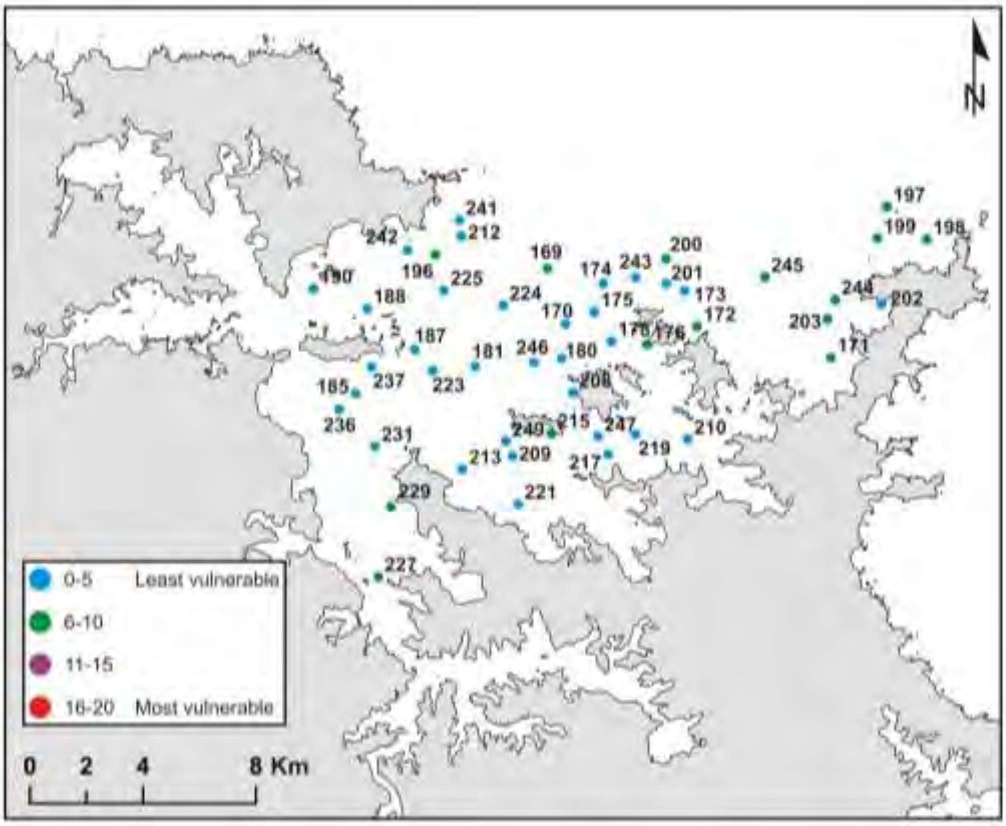

Figure 3-31: Vulnerability of subtidal communities sampled using DTIS in the Bay of Islands to potential sediment deposition. The larger the value, the more vulnerable the community is to sediment deposition.

3.14.4 Determination of likely sediment sources impacting on macro-benthic communities

The most likely sources of sediment depositing in the BOI system determined by this study and the LINZ Oceans 20/20 study (Gibbs & Olsen, 2010) are shown in Table 3-10. In summary, Te Puna, Waitangi and Waikare Rivers are minor inflows compared to the Kerikeri and Kawakawa Rivers. Resuspension occurs in both the Te Puna and Kerikeri Inlets and sediment and water is exchanged between the two inlets. Water (and sediment) from the Kerikeri River and Inlet also flows out into the northern half of the BOI, constrained in its exchange with the southern half by the presence of Moturoa Island. Resuspension, and exchange of resuspended material and water, also occurs in the Kawakawa and Waikare Inlet. Water (and sediment) from the Kawakawa River and the Kawakawa-Waikare Inlets system, flows down Veronica Channel and out into the southern half of the Bay. Dependent on wind direction it either enters the main section of the Bay, or is held against the coastline, entering Te Rawhiti Inlet.

Table 3-10: Areal sources of sediment for different areas within the Bay or Islands.

Description	Dominant Source	Other Sources
Te Puna Inlet	Kerikeri	Resuspension, Te Puna River
Kerikeri Inlet	Kerikeri	Resuspension, Te Puna
Northern Bay	Kerikeri	
Waitangi Inlet	Waitangi	
Veronica Channel	Kawakawa	Waitangi, Waikare
Kawakawa Inlet	Kawakawa	Resuspension, Waikare
Waikare Inlet	Kawakawa	Resuspension, Waikare River
Te Rawhiti Inlet	Kawakawa	Waikare, Waitangi
Southern Bay	Kawakawa	Waikare, Waitangi

These areas can also be ranked according to the average vulnerability of intertidal and subtidal sites sampled within them (Table 3-11).

Table 3-11: Average vulnerability and sources of sediment for different areas within in the Bay of Islands. Landuse source contributions from Table 2 Gibbs and Olsen (2010). Average subtidal variability includes both shallow and deep sites.

Description	Average vulnerability intertidal	Average vulnerability subtidal	Average vulnerability DTIS	Dominant sources
Veronica Channel	18	4.7	6.0	Kawakawa: Pasture cattle and pine clearfell
Te Rawhiti Inlet	10.5	12.2	6.7	Kawakawa: Pasture cattle and pine clearfell
Te Puna Inlet	6.6			Kerikeri; Pasture sheep and subsoil
Kerikeri Inlet	6.5	6		Kerikeri; Pasture sheep and subsoil
Kawakawa Inlet	6			Kawakawa: Pasture cattle and pine clearfell
Southern Bay	5.3	2.9	3.7	Kawakawa: Pasture cattle and pine clearfell
Waitangi Inlet	4			Waitangi: Pasture cattle and subsoil
Waikare Inlet	4			Kawakawa: Pasture cattle and pine clearfell
Northern Bay	2	1.5	3.5	Kerikeri; Pasture sheep and subsoil

Using all datasets, Veronica Channel and Te Rawhiti Inlet are the most vulnerable areas, with sediment sources primarily from Kawakawa River, where pasture cattle and pine clear-fell are the most likely contributors.

3.15 Recent historical changes in mangrove and salt marsh-habitat extent

In this section we report on changes in the spatial extent of mangrove and salt-marsh habitats in the BOI system during the 31-year period 1978 to 2009. These data are derived from GIS analysis of historical aerial photographs for each compartment. Due to missing coverage for the 1978 survey in the Veronica and Kerikeri compartments, the habitat change statistics were normalised by discarding the same areas from the 2009 survey. The total discarded area for mangrove and salt-marsh habitats were 11.8 ha and 2.9 ha respectively. The actual habitat areas (2009) within these two compartments are reported.

3.15.1 Summary of changes in vegetated intertidal habitats

Table 3-12 and Figures 3-32 and 3-33 summarises the total (2009) area of mangrove and salt-marsh habitats in each compartment and the annual average change in habitat area expressed as % per year (% yr^{-1}) relative to the 1978 habitat area.

Table 3-12: Summary of the present area (2009) and recent historical changes in mangrove and salt marsh habitat in the Bay of Islands system.

Compartment	Mangrove			Salt marsh		
	Area (ha)	Area (% of total)	Habitat change (% yr^{-1})	Area (ha)	Area (% of total)	Habitat change (% yr^{-1})
Waikare	666.0	56.4	0.27	219.7	78.3	-0.44
Veronica	247.7	20.9	0.33	21.3	7.6	0.55
Te Rawhiti	58.0	4.9	1.41	10.1	3.6	0.30
Kerikeri	105.9	9.0	0.68	12.7	4.5	-1.11
Te Puna	103.0	8.7	0.70	13.9	5.0	-0.34
Central BOI	0.8	0.1	-0.11	0.0	–	–
Total (ha)	1181.4			280.6		

Notes: (1) Habitat areas (hectares) are given for the 2009 aerial photography; (2) The rate of habitat change is given as an average percentage per year (1978–2009) relative to the 1978 habitat areas and does not include the missing coverage in the Kerikeri and Veronica compartments.

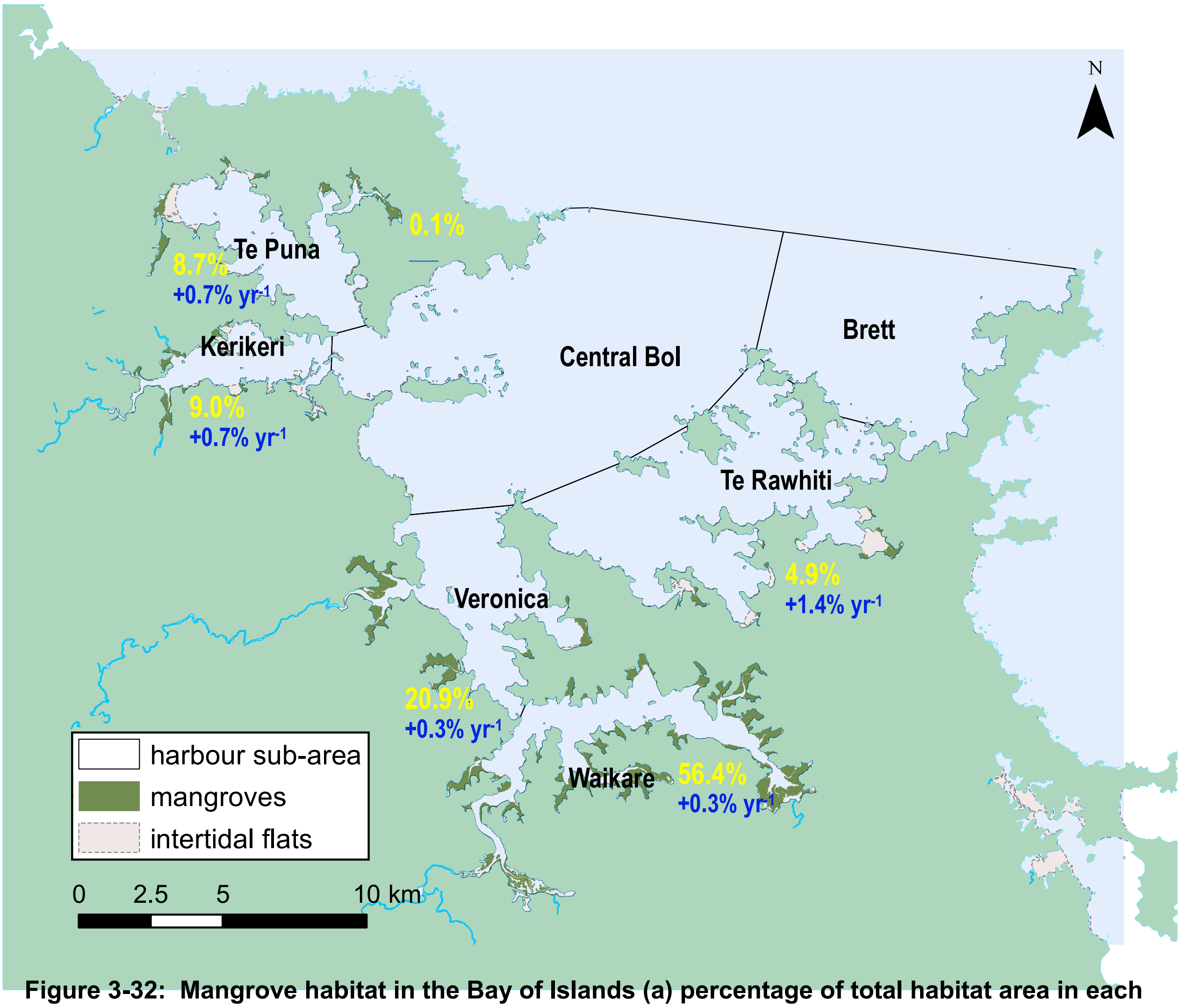

Figure 3-32: Mangrove habitat in the Bay of Islands (a) percentage of total habitat area in each compartment (% 2009, yellow text); and average rate of change in mangrove habitat (%/yr, 1978-2009, blue text). Source: NRC.

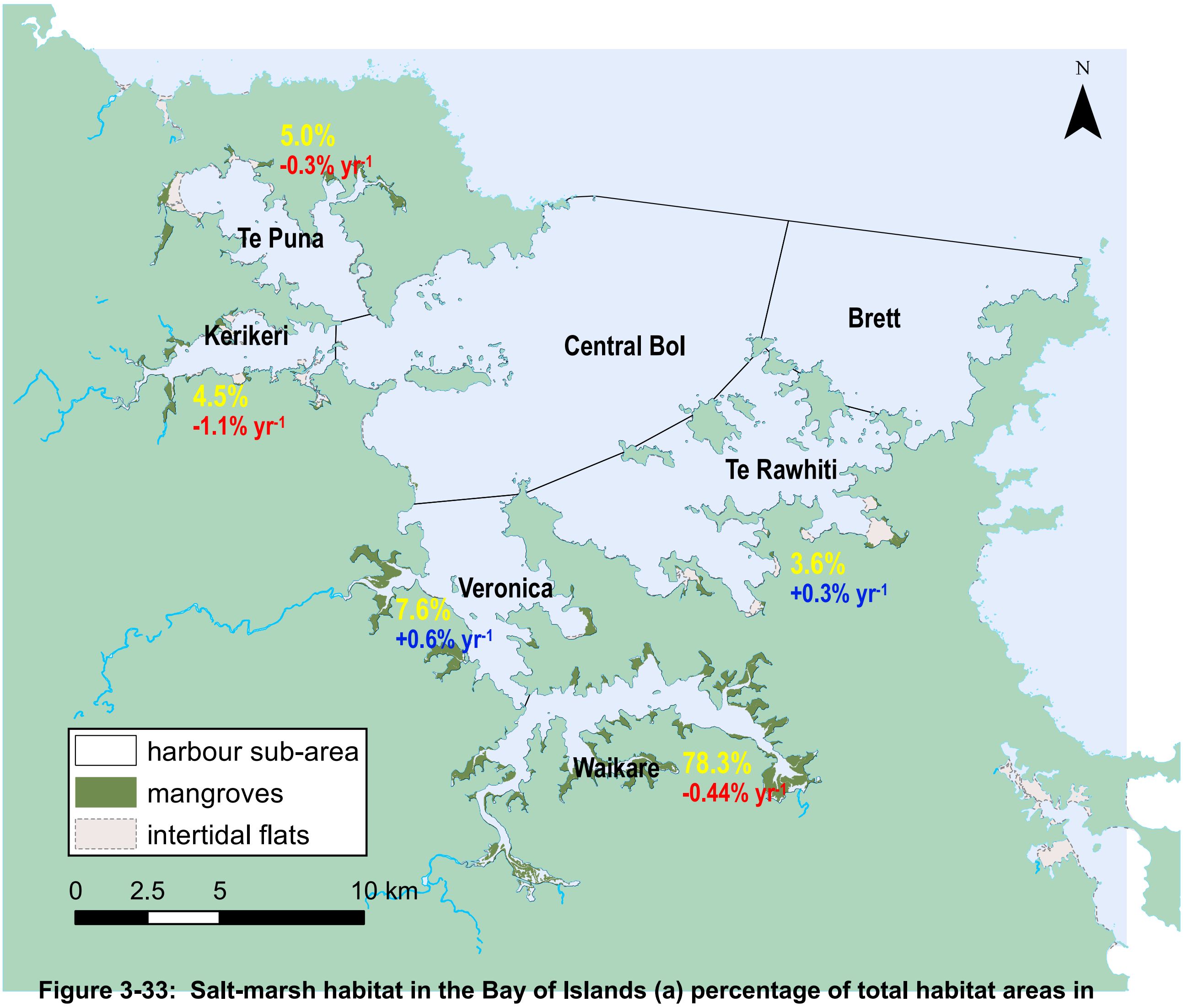

Figure 3-33: Salt-marsh habitat in the Bay of Islands (a) percentage of total habitat areas in each compartment (% 2009, yellow text); and average rate of change in salt-marsh habitat (%/yr, 1978-2009, blue and red text). Source: NRC.

The total area of mangrove in the BOI system has increased by at least 10.8% (126.9 ha) since 1978. A large proportion of this increase in mangrove habitat (51 ha, 40%) occurred in the Waikare Inlet. By comparison, the total area of salt marsh decreased by 12.3% (39 ha) during the same time period. Most of this salt-marsh habitat loss (34 ha, 89%) occurred in the Waikare Inlet. As observed in other North Island estuaries (Morrisey et al. 2010), loss of salt marsh habitat has most likely occurred due to the landward expansion of mangrove habitat and/or reclamation and/or die-off of salt marsh areas. Historical losses of mangrove and salt-marsh habitats in the Waikare Inlet and other estuaries of the BOI system have occurred due to reclamation (Chapman, 1978, Walls 1987). Further analysis of the aerial photographic record could establish the relative contribution of these potential causal factors, particularly in the Waikare Inlet were the largest net increase in mangrove habitat has occurred.

In the following sections, the spatial patterns of changes in mangrove and salt-marsh habitats in each of the compartments are briefly described.

3.15.2 Waikare Inlet

Table 3-13 and Figure 3-34 summarise the changes in mangrove and salt-marsh habitats that have occurred in the Waikare Inlet during the 31-year period 1978–2009. Mangrove and salt-marsh habitat in the Waikare Inlet accounts for 56% and 78% (2009) respectively of the total area of these vegetated habitats in the BOI system.

Table 3-13: Waikare Inlet: changes in the area (hectares) of mangrove and salt-marsh habitats (1978-2009).

Habitat	1978 (ha)	2009 (ha)	% change	%/yr
Mangrove	614.6	666.0	8.4	0.27
Salt marsh	254.4	219.7	-13.6	-0.44

The area of mangrove forest increased by 8.4% during the period 1978–2009, with mangrove stands occurring in the numerous bays and tidal creeks that fringe the Waikare Inlet (Figure 3-34). By comparison, the area of salt marsh declined by 13.6% during the same period, although the total area in 2009 (~220 ha) was only one third of the area occupied by mangrove habitat. The annual-average rates of change in mangrove and salt-marsh habitat were 0.27% yr^{-1} and 0.44% yr^{-1} respectively (1978–2009).

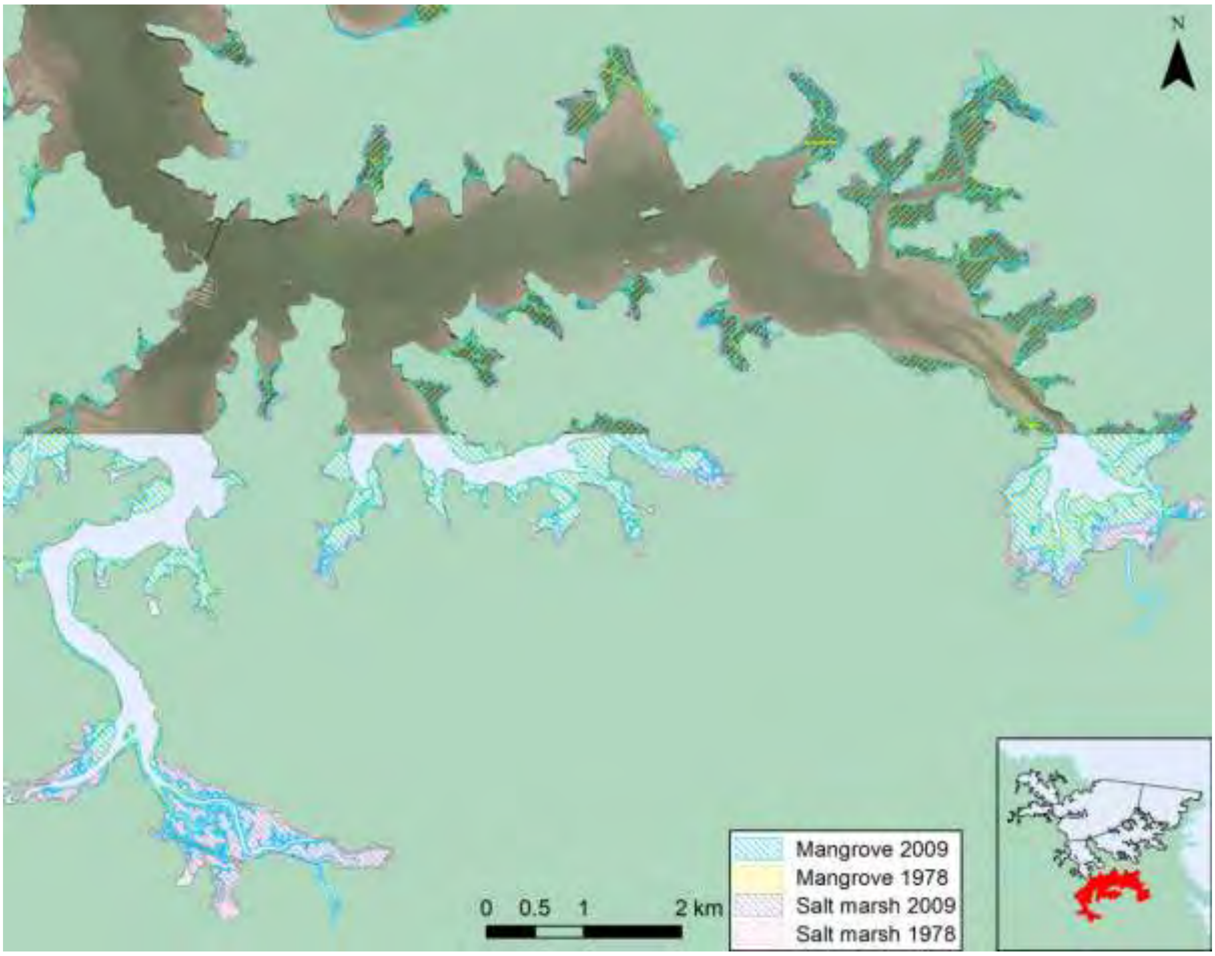

Figure 3-34: Waikare Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

3.15.3 Veronica Inlet

Table 3-14 and Figure 3-35 summarise the changes in mangrove and salt-marsh habitats that have occurred in the Veronica Inlet during the 31-year period 1978–2009. Mangrove and salt-marsh habitats in the Waikare Inlet account for 20.9% and 7.6% (2009) respectively of the total area of these vegetated habitats in the BOI system. The changes in the areas of these vegetated habitats could not be accurately estimated for the Veronica Inlet due to small gaps in the coverage of the 1978 aerial photography.

Table 3-14: Veronica Inlet: changes in the area (hectares) of mangrove and salt-marsh habitats (1978-2009).

Habitat	1978 (ha)	2009 (ha)	% change	%/yr
Mangrove	222.4	244.9	–	–
Salt marsh	18.3	21.4	–	–

Mangrove and salt marsh habitats in the Veronica Channel are largely restricted to several creek and bays which fringe the main channel: Waitangi and Haumi Rivers and Orongo Bay (Figure 3-35). Most of intertidal flats fringing the main channel are devoid of mangrove and salt marsh, which is consistent with increased wave exposure of these shorelines.

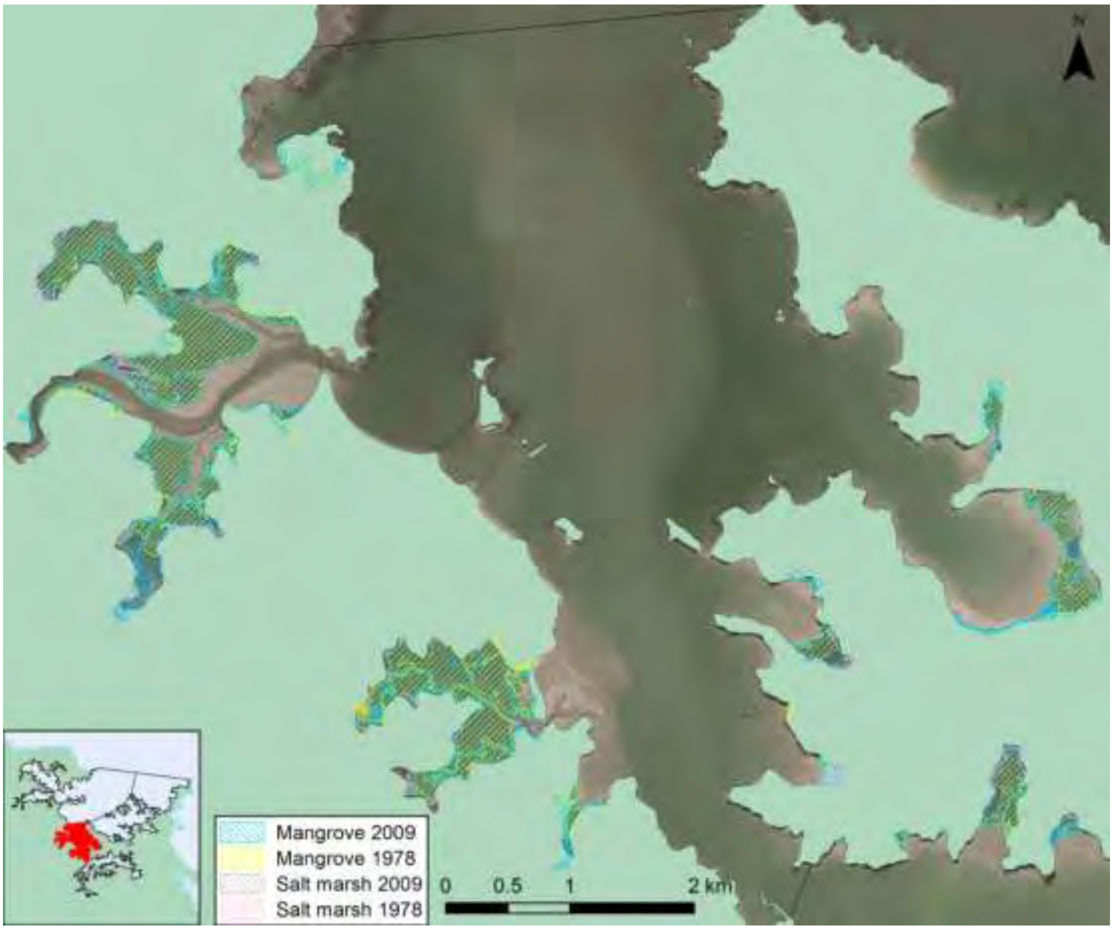

Figure 3-35: Veronica Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

3.15.4 Te Rawhiti Inlet

Table 3-15 and Figure 3-36 summarise the changes in mangrove and salt-marsh habitats that have occurred in the Te Rawhiti Inlet during the 31-year period 1978–2009. Mangrove and salt-marsh habitats in the Te Rawhiti Inlet account for 4.9% and 3.6% (2009) respectively of the total area of these vegetated habitats in the BOI system.

Table 3-15: Te Rawhiti Inlet: changes in the area (hectares) of mangrove and salt-marsh habitats (1978-2009).

Habitat	1978 (ha)	2009 (ha)	% change	%/yr
Mangrove	40.4	58.1	43.8	1.4
Salt marsh	9.2	10.1	9.4	0.3

Mangrove and salt marsh habitats in the Te Rawhiti Inlet are restricted to several sheltered small tidal creeks and bays within Paroa, Manawaora and Parekura Bays that indent the eastern shoreline of Te Rawhiti Inlet: Clendon Cove, Te Huruhi and Waipiro Bays (Figure 3-36).

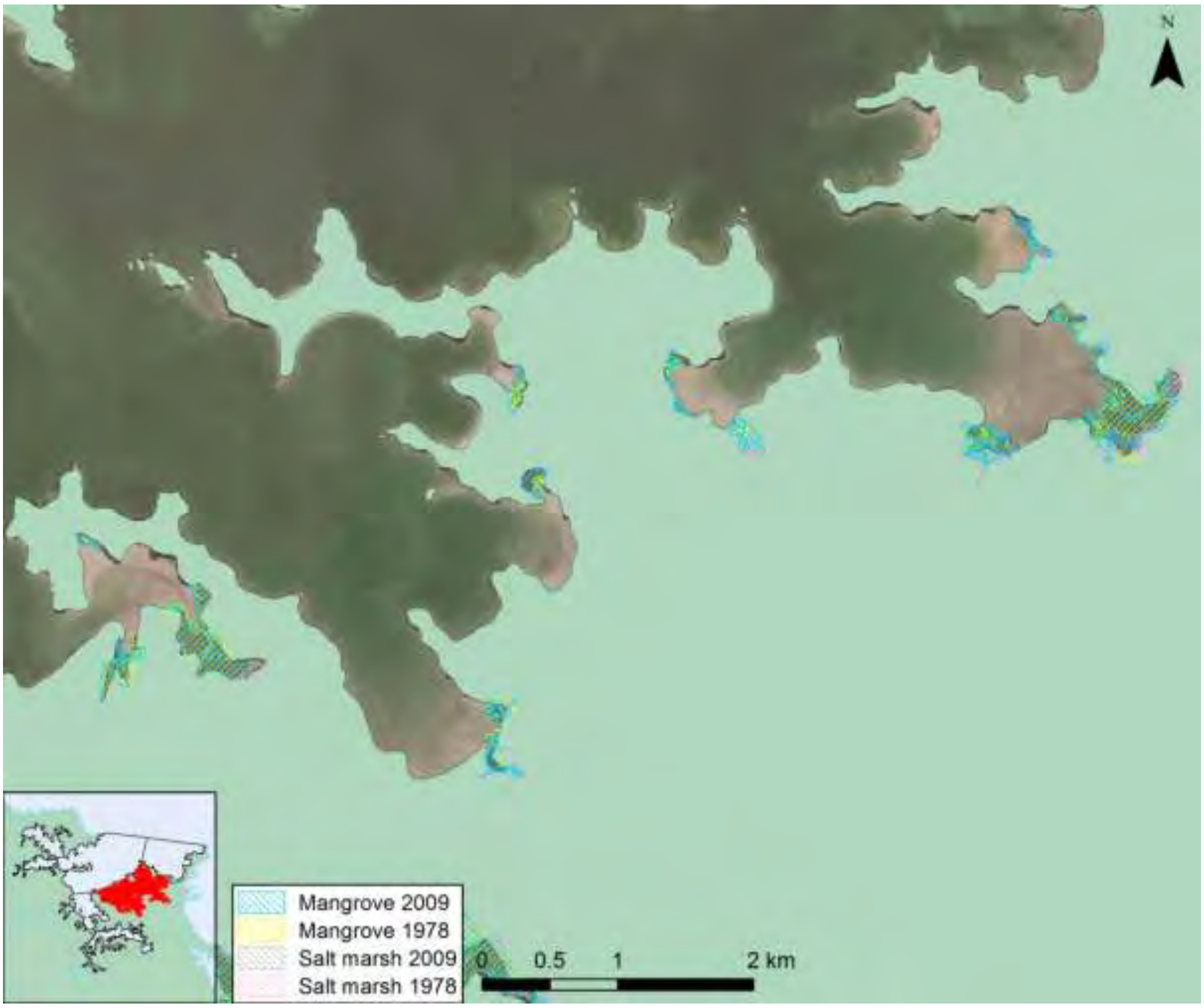

Figure 3-36: Te Rawhiti Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

As observed in the Veronica Inlet, most of Te Rawhiti shoreline is devoid of mangrove and salt marsh habitat, which is consistent with the wave exposure of these shorelines.

3.15.5 Kerikeri Inlet

Table 3-16 and Figure 3-37 summarise the changes in mangrove and salt-marsh habitats that have occurred in the Kerikeri Inlet during the 31-year period 1978–2009. Mangrove and salt-marsh habitats in the Kerikeri Inlet account for 9.0% and 4.5% (2009) respectively of the total area of these vegetated habitats in the BOI system. The changes in the areas of these vegetated habitats could not be accurately estimated for the Kerikeri Inlet due to small gaps in the coverage of the 1978 aerial photography.

Table 3-16: Kerikeri Inlet: changes in the area (hectares) of mangrove and salt-marsh habitats (1978-2009).

Habitat	1978 (ha)	2009 (ha)	% change	%/yr
Mangrove	80.0	97.0	–	–
Salt marsh	19.4	12.7	–	–

Mangrove and salt marsh habitats in the Kerikeri Inlet are restricted to several tidal creeks and bays in the upper reaches of Kerikeri Inlet: Okura River, Waipapa Stream, Kerikeri River and Pirikawau and Aroha Bays (i.e., islands) (Figure 3-37).

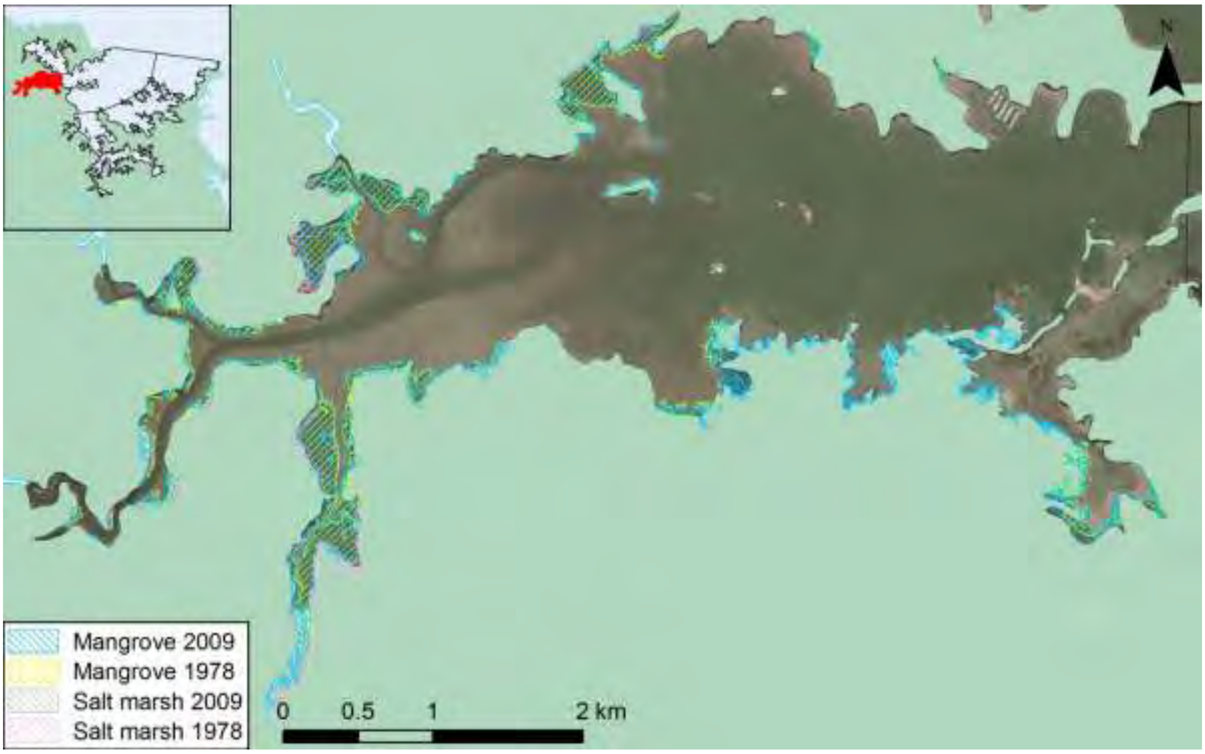

Figure 3-37: Kerikeri Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

3.15.6 Te Puna Inlet

Table 3-17 and Figure 3-38 summarise the changes in mangrove and salt-marsh habitats that have occurred in the Te Puna Inlet during the 31-year period 1978–2009. Mangrove and salt-marsh habitats in the Te Puna Inlet account for 8.7% and 5.0% (2009) respectively of the total area of these vegetated habitats in the BOI system.

The area of mangrove forest increased by 21.7% during the period 1978–2009 (Table 3-17). By comparison, the area of salt marsh declined by 10.5% during the same period, although the total area in 2009 (~220 ha) was only 13% of the area occupied by mangrove habitat. The annual-average rates of change in mangrove and salt-marsh habitat were 0.7% yr^{-1} and -0.3% yr^{-1} respectively (1978–2009).

Table 3-17: Te Puna Inlet: changes in the area (hectares) of mangrove and salt-marsh habitats (1978-2009).

Habitat	1978 (ha)	2009 (ha)	% change	%/yr
Mangrove	84.7	103.0	21.7	0.7
Salt marsh	15.6	14.0	-10.5	-0.3

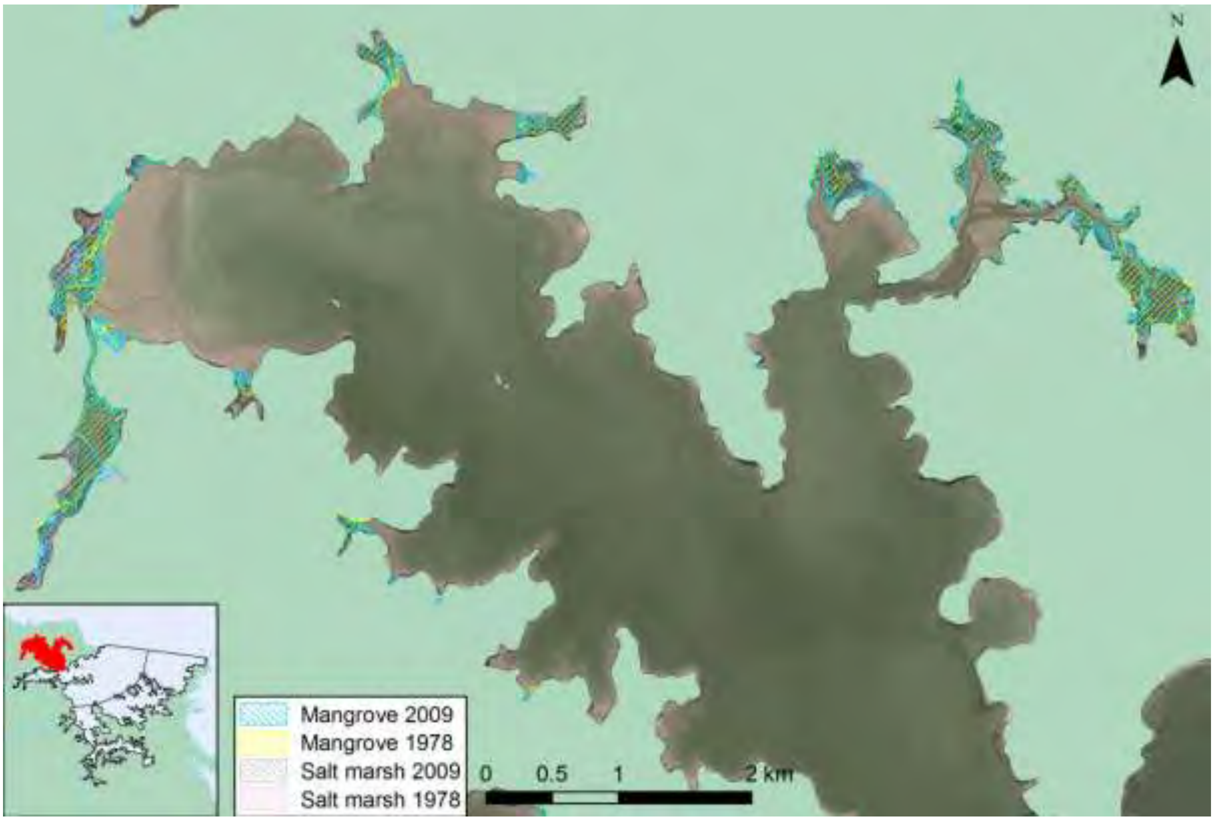

Figure 3-38: Te Puna Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

Mangrove and salt marsh habitats are restricted to several sheltered small tidal creeks in the upper reaches of Te Puna Inlet: Pokura Inlet and Te Arorua and Opete Creeks (Figure 3-38).

3.15.7 Central Bay of Islands

Table 3-18 and Figure 3-39 summarise the changes in mangrove and salt-marsh habitats that have occurred in the central BOI during the 31-year period 1978–2009. Mangrove habitat in the central BOI accounts for 0.1% (2009) of the total area of mangrove habitat in the BOI system. The small area of mangrove forest (~0.8 ha) did not measurably change during the period 1978–2009 (Table 3-18). Salt-marsh habitat was not detected in the analysis of the 1978 and 2009 aerial photography.

Table 3-18: Central Bay of Islands: changes in the area (hectares) of mangrove and salt-marsh habitats (1978-2009).

Habitat	1978 (ha)	2009 (ha)	% change	%/yr
Mangrove	0.83	0.80	–	–
Salt marsh	–	–	–	–

Mangrove habitat is restricted to small areas in Wairoa Bay and on the upper intertidal zone of the Brampton Shoal. It is notable that mangroves were present at the latter location in 1978 and 2009, suggesting that the shelter from wave action afforded by the Brampton shoal is sufficient for mangroves to persist (Figure 3-39).

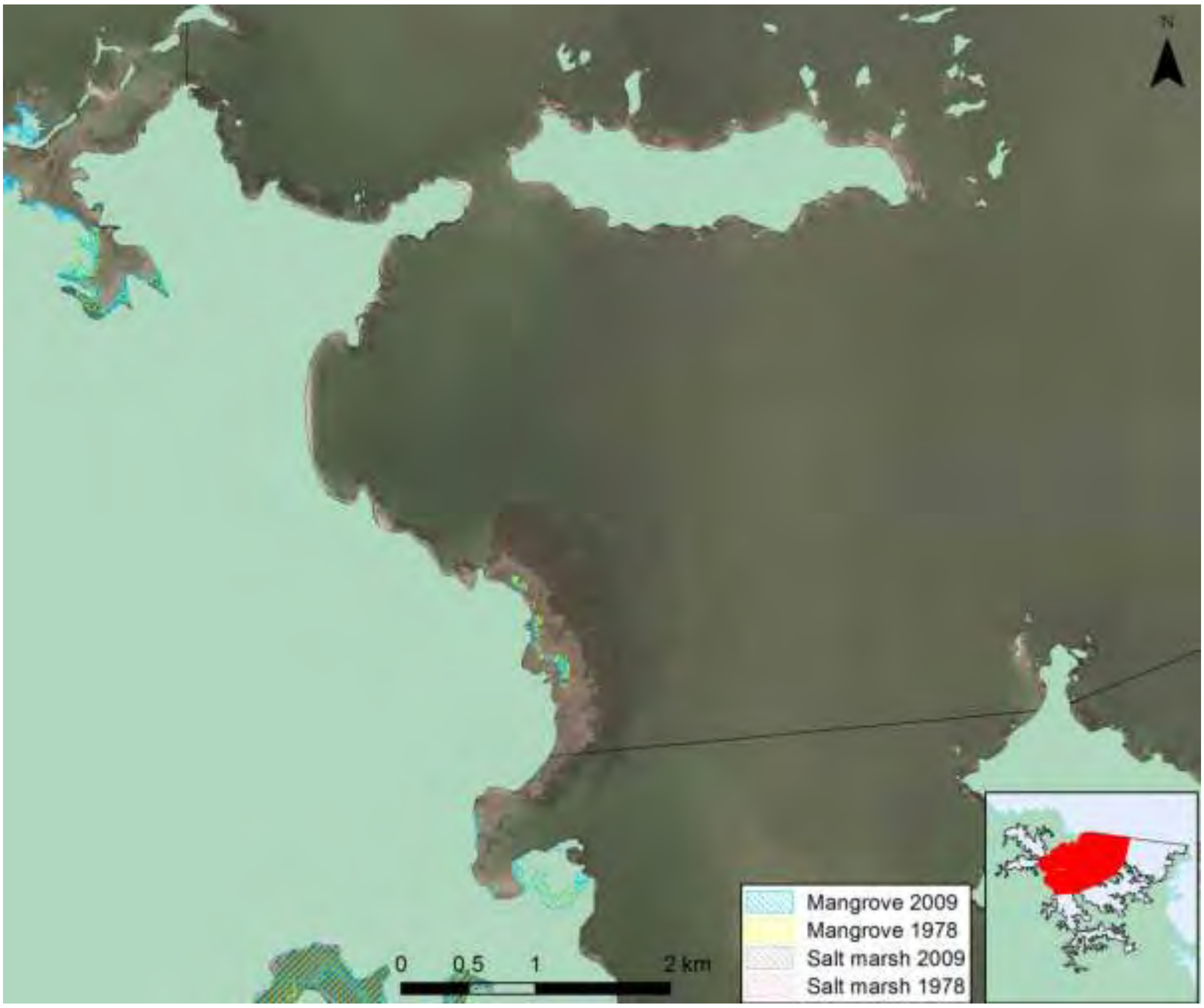

Figure 3-39: Central Bay of Islands: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

3.15.8 Interpretation of historical changes in mangrove-habitat extent

Mangrove-habitat expansion occurred in all of the estuaries of the Bay of Islands system over the last three decades (Table 3-12). The largest increases in mangrove habitat have occurred in the estuaries with the largest total areas of mangrove habitat: Waikare (+51.5 ha) and Veronica (+22.6 ha). By comparison, smaller, although substantial increases have occurred in Te Rawhiti (+17.7 ha), Kerikeri (+17 ha) and Te Puna (+18.4ha) Inlets. When transformed to percentage data, the largest increases in mangrove habitat have occurred in the estuaries with smallest habitat areas: Te Rawhiti (+43.8%); Te Puna (+22%); Kerikeri (+21%); Veronica (+10%) and Waikare (8%).

These spatial patterns in mangrove-habitat expansion are consistent with, and perhaps driven by, more rapid infilling of estuaries near major river outlets (section 3.1, Figure 3-1), in particular the Veronica and Waikare compartments into which the Kawakawa and Waitangi river catchments discharge. The relatively large areas of mangrove habitat present in these compartments in 1978 suggest that these forests had been established for decades on intertidal-flats built from eroded catchment soils. These accreting tidal flats became suitable for mangrove-seedling establishment once the sea-bed surface elevation exceeded mean sea level. In contrast and in areas with wave fetches of a km or more, mangrove-seedling recruitment and subsequent forest development will also have been retarded by reworking of intertidal flat sediments by waves (Morrisey et al. 2010). In the Waikare and Veronica compartments it is likely that most of the intertidal flat suitable for mangroves had been colonised prior to the 1970s, so that subsequent increases in mangrove habitat have been relatively modest. In estuaries and bays more remote from the major river inflows, infilling has occurred at a lower rate, with new areas of intertidal flat becoming progressively available for mangrove colonisation as tidal flats attain the MSL threshold.

Despite the large percentage increase in mangrove habitat in Te Rawhiti Inlet since 1978, mangroves remain restricted to sheltered creeks in the upper reaches of Paroa, Manawaora and Parekura Bays. There is limited remaining capacity for additional mangrove habitat expansion within these creeks and extensive upper intertidal flats within the bays have not been colonised by mangroves, most likely due their wave exposure.

The rates of mangrove habitat expansion in the BOI system of 0.3–1.4% yr^{-1} are in the range observed in other North Island estuaries (0.2–20% yr^{-1}), although substantially less than the average rate of 4% yr^{-1} since the 1940s (Morrisey et al. 2010). These data include studies of small mangrove stands as well as large forests (10^0–10^3 ha) and all major estuary types: drowned river valleys, barriers, embayments and coastal lagoons.

3.16 Potential for future mangrove-habitat expansion

The potential for future mangrove-habitat expansion in the BOI system will largely be limited to local estuarine sites in tidal creeks and small bays sheltered from wave action. In estuaries such as the Waikare Inlet, the mangroves will continue to gradually colonise tidal flats seaward of existing mangrove stands as tidal-flats accrete above MSL elevation.

The potential for future large-scale mangrove-habitat expansion in many of these estuaries is likely to be limited because of:

- The low historical rate of forest expansion in many estuaries. The analysis of the aerial photography (1978, 2009) shows that large areas of the BOI system have not been colonised by mangroves (section 3.12).
- Widespread effects of seabed disturbance due to sediment resuspension by waves. This is shown by the depth of the ^{7}Be surface-mixed layer preserved in the sediment cores and measurements of sediment resuspension in BOI estuaries (Gibbs & Olsen, 2010).
- The future effects of accelerated sea-level rise on the area of suitable intertidal flat that will be available for mangrove colonisation. The likely effects of accelerated sea-level rise on BOI mangrove forests are described below.

Future increases in mangrove-habitat extent in the BOI system will largely depend on whether intertidal-flat elevations will continue to increase more rapidly than the rate of relative sea-level rise (RSLR).

A regional study of mangrove forests in Auckland's east-coast estuaries (Swales et al. 2009) evaluated the potential for future mangrove-habitat expansion under historical rates of sedimentation and RSLR as well as several scenarios for future sea-level rise. These scenarios were developed from the Intergovernmental Panel on Climate Change (IPCC

2007) projections. This assessment of future mangrove-habitat expansion was supported by estuary-specific information on sedimentation rates, intertidal-flat surface elevations and wave exposure. These sea-level-rise projections have been tailored for application in New Zealand for planning timeframes out to the 2090s (MfE, 2008). Swales et al. (2009) adopted three SLR scenarios based on the MfE (2008) Guidance Manual:

- **Scenario One (S1):** the historical trend in sea level observed at the Port of Auckland since 1950. Average SLR of 1.6 mm yr-1 resulting in an increase in sea level of 0.08 m by the 2050s and 0.14 m by the 2090s.
- **Scenario Two (S2):** based on the MfE (2008) guidance incorporating the IPCC (2007) projections. Average SLR of 4.6 mm yr-1 resulting in an increase in sea level of 0.22 m by the 2050s and 5.4 mm yr-1 (+0.47 m) by the 2090s. Scenario Two represents a mid-range SLR projection.
- **Scenario Three (S3):** based on the MfE (2008) guidance incorporating the IPCC (2007) projections. Average SLR of 6.9 mm yr-1 resulting in an increase in sea level of 0.33 m by the 2050s and 8.8 mm yr-1 (+0.77 m) by the 2090s. Scenario Two represents a possible upper-range SLR projection.

Research published after the IPCC (2007) assessment, including Hansen (2007), Rahmstorf et al. (2007) and Rignot et al. (2008) suggests that eustatic (global) sea-level increases of one metre or more could be possible by 2100 AD if ice-sheet melt rates accelerate. It is likely to be some time before the upper limit of potential sea level rise this century can be defined worth some degree of confidence. The MfE (2008) manual recognises that local government must continue to make planning decisions in the coastal environment despite the uncertainty about future sea-level changes.

The Swales et al. (2009) study concluded that there was a low likelihood of large-scale mangrove habitat expansion in most of Auckland’s east-coast estuaries. The pace of future sea-level rise relative to sedimentation rates will ultimately determine the long-term fate of mangrove forests. Although there is some potential for increases in mangrove habitat in rapidly infilling estuaries under S1 (i.e., historical SLR trend), reductions in mangrove habitat are likely to occur under S2 and S3. The main driver of mangrove-habitat loss under S2 and S3 is that the average sediment accumulation rate (SAR) in Auckland’s east-coast estuaries (3.8 mm yr^{-1}) is less than the projected rate of RSLR. The key exception to these outcomes is that mangrove forests in tidal creeks will be able to keep pace with RSLR due to higher SAR. In most estuaries, loss of present-day mangrove habitat from tidal flats is unlikely to occur until after the 2090s. Tidal creeks will provide refuges for mangroves, assuming that rapid sedimentation over the last ~50 years measured in these environments occurs in the future.

The findings of the Auckland mangrove study have implications for the future fate of mangrove habitats in the BOI system:

- Average SAR in Bay of Island estuaries are typically lower than in Auckland’s east-coast estuaries. Consequently maintenance or even modest increases in mangrove habitat area over the next century are only likely to occur under scenario one (i.e., historical sea-level trend).

- Large-scale loss of mangrove habitat is likely to occur in the Bay of Islands latter this century after the 2090s if the rate of sea-level rise accelerates (scenarios 2 and 3).

4 Summary and conclusions

The Northland Regional Council (NRC) commissioned NIWA to analyse and report on sediment and benthic ecological data collected as part of the 2010 LINZ Oceans 20/20 Bay of Islands (BOI) survey. These data provide: 1) detailed and robust information on the state of the environment; and 2) an opportunity to inform the future management of the catchment and the receiving coastal marine environment of the BOI system.

In this section we summarise the key findings of this study.

4.1 Catchment history

The original native-forest landcover of the Bay of Islands catchment was dominated by rimu, totara, tanekaha and kauri. Natural erosion of native-forest catchment soils occurred for thousands of years before people arrived in the Bay of Islands, as indicated by compound-specific stable-isotope (CSSI) analysis of dated sediment cores (section 3.9).

Previous paleoenvironmental studies and historical accounts show that large-scale catchment deforestation began in the Bay of Islands soon after Polynesian arrival (mid-1300s) and several centuries before European settlement began in the1820s Catchment deforestation appears to have occurred earlier than in many other locations in the North Island due to the relatively high Māori population density (section 1.5). The Waitangi and Kerikeri catchments were major population centres from the early Māori period due to the fertile volcanic soils and land cover in pre-European times was a patch-work of gardens, forest remnants and scrub (section 2.8). By the early-1800s extensive gardens of potatoes, kumara and other introduced vegetables were cultivated by Māori.

large-scale deforestation continued following European settlement even though large native-forest remnants are still found in the Waikare and Kawakawa catchments today. Wheat and maize crops were established at Okaihau (north of Lake Omapere) in the 1860s but were short lived due to the warm and humid climate. Dairying was initially established at this time on smaller farms with sheep and cattle farming occurring on larger land holdings. By the early 1900s a substantial proportion of the BOI catchment was dominated by pastoral agriculture. In the Kerikeri catchment, citrus orchards were first established in the late-1920s by George Alderton, who planted 10,000 citrus trees. Citrus production increased after World War Two as well as the introduction of other crops (e.g., kiwi fruit) from the early 1970s.

The present-day landcover of the 1294 km^2 BOI catchment is dominated by pasture (46%), with smaller areas of native forest (20%) and scrub (10%), pine forest (11%) and orchards (3%).

4.2 Sedimentation

The general approach taken in the coring study was to quantify sediment accumulation rates (SAR) along an effects gradient from major catchment outlets in the upper reaches of estuaries to the inner continental shelf.

The recent sedimentation history of the BOI system was reconstructed from historical records and dated sediment cores collected at twenty-three sites in water depths ranging from 1 m to 100 m (Fig. 2.1). Sediment cores have been dated using lead-210 (^{210}Pb), caesium-137 (^{137}Cs) and radiocarbon (^{14}C) to establish time-averaged SAR and to construct the sedimentation history of the BOI system over the last several thousand years.

Geophysical data from the Oceans 20/20 survey also provided information on seabed type and the thickness of unconsolidated sediment layers deposited over bedrock during the last ~12,000 years (Bostock et al. 2010).

The residence time of sediments in the surface-mixed layer (SML) of the seabed was evaluated at each core site using the maximum penetration depth of the short-lived berrylium-7 (^{7}Be, half-life 53 days) and ^{210}Pb SAR.

These various information strands are used to develop: (1) a conceptual understanding of sedimentation; and (2) a sedimentation budget for the BOI system over the last several thousand years.

The key results of the radioisotope analyses of the sediment cores are:

- The thickness of the active seabed layer as defined by ^{7}Be-labelled sediments is 1–5 cm. Sediments in this layer are reworked by waves and currents, and benthic fauna and are eventually removed from the SML by progressive burial. The relative contribution of physical and biological processes will vary between habitat types. The average residence time of sediments in the SML is 16 ±4.3 years (95% Confidence Interval, CI).

- Sediments in the seabed SML are composed of soils eroded by seasonal–annual storms, soils delivered within the last ~two decades and older sediments reworked within the marine–estuarine environment.

- Sediment cores from the central BOI and inner shelf preserve evidence of deep seabed erosion (~10-cm) by a large magnitude storm that most likely occurred in the early 1900s (section 3.3).

- Lead-210 (^{210}Pb) dating of sediment cores at each site yields time-averaged SAR of 1–5 mm/yr over the last 80–200 years. Fringing estuaries close to major river outlets are accumulating sediment more rapidly (<5 mm/yr) than the central Bay and inner shelf (<2.5 mm/yr). A notable exception to this general pattern is the high ^{210}Pb SAR (2.3–4.9 mm/yr) observed in Te Rawhiti Inlet. Stable-isotope data indicate that present-day sediments depositing in Te Rawhiti Inlet are most-likely derived from the Kawakawa and Waitangi Rivers. This suggests that silt discharged from these rivers during floods are transported and dispersed widely by freshwater runoff and tidal currents into the central Bay from where flood tides transport them into the Rawhiti Inlet where they accumulate, in the shelter from the ocean swell afforded by the islands of the eastern bay.

- The BOI system is infilling more slowly with sediment than other North Island estuaries. The average ^{210}Pb SAR for the entire BOI system is 2.4 mm/yr in comparison to 2.4–6.7 mm/yr in other North Island estuaries (section 3.6). This is primarily a result of the large sediment accommodation capacity of the BOI system relative to the sediment-supply rate.

- Sediment accumulation rates in the BOI system have increased by an order of magnitude following catchment deforestation. Radiocarbon dating of shell material preserved deep in the BOI sediment cores yields calibrated ages ranging from 2170 to 9409 years before present (B.P., 1950 A.D.). The long-term ^{14}C SAR of 0.23 ±0.1 mm/yr (95% CI) over the last several thousand years is an order of magnitude lower than ^{210}Pb SAR over the last 80–200 years. It should be noted that the ^{14}C SAR includes the effects Māori land-use practices since the mid-1300s. Consequently, the ^{14}C SAR values are likely to be higher than actual pre-human sedimentation rates. The order of magnitude increases in SAR following deforestation of the BOI catchment are consistent with data from other North Island estuaries.

- Comparison of the Holocene and recent sedimentation budgets indicate a major shift in the sedimentary regime of the BOI system. Annual sediment deposition in the BOI system has averaged 509,000 ±210,000 tonnes per year (t/yr, 95% CI) over the last ~150 years. This recent deposition rate compares with an average of 20,000 ±9,000 to 50,000 ±23,000 t/yr over the last several thousand years prior to catchment deforestation. The order of magnitude increase in sedimentation in the BOI system is consistent with increased soil erosion following large-scale deforestation. This is a global phenomenon (Thrush et al. 2004), although the timing and intensity of deforestation varies with location. New Zealand was the last major land mass to be colonised by humans, so that these major environmental changes have occurred in just a few hundred years.

- The capacity of the BOI estuaries to accommodate sediment inputs over the next century was evaluated based on measured ^{210}Pb SAR and historical rates of sea-level rise (SLR) at the Port of Auckland (1.5 mm ±0.1 mm/yr), which is the closest tie-gauge with a reliable long-term record. To a first approximation, estuary infilling occurs when SAR >SLR and in the opposite case the average depth of the estuary increases over time when SAR <SLR. The resulting net change in sediment accommodation space can be negative (infilling) or positive (increasing water depth). Long-term net changes in sediment accommodation space are in the range +0.5 to -3.5 mm/yr. The most rapid loss of accommodation space has occurred in the Waikare, Veronica and Te Rawhiti compartments. These areas are most likely to experience large-scale environmental changes, such as loss of subtidal habitats and are likely to have already lost macrobenthic communities composed of plant and animal species (e.g., sea grass, filter-feeding bivalves) most sensitive to the effects of fine sediments. This appears to be the case in the Waikare/Kawakawa Inlet whereas sensitive macrobenthic communities still occur in the Te Rawhiti Inlet, which is more remote from major river inputs (section 3.11).

4.3 Sediment sources

Present-day and past sources of terrigenous sediments deposited in the estuarine and coastal waters of the BOI system were determined using the Compound Specific Stable Isotope (CSSI) method (Gibbs 2008). The CSSI method was applied to present-day (i.e., surface) 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 impart a unique isotopic signature to soils. Fatty acids (FA) have been demonstrated to be particularly suitable 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 catchment soils and reworked marine sediments from various sources. To identify the sources of sediment in a deposit, the isotopic signatures of individual sources were determined by sampling soils for each major vegetation type (e.g., native forest, pine, pasture etc.). The feasible soil sources in each sediment mixture were then evaluated using the IsoSource model (Phillip & Gregg, 2003). The output from this model is statistical information about the feasible isotopic proportion of each source (i.e., % average, standard deviation and range).

The CSSI method has not previously been applied to reconstruct historical changes in the sources of terrigenous sediment. This has been achieved in the present study by extending the CSSI method to the analysis of dated sediment cores. Importantly, this work incorporates a time-dependent correction factor that accounts for changes in the isotopic signatures of organic compounds due to deforestation and burning of fossil fuels since the early 1700s. Long-term changes in the sources of catchment sediment delivered to the BOI system were reconstructed from cores collected in the Waikare Inlet, Veronica Channel near Russell, Kerikeri Inlet, the inner Bay of Islands and the inner continental shelf near the 30-m and 100-m isobaths respectively.

In interpreting these results it is important to bear in mind that the suite of soil types detected in a dated sediment sample does not imply that these were the only vegetation types present in the catchment. What these results do indicate is the major sources of eroded soils that were eventually deposited at a site in the receiving environment.

The key results of the analysis of present-day and past sources of catchment sediments accumulating in the BOI system are:

- Soil eroded from pasture (cattle and sheep) accounts for more than 60% of the present-day sediment delivery to the BOI system. In the Kerikeri and Waitangi sub-catchments a large proportion of these eroded pasture soils are composed of subsoils. This suggests deep erosion of hillslope pasture in these sub-catchments. Production forestry (pine) also accounts for a substantial proportion of the soil deposited in the Te Puna (36%) and Kawakawa (27%) Inlets. In the Waikare sub-catchment most of the soil was eroded from kanuka scrub (70%) and native forest (26%), which reflects the large proportion of native landcover that remains in this sub-catchment today.
- The CSSI method has been extended to determine long-term changes in sources of catchment soil deposited in the BOI system over the last ≤2700 years.
- Bracken-labelled sediments are present in cores at most sites and occur hundreds to thousands of years before the arrival of people and subsequent catchment deforestation from the mid-1300s onwards. These data indicate that natural disturbance of the landscape was a feature of this environment. Likely

causes of forest disturbance include landslides during high-intensity rainstorms and/or fires.

- The effects of Māori on catchment soil erosion are not well represented in the sediment cores that were analysed. Typically the Māori period (~1300–1800 AD) occupies only a 10–20 cm-thick sediment layer in the cores. We do know from historical accounts of early Europeans that Māori had cleared large areas of native forest from the catchment. Bracken would have established on these cleared areas but this anthropogenic effect cannot be distinguished from natural catchment disturbance after 1300 AD. Only in the Kerikeri Inlet (core RAN-S18) is their some evidence of the cultivation of root crops, such as kumara. This is indicated by the presence of potato-labelled soils in single sample dated to the 1500s, which is likely to have a similar signature to kumara.

- The effects of Europeans on soil erosion over the last century are clearly evident due to the introduction of exotic plants, which over time isotopically labelled the soils. The signatures of dry-stock pasture and potato cultivation enter the sedimentary record from the mid-1800s, although the exact timing varies between core sites. In the Kerikeri Inlet, soils eroded from citrus orchards occur in the estuarine sediments from the late 1940s onwards.

- The long-term impact of soil erosion from pastoral agriculture on the BOI system is clearly shown in a core collected from 30-m water depth in the inner Bay (site KAH S-20). This core contains sediments deposited since the early 1960s and pasture soils have accounted for most of the sediment deposited at this site since the early 1980s at a rate averaging 2.4 mm/yr.

4.4 Macro-benthic communities

Benthic macro-faunal community data collected during the Oceans 20/20 BOI survey as well as monitoring data collected by NRC have been analysed to identify: (1) possible linkages between sedimentation rates and the composition of soft-sediment benthic communities; and (2) soft-sediment benthic communities at risk from sedimentation.

The macro-benthic fauna of the soft-sediment habitats of the BOI system are highly diverse and contain many taxa that are expected to be sensitive to increased terrestrial sediment inputs. In this report, we have used the known and predicted tolerance of key habitat-forming taxa, together with information on biodiversity, to determine areas that have already begun to be impacted by sediment deposition and those that would be expected to be sensitive to future deposition.

The key results of this analysis of soft-sediment macro-faunal data are:

- Sensitive intertidal areas are dispersed around the Bay, although those with low sensitivity are mainly concentrated in the Inlets close to major catchment sediment sources (e.g., Kawakawa, Waikare Inlets and in the upper reaches of the Te Puna and Kerikeri Inlets). Communities in these areas are dominated by mud-tolerant species including the mud crab *Austrohelice crassa*, annelids including *Nereidae* and bivalve *Theora lubrica*.

- Sensitive subtidal macrofaunal communities are mainly found within Te Rawhiti Inlet and the outer deeper areas of the Bay. Te Rawhiti Inlet and the sandy areas around Waitangi and in Veronica Channel are at highest risk, mainly driven by the higher risk associated with sedimentation. Stable-isotope analysis of sediment deposits indicates that sediments in the Te Rawhiti Inlet are primarily derived from runoff from catchment dominated by pasture and clear-felled pine forests in the Kawakawa catchment.
- Non-site specific SAR and source information make it difficult to link SAR and sediment sources to the macrobenthic communities observed at a specific site. This is not necessarily a problem that can be solved by collecting more information on SAR and sediment sources because it is difficult to interpolate subtidal SAR measurements to intertidal areas, where the properties that determine rates of sedimentation are quite different to those subtidally. This also highlights the problem of initial deposition versus resuspension and redeposition and macrofaunal effects from sedimentation versus suspended sediment. Indeed one reason why SAR from subtidal sites gave better than expected predictions for intertidal sites may have been that the subtidal deposition was higher than we would expect to see on the nearby intertidal flat. Thus it was a good proxy for the intertidal area where resuspension removes accumulated sediment but the communities are impacted both by the initial settlement of sediment and suspended sediment passing over the area.

4.5 Changes in mangrove and saltmarsh-habitats extent

Changes in the spatial extent of mangrove and saltmarsh-habitats during the time period 1978–2009 were determined from GIS analysis of aerial photographs. The total area and rate of change in the area of both habitat types (%/yr) were evaluated for each compartment of the BOI system.

The key results are:

- Mangrove and saltmarsh habitats occupy 1181 hectares (ha) and 280 ha respectively of intertidal flat in the BOI system (2009). Most of the mangrove habitat occurs in the estuaries of the eastern BOI (77%), within the Waikare and Veronica Inlets. These estuaries receive runoff from the large Kawakawa and Waitangi sub-catchments. The large areas of mangrove habitat present in these two inlets in 1978 suggests that these forests had been established decades earlier. These spatial patterns are consistent with more rapid infilling of estuaries near major river outlets and the consequent development of intertidal flats suitable for colonisation by mangroves.
- The total area of mangrove habitat increased by 10.8% (127 ha) during the period 1978–2009, while saltmarsh habitat declined by 12.3% (39 ha). Large proportions of the increase in mangrove-habitat 40%, 51 ha) and decrease in saltmarsh habitat (61% -24 ha) have occurred in the Waikare Inlet. As observed in other NZ estuaries (Morrisey et al. 2010), the loss of saltmarsh-habitat is consistent with landward expansion of mangrove into saltmarsh habitat and/or reclamations along the foreshore. Further analysis of historical

aerial photographs and/or council records could establish the relative contributions of these potential causal factors.

- The rates of mangrove-habitat expansion in the BOI system of 0.3–1.4% yr^{-1} are in the range observed in other North Island estuaries (0.2–20 % yr^{-1}) although substantially less than the average rate of 4 % yr^{-1} since the 1940s (Morrisey et al. 2010).
- Historical increases in mangrove habitat (1978–2009) has occurred most rapidly in the Te Rawhiti Inlet (1.4%), although mangrove in this compartment accounts for less than 5% of the BOI system total. Mangroves have colonised bays and small inlets that indent the eastern shoreline of Te Rawhiti, which afford shelter from wave action.
- The potential for future mangrove-habitat expansion in BOI estuaries is likely to be limited based on the low historical rate of forest expansion, deep reworking of intertidal sediments by waves (as indicated by ^{7}Be mixing depths), which will restrict seedling recruitment and the future effects of sea-level rise, which are likely to outpace tidal-flat accretion due to sedimentation.
- The findings of a study of potential future mangrove-habitat expansion in Auckland's east-coast estuaries (Swales et al. 2009) provide guidance on the likely fate of mangrove habitat in the Bay of Islands. Average SAR in BOI estuaries are typically lower than in Auckland estuaries so that even maintenance of existing mangrove habitat over the next century is only likely to occur under the historical rate of sea-level rise since 1950 (1.6 mm yr^{-1}). Large-scale loss of mangrove habitat is predicted to occur under the most likely scenarios for accelerated SLR over the next century of 5.5–8.8 mm yr^{-1}. Under these scenarios, tidal creeks would provide refuges for mangroves assuming that rapid sedimentation observed in these environments over the last 50 years continues.

5 Acknowledgements

We thank NIWA staff, Rod Budd, Glen Reeves and Kerry Costley, Scott Nodder and Lisa Northcote (NIWA Greta Point) and the crew of NIWA R.V. *Kaharoa* who conducted sediment coring in the Bay of Islands. Ron Ovenden of NIWA processed the sediment cores for radioisotope dating, which was conducted by the National Radiation Laboratory. Stable-isotope analyses were undertaken by Sarah Bury (NIWA Greta Point) and the University of California at Davis. The extension of the CSSI method to the reconstruction of past soil sources was undertaken as part of a NIWA Innovation Seed Fund project *Unlocking sediment records in aquatic sinks* (SA122066).

6 References

Alexander, C.R.; Smith, R.G.; Calder, F.D.; Schropp, S.J.; Windom, H.L. (1993). The historical record of metal enrichment in two Florida estuaries. *Estuaries 16(3B)*: 627–637.

Armstrong, P. (1992). Charles Darwin's visit to the Bay of Islands, December 1935. *Auckland-Waikato Historical Journal 60*: 10–24.

Beaglehole, J.C. (1955). The journals of Capt. James Cook on his voyages of discovery. Cambridge University Press, 4 volumes.

Benoit, G.; Rozan, T.F.; Pattoon, P.C.; Arnold, C.L. (1999). Trace metals and radionuclides reveal sediment sources and accumulation rates in Jordan Cove, Connecticut. *Estuaries 22(1)*: 65–80.

Bostock, H.; Maas, E.; Mountjoy, J.; Nodder, S. (2010). Bay of Islands OS20/20 survey report. Chapter 3: Seafloor and subsurface sediment characteristics. *NIWA Client Report WG2010-38*.

Bowden, D.; Fenwick, M.; Spong, K.; Chin, C.; Miller, A. (2010). Chapter 9: Seafloor assemblage and habitat assessment using DTIS. Bay of Islands OS20/20 survey report. Prepared by NIWA for LINZ, *Client Report Number WLG2010-38*. 42 p.

Bromley, R.G. (1996). Trace fossils: biology, taphonomy and applications, second edition. Chapman and Hall, London, 361 p.

Chapman, V.J. (1978). Mangroves and salt marshes of the Whangaroa, and Whangaruru Harbours and the Bay of Islands. Department of Lands and Survey, Auckland. 35 p not including maps.

Clarke, R.T.; Gorley, R.N. (2006). Primer v6. PrimerE, Plymouth.

Elliot, M.B.; Striewski, B.; Flenley, J.R.; Kirkman, J.H.; Sutton, D.G. (1997). A 4300 year palynological and sedimentological record of environmental change and human impact from Wharau Road Swamp, Northland, New Zealand. *Journal of the Royal Society of New Zealand 27(4)*: 401–418.

Ellis, J.; Cummings, V.; Hewitt, J.; Thrush, S.; Norkko, A. (2002). Determining effects of suspended sediment on condition of a suspension feeding bivalve (*Atrina zelandica*): results of a survey, a laboratory experiment and a field transplant experiment. *Journal of Experimental Marine Biology and Ecology 267*: 147–174.

Eyles, G.; Fahey, B. (Eds.) (2006). Pakuratahi land use study. *Hawkes Bay Regional Council report HBRC plan number 3861.* June. 128 p.

Ferrar, H.T. (1925). The geology of the Whangarei–Bay of Islands Subdivision, Kaipara Division. Department of Mines. *Geological Survey Branch, Bulletin No. 27 (New Series)*, W.A.G. Skinner, Government Printer, Wellington.

Gehrels, W.R.; Hayward, B.W.; Newnham, R.M.; Southall, K.E. (2008). A 20th century acceleration of sea-level rise in New Zealand. *Geophysical Research Letters 35*, L02717, doi:10.1029/2007GL032632.

Gibbs, M.; Hewitt, J. (2004). Effects of sedimentation on macrofaunal communities: a synthesis of research studies for ARC. Prepared by NIWA for Auckland Regional Council, *NIWA Client Report: HAM2004-060.*

Gibbs, M.; Olsen, G. (2010). Chapter 5: Determining sediment sources and dispersion in the Bay of Islands. Bay of Islands OS20/20 survey report. Prepared by NIWA for LINZ, *Client Report Number WLG2010-38*. 30 p

Gibbs, M. (2006a). Source mapping in Mahurangi Harbour. *Auckland Regional Council Technical Publication TP321.*

Gibbs, M. (2006b). Whangapoua Harbour sediment sources*. Environment Waikato Technical Report No. 2006/42.* 49 p.

Gibbs, M.; Bremner, D. (2007). Wharekawa Estuary sediment sources. *NIWA Client Report HAM2007-111 for Environment Waikato.*

Gibbs, M.; Elliott, S.; Basher, L. (2008). Sediment source identification and apportionment by land-use: testing a new stable isotope technique in the Waitetuna River catchment. Poster paper presented at the IAHS-ICCE International Symposium, 1–5 December, Christchurch, New Zealand.

Gibbs, M. (2008). Identifying source soils in contemporary estuarine sediments: a new compound specific isotope method. *Estuaries and Coasts 31*: 344–359.

Gibbs, M.; Funnell, G.; Pickmere, S.; Norkko, A.; Hewitt, J. (2005). Benthic nutrient fluxes along an estuarine gradient: influence of the pinnid bivalve *Atrina zelandica* in summer. *Marine Ecology Progress Series 288*: 151–164.

Goff, J.R. (1997). A chronology of natural and anthropogenic influences on coastal sedimentation, New Zealand. *Marine Geology 138*: 105–117.

Goldberg, E.D.; Kiode, M. (1962). Geochronological studies of deep sea sediments by the ionium/thorium method. *Geochemica et Cosmochimica Acta 26*: 417–450.

Griffiths, R. (2011). Kerikeri Inlet Estuary Monitoring Programme: Results from 2008–2010. Northland Regional Council. 45 p

Green, M.O.; Black, K.P.; Amos, C.L. (1997). Control of estuarine sediment dynamics by interactions between currents and waves at several scales. *Marine Geology 144*: 97–116.

Guinasso, N.L. Jr.; Schink, D.R. (1975). Quantitative estimates of biological mixing rates in abyssal sediments. *Journal of Geophysical Research 80*: 3032–3043.

Hannah, J.; Bell, R.G.; Paulik, R. (2010). Sea level change in the Auckland Region. Report prepared for the Auckland Regional Council. *Report No. TR2010/065.*

Hewitt, J.; Chiaroni, L.; Hailes, S. (2010). Chapter 11: Soft Sediment Habitats and Communities. Bay of Islands OS20/20 survey report. Prepared by NIWA for LINZ, *Client Report Number WLG2010-38.* 46 p.

Hume, T.M.; McGlone, M.S. (1986). Sedimentation patterns and catchment use changes recorded in the sediments of a shallow tidal creek, Lucas Creek, Upper Waitemata Harbour, New Zealand. *Journal of the Royal Society of New Zealand 19*: 305–317.

Hume, T.M.; Dahm, J. (1992). An investigation of the effects of Polynesian and European land use on sedimentation in the Coromandel estuaries. Water Quality Centre, *DSIR consultancy report 6104*, prepared for the Department of Conservation.

Jantschik, R.; Nyffler, F.; Donard, O.F.X. (1992). Marine particle size measurement with a stream-scanning laser system. *Marine Geology 106*: 239–250.

Lee, J. (1983). The Bay of Islands. Reed Publishing Ltd, Birkenhead, Auckland, 328 p. ISBN 0 7900 0523 9.

Lohrer, A.M.; Hewitt, J.E.; Thrush, S.F.; Lundquist, C.J.; Nicholls, P.E.; Liefting, R. (2003). Impact of terrigenous material deposition on subtidal benthic communities. ARC Technical report 217. *NIWA Client Report HAM2003-055.*

Maas, E.; Nodder, S. (2010). Bay of Islands OS20/20 survey report. Chapter 8: water column and water quality. *NIWA Client Report WG2010-38*.

MacDiarmid, A.; Sutton, P.; Chiswell, S.; Stewart, C.; Zeldis, J.; Schwarz, J.; Palliser, C.; Harper, S.; Maas, E.; Stevens, C. Taylor, P.; Thompson, D.; Torres, L.; Bostock, H.; Nodder, S.; MacKay, K.; Hewitt, H.; Halliday, J.; Julian, K.; Baird, S.; Hancock, N.; Neil, K.; D'Archino, R.; Sim-Smith, C.; Francis, M.; Leathwick, J.; Sturman, J. (2009). OS2020 Bay of Islands Coastal Project Phase 1 – Desktop Study. *NIWA Client Report WLG2009-3*. Wellington, New Zealand. 385 p.

Matthews, K.M. (1989). Radioactive fallout in the South Pacific, a history. Part 1. Deposition in New Zealand. *Report NRL 1989/2.* National Radiation Laboratory, Christchurch, New Zealand.

McGlone, M.S. (1983). Polynesian deforestation of New Zealand: a preliminary synthesis. *Archaeology in Oceania* 18: 11–25.

Middleton, A. (2003). Māori and European landscapes at Te Puna, Bay of Islands, New Zealand, 1805–1850. *Archaeology in Oceania 38*: 110–124.

Ministry for the Environment (2008). Coastal hazards and climate change. A guidance manual for local government in New Zealand, 2nd Edition. Ministry for the Environment, Wellington.

Oldman, J.W.; Swales, A. (1999). Maungamaungaroa Estuary numerical modelling and sedimentation. *NIWA Client Report ARC70224* prepared for Auckland Regional Council.

Richie, R. (1990). Turn of the Tide. Bay of Islands County Council, 1877–1989.

Ritchie, J.C.; McHenry, J.R. (1989). Application of radioactive fallout caesium-137 for measuring soil erosion and sediment accumulation rates and patterns: A review with bibliography. Hydrology Laboratory, Agriculture Research Service, U.S. Department of Agriculture, Maryland.

Robbins, J.A.; Edgington, D.N. (1975). Determination of recent sedimentation rates in Lake Michigan using ^{210}Pb and ^{137}Cs. *Geochimica et Cosmochimica Acta 39*: 285–304.

Robertson, B.M.; Gillespie, P.S.; Asher, R.A.; Frisk, S.; Keeley, N.B.; Hopkins, G.A.; Thompson, S.J.; Tuckey, B.J. (2002). Estuarine environmental assessment and monitoring: A national protocol. Part A. Development, Part B. Appendices and Part C. Application. Prepared for supporting Councils and the Ministry of Environment, Sustainable Management Fund Contract No 5096. Part A. 93 p. Part B. 159 p. Part C. 40 p plus field sheets.

Sharma, K.; Gardner, L.R.; Moore, W.S.; Bollinger, M.S. (1987). Sedimentation and bioturbation in a saltmarsh revealed by ^{210}Pb, ^{137}Cs and ^{7}Be studies. *Limnology and Oceanography 32(2)*: 313–326.

Sheffield, A.T.; Healy, T.R.; McGlone, M.S. (1995). Infilling rates of a steepland catchment estuary, Whangamata, New Zealand. *Journal of Coastal Research 11(4)*: 1294–1308.

Sommerfield, C.K.; Nittrouer, C.A. & Alexander, C.R. (1999). ^{7}Be as a tracer of flood sedimentation on the Northern California margin. *Continental Shelf Research 19*: 335–361.

Swales, A.; Hume, T.M. (1995). Sedimentation history and potential future impacts of production forestry on the Wharekawa estuary, Coromandel Peninsula. *NIWA Client Report CHH003* for Carter Holt Harvey Ltd.

Swales, A.; Hume, T.M.; Oldman, J.W.; Green, M.O. (1997). Holocene sedimentation and recent human impacts in a drowned-valley estuary, p 895–900. *In:* Lumsden, J. (Ed.). Proceedings of the 13th Australasian Coastal and Ocean Engineering Conference, Centre for Advanced Engineering, University of Canterbury, Christchurch, New Zealand.

Swales, A.; Williamson, R.B.; Van Dam, L.F.; Stroud, M.J.; McGlone, M.S. (2002a). Reconstruction of urban stormwater contamination of an estuary using catchment history and sediment profile dating. *Estuaries 25(1)*: 43–56.

Swales, A.; Hume, T.M.; McGlone, M.S.; Pilvio, R.; Ovenden, R.; Zviguina, N.; Hatton, S.; Nicholls, P.; Budd, R.; Hewitt, J.; Pickmere, S.; Costley, K. (2002b). Evidence for the physical effects of catchment sediment runoff preserved in estuarine sediments: Phase II (field study). *Auckland Regional Council Technical Publication 221.* http://www.arc.govt.nz/plans/technical-publications/technical-publications/technical-publications-201-250.cfm.

Swales, A.; MacDonald, I.T.; Green, M.O. (2004). Influence of wave and sediment dynamics on cordgrass (*Spartina anglica*) growth and sediment accumulation on an exposed intertidal flat. *Estuaries 27(2)*: 225–243.

Swales, A.; Bentley, S.J.; McGlone, M.S.; Ovenden, R.; Hermansphan, N.; Budd, R.; Hill, A.; Pickmere, S.; Haskew, R.; Okey, M.J. (2005). Pauatahanui Inlet: effects of historical catchment landcover changes on estuary sedimentation. *NIWA Client Report HAM2004-149* for Wellington Regional Council and Porirua City Council.

Swales, A.; Stephens, S.; Hewitt, J.E.; Ovenden, R.; Hailes, S.; Lohrer, D.; Hermansphan, N.; Hart, C.; Budd, R.; Wadhwa, S.; Okey, M.J. (2007a). Central Waitemata Harbour Study. Harbour Sediments. *Auckland Regional Council Technical Report 2008/034,* http://www.arc.govt.nz/plans/technical-publications/technical-reports/technical-reports-2008/technical-reports-2008_home.cfm.

Swales, A.; Bell, R.G.; Ovenden, R.; Hart, C.; Horrocks, M.; Hermansphan, N.; Smith, R.K. (2007b). Mangrove-habitat expansion in the southern Firth of Thames: sedimentation processes and coastal-hazards mitigation. *Environment Waikato Technical Report 2008/13*, www.ew.govt.nz/Publications/Coastal/.

Swales, A.; Gibbs, M.; Ovenden, R.; Budd, R.; Hermansphan, N. (2008a). Sedimentation in the Okura – Weiti – Karepiro Bay system. *Auckland Regional Council Technical Report 2008/026.* http://www.arc.govt.nz/plans/technical-publications/technical-reports/technical-reports-2008/technical-reports-2008_home.cfm.

Swales, A.; Bentley, S.J. (2008b). Recent tidal-flat evolution and mangrove-habitat expansion: application of radioisotope dating to environmental reconstruction. Sediment Dynamics in changing environments. (Proceedings of a symposium held in Christchurch, New Zealand, December 2008). *IAHS Publication 325*: 76–84.

Swales, A.; Bell, R.G.; Gorman, R.; Oldman, J.W.; Altenberger, A.; Hart, C.; Claydon, L.; Wadhwa, S.; Ovenden, R. (2009). Potential future changes in mangrove habitat in Auckland's east-coast estuaries. *NIWA Client Report HAM2008-030* for Auckland Regional Council.

Swales, A.; Gibbs, M.; Ovenden, R.; Costley, K.; Hermanspahn, N.; Budd, R.; Rendle, D.; Hart, C.; Wadhwa, S. (2011). Patterns and rates of recent sedimentation and intertidal vegetation changes in the Kaipara Harbour. *NIWA Client Report HAM2011-040.*

Valette-Silver, N.J. (1993). The use of sediment cores to reconstruct historical trends in contamination of estuarine and coastal sediments. *Estuaries 16(3B)*: 577–588.

Walls, K. (1978). Estuarine and Coastal Freshwater Wetlands of the Bay of Islands. Northland Harbour Board, 37 p (not including map sheets).

Wilmshurst, J.M.; Anderson, A.J.; Higham, T.F.G.; Worthy, T.H. (2008). Dating the late prehistoric dispersal of Polynesians to New Zealand using the commensal rat. Proceedings of the National Academy of Sciences 105(22): 7676–7680.

Wise, S. (1977). The use of radionuclides ^{210}Pb and ^{137}Cs in estimating denudation rates and in soil measurement. *Occasional paper No. 7 University of London*, Kings College, Department of Geography, London.

Thrush, S.F.; Hewitt, J.E.; Cummings, V.J.; Ellis, J.I.; Hatton, C.; Lohrer, A.; Norkko, A. (2004). Muddy waters: elevating sediment input to coastal and estuarine habitats. *Frontiers in Ecology and Evolution 2*: 299–306.

Appendix A Radioisotope dating

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

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

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

^{137}Cs dating

^{137}Cs was introduced to the environment by atmospheric nuclear weapons tests in 1953, 1955–1956 and 1963–1964. Peaks in annual ^{137}Cs deposition corresponding to these dates are the usual basis for dating sediments (Wise, 1977; Ritchie and McHenry, 1989). Although direct atmospheric deposition of ^{137}Cs into estuaries is likely to have occurred, ^{137}Cs is also incorporated into catchment soils, which are subsequently eroded and deposited in estuaries (Figure A1). In New Zealand, ^{137}Cs deposition was first detected in 1953 and its annual deposition was been measured at several locations until 1985. Annual ^{137}Cs deposition can be estimated from rainfall using known linear relationships between rainfall and Strontium-90 (^{90}Sr) and measured $^{137}Cs/^{90}Sr$ deposition ratios (Matthews, 1989). Experience in Auckland estuaries shows that ^{137}Cs profiles measured in estuarine sediments bear no relation to the record of annual ^{137}Cs deposition (i.e., 1955–1956 and 1963–1964 ^{137}Cs-deposition peaks absent), but rather preserve a record of direct and indirect (i.e., soil erosion) atmospheric deposition since 1953 (Swales et al. 2002). The maximum depth of ^{137}Cs occurrence in sediment cores (corrected for sediment mixing) is taken to coincide with the year 1953, when ^{137}Cs deposition was first detected in New Zealand. We assume that there is a negligible delay in initial atmospheric deposition of ^{137}Cs in estuarine sediments (e.g., ^{137}Cs scavenging by suspended particles) whereas there is likely to have been a time-lag (i.e., <1 yr) in ^{137}Cs inputs to estuaries from topsoil erosion, which would coincide with the occurrence of floods.

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

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

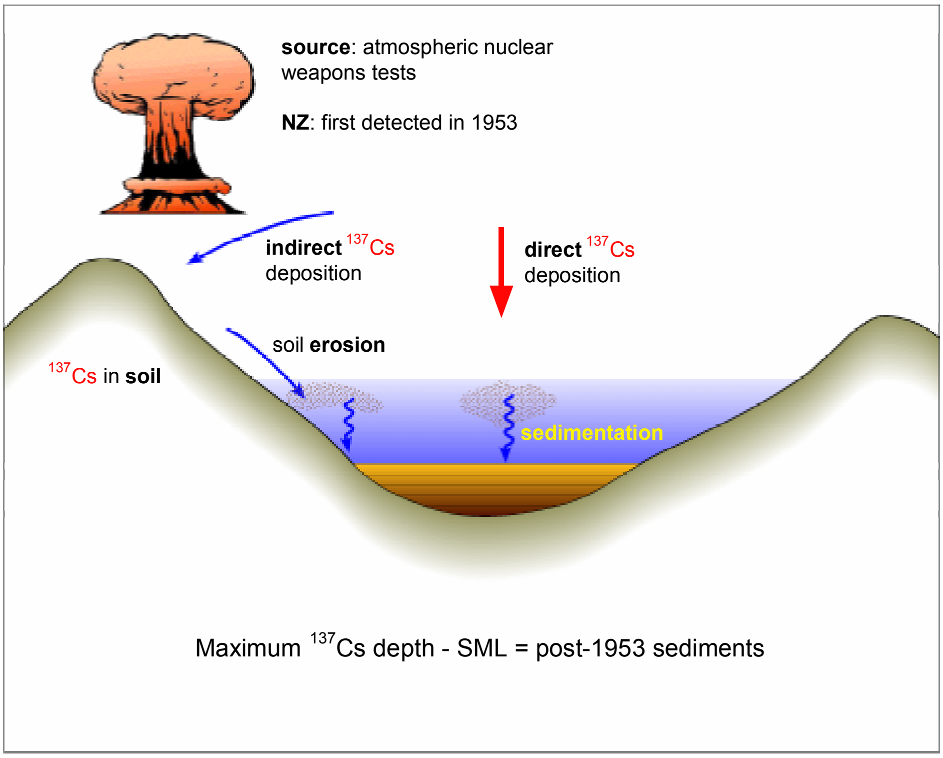

Figure A1: ^{137}Cs pathways to estuarine sediments.

^{210}Pb dating

^{210}Pb (half-life 22.3 yr) is a naturally occurring radioisotope that has been widely applied to dating recent sedimentation (i.e., last 150 yrs) in lakes, estuaries and the sea (Figure A2). ^{210}Pb is an intermediate decay product in the uranium-238 (^{228}U) decay series and has a radioactive decay constant (k) of 0.03114 yr^{-1}. The intermediate parent radioisotope radium-226 (^{226}Ra, half-life 1622 years) yields the inert gas radon-222 (^{222}Rn, half-life 3.83 days), which decays through several short-lived radioisotopes to produce ^{210}Pb. A proportion of the ^{222}Rn gas formed by ^{226}Ra decay in catchment soils diffuses into the atmosphere where it decays to form ^{210}Pb. This atmospheric ^{210}Pb is deposited at the earth surface by dry deposition or rainfall. The ^{210}Pb in estuarine sediments has two components: supported ^{210}Pb derived from *in situ* ^{222}Rn decay (i.e., within the sediment column) and an unsupported ^{210}Pb component derived from atmospheric fallout. This unsupported ^{210}Pb component of the total ^{210}Pb concentration in excess of the supported ^{210}Pb value is estimated from the ^{226}Ra assay (see below). Some of this atmospheric unsupported ^{210}Pb component is also incorporated into catchment soils and is subsequently eroded and deposited in estuaries. Both the direct and indirect (i.e., soil inputs) atmospheric ^{210}Pb input to receiving environments, such as estuaries, is termed the unsupported or excess ^{210}Pb.

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

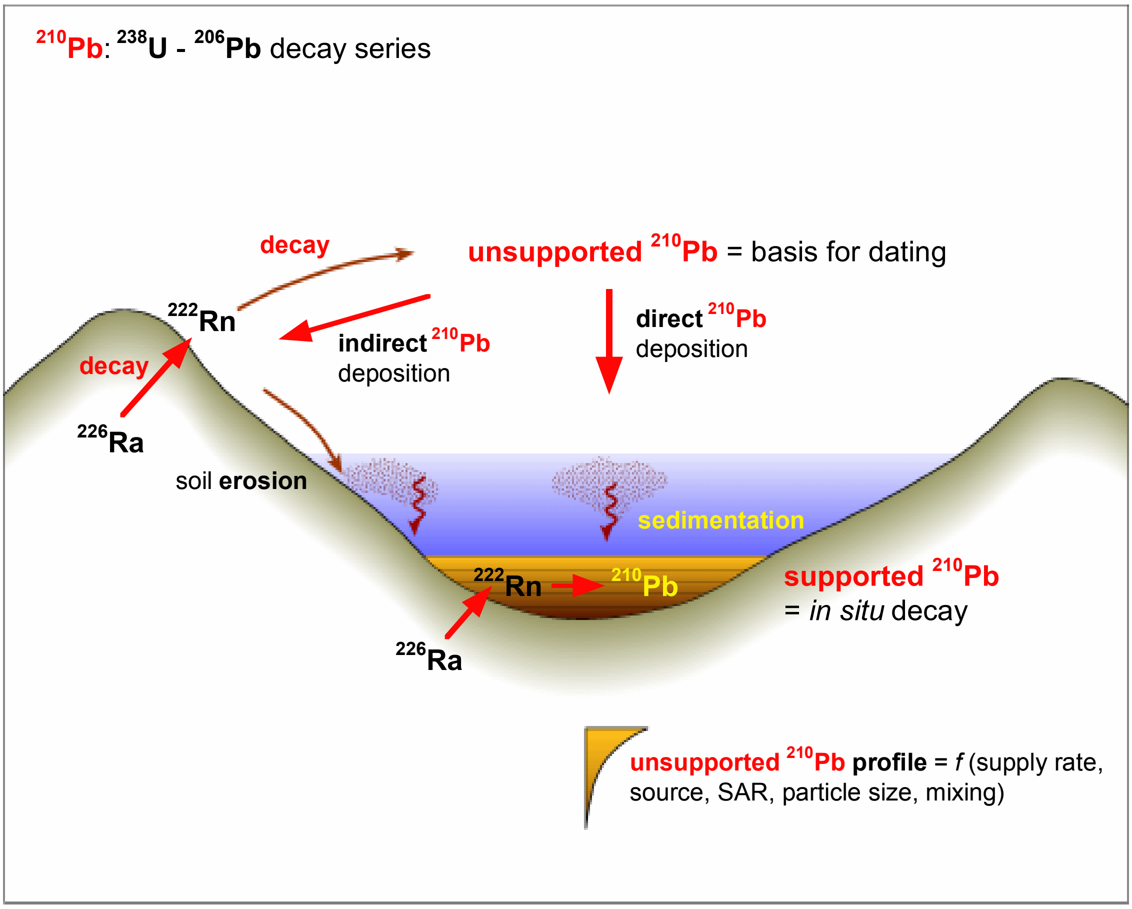

Figure A2: **^{210}Pb pathways to estuarine sediments.**

Sediment accumulation rates (SAR)

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

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

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

The equations used to estimate time-averaged SAR from the excess ^{210}Pb and ^{137}Cs profiles are described below.

Estimating SAR using ^{210}Pb profiles

The rate of decrease in excess ^{210}Pb activity with depth can be used to calculate a net sediment accumulation rate. The excess ^{210}Pb activity at time zero (C_0, Bq kg^{-2}), declines exponentially with age (*t*):

$$C_{\mathrm{t}} = C_0 e^{-kt}$$

Assuming that within a finite time period, sedimentation (*S*) is constant then $t = z/S$ can be substituted into the above equation and by re-arrangement:

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

Because excess $^{210}Pb_{us}$ activity decays exponentially and assuming that sediment age increases with depth, a vertical profile of natural log(C) should yield a straight line of slope $b = -k/S$. A linear regression model is fitted to natural-log transformed excess ^{210}Pb data to calculate *b*. The SAR over the depth of the fitted data is given by:

$$S = -(k)/b$$

An advantage of the ^{210}Pb-dating method is that the SAR is based on the excess ^{210}Pb profile rather than a single layer or horizon, as is the case for ^{137}Cs were the maximum penetration depth of this radioisotope is used for dating. Furthermore, if the ^{137}Cs tracer is present at the bottom of the core then the estimated SAR represents a minimum value.

Estimating SAR using ^{137}Cs profiles

The ^{137}Cs profiles will also be used to estimate time-averaged SAR based on the maximum depth of ^{137}Cs in the sediment column, corrected for surface mixing. The ^{137}Cs SAR is calculated as:

$$S = (M - L)/T - T_0$$

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

Sediment mixing

Biological and physical processes, such as the burrowing and feeding activities of animals and/or sediment resuspension by waves (Figure a3), mix the upper sediment column (Bromley, 1996). As a result, sediment profiles are modified and this limits the temporal resolution of dating. Various mathematical models have been proposed to take into account the effects of bioturbation on ^{210}Pb concentration profiles (e.g., Guinasso and Schink, 1975).

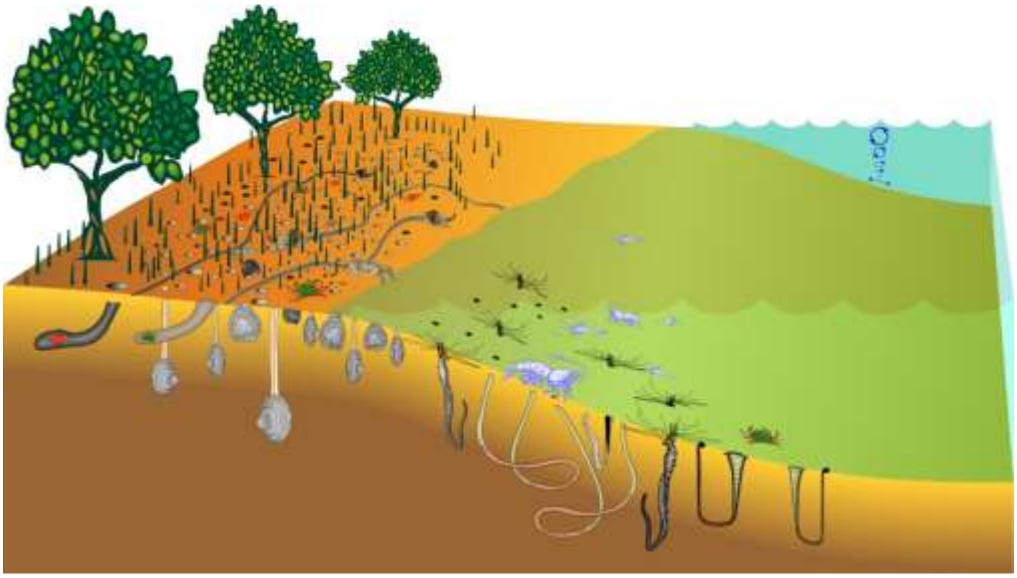

Figure A3: **Biological and physical processes, such as the burrowing and feeding activities of animals and/or sediment resuspension by waves, mix the upper sediment column. As a result, sediment profiles are modified and limit the temporal resolution of dating. The surface mixed layer (SML) is the yellow zone.**

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

Appendix B Compound Specific Stable Isotopes

Introduction to stable isotopes

In this section we describe how stable isotopes are used to identify the sources of catchment sediments deposited in lakes, estuaries and coastal waters and explain how isotopic data are interpreted.

Stable isotopes are non-radioactive and are a natural phenomenon in many elements. In the NIWA Compound Specific Stable Isotope (CSSI) method, carbon (C) stable isotopes are used to determine the provenance of sediments (Gibbs 2008). About 98.9% of all carbon atoms have an atomic weight (mass) of 12. The remaining ~1.1% of C atoms have an extra neutron in the atomic structure, giving it an atomic weight (mass) of 13. These are the two stable isotopes of carbon. Naturally occurring carbon also contains an extremely small fraction (about two trillionths) of radioactive carbon-14 (^{14}C). Radiocarbon dating is also used in the present study to determine long-term sedimentation rates.

To distinguish between the two stable isotopes of carbon, they are referred to as light (^{12}C) and heavy (^{13}C) isotopes. Both of these stable 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 an 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., $\delta^{13}C$. The units are expressed as "per mil" which uses the symbol "‰". The delta value of a sample is calculated using the equation:

$$\delta^{13}C = \left[\left(\frac{R_{sample}}{R_{standard}}\right) - 1\right]1000$$

where R is the molar ratio of the heavy to light isotope $^{13}C/^{12}C$. The international reference standard for carbon was a limestone, Pee Dee Belemnite (PDB), which has a $^{13}C/^{12}C$ ratio of 0.0112372 and a $\delta^{13}C$ value of 0 ‰. As all of this primary standard has been consumed, secondary standards calibrated to the PDB standard are used. Relative to this standard most organic materials have a negative $\delta^{13}C$ value.

Atmospheric CO_2, which is taken up by plants in the process of photosynthesis, presently has a $\delta^{13}C$ value of about -8.5. In turn, the $\delta^{13}C$ signatures of organic compounds produced by plants partly depends on their photosynthetic pathway, primarily either C_3 or C_4. During photosynthesis, carbon passes through a series of reactions or trophic steps along the C_3 or

C_4 pathways. At each trophic step, isotopic fractionation occurs and organic matter in the plant (i.e., the destination pool) is depleted by 1 ‰. The C_3 pathway is longer than the C_4 pathway so that organic compounds produced by C_3 plants have a more depleted $\delta^{13}C$ signature. There is also variation in the actual amount of fractionation between plant species having the same photosynthetic pathway. This results in a range of $\delta^{13}C$ values, although typical bulk values for C_3 and C_4 plants vary around -26 ‰ and -12 ‰ respectively. The rate of fractionation also varies between the various types of organic compounds produced by plants. Thus, by these processes a range of organic compounds each with unique $\delta^{13}C$ signatures are produced by plants that can potentially be used as natural tracers or biomarkers.

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 the stable isotopes in a sample, the $\delta^{13}C$ value obtained is referred to as the bulk $\delta^{13}C$ 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 $\delta^{13}C$ value can be used as an indicator of the likely source land cover 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 $\delta^{13}C$ 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 land cover 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, a dairy farm 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 the carbon in 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 in a deposit for comparison with signatures from a range of potential soil sources for different land cover types. This method is called the CSSI technique (Gibbs, 2008).

The CSSI technique is based on the concepts that:

1. land cover 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 and also because each land cover type has a characteristic composition of plant types that contribute to the CSSI signature.

The compounds commonly used for CSSI analysis of sediment sources 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 land cover type.

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). The IsoSource mixing model is described in more detail in a following section.

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 land cover 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 around +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‰.

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 hot 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).

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 the number (*n*) of 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. The isotopically feasible proportions of each soil source are then converted to soil proportions using the %C of each soil on a proportional basis. That is to that the higher the %C in the soil, the less of that soil source is required to obtain the isotopic balance. 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 of the BOI system using the contouring programme “Surfer-V8” (Golden Software), using linear kriging. Because of the paucity of data, the contour plots produced by linear kriging are indicative rather than definitive.

CSSI Method

The CSSI method applies the concept of using the $\delta^{13}C$ signatures of organic compounds produced by plants to distinguish between soils that develop under different land-cover types. With the exception of monocultures (e.g., wheat field), the $\delta^{13}C$ signatures of each land-cover type reflects the combined signatures of the major plant species that are present. For example, the isotopic signature of the Bay’s lowland native forest will be dominated by kauri, rimu, totara and tānekaha. A monoculture, such as pine forest, by comparison will impart an isotopic signature that largely reflects the pine species, as well as, potentially, any understory plants.

The application of the CSSI method for sediment-source determination involves the collection of sediment samples from potential sub-catchment and/or land cover sources as well as sampling of sediment deposits in the receiving environment. These sediment deposits are composed of mixtures of terrigenous sediments, with the contribution of each source potentially varying both temporally and spatially. The sampling of catchment soils provides a library of isotopic signatures of potential sources that is used to model the most likely sources of sediments deposited at any given location and/or time.

Straight-chain Fatty Acids (FA) with carbon-chain lengths of 12 to 24 atoms (C12:0 to C24:0) have been found to be particularly suitable for sediment-source determination as they are bound to fine sediment particles and long-lived (i.e., decades). In the present study, five types of FA were used to evaluate the present-day and historical sources of terrigenous sediments deposited in the Bay: Myristic Acid (C14:0); Palmitic (C16:0); Stearic (C18:0); Arachidic (C20:0) and Behenic (C22:0). Although breakdown of these FA to other compounds eventually occurs, the signature of a remaining FA in the mixture does not change.

The stable isotope compositions of N and C and the CSSI of carbon in the suite of fatty acid (FA) biomarkers are extracted from catchment soils and marine sediments. It is the FA signatures of the soils and marine sediments that are used in this study to determine sediment sources. Gibbs (2008) describes the CSSI method in detail.

In the present study, the CSSI method has also been extended to reconstruct the changes in sediment sources over time that are preserved in the sediment cores collected from the BOI system. We refer to this new method as the CSSI dating technique. To achieve this, the changes in the isotopic signatures of plants due to the “Suess Effect” needed to be incorporated into the CSSI method. The so-called Suess Effect refers to the change in the isotopic signatures of plants and animals due to the release of "old carbon" into the atmosphere associated with the burning of fossil fuels and deforestation since 1700. Consequently, the stable-isotope signatures of the FA tracers being produced by plants will have also changed over time and the CSSI signatures of sediment core samples of different ages are corrected for this effect to allow direct comparison with modern values for each soil source in the soil library. The methods used to correct the isotopic signatures of soil sources over the last ~300 years are described below.

Correction of CSSI signatures of old sediments for the Suess effect

The reconstruction of changes in sources of terrigenous sediment deposited in the BOI system is derived from dated cores using the FA isotope signatures preserved in the sediments. Before the feasible sources of these sediments could be evaluated using the IsoSource package, the isotope (i.e., input) data required correction for the effects of the release of "old carbon" into the biosphere over the last 300 years, associated with the burning of fossil fuels and deforestation.

Specifically, the release of old carbon with a depleted $\delta^{13}C$ signature has resulted in a decline in $\delta^{13}C$ in atmospheric CO_2 ($\delta^{13}CO_2$). The changing abundance of carbon isotopes in a carbon reservoir associated with human activities is termed the Suess effect (Keeling 1979). This depletion in atmospheric $\delta^{13}CO_2$ is of the order of 2 ‰ since 1700 and has accelerated substantially since the 1940s (Verburg 2007). Thus, the $\delta^{13}C$ signatures of plant biomarkers, 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.

Figure B1 presents the atmospheric $\delta^{13}C$ curve reconstructed by Verburg (2007) using data collected in earlier studies and includes measurements of material dating back to 1570 AD. These data indicate that the atmospheric $\delta^{13}C$ signature was stable until 1700 AD, with subsequent depletion of $\delta^{13}C$ due to release of fossil carbon.

In the present study, we use this atmospheric $\delta^{13}C$ curve to correct the isotopic values of the FA in sediment samples of varying ages taken from cores to equivalent modern values. This is required because the $\delta^{13}C$ values of the FA from the potential catchment sources are modern (i.e., 2010 AD), and are therefore depleted due to the Suess effect. For example, the $\delta^{13}C$ value of a Fatty Acid derived from a kauri tree growing today will be depleted by -2.15 ‰ in comparison to a kauri that grew prior to 1700 AD (Fig. 8.1). It can be seen that the isotopic correction for the period since 1700 is variable depending of age. Examples of this correction process for isotopic data for sediments taken from core RAN-5B are presented in Table B2.

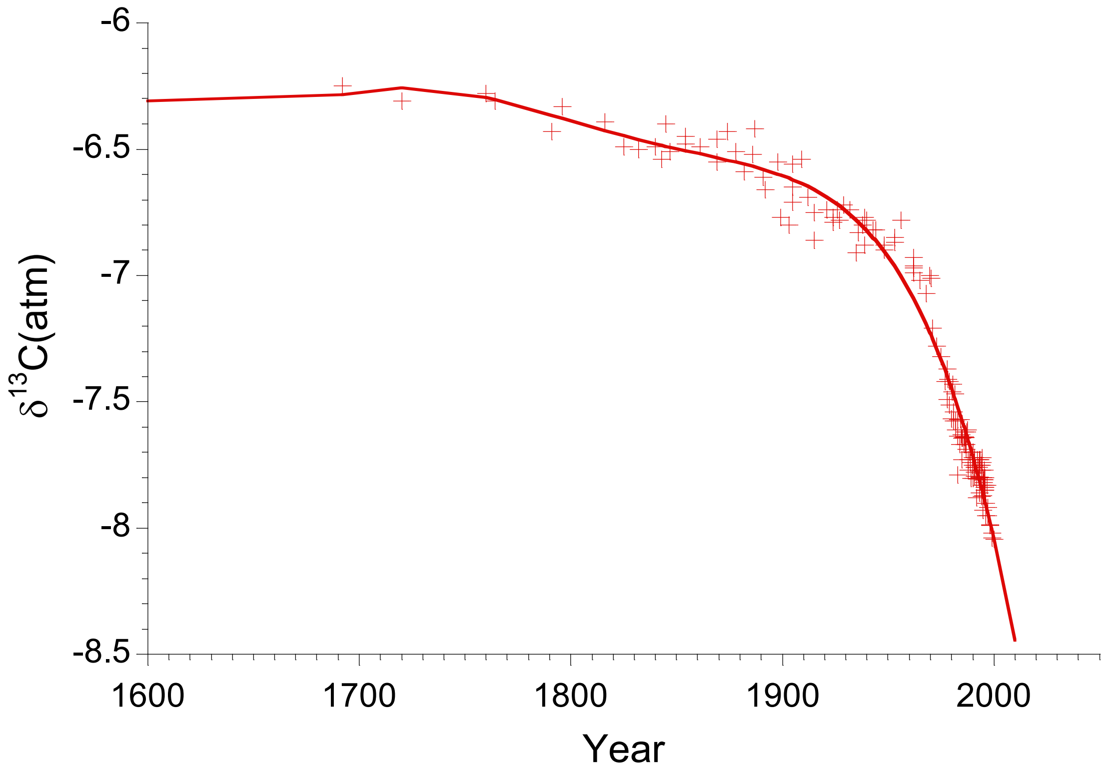

Figure B1: Historical change in atmospheric δ^{13}C (per mil) (1570–2010 AD) due to release of fossil carbon associated with anthropogenic activity (the so-called Suess effect), Source: Verburg (2007).

Table B2: Example of Suess correction applied to Palmitic Acid (C16:0) data from core RAN-5B.

Sample depth (cm)	Age	Suess Correction (‰)	Raw δ^{13}C value	Corrected δ^{13}C value
0–1	2010 AD	0.00	-28.44	-28.44
10–11	1977 AD	-1.08	-28.29	-29.37
70-71	633 AD	-2.15	-26.50	-28.65

IsoSources mixing model

The sources of terrigenous sediments deposited on the present-day seabed surface and at various times in the past, that are preserved in cores, were determined from analysis of the CSSI signatures of potential sources (i.e., soils) and mixtures (i.e., marine-sediment deposits). The library of isotopic signatures used included those derived from local (i.e., Bay of Islands) soils as well as other potential sources that were not sampled because (1) they could not be accessed or (2) no longer occur in the catchment (e.g., kumara gardens).

In the present study, the IsoSource mixing model (Phillips & Gregg, 2003) was used to evaluate the feasible sources of terrigenous sediments in the marine deposits. IsoSource requires a minimum of three sources and two isotopic tracers to run. In the present study, an iterative approach was taken to the selection of potential sediment sources, constrained by the recorded land-cover history. For example, citrus trees were not planted in large numbers in the Kerikeri catchment until the late 1920s (section 2.8.4) so that citrus is not a valid sediment source for sediments deposited before that time. The FA tracers Palmitic, Stearic and Arachidic Acids were most consistently present in the dated sediment cores and were most commonly used to evaluate historical sediment sources using IsoSource.

IsoSource is not a conventional mixing model in that it iteratively constructs a table of all possible combinations of isotopic source proportions that sum to 100% and compares these predicted isotopic values with the isotopic values in the sediment mixture (i.e., deposit). If the predicted and observed stable isotope values are equal or within some small tolerance (e.g., 0.1 ‰, referred to as the mass-balance tolerance by Phillips and Gregg, 2003) then that predicted stable-isotope signature represents a feasible solution. Within a given tolerance, there may be few or many feasible solutions.

The total number of feasible solutions (*n*) provides 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 represents 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 about the mean.

In practice, the tolerance is reduced by iteration within the IsoSource model to obtain the lowest *n* and therefore the highest confidence in the result. The tolerance required to obtain any feasible solutions will be greater than 0.1 ‰ if the isotopic values of the source tracers differ markedly from those of the sediment mixture in the receiving environment. Together, the tolerance and number of feasible solutions (*n*) for each sediment mixture provide measures of uncertainty in the results in addition to the standard deviation and the range of the isotopic proportions for each soil source. An example result from this analysis is shown in Table B1 below.

Table B1: Example of IsoSource model result, Core RAN-5B (Waikare Inlet), 30–31 cm depth (1914 AD). The mean, median and standard deviation (SD) values are shown.

Tolerance	n	Nikau			Kauri			Bracken		
		mean	median	SD	mean	median	SD	mean	median	SD
0.9	3	0.317	0.32	0.006	0.55	0.55	0.01	0.133	0.13	0.006

This sample comes from core RAN-5B, which was collected in the Waikare Inlet. The catchment even today remains largely under native forest and scrub land cover, so that sediments deposited in the inlet should reflect these land cover signatures. The sample was taken from 30–31-cm depth in the core, with radioisotope dating indicating that it was deposited in the early 1900s. The feasible isotopic proportions of the three major sediment sources are shown in the table (range = 0–1, where 1 = 100%). Although mean, median and standard deviation values are shown, minimum and maximum values of the feasible isotopic proportions for each source are also calculated. **The reporting solely of mean values is not adequate** and a measure of uncertainty, such as the minimum, maximum and/or standard deviation should be included in the results (Phillips & Greg, 2003).

The results indicate that the soils that make up the sediment-core sample are largely derived from native forest (kauri and nikau associations), with a small contribution from bracken. The presence of bracken is a key indicator of catchment disturbance/forest clearing. The presence of bracken pollen in sediment deposits has long been used in historical reconstructions of the New Zealand environment (e.g., McGlone 1983). However, bracken pollen reflects the presence of these plants growing in the general area and may or may not be indicative of bracken soils being eroded. By comparison, the presence of a CSSI bracken signature in a deposit positively indicates that some proportion of the sediment sample is composed of eroded bracken soil. The tolerance at 0.9 ‰ is a mid-range value, with values as low as 0.01 ‰ possible in some of the samples that were analysed. The number of feasible solutions (n = 3) is low, which also provides high confidence in these results.

Typically less than 5% of most sediment samples is composed of carbon, and the isotopic balance evaluated by IsoSource is only applicable to the carbon content of each source. These isotopically feasible proportions must therefore be converted to soil proportions using a linear scaling factor to estimate the percent contribution of each feasible soil source. This conversion of feasible isotopic source proportions to soil source proportions is described in a following section.

Conversion of isotopic proportions to soil proportions

The IsoSource model provides estimates of the isotopic-proportional contributions of each land-cover (i.e., soil) type in each marine sample. Thus, these results are in terms of carbon isotopic proportions and not source soil proportions. Furthermore, the stable isotope tracers account for a small fraction, typically less than 2%, of total organic carbon (OC) in the soil and OC accounts for typically <10% of the soil by weight. These factors mean that the contribution of each source soil to a sediment mixture will scale with the soil carbon content. Consequently, a linear correction based on the soil OC is required to estimate the proportion of each soil source in a sediment sample from a receiving environment (Gibbs 2008).

To convert the isotopic proportions to soil proportions (S_n%) the simple linear correction equation below was used:

$$S_n\% = \frac{I_n / C_n\%}{\sum_n^1 \left(I_n / C_n\% \right)} * 100$$

Where I_n is the mean feasible isotopic proportion of source soil n in the mixture estimated using an isotopic mixing model and C_n% is the percentage organic carbon in the source soil.

Because this calculation only uses the OC% in the source soils for linear scaling, the proportional contribution of each source soil is not influenced by any loss of carbon (e.g., total carbon, Fatty Acids etc.) in the sediment mixture due to biodegradation. The level of uncertainty in the mean soil proportion is the same as that defined by the standard deviation about the mean isotopic proportion.

A simple example of this linear correction is illustrated here by considering a solution composed of an equal mixture of three different sodium (Na) salts (3 x 1/3 each): sodium chloride (NaCl, molecular weight 58.45); sodium nitrate ($NaNO_3$, mw 85.0); and sodium sulphate (Na_2SO_4, mw 142.0). Consider each of these salts to represent a different source soil, each of which are present in a sediment mixture. The %Na represents the % carbon in each source soil. The %Na in each salt is calculated by dividing the atomic weight of sodium (23) by the molecular weight of each salt compound.

Table B3 below presents the calculations required to apply the linear correction equation using the sodium salts example. The ratio M%/S% for each salt and sum of this ratio (4.14) represent the numerator and denominator respectively in the conversion equation. Thus, for example the proportion of NaCl salt in the mixture is given by (0.85/4.14)*100 = 20.5%.

In the present study this linear conversion of isotopic proportions to soil source proportions was applied to the present-day surficial sediments. This correction process was not applied to the historical soil-source data from cores because %C data was not available for all soil sources. For example, although kumara and potato cultivation were important landcover types in some sub-catchments in the past this is no longer the case. In this situation the isotopic signatures of the plants themselves and not the labelled soils were used in the isotope modelling.

Table B3: **Example of the linear correction method to convert the isotopic proportions to soil proportions using sodium (Na) salt compounds as analogies to various soil sources present in a mixture.**

Salt type	%Na in salt (S%)	%Na in mixture (M%)	M%/S%	% salt in mixture
$NaCl$	39.4	33.3	0.85	20.5
$NaNO_3$	27.1	33.3	1.23	29.8
Na_2SO_4	16.2	33.3	2.06	49.7
SUM			4.14	