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

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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 III, 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 excess ^{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

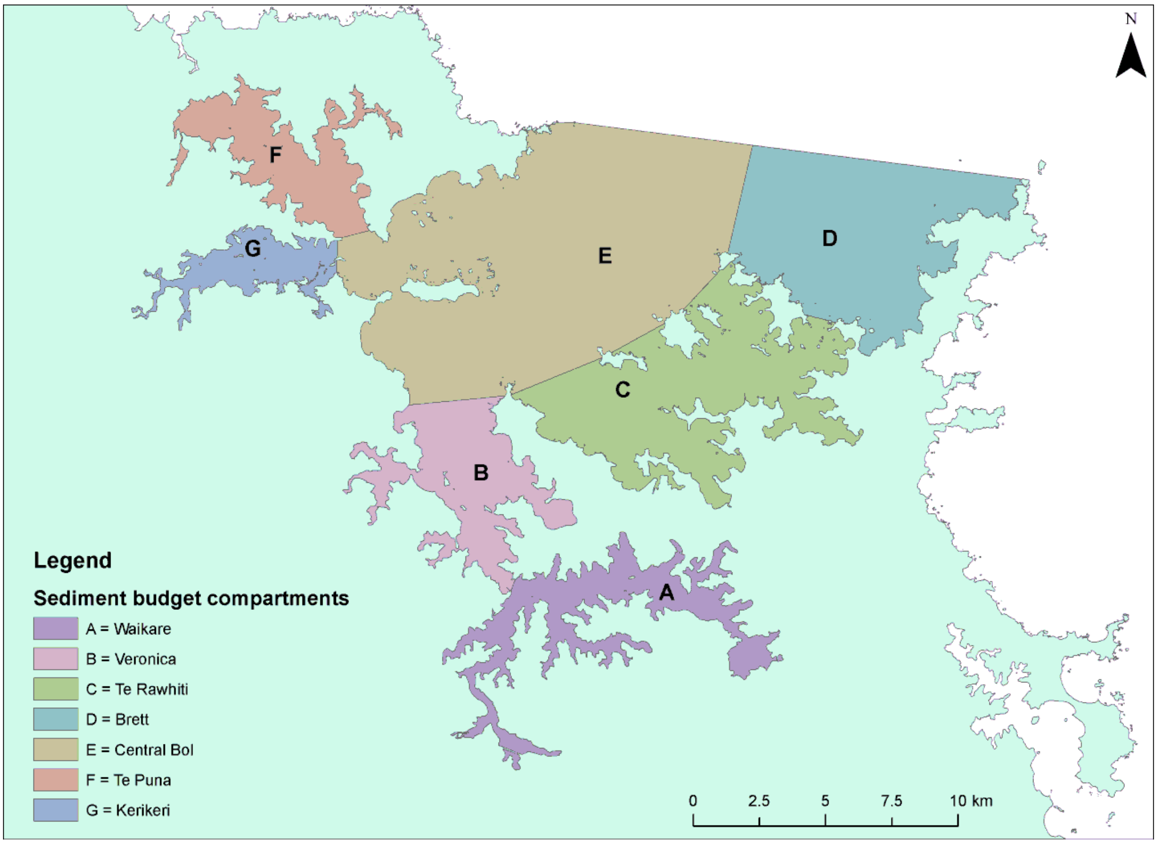

Figure 2-6: Sedimentation compartments defined for the Bay of Islands system.

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:

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

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

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

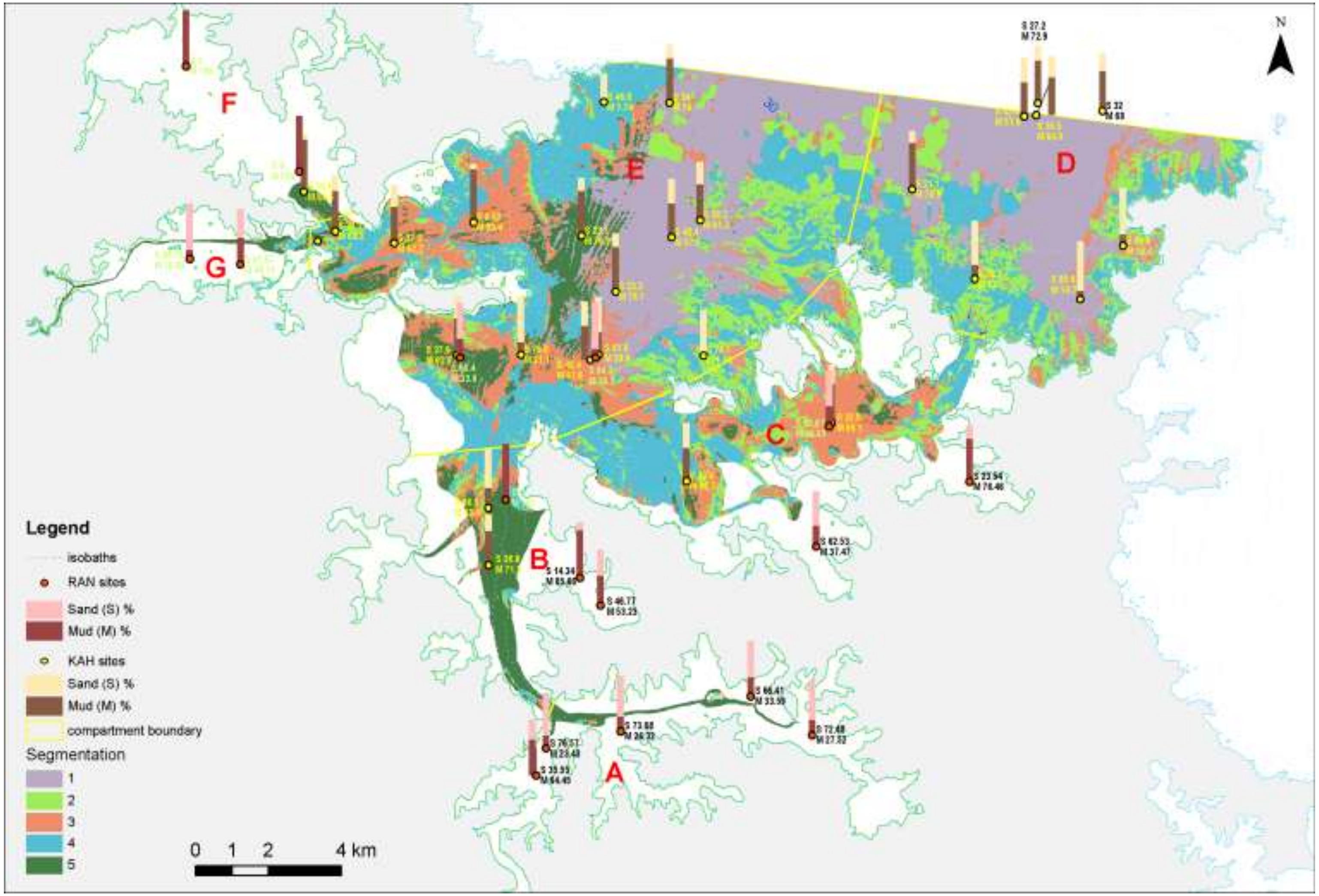

Figure 2-7: Bay of Islands system. Seabed texture classes defined by segmentation analysis of backscatter data with percentage mud and sand content of surface samples (0-1 cm depth) at core sites shown.

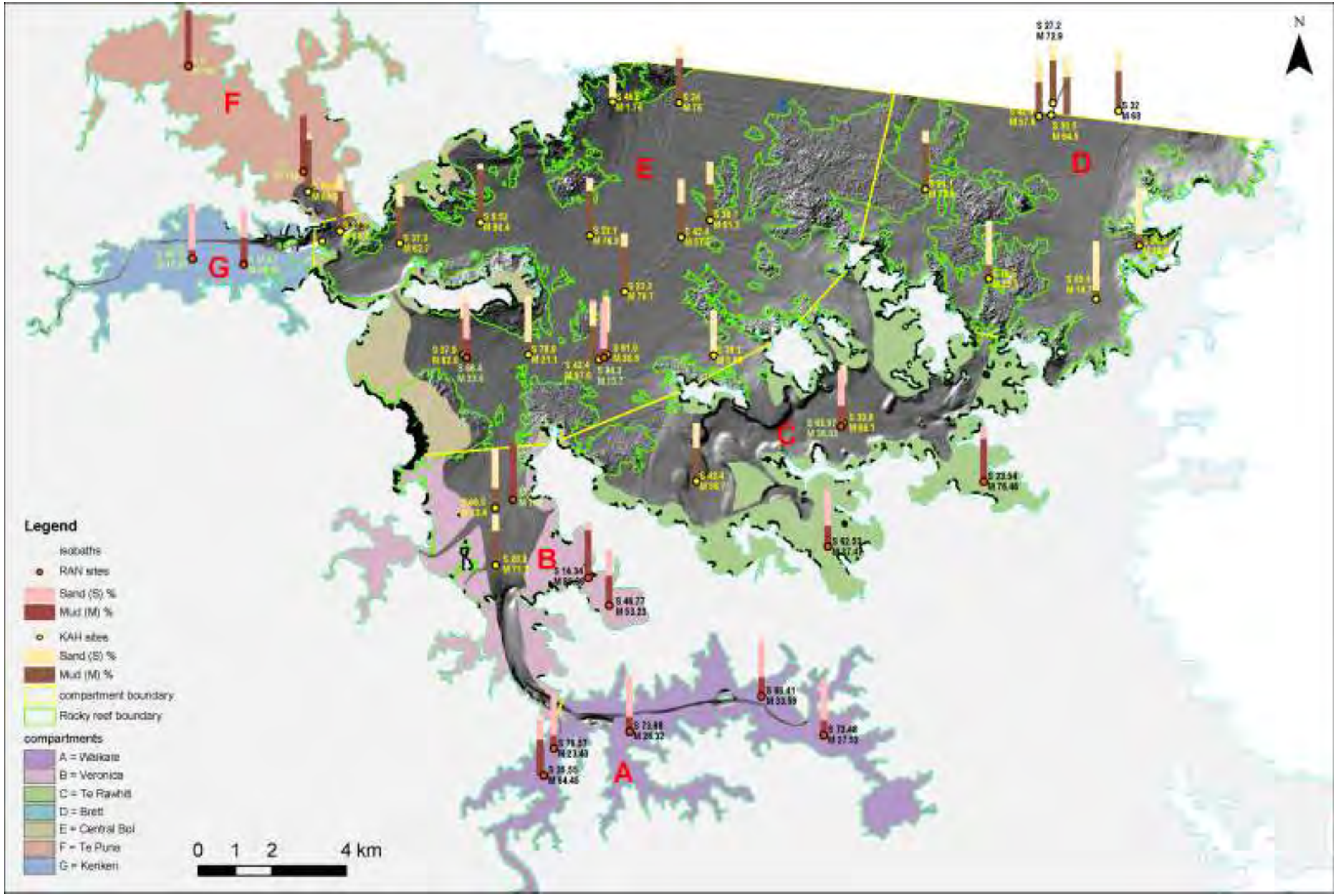

Figure 2-8: Bay of Islands system. Seabed type and areas of complex rocky reef defined by Hill Shade analysis of backscatter data with percentage mud and sand content of surface samples (0-1 cm depth) at core sites shown.

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).

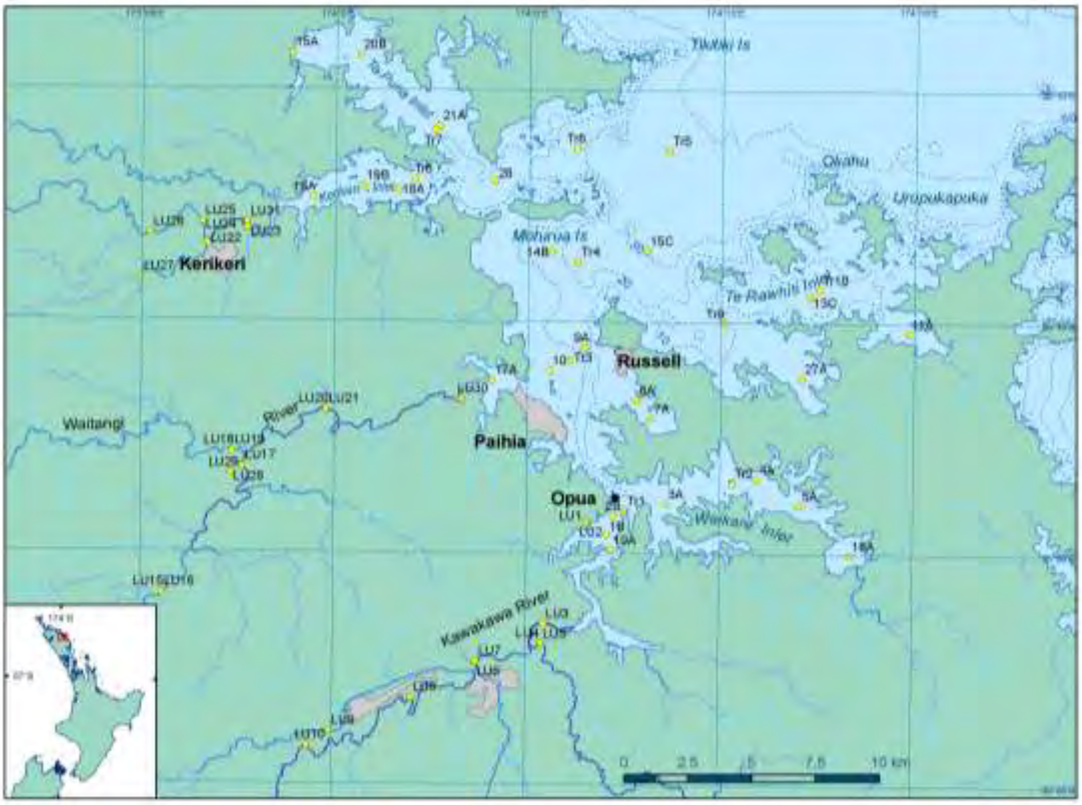

Figure 2-9: Location of sample sites for determination of catchment sources of present-day estuarine and marine sediment deposits, Bay of Islands system.

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).

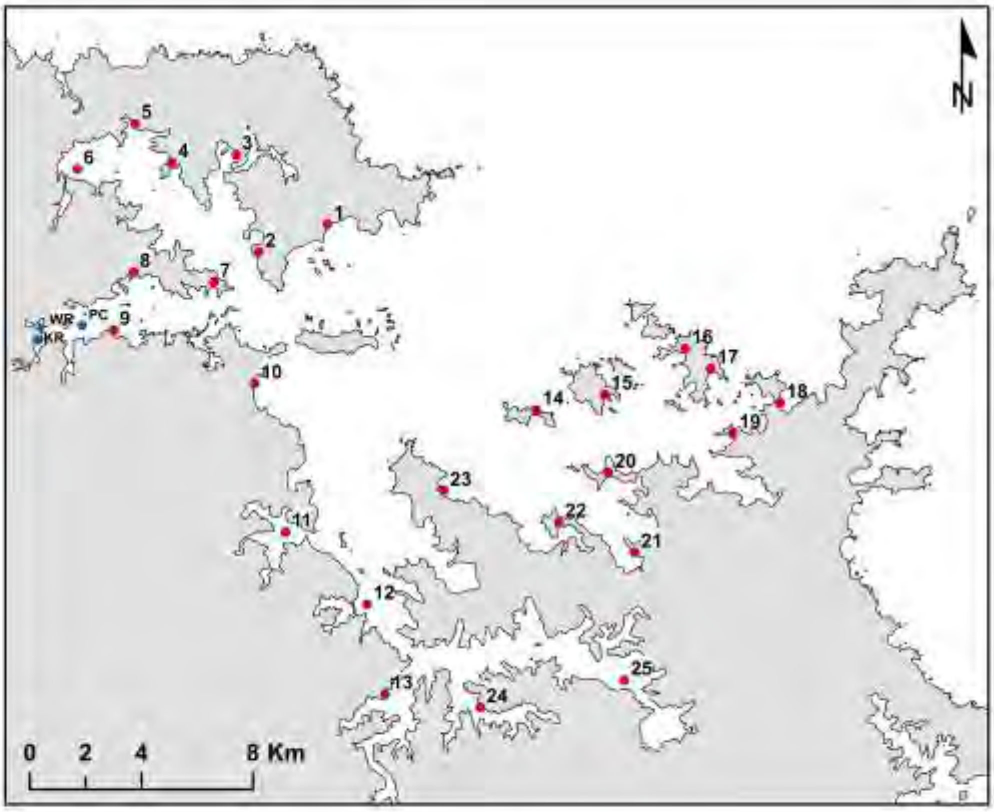

Figure 2-10: Intertidal sites sampled across the Bay of Islands as part of NRC's annual monitoring programme (KR, WR and PC denoted by blue circles) and the Oceans 2020 programme (sites 1-25 denoted by red circles).

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.

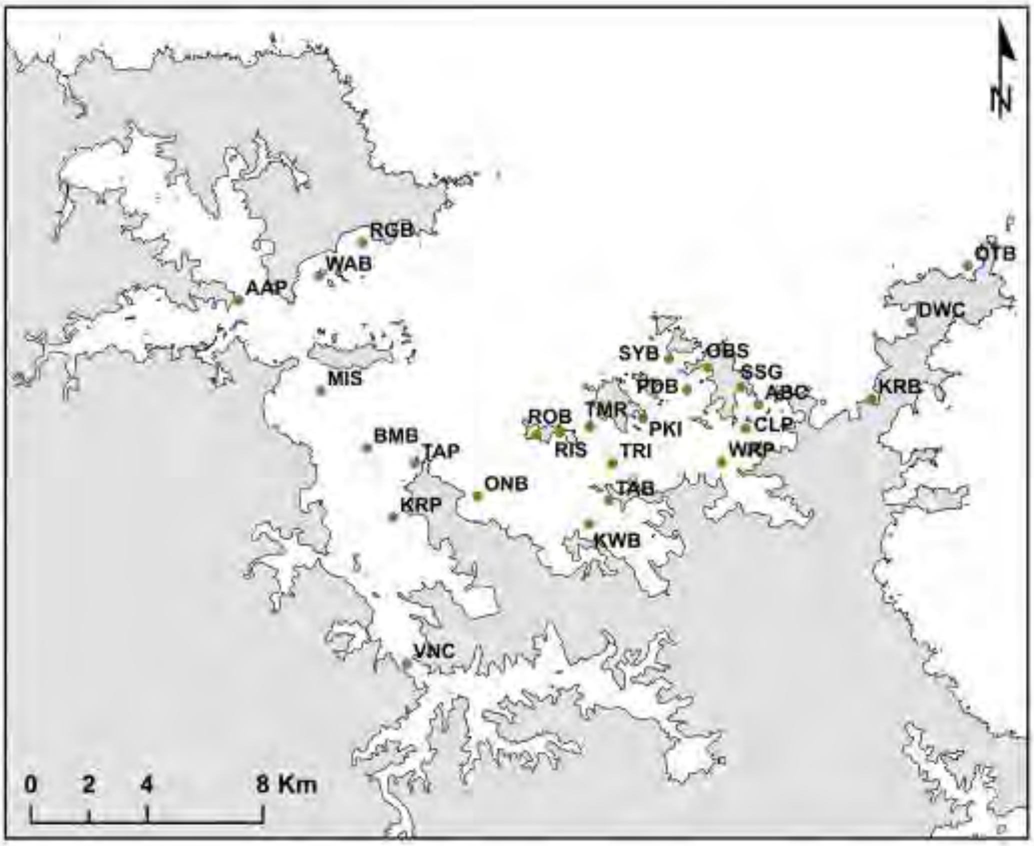

Figure 2-11: DTIS transect sites across the Bay of Islands, as part of the Oceans 20/20 programme.

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.

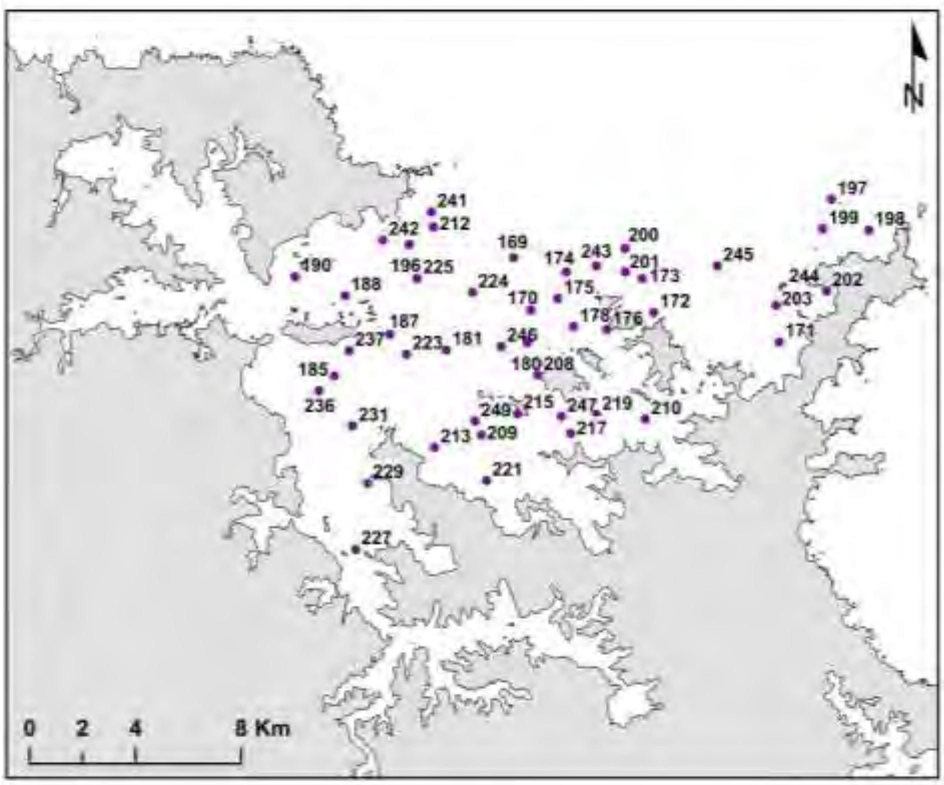

Figure 2-12:DTIS transect sites across the Bay of Islands, as part of the Oceans 20/20 programme.

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

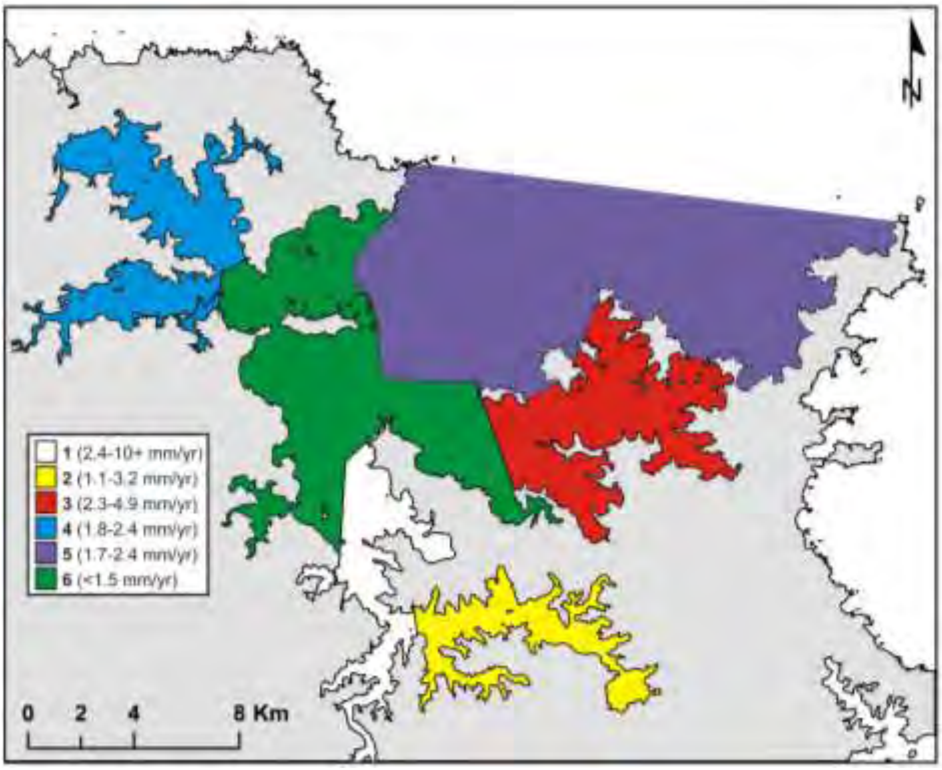

Figure 2-13: Estimated time-average sediment accumulation rate (SAR; mm/yr) zones of the Bay of Islands. SAR based on ^{210}Pb and ^{137}Cs dating of sediment cores.

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.