3 Results

3.1 Sedimentation patterns

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

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

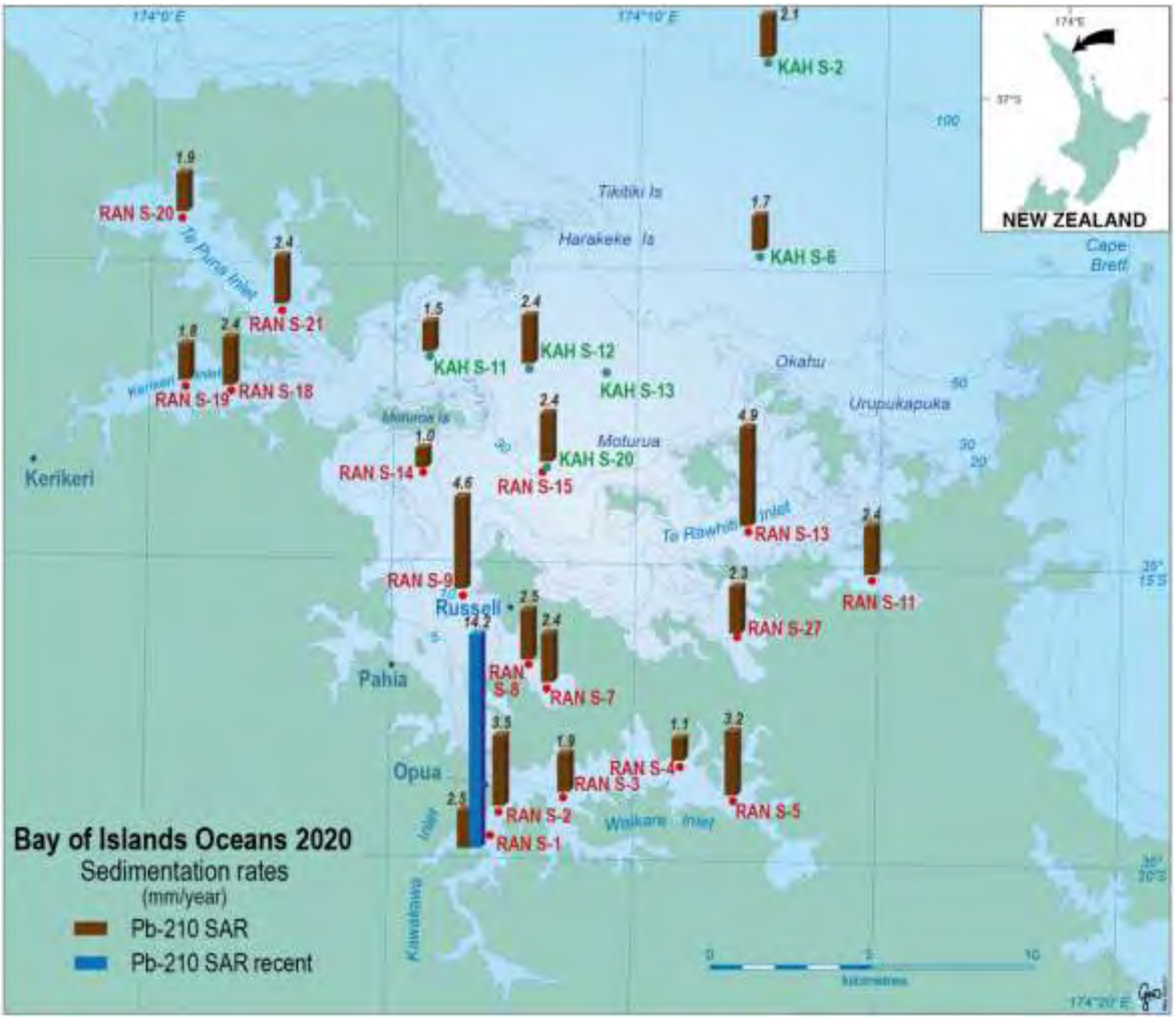

Figure 3-1: Time-averaged sediment accumulation rates in the Bay of Islands system estimated from excess ^{210}Pb profiles measured in RAN and KAH series sediment cores.

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

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

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

3.2 Estimating the surface mixed layer and recent sediment accumulation rates

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

3.2.1 Residence time of sediments in the surface mixed layer

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

$$R = T/S$$

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

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

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

3.2.2 Recent sediment accumulation rates in the BOI system

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

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

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

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

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

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

3.3 Spatial variations in recent sediment accumulation rates

3.3.1 Waikare Inlet

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

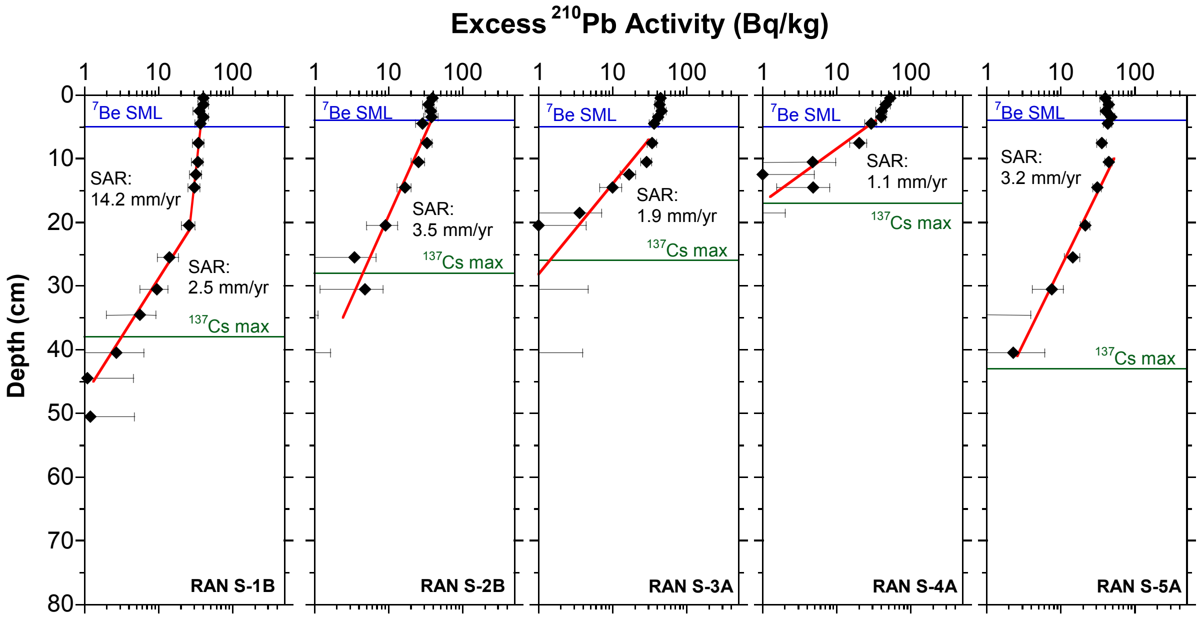

Figure 3-2: Waikare Inlet: sediment accumulation rates (SAR) for core sites RAN S-1 to S-5. Excess ^{210}Pb activity profiles with **95%** confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum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

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

3.3.2 Veronica Channel

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

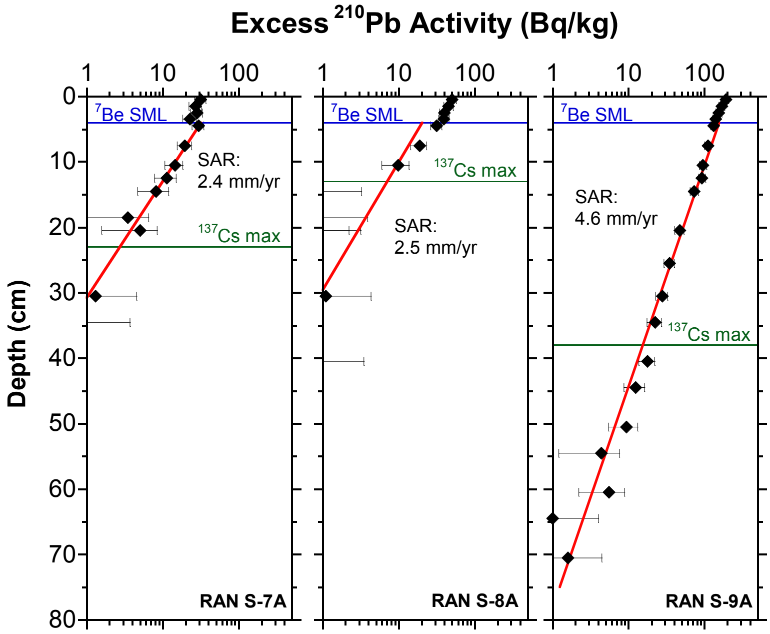

Figure 3-3: Veronica Inlet: sediment accumulation rates (SAR) for core sites RAN S-1 to S-5. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum depth of caesium-137 (^{137}Cs max) in each sediment core is also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

3.3.3 Te Rawhiti

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

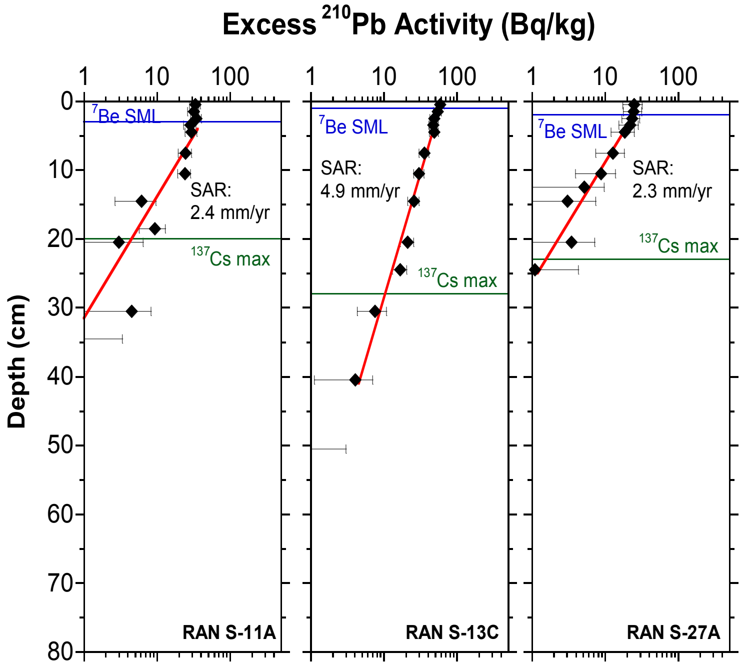

Figure 3-4: Te Rawhiti Inlet: sediment accumulation rates (SAR) for core sites RAN S-11, S-13 and to S-27. Excess ^{210}Pb activity profiles with 95% confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer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

3.3.4 Brett/Inner shelf

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

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

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

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

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

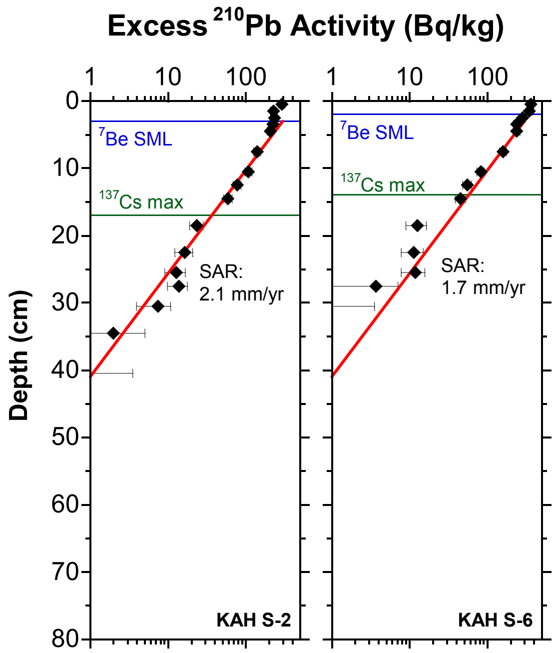

Figure 3-5: Brett: sediment accumulation rates (SAR) for core sites KAH S-2 and S-6. Excess ^{210}Pb activity profiles with 95% confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer (SML) and maximum depth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

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

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

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

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

3.3.5 Central Bay of Islands

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

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

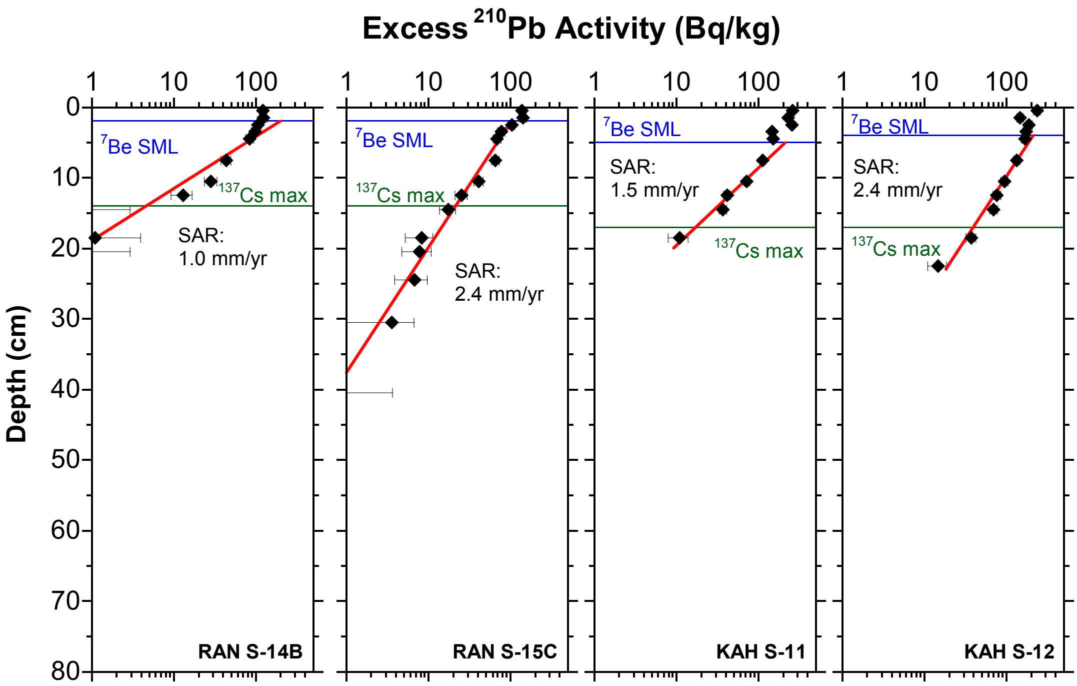

Figure 3-6: Central Bay of Islands: sediment accumulation rates (SAR) for core sites RAN S-14B and S-15C, and KAH S-11 and S-12. Excess 210Pb activity profiles with 95% confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface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

3.3.6 Kerikeri and Te Puna Inlets

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

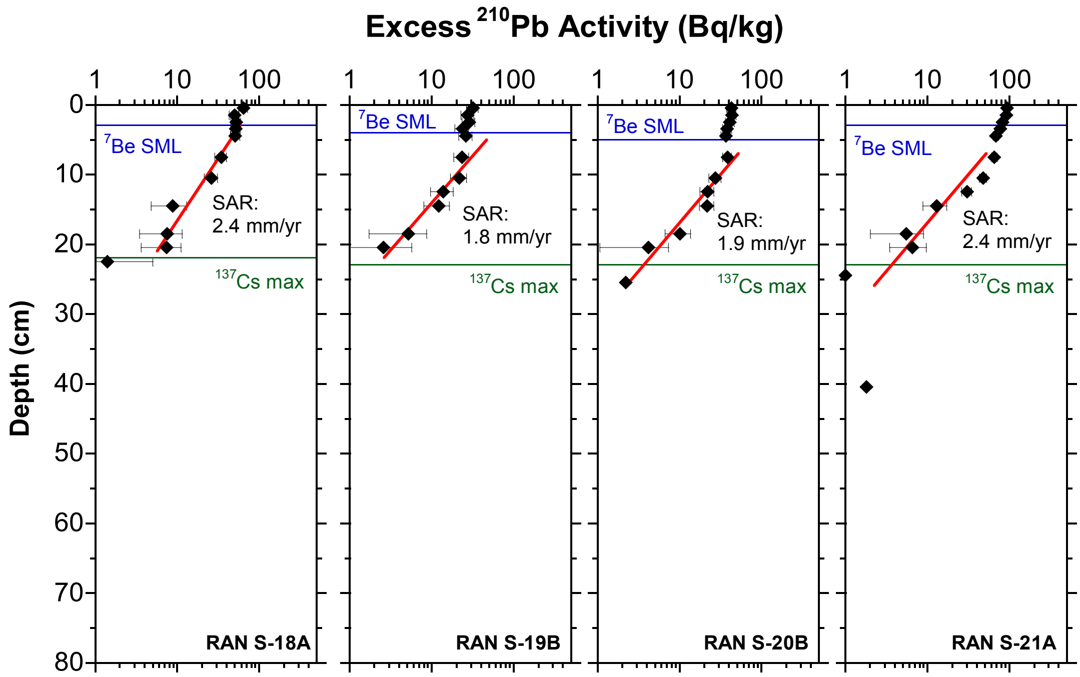

Figure 3-7: Kerikeri and Te Puna Inlets: sediment accumulation rates (SAR) for core sites RAN S-18A to S-21A. Excess ^{210}Pb activity profiles with 95% confidence intervals show. Time-averaged SAR derived from regression fit to natural-log transformed data. The berrylium-7 (^{7}Be) surface mixed layer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

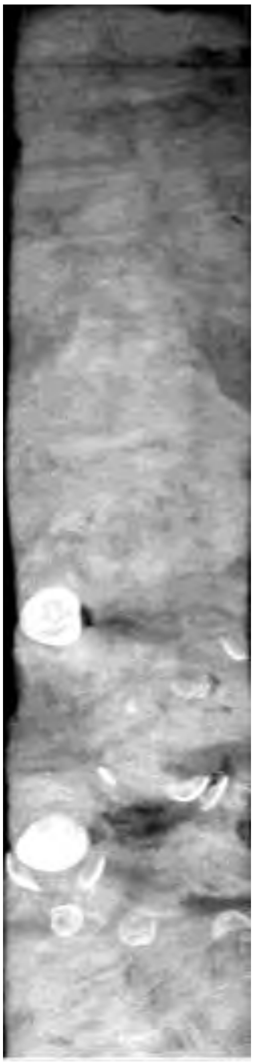

Figure 3-8: X-radiograph of the top 40 cm of core RAN S-18 collected in the Kerikeri Inlet (Exposure 25 mAs, 55 kV). The image has been inverted so that higher-density sediments appear white (e.g., quartz sand, shell, DBD ~2.7 g/cm^3) and low density and/or high-porosity sediments (e.g., saturated mud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

3.4 Long-term sediment accumulation rates

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

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

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

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

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

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

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

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

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

3.5 Influence of land-use changes on sedimentation

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

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

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

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

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

3.6 Particle size

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

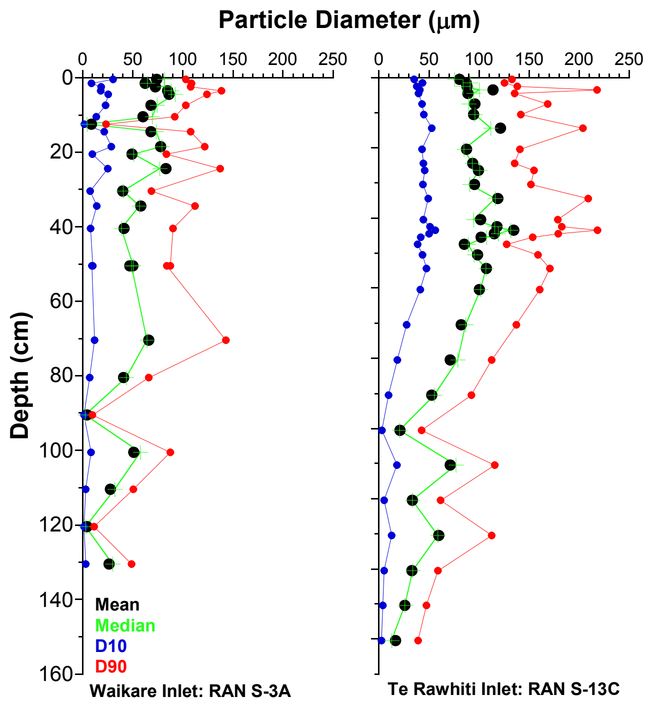

Figure 3-9: Depth profiles of key particle size statistics for cores from the Waikare (RAN S-3) and Te Rawhiti (RAN S-13) Inlets, Bay of Islands.

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

3.7 Recent sedimentation in the BOI system

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

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

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

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

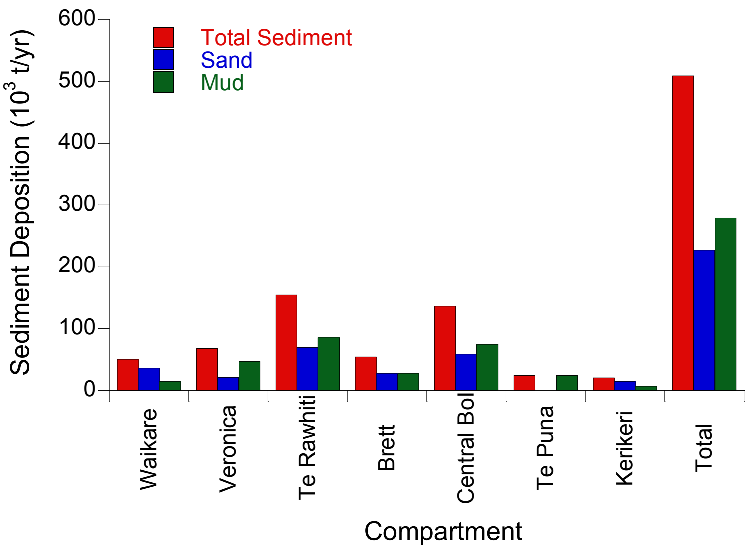

Figure 3-10: Annual sediment deposition rates (tonnes per year) in each compartment for total sediment mud and sand fractions.

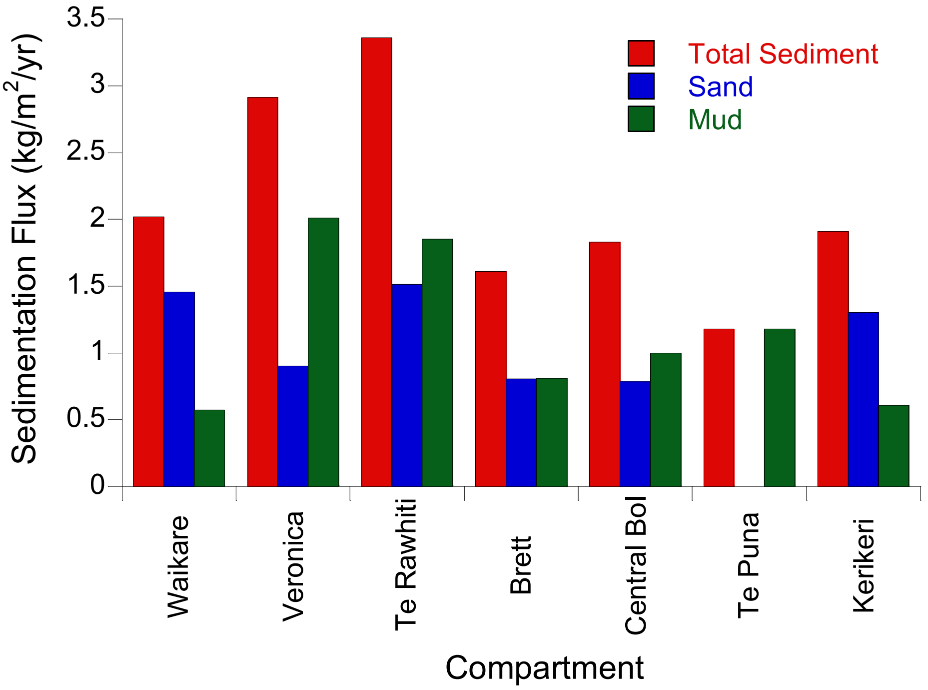

Figure 3-11: Annual sediment deposition rates in each sedimentary compartment expressed as unit-area sedimentation flux (kg/m^2/yr) for total sediment, mud and sand.

The key results of this analysis are:

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

3.8 Comparison of recent and prehistoric sediment budgets

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

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

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

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

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

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

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

3.9 Comparison with sedimentation rates in other North Island estuaries

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

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

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

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

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

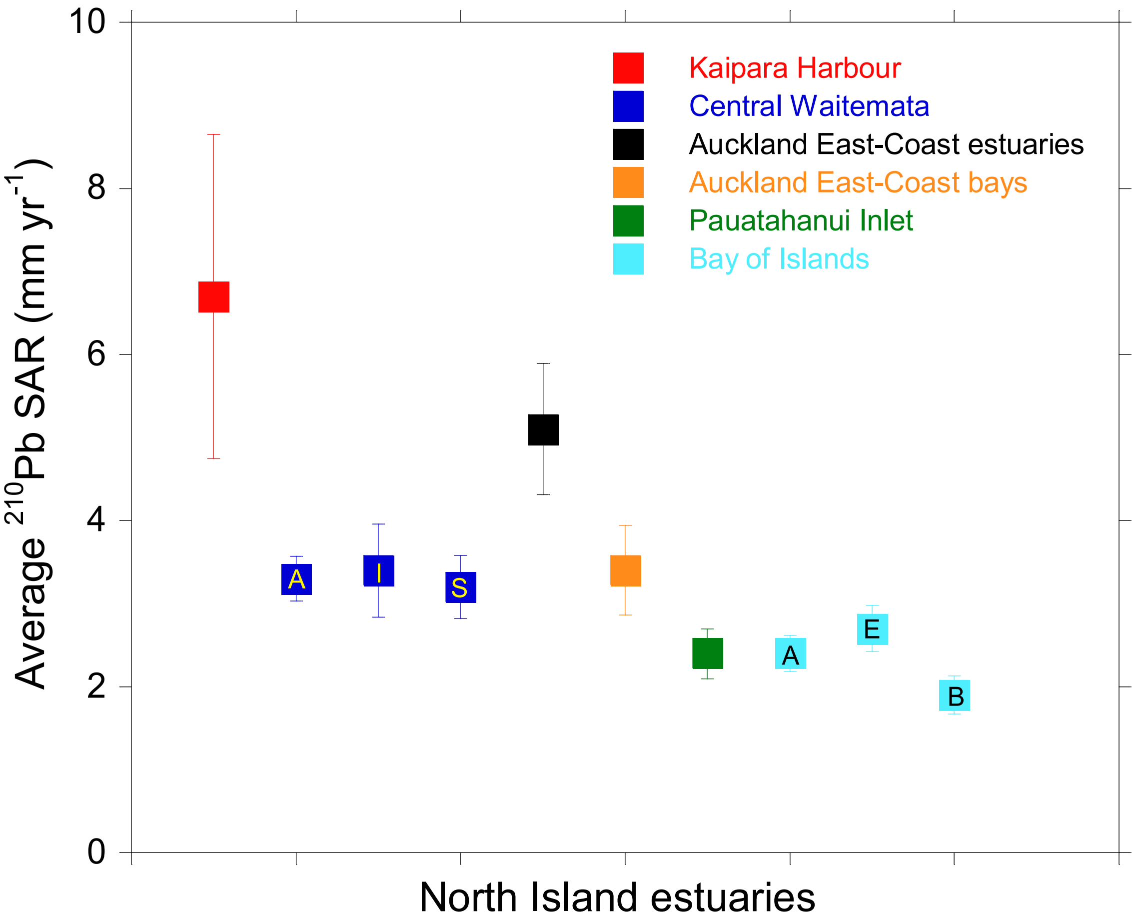

Figure 3-12: Comparison of average ^{210}Pb sediment accumulation rates (SAR) in North Island estuaries with standard errors shown. Notes: (1) key - all data (A), intertidal sites (I), subtidal sites (S), estuaries (E), coastal embayments (B); (2) Total number of cores = 85; (3) Data sources: Table 3-6.

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

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

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

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

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

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

3.10 Sediment accommodation capacity of fringing estuaries

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

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

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

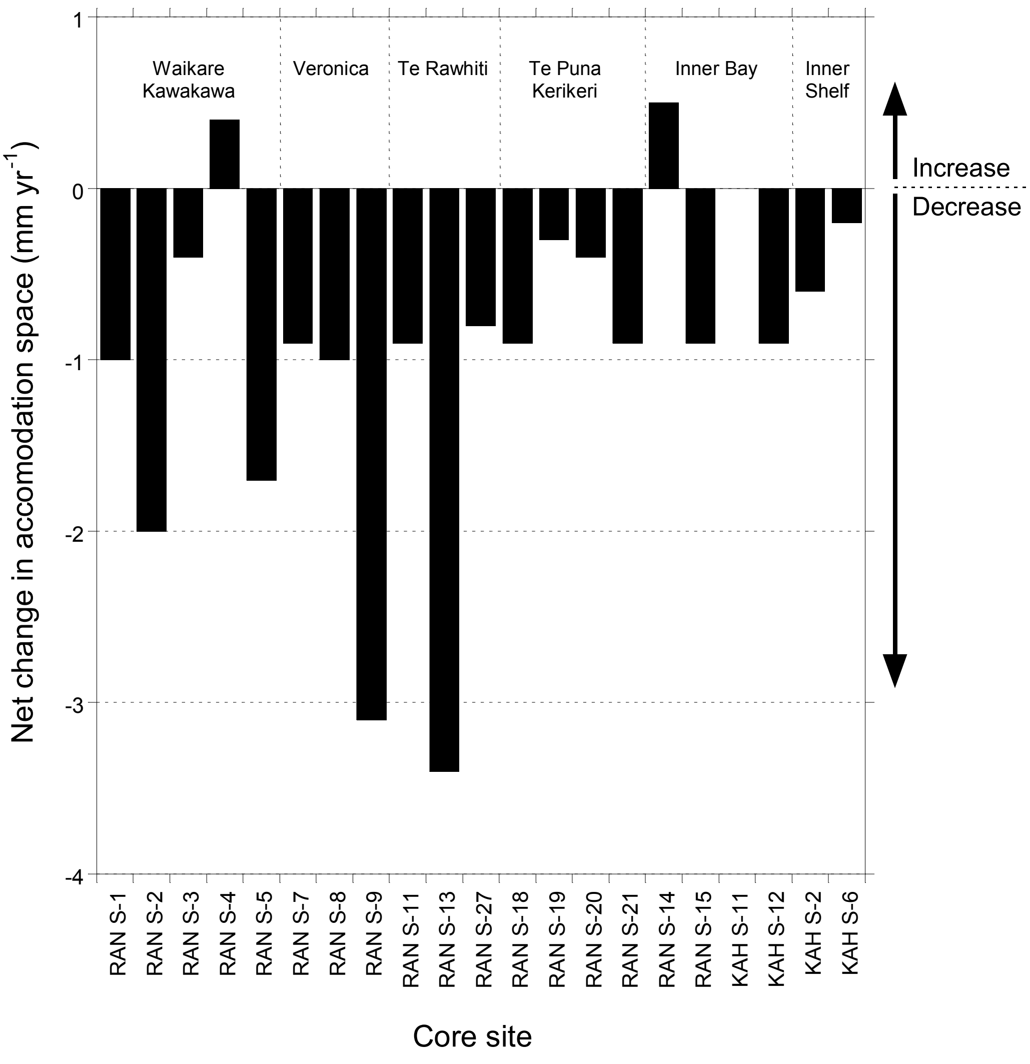

Figure 3-13: Net change in sediment accommodation space (mm/yr) in sedimentary compartments based on ^{210}Pb SAR measured at core sites and the historical rate of sea level rise at the Port of Auckland.

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

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

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

3.11 Present-day sources of Bay of Islands sediments

3.11.1 Spatial patterns

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

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

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

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

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

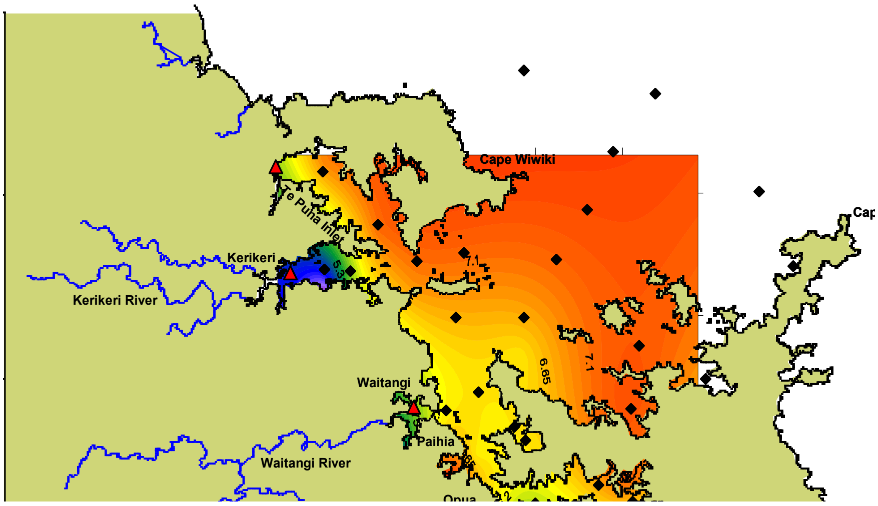

Figure 3-14: Spatial contour plot of ^{15}N stable isotope values in the surficial sediment of the Bay of Islands. The contour plot used linear krigging to interpolate between adjacent data points and is indicative rather than absolute.

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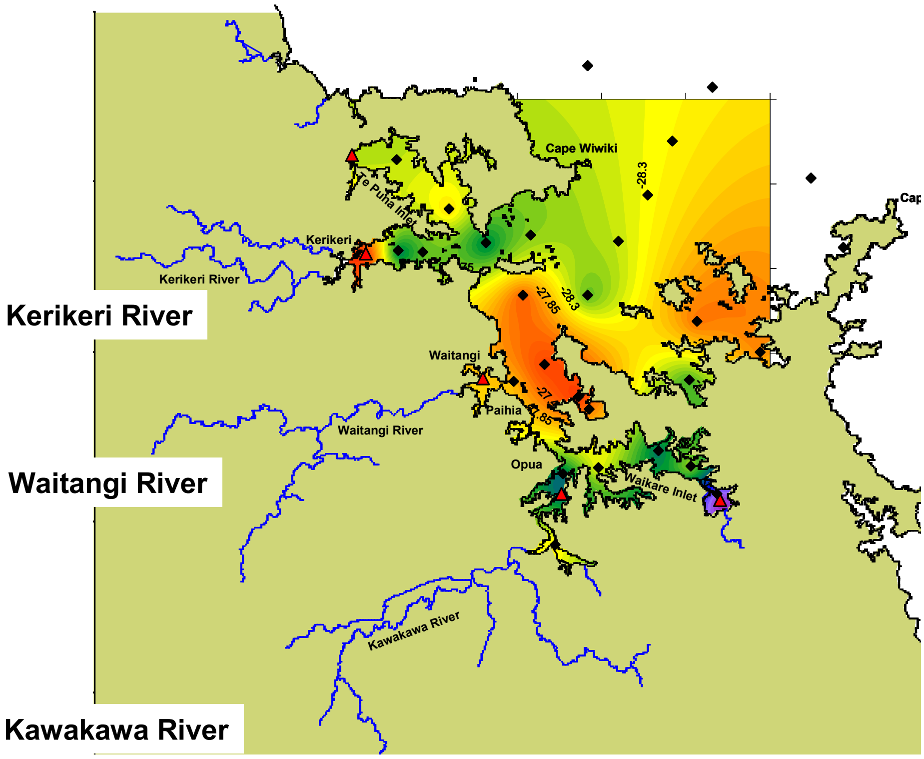

Figure 3-15: Spatial contour plot of the distribution of the compound-specific stable isotope $\delta^{13}C$ values of stearic acid (C18:0) in surficial sediments of the Bay of Islands. The contour plot used linear krigging to interpolate between adjacent data points and is indicative rather than absolute.

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

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

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

3.11.2 Present-day sediment sources

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

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

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

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

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

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

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

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

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

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

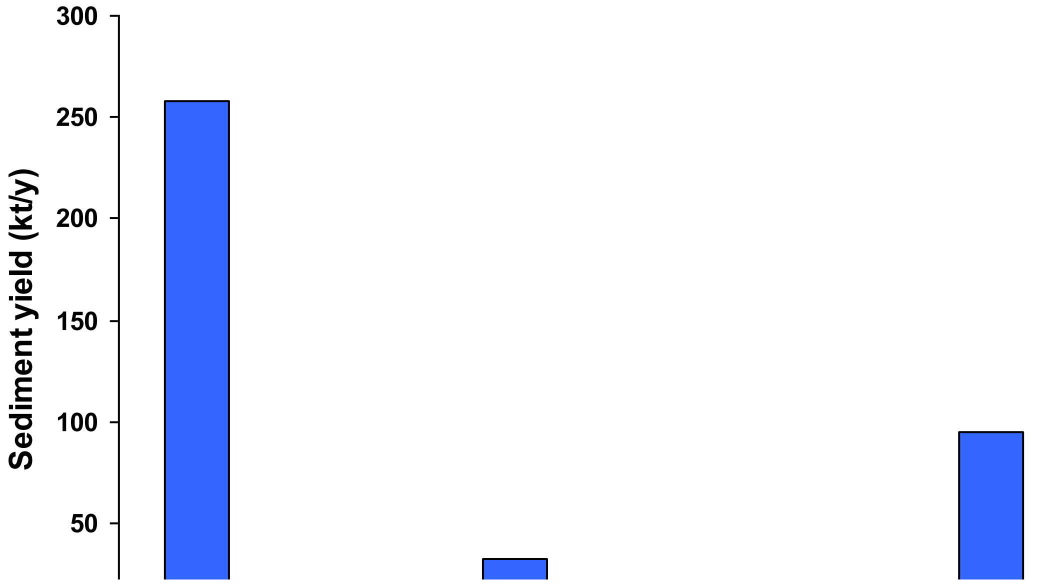

Figure 3-18: Estimated mean annual sediment loads (kt/y) on the Bay of Islands by present day land-use. (Sediment yield data: Pritchard et al. 2010).

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

3.12 Past sources of Bay of Islands sediments

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

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

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

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

3.12.1 Waikare Inlet

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

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

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

3.12.2 Veronica channel at Russell

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

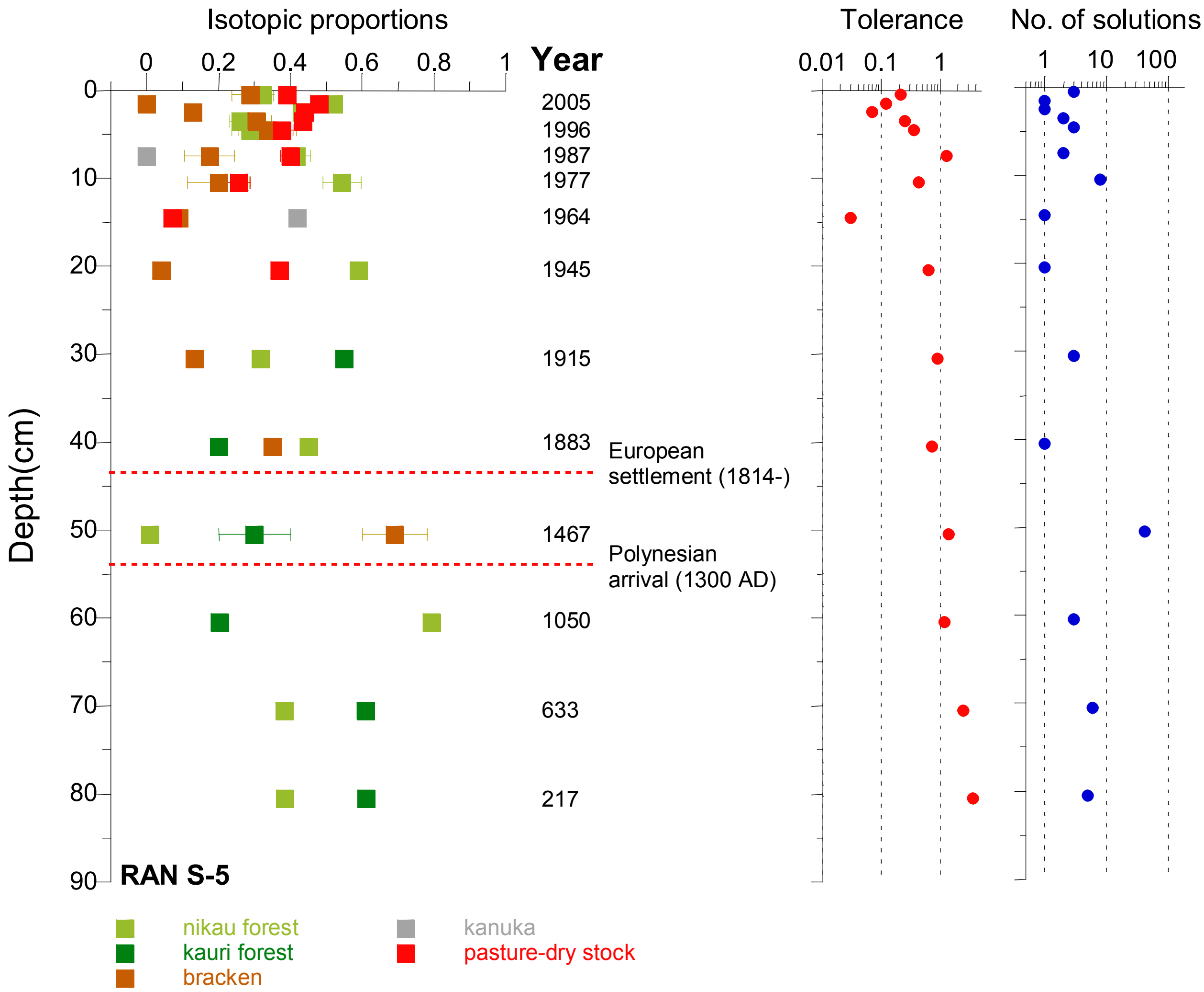

Figure 3-19: Waikare Inlet (RAN-S5): (a) feasible isotopic proportions (average and standard deviation) of soil courses in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic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

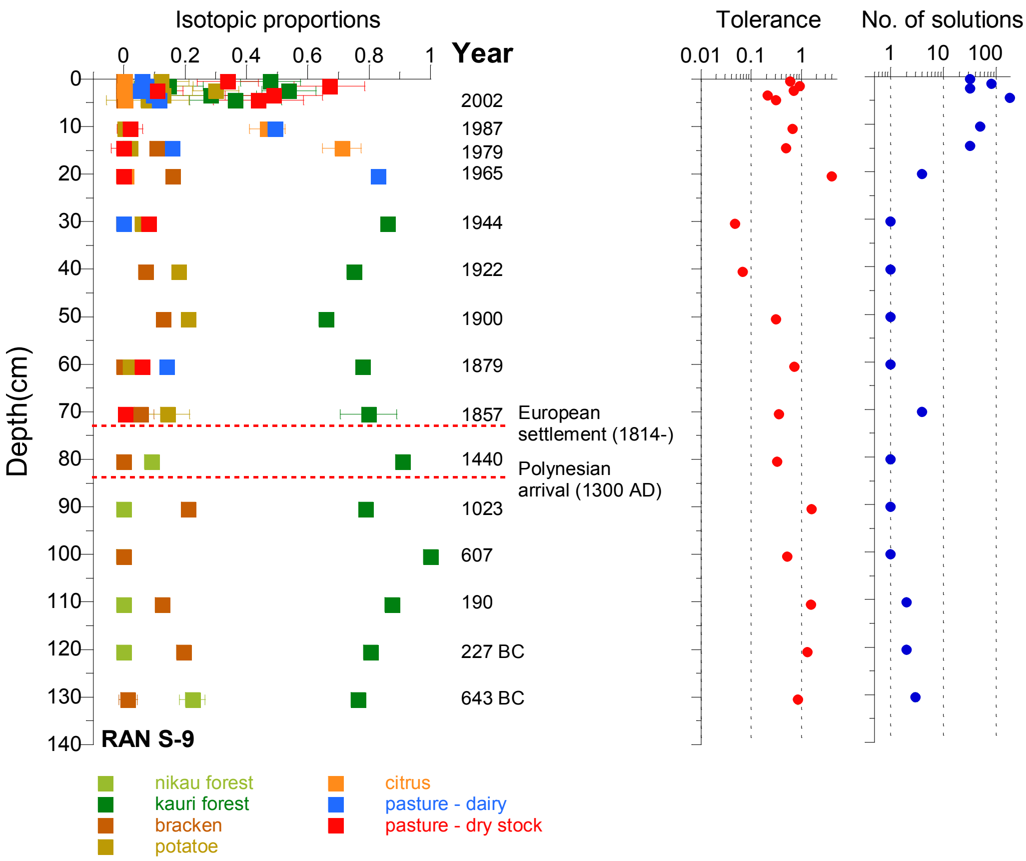

Figure 3-20: Veronica channel at Russell (RAN-S9): (a) feasible isotopic proportions of soil sources in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modelling of sources;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

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

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

3.12.3 Kerikeri Inlet

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

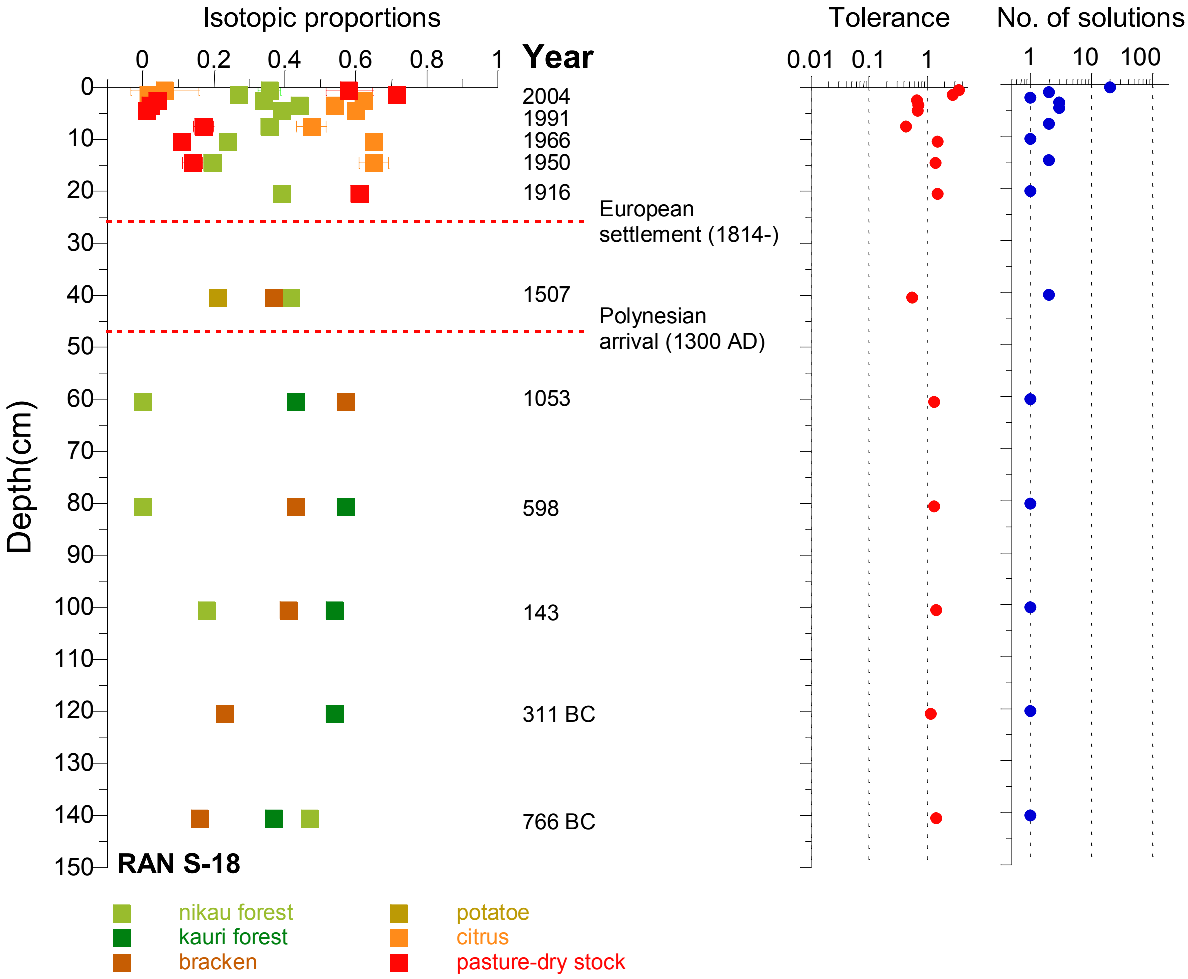

Figure 3-21: Kerikeri (RAN-S18): (a) feasible isotopic proportions of soil sources in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modelling of sources; and (c) number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

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

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

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

3.12.4 Inner Bay of Islands

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

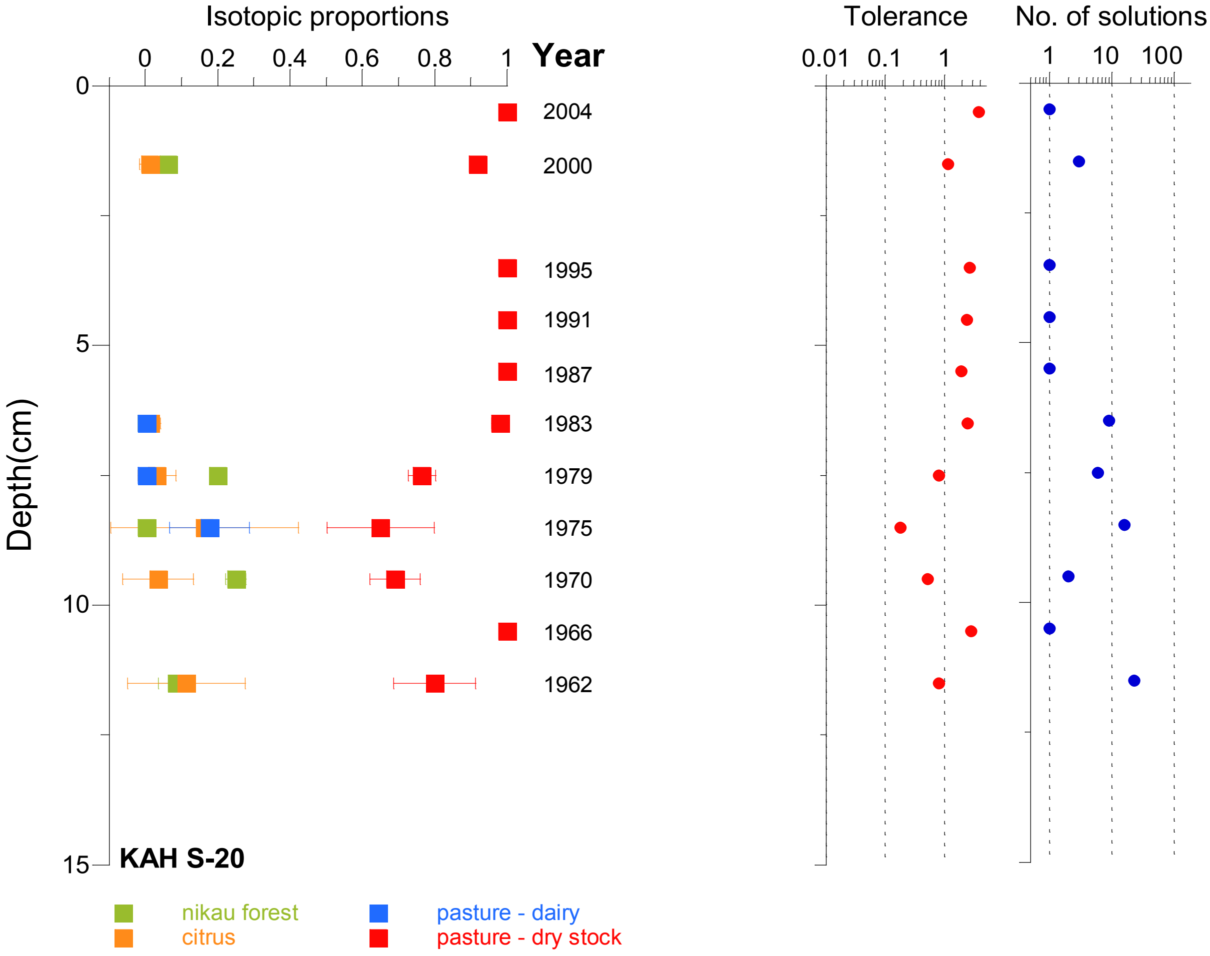

Figure 3-22: Inner Bay of Islands at ~30-m isobath (KAH-S20): (a) feasible isotopic proportions of soil sources in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modeling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

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

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

3.12.5 Inner shelf

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

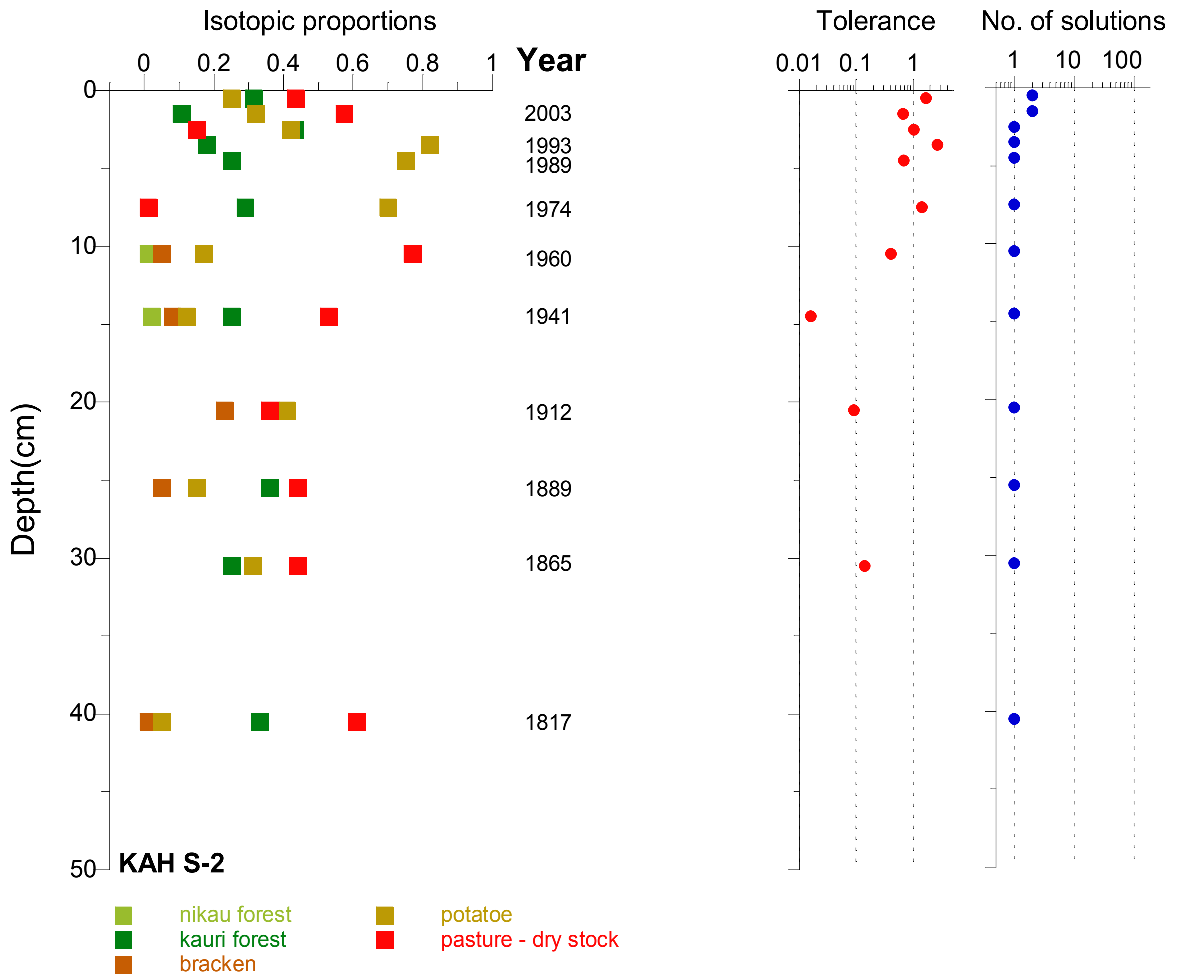

Figure 3-23: Inner shelf at 100 m isobath (KAH-S2): (a) feasible isotopic proportions of soil sources in the sediment core at various depths below the sediment surface. The ages of sediment layers have been determined from ^{210}Pb and ^{14}C dating; (b) minimum tolerance for isotopic modelling of sources;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

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

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

3.13 Present-day deposits – recent or historical sediments?

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

1. The lag time between soil erosion at a site and sediment delivery and deposition in the BOI system. This is evaluated using a sediment-core record from the Kerikeri Inlet.
2. Potential for sediment remobilisation (mixing and/or resuspension) of near-surface sediment deposits. It is in this surface mixed layer (SML) that plants and animals live and sediments are frequently or episodically reworked by physical processes, such as waves and currents. The depth of the SML and the sediment accumulation rate determines the residence time of sediments in the active sedimentary system. This SML is evaluated for all cores sites in section 3.2.1.

3.13.1 Time-scale for sediment delivery to the BOI system

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

The requirements for this analysis include:

1. availability of a suitable plant tracer
2. reliable history of plant introduction to the catchment
3. the degree of preservation of the original sediment record, which depends on the degree of sediment mixing subsequent to initial sediment deposition
4. down-core sampling frequency. The ability to detect the initial appearance of a tracer in the sediment record depends on the sampling frequency. For example a core sampled at 1-cm intervals will provide a more detailed record than a core sampled at 10-cm intervals, and
5. the temporal resolution of the sediment record, which depends on the sediment sample increment, sediment accumulation rate and residence time in the SML. For example, the time increment represented by a 10-mm thick sediment sample extracted from a core with SAR = 2 mm yr^{-1} is 10 mm/2 mm yr^{-1} = 5 years. The uncertainty in sediment dating or recent sediments is also increased by mixing within the SML, which is discussed in the next section.

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

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

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

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

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

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

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

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

3.14 Benthic ecology

3.14.1 Comparison of NRC and Oceans 20/20 Intertidal data

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

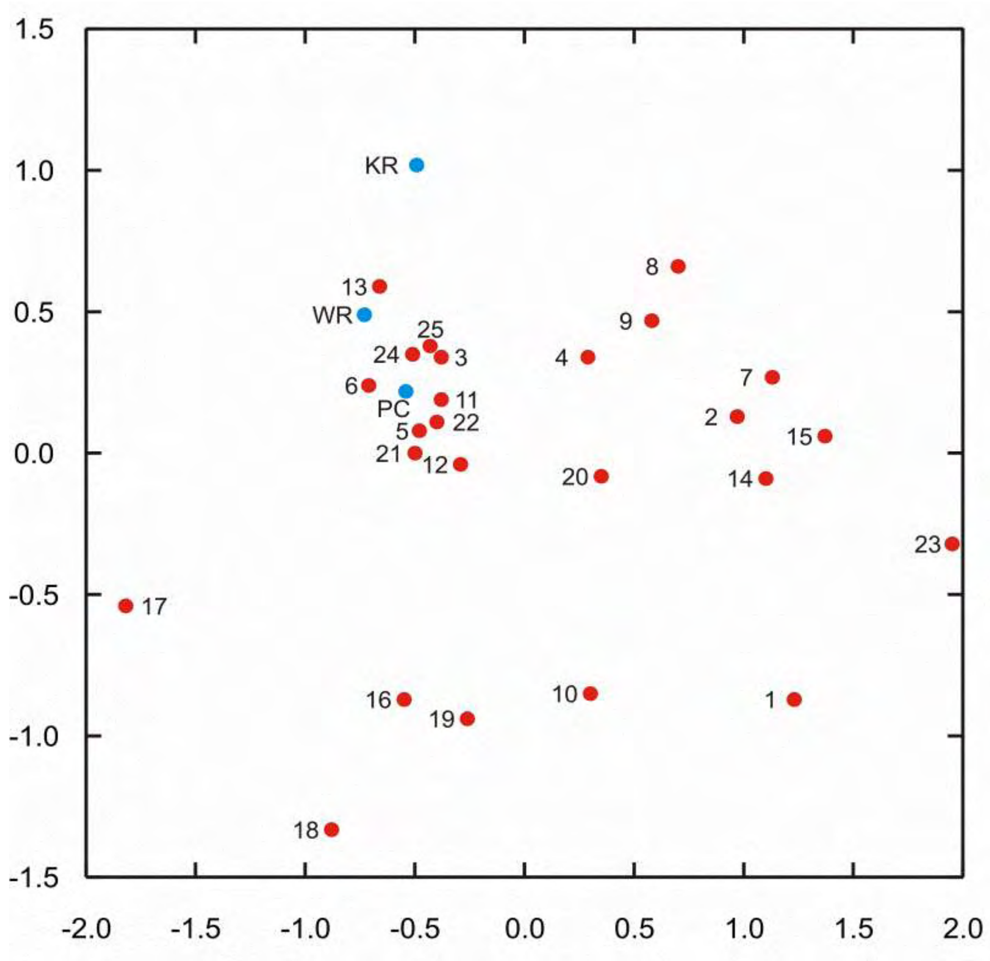

Figure 3-24: Multi-dimensional Scaling (MDS) plot of the dissimilarity in macrofaunal communities at NRC monitoring sites (blue circle) Kerikeri River (KR), Waipapa River (WR) and Pickmere Channel (PC) and Oceans 20/20 sites (red circles) labelled 1-25 (Log transformed data). The further away the points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

3.14.2 Estimation of site sensitivity

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

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

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

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

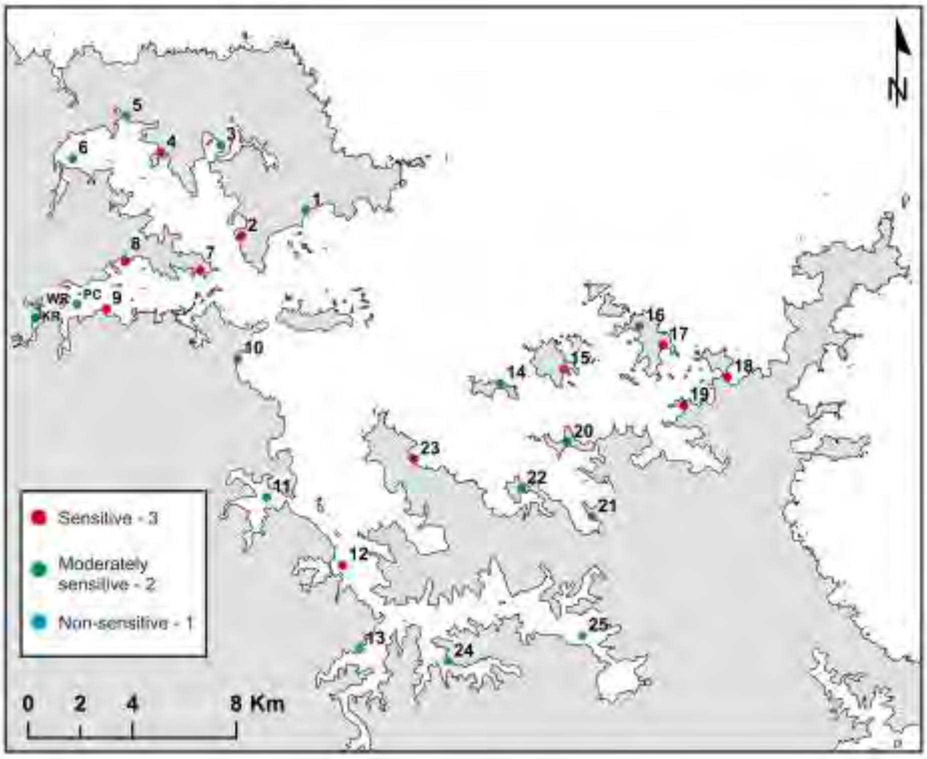

Figure 3-25: Spatial distribution of intertidal macrobenthic communities in the Bay of Islands with varying sensitivity to terrestrial sediment inputs.

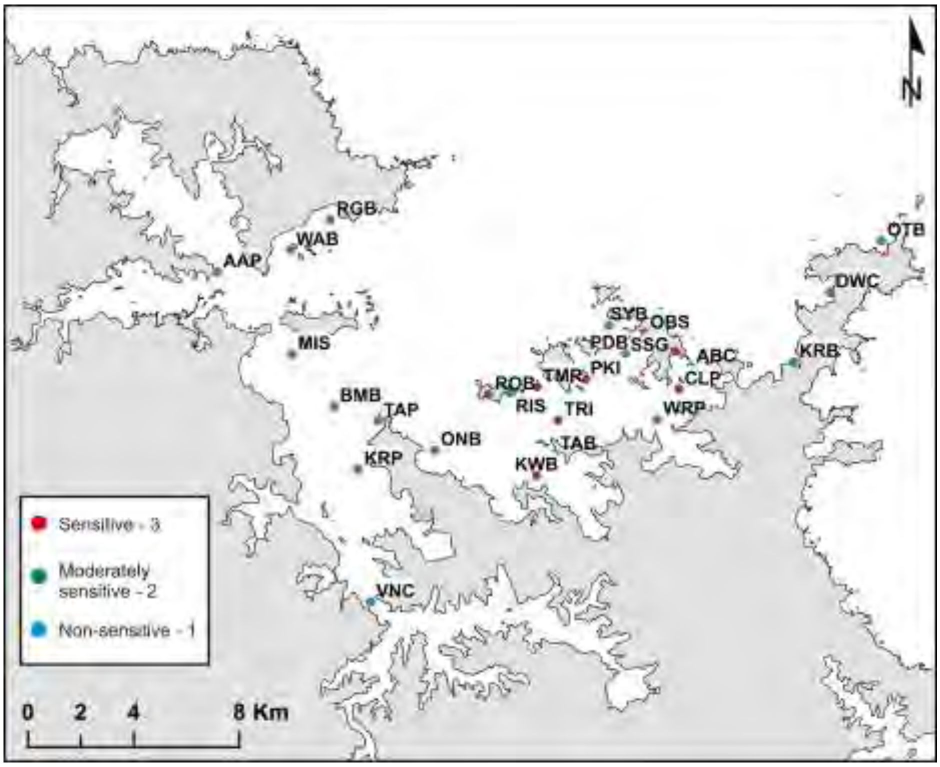

Figure 3-26: Spatial distribution of shallow subtidal macrobenthic communities in the Bay of Islands with varying sensitivity to terrestrial sediment inputs.

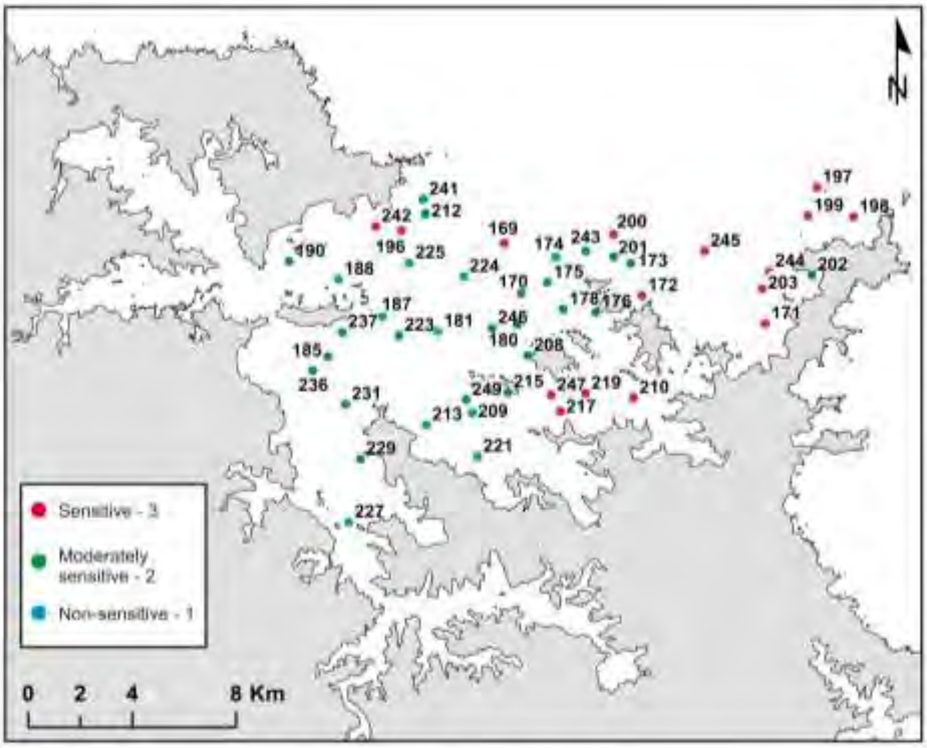

Figure 3-27: Spatial distribution of DTIS macrobenthic communities in the Bay of Islands with varying sensitivity to terrestrial sediment inputs.

3.14.3 Estimation of vulnerability at site locations

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

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

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

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

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

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

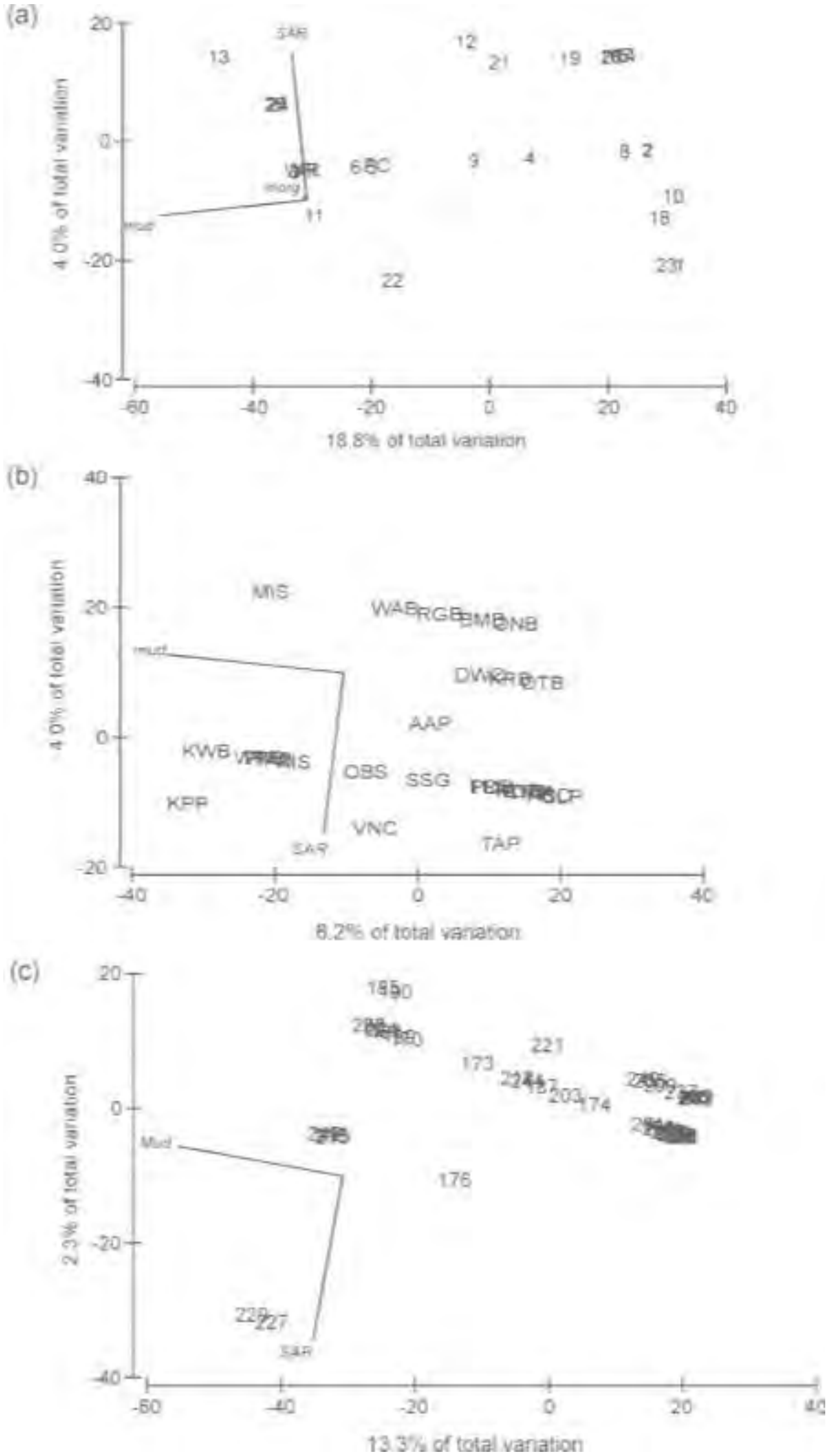

Figure 3-28: Distance-based redundancy analysis of the communities observed in (a) intertidal, (b) shallow subtidal and (c) deeper subtidal areas. Sites that are closest together are most similar, and the length and direction of arrows relative to the amount explained by the horizontal and vertical axis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

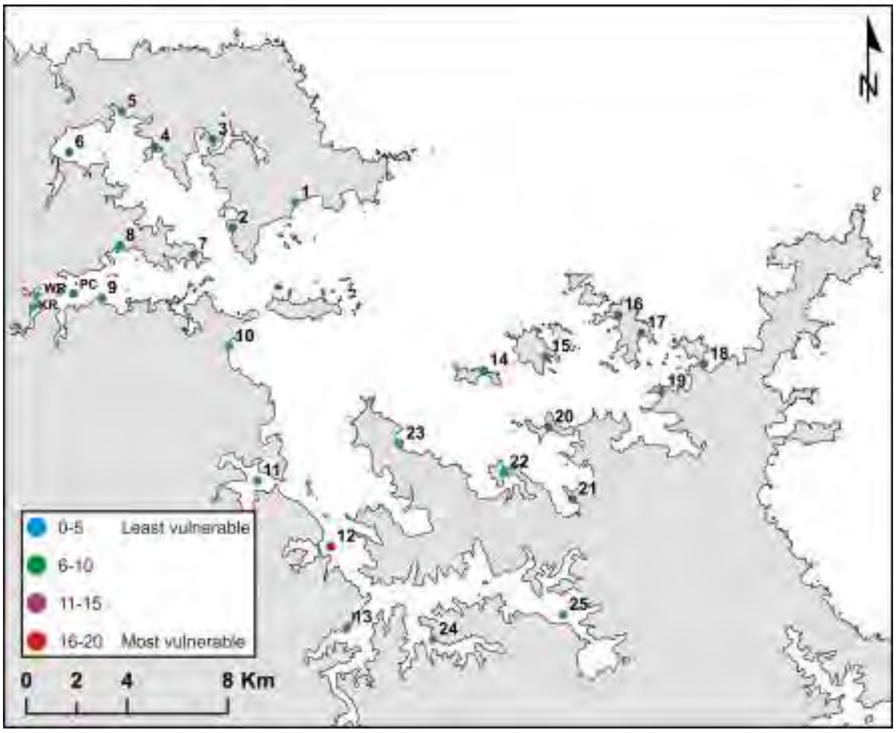

Figure 3-29: Vulnerability of intertidal communities in the Bay of Islands to potential sediment deposition. The larger the value, the more vulnerable the community is to sediment deposition, at estimated rates described from interpolated SAR values calculated in the present study.

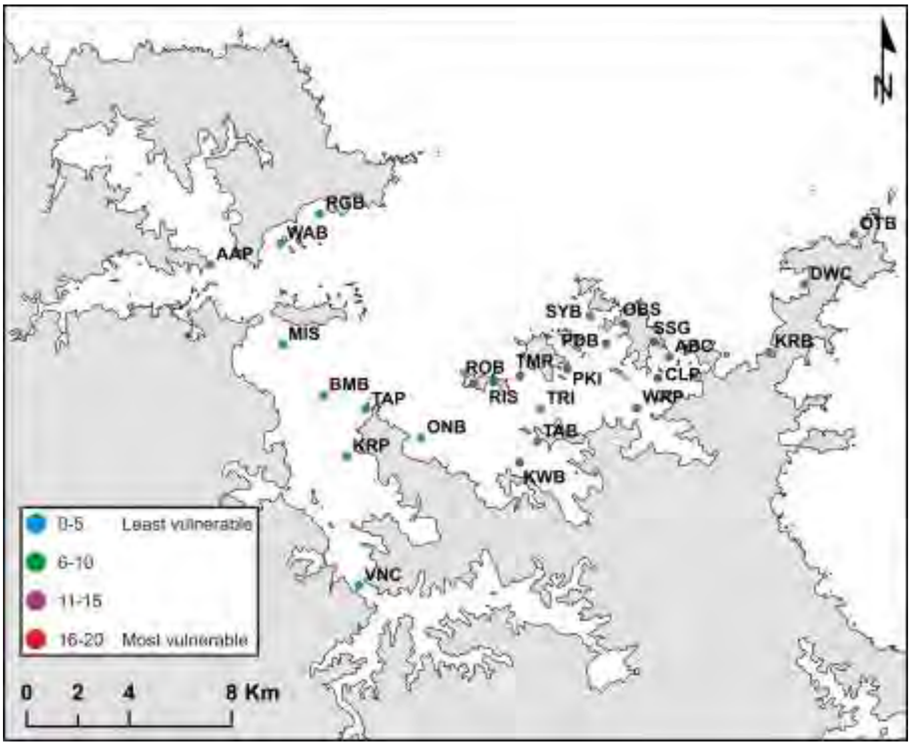

Figure 3-30: Vulnerability of subtidal communities in the Bay of Islands to potential sediment deposition. The larger the value, the more vulnerable the community is to sediment deposition, at estimated rates described from interpolated SAR values calculated in the present study.

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

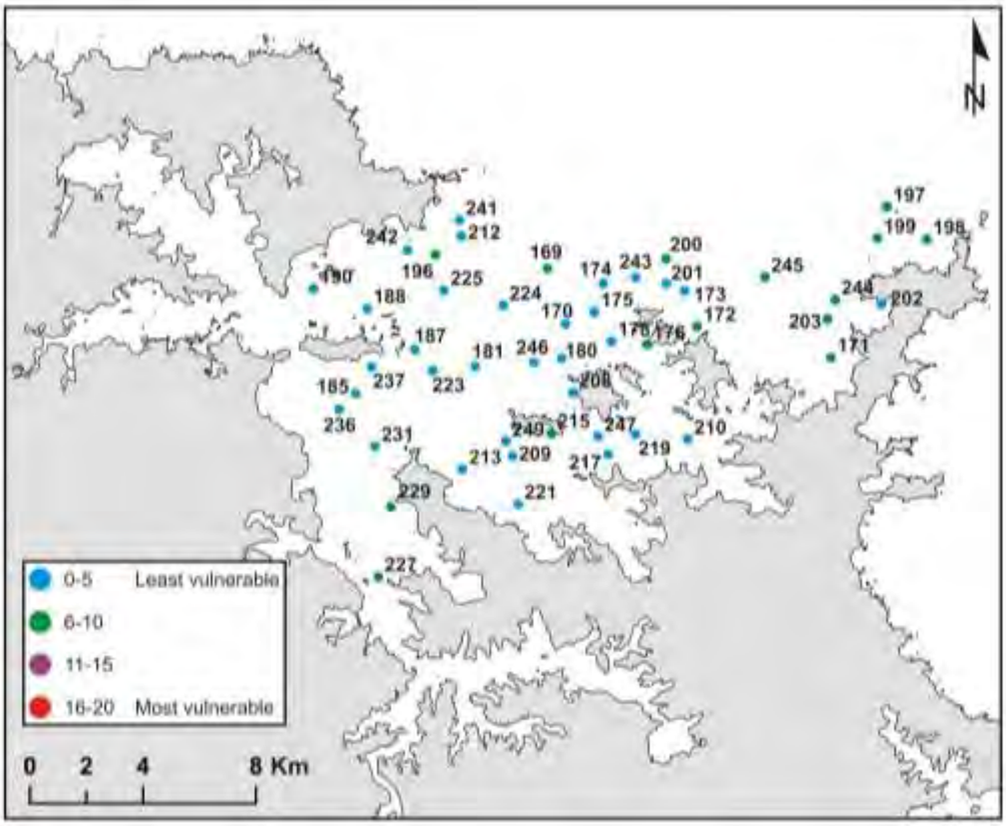

Figure 3-31: Vulnerability of subtidal communities sampled using DTIS in the Bay of Islands to potential sediment deposition. The larger the value, the more vulnerable the community is to sediment deposition.

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

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

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

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

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

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

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

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

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

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

3.15.1 Summary of changes in vegetated intertidal habitats

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

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

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

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

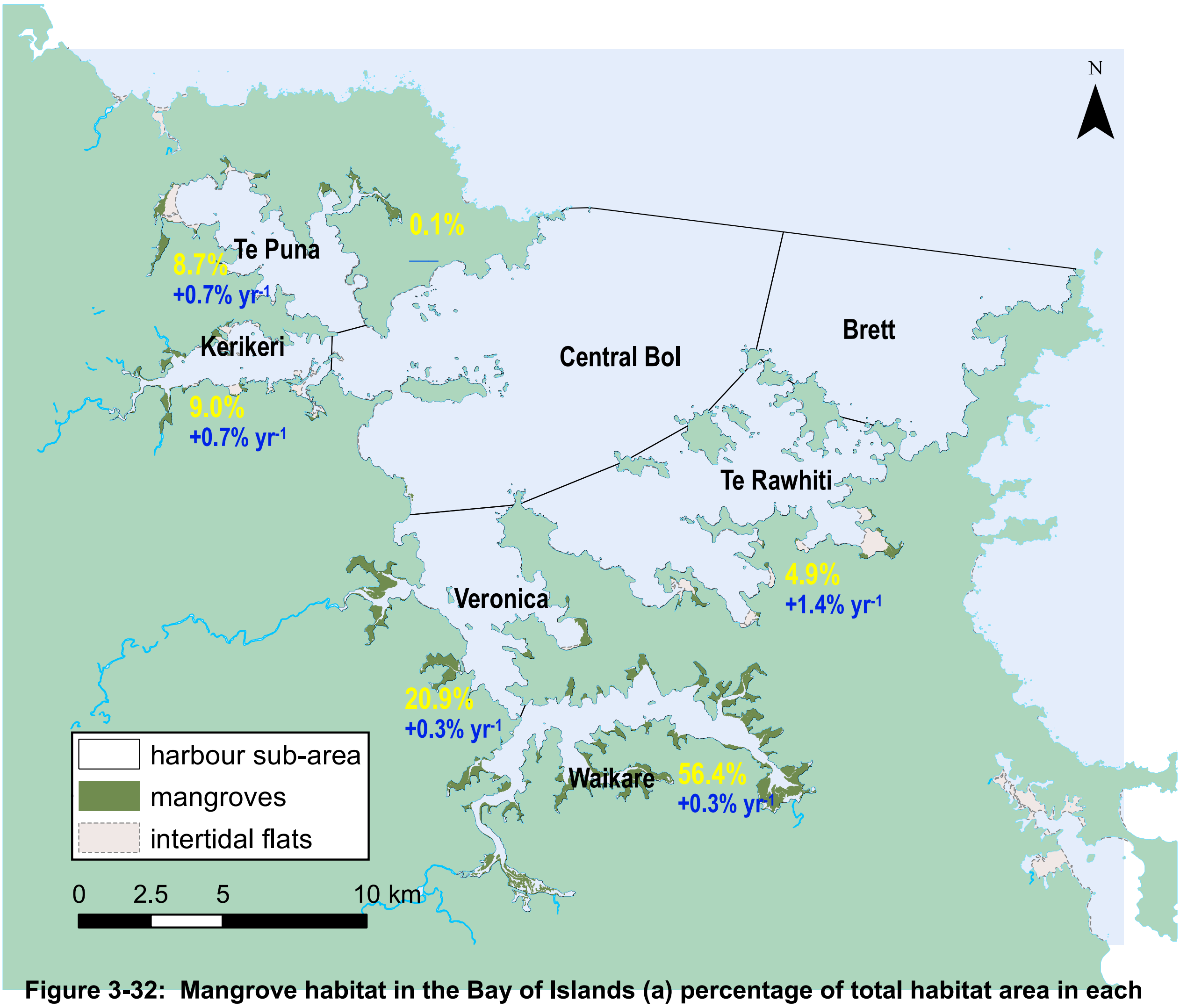

Figure 3-32: Mangrove habitat in the Bay of Islands (a) percentage of total habitat area in each compartment (% 2009, yellow text); and average rate of change in mangrove habitat (%/yr, 1978-2009, blue text). Source: NRC.

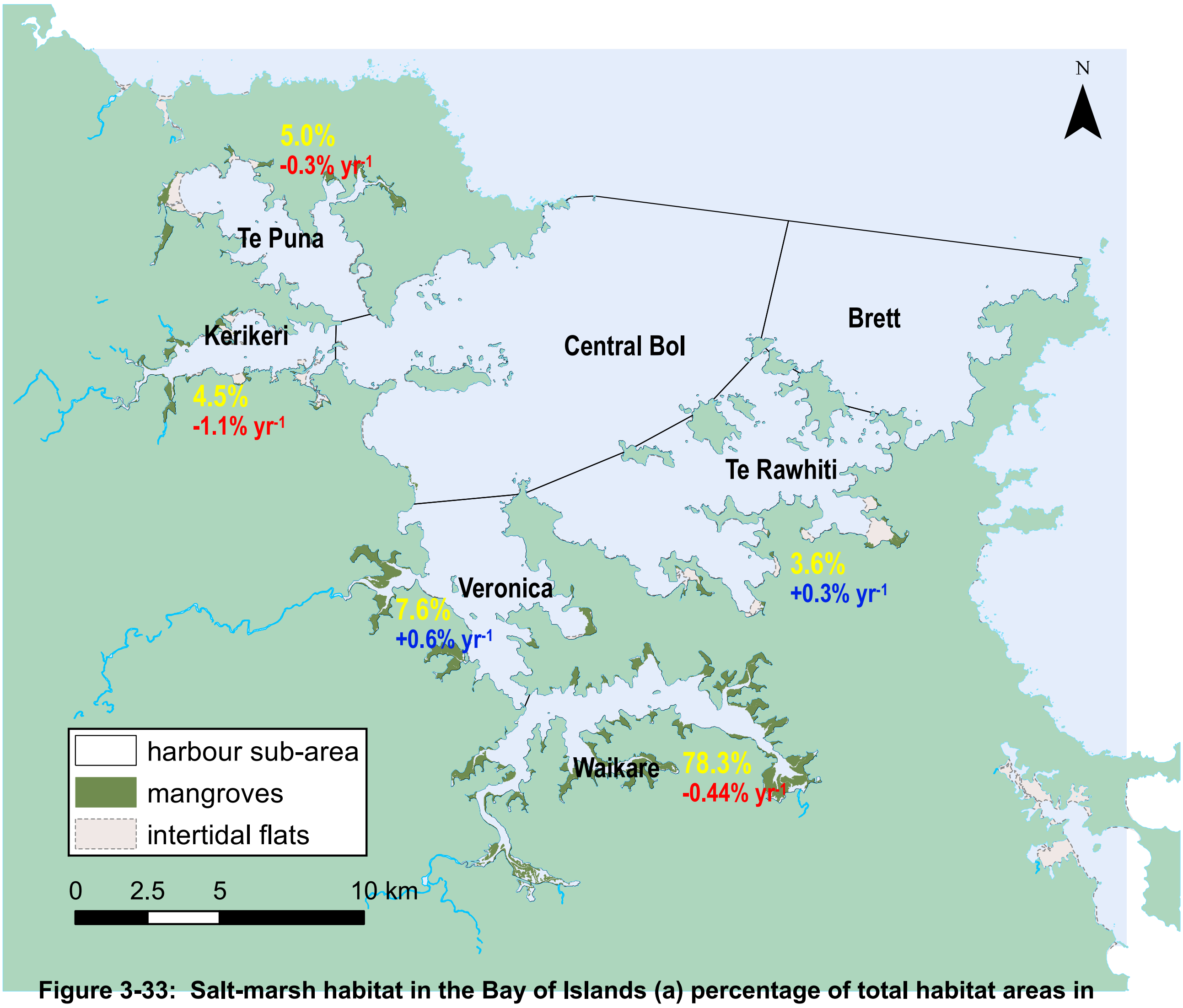

Figure 3-33: Salt-marsh habitat in the Bay of Islands (a) percentage of total habitat areas in each compartment (% 2009, yellow text); and average rate of change in salt-marsh habitat (%/yr, 1978-2009, blue and red text). Source: NRC.

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

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

3.15.2 Waikare Inlet

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

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

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

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

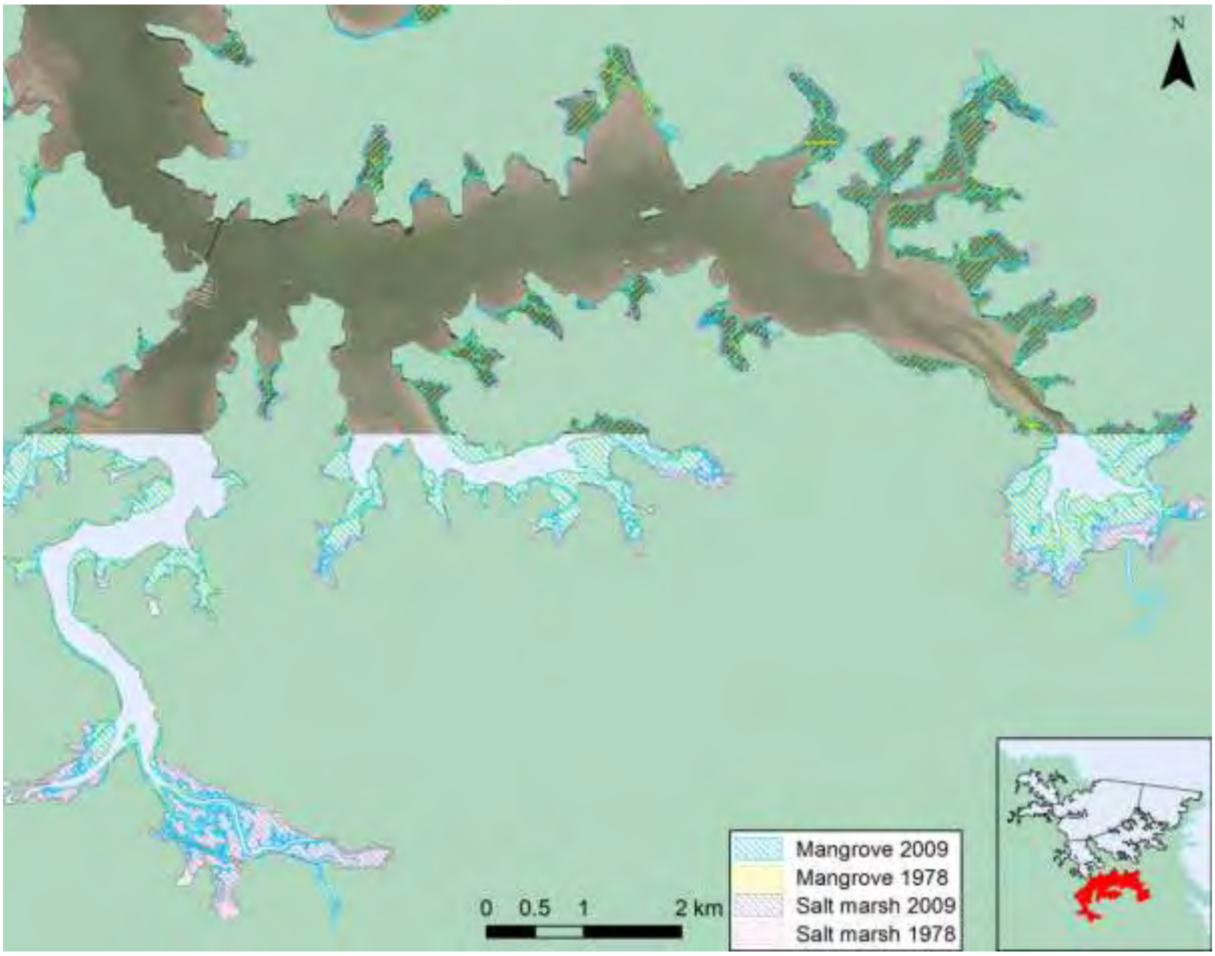

Figure 3-34: Waikare Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

3.15.3 Veronica Inlet

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

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

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

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

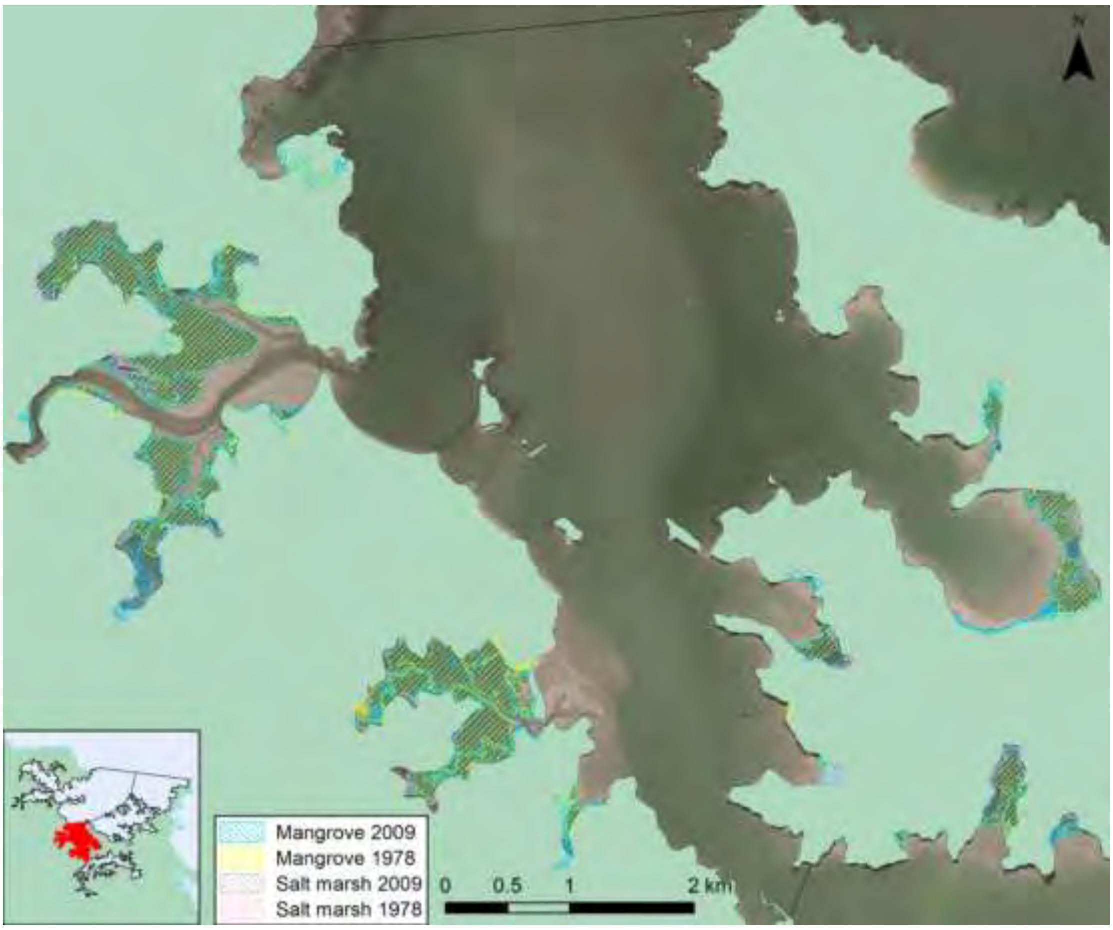

Figure 3-35: Veronica Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

3.15.4 Te Rawhiti Inlet

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

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

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

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

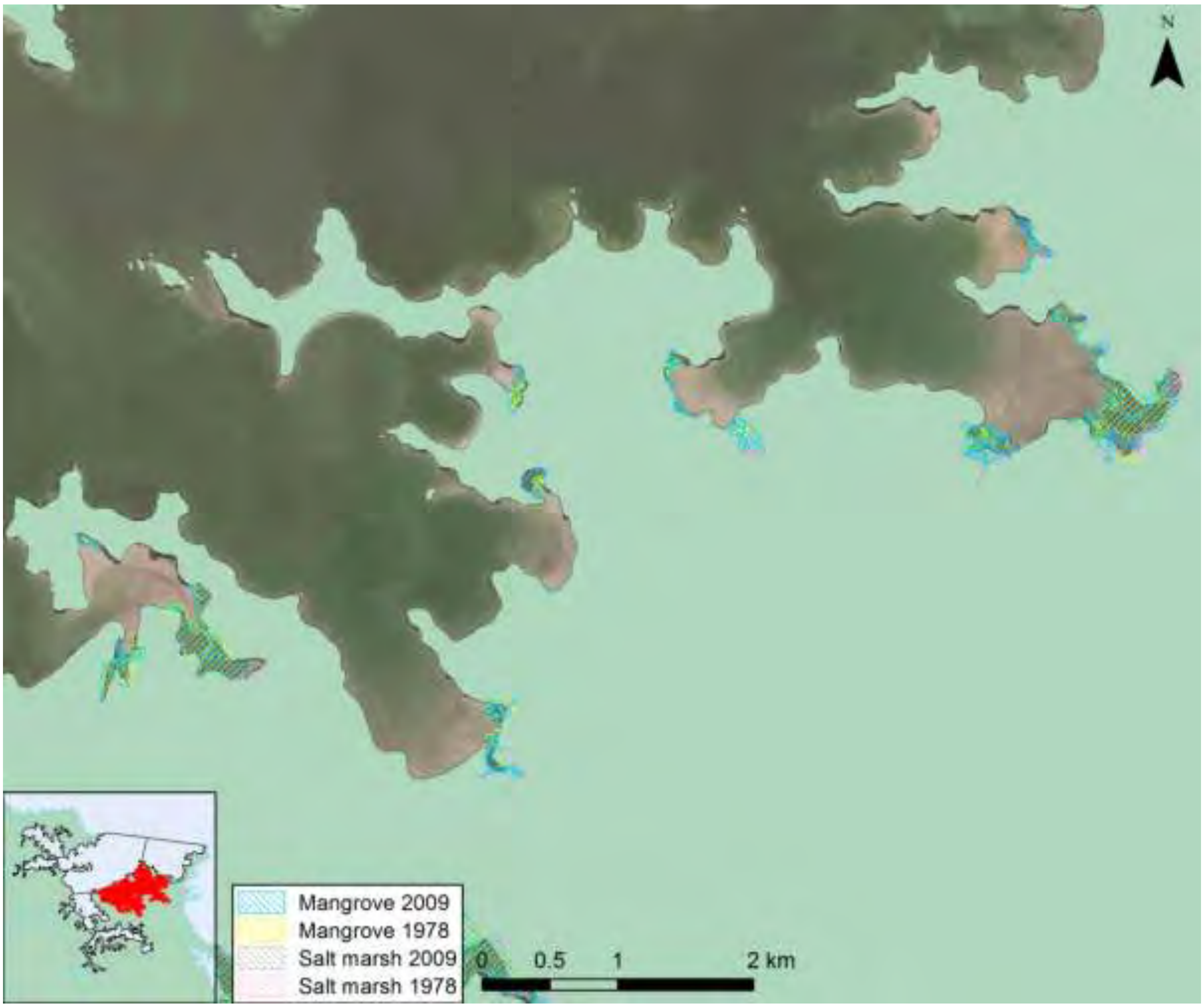

Figure 3-36: Te Rawhiti Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

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

3.15.5 Kerikeri Inlet

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

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

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

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

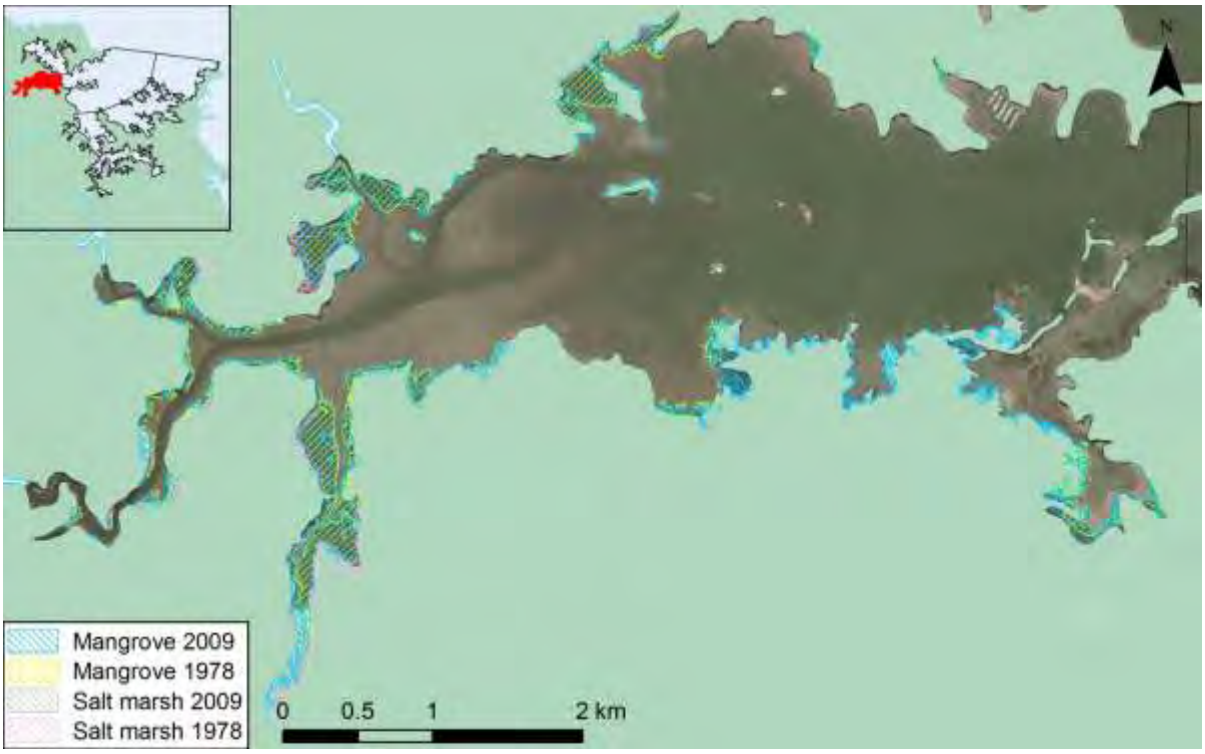

Figure 3-37: Kerikeri Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

3.15.6 Te Puna Inlet

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

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

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

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

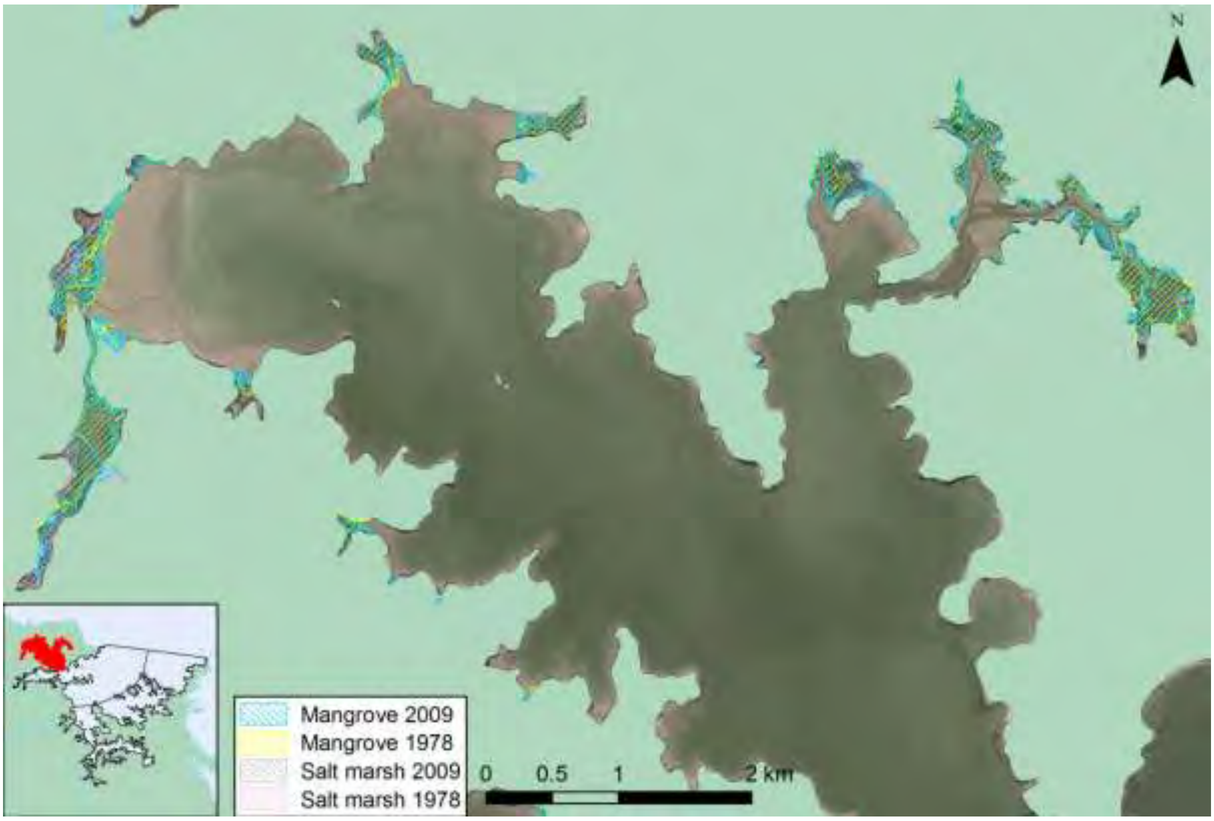

Figure 3-38: Te Puna Inlet: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

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

3.15.7 Central Bay of Islands

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

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

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

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

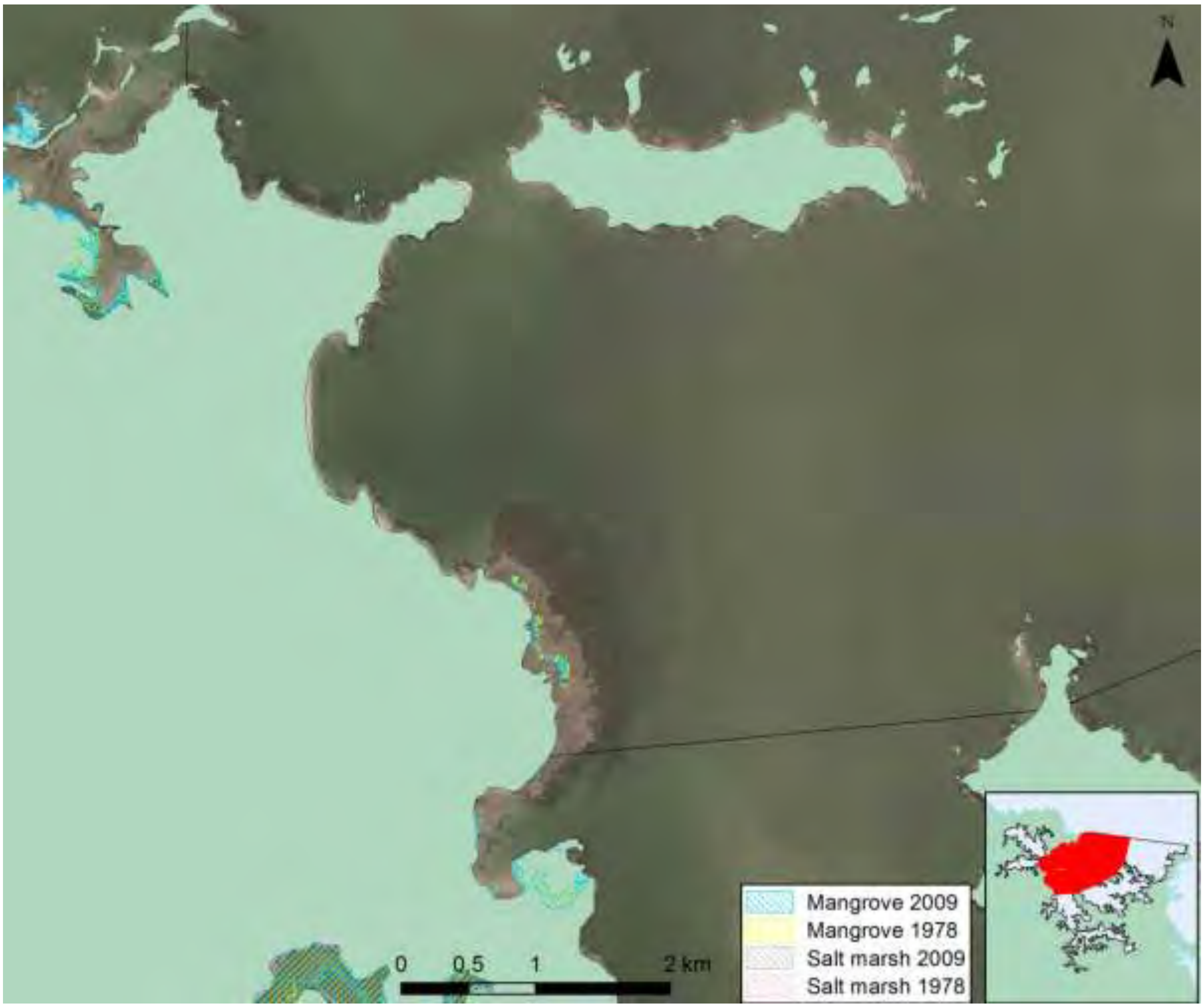

Figure 3-39: Central Bay of Islands: changes in the spatial distribution of intertidal mangrove and salt marsh habitats (1978-2009). Source: Northland Regional Council.

3.15.8 Interpretation of historical changes in mangrove-habitat extent

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

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

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

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

3.16 Potential for future mangrove-habitat expansion

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

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

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

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

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

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

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

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

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

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

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

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