SALT ECOLOGY

Fine Scale Intertidal Monitoring of Waikanae Estuary, December 2022

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Cover photo: Intertidal flats in the lower Waikanae Estuary, December 2022.

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Fine Scale Intertidal Monitoring of Waikanae Estuary

Prepared by

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for

Greater Wellington Regional Council

September 2023

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GLOSSARY

AMBI	AZTI Marine Biotic Index
ANZG	Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2018)
aRPD	Apparent Redox Potential Discontinuity
As	Arsenic
BHM	Benthic Health Model
Cd	Cadmium
CMEC	Coastal Marine Ecology Consultants
Cr	Chromium
Cu	Copper
DGV	Default Guideline Value
Epibiota	Animals (epifauna) and seaweeds (macroalgae) visible on the surface on the sediment
ETI	Estuary Trophic Index
Hg	Mercury
GWRC	Greater Wellington Regional Council
NEMP	National Estuary Monitoring Protocol
Ni	Nickel
NIWA	National Institute of Water and Atmospheric Research
Pb	Lead
SACFOR	Epibiota categories of: Super-abundant, Abundant, Common, Frequent, Occasional, Rare
SOE	State of the Environment (monitoring)
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
Zn	Zinc

ACKNOWLEDGEMENTS

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BACKGROUND

As part of its State of the Environment programme, Greater Wellington Regional Council (GWRC) undertakes monitoring and assessment of the ecological condition of estuaries and other coastal environments in its region. This report describes an intertidal survey (undertaken 12 Dec 2022) of a monitoring site in Waikanae Estuary, following the previously used fine scale survey methods adapted from New Zealand's National Estuary Monitoring Protocol. Findings are compared with four previous surveys undertaken from 2010-2017, and supplemented with the results of annual sedimentation monitoring undertaken using the 'sediment plate' method. The status and long-term trends in estuary health are evaluated, and future monitoring and management needs are discussed.

KEY FINDINGS

The following table presents mean values of sediment indicators in each survey at fine scale Site A, relative to established rating criteria of ecological health for New Zealand estuaries (see Glossary for definition of indicators).

Year	Sed rate	Mud	aRPD	TN	TP	TOC	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn	AMBI
	mm/yr	%	mm			%									na
2010	na	26.7	30	483*	333	0.46	-	0.036	11.3	7.0	10.0	-	9.4	44.3	3.1
2011	45.5	18.0	51	633	377	0.36	-	0.033	12.3	6.3	9.5	-	9.5	40.7	3.1
2012	23.0	38.7	11	1433	523	1.70	-	0.053	14.8	8.7	10.7	-	11.6	49.3	3.1
2017	-1.7	13.2	30	<500	377	0.32	3.1	0.034	13.7	8.6	11.1	0.03	11.9	49.3	3.1
2022	-24.5	20.0	23	367*	377	0.56	3.1	0.029	12.3	6.9	9.9	0.04	10.4	48.7	3.0

** Sample mean includes values below lab detection limits*
< All values below lab detection limit
Analyte units are mg/kg dry wt except as noted

Very Good	Good	Fair	Poor

Key findings with respect to these and other indicators described in the main report are as follows:

- Sedimentation monitoring (measured at three locations) revealed a long-term net accrual of >10mm/yr, but marked periods of accretion and erosion have occurred. It is likely that the changes in sediment depth are attributable to the movement of bed sediments (e.g. due to Waikanae River flow effects), with periods of accrual not necessarily attributable to the deposition of catchment-derived sediment. As such, exceedances of the 2mm/yr guideline on which the 'poor' rating is based in the above Table are not of any significant concern.
- Across the five surveys, mean sediment mud content at the fine scale site has ranged from ~13 to 39% (rated 'fair' or 'poor'). The annual time series of sediment grain size analysis from samples collected at sediment plate sites (see main report Section 3.1) shows marked inter-annual variability in sediment mud content, which also appears linked to Waikanae River flow; i.e., sediments are less muddy following high flows.

- Total organic carbon (%TOC) and nutrients (TN, total nitrogen; TP, total phosphorus) were at low levels, except where elevated in 2012 due to the high sediment mud content that year.
- Concentrations of trace contaminants (metals and organochlorine pesticides) were generally low, and detectable concentrations were less than threshold values defined in national sediment quality guidelines.
- Surface-dwelling mud snails were relatively abundant in early surveys but were absent from the monitoring site in 2017 and sparse in 2020. The sediment-dwelling macrofauna was relatively species-poor, and dominated by a few hardy species that are tolerant of a wide range of environmental conditions.

Overall, the estuary has shown marked variation in sedimentation, sediment mud content, and other indicator values. Rather than any directional trends that would suggest a degradation in estuary state since monitoring began in 2010, the analysis in this report suggests that strong variability in environmental conditions is an inherent characteristic of the estuary, and is determined mainly by flow conditions in Waikanae River. Although this situation means that anthropogenic changes (e.g., from increases in catchment sediment loads) may be difficult to disentangle from other processes, there is nonetheless merit in continuing the fine scale approach in the long term, and investigating current and future catchment activities that could adversely affect estuary state (e.g., harvest of plantation forestry). Due to the river-dominated nature of the estuary, it is also suggested that the vulnerability of subtidal habitats be considered as part of future monitoring and assessment. Ideally, however, the priorities for future monitoring and assessment in Waikanae Estuary would be considered as part of a wider review of SOE monitoring needs for estuaries regionally.

RECOMMENDATIONS

- Continue fine scale monitoring surveys in Waikanae Estuary at intervals of ~5-years, as is typical for this method. To track key changes in the estuary in intervening years, annual sediment plate monitoring should be continued, along with measurement of sediment grain size and oxygenation (aRPD).
- Schedule 5-10 yearly broad-scale NEMP surveys simultaneously with fine scale surveys to enable a more holistic assessment of estuary condition.
- Consider undertaking an assessment to prioritise monitoring in regional estuaries according to estuary vulnerability, condition and current and future pressures.
- Depending on the outcome of the regional assessment, consider expanding the scope of monitoring in Waikanae Estuary to include a synoptic assessment of subtidal conditions.

Lower Waikanae Estuary view toward Kāpiti Island.

1. INTRODUCTION

Monitoring the ecological condition of estuarine habitats is critical to their management. Estuary monitoring is undertaken by most councils in New Zealand as part of their State of the Environment (SOE) programmes. The most widely-used monitoring framework is that outlined in New Zealand's National Estuary Monitoring Protocol (NEMP, Robertson et al. 2002). The NEMP is intended to provide resource managers nationally with a scientifically defensible, cost-effective and standardised approach for monitoring the ecological status of estuaries in their region. The results establish a benchmark of estuarine health to better understand human influences, and against which future comparisons can be made. The NEMP approach involves two main types of survey:

- Broad scale monitoring to map estuarine intertidal habitats, typically undertaken every 5 to 10 years.
- Fine scale monitoring of estuarine biota and sediment quality, typically conducted at intervals of 5 years after initially establishing a baseline.

A commonly-used addition to the NEMP fine scale approach is to install sediment 'plates' (buried concrete pavers) at fine scale sites, or elsewhere in an estuary, as a means of monitoring sedimentation. This approach involves monitoring temporal change in the depth of sediment that occurs over each plate, which indicates whether sediment is accumulating (sediment depth increases) or eroding (sediment depth decreases). As well as providing insight into estuary sedimentation processes, the sediment plate method provides supporting data that assists in the interpretation of changes occurring at fine scale sites.

Greater Wellington Regional Council (GWRC) has undertaken monitoring of selected estuaries in the region using the NEMP methods, sediment plates and other approaches (e.g., synoptic surveys) for over a decade. One of these locations is Waikanae Estuary on the region's west coast (Fig. 1), where sediment plates were installed in 2010 and a NEMP fine scale survey was undertaken (Robertson & Stevens 2010). Sediment plate monitoring has been conducted annually since then, with further fine scale surveys undertaken in 2011, 2012 and 2017 (Robertson & Stevens 2017). Supporting this work, a comprehensive broad scale survey was undertaken in 2015 (Stevens & Robertson 2015), with annual mapping of 'nuisance' macroalgae extent from 2010 to 2014.

This report describes the methods and results of a fine scale and sedimentation survey conducted 12 December 2022. Findings are compared with earlier work in terms of the current status and trends in estuary health, and recommendations are made for future management and monitoring. Relevant background information on Waikanae Estuary, and some of the survey findings to date, are provided in Box 1.

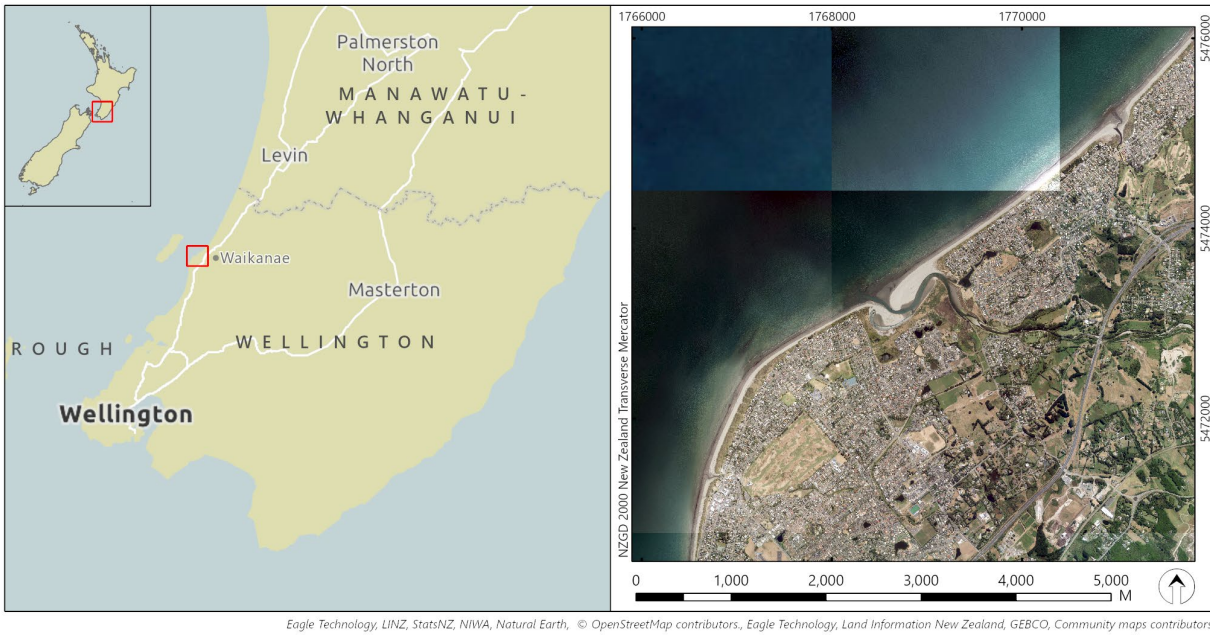


Fig. 1 Location of Waikanae Estuary.

Box 1. Summary of Waikanae Estuary and key findings from past monitoring.

This synopsis has been adapted from previous SOE reports on Waikanae Estuary (Stevens & Robertson 2015; Robertson & Stevens 2017). The estuary was defined by Robertson and Stevens (2017) as a moderate-sized (2km long, 40-50m wide, 1-2m deep) "shallow, short residence, tidal river" type estuary (SSRTRE). The estuary drains onto a broad beach just north of Paraparaumu. The majority of the estuary area consists of a long, shallow lagoon type system running along the back of the beach parallel to the sea. The lower part of the estuary is periodically changed when the channel naturally realigns, or opens more directly to the sea at the north end before progressively migrating south (see inset map below). Floodgates restrict tidal action and flushing to a large historical estuarine arm. The middle and upper estuary in the main channel are more stable, and have been targeted for fine scale and sedimentation monitoring.

Like other moderate-sized tidal river estuaries, the Waikanae is usually freshwater dominated at low tide and at high tide consists of a freshwater layer on top of saline bottom water. Plant and animal life is therefore restricted to those that tolerate regular salinity extremes. Some of the ecological values in the estuary are high. For example, it is one of very few sizable estuary/wetland areas in the southwestern North Island, and is a nationally significant wetland habitat for waders, seabirds and waterfowl, both local and migratory. In terms of human use, the estuary is a local focal point for conservation, walking, picnicking, boating, fishing, paddling, bird watching, bathing, and white-baiting.

The estuary receives moderate inputs of nutrients and sediment from its large (15,245ha) catchment, and tertiary treated wastewater from an upstream Wastewater Treatment Plant discharge. Around 41% of the catchment is in land uses associated with the run-off of fine, muddy sediment, namely farmland (~20% of catchment), exotic plantation forestry (~14%) and urban development (~7%). The 2015 broad scale mapping results showed that the most significant modifications to the estuary have been from historical habitat loss through the displacement and reclamation of saltmarsh, seagrass, and the vegetation of the estuary's terrestrial margin (Stevens & Robertson 2015). The broad and fine scale surveys identified the accumulation of fine, muddy sediment as the most significant issue for the estuary. Muddy sediments were considered likely to contribute to losses of shellfish and cause other adverse impacts on sediment-dwelling fauna, with potential flow-on effects to fish and birdlife. Targeted investigations were recommended (but not implemented) to address the issues identified, including determining the main sources of fine sediments depositing in the estuary and exploring catchment management and estuary restoration options.

Downstream view to sand spit at entrance (top) and upstream view across intertidal flats to where monitoring is undertaken (bottom).

Main outlet channel location and indication of where the Waikanae River occasionally pushes directly across the beach. Fine scale site location indicated by white circle.

2. FINE SCALE METHODS

The survey methods are detailed in Appendix 1, with a summary below.

2.1 FINE SCALE AND SEDIMENT PLATE SITES

Fine scale monitoring is conducted at a single site (Site A), located on the only area of stable tidal flats available in the estuary (Fig. 2). The site was marked with pegs at the time of the first survey in 2010. Due to the limited intertidal area, the site is 15m x 60m, rather than the 30m x 60m site dimensions recommended in the NEMP. Sediment plates were installed at Site A at the time of the 2010 survey, and supplemented with plates installed in 2017 at two additional sites (B, C) further upstream on the same tidal flat (Fig. 2).

Appendix 2 provides GPS positions and other location information for the fine scale and sediment plate sites. Fig. 2 shows a schematic of the layout and sampling approach for fine scale monitoring.

2.2 SEDIMENT PLATES

At all three sites, sediment plates are spaced at intervals of 2m, with Plate 1 being closest to the river channel. The measurement method is provided in Appendix 1. At the time of annual measurement, a single composite sediment sample is collected from next to the sediment plates, and sent to Hill Labs for particle grain size analysis by wet sieving (mud, sand and gravel fractions; see Table A2 of Appendix 1).

Sediment plate data for all years were compiled to display: (i) cumulative change in sediment depth since baseline plate installation; (ii) annual sedimentation rate, which involved an adjustment to annualise the plate depth at the time of each survey to a 12-month period; and (iii) longer-term sedimentation rate (5-yr and overall average).

2.3 FINE SCALE SAMPLING AND INDICATORS

As depicted in Fig. 2, each fine scale site was divided into a 3 x 4 grid of 12 plots, with sampling conducted in 10 of these plots. A summary of the NEMP indicators, the rationale for their inclusion, and the field sampling

Fig. 2 Location of Waikanae Estuary monitoring sites. Sediment plates are installed at all sites, but NEMP fine scale sampling is undertaken at Site A only (represented by rectangle). The schematic depicts the sample collection for 10 sediment cores at Site A. Appendix 1 provides sampling design and method details, with the sediment plate layout shown in Appendix 2.

methods is provided in Table 1. Although the general sampling approach closely follows the NEMP, several alterations and additions to early NEMP methods have been introduced over the last 15 or more years, including for the Waikanae Estuary surveys. We have adopted these modifications as indicated in Table 1. The key sampling elements are summarised below.

Sediment quality: NEMP Indicators included sediment mud content, oxygenation status (measured as the apparent Redox Potential Discontinuity depth; aRPD), nutrients and organic content, and selected trace element contaminants. Sediment aRPD was measured in the field. For the other variables, three composite samples (each composited from 3-4 sub-samples) were collected, and sent to Hill Labs for analysis. Although not part of the NEMP, a single composite sample was collected for analysis of a range of semi-volatile organic compounds (SVOCs), which include toxicants such as biocides and plasticisers.

Where sediment quality results included values less than laboratory method detection limits, half of the detection limit value was used for data averaging, according to standard convention.

Table 1. Summary of fine scale indicators, rationale for their use, and sampling method. The main departures from the NEMP are described in footnotes.

Indicator	General rationale	Sampling method
Physical and chemical		
Sediment grain size	Indicates the relative proportion of fine-grained sediments that have accumulated.	Composited surface scrape to 20mm sediment depth.
Nutrients (nitrogen and phosphorus), organic matter & total sulfur	Reflects the enrichment status of the estuary and potential for algal blooms and other symptoms of enrichment.	Surface scrape to 20mm sediment depth. Organic matter measured as Total Organic Carbon (TOC) (note 1).
Trace elements (arsenic copper, chromium, cadmium, lead, mercury, nickel, zinc)	Common toxic contaminants generally associated with human activities. High concentrations may indicate a need to investigate other anthropogenic inputs, e.g., pesticides, hydrocarbons.	Surface scrape to 20mm sediment depth (note 2).
Substrate oxygenation (apparent Redox Potential Discontinuity depth; aRPD)	Measures the enrichment/trophic state of sediments according to the depth of the apparent Redox Potential Discontinuity layer (aRPD). This is the visual transition between brown oxygenated surface sediments and deeper less oxygenated black sediments. The aRPD can occur closer to the sediment surface as organic matter loading or sediment mud content increase.	Sediment core, split vertically, with average depth of aRPD recorded in the field where visible.
Biological		
Macrofauna	Abundance, composition and diversity of infauna living with the sediment are commonly-used indicators of estuarine health.	130mm diameter sediment core to 150mm depth (0.013m^2 sample area, 2L core volume), sieved to 0.5mm to retain macrofauna.
Epibiota (epifauna)	Abundance, composition and diversity of epifauna are commonly-used indicators of estuarine health.	Abundance based on SACFOR in Appendix 1, Table B3 (note 3).
Epibiota (macroalgae)	The composition and prevalence of macroalgae are indicators of nutrient enrichment.	Percent cover based on SACFOR in Appendix 1, Table B3 (note 3).
Epibiota (microalgae)	The prevalence of microalgae is an indicator of nutrient enrichment.	Visual assessment of conspicuous growths based on SACFOR in Appendix 1, Table B3 (notes 3, 4).

[1] Since the NEMP was published, Total Organic Carbon (TOC) has become available as a routine low-cost analysis which provides a more direct and reliable measure than the NEMP recommendation of converting Ash Free Dry Weight (AFDW) to TOC.

[2] Arsenic and mercury are not specified in the NEMP, but can be included in the trace element suite by the analytical laboratory.

[3] Assessment of epifauna, macroalgae and microalgae uses the SACFOR approach instead of the quadrat sampling outlined in the NEMP. Quadrat sampling is subject to considerable within-site variation for epibiota that have clumped or patchy distributions.

[4] NEMP recommends taxonomic composition assessment for microalgae but this is not typically undertaken due to clumped or patchy distributions and the lack of demonstrated utility of microalgae as a routine indicator.

Biota: To characterise the fine scale site, we used qualitative field methods ('SACFOR'; see Appendix 1) to estimate the abundance or percent cover of conspicuous surface-dwelling estuary snails, macroalgae and microalgae. In addition, quantitative sampling was undertaken of macrofauna, which are small organisms that live within or on the sediment matrix. Macrofauna were sampled using sediment cores (130mm diameter, 150mm deep, ~2L volume), which were sieved through a 0.5mm mesh to remove mud and sand. In 2022, the composition of the sieved core samples in terms of macrofauna species (or higher taxa) and their abundance, was determined by taxonomic experts at NIWA. Macrofauna analyses included the following:

- Derivation of richness and abundance, which are simple measures that describe the number of different species present in a sample (i.e., richness), and total organism abundances, respectively.
- Calculation of 'AMBI' scores. The AMBI is an international biotic health index (Borja et al. 2000) whose calculation is based on the proportion of macrofauna species falling into one of five eco-groups (EG) that reflect sensitivity to pollution, ranging from relatively sensitive (EG-I) to relatively hardy (EG-V). AMBI scores were compared against thresholds for estuary health that are described in Section 2.4.
- Multivariate analysis methods, including the BEST procedure in the software Primer v7.0.13 (Clarke et al. 2014; Clarke & Gorley 2015), were used to assess temporal changes in the composition of the entire macrofauna assemblage.
- Correlation based univariate and multivariate approaches were used to relate macrofaunal changes to changes in sediment quality, sedimentation, and Waikanae River flow conditions.

2.4 ASSESSMENT OF ESTUARY CONDITION

In addition to the authors' expert interpretation of the data, results are assessed against established or developing estuarine health metrics ('condition ratings'), drawing on approaches from New Zealand and overseas (FGDC 2012; Townsend & Lohrer 2015; Robertson et al. 2016; ANZG 2018). These metrics assign different indicators to one of four colour-coded 'health status' bands, as shown in Table 2.

Table 2. Condition ratings for assessing estuary health. See Glossary for definitions.

Indicator	Unit	Very good	Good	Fair	Poor
Sediment quality and macrofauna					
Mud content[1]	%	< 5	5 to < 10	10 to < 25	≥ 25
aRPD depth[2]	mm	≥ 50	20 to < 50	10 to < 20	< 10
TN[1]	mg/kg	< 250	250 to < 1000	1000 to < 2000	≥ 2000
TP			Requires development		
TOC[1]	%	< 0.5	0.5 to < 1	1 to < 2	≥ 2
TS			Requires development		
Macrofauna AMBI[1]	na	0 to 1.2	> 1.2 to 3.3	> 3.3 to 4.3	≥ 4.3
Sediment trace contaminants[3]					
As	mg/kg	< 10	10 to < 20	20 to < 70	≥ 70
Cd	mg/kg	< 0.75	0.75 to <1.5	1.5 to < 10	≥ 10
Cr	mg/kg	< 40	40 to <80	80 to < 370	≥ 370
Cu	mg/kg	< 32.5	32.5 to <65	65 to < 270	≥ 270
Hg	mg/kg	< 0.075	0.075 to <0.15	0.15 to < 1	≥ 1
Ni	mg/kg	< 10.5	10.5 to <21	21 to < 52	≥ 52
Pb	mg/kg	< 25	25 to <50	50 to < 220	≥ 220
Zn	mg/kg	< 100	100 to <200	200 to < 410	≥ 410
Sedimentation					
Sedimentation rate[4]	mm/yr		< 0.5	≥0.5 to < 1	≥1 to < 2 ≥ 2

1. Ratings from Robertson et al. (2016).
2. aRPD based on FGDC (2012).
3. Trace element thresholds scaled in relation to ANZG (2018) as follows: Very good <0.5 x DGV; Good 0.5 x DGV to <DGV; Fair DGV to <GV-high; Poor >GV-high. DGV = Default Guideline Value, GV-high = Guideline Value-high.
4. Sedimentation rate adapted from Townsend and Lohrer (2015).

3. KEY FINDINGS

3.1 SEDIMENTATION

Sediment plate raw data and associated sediment grain size information are provided in Appendix 3. At Site A there was a steady period of sediment accrual from 2010 to 2016. However, sedimentation has been highly variable since then, with periods of both erosion and accretion apparent from 2017 to 2023 (Fig. 4). This same variability has also been evident at Sites B and C since plates were installed in 2017. However, note that plates at Site B have not been found in the last two surveys due to burial of the site marker pegs under gravel, hence monitoring at that site has not been possible.

Across all sites, annualised mean sedimentation has ranged from accrual of 45mm/yr to erosion of 28mm/yr (Appendix 3). Average long-term sedimentation (since the baseline at each site) has ranged from 10.2mm/yr at Site A (13yr record) to 15.7mm/yr at Site C (~3yr record), which greatly exceeds the national estuary guideline of 2mm/yr (Townsend & Lohrer 2015). However, in the last 5 years the average net sedimentation at fine scale Site A has been near-zero (average erosion of 0.5mm over 5-yr), with significant erosion evident in the two most recent surveys.

Patterns of erosion and accretion are likely to be influenced by Waikanae River flows. Based on GWRC flow data in Appendix 3, across all years there was a significant negative correlation of mean daily flows in the year preceding each survey) with annual sedimentation (Pearson r^2=-0.59). As such, it is likely that the changes in sediment depth are attributable to the movement of bed sediments due to flow influences from the Waikanae River, with periods of accrual not necessarily attributable to the deposition of catchment-derived sediment.

Sediment plate measurement at Site C in January 2021, with gravel amongst a muddy-sand matrix following flooding in the previous month.

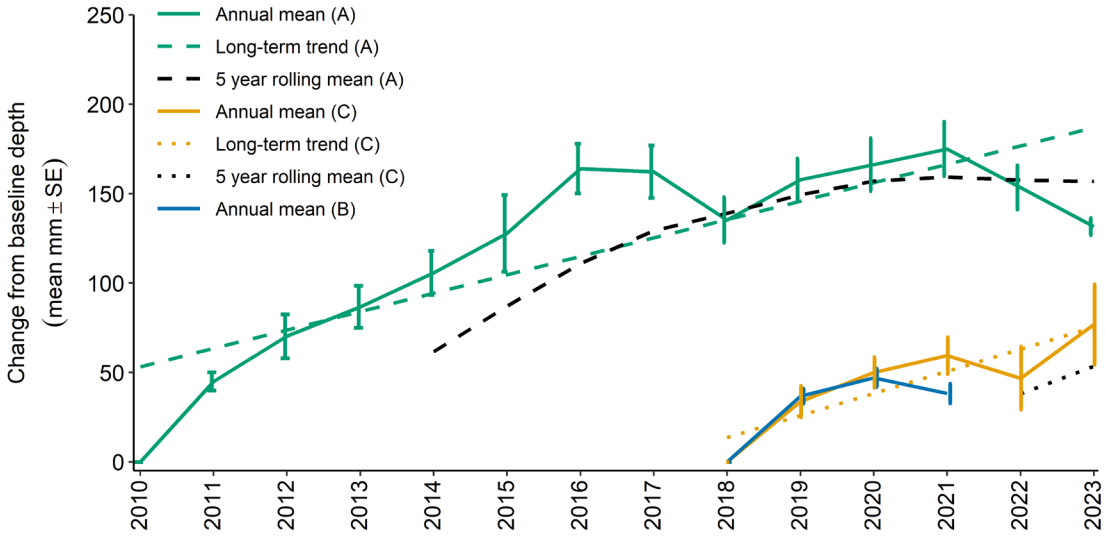


Fig. 3. Change in sediment depth over buried plates since the baseline was established at each site. Error bars on annual mean values are ± SE. Data are shown as a continuous annual time series across surveys conducted from Jan-2010 to Dec-2022.

3.2 SEDIMENT MUD, TOC AND NUTRIENTS

Composite sediment sample data for fine scale Site A are provided in Appendix 4, with a summary in Fig. 4 for the five survey years. Fig. 5 shows the annual time series of change in grain size composition based on samples taken from the sediment plate sites. Both graphs highlight a pronounced variability in sediment composition over time. Average sediment mud content has ranged from ~7-39%. Mud content was relatively high at all sites in 2018, 2020 and December 2022, but the highest average of 39% was recorded at Site A in 2012.

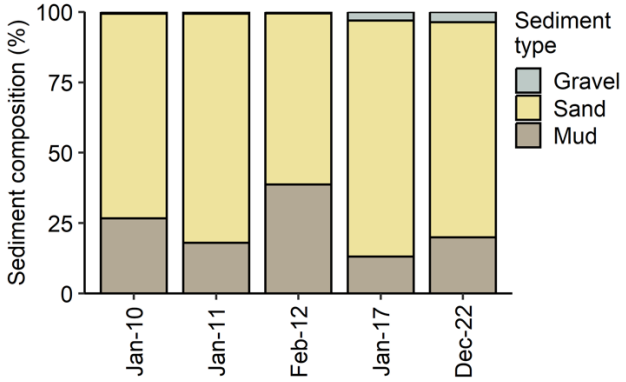


Fig. 4. Percentage composition of mud (<63µm), sand (<2mm to ≥63µm) and gravel (≥2mm) for fine scale survey years at Site A.

In the fine scale survey years at Site A, sediment mud content was strongly negatively correlated with daily mean river and peak flows (Pearson r^2=-0.71 & -0.95). Peak flows are defined here as the maximum of the daily mean flow. The association was also negative although weaker (Pearson r^2=-0.59 & -0.56) for the entire sediment plate time series data.

To provide a visual impression of sediment quality in fine scale survey years relative to the Table 2 condition ratings, Fig. 6 compares the mean percentage mud, total organic carbon (TOC) and total nitrogen (TN) from composite samples against the rating thresholds. For mud content, site ratings range from 'fair' to 'poor', with the 'poor' rating reflecting where mud content exceeds the threshold of 25%. Highest levels of sediment TOC and TN occurred in 2012 (rated 'fair') when sediment mud content was greatest, but otherwise have remained quite low (rated 'good' or 'very good'. Levels of the nutrient total phosphorus (TP, no rating criteria) have followed a similar trend (Appendix 4).

Site A in December 2022.

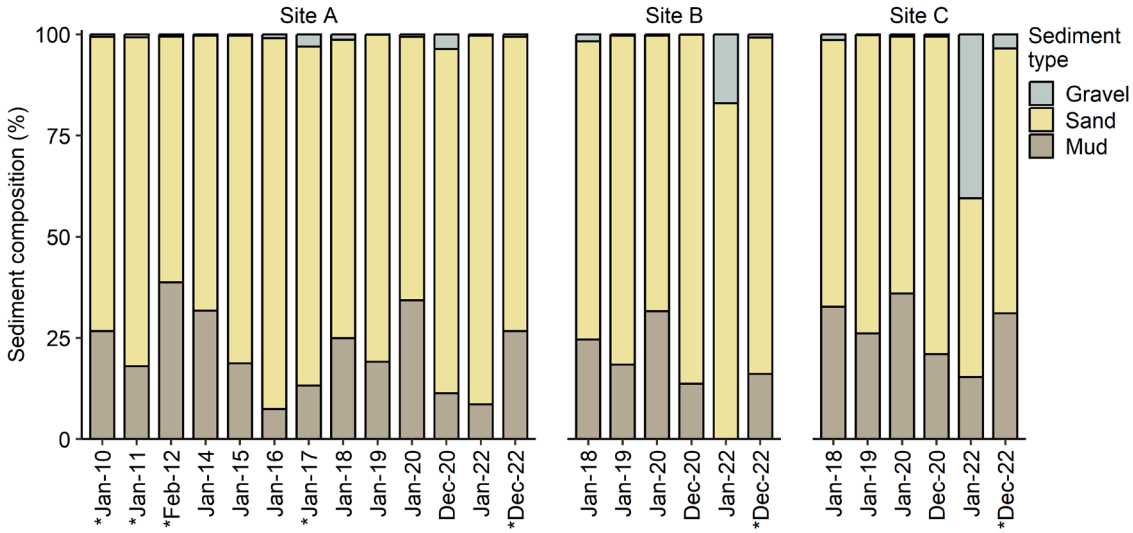


Fig. 5. Percentage composition of mud (<63µm), sand (<2mm to ≥63µm) and gravel (≥2mm) at sediment plate sites. Fine scale survey years are marked with an asterisk (*).

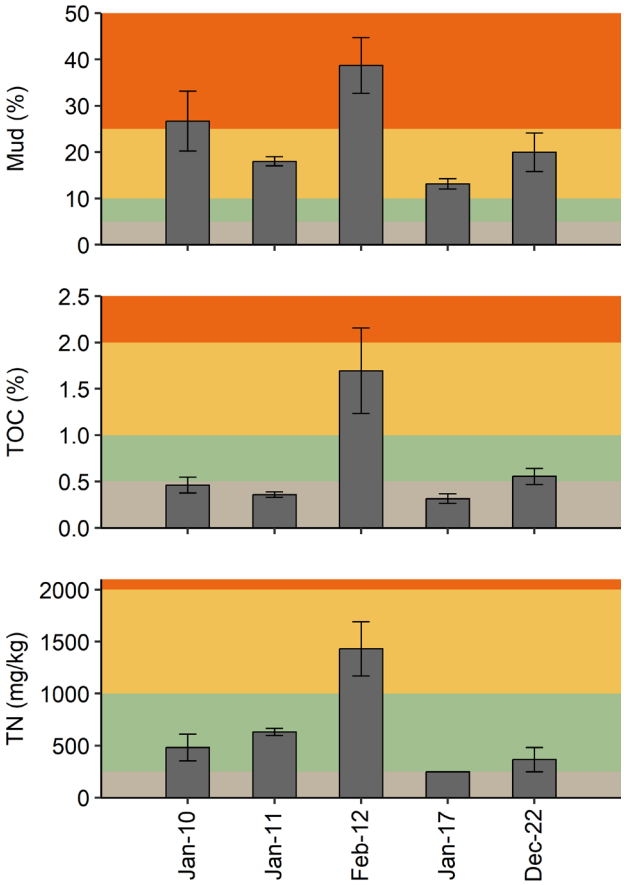


Fig. 6. Grey bars show sediment mud content, total organic carbon (TOC), and total nitrogen (TN) relative to condition ratings. All values are mean ± SE. TN in 2017 was less than method detection limit (MDL), hence half of the MDL value is shown.

Sediment cores collected in Dec-2022 from (top to bottom) sampling plots X1, Y4, and Z7 (see Fig. 2). The aRPD transition from brown surface sediment to deeper grey/black can be indistinct. Oxidised surface sediment can be mixed into deeper layers by bioturbation.

3.3 SEDIMENT OXYGENATION

Example sediment cores are shown in the adjacent photos, with mean aRPD values in fine scale survey years compared to condition ratings in Fig. 7. The aRPD data suggest high sediment oxygenation (rated 'good') in all surveys except 2012. The 2012 result most likely reflects the relatively high sediment mud content (mean 39%), as mud-size particles inhibit flushing and oxygen diffusion into the sediment matrix. However, aRPD can vary greatly due to a range of other factors, including the subjective nature of the estimation method (i.e., based on sediment core colour) and processes such as 'bioturbation'. This term refers to sediment mixing and disturbance by organisms like worms, shellfish and crabs, which can promote oxygenation of deeper oxygen-reduced sediment layers (see photos). As such, the depth of the aRPD is not always well-defined.

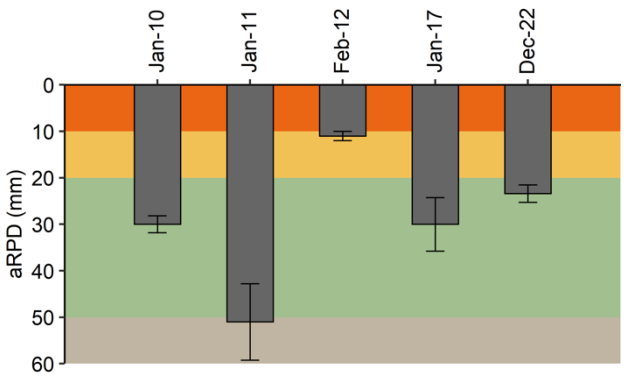


Fig. 7. Grey bars show aRPD depth (mean ± SE) in sediment relative to condition ratings. Rating colour key as per Fig. 6.

3.4 TRACE CONTAMINANTS

Trace metals and SVOCs are indicators of potential catchment contaminant inputs. They can be elevated around point sources in urban environments and may also originate from pastoral land uses due to practices such as fertiliser application (Gaw et al. 2006; Lebrun et al. 2019). In Fig. 9, trace metal contaminant levels are compared to condition ratings derived from ANZG (2018) sediment quality guidelines, with raw data and guideline values in Appendix 4. Mean metal concentrations have consistently been very low, and rated 'good' or 'very good'.

Concentrations of all SVOCs (e.g., biocides, hydrocarbons) were less than the method detection limits used for the broad screening approach undertaken in 2022. However, for most of the SVOC analytes (except total PAHs) the laboratory detection limit was greater than DGV thresholds (noting there are only a few analytes for which DGVs are available). As such, the screening approach would detect only gross contamination. However, in the 2010 baseline survey a single composite sample was analysed for a small subset of SVOC analytes (organochlorine pesticides) using very low method detection limits. Results of that survey revealed that concentrations of all detected analytes were less than DGV or GV-high values.

As DGVs are defined as the "*...concentrations below which there is a low risk of unacceptable effects...*", the trace contaminant sampling conducted over 2010-2022 provides assurance that contaminant inputs from the Waikanae catchment have not accumulated to any significant level on the tidal flats of the estuary at Site A.

Sediment core collection from Site A in 2022.

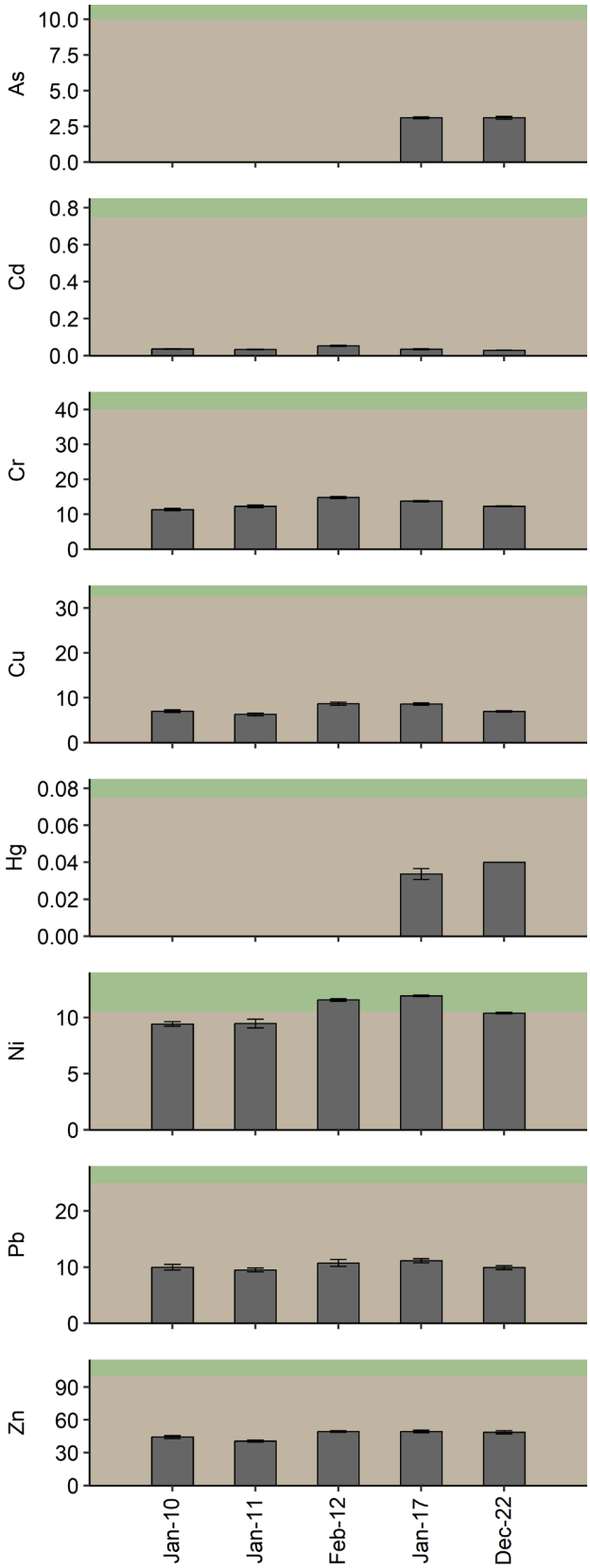


Fig. 8. Grey bars show trace metal concentrations (mg/kg, mean ± SE) relative to condition ratings. The boundary between grey and green represents half the ANZG (2018) Default Guideline Value.

3.5 MACROFAUNA

3.5.1 Conspicuous surface epibiota

Macroalgae have been consistently absent from the fine scale site since monitoring began in 2010, and elsewhere in the estuary there is only a very low prevalence of *Ulva* spp. Conspicuous growths of microalgae can occur on the upper estuary flats (Stevens & Robertson 2015), but were not noted in 2022. In terms of surface-dwelling epifauna, the only conspicuous species that has been recorded is the mud snail *Amphibola crenata*. Average or site-level densities in the surveys conducted 2010-2012 were equivalent to a SACFOR rating of 'common' (>100/m^2). However, mud snails were not recorded in 2017 and in 2022 were rated as 'rare' (<1/m^2) with only a few individuals seen across the site. Note that the very small snail *Potamopyrgus estuarinus* is also part of the epibiota, but is more reliably sampled in cores (see below).

Conspicuous epibiota were sparse in 2022, consisting only of mud snails *Amphibola crenata*.

3.5.2 Macrofauna cores

Raw macrofaunal data for 2022 are provided in Appendix 5. In total, 24 species (or higher taxa) have been recorded over the five surveys, representing nine main organism taxa. Species abundances summed across cores for each survey are provided in Table 3, with a description of the dominant species provided in Table 4.

The macrofauna community has consistently been numerically dominated by taxa from three main groups that represent hardy, freshwater-tolerant organisms (see photos in Table 4), as follows:

- Amphipods: shrimp like crustaceans represented by high abundances of *Paracorophium* spp. This is an opportunistic tube-dwelling species that can occur in high densities, often in muddy habitats subjected to disturbance and low salinity water.
- Gastropods: this group was represented by high densities of the small endemic snail *Potamopyrgus estuarinus*, which is often found in low salinity estuarine habitats.
- Polychaetes: this group was dominated by nereid worms, notably the freshwater-tolerant species *Nicon aestuariensis*, and the nationally ubiquitous deposit feeding spionid worm *Scolecolepides benhami*.

Mean species richness has been low in most surveys, ranging from ~7-10 taxa/core, with mean abundances ranging from 70-703 individuals/core (Fig. 9). High variability in abundances is attributable to fluctuating densities of the dominant species noted above.

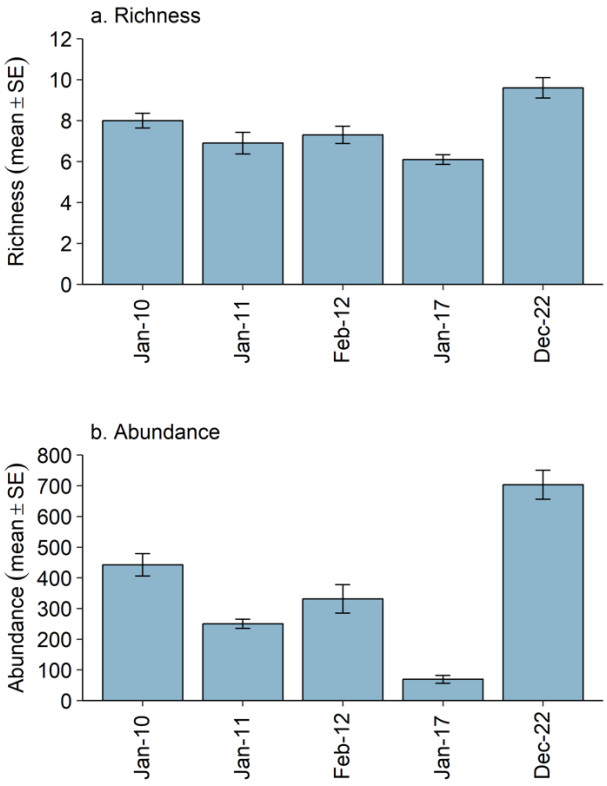


Fig. 9. Patterns in taxon richness and abundance per core (mean ± SE). Cores 0.013m^2, 150mm deep, volume ~2L.

Table 3. Abundance of sediment-dwelling macrofauna in each survey summed across cores. Eco-groups (EG) range from species that are sensitive to pollution/disturbance (EG-I) to those that are hardy (EG-V). Taxonomic aggregation was necessary in some instances to enable comparison of NIWA 2022 taxonomy to the earlier surveys where a different provider was used.

Main group	Taxa	Habitat[1]	EG	2010	2011	2012	2017	2022
Amphipoda	*Josephosella awa*	Infauna	II	17	15	20	31	36
Amphipoda	*Paracorophium* spp.	Infauna	IV	1778	818	2108	520	4394
Bivalvia	*Cyclomactra tristis*	Infauna	I	4	8	4	1	
Bivalvia	*Paphies australis*	Infauna	II		2			
Decapoda	*Austrohelice crassa*	Infauna	V		1	17	2	1
Decapoda	*Decapod megalopa*	Larva	II		1			
Decapoda	*Halicarcinus whitei*	Infauna	III		2	6		
Decapoda	*Hemigrapsus sexdentatus*	Infauna	II					5
Decapoda	*Hemiplax hirtipes*	Infauna	III		1			
Diptera	*Diptera* spp.	Larva	IV	3		2	19	2
Gastropoda	*Amphibola crenata*	Epibiota	III	20	4	2		3
Gastropoda	*Potamopyrgus estuarinus*	Epibiota	IV	2317	1407	977	2	2302
Isopoda	*Exosphaeroma* spp.	Infauna	V	3	7	9	1	17
Isopoda	*Isopoda Anthuroidea*	Infauna	I				1	
Isopoda	*Paranthura* sp. 1	Infauna	III		2			25
Nematoda	*Nematoda*	Infauna	III	1	2			27
Oligochaeta	*Oligochaeta* spp.	Infauna	V					3
Polychaeta	*Boccardiella magniovata*	Infauna	III	1	2			
Polychaeta	*Capitella* spp.	Infauna	V	1				19
Polychaeta	*Nereididae* (juvenile)	Infauna	na	91			48	
Polychaeta	*Nicon aestuariensis*	Infauna	III	52	143	116	20	112
Polychaeta	*Paradoneis lyra*	Infauna	III					2
Polychaeta	*Perinereis vallata*	Infauna	III	4			5	
Polychaeta	*Scolecolepides benhami*	Infauna	IV	134	87	52	47	85
		Total richness		14	16	11	12	15
		Total abundance		4440	2518	3324	709	7048

1. Epibiota with assigned eco-groups (e.g. *Potamopyrgus estuarinus*) are excluded from AMBI calculation.

Table 4. Description of the dominant macrofauna species. Specimen photos provided by NIWA. Pink colour due to a vital stain.

Main group	Description	Image
Paracorophium spp. (Amphipod)	Identified by NIWA in 2022 as *Paracorophium excavatum*, a corophioid amphipod that is an opportunistic tube-dweller, and is tolerant of muddy and low salinity conditions.	
Potamopyrgus estuarinus (Gastropod snail)	Small endemic snail, requiring brackish conditions. Eats detritus, microbes and algae. Tolerant of muddy sediments and organic enrichment.	
Nicon aestuariensis (Nereid polychaete worm)	A deposit feeding omnivorous worm that is tolerant of freshwater.	
Scolecolepides benhami (Spionid polychaete worm)	A relatively hardy, deposit feeding spionid worm that is common in estuaries and coastal areas throughout New Zealand.	

Across the five surveys, richness and abundance values were lowest in 2017 and highest in 2022. High abundances in 2022 were attributable to very high densities of *Paracorophium excavatum*.

Values for the infauna biotic index AMBI have remained around a score of just over 4 for all surveys (rated 'fair' or 'poor') (Fig. 11). These scores are strongly influenced by the fact that the most dominant infauna species, *Paracorophium excavatum*, represents the hardy eco-group EG-IV, and that the most abundant taxa are from EGs III and IV (Fig. 11, Table 3).

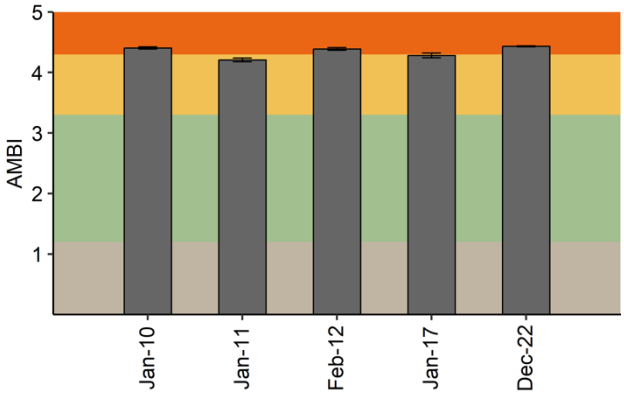


Fig. 10. Patterns in AMBI scores (mean ± SE) relative to condition ratings.

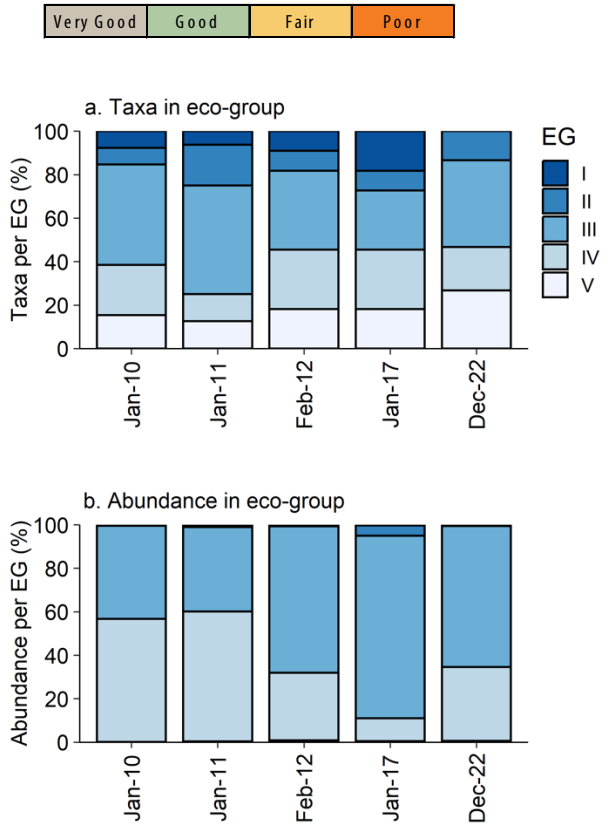


Fig. 11. Number of taxa and organisms within eco-groups ranging from sensitive (EG-I) to hardy (EG-V).

To further explore differences among surveys in terms of the macrofauna present and their relative abundances, the nMDS ordination in Fig. 12 places years of similar macrofauna composition close to each other in a 2-dimensional plot, with less similar years being further apart. This plot helps to visualise patterns in the sub-dominant species in Table 3.

Fig. 12a reveals strong compositional changes in 2017 and 2022 compared with the three surveys over 2010-2012. To a large extent the site differences in 2017 and 2022 are influenced by shifts in species dominance patterns. However, more subtle changes that influence the separation of 2017 include increased densities of Diptera larvae, simultaneous with a marked decline in abundances of estuarine snails (*Potamopyrgus estuarinus*) and the amphipod *Paracorophium*. In 2022, the macrofauna included capitellid worms (*Capitella* spp.) and nematode worms in moderate abundance. These species are commonly associated with disturbed conditions, and were only rarely present prior to 2022. Isopods, which are the estuarine equivalent of a terrestrial slater, were also relatively abundant in 2022.

3.5.3 Environmental drivers of macrofauna changes

Fig. 12 shows overlays of environmental variables on the macrofauna grouping. None of the NEMP sediment indicators were correlated closely with the patterns of change in macrofauna composition (Spearman rank correlation $\rho \leq 0.224$; Appendix 6). An analysis that included a broader suite of environmental variables suggested that sedimentation rate and Waikanae River flows were more strongly correlated with macrofauna changes. The maximum of mean daily flows (since the previous survey; see data in Appendix 4) was the single variable that best explained the left-to-right spread of survey years in Fig. 13 (Pearson r^2 =-0.78), whereas increasing sedimentation rate strongly explained the top-to-bottom pattern (Pearson r^2=-0.97). Biota-Environment matching (BEST) analyses showed that the macrofauna change was attributable to the combined influenced of both of these variables (Spearman rank ρ=0.70; Appendix 6). Despite correlations with flow and sedimentation, the actual causal drivers of macrofauna change are unclear. For example sedimentation rate is itself moderately negatively correlated with river flow as noted in Section 3.1. Physical disturbance associated with peak flood flows in the Waikanae River may have a particularly strong influence on sediment stability (e.g., cause erosion) and macrofauna composition. However, differences in mean river flow among years was also selected in the analyses described above as a variable that was moderately correlated with macrofauna changes.

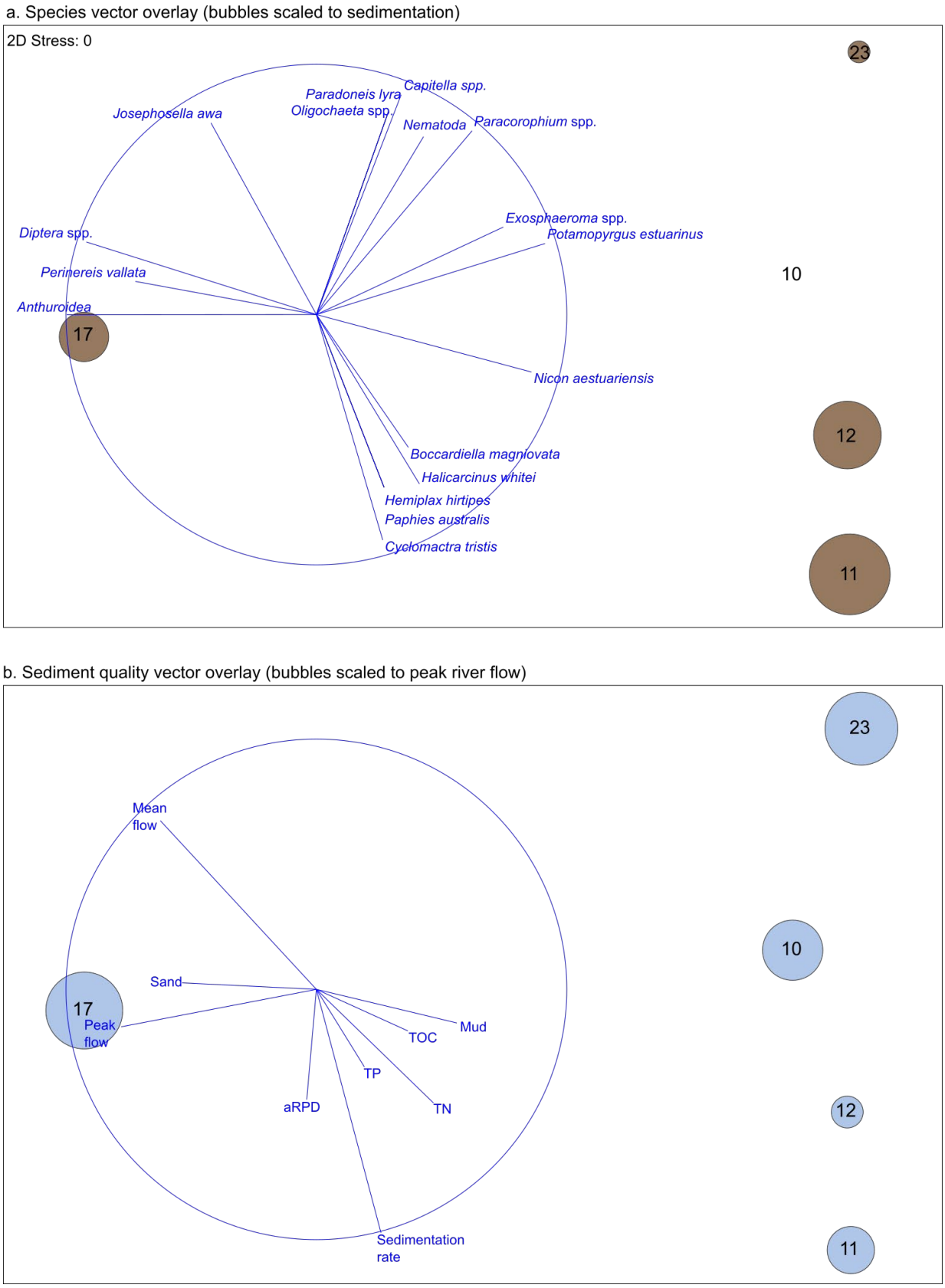


Fig. 12. Non-metric MDS ordination of macrofaunal data for the five survey years.

Years are placed such that those more similar in macrofaunal composition are nearer to each other than less similar years. A 'stress' value of 0 for the nMDS indicates that a 2-dimensional plot provides an excellent representation of year differences. Vector overlays indicate the direction and strength of association (length of line relative to circle) of grouping patterns in terms of: a) the most correlated macrofauna species, and b) key sediment quality variables. Bubble sizes are scaled to sedimentation (top) and peak flows in the Waikanae River (bottom), which were the variables most closely correlated with macrofaunal composition differences. Note that 2010 was the baseline sedimentation year when plates were installed.

Mean flow may be a proxy for unmeasured variables such as salinity, with higher average flows creating regular low salinity conditions in the estuary. For example, the highest mean daily and monthly flows in the Waikanae River occurred prior to the 2017 and 2022 surveys (Fig. 13), and corresponded to macrofaunal changes characterised by freshwater-tolerant *Diptera* larva (2017) and disturbance-tolerant *Paracorophium* spp. (2017).

Sediment mud content can be a strong driver of macrofaunal composition in New Zealand estuaries (Cummings et al. 2003; Robertson et al. 2015; Berthelsen et al. 2018; Clark et al. 2021). A mud content of 25% is often regarded as an important threshold above which marked biological changes can occur (Robertson et al. 2015; Ward & Roberts 2021), which is the basis for the fair/poor threshold in the Table 2 condition ratings. Although mud content negatively decreased as a response to peak river flow (Pearson r^2=-0.74), it was not selected as an important variable in the multivariate macrofauna analysis (BEST; ρ=-0.24).

To further explore mud effects, Fig. 14a-c show the relationship between the univariate responses discussed above (richness, abundance, AMBI) to sediment mud content. Added to this plot (Fig. 14d) are scores from a National Benthic Health Model (BHM) that were separately calculated for GWRC by Cawthron Institute for the Waikanae Estuary surveys conducted over 2010-2017 (Clark 2022). The BHM response to mud is described by a 'mudBHM' score, with national comparisons among sites and estuaries showing a relationship of increasing mudBHM scores with increasing sediment mud content (Clark et al. 2020).

As was the case for the community analysis, none of these univariate measures appreciably or directionally increase or decrease in response to an increase in sediment mud content. Fig. 14 highlights that the marked variability in richness and abundance are not clearly related to changes in mud content. In addition, AMBI and mudBHM scores change little among survey years despite a 30-40% range of % mud values. Clark et al. (2020, Supplementary Material C) recommended that BHM score changes of ≤ ± 1 should be considered within the range of natural variation.

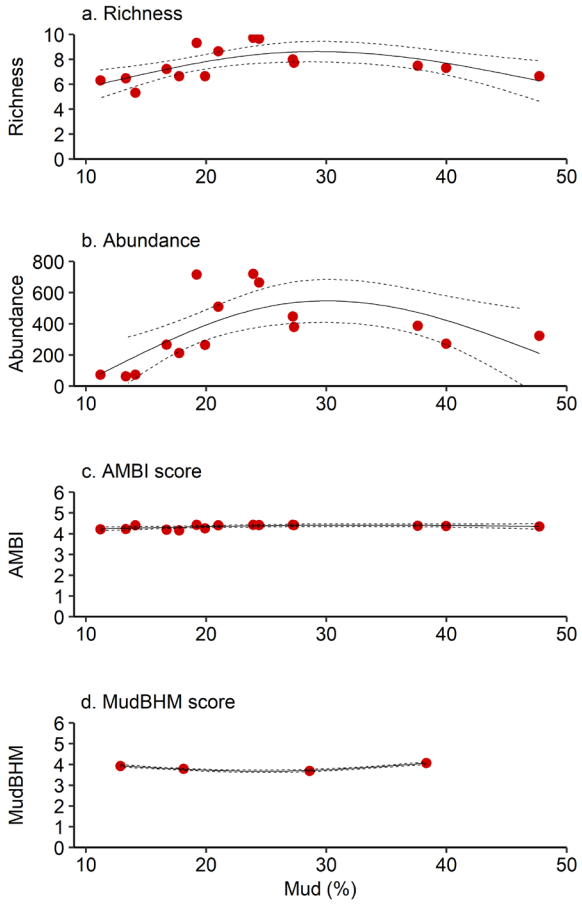


Fig. 14. Relationships between sediment mud content and macrofauna response variables. A smoothing line (solid black) is fitted with a 95% confidence interval (dashed). Values are at site-level for BHM (2020-2017) but for other responses are based on three composite samples per survey 2010-2023.

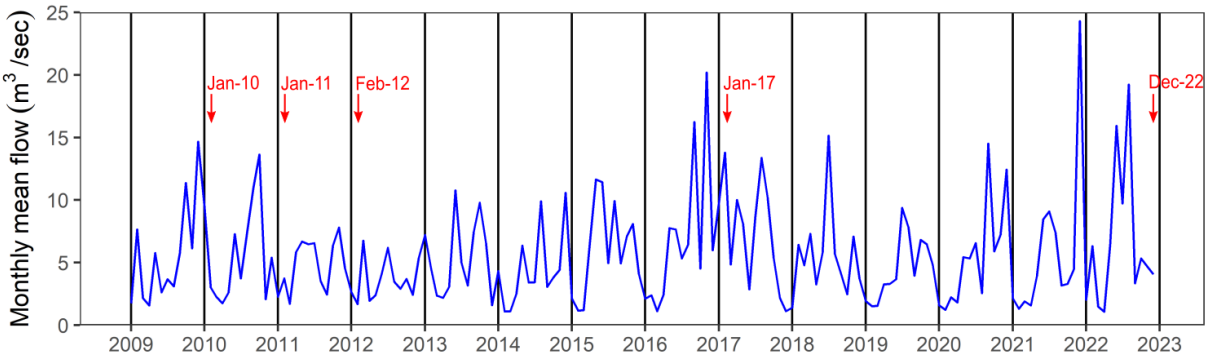


Fig. 13. Waikanae River monthly mean daily flows at Water Treatment Plant station ~4km upstream. Significant flood events and higher mean flows occurred in the year before each of the 2017 and 2022 fine scale surveys.

It is possible that the absence of a consistent or strong macrofauna-mud relationship reflects that the NEMP method requires only surface mud (20mm depth) to be collected, which may not represent the sediment across the 150mm depth of the macrofauna core. However, it is more likely that factors relating directly to the river flow regime (e.g., salinity, flood scour, turbidity) have an over-riding effect on the sediment-dwelling macrofauna, which masks the effect of mud and other NEMP sediment quality indicators.

Sediment core sampling at Site A in Waikanae Estuary.

4. SYNTHESIS AND RECOMMENDATIONS

4.1 SYNTHESIS OF KEY FINDINGS

This report has described the findings of five intertidal surveys (from 2010 to 2022) of Waikanae Estuary, largely following the fine scale survey methods described in New Zealand's NEMP. The results have been supplemented with annual sedimentation data from sediment plate surveys.

A summary of mean values of key physical and biological indicators in relation to ecological condition ratings is provided for the fine scale survey years in Table 5. The Table highlights the generally 'good' or 'very good' ratings for trace metals, and for trophic state variables (TOC, TN, aRPD) except for the 2012 survey. In 2012, an increase in sediment mud content relative to the two earlier surveys (rated 'poor') and ongoing high sedimentation (also rated 'poor) led Robertson and Stevens (2012) to question whether conditions at the fine scale site were on the decline.

However, based on annual sediment plate monitoring since then, and the subsequent fine scale surveys in 2017 and 2022, it is clear that the estuary can experience marked temporal variability in sedimentation, sediment mud content, and other indicator values. Rather than any directional trends that would suggest a degradation in estuary state since monitoring began in 2010, the analysis in this report suggests that strong variability in environmental conditions is an inherent characteristic of the estuary, and is determined mainly by flow conditions in Waikanae River. A comparison of Waikanae Estuary

Table 5. Summary of condition scores of ecological health based on mean values of key indicators for fine scale survey years (rating criteria not established for TP). See Glossary for definition of indicators.

Year	Sed rate	Mud	aRPD	TN	TP	TOC	As	Cd	Cr	Cu	Pb	Hg	Ni	Zn	AMBI
	mm/yr	%	mm			%									na
2010	na	26.7	30	483*	333	0.46	-	0.036	11.3	7.0	10.0	-	9.4	44.3	3.1
2011	45.5	18.0	51	633	377	0.36	-	0.033	12.3	6.3	9.5	-	9.5	40.7	3.1
2012	23.0	38.7	11	1433	523	1.70	-	0.053	14.8	8.7	10.7	-	11.6	49.3	3.1
2017	-1.7	13.2	30	< 500	377	0.32	3.1	0.034	13.7	8.6	11.1	0.03	11.9	49.3	3.1
2022	-24.5	20.0	23	367*	377	0.56	3.1	0.029	12.3	6.9	9.9	0.04	10.4	48.7	3.0

** Sample mean includes values below lab detection limits*

< All values below lab detection limit

Analyte units are mg/kg dry wt except as noted

Very Good	Good	Fair	Poor

results with other estuaries regionally shows that, despite the high variability in indicator values, Waikanae is not that dissimilar to other regional estuaries, although abundances of macrofauna are relatively high (Fig. 15).

River flow conditions clearly have a strong influence on the tidal flats of Site A and the sediment plates in the vicinity, with gravel substrates at time evident after flushing flows. River conditions that lead to scouring of substrates, sediment deposition, regular exposure of the tidal flats to low salinity water, and other effects (e.g., high suspended sediment load and turbidity) create a harsh environment for intertidal biota. The macrofauna is therefore characterised by a hardy suite of species that are resilient to disturbance; because of their capacity to either tolerate adverse conditions, or to recover quickly due to their 'opportunistic' life-history characteristics (e.g., *Paracorophium excavatum*). In the latter two survey years where prior river flows were relatively high (e.g., Fig. 13), a river flow-related effect was even more conspicuous, with an increased prevalence of freshwater-tolerant macrofauna. The absence or near-absence of epibiota such as mud snails in 2017 and 2023 compared to earlier years is also likely to be attributable to an increased river influence.

As a reflection of the macrofauna dominance by hardy species, values of the biological index AMBI were similar over all surveys (rated 'fair'), despite marked changes in the receiving environment. The absence of a significant macrofauna response to any of the NEMP indicators, including the absence of a significant mudBHM response to fluctuations in sediment mud content, raises two related considerations for ongoing monitoring. The first is the utility of the NEMP indicators in a river-dominated environment where marked variability in indicator values occurs naturally. The second related question is the vulnerability of the estuary to any changes in the catchment that increase mass loads of sediments, trophic state indicators, or chemical contaminants.

The catchment of ~15,345ha is already heavily urbanised or otherwise modified in the lower reaches. LCDB5 (2018) land cover data indicate that around 41% of the catchment is in land uses that can generate high loads of sediments, nutrients and/or trace contaminants. These include urban areas, farmland, and exotic plantation forestry (Table 6). For example, plantation forestry can be a particularly significant source of muddy sediment during forest harvest and for a few years after, when it can contribute a disproportionately high sediment load per catchment hectare (e.g. Gibbs & Woodward 2018). The findings from the current report suggest that the estuary fine scale site may itself be resilient to future load increases. However, depositional areas in the wider estuary may be more vulnerable to catchment-derived sediment or other contaminants (Stevens & Robertson 2015).

Table 6. LCDB5 (2018) land use classifications for Waikanae Estuary catchment.

Catchment Land Use in 2018	ha	%
Artificial Surfaces		
Built-up Area (settlement)	858.5	5.6
Surface Mines and Dumps	19.6	0.1
Transport Infrastructure	24.5	0.2
Urban Parkland/Open Space	100.2	0.7
Bare or Lightly Vegetated Surfaces		
Sand and Gravel	0.5	0.0
Landslide	0	0
Alpine Grass/Herbfield	0	0
Gravel and Rock	13.3	0.1
Water Bodies		
River, Lake or Pond	27.1	0.2
Cropland		
Short-rotation Cropland	0	0
Orchard Vineyard and Other Perennial Crops	13.3	0.1
Grassland, Sedge and Saltmarsh		
High Producing Exotic Grassland	2,915.1	19.0
Low Producing Grassland	203.5	1.3
Tall Tussock Grassland	17.4	0.1
Depleted Grassland	0	0
Herbaceous Freshwater Vegetation	25.3	0.2
Herbaceous Saline Vegetation	0	0
Flaxland		
Scrub and Shrubland	0	0
Fernland	10.2	0.1
Gorse and/or Broom	60.7	0.4
Manuka and/or Kanuka	252.7	1.6
Broadleaved Indigenous Hardwoods	1,552.5	10.1
Sub Alpine Shrubland	0	0
Mixed Exotic Shrubland	2.9	0.0
Matagouri or Grey Scrub	11.5	0.1
Forest		
Forest Harvested	209.6	1.4
Deciduous Hardwoods	56.3	0.4
Indigenous Forest	6,975.6	45.5
Exotic Forest	1,994.4	13.0
	15,344.7	100.0

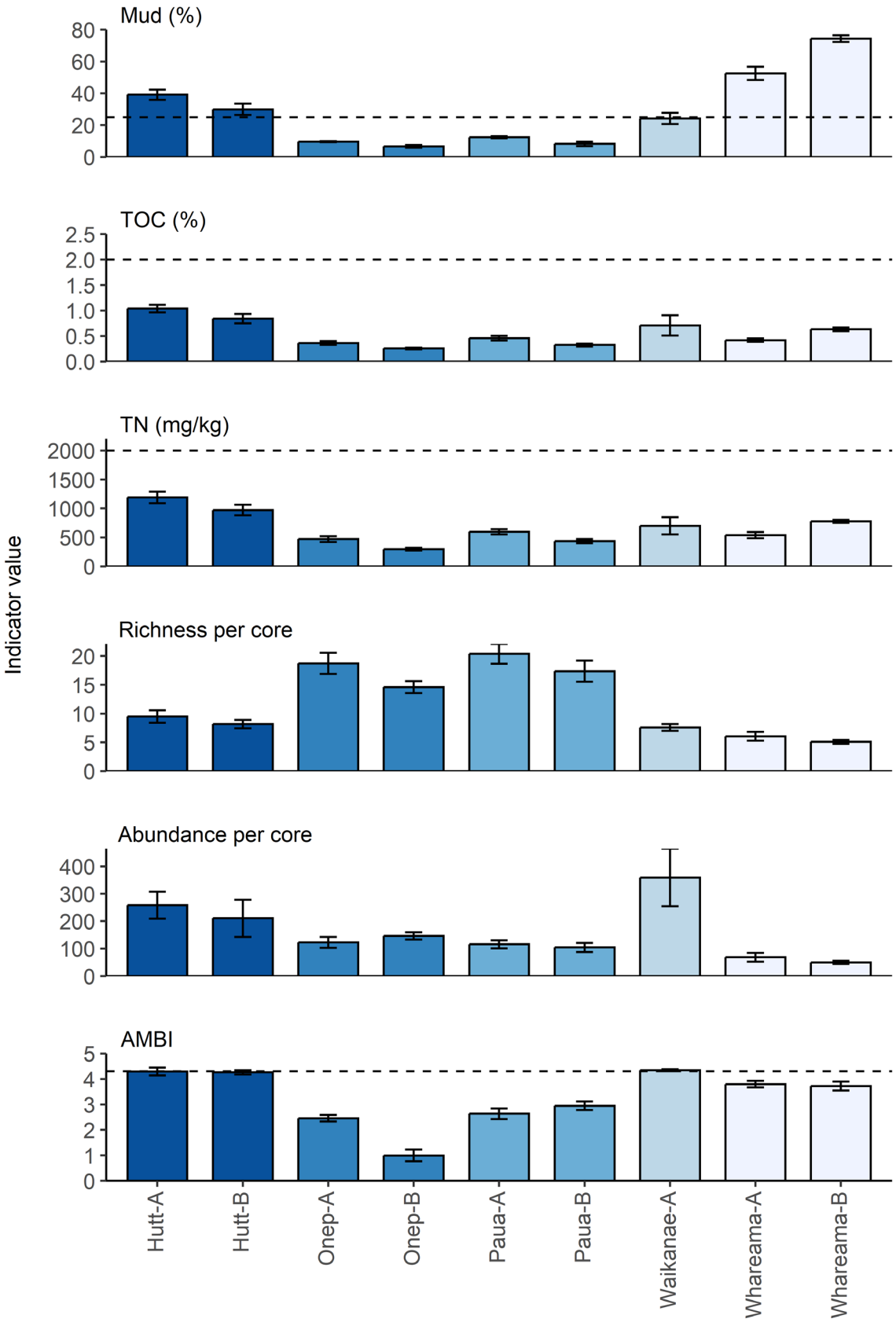


Fig. 15. Broad patterns in key sediment quality and macrofauna indicators, comparing Waikanae Estuary sites with other key estuaries in the Wellington region (mean ± SE for surveys pooled over time within each site). Note, all estuaries except the Porirua Harbour (Onep and Paua) are river-dominated systems. 'Poor' condition rating thresholds indicated (where available) by dashed line.

Furthermore, whereas the focus of the NEMP is on the intertidal, in river-dominated systems the potential for degradation of subtidal areas should also be considered. For example, in systems where the water column is prone to stratification, blooms of phytoplankton can occur and saline bottom waters can become depleted in dissolved oxygen. These types of effects have been described in river dominated estuaries along northern catchments of the Kāpiti and Wairarapa coast (e.g., Stevens et al. 2020; Forrest et al. 2022a). The 2015 broad scale assessment described a distinctive green tinge in the Waikanae Estuary channel, which can indicate a high phytoplankton abundance. A synoptic survey of Waikanae Estuary subtidal areas during summer low flows would be a means of quickly ascertaining estuary water column condition and vulnerability.

Notwithstanding the apparent limitations of the NEMP fine scale indicators, there is still value in continued periodic monitoring of the fine scale site (e.g., every 5-years), in order to track long term changes over coming decades. This is especially important given the potential for significant catchment load increases (e.g., sediments from plantation forest harvest). Ideally the fine scale and broad-scale NEMP surveys would be conducted simultaneously, as the information provided by the broad scale approach provides a context that improves understanding of fine scale changes. Given the value placed by the wider community on Waikanae Estuary, there would be a benefit in undertaking a more holistic assessment of estuary condition that also considered subtidal areas as noted above, and the vulnerability of the estuary to future threats.

In a broader SOE monitoring context, Waikanae Estuary is one of five estuaries in the Greater Wellington region where NEMP and sediment plate monitoring has been undertaken. The other locations are Porirua Harbour, Whareama Estuary, Hutt River Estuary and (historically) targeted investigations in the Waiwhetu Estuary (e.g., Forrest et al. 2020; Forrest et al. 2022b; Stevens et al. 2022). A range of smaller estuaries has also been assessed as part of regional or sub-region ecological vulnerability assessments (Stevens & Forrest 2019; Stevens & Roberts 2023). Given the effort to date, it would be timely to review the SOE estuary monitoring programme. With multi-year data now available for the key estuaries, and synoptic data for the smaller ones, the available information could be assessed in a holistic manner taking into account estuary vulnerability, condition and current and future pressures in a regional context. A future regional monitoring programme could then be tailored to address key management priorities, including for Waikanae Estuary.

4.2 RECOMMENDATIONS

- Continue fine scale monitoring surveys in Waikanae Estuary at intervals of ~5-years, as is typical for this method. To track key changes in the estuary in intervening years, annual sediment plate monitoring should be continued, along with measurement of sediment grain size and oxygenation (aRPD).
- Schedule 5-10 yearly broad-scale NEMP surveys simultaneously with fine scale surveys to enable a more holistic assessment of estuary condition.
- Consider undertaking an assessment to prioritise monitoring in regional estuaries according to estuary vulnerability, condition and current and future pressures.
- Depending on the outcome of the regional assessment, consider expanding the scope of monitoring in Waikanae Estuary to include a synoptic assessment of subtidal conditions.

5. REFERENCES CITED

ANZG 2018. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian State and Territory Governments, Canberra ACT, Australia. Available at https://www.waterquality.gov.au/anz-guidelines/guideline-values/default/sediment-quality-toxicants.

Berthelsen A, Atalah J, Clark D, Goodwin E, Patterson M, Sinner J 2018. Relationships between biotic indices, multiple stressors and natural variability in New Zealand estuaries. Ecological Indicators 85: 634-643.

Clark D 2022. Benthic Health Model scores for Wellington estuaries. Prepared for Greater Wellington Regional Council by Cawthron Institute. Cawthron Report 2287. 7p.

Clark DE, Hewitt JE, Pilditch CA, Ellis JI 2020. The development of a national approach to monitoring estuarine health based on multivariate analysis. Marine Pollution Bulletin 150: 110602.

Clark DE, Stephenson F, Hewitt JE, Ellis JI, Zaiko A, Berthelsen A, Bulmer RH, Pilditch CA 2021. Influence of land-derived stressors and environmental variability on compositional turnover and diversity of estuarine benthic communities. Marine Ecology Progress Series 666: 1-18.

Clarke KN, Gorley RN 2015. PRIMER v7: User Manual/Tutorial. PRIMER-E, Plymouth.

Clarke KR, Gorley RN, Somerfield PJ, Warwick RM 2014. Change in marine communities: an approach to statistical analysis and interpretation, 3rd edition. PRIMER-E, Plymouth, UK. 260p.

Cummings V, Thrush S, Hewitt J, Norkko A, Pickmere S 2003. Terrestrial deposits on intertidal sandflats: sediment characteristics as indicators of habitat suitability for recolonising macrofauna. Marine Ecology Progress Series 253: 39-54.

FGDC 2012. Coastal and Marine Ecological Classification Standard. Standard FGDC-STD-018-2012, Marine and Coastal Spatial Data Subcommittee, Federal Geographic Data Committee, June 2012. 343p. Available at: https://www.fgdc.gov/standards/projects/cmecs-folder/CMECS_Version_06-2012_FINAL.pdf.

Forrest BM, Stevens LM, Rabel H 2020. Fine Scale Intertidal Monitoring of Te Awarua-o-Porirua Harbour. Salt Ecology Report 044, prepared for Greater Wellington Regional Council, August 2020. 33p.

Forrest BM, Roberts KL, Stevens LM 2022a. Synoptic broad scale survey of Ākitio Estuary. Salt Ecology Report 104, prepared for Horizons Regional Council, November 2022. 33p (Draft).

Forrest BM, Stevens LM, Roberts KL 2022b. Fine scale intertidal monitoring of Whareama Estuary. Salt Ecology Report 098, prepared for Greater Wellington Regional Council, February 2023. 33p.

Gaw SK, Wilkins AL, Kim ND, Palmer GT, Robinson P 2006. Trace element and ΣDDT concentrations in horticultural soils from the Tasman, Waikato and Auckland regions of New Zealand. Science of The Total Environment 355(1): 31-47.

Gibbs M, Woodward B 2018. Waimea and Moutere sediment sources by land use. NIWA Client Report No: 2018026HN, Prepared for Tasman District Council, February 2018. 63p.

Lebrun JD, Ayrault S, Drouet A, Bordier L, Fechner LC, Uher E, Chaumont C, Tournebize J 2019. Ecodynamics and bioavailability of metal contaminants in a constructed wetland within an agricultural drained catchment. Ecological Engineering 136: 108-117.

Robertson B, Gillespie P, Asher R, Frisk S, Keeley N, Hopkins G, Thompson S, Tuckey B 2002. Estuarine Environmental Assessment and Monitoring: A National Protocol. Part A, Development; Part B, Appendices; and Part C, Application. Prepared for supporting Councils and the Ministry for the Environment, Sustainable Management Fund Contract No. 5096. Part A, 93p; Part B, 159p; Part C, 40p plus field sheets.

Robertson BM, Stevens LM 2010. Waikanae Estuary: Fine Scale Monitoring 2009/10. Prepared for Greater Wellington Regional Council. 20p.

Robertson BM, Stevens LM 2012. Waikanae Estuary: Fine Scale Monitoring 2011/12. Prepared for Greater Wellington Regional Council. 22p.

Robertson BM, Stevens LM 2017. Waikanae Estuary: Fine Scale Monitoring 2016/17. Prepared for Greater Wellington Regional Council. 27p.

Robertson BM, Stevens L, Robertson B, Zeldis J, Green M, Madarasz-Smith A, Plew D, Storey R, Hume T, Oliver M 2016. NZ Estuary Trophic Index Screening Tool 2: determining monitoring indicators and assessing estuary trophic state. Prepared for Envirolink Tools Project: Estuarine Trophic Index MBIE/NIWA Contract No: C01X1420. 68p.

Robertson BP, Gardner JPA, Savage C 2015. Macrobenthic–mud relations strengthen the foundation for benthic index development: A case study from shallow, temperate New Zealand estuaries. Ecological Indicators 58: 161-174.

Stevens LM, Robertson BM 2015. Waikanae Estuary: Broad Scale Habitat Monitoring 2014/15. Prepared for Greater Wellington Regional Council. 32p.

Stevens LM, Forrest BM 2019. Kāpiti Whaitua. Salt Ecology Report 028, prepared for Greater Wellington Regional Council, November 2019. 60p.

Stevens LM, Roberts KL 2023. Wairarapa Coastal Risk Assessment. Salt Ecology Report 108, prepared for Greater Wellington Regional Council (draft). .

Stevens LM, O'Neill-Stevens S, Forrest BM 2020. Synoptic Subtidal Monitoring of Waikawa Estuary. Salt Ecology Report 046, prepared for Horizons Regional Council, July 2020. 42p.

Stevens LM, Rabel H, Forrest BM 2022. Te Awarua-o-Porirua Harbour Sediment Plate Monitoring 2021/2022. Salt Ecology Report 090, prepared for Greater Wellington Regional Council, July 2022. 23p.

Townsend M, Lohrer D 2015. ANZECC Guidance for Estuary Sedimentation. NIWA client report number HAM2015-096, prepared for Ministry for the Environment. 45p.

Ward N, Roberts K 2021. Estuaries and Coast: Classification and Attributes for Southland. Environment Southland publication number 2020-03, Environment Southland: Invercargill. 107p. ISBN 978-0-909043-63-6.

APPENDIX 1. NEMP FINE SCALE AND SEDIMENT PLATE METHODS

Mapping the main habitats in an estuary using the NEMP broad scale approach provides a basis for identifying representative areas to sample sediment quality and associated biota using the NEMP fine scale approach.

This Appendix details the fine scale survey approach used by Salt Ecology for assessing intertidal estuary condition. This is a generic approach that follows the NEMP methodology except as described below. Any deviation from the NEMP that is site-specific for a given estuary is described in the main report. For example, the NEMP recommends fine scale sites be 30m x 60m in area and set-up in unvegetated mud/sand habitats in the mid-tidal range. However, site dimensions may be smaller sue to habitat availability, sites are sometimes set-up in vegetated seagrass or macroalgal habitats, and may be higher than mid-tide elevation where estuary flats are 'perched' high in the tidal zone.

A commonly-used addition to the NEMP fine scale approach is to install sediment 'plates' (buried concrete pavers) at fine scale sites, or the wider estuary environs, as a means of monitoring sedimentation. This approach involves monitoring temporal change in the depth of sediment that occurs over each plate, which indicates whether sediment is accumulating (sediment depth increases) or eroding (sediment depth decreases). As well as providing insight into estuary sedimentation processes, the sediment plate method provides supporting data that assists in the interpretation of changes occurring at fine scale sites.

The NEMP fine scale sampling approach is described in Section A below, with the additional sediment plate monitoring component described in Section B. General approaches to data recording, QA/QC and analysis are described in Section C.

A. FINE SCALE METHOD DESCRIPTION

A1. Sampling design and indicators

A summary of fine scale sediment and biota indicators, the rationale for their use, and field sampling methods, is provided in Table A1. As per the NEMP, each fine scale site is divided into a 3 x 4 grid of 12 plots and sampling is conducted in 10 of these plots. Fig. A1 shows the standard numbering sequence for replicate plots (1-10) and the indicator sampling approach that is used by Salt Ecology. Although the approach closely follows the NEMP, alterations and additions to early NEMP methods have been introduced over the last 10 or more years. Salt Ecology has adopted these modifications as described in footnotes to the Table. The general approach can be summarised as follows:

- From each plot, a discrete macrofauna sample core is collected and sediment oxygenation is assessed according to the depth of the apparent Redox Potential Discontinuity (aRPD).
- Sediment samples for laboratory analysis are also collected from each plot, but for instead of analysing discrete samples (as specified in the NEMP) three composite samples are analysed, consisting of subsamples pooled across each of plots (X1-4, Y4-6 & Z7-10).

The fine scale methods are detailed in subsequent sections.

A2. Sediment quality sampling and laboratory analyses

The three composite sediment samples collected from each site should aim to have a total wet weight of ~500g, with the sub-samples that make up each composite collected to 20mm depth using a trowel. Samples are stored on ice and sent to Hill Labs for analysis of: particle grain size in three categories (%mud <63µm, sand <2mm to ≥63µm, gravel ≥2mm); organic matter (total organic carbon, TOC); nutrients (total nitrogen, TN; total phosphorus, TP); and trace contaminants (arsenic, As; cadmium, Cd; chromium, Cr; copper, Cu; mercury, Hg; lead, Pb; nickel, Ni; zinc, Zn). Details of laboratory methods and detection limits are provided in Table A2.

Table A1. Summary of NEMP sediment quality and biota indicators, rationale for their use, and sampling method. Any significant departures from the NEMP are described in footnotes.

Indicator	General rationale	Sampling method
Physical and chemical		
Sediment grain size	Indicates the relative proportion of fine-grained sediments that have accumulated.	Composited surface scrape to 20mm sediment depth.
Nutrients (nitrogen and phosphorus), organic matter & total sulfur	Reflects the enrichment status of the estuary and potential for algal blooms and other symptoms of enrichment.	Surface scrape to 20mm sediment depth. Organic matter measured as Total Organic Carbon (TOC) (note 1).
Trace elements (arsenic copper, chromium, cadmium, lead, mercury, nickel, zinc)	Common toxic contaminants generally associated with human activities. High concentrations may indicate a need to investigate other anthropogenic inputs, e.g., pesticides, hydrocarbons.	Surface scrape to 20mm sediment depth (note 2).
Substrate oxygenation (apparent Redox Potential Discontinuity depth; aRPD)	Measures the enrichment/trophic state of sediments according to the depth of the apparent Redox Potential Discontinuity layer (aRPD). This is the visual transition between brown oxygenated surface sediments and deeper less oxygenated black sediments. The aRPD can occur closer to the sediment surface as organic matter loading or sediment mud content increase.	Sediment core, split vertically, with average depth of aRPD recorded in the field where visible.
Biological		
Macrofauna	Abundance, composition and diversity of infauna living with the sediment are commonly-used indicators of estuarine health.	130mm diameter sediment core to 150mm depth (0.013m^2 sample area, 2L core volume), sieved to 0.5mm to retain macrofauna.
Epibiota (epifauna)	Abundance, composition and diversity of epifauna are commonly-used indicators of estuarine health.	Abundance based on SACFOR in Appendix 1, Table B3 (note 3).
Epibiota (macroalgae)	The composition and prevalence of macroalgae are indicators of nutrient enrichment.	Percent cover based on SACFOR in Appendix 1, Table B3 (note 3).
Epibiota (microalgae)	The prevalence of microalgae is an indicator of nutrient enrichment.	Visual assessment of conspicuous growths based on SACFOR in Appendix 1, Table B3 (notes 3, 4).

[1] Since the NEMP was published, Total Organic Carbon (TOC) has become available as a routine low-cost analysis which provides a more direct and reliable measure than the NEMP recommendation of converting Ash Free Dry Weight (AFDW) to TOC.

[2] Arsenic and mercury are not specified in the NEMP, but can be included in the trace element suite by the analytical laboratory.

[3] Assessment of epifauna, macroalgae and microalgae uses the SACFOR approach instead of the quadrat sampling outlined in the NEMP. Quadrat sampling is subject to considerable within-site variation for epibiota that have clumped or patchy distributions.

[4] NEMP recommends taxonomic composition assessment for microalgae but this is not typically undertaken due to clumped or patchy distributions and the lack of demonstrated utility of microalgae as a routine indicator.

Fig. A1. Fine scale survey design at Waikanae Estuary monitoring sites. Sediment plates are installed at all sites (see Section B), but NEMP fine scale sampling is undertaken at Site A only (represented by rectangle).

A3. Field sediment oxygenation assessment

The aRPD depth (see Table A1) is used to assess the trophic status (i.e., extent of excessive organic or nutrient enrichment) of soft sediment. The aRPD provides an easily measured, time-integrated, and relatively stable indicator of sediment enrichment and oxygenation conditions (Rosenberg et al. 2001; Gerwing et al. 2013). Sediments are considered to have poor oxygenation if the aRPD is consistently <10mm deep and shows clear signs of organic enrichment, indicated by a distinct colour change to grey or black in the sediments. Extremely enriched sediments typically have an intense black sediment profile with aRPD at the surface, emit a rotten egg smell of hydrogen sulfide, and may have surface growths of sulfur oxidising bacteria.

Example of aRPD profile.

Salt Ecology assesses mean aRPD depth (to the nearest mm) after extracting a large sediment core (130mm diameter, 150mm deep, ~2L volume) from each of the 10 plots, placing it on a tray, and splitting it vertically. Representative split cores are also photographed.

A4. Biological sampling: sediment-dwelling macrofauna

To sample sediment-dwelling macrofauna in each of the 10 plots, a large sediment core (130mm diameter, 150mm depth, ~2L volume) is collected, and placed in a 0.5mm mesh sieve bag, which is gently washed in seawater to remove fine sediment. The retained animals are preserved in a mixture of ~75% isopropyl alcohol and 25% seawater for later sorting and taxonomic identification by a skilled taxonomic laboratory (e.g., NIWA). The types of animals present in each sample, as well as the range of different species (i.e., richness) and their abundance, are well-established indicators of ecological health in estuarine and marine soft sediments.

Table A2. Analytical methods and detection limits for sediment samples used by Hill Labs.

Summary of Methods

The following table(s) gives a brief description of the methods used to conduct the analyses for this job. The detection limits given below are those attainable in a relatively simple matrix. Detection limits may be higher for individual samples should insufficient sample be available, or if the matrix requires that dilutions be performed during analysis. A detection limit range indicates the lowest and highest detection limits in the associated suite of analytes. A full listing of compounds and detection limits are available from the laboratory upon request. Unless otherwise indicated, analyses were performed at Hill Laboratories, 28 Duke Street, Frankton, Hamilton 3204.

Sample Type: Sediment			
Test	**Method Description**	**Default Detection Limit**	**Sample No**
Individual Tests			
Environmental Solids Sample Drying*	Air dried at 35°C Used for sample preparation. May contain a residual moisture content of 2-5%.	-	1-3
Environmental Solids Sample Preparation	Air dried at 35°C and sieved, <2mm fraction. Used for sample preparation May contain a residual moisture content of 2-5%.	-	1-3
Dry Matter (Env)	Dried at 103°C for 4-22hr (removes 3-5% more water than air dry) , gravimetry. (Free water removed before analysis, non-soil objects such as sticks, leaves, grass and stones also removed). US EPA 3550.	0.10 g/100g as rcvd	4
Dry Matter for Grainsize samples (sieved as received)*	Drying for 16 hours at 103°C, gravimetry (Free water removed before analysis).	0.10 g/100g as rcvd	1-3
Total Recoverable digestion	Nitric / hydrochloric acid digestion. US EPA 200.2.	-	1-3
Total Recoverable Phosphorus	Dried sample, sieved as specified (if required). Nitric/Hydrochloric acid digestion, ICP-MS, screen level. US EPA 200.2.	40 mg/kg dry wt	1-3
Total Nitrogen*	Catalytic Combustion (900°C, O2), separation, Thermal Conductivity Detector [Elementar Analyser].	0.05 g/100g dry wt	1-3
Total Organic Carbon*	Acid pretreatment to remove carbonates present followed by Catalytic Combustion (900°C, O2), separation, Thermal Conductivity Detector [Elementar Analyser].	0.05 g/100g dry wt	1-3
Heavy metals, trace As,Cd,Cr,Cu,Ni,Pb,Zn,Hg	Dried sample, <2mm fraction. Nitric/Hydrochloric acid digestion, ICP-MS, trace level.	0.010 - 0.8 mg/kg dry wt	1-3
Semivolatile Organic Compounds Trace in Soil by GC-MS	Sonication extraction, GC-MS analysis. Tested on as received sample. In-house based on US EPA 8270.	0.10 - 6 mg/kg dry wt	4
3 Grain Sizes Profile as received			
Fraction >/= 2 mm*	Wet sieving with dispersant, as received, 2.00 mm sieve, gravimetry.	0.1 g/100g dry wt	1-3
Fraction < 2 mm, >/= 63 µm*	Wet sieving using dispersant, as received, 2.00 mm and 63 µm sieves, gravimetry (calculation by difference).	0.1 g/100g dry wt	1-3
Fraction < 63 µm*	Wet sieving with dispersant, as received, 63 µm sieve, gravimetry (calculation by difference).	0.1 g/100g dry wt	1-3

A5. Biological sampling: surface-dwelling epibiota

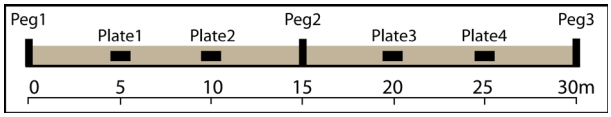
In addition to macrofaunal core sampling, epibiota (macroalgae and conspicuous surface-dwelling animals nominally >5mm body size) visible on the sediment surface at each site are semi-quantitatively categorised using 'SACFOR' abundance (animals) or percentage cover (macroalgae) ratings shown in the Table inset. These ratings represent a scoring scheme simplified from established monitoring methods (MNCR 1990; Blyth-Skyrme et al. 2008).

SACFOR category	Code	Density per m^2	Percent cover
Super abundant	S	> 1000	> 50
Abundant	A	100 - 999	20 - 50
Common	C	10 - 99	10 - 19
Frequent	F	2 - 9	5 - 9
Occasional	O	0.1 - 1	1 - 4
Rare	R	< 0.1	< 1

The SACFOR method is ideally suited to characterise intertidal epibiota with patchy or clumped distributions. It was conducted as an alternative to the quantitative quadrat sampling specified in the NEMP, which is known to poorly characterise scarce or clumped species. Note that our epibiota assessment does not include infaunal species that may be visible on the sediment surface, but whose abundance cannot be reliably determined from surface observation (e.g., cockles). Nor does it include very small organisms such as the estuarine snail *Potamopyrgus* spp.

B. SEDIMENT PLATES

The sediment plate method involves burying and levelling four (typically) concrete 'plates' (pavers, 19cm x 23cm) along a transect at each site, with pavers spaced between 2m and 5m apart. Plates are typically buried ~100m deep, and transect start, middle and end points marked with wooden pegs to enable relocation. At the time of baseline plate installation and on each subsequent sampling occasion, plate depth is measured by placing a 2m straight edge over each plate position to average out small-scale irregularities in surface topography, with the depth to each plate from the base on the straight edge measured by vertically inserting a probe into the sediment. Depth is measured to the nearest millimetre, with triplicate measures taken for each plate and averaged. Routine sediment plate measurements are made annually, and sometimes in response to event-related sediment inputs (e.g., after flooding). At the time of sampling, a single composite sediment sample is collected to 20mm depth for particle grain size analysis (see Section A2) and aRPD is usually also measured (see Section A3).



Example sediment plate array from Peg 1 (see Fig. A1) , in this case representing sediment plates installed along a 30m upstream boundary of a fine scale site

Measuring a sediment plate using a probe and straight edge.

C. DATA RECORDING, QA/QC AND ANALYSIS

All sediment and macrofaunal samples sent to analytical laboratories are tracked using standard Chain of Custody forms, and results are transferred electronically from the laboratory to avoid transcription errors. Field measurements (aRPD, sediment plate depth) and site metadata are recorded electronically in templates custom-built using Fulcrum app software (www.fulcrumapp.com). Pre-specified data entry constraints in the app (e.g., with minimum or maximum values for each data type) minimise the risk of erroneous data recording.

Excel sheets that contain the above data are imported into the software R 4.2.3 (R Core Team 2023) and assigned sample identification codes. All summaries of univariate responses (e.g., sediment analyte concentrations, macrofauna abundances, sediment plate depths) are produced in R, including tabulated or graphical representations of the data. Specific further data handling and analysis approaches for the different data types are describe below.

1. Sediment plates

Sediment plate data are compiled to display: (i) cumulative change in sediment depth since baseline plate installation; (ii) annual sedimentation rate, which usually involves an adjustment to annualise the plate depth to 365 days; and (iii) longer-term sedimentation rate (e.g., 5-yr or overall average).

2. Sediment quality

Where sediment quality data include values less than analytical detection limits, half of the detection limit value is used for data averaging, according to standard convention.

3. Macrofauna

Sediment-dwelling macrofauna data preparation and analysis involves multiple steps, as follows:

- The data are screened to remove species that are not regarded as a true part of the macrofaunal assemblage; these are planktonic life-stages and non-marine organisms (e.g., freshwater drift).

- To facilitate comparisons with among surveys and other estuaries, cross-checks are made to ensure consistent naming of species and higher taxa. For this purpose, the adopted name is that accepted by the World Register of Marine Species (WoRMS, www.marinespecies.org).
- Macrofauna response variables are derived which include richness and abundance by species and higher taxonomic groupings, and calculation of scores for the biotic health index AMBI (Borja et al. 2000; Borja et al. 2019).
- AMBI scores reflect the proportion of taxa falling into one of five eco-groups (EG) that reflect sensitivity to pollution, ranging from relatively sensitive (EG-I) to relatively resilient (EG-V), and their calculation involves the following steps:
    - To meet the criteria for AMBI calculation, macrofauna data are reduced to a subset that includes only adult 'infauna' (those organisms living within the sediment matrix), which involves removing surface dwelling epibiota and any juvenile organisms.
    - AMBI scores are calculated based on standard international eco-group classifications where possible (http://ambi.azti.es). To reduce the number of taxa with unassigned eco-groups, international data are supplemented as appropriate with more recent eco-group classifications for New Zealand (Keeley et al. 2012; Robertson et al. 2016; Robertson 2018).
    - AMBI scores are not calculated for macrofauna cores that do not meet operational limits defined by Borja et al. (2012), in terms of the percentage of unassigned taxa (>20%), or low sample richness (<3 taxa) or abundances (<6 individuals).
- Multivariate analyses of macrofaunal community data are undertaken using the software package Primer v7.0.13 (Clarke et al. 2014), with the following being the main elements:
    - Prior to multivariate analysis, macrofaunal abundance data are transformed (e.g., square root) to down-weight the influence of the dominant species or higher taxa.
    - Patterns in site similarity as a function of macrofaunal composition and abundance are assessed using an 'unconstrained' non-metric multidimensional scaling (nMDS) ordination plot, based on pairwise Bray-Curtis similarity index scores among samples.
    - Overlay vectors and bubble plots on the nMDS are used to visualise relationships between multivariate biological patterns and sediment quality data.
    - Other Primer procedures (e.g., BEST) are used to evaluate the suite of sediment quality variables that best explain the macrofauna ordination pattern.

C. METHODS REFERENCES

Blyth-Skyrme V, Lindenbaum C, Verling E, Van Landeghem K, Robinson K, Mackie A, Darbyshire T 2008. Broad-scale biotope mapping of potential reefs in the Irish Sea (north-west of Anglesey). JNCC Report No. 423, Joint Nature Conservation Committee. 210p.

Borja A, Franco J, Pérez V 2000. A Marine Biotic Index to Establish the Ecological Quality of Soft-Bottom Benthos Within European Estuarine and Coastal Environments. Marine Pollution Bulletin 40(12): 1100-1114.

Borja A, Chust G, Muxika I 2019. Forever young: The successful story of a marine biotic index. Advances in marine biology 82: 93-127.

Borja Á, Mader J, Muxika I 2012. Instructions for the use of the AMBI index software (Version 5.0). Revista de Investigación Marina, AZTI-Tecnalia 19(3): 71-82.

Clarke KR, Gorley RN, Somerfield PJ, Warwick RM 2014. Change in marine communities: an approach to statistical analysis and interpretation, 3rd edition. PRIMER-E, Plymouth, UK. 260p.

Gerwing TG, Gerwing AMA, Drolet D, Hamilton DJ, Barbeau MA 2013. Comparison of two methods of measuring the depth of the redox potential discontinuity in intertidal mudflat sediments. Marine Ecology Progress Series 487: 7-13.

Keeley NB, Forrest BM, Crawford C, Macleod CK 2012. Exploiting salmon farm benthic enrichment gradients to evaluate the regional performance of biotic indices and environmental indicators. Ecological Indicators 23: 453-466.

MNCR 1990. Use of the Marine Nature Conservation Review SACFOR abundance scales. Joint Nature Conservation Committee. www. jncc.gov.uk/page-2684 (accessed 15 April 2019).

R Core Team 2023. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Robertson BP 2018. Optimising indicators of ecological condition in shallow tidal estuaries as function of nitrogen loading. A thesis submitted for the degree of Doctor of Philosophy at the University of Otago, Dunedin, New Zealand. 125p.

Robertson BP, Savage C, Gardner JPA, Robertson BM, Stevens LM 2016. Optimising a widely-used coastal health index through quantitative ecological group classifications and associated thresholds. Ecological Indicators 69: 595-605.

Rosenberg R, Nilsson HC, Diaz RJ 2001. Response of Benthic Fauna and Changing Sediment Redox Profiles over a Hypoxic Gradient. Estuarine, Coastal and Shelf Science 53(3): 343-350.

APPENDIX 2. SITE LOCATION INFORMATION

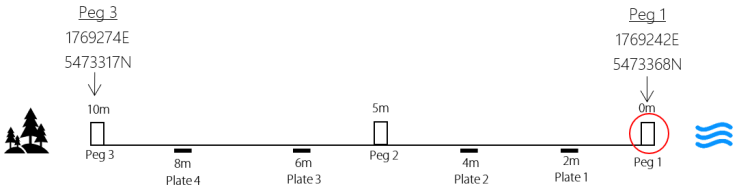
Site locations and schematics of sediment plate positions and marker pegs are shown.

Fine scale Site A

Site Corner	NZTM EAST	NZTM NORTH
1	1769242	5473368
2	1769257	5473375
3	1769252	5473370
4	1769248	5473370

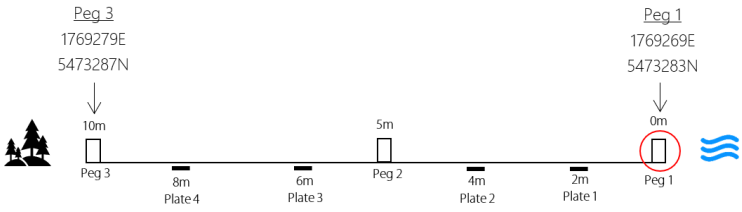
Sediment plate Site A

Plate	NZTM East	NZTM North	Distance from channel peg (m)
1	1769247	5473369	2
2	1769249	5473370	4
3	1769252	5473371	6
4	1769253	5473371	8



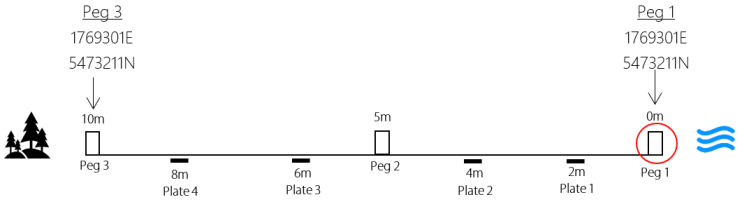
Sediment plate Site B

Plate	NZTM East	NZTM North	Distance from channel peg (m)
1	1769272	5473284	2
2	1769273	5473284	4
3	1769275	5473285	6
4	1769277	5473285	8



Sediment plate Site C

Plate	NZTM East	NZTM North	Distance from channel peg (m
1	1769307	5473212	2
2	1769308	5473213	4
3	1769309	5473215	6
4	1769310	5473215	8



APPENDIX 3. SEDIMENTATION AND GRAIN SIZE DATA FOR SEDIMENT PLATES

A. Raw sediment plate depths and grain size. Dash (-) = no data. Plates at Site B were buried and could not be relocated in 2022.

Date	Site	Plate 1	Plate 2	Plate 3	Plate 4	Mud%	Sand%	Gravel%	aRPD (mm)
2010-01-20	A	180	213	231	235	26.7	72.7	0.6	30
2011-01-16	A	238	261	270	270	18	81.3	0.7	51
2012-02-20	A	276	295	295	274	38.7	60.7	0.5	11
2013-01-14	A	296	305	310	295	-	-	-	11
2014-01-20	A	315	324	333	310	31.7	68	0.3	15
2015-01-18	A	361	355	335	319	18.7	81	0.3	15
2016-01-28	A	378	380	392	365	7.4	91.7	0.9	25
2017-01-29	A	383	374	382	369	13.2	83.8	3	29
2018-01-22	A	346	350	365	339	24.9	73.8	1.3	30
2019-01-17	A	367	373	386	364	19.1	80.9	0.1	26
2020-01-17	A	384	383	389	368	34.3	65.1	0.6	30
2020-12-09	A	392	392	402	373	11.3	85.1	3.6	40
2022-01-21	A	355	354	404	360	8.6	91.1	0.3	30
2022-12-12	A	325	341	362	358	26.7	72.7	0.6	30
2018-01-22	B	50	59	48	55	24.6	73.7	1.7	30
2019-01-17	B	84	96	96	83	18.4	81.3	0.3	22
2020-01-17	B	101	106	105	88	31.6	68.1	0.3	11
2020-12-09	B	89	103	95	78	13.7	86.2	0.1	20
2022-01-21	B	-	-	-	-	<0.1	83	17	30
2022-12-12	B	-	-	-	-	16.1	83.1	0.8	-
2018-01-22	C	55	63	67	50	32.7	65.8	1.4	20
2019-01-17	C	98	111	102	59	26.1	73.6	0.2	25
2020-01-17	C	115	126	118	76	36	63.5	0.5	8
2020-12-09	C	131	137	123	82	21	78.5	0.5	23
2022-01-21	C	111	150	109	52	15.3	44.2	40.5	25
2022-12-12	C	147	186	143	66	31.1	65.4	3.5	30

B. Annualised sedimentation rate. Dash (-) = no data, asterisk (*) = baseline year of plate installation. Plates at Site B could not be relocated in Jan and Dec 2022.

Date	Site	Sedimentation rate (mm/yr)		
		Site A	Site B	Site C
2010-01-20	A	*	-	-
2011-01-16	A	45	-	-
2012-02-20	A	23	-	-
2013-01-14	A	18	-	-
2014-01-20	A	19	-	-
2015-01-18	A	22	-	-
2016-01-28	A	35	-	-
2017-01-29	A	-2	-	-
2018-01-22	A	-28	*	*
2019-01-17	A	23	37	34
2020-01-17	A	9	10	16
2020-12-09	A	10	-10	11
2022-01-21	A	-19	-	-11
2022-12-12	A	-25	-	34

APPENDIX 4. SEDIMENT QUALITY AND ENVIRONMENTAL DATA

A. NEMP indicators at fine scale Site A.

Values based on a composite sample within each of X1-3, Y4-6, Z7-10, except for aRPD in 2022 for which the mean and range is shown for 10 replicates.

Year	Zone	Gravel	Sand	Mud	TOC	TN	TP	aRPD	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn
		%	%	%	%	mg/kg	mg/kg	mm	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
2010	X	0.5	84.2	15.3	0.35	510	310	35	-	0.036	11	6.7	-	9.3	9.4	43
	Y	0.7	72.1	27.2	0.41	<500	330	31.7 (30 to 35)	-	0.034	11	6.8	-	9.2	9.6	43
	Z	0.6	61.7	37.6	0.63	690	360	25.0 (20 to 30)	-	0.037	12	7.6	-	9.8	11	47
2011	X	0.5	82	17.5	0.38	600	380	70.0 (50 to 80)	-	0.031	12.4	6.5	-	9.7	9.7	41
	Y	0.7	79.4	19.9	0.4	700	390	53.3 (30 to 100	-	0.035	12.8	6.7	-	10	10	42
	Z	0.9	82.5	16.7	0.3	600	360	35.0 (30 to 40)	-	0.033	11.6	5.7	-	8.7	8.8	39
2012	X	0.4	58.4	41.2	1.69	1400	530	13.3 (10 to 20)	-	0.052	15	8.9	-	11.8	11.5	50
	Y	0.9	51.4	47.7	2.5	1900	540	10	-	0.058	14.2	9.1	-	11.5	11.2	50
	Z	0.3	72.4	27.3	0.9	1000	500	10	-	0.049	15.2	8	-	11.4	9.5	48
2017	X	2.8	82.1	15	0.42	<500	410	20	3.2	0.037	14	8.9	0.04	12	11.6	51
	Y	0.4	88.4	11.2	0.25	<500	360	30	3	0.028	13.4	8.1	0.03	11.8	10.4	47
	Z	5.9	80.9	13.3	0.28	<500	360	40	3.1	0.038	13.8	8.8	0.03	12	11.4	50
2022	X	0.4	87.9	11.7	0.42	<500	350	24.0 (20 to 28)	3	0.029	12.1	6.6	0.04	10.3	9.3	46
	Y	1	75.1	23.9	0.53	<500	380	18.0 (16 to 20)	3	0.03	12.3	7	0.04	10.4	10	49
	Z	9.5	66.1	24.4	0.72	600	400	27.0 (20 to 35)	3.3	0.028	12.5	7.2	0.04	10.5	10.5	51
								DGV	20	1.5	80	65	0.15	21	50	200
								GV-high	70	10	370	270	1	52	220	410

B. Semi-volatile organic compounds (SVOCs) in single composite samples from fine scale Site A.

(a) 2010 targeted sampling of organochlorine pesticides. Half of the detection limit value is used by convention, with numeric values normalised to the mean site Total Organic Carbon of 0.46%. Isomers of certain compounds (e.g., chlordane, DDT) are summed as appropriate. Where ANZG (2018) sediment quality guidelines are available, values are compared to the Default Guideline Value (DGV) and the Guideline Value-high (GV-high).

Analyte	Concentration (mg/kg dry wt)	Half MDL normalised to 0.46% TOC	Totals	DGV	GV-high
DDT Screening in Soil					
2,4'-DDD	< 0.0050	0.0054			
4,4'-DDD	< 0.0050	0.0054			
2,4'-DDE	< 0.0050	0.0054			
4,4'-DDE	< 0.0050	0.0054			
2,4'-DDT	< 0.0050	0.0054			
4,4'-DDT	< 0.0050	0.0054			
Total DDT Isomers	< 0.030	0.0326			
Organochlorine Pesticides Trace in Soil					
Aldrin	< 0.00099	0.0011			
alpha-BHC	< 0.00099	0.0011			
beta-BHC	< 0.00099	0.0011			
delta-BHC	< 0.00099	0.0011			
gamma-BHC (Lindane)	< 0.00099	0.0011	0.0011	0.0009	0.0014
cis-chlordane	< 0.00099	0.0011	0.0022	0.0045	0.009
trans-chlordane	< 0.00099	0.0011			
2,4'-DDD	< 0.00099	0.0011			
4,4'-DDD	< 0.00099	0.0011			
2,4'-DDE	< 0.00099	0.0011	0.0022	0.0012	0.007
4,4'-DDE	< 0.00099	0.0011			
2,4'-DDT	< 0.00099	0.0011	0.0022	0.0012	0.005
4,4'-DDT	< 0.00099	0.0011			
Dieldrin	< 0.00099	0.0011	0.0011	0.0028	0.007
Endosulfan I	< 0.00099	0.0011			
Endosulfan II	< 0.00099	0.0011			
Endosulfan sulphate	< 0.00099	0.0011			
Endrin	< 0.00099	0.0011	0.0032	0.0027	0.06
Endrin aldehyde	< 0.00099	0.0011			
Endrin Ketone	< 0.00099	0.0011			
Heptachlor	< 0.00099	0.0011			
Heptachlor epoxide	< 0.00099	0.0011			
Hexachlorobenzene	< 0.00099	0.0011			
Methoxychlor	< 0.00099	0.0011			

(b) 2022 screening for a broad range of SVOCs. Total PAHS were less than ANZG (2018) Default Guideline Values. Other analyte detection limits exceeded ANZG thresholds and, as such, are screening levels for gross contamination only.

Analyte	Concentration (mg/kg dry wt)
Haloethers Trace in SVOC Soil Samples by GC-MS	
Bis(2-chloroethoxy) methane	< 0.10
Bis(2-chloroethyl)ether	< 0.10
Bis(2-chloroisopropyl)ether	< 0.10
4-Bromophenyl phenyl ether	< 0.10
4-Chlorophenyl phenyl ether	< 0.10
Nitrogen containing compounds Trace in SVOC Soil Samples, GC-MS	
N-Nitrosodiphenylamine + Diphenylamine	< 0.16
2,4-Dinitrotoluene	< 0.2
2,6-Dinitrotoluene	< 0.2
Nitrobenzene	< 0.10
N-Nitrosodi-n-propylamine	< 0.16
Organochlorine Pesticides Trace in SVOC Soil Samples by GC-MS	
Aldrin	< 0.10
alpha-BHC	< 0.10
beta-BHC	< 0.10
delta-BHC	< 0.10
gamma-BHC (Lindane)	< 0.10
4,4'-DDD	< 0.10
4,4'-DDE	< 0.10
4,4'-DDT	< 0.2
Dieldrin	< 0.10
Endosulfan I	< 0.2
Endosulfan II	< 0.5
Endosulfan sulphate	< 0.2
Endrin	< 0.16
Endrin ketone	< 0.2
Heptachlor	< 0.10
Heptachlor epoxide	< 0.10
Hexachlorobenzene	< 0.10
Polycyclic Aromatic Hydrocarbons Trace in SVOC Soil Samples	
Acenaphthene	< 0.10
Acenaphthylene	< 0.10
Anthracene	< 0.10
Benzo[a]anthracene	< 0.10
Benzo[a]pyrene (BAP)	< 0.10
Benzo[b]fluoranthene + Benzo[j]fluoranthene	< 0.10
Benzo[g,h,i]perylene	< 0.10
Benzo[k]fluoranthene	< 0.10
1&2-Chloronaphthalene	< 0.10
Chrysene	< 0.10
Dibenzo[a,h]anthracene	< 0.10
Fluoranthene	< 0.10
Fluorene	< 0.10
Indeno(1,2,3-c,d)pyrene	< 0.10
2-Methylnaphthalene	< 0.10
Naphthalene	< 0.10
Phenanthrene	< 0.10
Pyrene	< 0.10
Benzo[a]pyrene Potency Equivalency Factor (PEF) NES	< 0.25
Benzo[a]pyrene Toxic Equivalence (TEF)	< 0.25

Analyte	Concentration (mg/kg dry wt)
Phenols Trace in SVOC Soil Samples by GC-MS	
4-Chloro-3-methylphenol	< 0.5
2-Chlorophenol	< 0.2
2,4-Dichlorophenol	< 0.2
2,4-Dimethylphenol	< 0.4
3 & 4-Methylphenol (m- + p-cresol)	< 0.4
2-Methylphenol (o-cresol)	< 0.2
2-Nitrophenol	< 0.4
Pentachlorophenol (PCP)	< 6
Phenol	< 0.2
2,4,5-Trichlorophenol	< 0.2
2,4,6-Trichlorophenol	< 0.2
Plasticisers Trace in SVOC Soil Samples by GC-MS	
Bis(2-ethylhexyl)phthalate	< 0.5
Butylbenzylphthalate	< 0.2
Di(2-ethylhexyl)adipate	< 0.2
Diethylphthalate	< 0.2
Dimethylphthalate	< 0.2
Di-n-butylphthalate	< 0.2
Di-n-octylphthalate	< 0.2
Other Halogenated compounds Trace in SVOC Soil Samples by GC-MS	
1,2-Dichlorobenzene	< 0.16
1,3-Dichlorobenzene	< 0.16
1,4-Dichlorobenzene	< 0.16
Hexachlorobutadiene	< 0.16
Hexachloroethane	< 0.16
1,2,4-Trichlorobenzene	< 0.10
Other SVOC Trace in SVOC Soil Samples by GC-MS	
Benzyl alcohol	< 1.0
Carbazole	< 0.10
Dibenzofuran	< 0.10
Isophorone	< 0.10

C. Waikanae River flows at Water Treatment Plant gauging station (https://graphs.gw.govt.nz/).

Summary statistics calculated from daily mean flow data. Flows in cumec (m^3/sec).

Date	3 months before survey		6 months before survey		Since previous survey*	
	Mean	Max	Mean	Max	Mean	Max
2010-01-20	10.583	43.634	8.601	48.901	6.113	48.901
2011-01-16	3.828	28.258	7.109	96.434	5.300	96.434
2012-02-20	3.715	19.567	4.319	31.837	4.587	36.055
2013-01-14	4.141	28.686	4.187	50.010	3.940	50.010
2014-01-20	4.885	53.488	5.581	53.488	5.326	64.794
2015-01-18	6.374	72.674	5.726	72.674	4.375	72.674
2016-01-28	5.989	87.084	6.208	87.084	6.013	94.522
2017-01-29	11.861	98.228	10.466	130.742	7.424	130.742
2018-01-22	1.764	5.727	5.858	48.951	6.859	87.861
2019-01-17	4.336	26.171	4.607	26.171	5.685	123.732
2020-01-17	5.481	26.128	5.990	30.985	4.547	35.779
2020-12-09	10.114	61.008	7.593	61.008	5.395	61.008
2022-01-21	10.442	141.272	7.883	141.272	6.052	141.272
2022-12-12	4.304	36.591	8.882	69.137	7.077	69.137

* 12-month preceding flow period used for 2010 survey.

APPENDIX 5. MACROFAUNA CORE DATA ALL YEARS

Cores 130mm diameter to 150mm deep, 0.013m^2 sample area, ~2L core volume. EG = AMBI Eco-group.

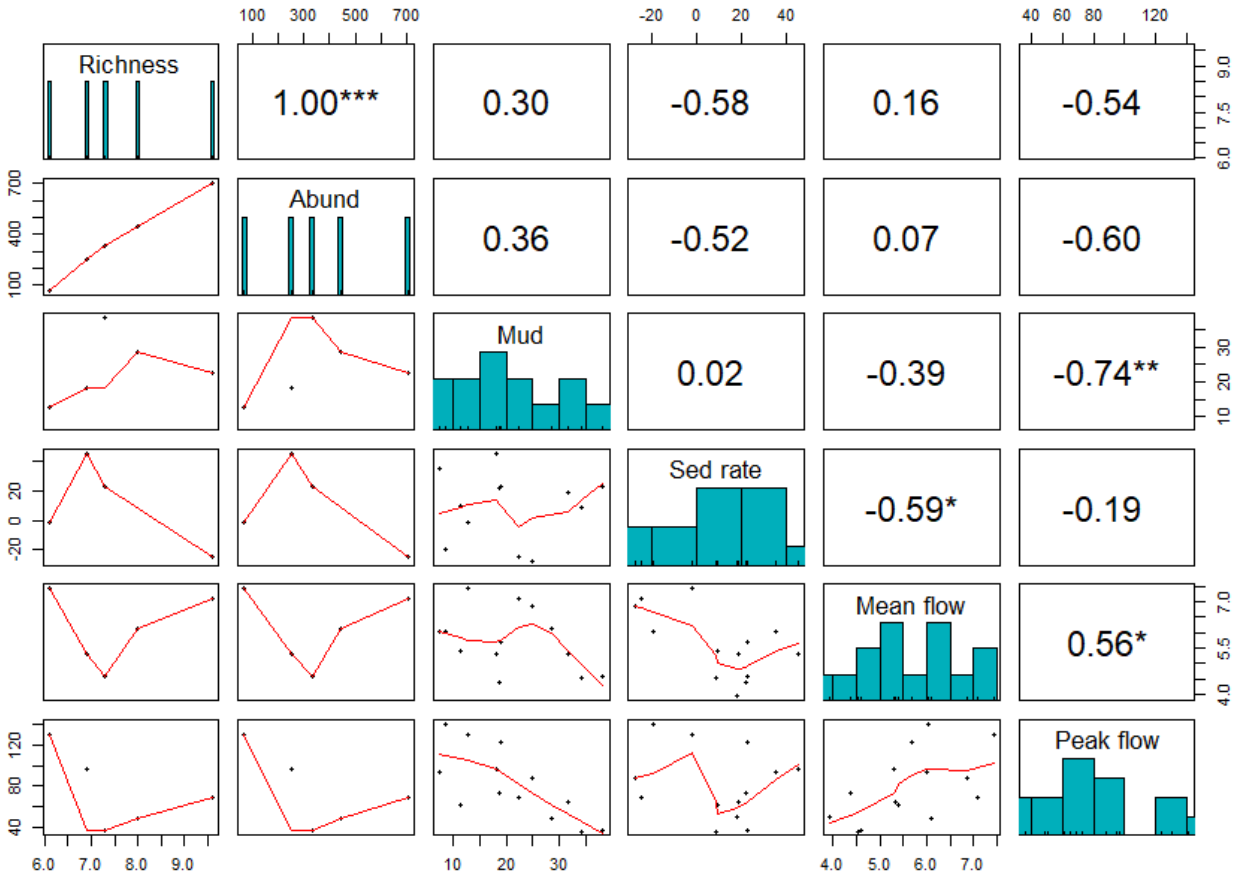
Main group	Amphipoda		Bivalvia		Decapoda					Diptera	Gastropoda		Isopoda			Nematoda	Oligochaeta	Polychaeta						
EG	II	III	I	II	V	II	III	II	III	IV	III	IV	V	I	III	III	V	III	V	na	III	III	III	IV
Year and core #	*Josephosella awa*	*Paracorophium* spp.	*Cyclomactra tristis*	*Paphies australis*	*Austrohelice crassa*	*Decapod megalopa*	*Halicarcinus whitei*	*Hemigrapsus sexdentatus*	*Hemiplax hirtipes*	*Diptera* spp.	*Amphibola crenata*	*Potamopyrgus estuarinus*	*Exosphaeroma* spp.	*Isopoda Anthuroidea*	*Paranthura* sp. 1	*Nematoda*	*Oligochaeta spp.*	*Boccardiella magniovata*	*Capitella* spp.	*Nereididae* (juvenile)	*Nicon aestuariensis*	*Paradoneis lyra*	*Perinereis vallata*	*Scolecolepides benhami*
2010-1	1	294								2	1	203							1	8				17
2010-2	1	143	2									241				1		1		7	2		2	12
2010-3	3	94	1								1	465								10	1			18
2010-4	2	69									1	367								14	1			12
2010-5	4	185								1	3	219								16	3		1	19
2010-6	1	223									2	175	1							12	5			7
2010-7		231										93	1							9	13			10
2010-8	2	49									2	102	1							1	7		1	11
2010-9	1	226	1								5	237								8	9			15
2010-10	2	264									5	215								6	11			13
2011-1		94									1	111						1			12			14
2011-2		40	4						1			115	2								14			14
2011-3	3	66	1									116	1								15			15
2011-4		44									1	175						1			8			5
2011-5	1	64					1					183	1			1					14			14
2011-6	2	118										131	2								20			8
2011-7	5	137	1								2	169									18			6
2011-8	4	108	1			1	1					148	1		2	1					15			6
2011-9		106	1		1							122									16			2
2011-10		41		2								137									11			3
2012-1	5	224	1				2					70									9			5
2012-2		230	1		5		1			1		85	3								11			3
2012-3	1	102	1									45									9			5
2012-4	4	426					1					133	2								13			3
2012-5	1	122										91	1								5			7
2012-6	5	117			1							12	1								21			4
2012-7	2	162			4		1				1	80									7			1
2012-8	1	212			2							46									13			13
2012-9		251	1		3							271	1								13			8
2012-10	1	262			2		1			1	1	144	1								15			3
2017-1	2	45								2										8				12
2017-2	1	57								1										7	1			3
2017-3	1	72																		4	2			2
2017-4	12	115			1					2										5	4			
2017-5		33								4				1						3			2	3
2017-6	1	18								2										3	2		3	8
2017-7	6	114			1					3										5	6			4
2017-8	5	38	1																	4	2			6
2017-9	3	23								4			1							2	2			5
2017-10		5								1		2								7	1			4
2022-1		194										348	1		3	1	1		3		9			5
2022-2		371									1	440	1		2	3			3		13			11
2022-3	2	293								1		411	4		1	8			4		13			2
2022-4	8	511									1	342	1		2	3			1		10			16
2022-5	1	503			1					1		257	1		2	2			4		15			11
2022-6	4	568						1				204	6			1					12			4
2022-7	3	280						2				75	2		3	1			2		11			13
2022-8	3	561						1			1	112	1		1	4	2		1		6	2		11
2022-9	9	561						1				31			7	2					14			5
2022-10	6	552										82			4	2			1		9			7

APPENDIX 6. CORRELATIONS AMONG KEY VARIABLES AND BIO-ENVIRONMENT MATCHING (BEST) RESULTS

A. Macrofauna composition associations (Spearman rank correlation) with key sediment quality variables based on multivariate BEST procedure in Primer v7.0.13.

Spearman corr.	Variables
Best overall model:	
0.697	Sed rate, Max flow
Best individual variable:	
0.515	Max flow
0.444	Sed rate
0.236	Mean flow
0.224	Gravel
-0.134	Total nitrogen
-0.212	Total organic carbon
-0.236	Mud
-0.297	Sand
-0.324	aRPD
-0.636	Total phosphorus

B. Macrofauna associations with key sediment and flow variables based on Pearson correlation.

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