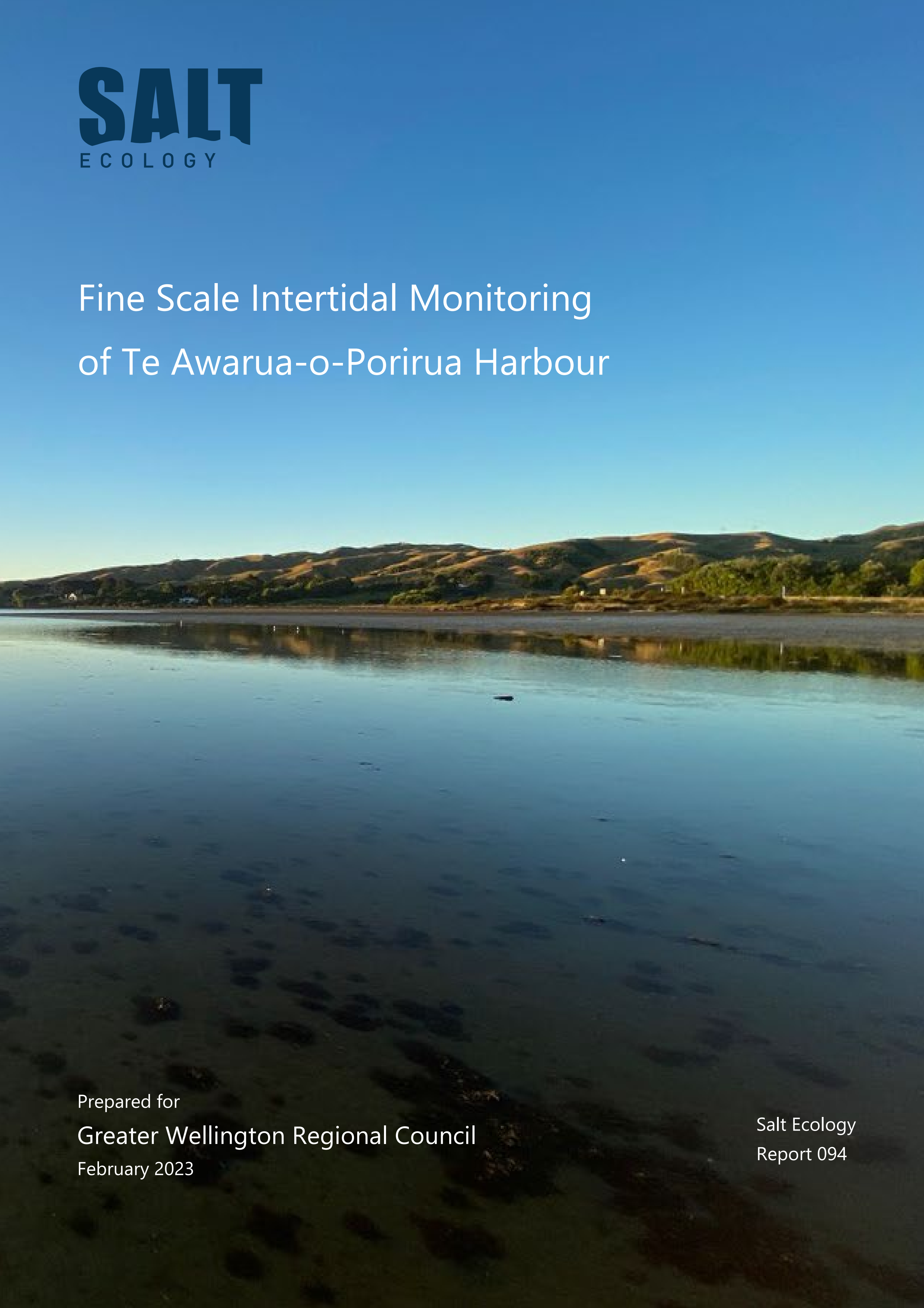

SALT ECOLOGY

Fine Scale Intertidal Monitoring of Te Awarua-o-Porirua Harbour

Prepared for

Greater Wellington Regional Council

February 2023

Salt Ecology Report 094

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For the People
Mō ngā tāngata

Fine Scale Intertidal Monitoring of Te Awarua-o-Porirua Harbour

Prepared by

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for

Greater Wellington Regional Council

February 2023

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For the environment
Mō te taiao

GLOSSARY

AMBI	AZTI Marine Biotic Index
ANZECC	Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000)
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

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TABLE OF CONTENTS

FIGURES

TABLES

EXECUTIVE SUMMARY

BACKGROUND

As part of its State of the Environment programme, Greater Wellington Regional Council (GWRC) undertakes monitoring and assessment of estuaries and other coastal environments in its region. A focus of GWRC's work has been Te Awarua-o-Porirua Harbour (hereafter Porirua Harbour), where monitoring over the 14 years has included periodic 'fine scale' and 'broad scale' surveys following methodologies described in New Zealand's National Estuary Monitoring Protocol (NEMP). This report describes an intertidal fine scale survey conducted in the harbour in January 2022, which involved assessing sediment quality and biological indicators at four sites, two in the Onepoto (Onep) Inlet of the harbour and two in the Pāuatahanui Inlet (Paua). A key purpose was to assess the response of the estuary to increases in sediment mud content that had been recorded in 2020 and re-evaluate declining estuarine health using sediment and macrofaunal indicators.

KEY FINDINGS

The table below presents the mean values of key indicators, assessed against established ecological health rating criteria for New Zealand estuaries. See Glossary for definition of indicators and Fig. 3 (p. 4) for site locations.

Site	Year	Mud %	aRPD mm	TN mg/kg	TP mg/kg	TOC %	As mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Pb mg/kg	Hg mg/kg	Ni mg/kg	Zn mg/kg	AMBI na
Onep-A	2008	10.0	28	685	442	-	-	0.028	11.3	5.1	6.1	-	8.4	39.4	2.9
	2009	9.2	27	643	397	0.39	-	0.034	12.3	5.0	6.7	-	8.5	41.0	2.7
	2010	10.0	14	< 503	393	0.26	-	0.029	10.6	3.8	5.3	-	7.1	35.7	2.2
	2015	8.3	10	< 500	397	0.58	6.2	0.023	10.8	4.2	5.7	0.02	8.0	38.0	2.6
	2020	11.0	6	< 500	407	0.30	5.5	0.029	10.8	4.5	5.5	< 0.02	8.5	46.3	2.1
	2022	8.2	15	< 500	363	0.29	5.6	0.027	10.5	3.6	5.6	0.01*	7.1	38.0	2.2
Onep-B	2008	4	-	305*	158	-	-	0.041	5.1	3.6	9.5	-	3.6	59.9	2.0
	2009	5.7	23	< 507	147	0.21	-	0.046	5.6	4.0	8.9	-	3.7	57.7	1.0
	2010	9.4	10	453*	163	0.19	-	0.044	5.2	3.4	9.1	-	3.4	62.3	1.1
	2015	4.3	10	< 500	196	0.29	3.2	0.046	5.6	3.9	9.9	0.02	4.0	77.7	0.9
	2020	14.1	13	< 500	267	0.36	3.6	0.058	8.5	7.5	13.5	0.02*	10.4	135.7	0.5
	2022	8.6	20	< 500	142	0.24	2.3	0.041	5.9	4.2	9.3	0.02*	3.9	69.7	0.4
Paua-A	2008	12.2	37	823	447	-	-	0.029	10.7	4.9	8.8	-	6.5	36.7	3.0
	2009	9.9	17	700	437	0.38	-	0.025	11.0	4.6	6.1	-	7.7	35.0	2.8
	2010	15.1	10	673	470	0.35	-	0.025	10.7	4.8	6.8	-	7.4	37.3	2.7
	2015	9.2	10	600	450	0.79	7.5	0.022	11.0	4.8	6.6	0.03	8.1	37.3	3.2
	2020	12.7	12	< 500	453	0.31	7.2	0.023	10.6	4.8	6.1	0.01*	7.7	41.7	1.9
	2022	15.3	28	533	467	0.45	7.5	0.025	11.6	5.1	7.8	0.03	7.6	41.7	2.2
Paua-B	2008	4.5	33	547	150	-	-	0.020	4.7	2.3	3.9	-	4.7	23.0	2.8
	2009	4.4	37	470*	137	0.23	-	0.019	4.6	2.0	4.5	-	3.4	21.0	2.5
	2010	7.5	10	597	120	0.23	-	0.019	4.1	1.8	4.2	-	3.0	19.3	3.5
	2015	3.3	10	< 500	118	0.32	2.0	0.021	4.1	2.0	4.1	0.02	3.3	20.2	3.4
	2020	19.7	10	417*	202	0.51	2.9	0.029	5.8	3.8	6.2	0.03	4.4	31.0	2.7
	2022	10.0	28	333*	157	0.33	2.7	0.023	4.9	2.4	5.2	0.03	3.4	23.3	2.8

** Sample mean includes values below lab detection limits. '<' All values below lab detection limit. Dash (–) not analysed*

Condition Rating Key: Very Good | Good | Fair | Poor *Rating criteria not established for TP*

Sedimentation and sediment quality indicators

- Sedimentation has been highly variable year-to-year. Mean annual sedimentation data presented in a separate report shows that 5-yr rates have slightly exceeded the national guideline value of 2mm/yr at Onep-A and Paua-B. Among the fine scale sites, 10-yr mean rates have exceeded the guideline at Onep-A only.

- There has been a small (and variable) overall trend of increasing sediment mud content at Onep-B and Paua-B, with a noticeable spike in 2020. However, in 2022 sediment mud content increased slightly at Paua-A relative to 2020, but decreased elsewhere.
- Measures of TOC, TN and TP indicated organic enrichment was relatively low at the measured sites, and was considered to be of no significant ecological concern.
- Levels of trace metals contaminants were very low and were considered to be of no ecological concern. Levels of other contaminants, including pesticides, were less than laboratory method detection limits.
- Sediment 'aRPD' depth was rated 'good' to 'poor' across survey years, with an overall decline evident from the 2008 baseline. In the absence of corresponding changes in other enrichment indicators (i.e. TOC) this result may be associated with increased sediment mud content, as mud-size particles inhibit flushing and oxygen diffusion into the sediment matrix. However, a weak correlation between grain size and aRPD suggests other potential variables such as bioturbation, drift algal decay, and subjectivity in measurements, may contribute to the apparent discrepancies.

Epibiota and sediment-dwelling macrofauna

- Nuisance macroalgae (seaweeds) were at a low prevalence across all years at the fine scale sites. The green mat-forming algal species that was conspicuous in 2020 near outer harbour Onep-A and Paua-A sites was not observed in 2022 during fine scale sampling, nor during harbour-wide sediment plate monitoring.
- Core sampling revealed 100 different sediment-dwelling macrofauna taxa over the six surveys. Relative to the low macrofauna species richness and abundances evident in 2020 (which corresponded with an estuary-wide increase in sediment mud content compared to previous years), the macrofaunal community condition appears to have improved in 2022.
- Changes in macrofauna richness, abundance and composition were not clearly or plausibly related to any of the measured sediment variables. Hence, the reasons for the apparent improvement from 2020 to 2022 are unclear. There appear to be drivers (e.g. hydrodynamic processes, sea surface temperature) of spatial and temporal change in the intertidal habitats of the harbour that are not reflected in any of the sediment constituents that are routinely measured using NEMP methods. As the NEMP fine scale sites are intentionally located away from the direct effects of point sources, they provide an excellent basis (using the current indicators) for monitoring long-term changes (i.e. over time scales of decades) in the harbour as a whole. However, the NEMP fine scale sites do not necessary provide a strong foundation for capturing changes in the state of the estuary that may arise in the near-future, or which are localised to areas around point sources such as river outflows (e.g. pulse inputs of sediment from catchment sources). As such, the report discusses some of the considerations for ongoing monitoring.

RECOMMENDATIONS

Except for a slight increase in % mud at Paua-A, there has been an improvement in the sediment quality and ecological condition of Porirua Harbour since 2020. As such, there is no immediate need for additional or targeted follow-up monitoring. However, it is suggested that GWRC work towards developing a future-focused programme that integrates monitoring across intertidal, subtidal and catchment domains. Background desktop investigations that will contribute to this goal include the following:

- A synthesis of the learnings from environmental studies that have been undertaken in the harbour to date.
- A synthesis of the catchment studies that have been undertaken, and an evaluation of likely drivers of future change in the harbour.
- An assessment of the harbour locations and habitats that are the most vulnerable to future pressures.

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 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 defensible, cost-effective and standardised approach for monitoring the ecological status of estuaries in their region. The results establish a benchmark of estuarine health in order 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. This type of monitoring is typically undertaken every 5 to 10 years.
- Fine scale monitoring of estuarine biota and sediment quality. This type of monitoring is typically conducted at intervals of 5 years after initially establishing a baseline.

Greater Wellington Regional Council (GWRC) has undertaken monitoring of selected estuaries in its region using the NEMP methods and other approaches (e.g. synoptic surveys, sedimentation monitoring) for over a decade. A focus of GWRC's work has been in Te Awarua-o-Porirua Harbour (Fig. 1, hereafter Porirua Harbour), and has included:

- Three NEMP broad scale, and four fine scale surveys, with the first surveys being in 2008 (Robertson & Stevens 2008; Stevens & Robertson 2008) and the most recent in 2020 (Forrest et al. 2020; Stevens & Forrest 2020).
- Annual monitoring of sedimentation rates at intertidal and subtidal sites (e.g. Stevens et al. 2022).
- Targeted assessment of opportunistic intertidal macroalgae species (*Agarophyton* spp. and *Ulva* spp.) that can reach nuisance levels under certain conditions (e.g. Stevens & O'Neill-Stevens 2017).
- Subtidal habitat mapping and ecological surveys that match the intertidal fine scale approach (e.g. Milne et al. 2008; Oliver & Conwell 2014; Stevens & Robertson 2014; Cummings et al. 2022).

Salt Ecology was contracted to carry out a further NEMP intertidal fine scale survey in January 2022, alongside the annual sedimentation monitoring. A key purpose of the fine scale fine survey was to understand whether declines in key indicators of estuary condition that were observed in 2020 (relative to earlier years) reflected ongoing degradation in Porirua Harbour. This latest report describes the methods and results of fine scale survey conducted in January 2022, compares findings with earlier work in terms of the current status and trends in estuary health, and makes recommendations for future management and monitoring.

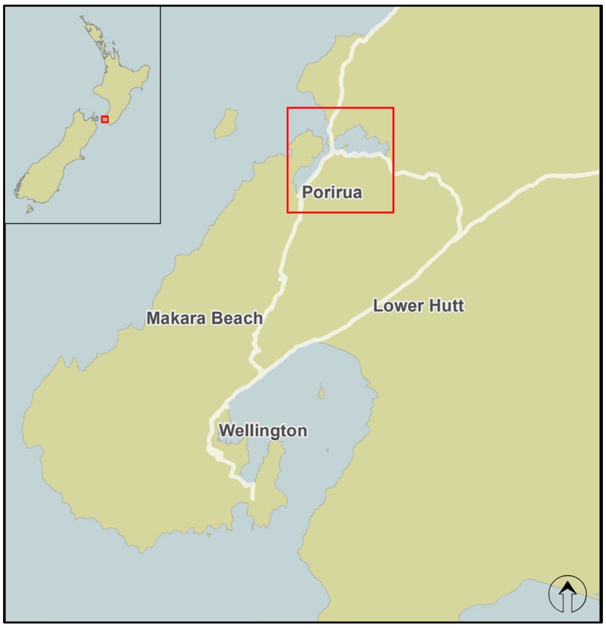


Fig. 1 Location of Te Awarua-o-Porirua Harbour.

2. BACKGROUND INFORMATION

Background information on Porirua Harbour described in previous reports is summarised below. The harbour is a large (807ha, Fig. 2), well flushed estuary fed by a number of small streams. It comprises two inlets, each a relatively simple shape - Onepoto (283ha) and Pāuatahanui (524ha). The inlets are connected by a narrow channel at Paremata, and the estuary discharges to the sea via a narrow entrance west of Plimmerton.

Flushing time in the harbour is reported to be 7.4 days (Plew et al. 2018). Compared to the majority of New Zealand's tidal lagoon estuaries which tend to drain almost completely at low tide, 65% of the harbour has a shallow subtidal component (mean depth of ~1m). Nonetheless, the intertidal area is large (287ha) and

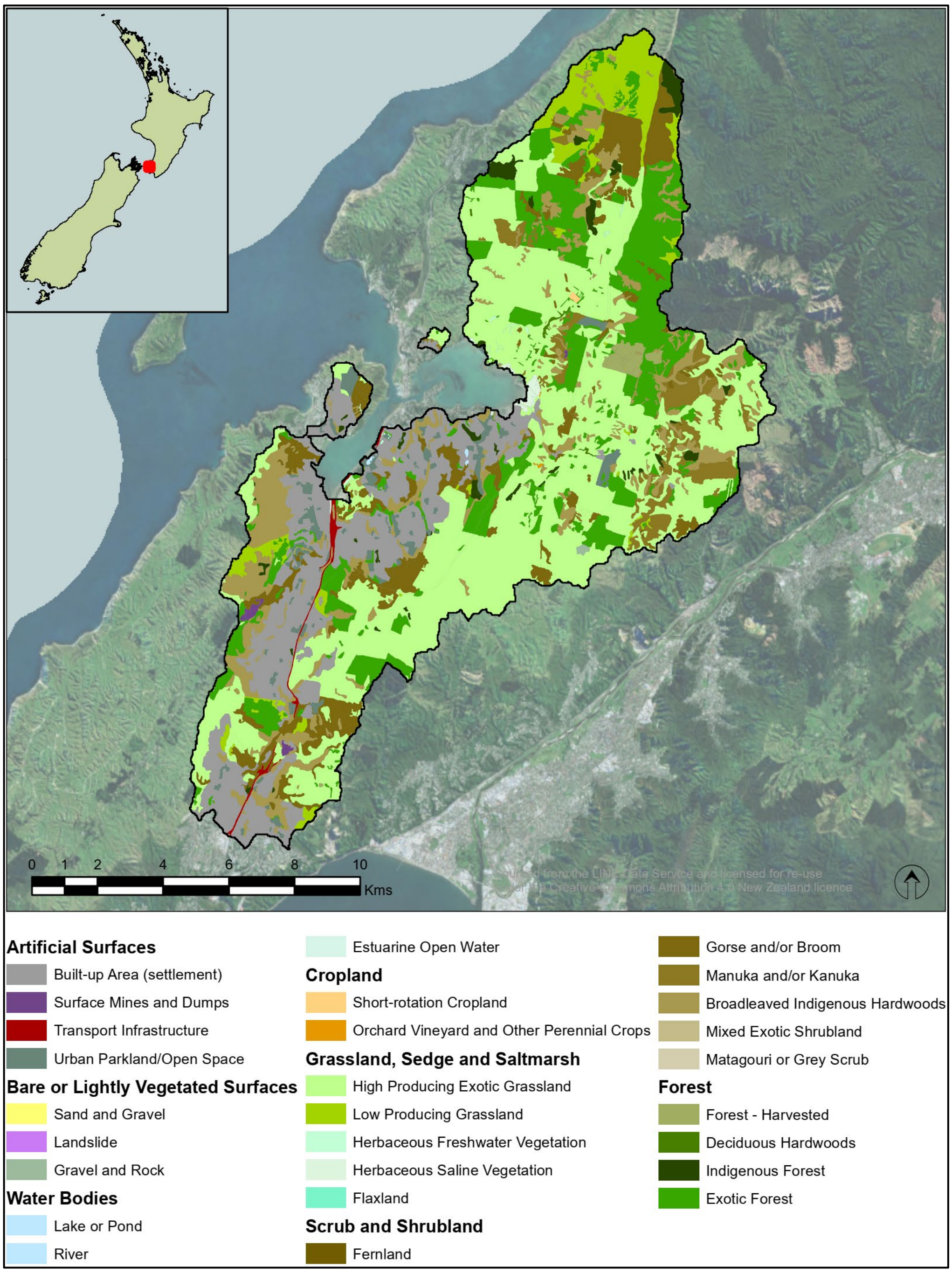


Fig. 2 Te Awarua-o-Porirua Harbour and surrounding catchment land use classifications from LCDB5 (2017/18) database. Some recent changes since 2017/18 are not shown. The new Transmission Gully motorway passes to the east of the harbour.

supports extensive areas (59ha) of high value seagrass habitat growing in firm mud/sand, and shellfish beds.

The harbour has been extensively modified over the years, particularly Onepoto Inlet, where almost all of the historical shoreline and salt marsh have been reclaimed and most of the inlet is now lined with steep straight rock walls flanked by road and rail corridors. Pāuatahanui Inlet is less modified (although most of the margin is encircled by a road), with extensive areas of salt marsh remaining in the north and east, much of which has been improved through local community enhancement efforts. Nonetheless, the 2020 broad scale report described a significant (43%) decline in salt marsh extent between 2013 and 2020, which occurred primarily in eastern Pāuatahanui Inlet where the salt marsh is transitioning to terrestrially dominated vegetation as a consequence of land drainage (Stevens & Forrest 2020).

Catchment land use around Onepoto Inlet is dominated by urban (residential and commercial) development (Fig. 2). In the steeper Pāuatahanui Inlet, grazing is the dominant land use, although urban (residential) development is significant in some areas. Various reports have identified sedimentation as a major problem in the estuary, particularly in Pāuatahanui Inlet, where past or potential pulse sources include land disturbance associated with subdivisions, the Transmission Gully motorway development, and exotic forest harvesting. The 2020 broad scale survey described an increase in the spatial extent of mud-dominated sediment (>50% mud content) from ~1% of the intertidal area in 2008 to ~14% in 2020 (Stevens & Forrest 2020). Most of that increase occurred in Pāuatahanui Inlet, with the most recent survey revealing that the 5-year mean sedimentation rate averaged across all five intertidal monitoring sites has exceeded regional goals and national guidelines (Stevens et al. 2022).

Except for a trend of increasing sediment mud content at the time of the 2020 fine scale survey, and signs of moderate enrichment of the sediment profile, that survey did not find any significant degradation of other sediment quality indicators (organic matter, nutrients, trace metals). However, biological changes observed included an apparent decline in the diversity of sediment-dwelling macrofauna, along with extensive mats of a green seaweed (*Chaetomorpha ligustica*) that were recorded in outer harbour areas. Collectively, these changes raised concerns about a gradual deterioration in the state of the harbour, and were the impetus for the follow-up survey described in this report.

3. FINE SCALE METHODS

3.1 OVERVIEW OF FINE SCALE SITES

Following the first broad scale habitat mapping survey in 2008, four sites for fine scale monitoring were selected. These sites were established in January 2008, with two being in Onepoto Inlet (Onep A, Onep B) and two in Pāuatahanui Inlet (Paua A, Paua B) (Fig. 3). At the inception of sampling in 2008, these sites were largely unvegetated except for patches of seagrass at Onep A.

Each site has dimensions of 30 x 60m and has 'sediment plates' (buried concrete pavers) for sedimentation monitoring installed at one end. The co-location of sediment plates provides information on patterns of sediment accretion and erosion that aids interpretation of physical and biological changes at the fine scale sites. Site GPS positions are provided in Appendix 1. A schematic of the site layout and sampling approach for fine scale monitoring is provided in Fig. 3, with methods detailed below.

Onep A in northeast Onepoto Inlet next to Paremata station

Onep B in southwest Onepoto Inlet next to Porirua City

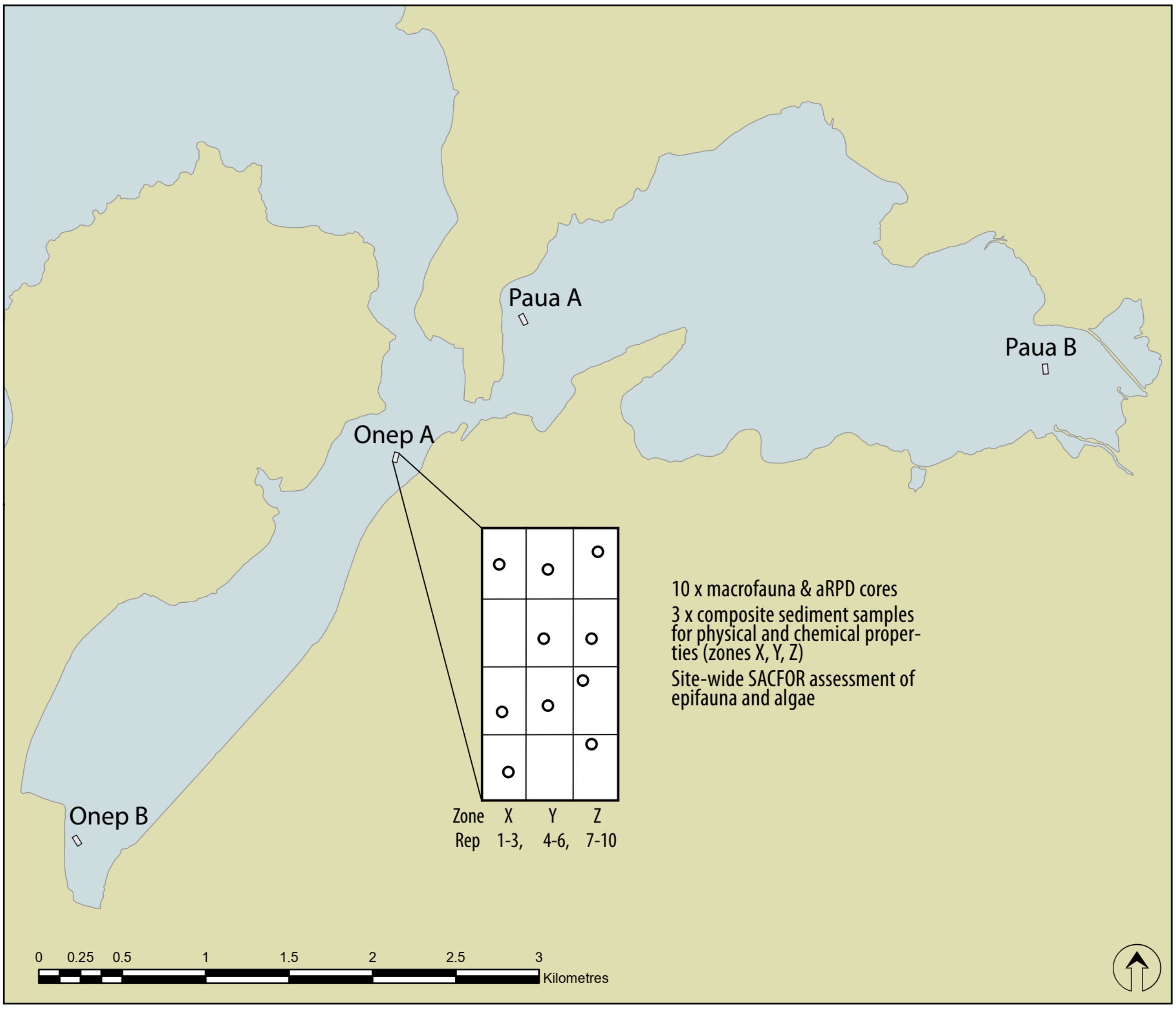


Fig. 3 Location of Onepoto and Pāuatahanui sites A and B, and schematic of sampling design.

Paua A in western Pāuatahanui Inlet opposite Ivey Bay

Paua B in eastern Pāuatahanui Inlet

3.2 FINE SCALE SAMPLING AND BENTHIC INDICATORS

Each fine scale site was divided into a 3 x 4 grid of 12 plots. Fine scale sampling for benthic indicators was conducted in 10 of these plots, with Fig. 3 showing the standard numbering sequence for replicate plots used at sampling sites, and the designation of zones X, Y and Z (for compositing sediment samples; see below). A summary of the NEMP benthic indicators, the rationale for their inclusion, and the field sampling methods, is provided in Table 1. Although the general sampling approach closely follows the NEMP, Table 1 describes modifications to the protocol that have been introduced in the surveys of Porirua Harbour and many other estuaries nationally.

For sediment quality assessment, three composite sediment samples (each ~250g) were collected (to 20mm depth) from sub-samples pooled across each of plots X, Y and Z (replicates 1-3, 4-6 and 7-10, respectively). Samples were stored on ice and sent to RJ Hill Laboratories 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 metals or metalloids (arsenic, As; cadmium, Cd; chromium, Cr; copper, Cu; mercury, Hg; lead, Pb; nickel, Ni; zinc, Zn).

As a check on the occurrence of other common anthropogenic contaminants know to be at elevated concentrations near Porirua Harbour stormwater discharges and stream inflows (Sorensen & Milne 2009), a separate single composite sample was collected from each site and analysed for a suite of semi-volatile organic compounds (SVOCs). These include pesticides, herbicides, combustion by-products (polycyclic aromatic hydrocarbons), and a range of compounds used in manufacturing (e.g. plasticizers). Details of laboratory methods and detection limits for these contaminants are provided in Appendix 2.

The apparent redox potential discontinuity (aRPD) depth (Table 1) is a subjective measure of the enrichment state of sediments according to the depth of visible transition between oxygenated surface sediments (typically brown in colour) and deeper less oxygenated sediments (typically dark grey or black in colour). The aRPD depth was measured 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 were also photographed.

Each of the large sediment cores used for assessment of aRPD was placed in a separate 0.5mm sieve bag, which was gently washed in seawater to remove fine sediment. The retained animals were preserved in a mixture of 80% isopropyl alcohol and 20% seawater for later sorting and taxonomic identification by NIWA. The types of animals present in each sample (commonly referred to as 'macrofauna'), 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.

In addition to macrofaunal core sampling, conspicuous epibiota (macroalgae, and surface-dwelling animals nominally >5mm body size) visible on the sediment surface at each site were semi-quantitatively categorised using the 'SACFOR' abundance (animals) or percentage cover (macroalgae) ratings shown in Table 2.

The SACFOR method is ideally suited to characterise intertidal epibiota with patchy or clumped distributions and was used in 2020 and 2022 as an alternative to the quantitative quadrat sampling specified in the NEMP. As quadrat counts (10 x 0.25m^2 quadrats) were undertaken in earlier surveys, these were converted to SACFOR ratings for comparative purposes.

Note that the epibiota assessment did 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).

Processing macrofauna samples

Table 1. Summary of NEMP fine scale benthic indicators, rationale for their use, and sampling method. Any significant departures from NEMP are described in footnotes.

NEMP benthic indicators	General rationale	Sampling method
Physical and chemical		
Sediment grain size	Indicates the relative proportion of fine-grained sediments that have accumulated	1 x surface scrape to 20mm sediment depth, with 3 composited samples taken across the 10 plots (see note 1)
Nutrients (nitrogen and phosphorus) and organic matter	Reflects the enrichment status of the estuary and potential for algal blooms and other symptoms of enrichment	1 x surface scrape to 20mm sediment depth, with 3 composited samples taken across the 10 plots (see note 1)
Trace metals (copper, chromium, cadmium, lead, nickel, zinc)	Common toxic contaminants generally associated with human activities	1 x surface scrape to 20mm sediment depth, with 3 composited samples taken across the 10 plots (see notes 1, 2)
Depth of apparent redox potential discontinuity layer (aRPD)	Subjective measure of the enrichment state of sediments according to the visual transition between brown oxygenated surface sediments and deeper grey/black oxygen-depleted sediments. The aRPD can occur closer to the sediment surface as organic matter loading increases.	1 x 130mm diameter sediment core to 150mm deep for each of 10 plots, split vertically, with depth of aRPD recorded in the field where visible
Biological		
Macrofauna	The abundance, composition and diversity of macrofauna, especially the infauna living with the sediment, are commonly-used indicators of estuarine health	1 x 130mm diameter sediment core to 150mm deep (0.013m^2 sample area, ~2L core volume) for each of 10 plots, sieved to 0.5mm to retain macrofauna
Epibiota (epifauna)	Abundance, composition and diversity of epifauna are commonly-used indicators of estuarine health	Abundance score based on ordinal SACFOR scale in Table 2 (see note 3)
Epibiota (macroalgae)	The composition and prevalence of macroalgae are indicators of nutrient enrichment	Percent cover score based on ordinal SACFOR scale in Table 2 (see note 3)
Epibiota (microalgae)	The composition and prevalence of microalgae are indicators of nutrient enrichment	Visual assessment of conspicuous growths based on ordinal SACFOR scale in Table 2 (see notes 3, 4)

Notes:

[1] For cost reasons, sediment quality is assessed in 3 composite samples rather than 10 discrete samples as specified in the NEMP.

[2] Arsenic and mercury not required by NEMP, but were included in the trace metal suite.

[3] Assessment of epifauna, macroalgae and microalgae used SACFOR in favour of quadrat sampling outlined in NEMP. Quadrat sampling 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 in NEMP studies due to unavailability of expertise and lack of demonstrated utility of microalgae as a routine indicator.

3.3 DATA RECORDING, QA/QC AND ANALYSIS

All sediment and macrofaunal samples were tracked using standard Chain of Custody forms, and results were transferred electronically to avoid transcription errors. In 2020, field measurements were recorded electronically in templates that were custom-built using software available at www.fulcrumapp.com. Pre-specified constraints on data entry (e.g. with respect to data type, minimum or maximum values) ensured that the risk of erroneous data recording was minimised. Each sampling record created in Fulcrum generated a GPS position for that record (e.g. a sediment core). Field data were exported to Excel, together with data from the sediment and macrofaunal analyses.

To assess changes over the surveys, and minimise the risk of data manipulation errors, Excel sheets for the different data types and years were imported into the software R 3.6.0 (R Core Team 2022) and merged by common sample identification codes. All summaries of univariate responses (e.g. totals, means ± 1 standard error) were produced in R, including tabulated or graphical representations of data from sediment plates, laboratory sediment quality analyses, and macrofauna.

Where results for sediment quality parameters were below analytical detection limits, averages were calculated using half the detection limit value, according to convention.

For the macrofauna data, an extensive QA process was undertaken to achieve consistency in the naming of species and high taxonomic groups across years. This step was necessary as NIWA undertook the taxonomic identifications in 2022, whereas in previous surveys this component was undertaken by Coastal Marine Ecology Consultants (CMEC). To resolve issues identified:

- All macrofauna names were updated to that accepted by the World Register of Marine Species (WoRMS, www.marinespecies.org/).
- Taxonomic QA was undertaken by CMEC and NIWA on archived samples collected by CMEC since 2008, in part during an Envirolink project (Mills et al. 2021) but also subsequently by CMEC.
- Minor remaining differences between CMEC and NIWA data were addressed by aggregation to a common taxonomic level. The main requirement was for CMEC's morphospecies identifications for certain taxa to be aggregated to the single groups used by NIWA (e.g. CMEC's Nemertea sp. 1, sp. 2, etc, were grouped to 'Nemertea' to match NIWA's coarser taxonomic resolution).

Before macrofaunal analyses, the data were screened to remove species that were not regarded as a true part of the macrofaunal assemblage; these were planktonic life-stages and non-marine organisms (e.g. terrestrial beetles or freshwater drift). Macrofaunal univariate response variables were derived from raw data, namely richness and abundance by species and higher taxonomic groupings, and scores for the biotic health index AMBI (Borja et al. 2000). AMBI scores reflect the proportion of taxa falling into one of five eco-groups (EG) that reflect sensitivity to pollution (in particular eutrophication), ranging from relatively sensitive (EG-I) to relatively resilient (EG-V). To meet AMBI criteria, macrofauna data were reduced to a subset that included only adult 'infauna' (those organisms living within the sediment matrix), which involved removing surface dwelling epibiota and any juvenile organisms. AMBI scores were calculated based on standard international eco-group classifications where possible (http://ambi.azti.es), with the most recent eco-group list developed in December 2020. To reduce the number of taxa with unassigned eco-groups, international data were supplemented with eco-group classifications for New Zealand (e.g. Cawthron EGs used by Berthelsen et al. 2018). Note that AMBI scores were not calculated if macrofaunal cores did not meet operational limits suggested by Borja et al. (2012), in terms of the percentage of unassigned taxa (>20%), or low sample richness (<3 taxa) or abundances (<6 individuals).

Using zone data within each site (zones X, Y and Z; i.e. replicates 1-3, 4-6 and 7-10, respectively, as per Fig. 3), simple Pearson correlation was undertaken to describe associations between pairwise combinations of macrofauna (richness and abundance) and sediment quality variables. Potential predictors of change in macrofauna composition were also investigated, using multivariate analysis procedures in the software Primer v7.0.13 (Clarke et al. 2014). Patterns in similarity as a function of macrofauna composition were visualised using a non-metric multidimensional scaling (nMDS) biplot, based on pairwise Bray-Curtis similarity index scores among samples aggregated within sites. Overlay vectors and/or bubble plots of site-averaged sediment quality and sedimentation variables were used to visualise relationships between multivariate biological patterns and sediment attributes. Using a Bray-Curtis similarity matrix of zone data, a more detailed analysis of macrofauna community-environment relationships was undertaken using the Primer procedure BIOENV. Prior to all multivariate analyses, macrofaunal abundance data were fourth-root transformed to down-weight the influence of the dominant species or higher taxa.

Table 2. SACFOR ratings for assessing site-scale abundance (macrofauna) and percent cover (macroalgae) of epibiota.

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

3.4 ASSESSMENT OF ESTUARY CONDITION

To supplement our analysis and interpretation of the data, fine scale survey results across all years were assessed against 'condition ratings' of estuary health, drawing on approaches from New Zealand and overseas. These metrics assign different indicators to one of four 'health status' bands, colour coded as shown in Table 3. The condition ratings in Table 3 were derived from a New Zealand Estuary Trophic Index (Robertson et al. 2016a, b) and other sources, as follows:

New Zealand Estuary Trophic Index (ETI): The ETI provides screening guidance for assessing where an estuary is positioned on a eutrophication gradient. While many of the constituent metrics are intended to be applied to the estuary as a whole (i.e. in a broad scale context), site-specific thresholds for %mud, TOC, TN, aRPD and AMBI are described (Robertson et al. 2016b). We adopted those thresholds for present purposes, except: (i) for %mud we adopted the refinement to the ETI thresholds described by Robertson et al. (2016c); and (ii) for aRPD we modified the ETI ratings based on the US Coastal and Marine Ecological Classification Standard Catalog of Units (FGDC 2012).

ANZG (2018) Sediment Quality Guidelines: The condition rating categories for trace metals and metalloids are benchmarked to ANZG (2018) sediment quality guidelines as described in Table 4. The Default Guideline Value (DGV) and Guideline Value-High (GV-high) specified in ANZG are thresholds that can be interpreted as reflecting the potential for 'possible' or 'probable' ecological effects, respectively.

Sedimentation rate: Sedimentation data from harbour-wide monitoring are described in another report (Stevens et al. 2022). In the present report, the trends at the four fine scale sites are presented, and long-term sedimentation rates reported by Stevens et al. (2022) for those sites are evaluated against national guideline values (Townsend & Lohrer 2015).

The scoring categories in Table 3 provide a general guide to assist with interpretation of estuary health status. It is major spatio-temporal changes in the health categories that are of most interest, rather than their subjective condition descriptors, i.e. descriptors such as 'poor' health status should be regarded more as a relative rather than absolute rating.

Table 3. Condition ratings used nationally to characterise estuarine health for key fine scale indicators. See text for explanation of the origin or derivation of the different metrics.

Indicator	Unit	Very good	Good	Fair	Poor
General indicators[1]					
Sedimentation rate[2]	mm/y	< 0.5	≥ 0.5 to < 1	≥ 1 to < 2	≥ 2
Mud content	%	< 5	5 to < 10	10 to < 25	≥ 25
aRPD depth	mm	≥ 50	20 to < 50	10 to < 20	< 10
TN	mg/kg	< 250	250 to < 1000	1000 to < 2000	≥ 2000
TOC	%	< 0.5	0.5 to < 1	1 to < 2	≥ 2
AMBI	na	0 to 1.2	> 1.2 to 3.3	> 3.3 to 4.3	≥ 4.3
Trace elements3					
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

1. General indicator thresholds derived from a New Zealand Estuarine Tropic Index, with adjustments for mud and aRPD as described in the main text.
2. Thresholds derived from the ANZECC Estuary Sedimentation Guideline (Townsend & Lohrer 2015).
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. These were formerly the ANZECC (2000) sediment quality guidelines whose exceedance roughly equates to the occurrence of 'possible' and 'probable' ecological effects, respectively.

4. KEY FINDINGS

4.1 GENERAL FEATURES OF FINE SCALE SITES

All sites were classified according to revised NEMP broad scale sediment criteria (e.g. Stevens & Forrest 2019) as consisting of 'firm sand' or 'firm muddy sand'. The shell component of samples was highly variable, but a combination of whole shell and live cockles in some instances made it difficult to take sediment cores.

Consistent with previous surveys, seagrass was conspicuous at outer Onepoto site Onep-A, where the cover was estimated at ~20%. Seagrass was also described for the first time at outer Pāuatahanui site Paua-A (~40% cover), reflecting an expansion of the beds in the general vicinity of the site. There was no evidence of the extensive mats of drift macroalgae *Chaetomorpha ligustica* that had been observed around both Paua-A and Onep-A in 2020.

Upper harbour sites Paua-B and Onep-B were superficially similar to previous surveys. Onep-B next to Porirua City was characterised by indicators of a relatively strong catchment influence, notably a high terrestrial detrital content in the core samples, as well as woody debris and litter (e.g. road cones, plastic rubbish) across the general area.

4.2 SEDIMENTATION

Sedimentation patterns at the intertidal fine scale sites are illustrated in Fig. 4. Sedimentation has been highly variable year-to-year, with periods of marked deposition and erosion evident at most sites. A separate analysis of long-term trends (Stevens et al. 2022) shows that mean annual 5-yr sedimentation rates slightly exceed the national guideline value of 2mm/yr, at Onep-A and Paua-B. However, Onep-A is the only fine scale site with a 10-yr mean value (2.4mm/yr) that exceeds the guideline.

High densities of cockles made sediment coring difficult at times

Fig. 4. Mean change (± SE) in sediment depth over buried plates since the baseline was established in 2008.

Green drift mats of the macroalga *Chaetomorpha ligustica* were were not recorded in 2022 despite being conspicuous at or near outer harbour 'A' sites in 2020.

4.3 SEDIMENT GRAIN SIZE, TOC AND NUTRIENTS

Composite sediment sample raw data for 2022 are tabulated in Appendix 3. Laboratory analyses of particle grain size (Fig. 5) confirmed field observations of the sand fraction being dominant at all sites, with mud content ranging from mean values of ~8 to 15%. Values at each site were largely within the previous range recorded at that site. Sediment mud content declined at all sites except Paua-A between 2020 and 2022; however, current levels at the upper harbour 'B' sites are greater than was measured during 2008 and 2009.

To provide a visual impression of sediment quality relative to the Table 3 condition ratings, Fig. 5 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 ranged from 'very good' to 'fair' over all surveys.

Levels of sediment organic matter (TOC) and TN have remained quite low at all sites and years, consistent with the primarily sandy nature of the sediments. Accordingly, condition rating scores were 'good' or 'very good'. Levels of the nutrient total phosphorus (TP, no rating criteria) have also been relatively low (Appendix 3).

4.4 REDOX STATUS

The aRPD was relatively deep (~23-50mm on average) in the first two surveys (2008 and 2009), relatively shallow (~6-14mm) in the three surveys conducted between 2010 and 2020, and deeper again in 2022 (~15-30mm). A shallow aRPD, especially values in the range measured during 2010-2020, can be associated with conditions of moderate organic enrichment in the sediment. However, %TOC has not been concurrently elevated. A shallow aRPD can also be associated with increased sediment mud content, as mud-size particles inhibit flushing and oxygen diffusion into the sediment matrix. However, the correlation between these variables is weak (Pearson r = -0.26). For example, although sediment mud content increased at Paua-A in 2022 relative to the previous year, the aRPD become deeper. There are several plausible explanations for the apparent discrepancies, such as:

- Sampling the sediment to 20mm for mud grain size analysis may not accurately reflect the influence on aRPD of recently deposited muddy surface sediments
- Bioturbation (e.g. by worms, shellfish, crabs) can lead to mixing of oxic surface sediments with deeper oxygen-reduced sediments, meaning the depth of the aRPD is not always well-defined, particularly in sandy sediments.
- The aRPD may be shallow if drift algae has recently smothered the sediment surface.

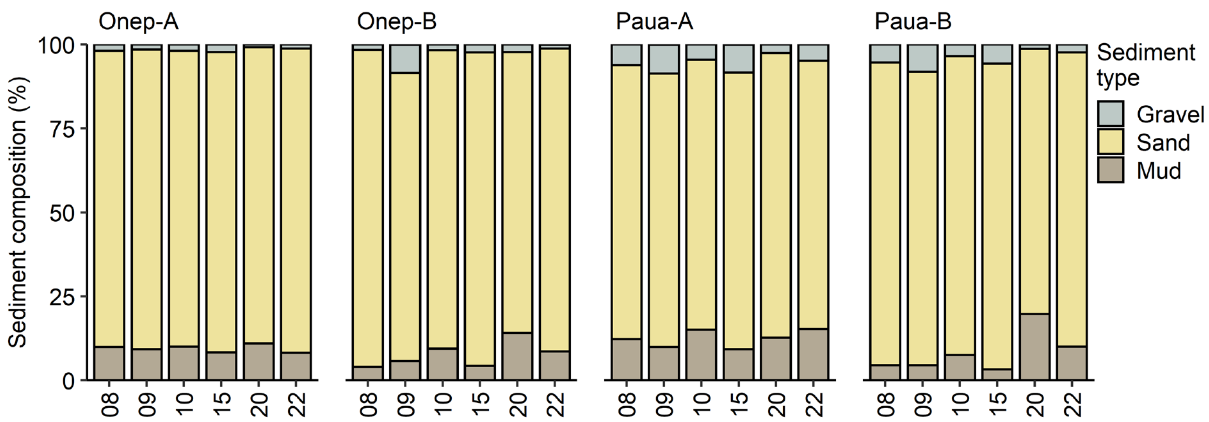


Fig. 5. Sediment particle grain size analysis, showing site-averaged percentage composition of mud (<63µm), sand (<2mm to ≥63µm) and gravel (≥2mm).

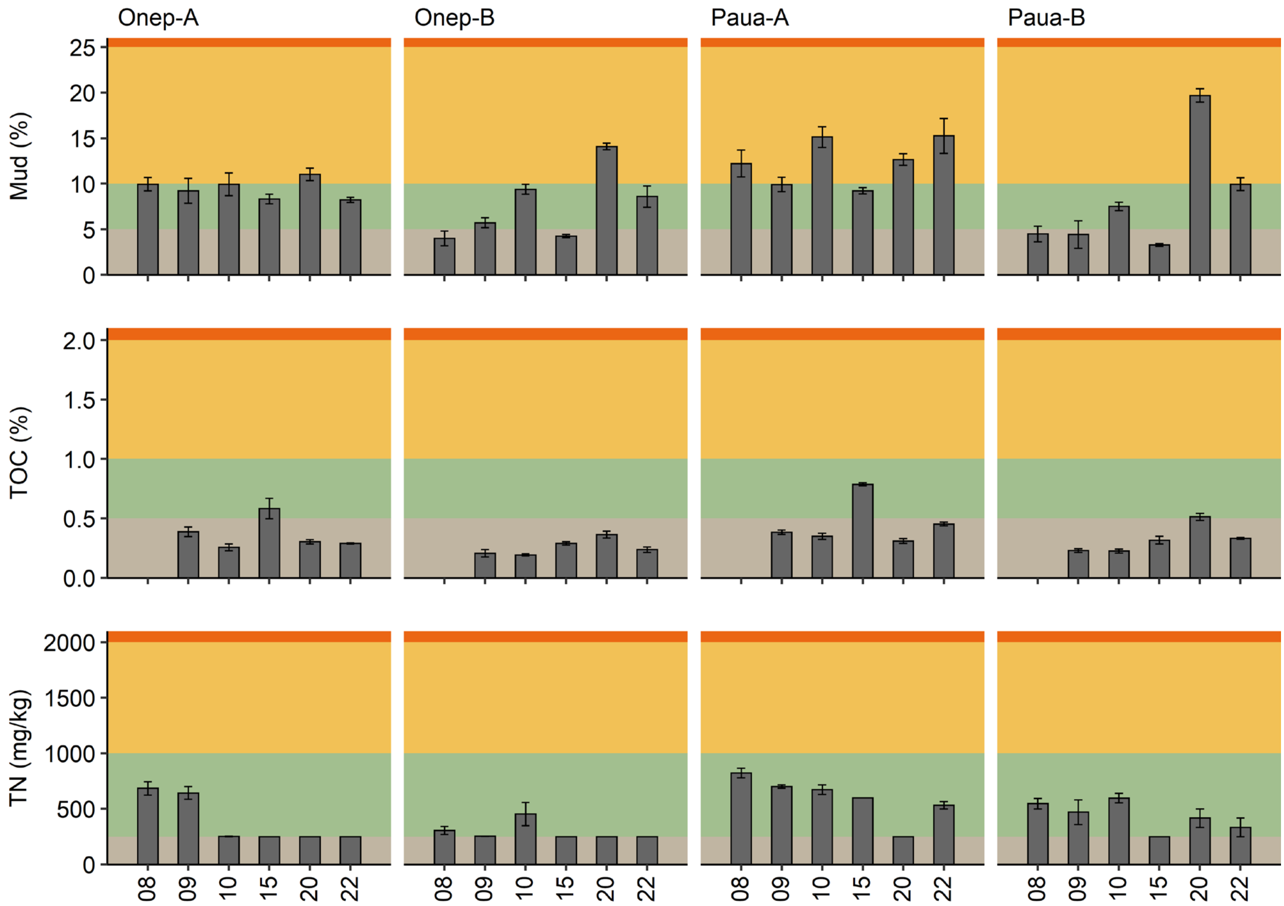


Fig. 6. Sediment mud content (Mud%), total organic carbon (TOC), and total nitrogen (TN) concentrations relative to condition ratings. In 2008, TOC was derived by calculation from ash-free dry weight (AFDW) data and may be inaccurate. Condition rating key as follows:

Very Good	Good	Fair	Poor

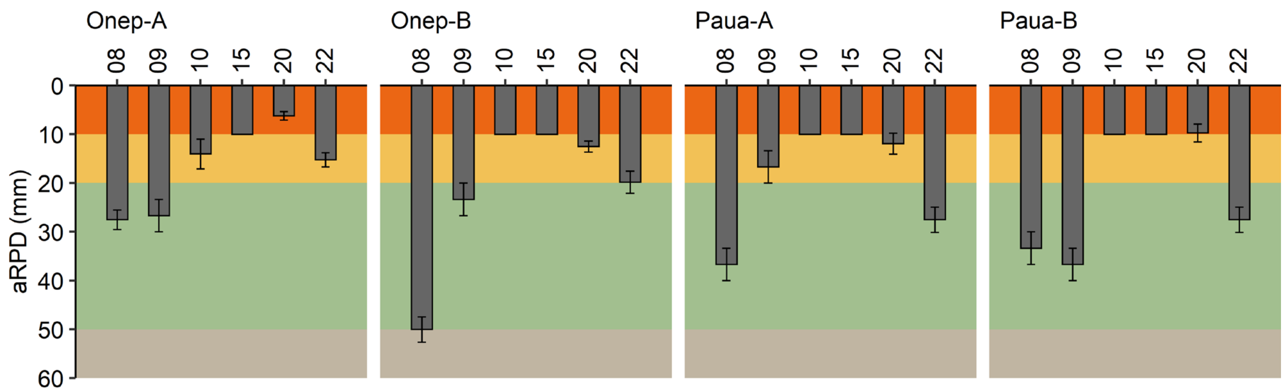


Fig. 7. aRPD depth in sediment relative to condition ratings. Condition rating key as per above Figure.

Notwithstanding these issues, the aRPD in most cases in 2022 was quite well-defined, with the depth of transition between brown oxygenated surface sediment and deeper grey or black less oxygenated sediment clearly visible in the photos shown in Fig. 8.

Note, however, that there is an element of subjectivity in aRPD measurement, such that variability across surveys due to interpretation can be expected. However, the same practitioner made the aRPD assessment from 2008 to 2015 when aRPD deteriorated, and the same practitioner recorded the apparent improvement between 2020 and 2022. On this basis, it is reasonable to attribute the overall changes in aRPD in Fig. 7 (i.e. the difference between early vs the most recent surveys) to be a reasonable reflection of changes in trophic state over time.

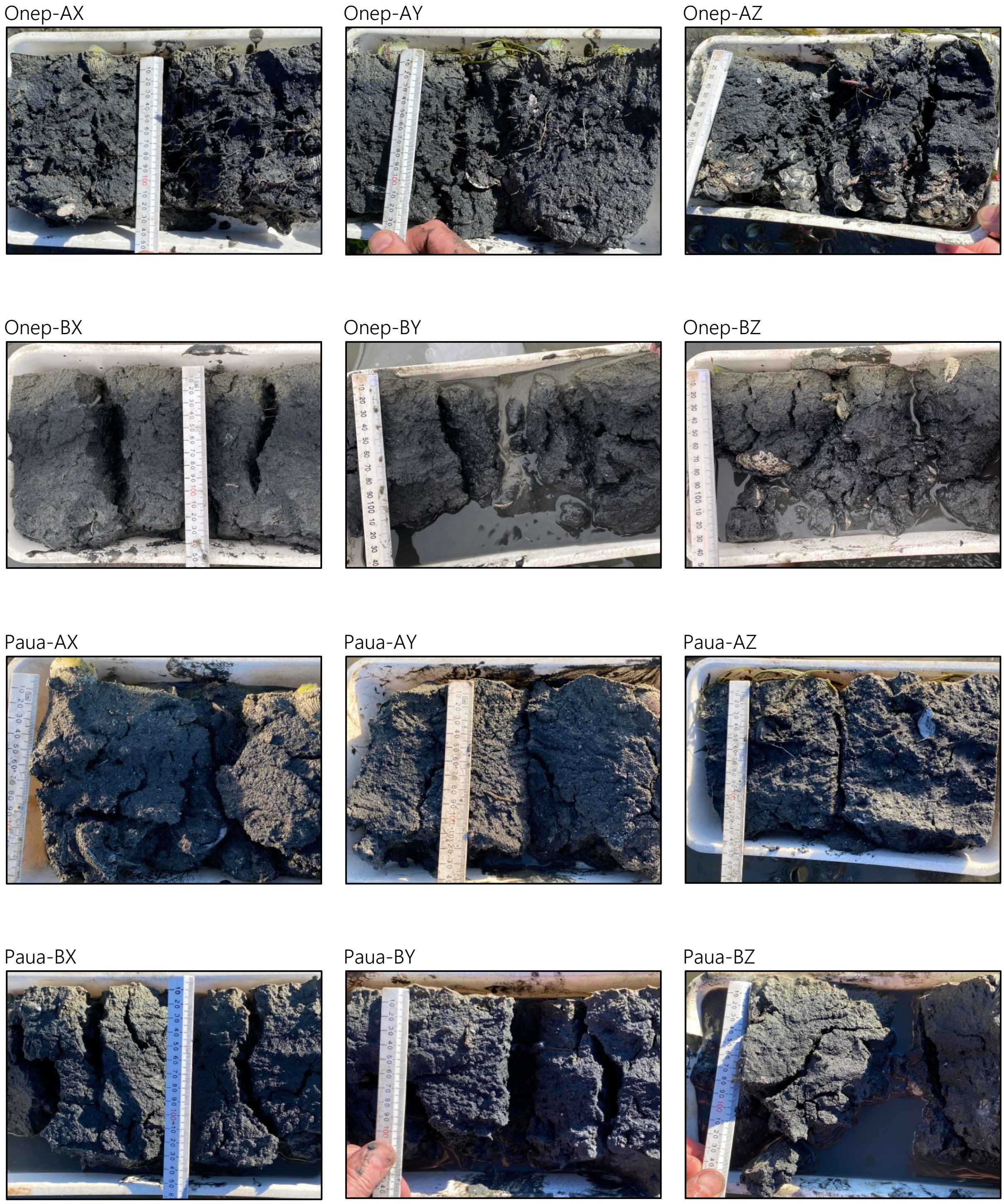


Fig. 8. Example sediment cores from the 2022 survey. The aRPD is visible as the transition from brown surface sediment to deeper grey or black.

4.5 TRACE CONTAMINANTS

Trace metal contaminant levels in relation to condition ratings and ANZG (2018) sediment quality guidelines (DGV) are plotted in Fig. 9, with 2022 raw data and guideline values in Appendix 3. Mean concentrations have been well below DGV levels at all sites over the six surveys, and generally within the 'very good' condition rating bracket.

Paua-B has the lowest metal concentrations overall, consistent with the relatively low urban development in the eastern upper harbour. At Onep-B, some metals (zinc, Zn; cadmium, Cd; lead, Pb) were up to twice the concentration recorded at other sites, likely reflecting urban sources such as runoff from roads (e.g. from vehicle component wear). By contrast, at both outer harbour 'A' sites, concentrations of arsenic (As), chromium (Cr) and nickel (Ni) were roughly double that recorded at 'B' sites, for reasons that are unknown.

Previous studies have demonstrated significant urban contaminant inputs to the harbour from streams and stormwater, with locally elevated concentrations of sediment contaminants at intertidal point sources (e.g. outfalls) around harbour margins (Milne & Watts 2008; Sorensen & Milne 2009; Blaschke et al. 2010). However, the fine scale results provide no evidence of a widespread trace metal contaminant issue across the main intertidal flats of the harbour.

In additional to trace metals, a range of semi-volatile organic compounds (SVOCs) such as various pesticides and hydrocarbons were analysed in a single composite sample from each site. Results showed that concentrations of all analytes were less than laboratory method detection limits (Appendix 3).

4.6 MACROFAUNA

4.6.1 Conspicuous surface epibiota

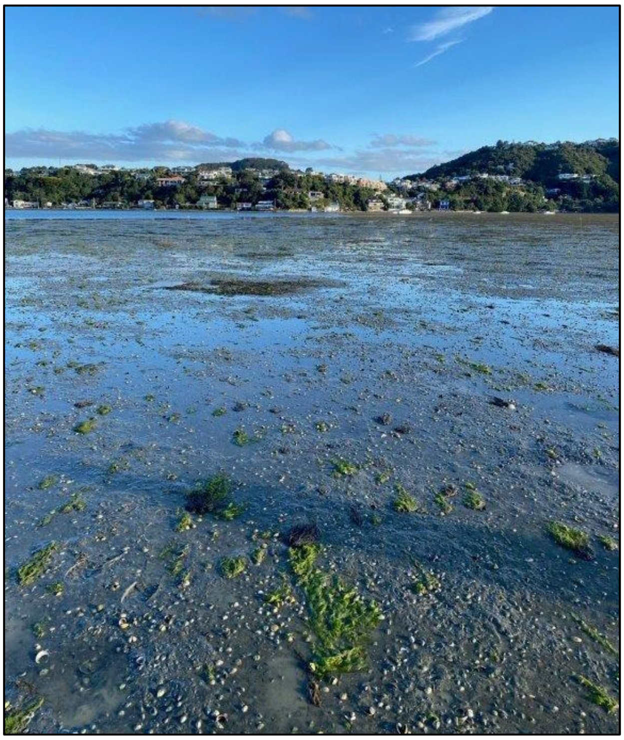
The density or percentage cover of surface-dwelling epifauna and macroalgae was highly variable among sites and over survey years. In general, epibiota tended to be more diverse and abundant in the two outer 'A' sites where seagrass *Zostera muelleri* was abundant in 2022 (Table 4).

The most frequently-occurring epifauna described in the last two surveys were mud whelks (*Cominella glandiformis*), large horn snails (*Zeacumantus lutulentus*), and mudflat snails (*Diloma subrostratum*), which occur in varying abundances. In 2022 no epibiota were noted at upper harbour site Onep-B.

Zeacumantus and *Cominella* are deposit feeders that ingest mud and extract the organic matter, whereas *Cominella glandiformis* is a scavenger and predator and often has a highly clumped distribution reflecting aggregation around food items. *Diloma subrostratum* is a grazer of microalgal films and was reasonably prevalent in 2020 and 2022. It is unclear whether the apparent absence or scarcity of epifauna prior to 2020 reflects a true absence or the lack of recording.

The bubble shell *Papawera zelandiae*, is an additional epifauna species that is commonly collected in the sediment core samples but has not been previously recorded as part of the epibiota survey, possibly because of its tendency to burrow into surface sediments making it less conspicuous. While not recorded in Table 4, it was present (but rare) at the 'A' sites, and at moderate densities (~5/m^2) at Paua-B.

Seaweeds present at most sites in most years were the red *Agarophyton* spp. and the green *Ulva* spp. However, in 2022 both species were absent from Onep-B, and *Ulva* spp. was absent from Paua-B. Both of these species are considered opportunistic and can form extensive beds under certain conditions (e.g. high nutrient enrichment). However, their presence at a surface cover of <5% (SACFOR 'R' or 'O') is not considered to be ecologically significant (WFD-UKTAG 2014), and it is not uncommon for seasonal or interannual fluctuations up to a SACFOR rating of common ('C'; 10-19% cover).



Seaweeds *Ulva* spp. and *Agarophyton* spp. at Paua-A.

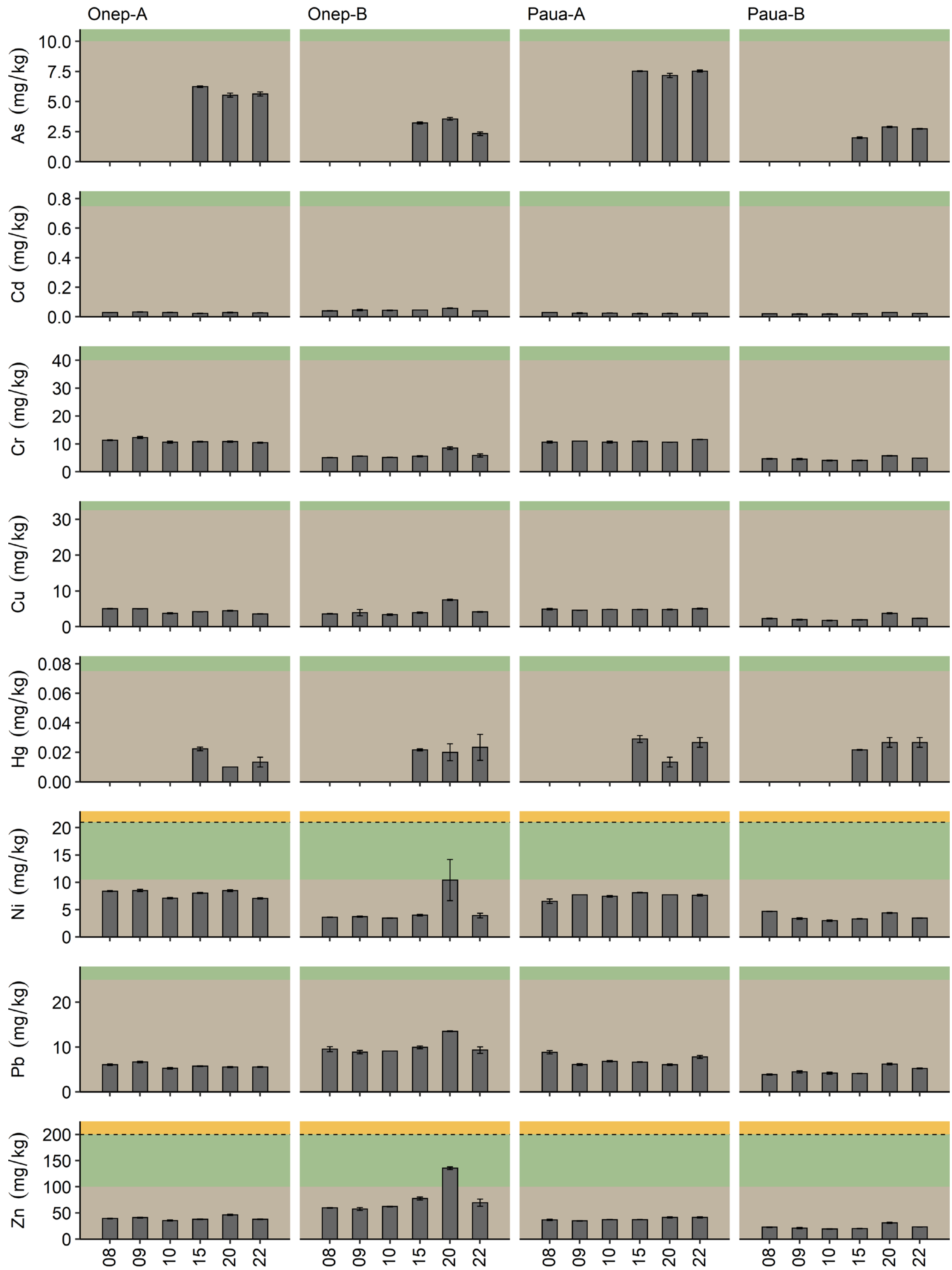


Fig. 9. Plots for trace metals (mean values, mg/kg ± SE). For Ni and Zn, the dotted line on the boundary between 'good' and 'fair' represents the national Default Guideline Value (DGV) for sediment quality. The boundary between grey and green represents half the DGV. As and Hg not measured prior to 2015. Condition rating key as follows:

Very Good	Good	Fair	Poor

Table 4. SACFOR scores for conspicuous epibiota over the six surveys, based on the scale in Table 2 (see also footnote below).

Year	Site	Epifauna			Seaweeds and seagrass		
		Cominella glandiformis (Mud whelk)	*Diloma subrostratum* (Mudflat snail)	*Zeacumantus lutulentus* (Horn snail)	*Agarophyton chilense* (Red seaweed)	*Ulva* spp. (Green seaweed)	*Zostera muelleri* (Seagrass)
2008	Onep-A	-	-	-		R	-
	Onep-B	-	-	-	O	R	-
	Paua-A	-	C	-	O		-
	Paua-B	C	C	C	F	R	-
2009	Onep-A	-	-	-			-
	Onep-B	-	-	-	O	C	-
	Paua-A	-	-	-	O	R	-
	Paua-B	-	-	-	C	C	-
2010	Onep-A	C	-	-	O	F	-
	Onep-B	-	-	-		C	-
	Paua-A	-	-	-	O	O	-
	Paua-B	C	-	-	C	O	-
2015	Onep-A	-	-	-	-	-	-
	Onep-B	-	-	-	-	-	-
	Paua-A	-	-	-	-	-	-
	Paua-B	C	-	C	-	-	-
2020	Onep-A	F	C	O	O	C	S
	Onep-B	R	R	F	O	O	-
	Paua-A	F	-	C	C	O	-
	Paua-B	O	F	O	O	R	-
2022	Onep-A	C	F	O	F	O	A
	Onep-B	-	-	-	-	-	-
	Paua-A	C	C	C	O	C	A
	Paua-B	O	O	-	C	-	-
Example							

SACFOR rating: S=Super abundant, A=Abundant, C=Common, F=Frequent, O=Occasional, R=Rare.

Dash (-) means not present (note: seagrass was not assessed prior to 2020).

4.6.2 Macrofauna cores

Raw macrofaunal data are provided in Appendix 4. Tables 5 and 6, respectively, provide descriptions and abundance summaries of the dominant taxa.

Richness, abundance and AMBI

Based on the aggregated dataset, 100 species or higher taxa have been recorded in the harbour over the six surveys. Mean taxon richness was moderately high overall (12-24 species/core), but in 2020 was generally toward the low end of mean values recorded in previous surveys (Fig. 10a). In the latest survey, richness values were relatively high by comparison with previous years.

Similarly, macrofaunal abundances were relatively high in 2022, compared with 2020 when abundances at three of the four sites were at the lowest levels recorded (Fig10b). Hence, in 2022 there appears to have been a 'recovery' in the apparent macrofauna decline that was evident at the time of the 2020 survey. However, temporal changes in richness and abundance over the monitoring period were not clearly or meaningfully correlated with changes in the measured sediment quality variables. Appendix 5 shows the strength of association between sediment quality variables and macrofauna richness and abundance values was generally weak and inconsistent among sites.

Table 5. Description and eco-group sensitivities of the most commonly occurring sediment-dwelling macrofauna. (EG-I = most sensitive to pollution/disturbance, EG-V = most tolerant). Specimen photos provided by NIWA. Pink colour due to a vital stain.

Main group	Description	Image
Paracalliope novizelandiae Amphipod, EG-I	Amphipods are shrimp-like crustaceans. This species is common in New Zealand estuaries. It is considered to be able to tolerate muddy habitats to some extent, despite the EG-I designation.	
Torridoharpinia hurleyi Amphipod, EG-I	Amphipods are shrimp-like crustaceans. This species contributes significantly to sediment turnover through its burrowing activities. It is an important prey item for birds and small fish.	
Arthritica sp. 5 Bivalve, EG-III	A small deposit feeding bivalve that lives buried in the mud. Tolerant of muddy sediments and moderate levels of organic enrichment. Reported in the 2020 report as *Arthritica* cf. *bifurca* (the sp. 5 designation used here refers to NIWA's voucher name).	
Austrovenus stutchburyi Bivalve, EG-II	Suspension feeding cockle, living near the sediment surface. Can improve sediment oxygenation, increasing nutrient fluxes and influence the type of macrofauna present. Sensitive to organic enrichment. Important in diet of certain birds, rays and fish.	
Linucula hartvigiana Bivalve, EG-II	Small estuarine bivalve mollusc commonly called a nut shell. Can be very abundant and tolerate mud and moderate enrichment, although is classified as EG-II.	
Macomona liliana Bivalve, EG-II	A deposit feeding wedge shell. Lives at depths of up to 10 cm in the sediment and uses a long inhalant siphon to feed on surface deposits and/or particles.	
Aonides trifida Polychaete, EG-I	Small surface deposit-feeding spionid polychaete worm that lives throughout the sediment to a depth of 10cm. Mud optimum <15%.	
Axiothella serrata Polychaete, EG-II	A deposit feeding maldanid (bamboo worm) polychaete worm that is a common infaunal species on the sheltered flats of central New Zealand estuaries.	
Boccardia acus Polychaete, EG-IV	A small surface deposit-feeding spionid. Found in a wide range of sand/mud habitats. Lives in flexible tubes constructed of fine sediment grains, and can form dense mats on the sediment surface.	
Heteromastus filiformis Polychaete, EG-IV	Small capitellid polychaete worm. A sub-surface, deposit-feeder that can thrive under conditions of moderate organic enrichment or disturbance.	
Paradoneis lyra Polychaete, EG-III	Common deposit feeding paraonid worm considered to be reasonably tolerant of muddy sediment and organic enrichment.	
Prionospio aucklandica Polychaete, EG-III	A surface deposit-feeding spionid common in harbours and estuaries. Associated mainly with muddy habitats. Considered tolerant to organic enrichment.	
Scoloplos cylindrifer Polychaete, EG-I	Common in estuaries. Long, slender, sand-dwelling unselective deposit feeder. Although designated EG I, can inhabit relatively muddy and organic-rich sediments.	

Table 6. Site data for each year showing abundances (summed across cores) of the most commonly occurring sediment-dwelling macrofauna.

		Paracalliope novizealandiae	*Torridoharpinia hurleyi*	*Arthritica* sp. 5	*Austrovenus stutchburyi* (cockle)	*Linucula hartvigiana*	*Macomona liliana* (wedge shell))	*Aonides trifida*	*Axiothella serrata*	*Heteromastus filiformis*	*Paradoneis lyra*	*Prionospio aucklandica*	*Scoloplos cylindrifer*
Site	Year	Amphipods		Bivalves				Polychaete worms					
Onep-A	2008	2	93	95	87	164	58	3	6	388	63	38	
Onep-A	2009		23	71	65	293	53	5	1	266	73	40	
Onep-A	2010	1	179	114	119	289	52			252	14	25	
Onep-A	2015	1	17	26	97	125	40		37	184	2	33	2
Onep-A	2020	6	26	8	76	200	45			73	3	83	2
Onep-A	2022	95	13	259	106	304	33	3	52	178	90	207	291
Onep-B	2008			18	309		55	156	191	195	1	4	41
Onep-B	2009			15	268		64	392	33	17		2	37
Onep-B	2010	1		12	281		66	729	18	55	6	2	33
Onep-B	2015			64	218		46	1182	69	97	5	18	24
Onep-B	2020	2		9	200		73	774	22	13	10	8	190
Onep-B	2022	16		13	105		53	822	5	12		6	380
Paua-A	2008			9	12	12	18	8	52	229	313	21	
Paua-A	2009		28	16	95	162	41		4	241	29	17	
Paua-A	2010	6	56	23	114	145	41			401	23	54	2
Paua-A	2015	4	17	2	75	106	31	1		351	39	44	
Paua-A	2020	22	19	4	82	88	46			85	11	131	100
Paua-A	2022	254	4	168	114	79	37		14	168	32	202	63
Paua-B	2008	11	43	24	110	18	110	20	98	332		46	4
Paua-B	2009			7	123	1	107	34	352	318	1	8	
Paua-B	2010	35		37	94	8	91	7	46	762	2	74	3
Paua-B	2015			4	77	26	55	3	33	407	12	60	
Paua-B	2020	1	1	3	66	12	59			103		45	1
Paua-B	2022	9		145	132	1	67	1	44	91	33	80	3

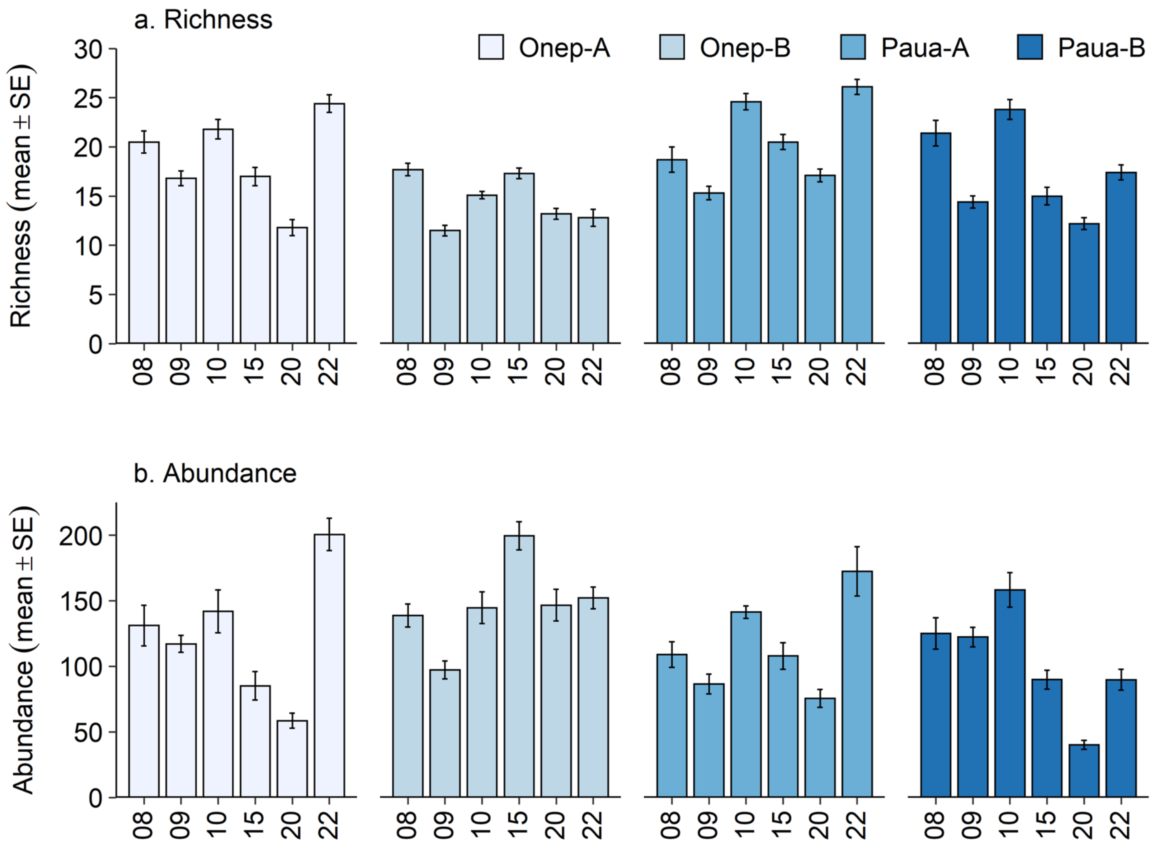


Fig. 10. Patterns (mean ± SE) in taxon richness and abundance per core (cores $0.013m^2$, 150mm deep, volume ~2L).

Values for the biotic index AMBI were within ecological condition ratings of 'good' or 'very good' (Fig. 11). At Onep-B, AMBI values suggest a marked improvement (i.e. decreasing AMBI values). This trend is driven by very high abundances of two polychaete worms (*Aonides trifida* and *Scoloplos cylindrifer*) that are classified as 'highly sensitive' EG-I (Fig. 12)

Main taxonomic groups and dominant species

In total across the three surveys, the 100 taxa recorded were derived from 19 main taxonomic groups. Most of these were poorly represented, with only seven groups present whose site abundances were ≥1% of the total in any one year. General patterns across sites and years in the composition of these eight main groups (in terms of their contribution to site richness and abundance) are shown in Fig. 13.

Polychaete worms were by far the most well-represented group, typically comprising almost half of the taxa present and up to ~80% of the abundance. Most prevalent among the polychaetes was the disturbance-tolerant capitellid worm *Heteromastus filiformis* (EG-IV), which was abundant at all sites. The spionid *Prionospio aucklandica* (EG-III) was especially abundant at outer harbour sites (Onep-A, Paua-A) in 2022, with Onep-B dominated by the two species of EG-I worm noted above (see Table 5 & Table 6).

Bivalve shellfish also made a substantial contribution to site abundances but were represented by fewer species than gastropods. The most abundant (Table 6) were cockles *Austrovenus stutchburyi* (EG-II), small nut shells *Linucula hartvigiana* (EG-II), wedge shells *Macomona liliana* (EG-II), and the small species *Arthritica* sp. 5 (EG-III). These species were quite common across all sites, except for the consistent absence of nut shells from Onep-B. Also, as evident in Table 6, densities of cockles and *Arthritica* sp. 5 were markedly greater in 2022 than previous years, except at Onep-B.

Other key groups represented included small anemones, small shrimp-like amphipods, segmented worms (oligochaetes, EG-V) and ribbon worms (nemerteans, EG-III) (Fig. 13). Amphipods were the most abundant of these groups, although were typically either absent or at very low densities at Onep-B. One particular species (*Paracalliope novizealandiae*, EG-I) occurred in very high abundances at outer harbour sites in 2022 compared to previous years. Collectively, the high abundances of the dominant polychaete, bivalve and amphipod species in 2022 explain the overall site abundance increases in Fig. 10b.

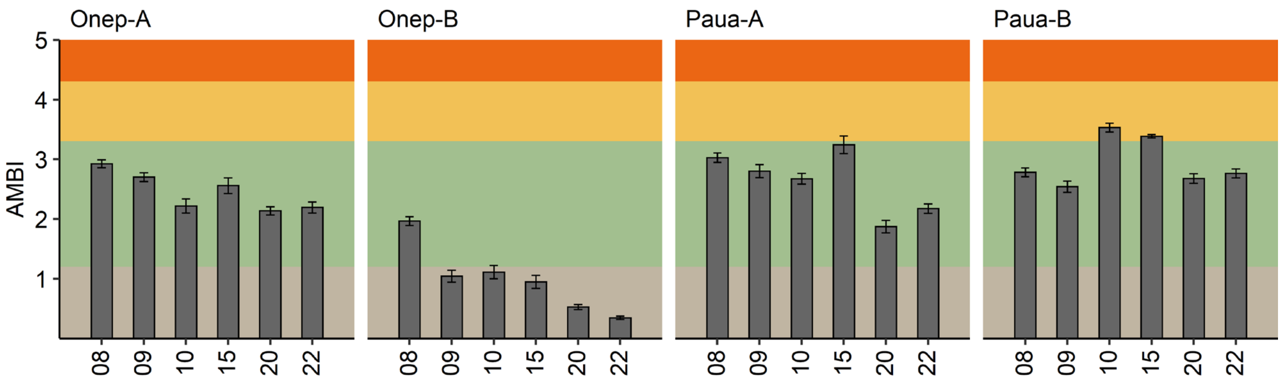


Fig. 11. Patterns (mean ± SE) in AMBI scores compared with condition rating criteria.

Very Good	Good	Fair	Poor

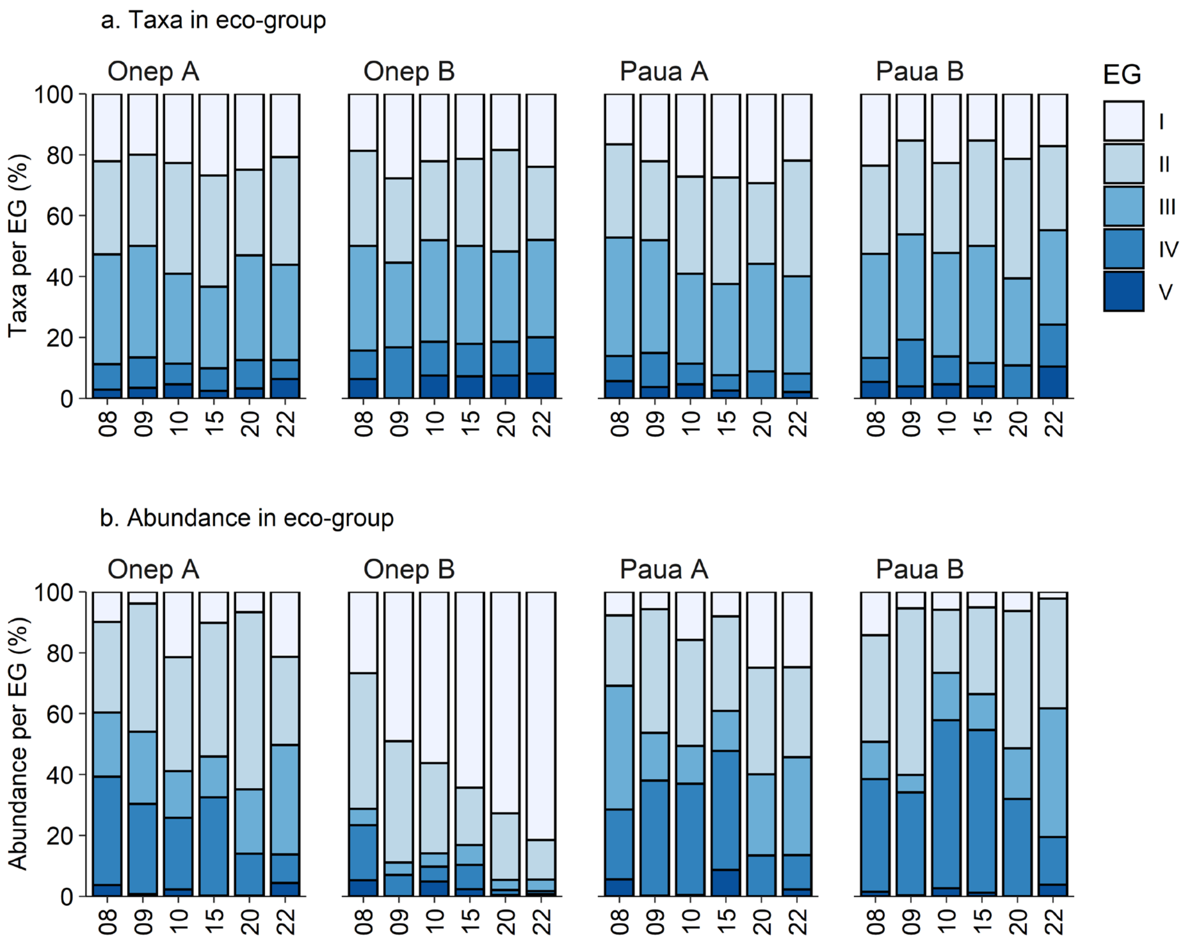


Fig. 12. Site-level data showing the number of taxa and organisms within eco-groups ranging from sensitive to pollution/disturbance (EG-I) to tolerant (EG-V).

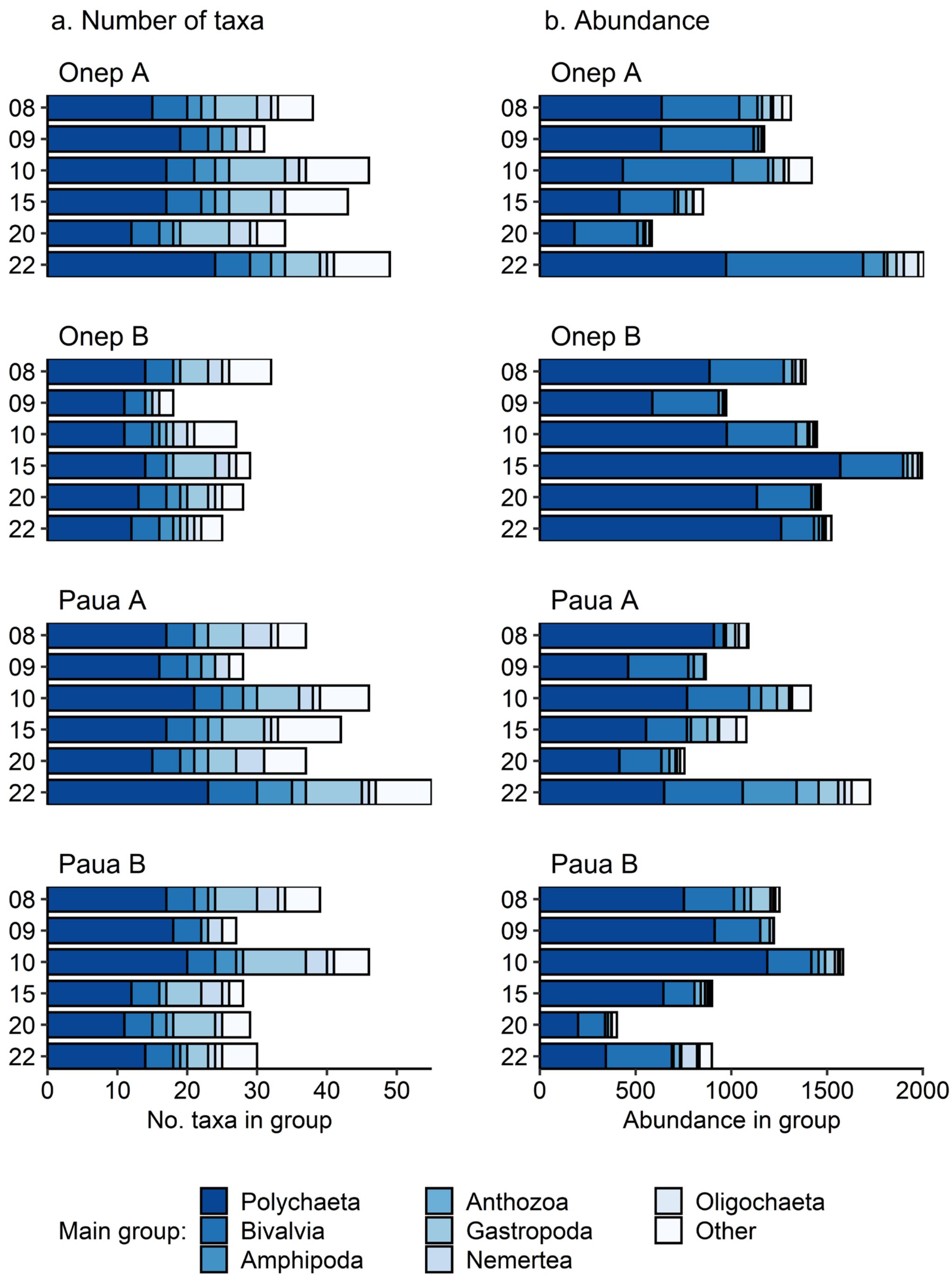


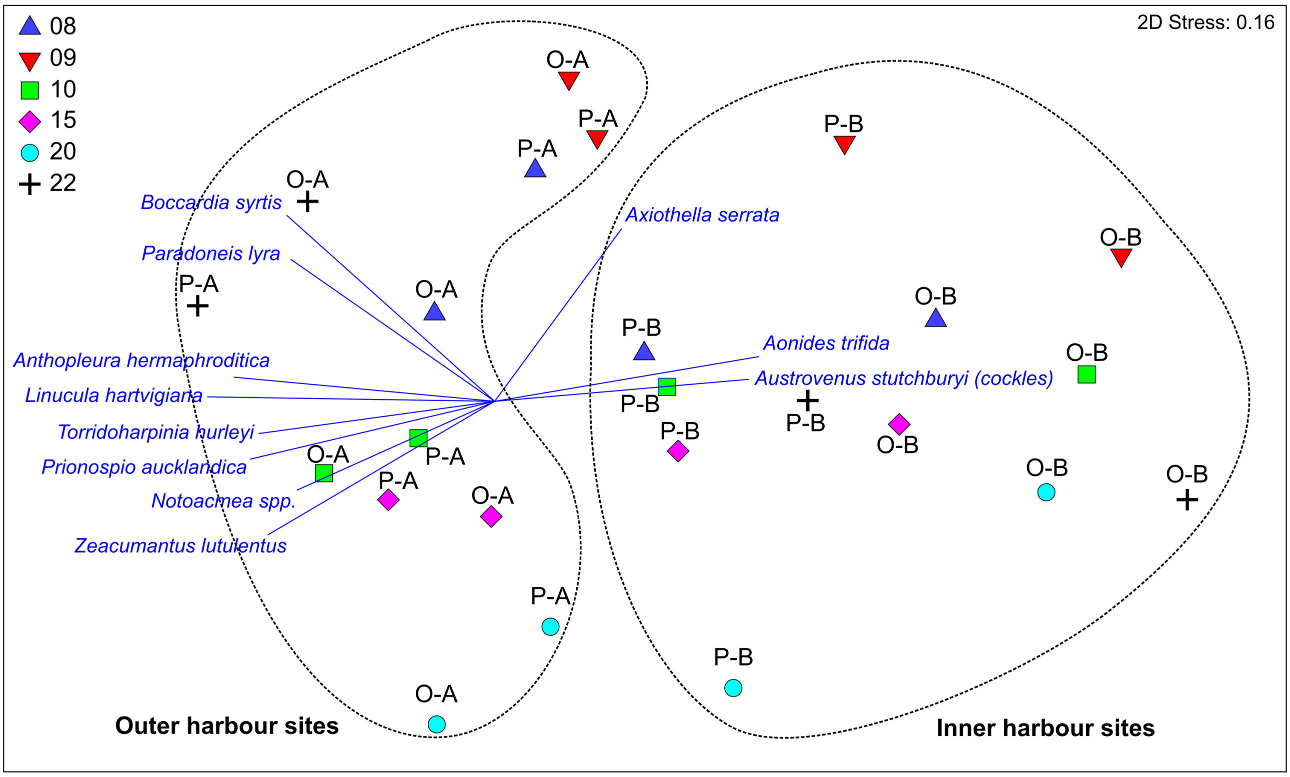
Fig. 13. Data aggregated across years showing the contribution of main taxonomic groups to site-level richness and abundance values. Groups contributing ≥1% of site abundance are shown, with those <1% pooled into 'Other'.

Macrofauna composition patterns

In order to further explore the differences and similarities among sites and surveys in terms of macrofauna, the nMDS ordination in Fig. 14 places sites of similar composition close to each other in a 2-dimensional plot, with less similar sites being further apart. From Fig. 14a, the following main patterns are evident:

- There is an overall spatial pattern in which the outer harbour 'A' sites form a group that is distinct from the upper harbour 'B' sites. The vector plots in Fig. 14a illustrate the dominant taxa that characterise the outer vs upper harbour compositional separation.
- Within the outer harbour 'A' cluster, Onep and Paua have a similar macrofauna composition in any one survey year (i.e. the two sites tend to form pairs in each year), and exhibit a similar trajectory characterised by strong temporal changes in composition.

a. Species overlay



b. Sediment overlay

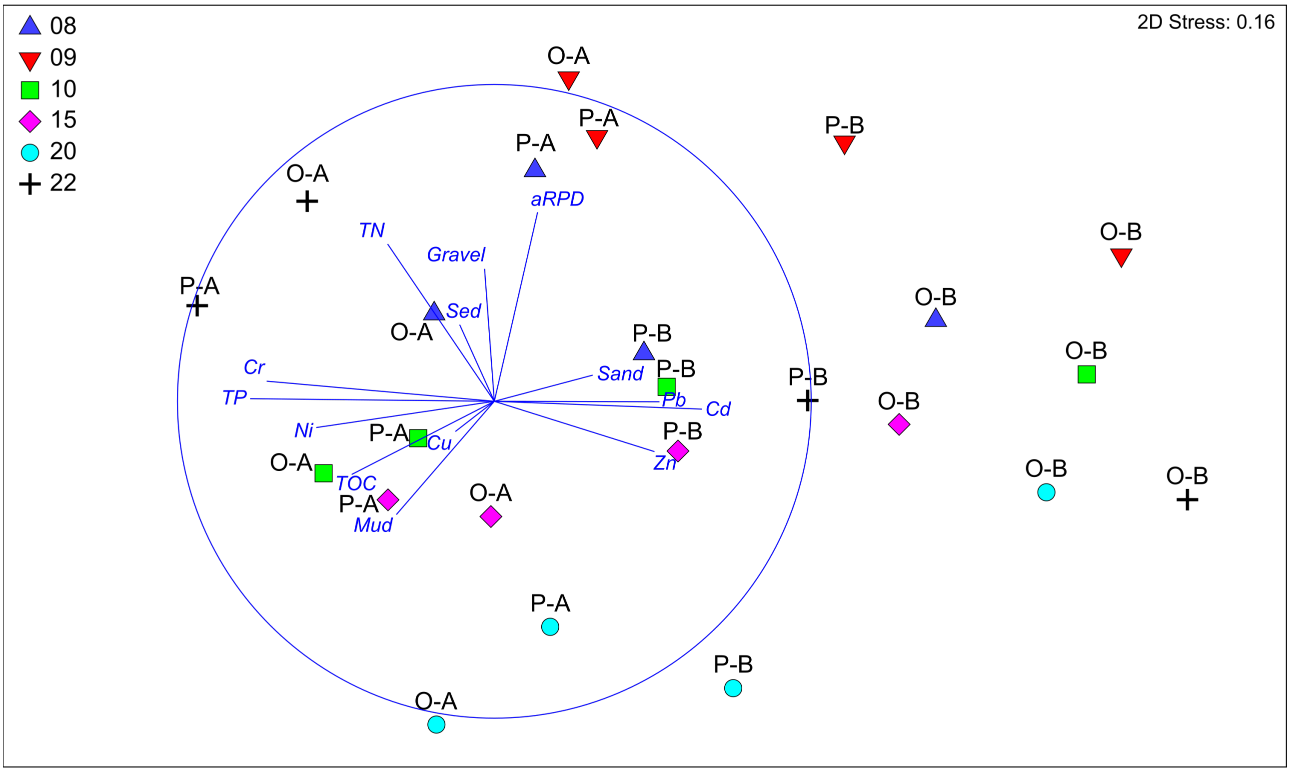


Fig. 14. Non-metric MDS ordination of site-average macrofauna data.

Top: Grouping of sites according to similarity in macrofauna composition (2D stress = 0.16). Ellipses enclose upper vs outer harbour sites, with the main taxa characterising each of these groups shown. The plot reveals that outer harbour sites track each other over time, whereas upper sites show no consistent pattern of temporal change. Bottom: Vectors represent the direction and strength of association (vector length) between the macrofauna grouping pattern and the measured sediment variables (Sed = sedimentation in the year prior to sampling). A perfect correlation would be represented as a vector extending to the circle, illustrating in this case that there is a weak association between macrofauna composition patterns and spatio-temporal changes in sediment quality and sedimentation.

- The upper harbour 'B' cluster has subclusters in which Onep and Paua retain individual site groups. Whereas the Onep-B site cluster is discrete, some of the Paua-B surveys share compositional similarities with the outer harbour sites in the same survey.

The above results make intuitive sense, suggesting that macrofaunal composition at outer harbour sites is strongly influenced by similar processes that, while temporally variable, apply equally to each location. For example, they are likely to be similarly influenced by relatively strong flushing effects of tidally-driven coastal water. By contrast, the upper sites are more likely to be influenced by location-specific processes that affect each upper harbour site in different ways or to different degrees. Examples include freshwater inflows, or sediment loads that may differ according to catchment size and land use (e.g. see GWRCs long-term load monitoring data: https://www.gw.govt.nz/annual-monitoring-reports-2/

Formal analyses of potential environmental predictors based on the Bio-Env procedure did not reveal any consistent or meaningful relationships between macrofauna composition and sedimentation or sediment quality. As was the case for analysis of changes in macrofauna richness and abundances described above, the strength of association between sediment attributes and macrofauna composition was often weak or inconsistent among sites (Appendix 5). This result is illustrated by the relatively short vectors (blue lines) for the sediment variables depicted on Fig. 14b.

Sediment attributes relating to mud content and trophic state (e.g. organic enrichment) are recognised as key drivers of macrofaunal response in estuarine sediments in New Zealand (Cummings et al. 2003; Robertson et al. 2015; Berthelsen et al. 2018; Clark et al. 2020; Clark et al. 2021). However, in the case of Porirua Harbour, the values recorded are generally less than the thresholds at which strong ecological shifts typically occur.

In the Bio-Env analysis, one of the strongest apparent 'explanations' for changes in macrofauna composition was attributed to the trace metal cadmium. Cadmium concentrations showed a moderate association with macrofauna composition for sites overall (Spearman $\rho=0.398$) and a strong association with the temporal variability in macrofauna at Onep-B (Spearman $\rho=0.674$). However, we consider these associations to be coincidental rather than meaningful in terms of cadmium having any causal influence on macrofauna. Cadmium concentrations were very low relative to sediment quality guidelines (see Fig. 8). Although the maximum recorded concentrations occurred at Onep-B (for which macrofaunal composition was reasonably distinct; see Fig. 14), even at that site cadmium values were <5% of the DGV for 'possible' ecological effects. On that basis we suggest that the apparent association between cadmium and macrofaunal change is highly unlikely to be of any ecological significance, even allowing for the possibility that metals collectively can have a chronic impact at concentrations that are less than indicated by individual DGV thresholds (Hewitt et al. 2009). However, it is also the case that the total extractable analytical method used for trace element analysis (i.e. hot, strong acid digestion of samples) is expected to greatly overestimate the fraction that is bioavailable (i.e. 'free' to exert toxic effects).

5. SYNTHESIS AND RECOMMENDATIONS

5.1 SYNTHESIS OF KEY FINDINGS

This report has described the findings of six intertidal surveys of Porirua Harbour, largely following the fine scale survey methods described in New Zealand's NEMP.

At the four fine scale sites, sedimentation has been highly variable over time, with year-to-year changes sometimes consisting of quite pronounced accrual or erosion (e.g. exceeding ±10mm/yr). Long-term average annual sedimentation has been greatest at Onep-A, with 5-yr and 10-yr rates slightly exceeding the national guideline of 2mm/yr. Across all eight intertidal sediment plate sites in the harbour (see Stevens et al. 2022), long-term sediment accretion is up to ~4mm/yr, and sedimentation at subtidal sites is generally even higher The magnitude of the 5-yr & 10-yr sedimentation rates reported by Stevens et al. (2022) is reasonably consistent with rates of 3-5mm/yr that are estimated (by radioisotope and pollen dating of sediment cores) to have occurred since the 1950s (Swales et al. 2005).

A summary of mean values of key physical and biological indicators in relation to ecological condition ratings is provided in Table 7. Almost all sediment quality indicators, except aRPD and mud, have low values that are consistent with 'good' or 'very good' condition. Sediment mud content and aRPD have at worst been rated 'fair' or 'poor', respectively, across survey years, and have shown an improvement (or remained similar) in the two years since the 2020 survey (except for a small increase in mud content at Paua-A).

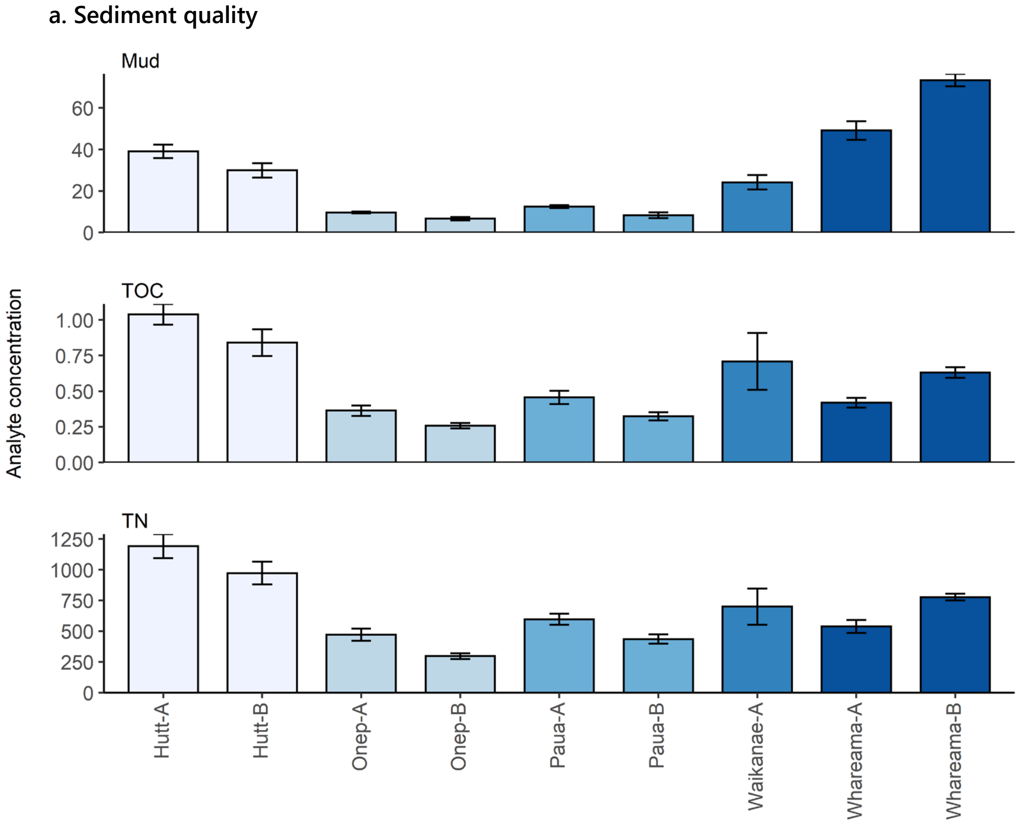
Nonetheless, there appears to be a small (and variable) overall trend of increasing sediment mud content at

Table 7. Synthesis of data for Te Awarua-o-Porirua Harbour fine scale sites summarising condition scores of ecological health, based on mean values of key indicators and criteria and ratings in Table 3. See Glossary for definition of indicators and Fig. 3 (p. 4) for site locations. Long-term sedimentation rate assessed in separate report (Stevens et al. 2022).

Site	Year	Mud %	aRPD mm	TN mg/kg	TP mg/kg	TOC %	As mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Pb mg/kg	Hg mg/kg	Ni mg/kg	Zn mg/kg	AMBI na
Onep-A	2008	10.0	28	685	442	-	-	0.028	11.3	5.1	6.1	-	8.4	39.4	2.9
	2009	9.2	27	643	397	0.39	-	0.034	12.3	5.0	6.7	-	8.5	41.0	2.7
	2010	10.0	14	< 503	393	0.26	-	0.029	10.6	3.8	5.3	-	7.1	35.7	2.2
	2015	8.3	10	< 500	397	0.58	6.2	0.023	10.8	4.2	5.7	0.02	8.0	38.0	2.6
	2020	11.0	6	< 500	407	0.30	5.5	0.029	10.8	4.5	5.5	< 0.02	8.5	46.3	2.1
	2022	8.2	15	< 500	363	0.29	5.6	0.027	10.5	3.6	5.6	0.01*	7.1	38.0	2.2
Onep-B	2008	4	-	305*	158	-	-	0.041	5.1	3.6	9.5	-	3.6	59.9	2.0
	2009	5.7	23	< 507	147	0.21	-	0.046	5.6	4.0	8.9	-	3.7	57.7	1.0
	2010	9.4	10	453*	163	0.19	-	0.044	5.2	3.4	9.1	-	3.4	62.3	1.1
	2015	4.3	10	< 500	196	0.29	3.2	0.046	5.6	3.9	9.9	0.02	4.0	77.7	0.9
	2020	14.1	13	< 500	267	0.36	3.6	0.058	8.5	7.5	13.5	0.02*	10.4	135.7	0.5
	2022	8.6	20	< 500	142	0.24	2.3	0.041	5.9	4.2	9.3	0.02*	3.9	69.7	0.4
Paua-A	2008	12.2	37	823	447	-	-	0.029	10.7	4.9	8.8	-	6.5	36.7	3.0
	2009	9.9	17	700	437	0.38	-	0.025	11.0	4.6	6.1	-	7.7	35.0	2.8
	2010	15.1	10	673	470	0.35	-	0.025	10.7	4.8	6.8	-	7.4	37.3	2.7
	2015	9.2	10	600	450	0.79	7.5	0.022	11.0	4.8	6.6	0.03	8.1	37.3	3.2
	2020	12.7	12	< 500	453	0.31	7.2	0.023	10.6	4.8	6.1	0.01*	7.7	41.7	1.9
	2022	15.3	28	533	467	0.45	7.5	0.025	11.6	5.1	7.8	0.03	7.6	41.7	2.2
Paua-B	2008	4.5	33	547	150	-	-	0.020	4.7	2.3	3.9	-	4.7	23.0	2.8
	2009	4.4	37	470*	137	0.23	-	0.019	4.6	2.0	4.5	-	3.4	21.0	2.5
	2010	7.5	10	597	120	0.23	-	0.019	4.1	1.8	4.2	-	3.0	19.3	3.5
	2015	3.3	10	< 500	118	0.32	2.0	0.021	4.1	2.0	4.1	0.02	3.3	20.2	3.4
	2020	19.7	10	417*	202	0.51	2.9	0.029	5.8	3.8	6.2	0.03	4.4	31.0	2.7
	2022	10.0	28	333*	157	0.33	2.7	0.023	4.9	2.4	5.2	0.03	3.4	23.3	2.8

** Sample mean includes values below lab detection limits. '<' All values below lab detection limit. Dash (–) not analysed*

Condition Rating Key: Very Good | Good | Fair | Poor *Rating criteria not established for TP*



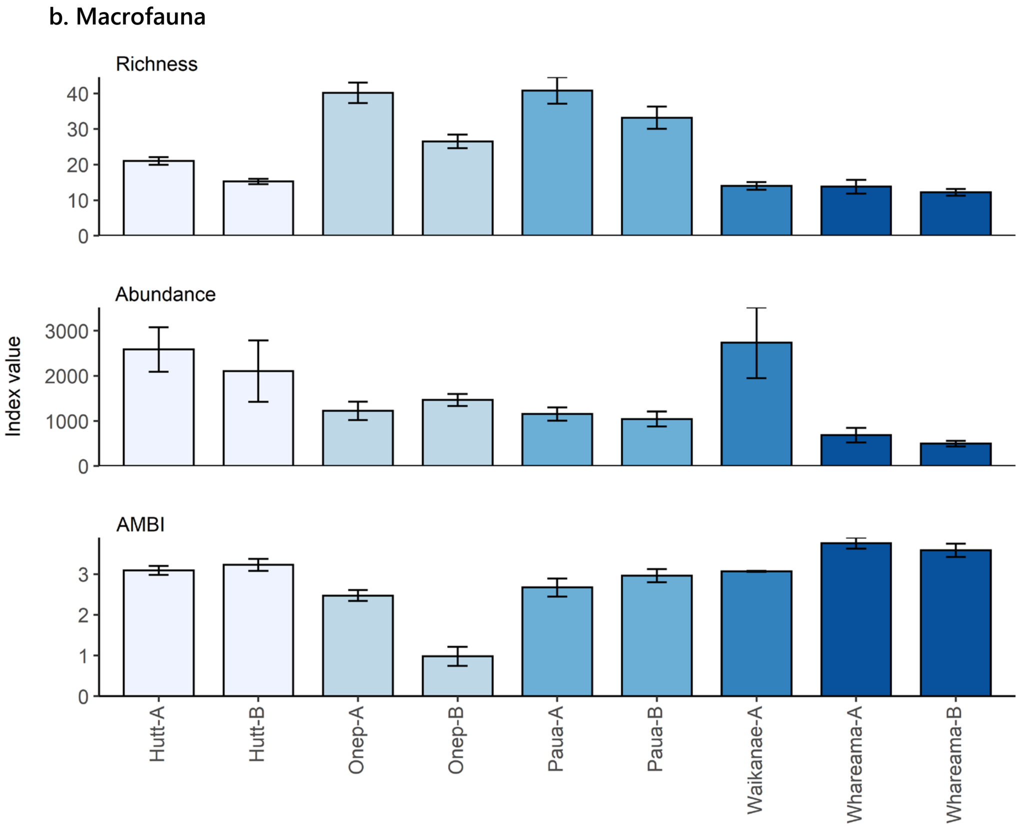


Fig. 15. Broad patterns in key sediment quality and macrofauna indicators, comparing Te Awarua-o-Porirua Harbour sites (Onep & Paua) with other key estuaries in the Wellington region (mean ± SE for surveys pooled over time within each site). Sediment analyte concentrations for mud and TOC are percentages, and for TN are mg/kg.

Onep-B and Paua-B, with current levels at these upper harbour sites greater than was measured during 2008 and 2009. Despite this pattern, the fine scale monitoring shows that the four sites in Porirua Harbour remain in a relatively healthy condition, and are in a better state than sites monitored in other estuaries regionally in terms of key mud, trophic state and macrofauna indicators (Fig. 15).

In addition, concentrations of trace metal contaminants have remained low, and a screening of sediment samples for a range of semi-volatile organic compounds (SVOCs; such as the pesticide DDT) did not reveal any analytes that exceeded method detection limits. While metal and SVOC concentrations can be elevated in harbour sediments near stormwater discharges and stream inflows (Sorensen & Milne 2009), the present results suggest that the intertidal fine scale sites are relatively uncontaminated. As already noted, trace metals individually or in combination may be associated with adverse ecological effects at concentrations less than national DGV thresholds. However, in the case of Porirua Harbour we consider adverse effects to be highly unlikely, reflecting the very low concentrations relative to DGV values, and related matters such as low metal bioavailability.

At the request of GWRC, the results of the fine scale monitoring have been briefly assessed below in the context of the findings of a separate study in which the fine scale data were analysed using a National Benthic Health Model (BHM). The BHM has been recently developed as a tool to provide a nationally standardised measure of the relative impact of muddy sediments (Mud BHM) and trace metal contamination (Metals BHM; based on copper, lead and zinc concentrations) on macrofaunal communities in New Zealand estuaries (Clark et al. 2020). For a given site and survey, the method provides a score of estuary health on a six-point scale relative to other New Zealand estuaries, with Metals BHM scores also benchmarked to sediment quality guidelines that are stricter than ANZG (2018) DGVs referred to in the present report. BHM scores for GWRC estuaries were recently provided to GWRC by Cawthron Institute as part of a separate analysis, with a summary in Appendix 6.

For Porirua Harbour, Mud BHM results indicate that most Onepoto and Pāuatahanui sites and surveys fall within a band consistent with a 'moderate' impact relative to other estuarine sites in New Zealand (i.e. BHM scores of 3 to <4, Appendix 6). Two Onepoto scores (Onep-A 2009, Onep-B 2022) are consistent with a 'low' mud impact (2 to <3), and one Pāuatahanui score (Paua-B 2022) is consistent with a 'high' impact (4 to <5). These results do not relate strongly to the %mud values for the estuary sites, with considerable variability in Mud BHM values across the range of sediment %mud values measured, and no significant increase in BHM in response to increasing mud (Fig. 16). For example, the highest relative impact score at Paua-B in 2022 (see Appendix 6) was associated with an average sediment mud content (~10%) that was about half of that measured in 2020 (see Table 7). An absence of a strong relationship between BHM scores and mud across the values measured at Porirua Harbour sites is consistent with other analyses described above (i.e. Bio-Env), which that did not show a strong association between mud content and macrofaunal community composition.

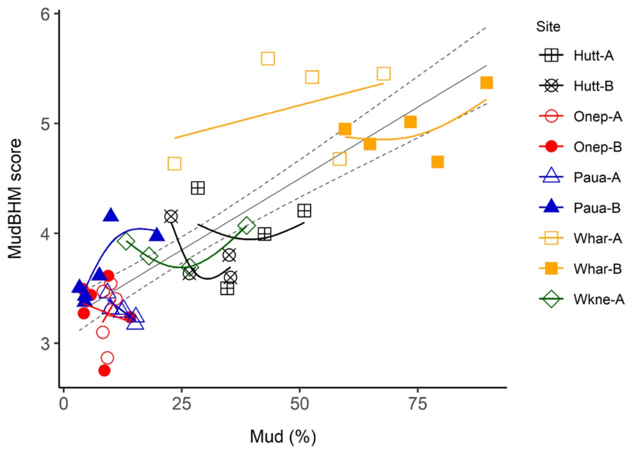


Fig. 16. Relationship between average sediment mud content and Mud BHM scores for GWRC estuary sites, showing Sites A and B in the Onepoto (red) and Pauatahanui (blue) Inlets of Porirua Harbour. Smoothing lines that allow for non-linear responses are fitted to the overall data (solid grey) with 95% confidence interval (dashed grey), and for individual estuaries.

Most Metals BHM scores also fell in a 'moderate' impact category relative to other estuaries in New Zealand. Interpretation of impacts is further aided by a rating scheme of 'absolute' impact boundaries (see Appendix 6), in which Metals BHM values <3.6 are rated 'good' and values of 3.6 to < 4.8 are rated fair. Metals BHM absolute scores were 'fair' for four Onepoto and two Pāuatahanui sites and surveys, with the remainder rated as 'good'. The highest impact score of 4.1 was for Onep-B in 2020, which is consistent with the highest copper, lead and zinc concentrations recorded in monitoring to date (see Fig. 9 and Table 7). However, these high concentrations were correlated with a correspondingly high sediment mud content, and were nonetheless very low relative to ANZG (2018) Default Guideline Values. The 'fair' rating reflects that the absolute scale draws on sediment quality guidelines that are more conservative than ANZG (2018) values. As for Mud BHM, Metals BHM scores also varied widely across a small range in metal concentration (note that the single 'metal concentration' variable used in the BHM was derived by aggregating copper, lead and zinc concentrations using Principal Component Analysis).

Overall, the BHM provides a useful means of placing the relative health of Porirua Harbour scale sites in context to other estuaries in the Wellington region and nationally. From a monitoring perspective in Wellington SOE estuaries specifically, the BHM appears to have less utility as a tool for tracking temporal changes in estuary health, due to the following:

- Within each estuary or site, there is considerable variability of BHM scores across the measured range of mud or metal values.
- The trend of an increasing BHM score (i.e. degrading condition) with increasing sediment mud content evident for Wellington estuaries collectively in Fig. 16 (also in Appendix 6 for estuaries nationally), is not mirrored within each site; BHM scores do not significantly increase across the range of mud values measured at each Wellington estuary site (Fig. 16).
- Together, these limitations suggest that the BHM will be relatively insensitive to changes in mud and metals in Wellington estuaries. Even in Whareama Estuary (see Fig. 16) where there was a particularly wide range in the mean sediment mud content(~23-90%), there was a trend for only a slight increase in BHM with increasing mud. It is important, therefore, that undue weight is not placed on small temporal changes in BHM scores; Clark et al. (2020, Supplementary Material C) recommended that BHM score changes of ≤ ± 1 should be considered within the range of natural variation.

A key purpose of the present survey was to check the overall decline in sediment quality (increased mud and shallowing of aRPD) and deterioration in macrofaunal indicators that was observed between 2008 and 2020. The latest survey has revealed an apparent 'recovery' in many of the indicators, suggesting improved conditions at the four monitoring sites. However, the reasons for the apparent improvement are unclear, as changes in macrofauna richness, abundance and composition were not clearly or plausibly related to any of the measured sediment variables. Such findings are further reinforced by the BHM results. As such, there appear to be other drivers (e.g. sea surface temperature, hydrodynamic factors) of spatial and temporal change in the intertidal habitats of the harbour that are not reflected in any of the sediment constituents that are routinely measured using NEMP methods. As noted in Section 4.6.2, it is conceivable that the relative importance of environmental factors, in terms of influences on sediment-dwelling macrofauna, differs across the harbour and over time. Whereas outer harbour sites appear to be similar ecologically, the upper harbour sites differ to each other and are conceivably more strongly influenced by inputs from adjacent catchments.

It should also be kept in mind that ecological communities may change due to factors that are not directly related to external environmental drivers. For example, the recognised vagaries of recruitment events in marine invertebrates can greatly influence community composition and organism abundances. As such, it is conceivable that the temporal changes in macrofauna described here are simply a reflection of natural variability. Nonetheless, at some level, external environmental factors will almost certainly be important to the ecological health of the harbour, even if the key drivers are not immediately apparent. In this respect, previous reports have discussed potential catchment pressures that lead to wider-harbour change, in particular sediment inputs from past, ongoing or future potential sources. These sources include urban subdivision, the Transmission Gully motorway development, and exotic forest harvest (Swales et al. 2005; Stevens et al. 2022). The latter activity has the potential to release large pulses of sediment during harvest and for a few years after (e.g. Gibbs & Woodward 2018).

5.2 KEY CONSIDERATIONS FOR FUTURE MONITORING

The fine scale monitoring programme from 2008-2022 has provided an invaluable record of the state and variability of sediments and sediment-dwelling biota in Porirua Harbour. One of the matters discussed in the 2020 fine scale report (Forrest et al. 2020) was whether the NEMP survey approach was fit-for-purpose in terms of ongoing needs. As the NEMP fine scale sites are intentionally located away from the direct effects of point sources, they provide an excellent basis (using the current indicators) for monitoring long-term changes (i.e. over time scales of decades) in the harbour as a whole.

However, the NEMP fine scale sites do not necessary provide a strong foundation for capturing changes in the state of the estuary that may arise in the near-future, or which are localised to areas around point sources such as river outflows (e.g. pulse inputs of sediment from catchment sources). As an example, the 2020 broad scale survey revealed extensive intertidal areas in Kakaho Bay that were affected by muddy sediment deposition, but the positioning of the existing fine scale sites meant they did not detect the ecological consequences of this sediment deposition.

The NEMP broad scale survey approach clearly has value in terms of capturing large scale habitat changes that occur in intertidal areas. However, the assessment methods are relatively coarse and subjective (e.g. sediment mud content is assessed across coarse spatial scales using subjective grain size categories), and ecological effects are focused on vegetation (e.g. seagrass or salt marsh loss) rather than faunal changes. This situation suggests that there is a need for a hybrid approach that sits between the broad scale methodology and the quantitative but highly site-specific fine scale methodology, and which provides for improved quantification of ecological condition in estuary locations that are most vulnerable.

Beyond NEMP survey limitations and improvements, there is a need for a more systematic and goal-directed approach to monitoring in Porirua Harbour. While there have clearly been many studies to date (see Sections 1 & 2), these have been undertaken in an ad hoc and/or fragmented way, without necessarily being targeted to specific goals or overarching management questions. It would be timely to consider a more integrated monitoring approach, which would ideally be underpinned and informed by the following related workstreams:

- A synthesis of the learnings from environmental studies that have been undertaken in the harbour; e.g. considering intertidal and subtidal SOE studies, point source investigations and consent-related monitoring.
- A synthesis of the catchment studies that have been undertaken, and an evaluation of likely drivers of future change in the harbour, considering catchment land use and pressures (e.g. exotic forest harvest patterns or subdivision plans) as well as wider environmental factors (e.g. increases in sea surface temperature or sea level rise).
- As assessment of the harbour locations and habitats that are the most vulnerable to future pressures. For example, the intertidal zone may be less prone to negative long-term impacts from catchment-derived muddy sediment inputs than subtidal basins where sediments tend to accumulate relatively quickly.

An assessment that considered the above matters, alongside the development of monitoring goals and aspirations, would provide a sound basis for the design of a fit-for purpose long-term programme for assessing and monitoring the health of the harbour.

5.3 RECOMMENDATIONS

As there has been an improvement in the sediment quality and ecological condition of the established intertidal fine scale SOE sites in Porirua Harbour since 2020, there is no immediate need for additional or targeted follow-up monitoring. It is recommended that GWRC continue to monitor sites at 5-yearly intervals but in the interim work towards developing a future-focused programme that integrates and optimises monitoring across intertidal, subtidal and catchment domains. As mentioned in the previous section, background desktop investigations that will contribute to this goal include:

- A synthesis of the learnings from environmental studies that have been undertaken in the harbour to date.
- A synthesis of the catchment studies that have been undertaken, and an evaluation of likely drivers of future change in the harbour.
- An assessment of the harbour locations and habitats that are the most vulnerable to future pressures.

The subsequent design of an improved monitoring programme would benefit from an analysis of the intertidal and subtidal monitoring data (macrofauna and sediment chemistry) to determine the optimal sampling effort for long-term monitoring.

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APPENDIX 1. COORDINATES OF FINE SCALE SITES (CORNERS)

Arm	Site	Description	Label	NZTM_East	NZTM_North
Onepoto	Onep-A	Railway downstream	O_A1	1756452	5447771
Onepoto	Onep-A	Railway downstream	O_A2	1756468	5447830
Onepoto	Onep-A	Railway downstream	O_A3	1756500	5447818
Onepoto	Onep-A	Railway downstream	O_A4	1756482	5447764
Onepoto	Onep-B	River upstream	O_B1	1754568	5445467
Onepoto	Onep-B	River upstream	O_B2	1754536	5445517
Onepoto	Onep-B	River upstream	O_B3	1754563	5445531
Onepoto	Onep-B	River upstream	O_B4	1754590	5445487
Pāuatahanui	Paua-A	Boatshed downstream	P_A1	1757240	5448655
Pāuatahanui	Paua-A	Boatshed downstream	P_A2	1757266	5448601
Pāuatahanui	Paua-A	Boatshed downstream	P_A3	1757242	5448587
Pāuatahanui	Paua-A	Boatshed downstream	P_A4	1757212	5448645
Pāuatahanui	Paua-B	Upstream	P_B1	1760353	5448353
Pāuatahanui	Paua-B	Upstream	P_B2	1760356	5448294
Pāuatahanui	Paua-B	Upstream	P_B3	1760386	5448298
Pāuatahanui	Paua-B	Upstream	P_B4	1760382	5448353

APPENDIX 2. RJ HILL ANALYTICAL METHODS

Sample Type: Sediment			
Test	**Method Description**	**Default Detection Limit**	**Sample No**
Environmental Solids Sample Drying*	Air dried at 35°C Used for sample preparation. May contain a residual moisture content of 2-5%.	-	1-12
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%.	-	1-12
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	13-16
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	1-12
Total Recoverable digestion	Nitric / hydrochloric acid digestion. US EPA 200.2.	-	1-12
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	1-12
Total Nitrogen*	Catalytic Combustion (900°C, O2), separation, Thermal Conductivity Detector [Elementar Analyser].	0.05 g/100g dry wt	1-12
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	1-12
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	1-12
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.	0.002 - 6 mg/kg dry wt	13-16
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	1-12
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	1-12
Fraction < 63 µm*	Wet sieving with dispersant, as received, 63 µm sieve, gravimetry (calculation by difference).	0.1 g/100g dry wt	1-12

APPENDIX 3. SEDIMENT QUALITY RAW DATA 2022

A. NEMP analytes: For aRPD, the range of values is based on 10 measurements per site.

Site	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
Onep-A	X	1	90.2	8.8	0.3	<500	380	13.3 (10 to 15)	5.9	0.026	10.6	3.7	<0.02	7.3	5.7	39
	Y	1.6	90.5	7.9	0.28	<500	370	18.0 (12 to 22)	5.7	0.028	10.7	3.6	0.02	7	5.6	38
	Z	1	91	8	0.29	<500	340	14.5 (10 to 20)	5.3	0.026	10.1	3.5	<0.02	6.9	5.4	37
Onep-B	X	0.8	92.4	6.8	0.21	<500	126	24.3 (15 to 30)	2.1	0.04	4.8	4.1	<0.02	3.1	8.1	57
	Y	1	90.8	8.2	0.28	<500	130	20.0 (15 to 25)	2.3	0.041	6	4	0.02	4	9.3	72
	Z	1.8	87.3	10.8	0.22	<500	169	16.3 (18 to 5)	2.6	0.041	6.8	4.4	0.04	4.6	10.6	80
Paua-A	X	1.9	79.2	18.9	0.48	600	460	26.7 (15 to 40)	7.7	0.025	11.7	5.3	0.03	7.9	8.4	44
	Y	3.9	81.6	14.5	0.43	500	470	28.3 (25 to 30)	7.4	0.025	11.7	4.8	0.03	7.4	7.7	41
	Z	8.7	78.9	12.4	0.45	500	470	27.5 (15 to 35)	7.5	0.024	11.5	5.1	0.02	7.6	7.3	40
Paua-B	X	1.7	88.7	9.6	0.34	500	165	20.0 (15 to 25)	2.7	0.025	5	2.4	0.03	3.5	5.1	24
	Y	3.1	85.6	11.3	0.32	<500	155	28.3 (15 to 35)	2.7	0.022	4.9	2.3	0.02	3.5	5.2	23
	Z	2.2	88.8	9	0.34	<500	151	32.5 (30 to 35)	2.8	0.022	4.8	2.4	0.03	3.3	5.4	23
								DGV	20	1.5	80	65	0.15	21	50	200
								GV-high	70	10	370	270	1	52	220	410

SALT ECOLOGY

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B. Semi-volatile organic compounds (SVOCs). All concentrations were below method detection limits.

Analyte	Sample Name:	Onep-A	Onep-B	Paua-A	Paua-B	Onep-A
Dry Matter	g/100g as rcvd	69	76	68	73	72.5
Haloethers Trace in SVOC Soil Samples by GC-MS						
Bis(2-chloroethoxy) methane	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Bis(2-chloroethyl)ether	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Bis(2-chloroisopropyl)ether	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
4-Bromophenyl phenyl ether	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
4-Chlorophenyl phenyl ether	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Nitrogen containing compounds Trace in SVOC Soil Samples, GC-MS						
N-Nitrosodiphenylamine + Diphenylamine	mg/kg dry wt	< 0.16	< 0.15	< 0.16	< 0.15	< 0.16
2,4-Dinitrotoluene	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
2,6-Dinitrotoluene	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Nitrobenzene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
N-Nitrosodi-n-propylamine	mg/kg dry wt	< 0.16	< 0.15	< 0.16	< 0.15	< 0.16
Organochlorine Pesticides Trace in SVOC Soil Samples by GC-MS						
Aldrin	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
alpha-BHC	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
beta-BHC	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
delta-BHC	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
gamma-BHC (Lindane)	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
4,4'-DDD	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
4,4'-DDE	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
4,4'-DDT	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Dieldrin	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Endosulfan I	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Endosulfan II	mg/kg dry wt	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Endosulfan sulphate	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Endrin	mg/kg dry wt	< 0.16	< 0.15	< 0.16	< 0.15	< 0.16
Endrin ketone	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Heptachlor	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Heptachlor epoxide	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Hexachlorobenzene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Polycyclic Aromatic Hydrocarbons Trace in SVOC Soil Samples						
Acenaphthene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Acenaphthylene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Anthracene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Benzo[a]anthracene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Benzo[a]pyrene (BAP)	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Benzo[b]fluoranthene + Benzo[j]fluoranthene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Benzo[g,h,i]perylene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Benzo[k]fluoranthene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
1&2-Chloronaphthalene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Chrysene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Dibenzo[a,h]anthracene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Fluoranthene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Fluorene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Indeno(1,2,3-c,d)pyrene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
2-Methylnaphthalene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Naphthalene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Phenanthrene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Pyrene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Benzo[a]pyrene Potency Equivalency Factor (PEF) NES	mg/kg dry wt	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3
Benzo[a]pyrene Toxic Equivalence (TEF)	mg/kg dry wt	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3
Phenols Trace in SVOC Soil Samples by GC-MS						
4-Chloro-3-methylphenol	mg/kg dry wt	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
2-Chlorophenol	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
2,4-Dichlorophenol	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
2,4-Dimethylphenol	mg/kg dry wt	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4
3 & 4-Methylphenol (m- + p-cresol)	mg/kg dry wt	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4
2-Methylphenol (o-cresol)	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
2-Nitrophenol	mg/kg dry wt	< 0.4	< 0.4	< 0.4	< 0.4	< 0.4
Pentachlorophenol (PCP)	mg/kg dry wt	< 6	< 6	< 6	< 6	< 6
Phenol	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
2,4,5-Trichlorophenol	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
2,4,6-Trichlorophenol	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Plasticisers Trace in SVOC Soil Samples by GC-MS						
Bis(2-ethylhexyl)phthalate	mg/kg dry wt	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5
Butylbenzylphthalate	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Di(2-ethylhexyl)adipate	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Diethylphthalate	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Dimethylphthalate	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Di-n-butylphthalate	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Di-n-octylphthalate	mg/kg dry wt	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
Other Halogenated compounds Trace in SVOC Soil Samples by GC-MS						
1,2-Dichlorobenzene	mg/kg dry wt	< 0.16	< 0.15	< 0.16	< 0.15	< 0.16
1,3-Dichlorobenzene	mg/kg dry wt	< 0.16	< 0.15	< 0.16	< 0.15	< 0.16
1,4-Dichlorobenzene	mg/kg dry wt	< 0.16	< 0.15	< 0.16	< 0.15	< 0.16
Hexachlorobutadiene	mg/kg dry wt	< 0.16	< 0.15	< 0.16	< 0.15	< 0.16
Hexachloroethane	mg/kg dry wt	< 0.16	< 0.15	< 0.16	< 0.15	< 0.16
1,2,4-Trichlorobenzene	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Other SVOC Trace in SVOC Soil Samples by GC-MS						
Benzyl alcohol	mg/kg dry wt	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0
Carbazole	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Dibenzofuran	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10
Isophorone	mg/kg dry wt	< 0.10	< 0.10	< 0.10	< 0.10	< 0.10

APPENDIX 4. MACROFAUNA CORE SUMMARY DATA FOR ALL YEARS

Cores 130mm diameter to 150mm deep, 0.013m^2 sample area, ~2L core volume. Data summed across cores within site and survey.

Main group	Taxa	Habitat	EG	08-Onep-A	08-Onep-B	08-Paua-A	08-Paua-B	09-Onep-A	09-Onep-B	09-Paua-A	09-Paua-B	10-Onep-A	10-Onep-B	10-Paua-A	10-Paua-B	15-Onep-A	15-Onep-B	15-Paua-A	15-Paua-B	20-Onep-A	20-Onep-B	20-Paua-A	20-Paua-B	22-Onep-A	22-Onep-B	22-Paua-A	22-Paua-B
Amphipoda	Amphipoda sp. 3	Infauna	II									5		2													
Amphipoda	Amphipoda sp. 5	Infauna	II																		1						
Amphipoda	Haplocheira barbimana	Infauna	-																							22	
Amphipoda	Josephosella awa	Infauna	II												1												
Amphipoda	Paracalliope novizealandiae	Infauna	I	2			11					1	1	6	35	1		4		6	2	22	1	95	16	254	9
Amphipoda	Paracorophium spp.	Infauna	III												1										9	1	
Amphipoda	Parawaldeckia sp. 1	Infauna	II					1																			
Amphipoda	Phoxocephalidae	Infauna	I							1														1		1	
Amphipoda	Torridoharpinia hurleyi	Infauna	I	93			43	23		28		179		56		17		17		26		19	1	13		4	
Anthozoa	Anthopleura hermaphroditica	Epibiota	III	16		1		10		21		17		15		27		25		10		1		15		14	
Anthozoa	Edwardsia sp.	Epibiota	II	8	44	10	34	8	22	33	50	9	61	67	34	15	23	60	33		17	30	13	3	19	100	34
Bivalvia	Arthritica sp. 5	Infauna	III	95	18	9	24	71	15	16	7	114	12	23	37	26	64	2	4	8	9	4	3	259	13	168	145
Bivalvia	Austrovenus stutchburyi	Infauna	II	87	309	12	110	65	268	95	123	119	281	114	94	97	218	75	77	76	200	82	66	106	105	114	132
Bivalvia	Cyclomactra ovata	Infauna	II													1										10	
Bivalvia	Lasaea parengaensis	Infauna	II																					14	1		
Bivalvia	Linucula hartvigiana	Infauna	II	164		12	18	293		162	1	289		145	8	125		106	26	200		88	12	304		79	1
Bivalvia	Macomona liliana	Infauna	II	58	55	18	110	53	64	41	107	52	66	41	91	40	46	31	55	45	73	46	59	33	53	37	67
Bivalvia	Paphies australis	Infauna	II		6								2								2						
Bivalvia	Scintillona zelandica	Infauna	-																							1	
Bivalvia	Solemya parkinsonii	Infauna	I	1																						1	
Brachypoda	Cephalocarida sp. 1	Infauna	-	1																							
Cirripedia	Austrominius modestus	Epibiota	II																					1		1	
Copepoda	Copepoda sp. 1	Infauna	II										1										1				
Copepoda	Copepoda sp. 2	Infauna	II									1															
Cumacea	Colurostylis whitireia	Infauna	I									1		3								1		5	1	49	
Decapoda	Austrohelice crassa	Infauna	V									8				1								1			1
Decapoda	Halicarcinus spp.	Infauna	III	14	2		6					9			3	2		4						1		9	
Decapoda	Halicarcinus whitei	Infauna	III		1		1					3	6	2	8	4	4		8		6	4	6	15	12	19	13
Decapoda	Hemigrapsus crenulatus	Infauna	II		1																						
Decapoda	Hemiplax hirtipes	Infauna	III	4		1								2				1			1			5		7	12
Decapoda	Paguristes pilosus	Infauna	II																	1							
Decapoda	Unidentified decapod megalopa	Larva	II																	2							
Diptera	Diptera sp. 2	Larva	IV								1		1														
Gastropoda	Coelotrochus tiaratus	Epibiota	I												1												
Gastropoda	Cominella glandiformis	Epibiota	III	11	3	5	19					6	9	10	13	6	9	9	3	9	4	2	4	16	4	4	3
Gastropoda	Diloma subrostratum	Epibiota	II	2	1	1	15					6		4	8	4	4	4	2				10				
Gastropoda	Eatoniella olivacea	Epibiota	I	1								2															
Gastropoda	Micrelenchus huttonii	Epibiota	-																							1	
Gastropoda	Neoguraleus spp.	Epibiota	-																	1		1				2	1
Gastropoda	Notoacmea spp.	Epibiota	II	10	8	11	27					9		27	11	16	8	20	6	4	2	2	1	7		44	3
Gastropoda	Papawera zelandiae	Epibiota	I	3	4	31	38					3		10	12	5	1	12	7	1			1	16		37	
Gastropoda	Philine sp. 1	Epibiota	II																				1				
Gastropoda	Potamopyrgus spp.	Epibiota	IV												3												
Gastropoda	Turbonilla zealandica	Epibiota	I									10		1	1					1				4		6	
Gastropoda	Xymene plebeius	Epibiota	I				1					4			1	1	2	2		1						2	
Gastropoda	Zeacumantus lutulentus	Epibiota	II	19		1	2					16		11	2	3	3	9	4	5	1	4	1	4		7	
Holothuroidea	Taeniogyrus dendyi	Infauna	I		10		11		5	3	3		1	8	2	2		4	5	1		9	8	1		3	3
Mysidacea	Mysida	Infauna	II		3		2						1		2						1		11	1	16	7	35
Nematoda	Nematoda	Infauna	III	3	2	1	1	5	2	1		1	1		1	1	1	4									

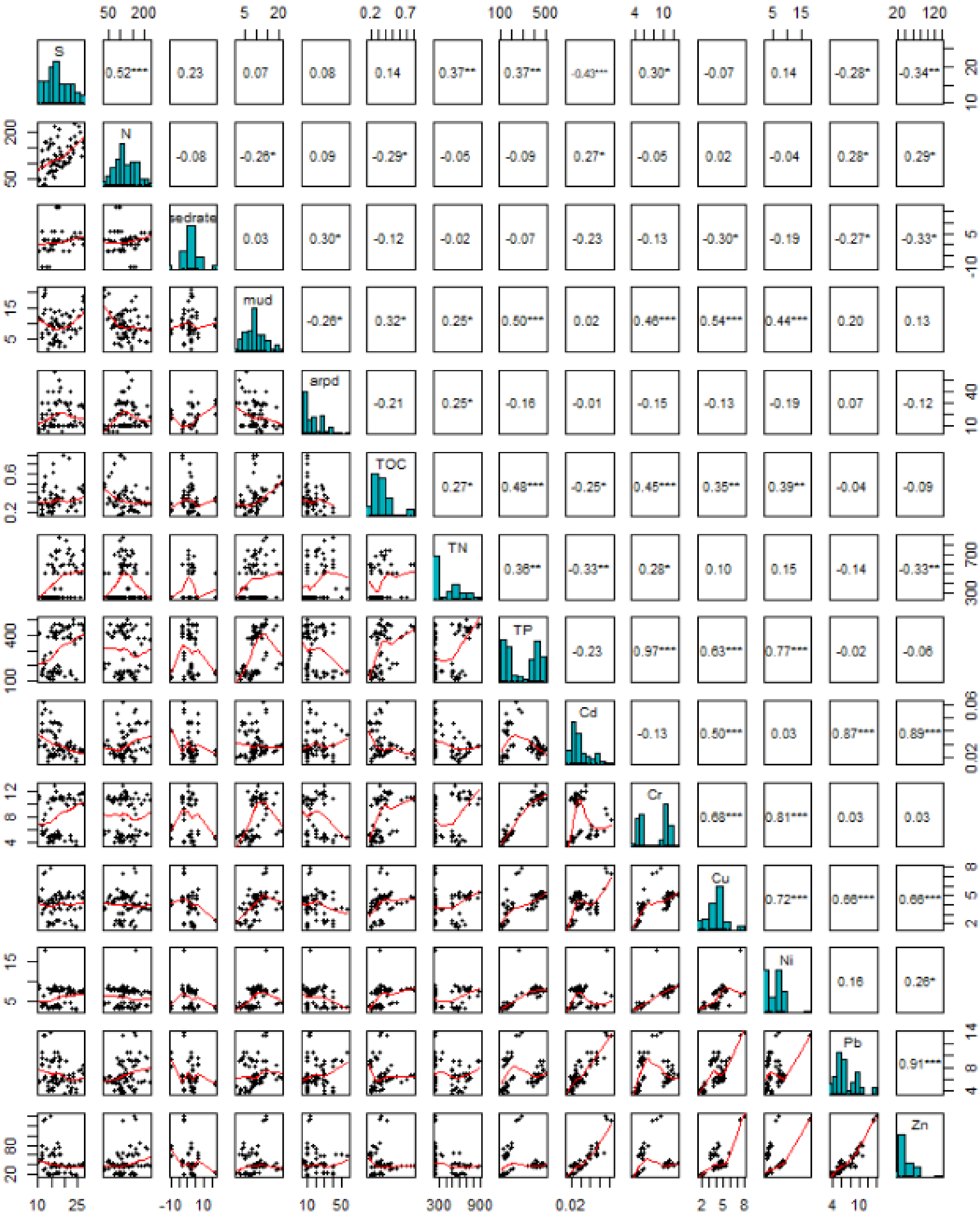
Appendix 4 (cont.)

Main group	Taxa	Habitat	EG	08-Onep-A	08-Onep-B	08-Paua-A	08-Paua-B	09-Onep-A	09-Onep-B	09-Paua-A	09-Paua-B	10-Onep-A	10-Onep-B	10-Paua-A	10-Paua-B	15-Onep-A	15-Onep-B	15-Paua-A	15-Paua-B	20-Onep-A	20-Onep-B	20-Paua-A	20-Paua-B	22-Onep-A	22-Onep-B	22-Paua-A	22-Paua-B
Nemertea	Nemertea	Infauna	III	12	29	18	14	7	10	4	18	3	20	12	17	4	27	6	14	6	10	16	3	39	9	33	82
Oligochaeta	Oligochaeta spp.	Infauna	V	48	6	43	12					23	8	4	9		16	90	10	1	3			75	4	37	13
Ostracoda	Ostracoda sp. 1	Infauna	I	23		6						62		12		29		23		1		3					
Ostracoda	Ostracoda sp. 2	Infauna	I			1						34		63		7		13				5					
Ostracoda	Ostracoda sp. 3	Infauna	I					1																			
Ostracoda	Ostracoda sp. 4	Infauna	I															1				1					
Platyhelminthes	Stylochidae	Infauna	II																							1	
Polychaeta	?Leodamas sp.	Infauna	III																					11			
Polychaeta	?Pirakia sp. 1	Infauna	II											1													
Polychaeta	Aglaophamus macroura	Infauna	II					1																			
Polychaeta	Aonides trifida	Infauna	I	3	156	8	20	5	392		34		729		7		1182	1	3		774			3	822		1
Polychaeta	Armandia maculata	Infauna	III			1	7	1		4	1			3	39			1	2	1		18	2	6		11	
Polychaeta	Axiothella serrata	Infauna	II	6	191	52	98	1	33	4	352		18		46	37	69		33		22			52	5	14	44
Polychaeta	Boccardia acus	Infauna	IV	75	54	4	123	75	48	79	91	76	14	90	91	74	55	54	65	1	8	9	15				37
Polychaeta	Boccardia syrtis	Infauna	II	26	1	95	9	62	1	9	28	10		33	20	2	3	6	15	3		2		45		23	8
Polychaeta	Capitella spp.	Infauna	V		67	16	5	8		1	3		62	1	32		29				2			10	6		20
Polychaeta	Cirratulidae	Infauna	IV											1											1		
Polychaeta	Euchone sp.	Infauna	II															2						1			
Polychaeta	Exogoninae	Infauna	II																					2		54	
Polychaeta	Glycera spp.	Infauna	II									2				1				1						1	
Polychaeta	Glycinde trifida	Infauna	II	4			6	4			2	1		2	3	3		4				2	3	3		1	
Polychaeta	Heteromastus filiformis	Infauna	IV	388	195	229	332	266	17	241	318	252	55	401	762	184	97	351	407	73	13	85	103	178	12	168	91
Polychaeta	Lagis australis	Infauna	III	1																				1			
Polychaeta	Lumbrineridae	Infauna	II																							1	
Polychaeta	Microphthalmus riseri	Infauna	II																					1			
Polychaeta	Microspio maori	Infauna	I		25				4		3		17		7		13				4				15		
Polychaeta	Myriochele sp.	Infauna	III																							9	
Polychaeta	Mysta platycephala	Infauna	II								3				1	2		1									
Polychaeta	Nereididae (juv)	Infauna (juvenile)	-									16		56	21	42	4	35	15	5	4	19	7				
Polychaeta	Nicon aestuariensis	Infauna	III		5	3	1	2	10	21	15	3	7	6	10			1		1		8	2	10	1	18	8
Polychaeta	Orbinia papillosa	Infauna	I	3	135	14	47	14	40	15	27	4	33	48	24	15	60	6	31		95	22	13		7	1	4
Polychaeta	Owenia petersenae	Infauna	II															1								2	
Polychaeta	Oxydromus angustifrons	Infauna	II									1															
Polychaeta	Paradoneis lyra	Infauna	III	63	1	313		73		29	1	14	6	23	2	2	5	39	12	3	10	11		90		32	33
Polychaeta	Perinereis vallata	Infauna	III	7	10	64	22	21		20	8	17		16	21	3	2		1	1	1		1	36	3	16	3
Polychaeta	Pettiboneia sp.	Infauna	II																					1			
Polychaeta	Platynereis spp.	Infauna	III	10			9	44			12	2		1	17			1						9		1	
Polychaeta	Polynoidae sp. 1	Infauna	I											1								1					
Polychaeta	Prionospio aucklandica	Infauna	III	38	4	21	46	40	2	17	8	25	2	54	74	33	18	44	60	83	8	131	45	207	6	202	80
Polychaeta	Pseudopolydora paucibranchiata	Infauna	IV																					3		22	6
Polychaeta	Sabellidae	Infauna	I			24		1		1														1			
Polychaeta	Schistomeringos sp.	Infauna	II			4						1		2				2				1		2		4	
Polychaeta	Scolecolepides benhami	Infauna	IV	1	1	14	1	2	3	4	2	1			2	3	8			6	3	4	8	8	2	1	6
Polychaeta	Scoloplos cylindrifer	Infauna	I		41		4		37				33	2	3	2	24			2	190	100	1	291	380	63	3
Polychaeta	Sphaerodoridae	Infauna	-	6		14	21	13		11	5	6		12	6	1		5	1			2		1		3	
Polychaeta	Spiophanes modestus	Infauna	III																							1	
Polychaeta	Spirobranchus cariniferus	Infauna	I				1			1				4													
Polychaeta	Terebellidae	Infauna	II	5		33				4		2		12		8										1	
Polychaeta	Travisia olens	Infauna	I					1								3											
Polyplacophora	Acanthochitona zelandica	Epibiota	I													1		1									
Polyplacophora	Chiton glaucus	Epibiota	II									1		7		1		2									

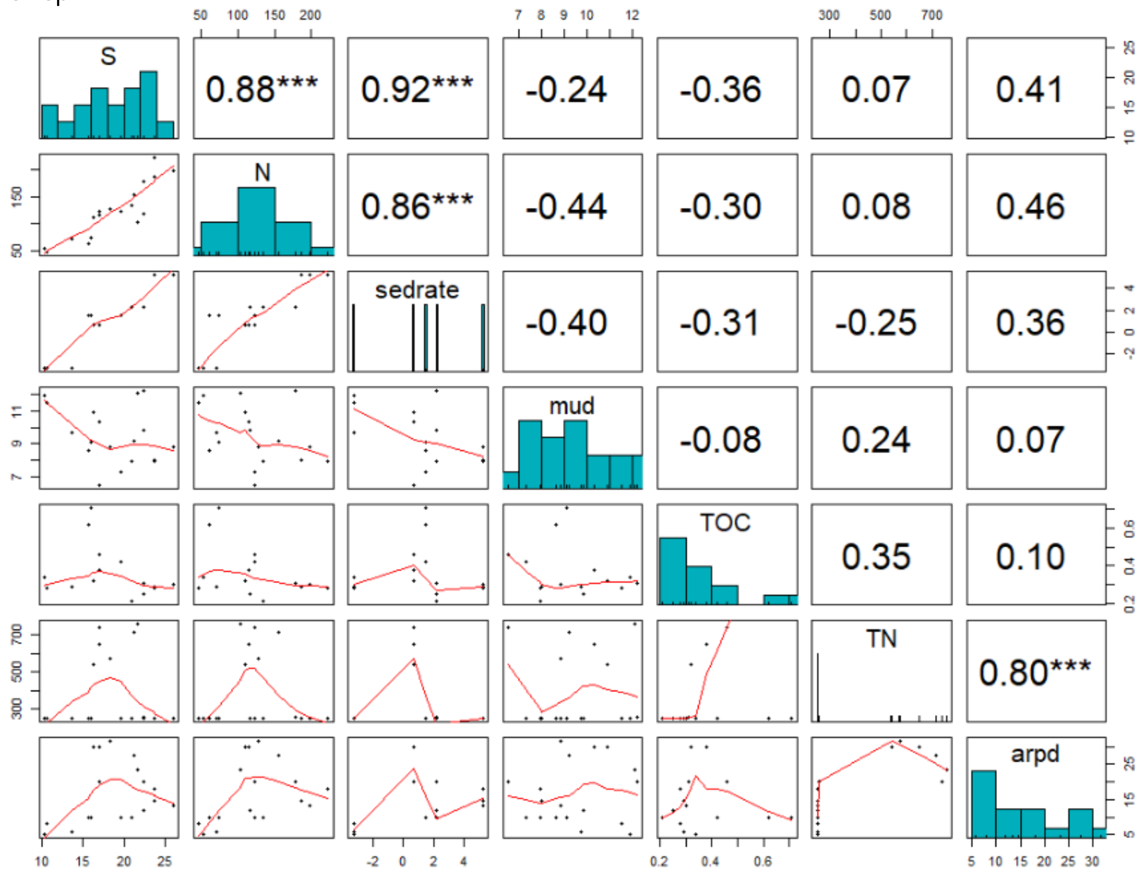
APPENDIX 5. ASSOCIATIONS BETWEEN MACROFAUNA AND SEDIMENT QUALITY

A. Macrofauna richness (S) and abundance (N) associations with key sediment variables based on Pearson correlation. Trace metals not shown for individual site plots.

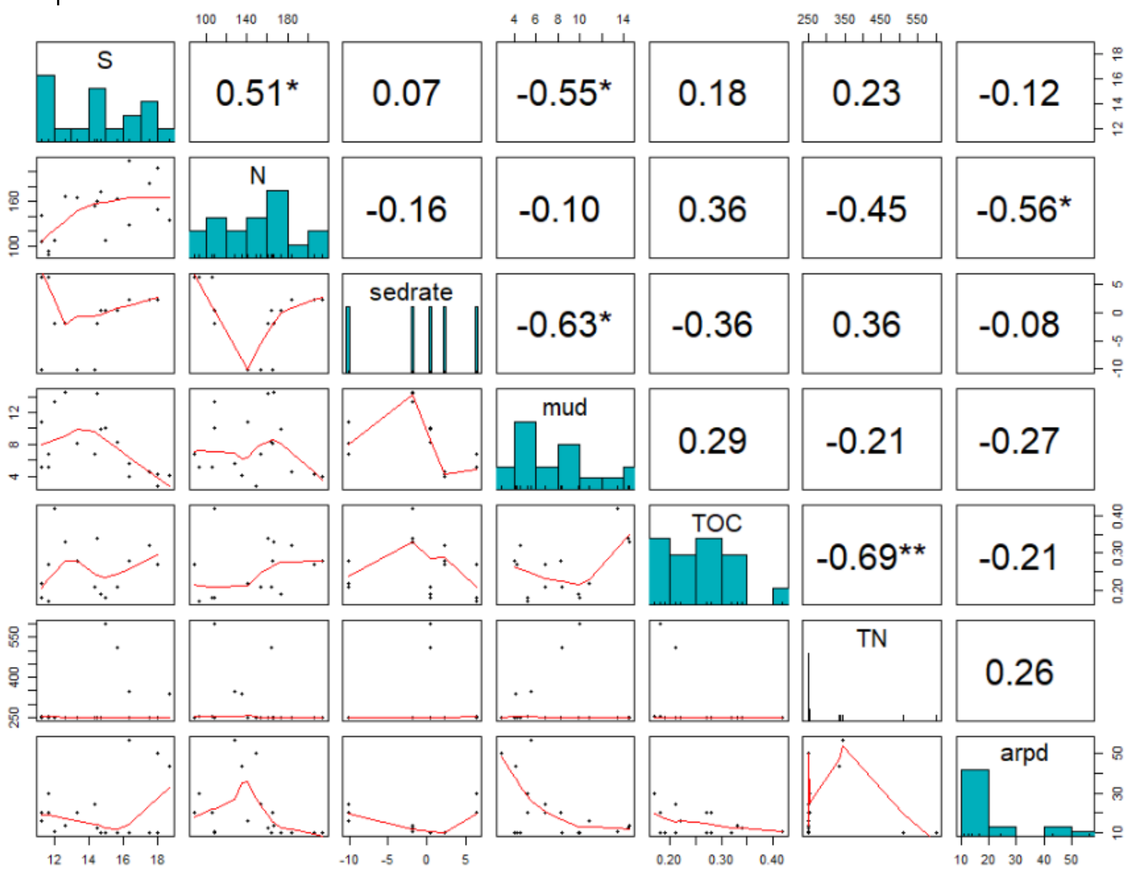
All sites



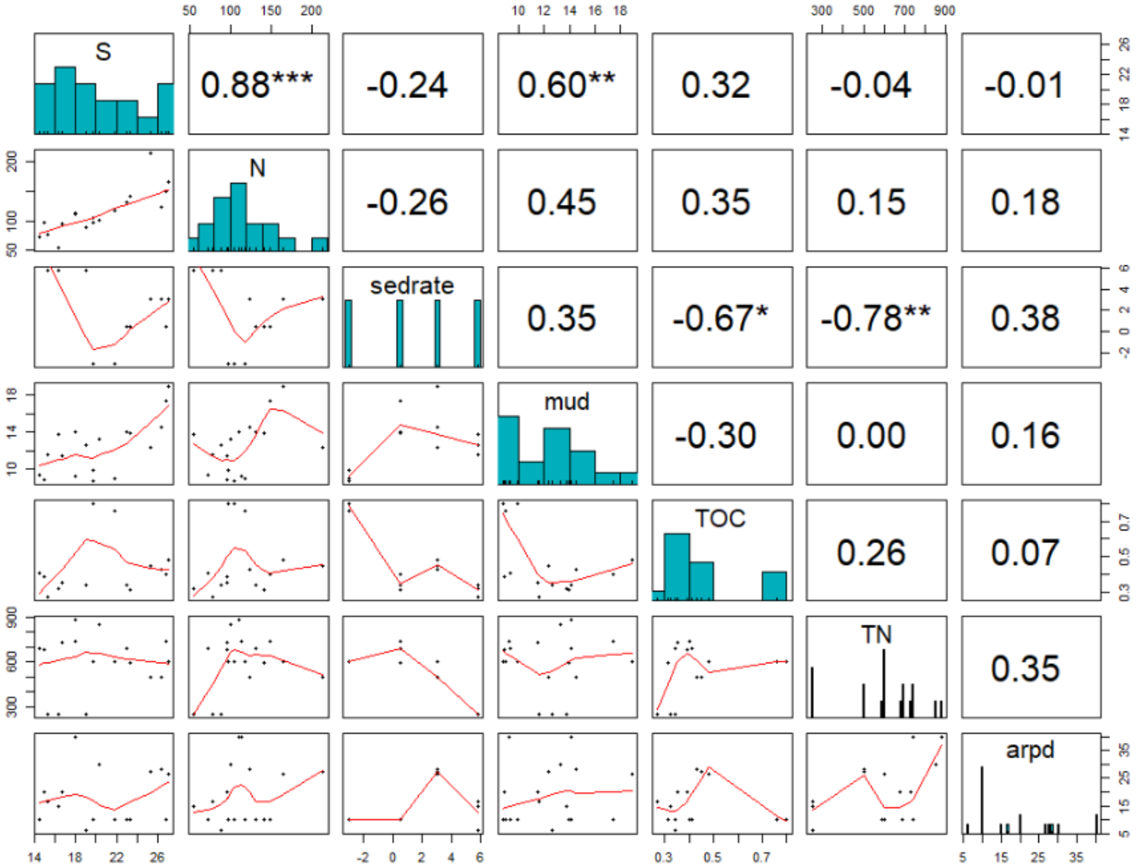
Onep-A

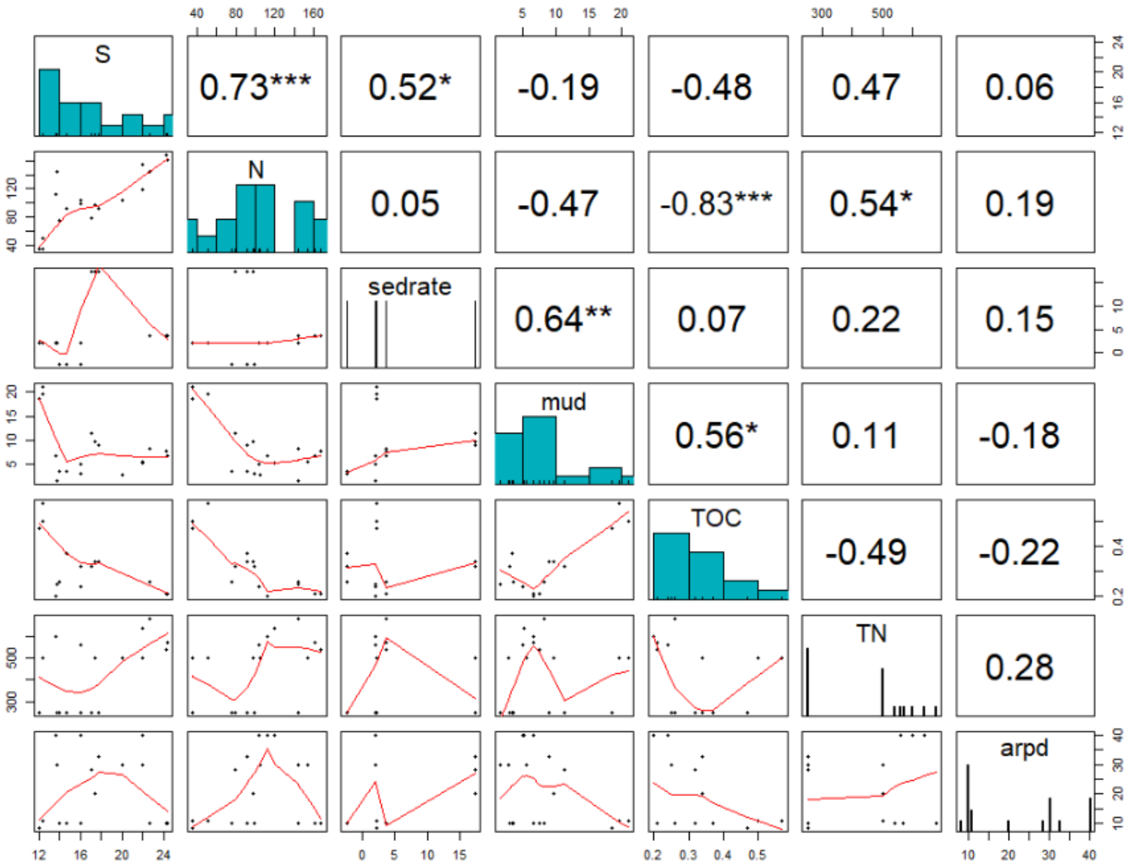

S
N
sedrate
mud
TOC
TN
arpd
0.88***
0.92***
-0.24
-0.36
0.07
0.41
0.86***
-0.44
-0.30
0.08
0.46
-0.40
-0.31
-0.25
0.36
-0.08
0.24
0.07
0.35
0.10
0.80***

Onep-B

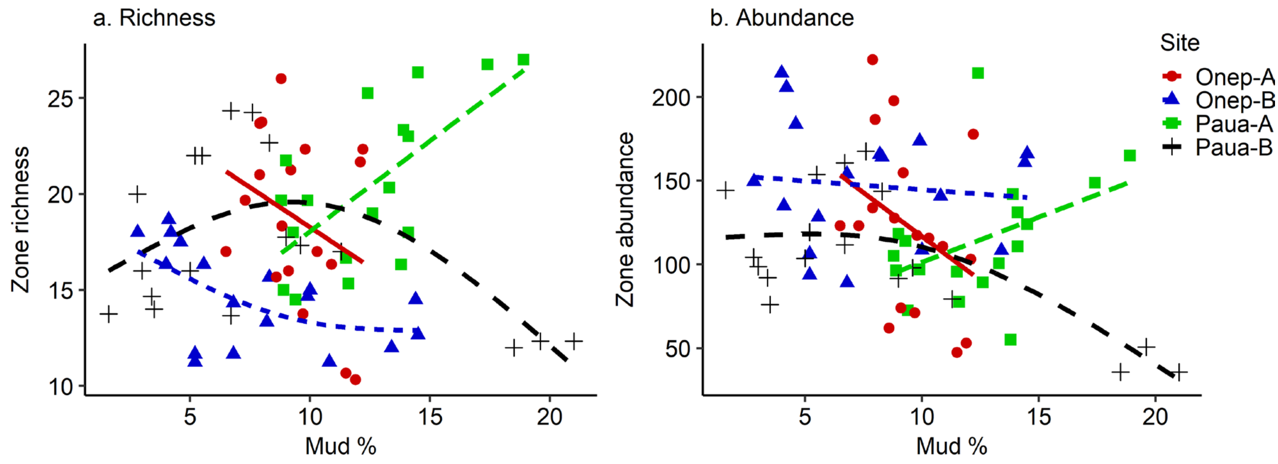

S
N
sedrate
mud
TOC
TN
arpd
0.51*
0.07
-0.55*
0.18
0.23
-0.12
-0.16
-0.10
0.36
-0.45
-0.56*
-0.63*
-0.36
0.36
-0.08
0.29
-0.21
-0.27
-0.69**
-0.21
0.26

Paua-A





B. Example of contrast among sites in relationship between richness (S), abundance (N) and % mud. GAM smoothers have been used to visualise the relationship for each site.



C. Macrofauna composition associations (Spearman rank correlation) with key sediment variables based on multivariate Bio-Env procedure in Primer v7.0.13.

All sites	Onep-A	Onep-B	Paua-A	Paua-B
0.398 Cd	0.549 sedrate	0.371 sedrate	0.563 Cu	0.674 Cd
0.378 TP	0.222 TOC	-0.004 Zn	0.498 Zn	0.521 Pb
0.348 Zn	0.214 mud	-0.004 TOC	0.435 Cr	0.491 TOC
0.347 Ni	0.189 arpd	-0.045 arpd	0.421 arpd	0.414 mud
0.333 Cr	0.179 Cr	-0.082 mud	0.379 Pb	0.336 sand
0.268 Pb	0.167 Zn	-0.098 Pb	0.171 TN	0.314 TP
0.162 TOC	0.011 Cu	-0.118 sand	0.101 Cd	0.300 Cr
0.117 sedrate	0.000 Ni	-0.121 Cr	0.075 sand	0.268 Cu
0.098 TN	-0.007 Pb	-0.121 TP	-0.073 Ni	0.229 Zn
0.062 mud	-0.020 Cd	-0.211 Cu	-0.079 mud	0.222 sedrate
0.057 arpd	-0.061 sand	-0.213 Ni	-0.185 TOC	0.197 arpd
-0.002 sand	-0.207 TN	-0.243 Cd	-0.355 sedrate	-0.257 Ni

APPENDIX 6. NATIONAL BENTHIC HEALTH MODEL RESULTS

National Benthic Health Model (BHM) results for GWRC estuaries provided by Dana Clarke, Cawthron Institute.

Table 1. Descriptive names and boundaries for Benthic Health Model (BHM) score categories.

BHM Group	Level of impact relative to other estuarine sites in New Zealand*	BHM score
1	Very low	1.0 to < 2.0
2	Low	2.0 to < 3.0
3	Moderate	3.0 to < 4.0
4	High	4.0 to < 5.0
5	Very high	≥ 5.0

* This is a relative measure of impact rather than an absolute measure of health.

Table 2. Absolute health boundaries for the National Metals Benthic Health Model (BHM).

Absolute health	Metals BHM score
Good	Less than 3.6
Fair	3.6 to < 4.8
Poor	4.8 or greater

Table 3. Raw BHM scores for GWRC estuaries. Porirua Harbour sites are for the Onepoto (Onep) and Pāuatahanui (Paua) arms.

Site	MudBHM	MetalsBHM
Hutt-A-2010	4.2	3.5
Hutt-A-2011	4.0	3.4
Hutt-A-2012	4.4	3.3
Hutt-A-2017	3.5	3.1
Hutt-B-2010	3.6	3.1
Hutt-B-2011	3.8	3.0
Hutt-B-2012	4.2	3.1
Hutt-B-2017	3.6	3.4
Onep-A-2008	3.5	3.5
Onep-A-2009	2.9	3.2
Onep-A-2010	3.3	3.0
Onep-A-2015	3.5	3.5
Onep-A-2020	3.4	2.4
Onep-A-2022	3.1	2.8
Onep-B-2008	3.5	3.8
Onep-B-2009	3.4	3.7
Onep-B-2010	3.6	3.8
Onep-B-2015	3.3	3.2
Onep-B-2020	3.2	4.1
Onep-B-2022	2.8	3.5
Paua-A-2008	3.3	3.6
Paua-A-2009	3.3	3.2
Paua-A-2010	3.2	3.1
Paua-A-2015	3.5	3.4
Paua-A-2020	3.3	2.7
Paua-A-2022	3.2	3.0
Paua-B-2008	3.4	3.6
Paua-B-2009	3.4	3.7
Paua-B-2010	3.6	3.6
Paua-B-2015	3.5	3.0
Paua-B-2020	4.0	3.2
Paua-B-2022	4.2	3.5

Site	MudBHM	MetalsBHM
Waiw-A-2009	3.8	3.5
Waiw-A-2012	3.9	4.1
Waiw-B-2009	4.2	4.3
Waiw-B-2012	4.0	4.4
Whar-A-2008	5.5	3.5
Whar-A-2009	5.6	4.1
Whar-A-2010	4.6	2.9
Whar-A-2016*	5.4	3.1
Whar-A-2022	4.7	3.2
Whar-B-2008	5.0	3.2
Whar-B-2009	4.9	3.2
Whar-B-2010	4.8	2.7
Whar-B-2016*	5.4	3.1
Whar-B-2022	4.7	2.7
Wkne-A-2010**	3.7	3.3
Wkne-A-2011**	3.8	3.9
Wkne-A-2012**	4.1	4.1
Wkne-A-2017**	3.9	4.2

* Unable to test the fit with the Metals BHM but given the good fit in other years, the Metals BHM is considered appropriate for determining the level of metal impact at this site relative to other estuarine sites across New Zealand

** Poor fit with the Metals BHM and unable fit unable to be tested with the Mud BHM - these scores should not be used to determine the level of metal or sediment impact relative to other estuarine sites across New Zealand but can be used to track health at these sites through time

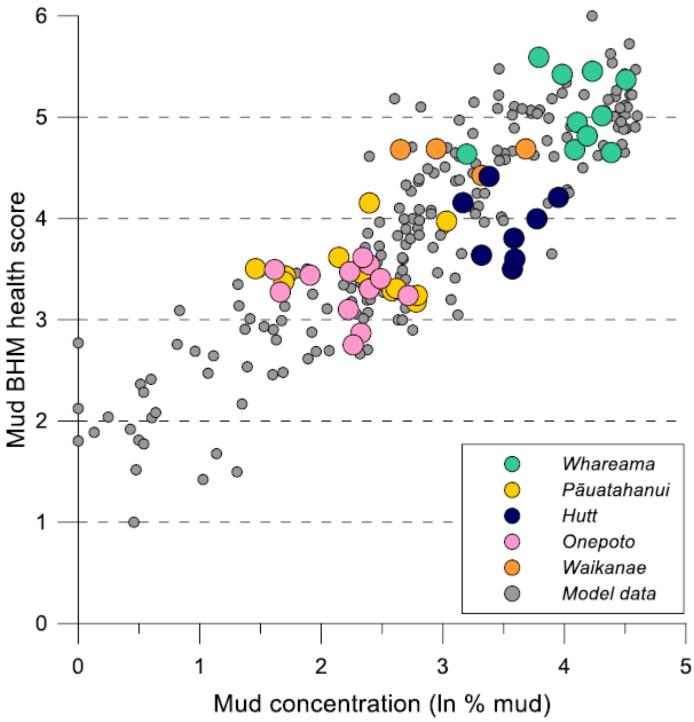


Figure 1. Comparison of Mud Benthic Health Model (BHM) scores from four Wellington estuaries (coloured circles) with those from sites used to develop the model (grey circles). Sediment mud content data were not available for the Waiwhetū sites, so the fit of these sites with the BHM data could not be tested. BHM scores range from 1 (least impacted) to 6 (most impacted) relative to other estuarine sites across New Zealand.

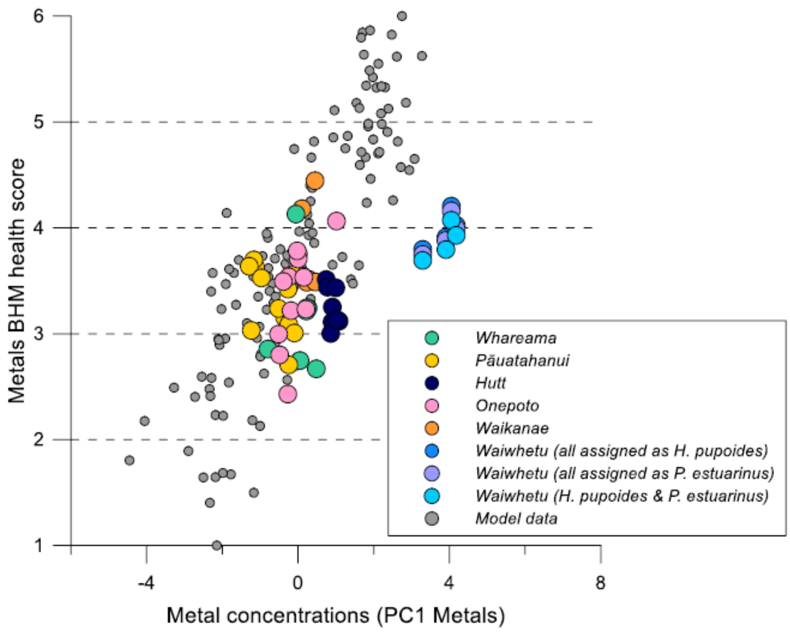


Figure 2. Comparison of Metals Benthic Health Model (BHM) scores from five Wellington estuaries (coloured circles) with those from sites used to develop the model (grey circles). Scores from Waiwhetū Stream estuary were calculated three different ways to assess the effect that differences in taxonomic resolution of *Halopyrgus pupoides* and *Potamopyrgus estuarinus* had on BHM scores. BHM scores range from 1 (least impacted) to 6 (most impacted) relative to other estuarine sites across New Zealand.

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