SALT ECOLOGY

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

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SALT ECOLOGY

For the People
Mō ngā tāngata

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

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for

Greater Wellington Regional Council

August 2020

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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
Cd	Cadmium
Cr	Chromium
Cu	Copper
DGV	Default Guideline Value
Epibiota	Animals (epifauna) and seaweeds (macroalgae) visible on the surface on the sediment
ETI	Estuarine Trophic Index
Hg	Mercury
GWRC	Greater Wellington Regional Council
NEMP	National Estuary Monitoring Protocol
Ni	Nickel
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 in Te Awarua-o-Porirua Harbour, where monitoring over the last decade or longer has included '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 2020, which involved assessing sediment quality and biological indicators at four sites, two in the Onepoto (Onep) arm of the harbour and two in the Pauatahanui arm (Paua). Findings are compared with four previous fine scale surveys undertaken in 2008, 2009, 2010 and 2015. The status and long-term trends in estuary health are evaluated, and future monitoring needs are discussed.

KEY FINDINGS

The table below (next page) compares mean values of sediment indicators against established rating criteria for New Zealand estuaries. Key findings with respect to these indicators are as follows:

Sediment quality indicators

- Sediment quality was for most indicators rated as 'good' or 'very good', with low and ecologically insignificant levels of trace metal contaminants, and low levels sediment total organic carbon (%TOC) and nutrients (TN, total nitrogen; TP, total phosphorus).
- Despite chemical indicators of trophic state (TOC, TN, TP) being at low levels, the sediment profile at all sites showed visible signs of moderate enrichment in 2020, evident as a shallow depth of transition between oxygenated surface sediments and deeper less oxygenated grey/black sediments (known as the apparent redox potential discontinuity 'aRPD' depth). The aRPD depth in 2020 was similar to 2010 and 2015, and rated as 'fair' or 'poor' compared with 'good' or 'very good' in the earlier surveys.
- Sediment mud content at all sites has been relatively low historically, but in 2020 there was a marked (3-4 fold) increase in the percentage mud of samples collected from the Pauatahanui upper harbour site (Paua-B), and also at the upper Onepoto (Onep-B) site, but to a lesser extent.

Epibiota and sediment-dwelling macrofauna:

- Different mud snail species were conspicuous among the surface-dwelling epifauna in 2020, but densities have varied widely over the years and among sites.
- Nuisance macroalgae (seaweeds) were at a low prevalence across all years at the fine scale sites. However, over the last year there has been an apparent 'bloom' of a filamentous green mat-forming species near outer harbour Onep-A and Paua-A sites.
- Core sampling revealed 96 different sediment-dwelling macrofauna species over the five surveys. The most notable change in the last three surveys has been a gradual decline in species richness (the range of species recorded) and their abundance, at all sites except Onep-B next to Porirua City. These declines appear in part attributable to increased sediment mud content, and in the case of Paua-B were accompanied in 2020 by the loss of several species intolerant of mud that had been common previously. In addition to sediment mud content, there appear to be other unknown drivers of the high spatial and temporal variability in the macrofauna assemblages.

The apparent decline in certain ecological health indicators in 2020 is consistent with parallel studies (sedimentation monitoring and a broad scale survey of estuary substrate and vegetation) that reveal a long-term harbour-wide increase in sediment and the extent of mud-dominated sediments. A previous study has discussed possible previous or ongoing sources of muddy sediments as being land disturbance in the eastern catchment (where Paua-B is located) associated with various subdivisions and the Transmission Gully motorway development.

In addition to an assessment of monitoring findings, the report discusses some of the considerations for ongoing monitoring, which are presented below.

RECOMMENDATIONS

It is recommended that GWRC consider the following:

- A further fine scale survey in January 2022 to further evaluate whether the results from the 2020 survey reflect an ongoing state of decline for parts of Te Awarua-o-Porirua Harbour.
- Implementing approaches (e.g. compound specific stable isotope analysis) to determine recent and ongoing sediment inputs, and the origin of muddy sediments, especially in the Pauatahanui arm.
- Assess the broader ecological implications of changes in key indicators revealed by the present report, and recent (broad scale) or planned (subtidal) surveys.

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

Site	Year	Mud	TOC	TN	TP	aRPD	As	Cd	Cr	Cu	Hg	Ni	Pb	Zn	AMBI
		%	%	mg/kg	mg/kg	mm	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	na
Onep-A	2008	10.0	-	685	442	28	-	0.028	11.3	5.1	-	6.0	8.4	39.4	2.3
	2009	9.2	0.39	643	397	27	-	0.034	12.3	5.0	-	8.5	6.7	41.0	2.1
	2010	10.0	0.26	< 503	393	14	-	0.029	10.6	3.8	-	7.1	5.3	35.7	2.0
	2015	8.3	0.58	< 500	397	10	6.2	0.023	10.8	4.2	0.02	8.0	5.7	38.0	1.9
	2020	11.0	0.30	< 500	407	6	5.5	0.029	10.8	4.5	< 0.02	8.5	5.5	46.3	1.8
Onep-B	2008	4.0	0.46	504	158	50	-	0.040	5.1	3.6	-	9.5	3.6	59.9	1.6
	2009	5.7	0.21	< 507	147	23	-	0.046	5.6	4.0	-	3.7	8.9	57.7	0.9
	2010	9.4	0.19	453*	163	10	-	0.044	5.2	3.4	-	3.4	9.1	62.3	0.9
	2015	4.3	0.29	< 500	196	10	3.2	0.046	5.6	3.9	0.02	4.0	9.9	77.7	0.8
	2020	14.1	0.36	< 500	267	12	3.6	0.058	8.5	7.5	0.02*	10.4	13.5	135.7	0.5
Paua-A	2008	12.2	-	823	447	37	-	0.029	10.7	4.9	-	6.5	8.8	36.7	2.4
	2009	9.9	0.38	700	437	17	-	0.025	11.0	4.6	-	7.7	6.1	35.0	2.1
	2010	15.1	0.35	673	470	10	-	0.025	10.7	4.8	-	7.4	6.8	37.3	1.9
	2015	9.2	0.79	600	450	10	7.5	0.022	11.0	4.8	0.03	8.1	6.6	37.3	2.2
	2020	12.7	0.31	< 500	453	12	7.2	0.023	10.6	4.8	0.01*	7.7	6.1	41.7	1.5
Paua-B	2008	4.5	0.44	547	150	33	-	0.020	4.7	2.3	-	4.7	3.9	23.0	1.9
	2009	4.4	0.23	470*	137	37	-	0.019	4.6	2.0	-	3.4	4.5	21.0	2.4
	2010	7.5	0.23	597	120	10	-	0.019	4.1	1.8	-	3.0	4.2	19.3	2.4
	2015	3.3	0.32	< 500	118	10	2.0	0.021	4.1	2.0	0.02	3.3	4.1	20.2	2.3
	2020	19.7	0.51	417*	202	10	2.9	0.029	5.8	3.8	0.03	4.4	6.2	31.0	2.0

** Sample mean includes values below lab detection limits*

< All values below lab detection limit

Condition rating key: Very Good | Good | Fair | Poor

1. INTRODUCTION

Monitoring the ecological condition of estuarine habitats is critical to their management. Estuary monitoring is undertaken by most councils in New Zealand as part of their State of the Environment (SOE) programmes. The most widely-used monitoring framework is that outlined in New Zealand's National Estuary Monitoring Protocol (NEMP, Robertson et al. 2002). The NEMP is intended to provide resource managers nationally with a scientifically defensible, cost-effective and standardised approach for monitoring the ecological status of estuaries in their region. The results establish a benchmark of estuarine health 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 the 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), where the first NEMP broad and fine scale surveys were undertaken in 2008 (Robertson & Stevens 2008; Stevens & Robertson 2008). Since then, GWRC has commissioned follow-up and related surveys, including:

- Two NEMP broad scale, and three fine scale surveys, most recently in 2013 and 2015, respectively (Stevens & Robertson 2013; Robertson & Stevens 2015).
- Targeted assessment of intertidal macroalgae, the most recent survey being in 2017 (Stevens & O'Neill-Stevens 2017).
- Subtidal habitat mapping and ecological surveys (Milne et al. 2008; Oliver & Conwell 2014; Stevens & Robertson 2014).
- Annual monitoring of sedimentation rates at intertidal and subtidal sites (e.g. Stevens & Forrest 2020).

Salt Ecology was contracted to carry out further NEMP broad scale and fine scale surveys in the harbour in January 2020. This report describes the methods and results of the fine scale survey, compares findings with earlier work in terms of the current status and trends in estuary health, and makes recommendations for future monitoring.

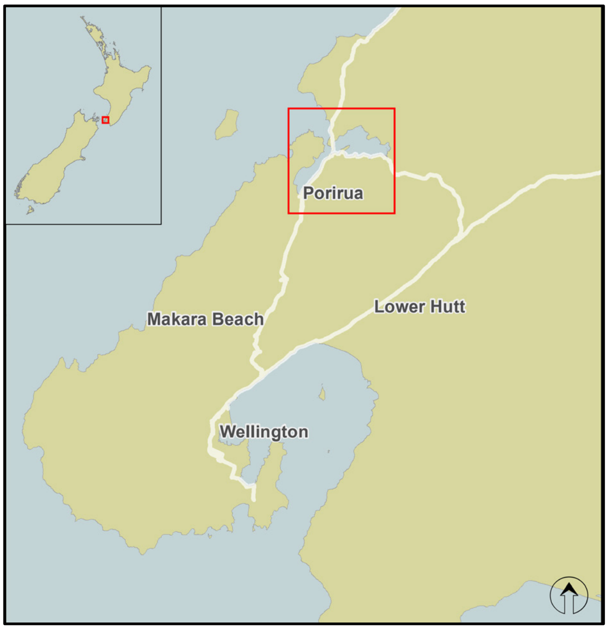


Fig. 1 Location of Te Awarua-o-Porirua Harbour

2. BACKGROUND TO TE AWARUA-O- PORIRUA HARBOUR

Background information on Te Awarua-o-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 arms, each a relatively simple shape, Onepoto (283ha) and Pauatahanui (524ha). The arms are connected by a narrow channel at Paremata, and the estuary discharges to the sea via a narrow entrance west of Plimmerton.

Residence time in the estuary is less than 3 days, however, compared to the majority of New Zealand's tidal lagoon estuaries which tend to drain almost completely at low tide, the harbour has a large shallow subtidal component (65%, mean depth of

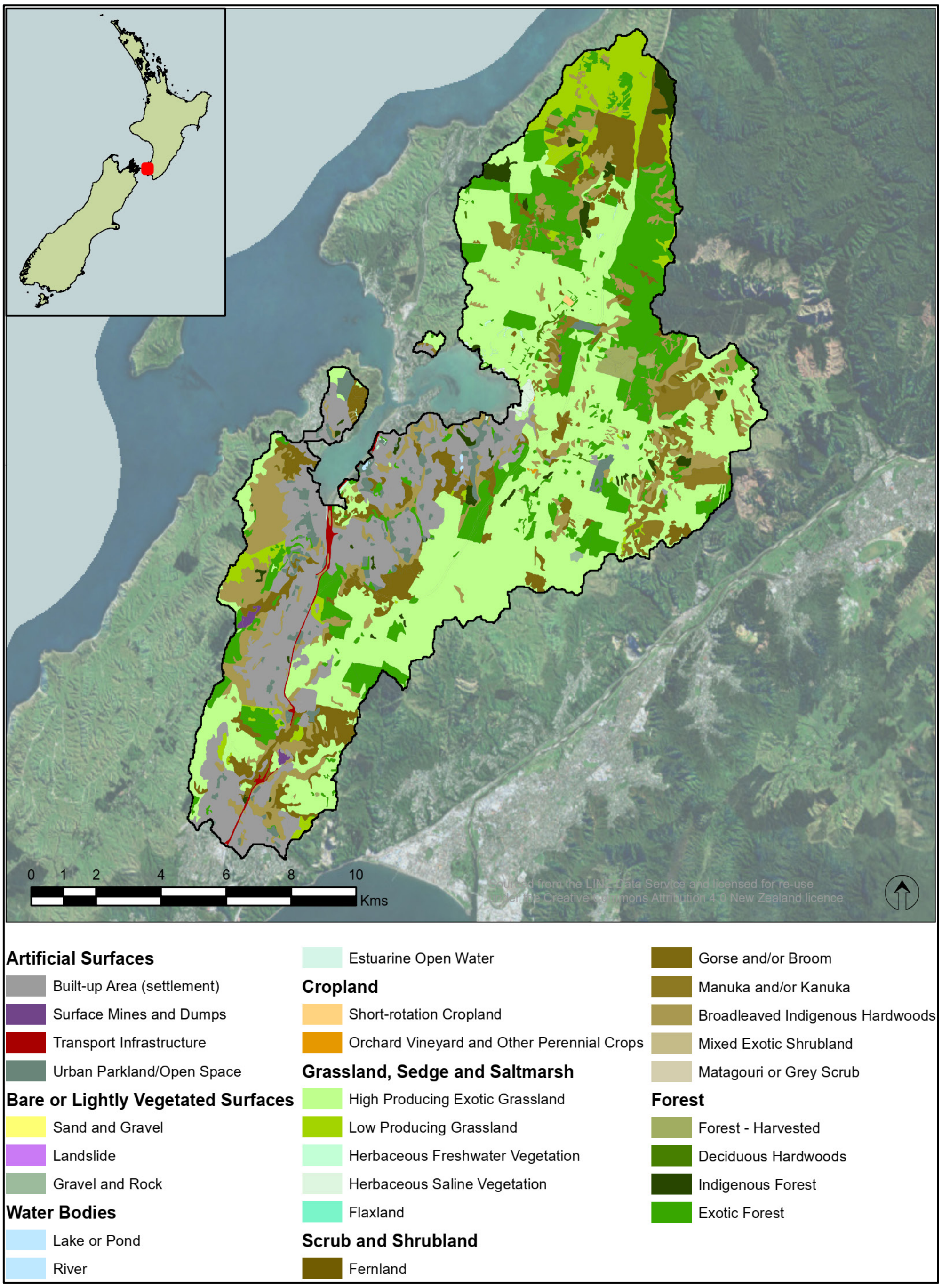


Fig. 2 Te Awarua-o-Porirua Harbour and surrounding catchment land use.

~1m). Nonetheless, the intertidal area is large (287ha) and supports extensive areas (59ha) of seagrass growing in firm mud/sand, and shellfish beds.

The estuary has high ecological values and high human use. However, the harbour has been extensively modified over the years, particularly the Onepoto arm, where almost all of the historical shoreline and salt marsh have been reclaimed and most of the arm is now lined with steep straight rock walls flanked by road and rail corridors. The Pauatahanui arm is less modified (although most of the arm's margins are also encircled by roads), with extensive areas of salt marsh remaining in the north and east, much of which has been improved through local community enhancement efforts.

Catchment land use in the Onepoto arm is dominated by urban (residential and commercial) development (Fig. 2). In the steeper Pauatahanui arm, 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 the Pauatahanui arm, where potential sources include land disturbance associated with a subdivision near Duck Creek, and the Transmission Gully motorway development (see Fig. 2). Elevated nutrient inputs are also considered to be causing moderate eutrophication symptoms (i.e. poor sediment oxygenation and moderate nuisance macroalgal cover) in the estuary (Robertson & Stevens 2015).

Fig. 3 Te Awarua-o-Porirua Harbour and surrounding catchment, showing land disturbances from earthworks.

3. FINE SCALE METHODS

3.1 OVERVIEW OF NEMP APPROACH

The first broad scale survey provided a basis for selection of the sites for fine scale monitoring. Broad scale surveys involve describing and mapping estuaries according to the dominant habitat features (substrate and vegetation) present. This procedure combines the use of aerial photography, detailed ground truthing, and digital mapping using Geographic Information System (GIS) technology. Once a baseline map has been constructed, changes in the position, size, or type of dominant habitats can be monitored by repeating the mapping exercise.

After an estuary has been classified according to its main habitats and their condition, representative habitats can be selected and targeted for fine scale monitoring. The NEMP advocates monitoring soft sediment (sand/mud) habitat in the mid to low tidal range of priority estuaries, although seagrass habitats or areas with high enrichment conditions are sometimes included.

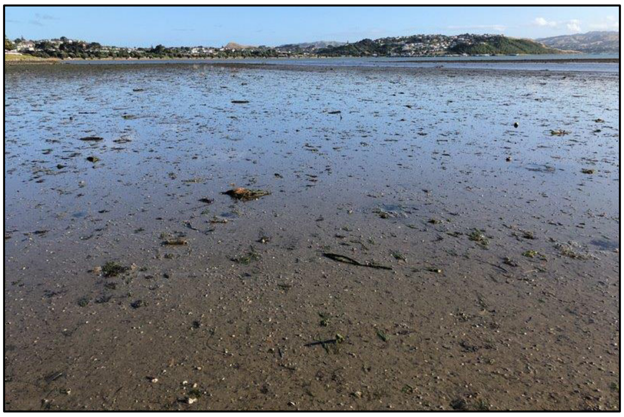
The environmental characteristics assessed in fine scale surveys incorporate a suite of common benthic indicators, including biological attributes (e.g. macrofauna) and physico-chemical characteristics (e.g. sediment mud content, trace metals, nutrients). Extensions to the NEMP methodology that support the fine scale approach include the development of various metrics for assessing ecological condition according to prescribed criteria, and inclusion of sedimentation monitoring.

3.2 PORIRUA FINE SCALE SITE INFORMATION

Four fine scale sites were first established in the harbour in January 2008, two in the Onepoto arm (Onep A, Onep B) and two in the Pauatahanui arm (Paua A, Paua B) (Fig. 3). Sites are largely unvegetated except for patches of seagrass at Onep A.

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

Onep A



Onep B

Paua A

Paua B

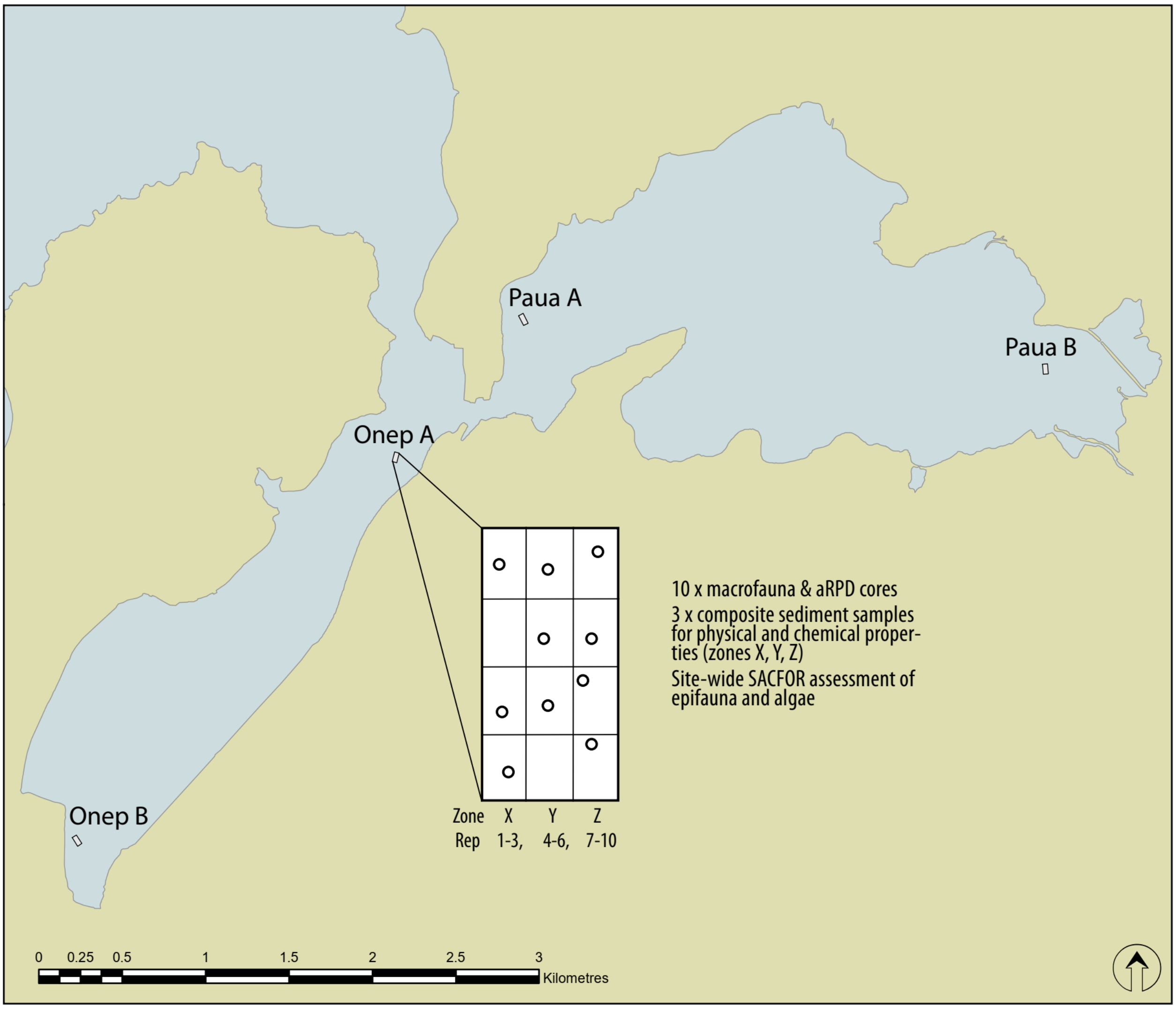


Fig. 4 Location of Onepoto and Pauatahanui sites A and B, and schematic of sampling design.

3.3 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 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, a recent review undertaken by Forrest and Stevens (2019a) highlighted that alterations and additions to early NEMP methods have been introduced in most surveys conducted over the last 10 or more years. For present purposes we have adopted these modifications as indicated in Table 1.

Three composite sediment samples (each ~250g) were collected from sub-samples (to 20mm depth) 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). Details of laboratory methods and detection limits are provided in Appendix 2.

Table 1. Summary of NEMP fine scale benthic indicators, rationale for their use, and sampling method. Any meaningful 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 time-integrated measure of the enrichment state of sediments according to the visual transition between oxygenated surface sediments and deeper deoxygenated black 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.

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) from each of the 10 plots, placing it on a tray, and splitting it vertically. Representative split cores (1X, 4Y and 7Z) 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 75% isopropyl alcohol and 25% seawater mixture for later sorting by Salt Ecology staff and taxonomic identification by Gary Stephenson, Coastal Marine Ecology Consultants (CMEC). 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. These ratings represent a scoring scheme simplified from established monitoring methods (MNCR 1990; Blyth-Skyrme et al. 2008).

The SACFOR method is ideally suited to characterise intertidal epibiota with patchy or clumped distributions. It was used in the 2020 survey as an alternative to the quantitative quadrat sampling specified in the NEMP, which is known to poorly characterise scarce or clumped species. 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).

3.4 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 2019) 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.

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

The SACFOR method is intended to characterise the most conspicuous epibiota that are readily apparent to the naked eye (typically epifauna and algae exceeding 5mm in size or area).

Before macrofaunal analyses, data were screened to remove species that were not considered a true part of the benthic macrofaunal assemblage; these were planktonic life-stages and non-marine organisms (e.g. terrestrial beetles). In addition, to enable comparisons across surveys, cross-checks were made to ensure consistent naming of species and higher taxa.

Macrofaunal response variables included richness and abundance by species and higher taxonomic groupings. In addition, scores for the biotic health index AMBI (Borja et al. 2000) were derived. AMBI scores reflect the proportion of taxa falling into one of five eco-groups (EGs) that reflect sensitivity to pollution (in particular, eutrophication), ranging from relatively sensitive (EG-I) to relatively resilient (EG-V). To meet the criteria for AMBI calculation, 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 EG classifications (http://ambi.azti.es) where possible. However, to reduce the number of taxa with unassigned EGs, international data were supplemented with eco-group classifications for New Zealand described by Berthelsen et al. (2018), which drew on prior New Zealand studies (Keeley et al. 2012; Robertson et al. 2015).

We also drew on recent work that assigned specific eco-group sensitivities to amphipods of known genus (Robertson et al. 2016c; Robertson 2018), but defaulted to the eco-group designation used in the Berthelsen et al. (2018) study for unclassified species (e.g. Amphipod sp. 1). Note that AMBI scores were not calculated for macrofaunal cores that did not meet operational limits defined by Borja et al. (2012), in terms of the percentage of unassigned taxa (>20%), or low sample richness (<3 taxa) or abundances (<6 individuals).

Multivariate representation of the macrofaunal community data used the software package Primer v7.0.13 (Clarke et al. 2014). Patterns in similarity as a function of macrofauna composition and abundance were assessed using non-metric multidimensional scaling (nMDS), based on pairwise Bray-Curtis similarity index scores among samples aggregated within sites or zones (X, Y and Z; i.e. replicates 1-3, 4-6 and 7-10, respectively, as per Fig. 3). The purpose of aggregation was to smooth over the 'noise' associated with a core-level analysis and also enable the relationship to patterns in sediment quality variables to be determined (i.e. as the sediment samples were composites for each corresponding zone). Following the nMDS, the similarity percentages procedure (SIMPER) was used to explore the main species or higher taxa that characterised the ordination groups or discriminated groups from each other. The Primer method BIOENV, as well as overlay vectors and bubble plots, were used to explore relationships between multivariate biological patterns and sediment quality data (and also cumulative sedimentation data, Stevens & Forrest 2020).

3.5 ASSESSMENT OF ESTUARY CONDITION

To supplement our analysis and interpretation of the data, fine scale survey results across all years were assessed within the context of established or developing estuarine health metrics ('condition ratings'), 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.

Most of the condition ratings in Table 3. were derived from those described in a New Zealand Estuary Trophic Index (Robertson et al. 2016a, b), which includes purpose-developed criteria for eutrophication, and also draws on wider national and international environmental quality guidelines.

Key elements of the rating approach are 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. Until recently, these thresholds were referred to as ANZECC (2000) Interim Sediment

Quality Guideline low (ISQG-low) and Interim Sediment Quality Guideline high (ISQG-high) values, respectively.

Note that the scoring categories described above and in Table 3. should be regarded only as a general guide to assist with interpretation of estuary health status. Accordingly, 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. For present purposes, our assessment of the multi-year data against the rating thresholds is based on site-level mean values for the different parameters.

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]					
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 elements [2]					
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. 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 muddy sand' with a moderate (10-25%) mud content. The shell component of samples was highly variable, but a combination of whole shell and live cockles in some instances (especially at Paua-A) made it difficult to take sediment cores. Consistent with previous surveys, sea grass was absent except at Onep-A, where the cover was estimated at ~60%.

In the general area of both Paua-A and Onep-A, extensive mats of drift macroalgae were present (see adjacent photos), consisting of a green filamentous species recently identified by NIWA as *Chaetomorpha ligustica*. This species belongs to a poorly understood group with a disjointed distribution in New Zealand. It appears to be the same species described as being present in the harbour since the 1950's (Adams 1994), although anecdotally has become more conspicuous in recent years. These mats have not been recorded in any of the previous NEMP surveys and were not noted during the sedimentation monitoring conducted in 2018/19 (authors, pers. obs.).

The macroalgal mats appeared to have a strong smothering effect on the underlying sediments, evident as black anoxic sediment (with a strong 'rotten egg' sulfide smell) and the presence of dead cockles. Macroalgal mats of the same species were also observed, but to a lesser extent, near Paua-B but were not observed at Onep-B next to Porirua City. However, Onep-B was characterised by superficial 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 SEDIMENT GRAIN SIZE, TOC AND NUTRIENTS

Composite sediment sample raw data are tabulated in Appendix 3. Laboratory analyses of particle grain size (Fig. 4) revealed that the sand fraction was dominant at all sites, with mud content ranging from mean values of ~3 to 20%. 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 rating ranged from 'very good' to 'fair' over the five years. At Paua-B in 2020 the mud content was high (~20%) relative to earlier surveys. An increase in mud content in 2020 was also evident at Onep-B, but to a lesser extent. These results are consistent with annual sampling undertaken as part of intertidal and subtidal sediment plate monitoring, which shows a gradual increase in sediment mud content over a period of 7-8 years, especially at upper estuary sites (Stevens & Forrest 2020). By contrast, the mud content at both 'A' sites has been variable but has not increased over time, possibly reflecting stronger flushing at those sites due to their location nearer the harbour entrance.

Levels of sediment organic matter (total organic carbon, TOC) and nutrients (total nitrogen, TN; total phosphorus, TP) were quite low at all sites and years, consistent with the primarily sandy nature of the sediments (Appendix 3). Accordingly, condition rating scores (not available for TP) were 'good' or 'very good', except in 2008 when %TOC at Onep-A and Paua-A was rated 'fair' (near the cusp of 'good' and 'fair').

Green drift macroalgal mats and anoxic sediments beneath (top near Paua-A, bottom near Onep-A)

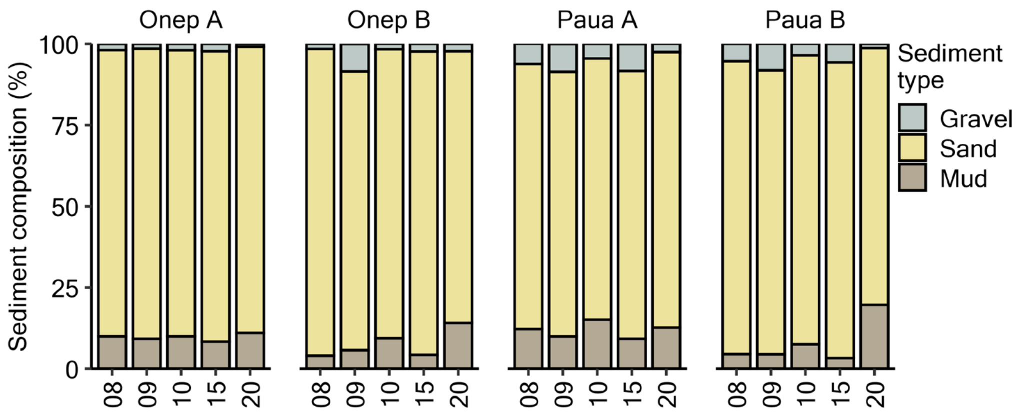


Fig. 5. Sediment particle grain size analysis, showing site-averaged percentage composition of mud (<63µm), sand (<2mm to ≥63µm) and gravel (≥2mm).

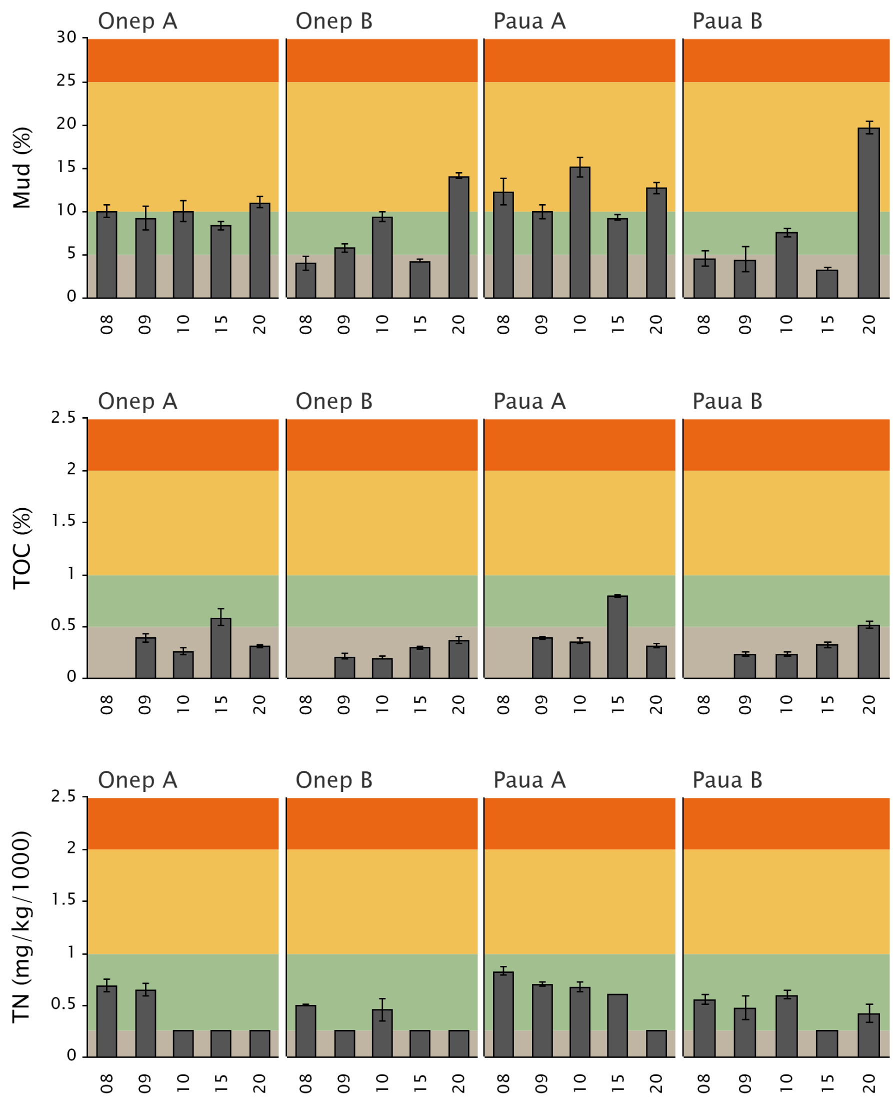


Fig. 6. Sediment mud content, total organic carbon, and total nitrogen concentrations relative to condition ratings.

Very Good	Good	Fair	Poor

4.3 REDOX STATUS

The depth to the aRPD transition was relatively deep (~23-50mm on average) in the first two surveys (2008 and 2009) by comparison with the last three surveys (~6-14mm), and as a general trend appears to have become shallower over time (Fig. 6). The aRPD depths measured in 2020 are similar to that recorded during harbour-wide monitoring of sedimentation rates described by Stevens and Forrest (2020).

A shallow aRPD, especially values in the range measured in recent surveys, can be associated with conditions of moderate organic enrichment in the sediment. However, in this instance %TOC was not elevated and the correlation of values with aRPD was not particularly strong (Pearson r = 0.26). 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 poor-moderate (Pearson r = -0.33). For example, the increased sample mud content at Paua-B in 2020 relative to earlier years is not mirrored in a shallowing of the aRPD. There are several plausible explanations for these apparent discrepancies, such as:

- Sampling the sediment to 20mm 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 where drift algal has smothered the sediment surface.

There is also inherent subjectivity in aRPD measurement, such that variability across surveys due to interpretation can be expected. Notwithstanding this issue, the aRPD in most cases in 2020 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 Fig. 7. Furthermore, the same practitioner made the aRPD assessment from 2008 to 2015. On this basis, it is reasonable to attribute the overall reduction in aRPD in Fig. 6 (i.e. the difference between early vs the most recent surveys) to be a true reflection of a deteriorating trophic state over time.

4.4 TRACE CONTAMINANTS

Trace metal contaminant levels in relation to condition ratings and ANZG (2018) sediment quality guidelines are plotted in Fig. 8, with raw data and guideline values in Appendix 3. Mean concentrations have been well below DGV levels at all sites over the five surveys, and generally within the 'very good' condition rating bracket.

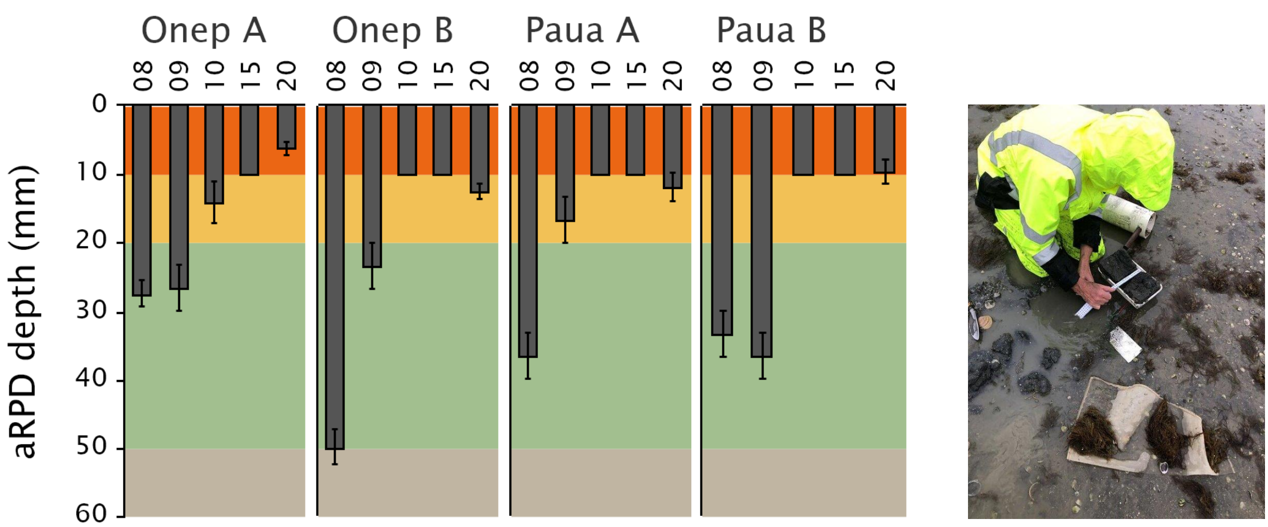


Fig. 7. aRPD depth in sediment and condition ratings. Photo inset shows measurement of aRPD. Condition rating key as follows:

Very Good	Good	Fair	Poor

Onep-AX

Onep-AY

Onep-AZ

Onep-BX

Onep-BY

Onep-BZ

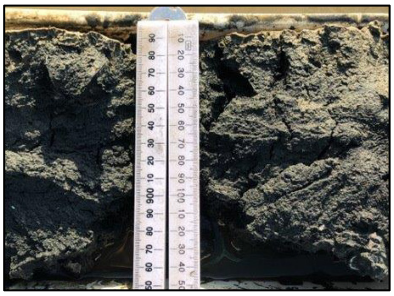
Paua-AX

Paua-AY

Paua-AZ

Paua-BX

Paua-BY



Paua-BZ

Fig. 8. Example sediment cores from the 2020 survey. The aRPD is visible as the transition from brown surface sediment to deeper grey or black. Close-up cores below.

Left: distinct aRPD at Onep-B illustrated by white dotted line.

Right: illustration of sediment mixing due to bioturbation by shellfish at Paua-A.

Paua-B had the lowest metal concentrations overall, consistent with the relatively low urban development in the eastern harbour (Appendix 3). 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 'A' sites, chromium (Cr) concentrations 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 harbor margins (Milne & Watts 2008; Sorensen & Milne 2009; Blaschke et al. 2010). However, the fine scale results provide no evidence of a widespread intertidal trace metal contaminant issue of any ecological concern.

4.5 MACROFAUNA

4.5.1 Conspicuous surface epibiota

The density or percentage cover of surface-dwelling epifauna and macroalgae was highly variable among sites and over survey years (Table 4). In 2020, the most frequently occurring epifauna were mud whelks (*Cominella glandiformis*) and large horn snails (*Zeacumantus lutulentus*), with mudflat snails (*Diloma subrostratum*) present but less abundant.

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.

Table 4. SACFOR scores for conspicuous epibiota over the five surveys, based on the scale in Table 2 (see also footnote below). Dashes (-) mean not present.

Year	Site	*Cominella glandiformis* (Mud whelk)	*Diloma subrostratum* (Mudflat snail)	*Zeacumantus lutulentus* (Horn snail)	*Gracilaria chilensis* (red seaweed)	*Ulva* spp. (green seaweed)
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
	Onep-B	R	R	F	O	O
	Paua-A	F	-	C	C	O
	Paua-B	O	F	O	O	R

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

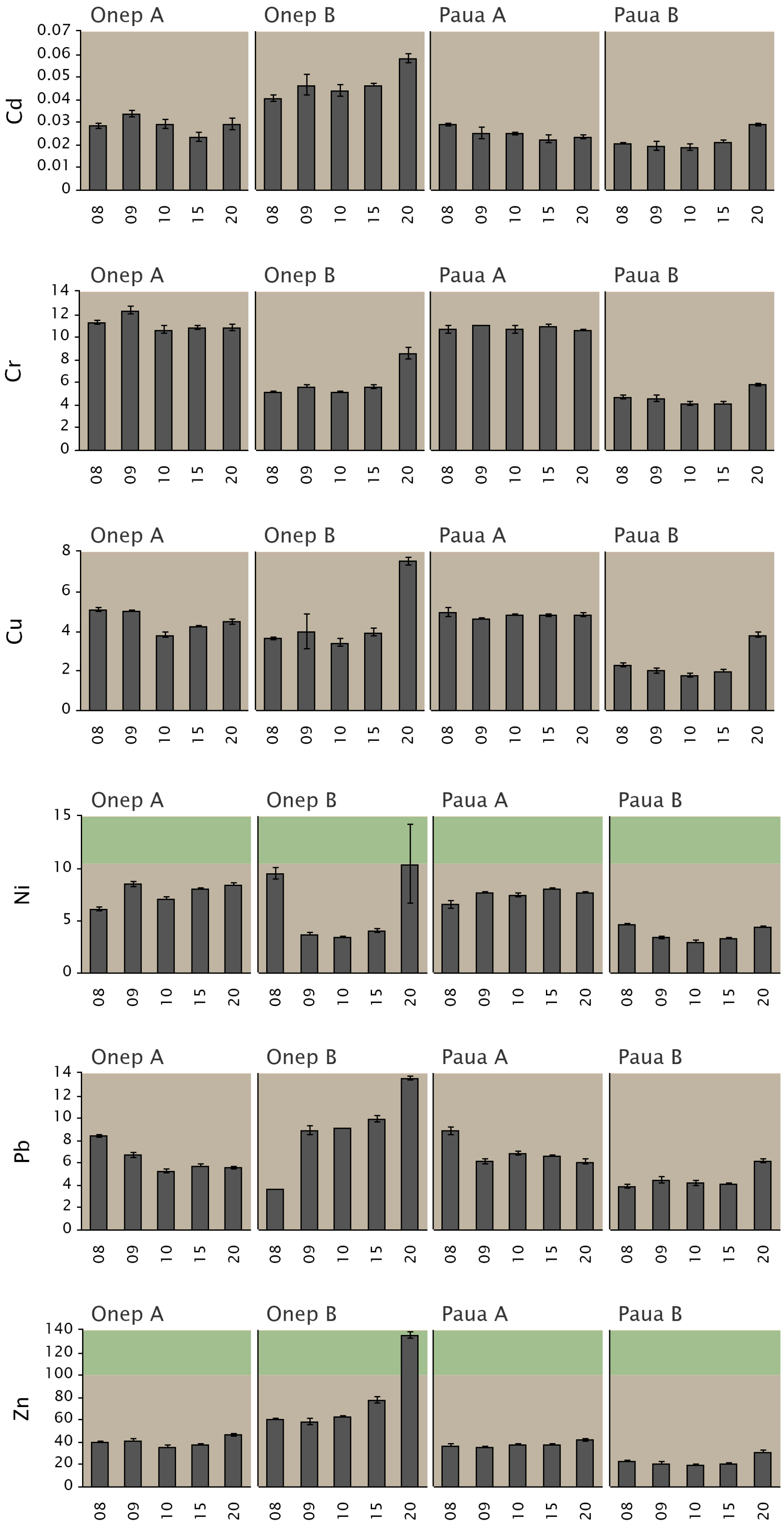


Fig. 9. Condition rating plots for trace metals (mean values, mg/kg ± SE). Levels of arsenic and mercury (not shown) were measured in 2015 and 2020, and were also very low (rated 'very good', Appendix 3). Condition rating key as follows:

Very Good	Good	Fair	Poor

Present at all sites in all years were the red seaweed *Gracilaria chilensis* and the green *Ulva* spp. In 2020 the prevalence of these two species was rated as 'occasional' (1-4% cover) and 'rare' (<1% cover), respectively. Both of these species are considered opportunistic and can form extensive beds under certain conditions (e.g. high nutrient enrichment). However, the prevalence of <5% measured at the fine scale sites is not considered to be ecologically significant (WFD-UKTAG 2014).

4.5.2 Macrofauna cores

Richness, abundance and AMBI

Raw macrofaunal data are provided in Appendix 4. In total, 96 species or higher taxa have been recorded in the harbour over the five surveys, with background information on the most common of these provided in Table 5. Mean species 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. 9a). Over the last three surveys (since 2010) there has been a decline in richness at all sites except Onep-B. Similarly, macrofaunal abundances at all sites except Onep-B are notably less then measured in previous surveys, and have declined since 2010 (Fig. 9b).

Whereas a decline in richness and abundance can be associated with stressor effects, values for the biotic index AMBI were within ecological condition ratings of 'good' or 'very good' (Fig. 10). For Onep sites, AMBI values generally show an improving trend in condition over the five surveys, which is at odds with sediment indicators. The trend appears to be driven by slightly increasing abundances of relatively sensitive (EG I and II) species, and/or a decline in densities of more resilient EG III-V species. However, confounding this result is poor or conflicting information on sensitivities (and EG classifications) for some species, meaning that results need to be interpreted with caution.

Main taxonomic groups and dominant species

In total across the three surveys, the 96 species recorded represented 18 main taxonomic groups. Most of these were poorly represented, with only eight groups whose site abundance was ≥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. 11.

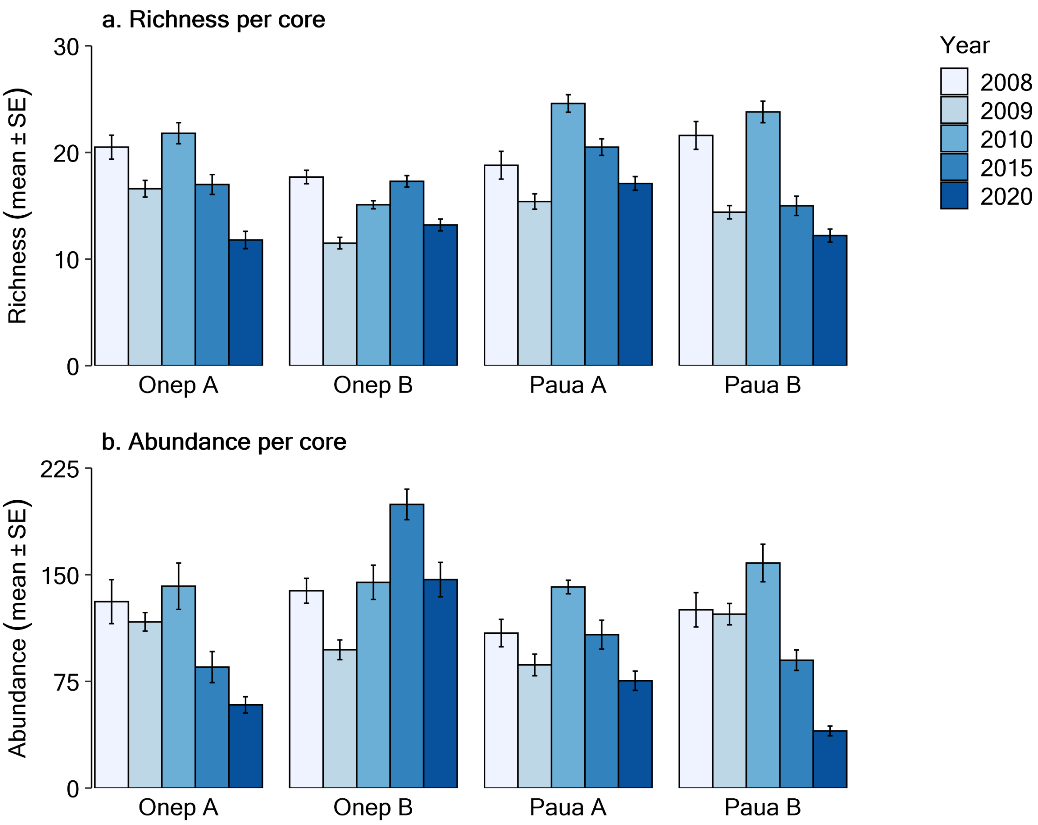
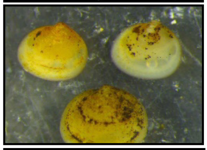
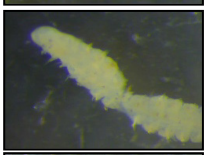


Fig. 10. Patterns (mean ± SE) in taxon richness and abundance per core (cores 0.013m², 150mm

Table 5. Description of the sediment-dwelling species that were consistently the most abundant (≥5% of total abundance) at one or more sites. Abundances are summed within each site across the five surveys. Eco-group (EG) classification from sensitive (EG I) to resilient (EG V) noted.

Main group	Onep-A	Onep-B	Paua-A	Paua-B	Description	Image
Amphipoda (Phoxocephalidae sp. 1)	338	0	120	44	A family of gammarid amphipods. Considered sensitive to disturbance (EG II) Functional role unclear.	
Bivalvia (*Arthritica* cf *bifurca*)	314	118	54	75	A small sedentary deposit feeding bivalve that lives buried in the mud. Tolerant of muddy sediments and moderate levels of organic enrichment. EG IV.	
Bivalvia (*Austrovenus stutchburyi*)	444	1276	378	470	Cockle. Suspension feeding bivalve, living near the sediment surface at mid-low tide. Considered sensitive to enrichment (EG II). Can tolerate sandy mud sediments, but optimum mud content is <50%.	
Bivalvia (*Linucula hartvigiana*)	1071	0	513	65	Small estuarine bivalve mollusc in the family Nuculidae, commonly called a nut shell. Can be very abundant and tolerate mud and moderate enrichment, although is classified as EG II.	
Bivalvia (*Macomona liliana*)	248	304	177	422	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. EG II.	
Polychaeta (*Aonides trifida*)	8	3233	9	64	Small surface deposit-feeding spionid polychaete worm that lives throughout the sediment to a depth of 10cm. Classified as EG II, with mud optimum <15%.	
Polychaeta (*Axiothella serrata*)	44	333	56	529	A deposit feeding maldanid (bamboo worm) polychaete worm that is a common infaunal species on the sheltered flats of central New Zealand estuaries. EG II.	
Polychaeta (*Boccardia acus*)	301	179	236	385	A small surface deposit-feeding spionid worm. Found in a wide range of sand/mud habitats. EG II.	
Polychaeta (*Heteromastus filiformis*)	1163	377	1307	1922	Small capitellid polychaete worm. A sub-surface, deposit-feeder that can thrive under conditions of moderate organic enrichment. EG III.	
Polychaeta (*Paradoneis* sp. 1)	155	22	415	15	A paraonid polychaete worm considered to be a deposit feeder. EG III.	
Polychaeta (*Prionospio aucklandica*)	219	34	267	233	A surface deposit-feeding spionid associated mainly with muddy sands, but is considered sensitive to changes in the level of silt/clay in the sediment. EG II.	

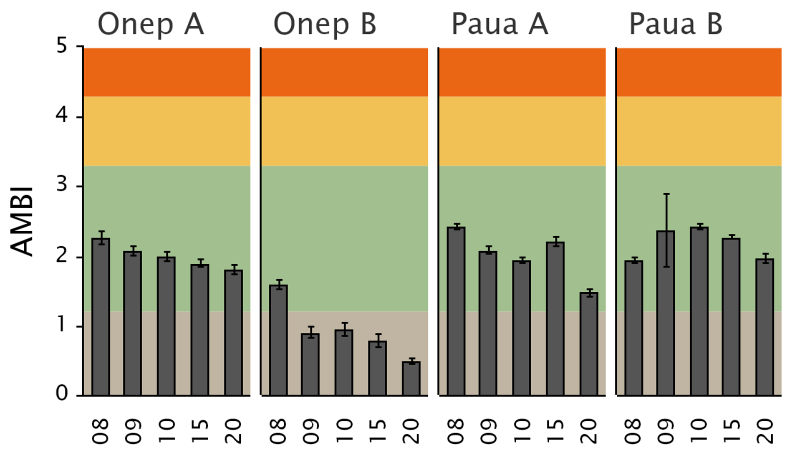


Fig. 11. Patterns (mean ± SE) in AMBI scores compared with condition rating criteria.

Polychaete worms were by far the most well-represented group, typically comprising around half of the taxa present and up to ~80% of the abundance. Most prevalent among the polychaetes were the disturbance-tolerant capitellid worm *Heteromastus filiformis*, the relatively 'sensitive' (EG II) maldanid 'bamboo worm' *Axiothella serrata*, and various EG II spionid species (Table 5). The small spionid *Aonides trifida* (EG II) was particularly abundant at Onep-B.

Bivalve shellfish also made a substantial contribution to site abundances but were represented by fewer species than gastropod snails. The most abundant bivalves were cockles *Austrovenus stutchburyi*, small nut shells *Linucula hartvigiana*, and wedge shells *Macomona liliana* (Table 5). These species can tolerate a wide range of sediment types (>50-80% mud) but have a sensitive EG II classification. Although not abundant, gastropod snails included the three larger species described above (see Table 4) and 13 other minor species (Appendix 4).

Other key groups represented at a lesser prevalence included small anemones, small shrimp-like amphipods, segmented worms (oligochaetes) and ribbon worms (nemerteans).

Multivariate patterns and association with sediment quality variables

In order to further explore the differences and similarities among sites and surveys in terms of macrofaunal assemblage composition, the species-level nMDS ordination in Fig. 12 places site-aggregated samples of similar composition close to each other in a 2-dimensional plot, with less similar sites being further apart. Fig. 12a reveals the following main trends:

- Onep and Paua 'A' sites (except for 2020, and Paua-A 2008), had similar macrofauna across years, dominated by the disturbance-tolerant worm *Heteromastus filiformis* (IG III) and the small bivalve *Linucula hartvigiana* (EG II)
- Onep-B formed a discrete group that included all survey years, and was characterised by high densities of the spionid *Aonides trifida* (EG I) and densities of cockles (EG II) that were 2-4 times greater than other locations.
- Three of the surveys (2008, 2010, 2015) at Paua-B grouped together, reflecting a macrofaunal assemblage whose dominant species were a blend of the above two groups, but included relatively high densities of *Heteromastus filiformis*.
- Except for Onep-B, the separation of 2020 primarily reflected the absence or reduced dominance of species present at other sites in previous surveys. For example, the relatively sensitive species *Axiothella serrata* (EG II) and *Aonides trifida* were abundant at Onep-B in all years, but were absent at other sites in 2020 despite having been recorded (abundant in the case of Paua-B) previously.

Although sediment mud content is often a strong determinant of macrofaunal composition, this variable explained very little of the overall difference among sites and surveys. In fact, none of the measured sediment quality nor sedimentation rate variables were strongly correlated with macrofaunal changes in any meaningful way, illustrated by the relatively short vectors (blue lines) on Fig. 13b. The progression to a shallower aRPD over time provided a partial explanation for the top-bottom separation of sites (aRPD Pearson r = -0.69). While the strongest correlation was evident for Cadmium (Cd) concentrations (Pearson r = 0.72), this was attributable to the concentrations at Onep B being high in a relative sense (Appendix 3). Given the very low absolute Cd concentrations overall with respect to sediment quality guidelines (see Fig. 8), this correlation is highly unlikely to be of any environmental significance.

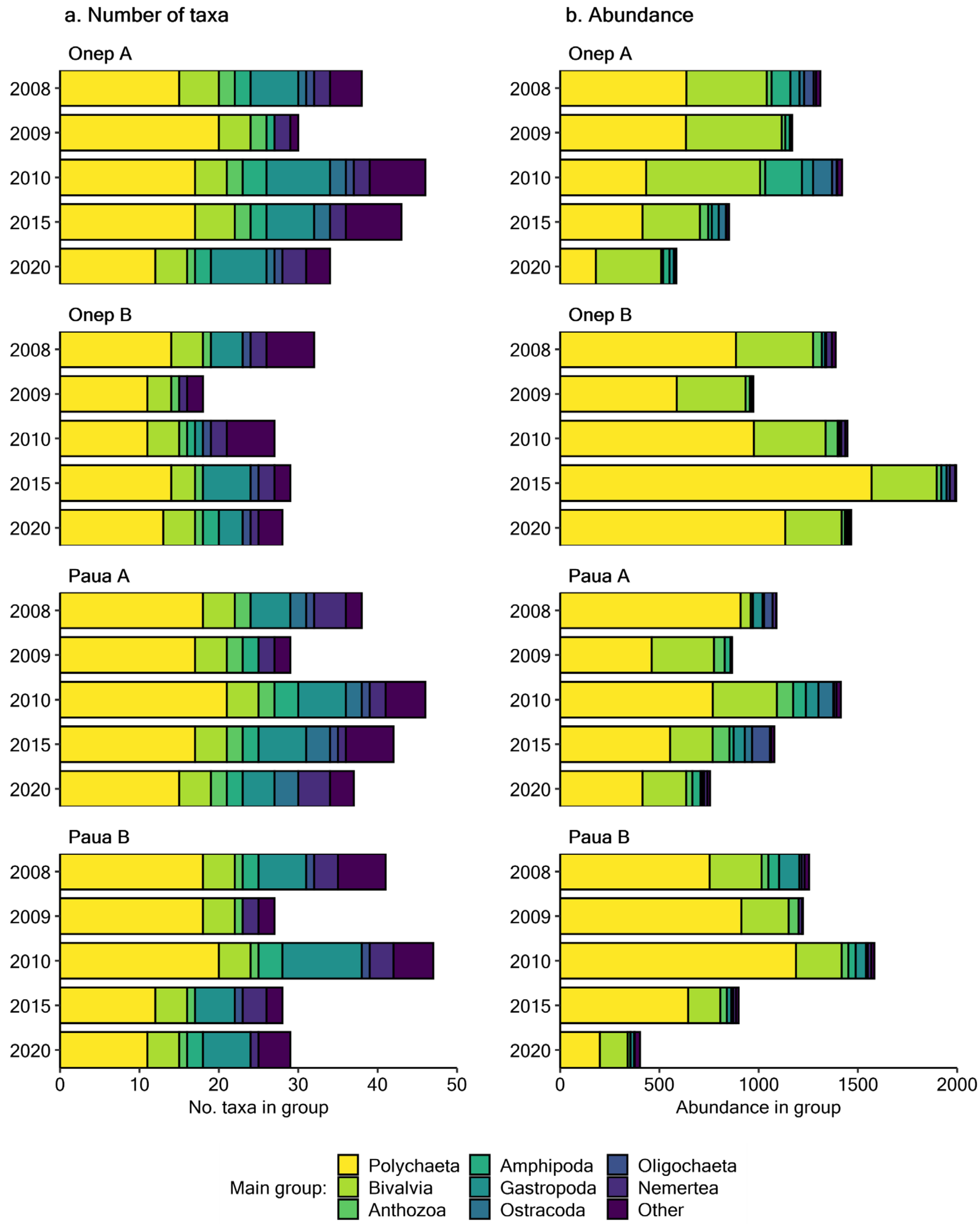


Fig. 12. Data pooled across years showing the contribution of main taxonomic groups to site-level richness and abundance values. Groups contributing ≥1% of site abundance are shown, with those <1% pooled into 'Other'.

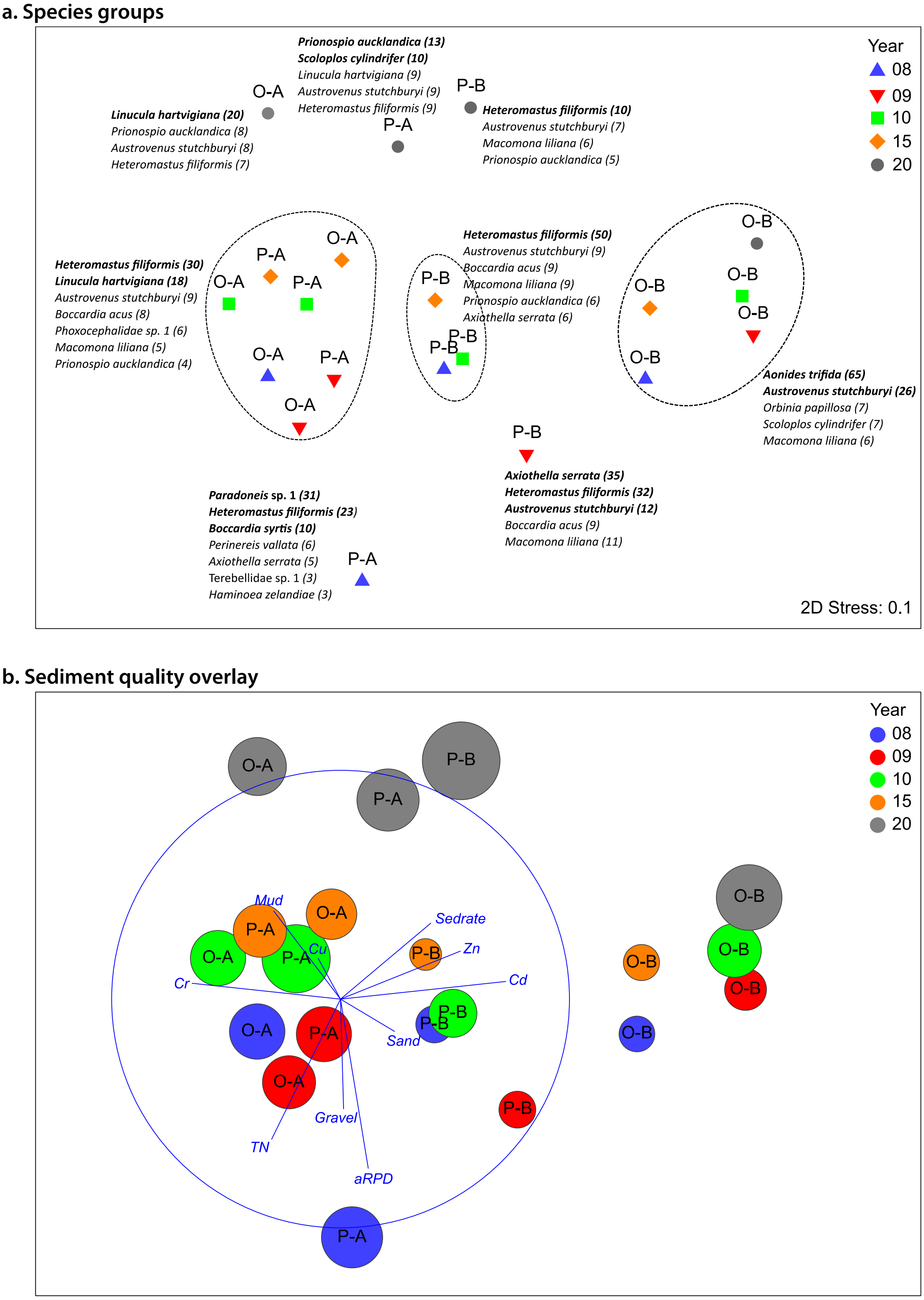


Fig. 13. Non-metric MDS ordination of macrofaunal data overall, with core samples aggregated within site for each survey year.

Top: ellipses enclose macrofaunal samples clustering at ≥65% Bray-Curtis similarity, with taxa identified (raw group-average abundances in brackets; if bold where ≥10%) that characterise or discriminate groups from each other. Bottom: Circle sizes are scaled to sediment mud content, and vectors represent the direction and strength of association (vector length) between the biological ordination pattern and the most highly correlated sediment quality variables. A perfect correlation would be represented as a vector extending to the circle.

To further explore the macrofaunal changes and environmental variables associated, an analysis was conducted that considered sites individually and used the full dataset of sediment samples (i.e. based on samples aggregated within the three zones at each site). The results in Fig. 13 indicate that in most years, zones within each site were reasonably similar in their macrofaunal composition; however, the year-to-year differences were generally quite pronounced. In addition, 2020 tends to consistently segregate as an anomalous year, reflected in Fig. 13 as the spatial separation of 2020 samples from other years, and strong within-site separation at the Onep sites (i.e. indicating relatively strong macrofaunal differences among zones within each site in 2020).

The most plausible environmental driver of the macrofaunal changes in 2020 at the upper estuary 'B' sites, is the sediment mud content. At these two sites, especially Paua-B, percentage mud markedly increased in 2020 and shows a moderate-strong correlation with the left-right ordination patterns (Pearson r = 0.77 for both sites). Analysis using the BIOENV method supported this result, highlighting mud as being the strongest plausible driver of the changes at Paua-B. The shift in aRPD from deeper to relatively shallow also explains some of the ordination pattern. However, many of the other apparent correlations (i.e. the longest vectors on Fig. 13), especially those with trace metals, are unlikely to have a meaningful causal association (i.e. due to their very low concentrations). Overall, it appears that much of the spatial and temporal variation in the macrofaunal assemblage cannot be explained by the environmental variables that were measured.

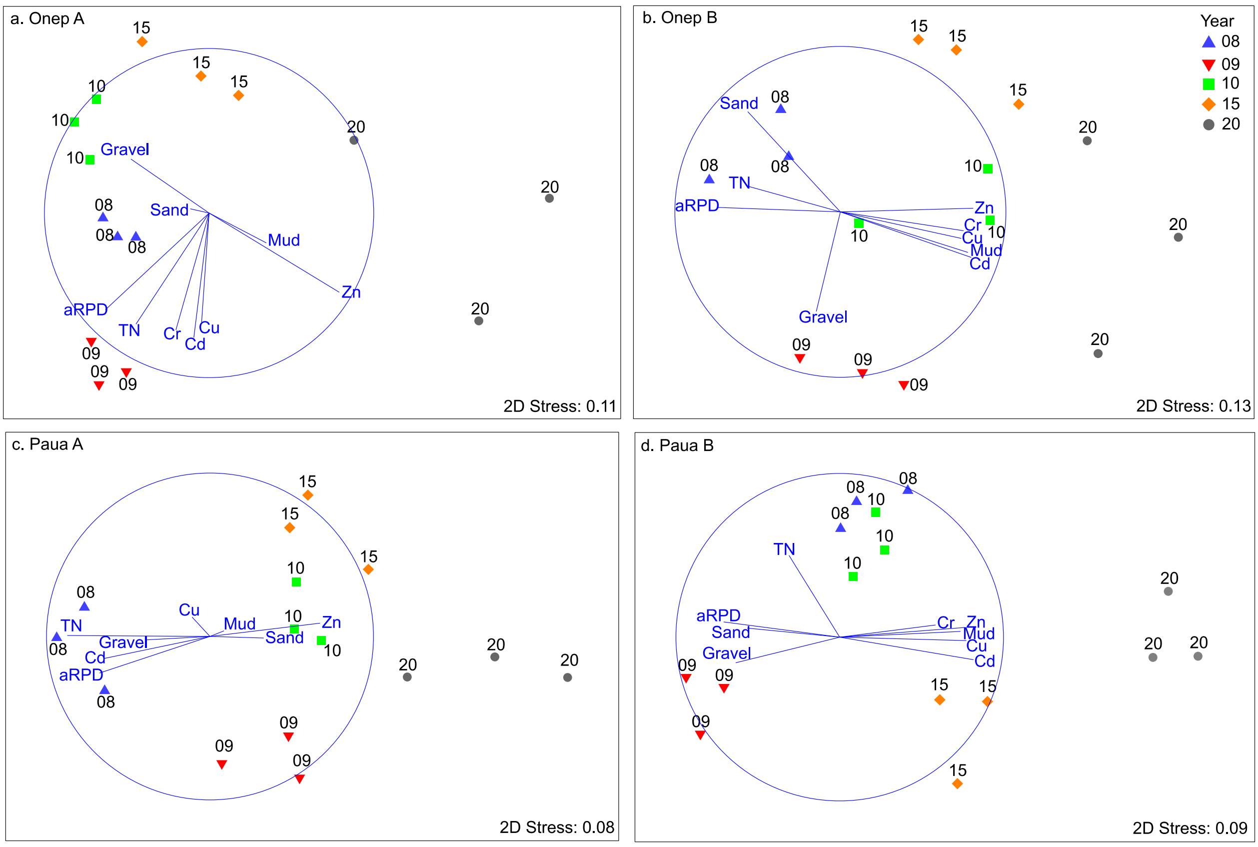


Fig. 14. Non-metric MDS ordination of macrofaunal data by site, with core samples aggregated by averaging within zones (X, Y and Z ; see Fig. 3) for each survey, resulting in triplicate representation of each year. Interpretation of vectors overlays as described for Fig. 12.

5. SYNTHESIS AND RECOMMENDATIONS

5.1 SYNTHESIS OF KEY FINDINGS

This report has described the findings of five intertidal surveys of Te Awarua-o-Porirua Harbour, largely following the fine scale survey methods described in New Zealand's NEMP. A summary of mean values of key physical and biological indicators in relation to ecological condition ratings is provided in Table 6. Table 6 highlights the low values of almost all indicators except aRPD and mud, consistent with 'good' or 'very good' ecological condition.

The relatively shallow depth of the aRPD in the last three surveys was rated as 'fair' or 'poor', indicative of moderate sediment enrichment. Despite this result, other sediment enrichment indicators (TOC, TN, TP) were not present at environmentally significant levels.

The 'poor' aRPD rating in 2020 at Paua-B is consistent with a marked increase in sediment mud content at that site. The mean mud content of ~20% in 2020 (rated 'fair') is 3-4 times the values recorded in earlier surveys (for which mud was generally rated 'good' or 'very good'). As noted previously, monitoring conducted over the last decade at a more extensive suite of intertidal and subtidal sites has shown a gradual increase in sediment mud content in both arms of the harbour, but especially in the Pauatahanui arm (Stevens & Forrest 2020). Associated with this change has been an increase in the areal extent of soft mud habitat. Stevens and Forrest (2020) discussed possible sources of muddy sediments as

Table 6. 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 4. Rating criteria not established for TP. See Glossary for definition of indicators.

Site	Year	Mud %	TOC %	TN mg/kg	TP mg/kg	aRPD mm	As mg/kg	Cd mg/kg	Cr mg/kg	Cu mg/kg	Hg mg/kg	Ni mg/kg	Pb mg/kg	Zn mg/kg	AMBI na
Onep-A	2008	10.0	-	685	442	28	-	0.028	11.3	5.1	-	6.0	8.4	39.4	2.3
	2009	9.2	0.39	643	397	27	-	0.034	12.3	5.0	-	8.5	6.7	41.0	2.1
	2010	10.0	0.26	< 503	393	14	-	0.029	10.6	3.8	-	7.1	5.3	35.7	2.0
	2015	8.3	0.58	< 500	397	10	6.2	0.023	10.8	4.2	0.02	8.0	5.7	38.0	1.9
	2020	11.0	0.30	< 500	407	6	5.5	0.029	10.8	4.5	< 0.02	8.5	5.5	46.3	1.8
Onep-B	2008	4.0	0.46	504	158	50	-	0.040	5.1	3.6	-	9.5	3.6	59.9	1.6
	2009	5.7	0.21	< 507	147	23	-	0.046	5.6	4.0	-	3.7	8.9	57.7	0.9
	2010	9.4	0.19	453*	163	10	-	0.044	5.2	3.4	-	3.4	9.1	62.3	0.9
	2015	4.3	0.29	< 500	196	10	3.2	0.046	5.6	3.9	0.02	4.0	9.9	77.7	0.8
	2020	14.1	0.36	< 500	267	12	3.6	0.058	8.5	7.5	0.02*	10.4	13.5	135.7	0.5
Paua-A	2008	12.2	-	823	447	37	-	0.029	10.7	4.9	-	6.5	8.8	36.7	2.4
	2009	9.9	0.38	700	437	17	-	0.025	11.0	4.6	-	7.7	6.1	35.0	2.1
	2010	15.1	0.35	673	470	10	-	0.025	10.7	4.8	-	7.4	6.8	37.3	1.9
	2015	9.2	0.79	600	450	10	7.5	0.022	11.0	4.8	0.03	8.1	6.6	37.3	2.2
	2020	12.7	0.31	< 500	453	12	7.2	0.023	10.6	4.8	0.01*	7.7	6.1	41.7	1.5
Paua-B	2008	4.5	0.44	547	150	33	-	0.020	4.7	2.3	-	4.7	3.9	23.0	1.9
	2009	4.4	0.23	470*	137	37	-	0.019	4.6	2.0	-	3.4	4.5	21.0	2.4
	2010	7.5	0.23	597	120	10	-	0.019	4.1	1.8	-	3.0	4.2	19.3	2.4
	2015	3.3	0.32	< 500	118	10	2.0	0.021	4.1	2.0	0.02	3.3	4.1	20.2	2.3
	2020	19.7	0.51	417*	202	10	2.9	0.029	5.8	3.8	0.03	4.4	6.2	31.0	2.0

** Sample mean includes values below lab detection limits*

< All values below lab detection limit

Condition rating key: Very Good | Good | Fair | Poor being land disturbance associated with subdivision in the eastern harbour catchment. This includes work in the Duck Creek and Whitby area over the last decade, and the Transmission Gully motorway development, which was started in late 2014 and is scheduled for completion in 2021.

As already noted, increasing mud content reduces oxygen penetration into the sediment, which can lead to a shallowing of the aRPD. Such changes would also be expected to result in adverse ecological effects, which are indicated by the results for Paua-B in particular. At Paua-B, species richness and abundance were particularly low in 2020. Some species that have been quite abundant in all surveys conducted over 2008-2015 were either absent or at greatly reduced densities in 2020. Notably absent were mud-sensitive worm species that had previously been common, namely *Axiothella serrata* and *Aonides trifida*, whose upper mud tolerance has been estimated at 15% (Robertson et al. 2015). Several other mud-sensitive species were also either absent or at greatly reduced abundances at Paua-B in 2020, including small epibenthic gastropods *Notoacmea* spp. (limpet) and *Haminoea zelandiae* (bubble shell), and various polychaete worm species such as *Orbinia papillosa*.

Despite this finding, it is apparent that richness and abundance were also reduced at Paua-A and Onep-A in 2020, for reasons that appear unrelated to sediment mud content. Furthermore, despite a compositional change in the macrofauna at Onep-B in 2020 being correlated with increased sediment mud, macrofauna richness and abundance did not decline. Clearly, therefore, there are additional factors driving ecological changes in the harbour.

However, none of the measured sediment quality or sedimentation variables provided plausible explanations. This result is consistent with a previous study of subtidal sediments in the harbour, which showed no clear association between biological patterns and individual sediment quality variables (Milne et al. 2009). In the present study, trace metal contaminants (especially Cd and Zn) in some instances correlated quite closely with the biological patterns. However, metal concentrations were very low relative to ANZG (2018) sediment quality guidelines, such that any causal association is highly unlikely, even allowing for the fact that ecological effects on sensitive species may occur at concentrations less than guideline values indicate (Hewitt et al. 2009).

Despite trace metals concentrations being generally low at the fine scale sites, previous investigations have revealed high concentrations of non-metal contaminants in harbour sediments near stormwater discharges and stream inflows (Sorensen & Milne 2009). Most significant are concentrations of DDT that greatly exceeding DGV thresholds in intertidal sediments across both arms of the harbour. Further investigation may reveal the occurrence and influence of such contaminants at the fine scale sites.

5.2 KEY CONSIDERATIONS FOR FUTURE MONITORING

After establishing an initial baseline, the intent for Te Awarua-o-Porirua Harbour was that fine scale monitoring should be undertaken at intervals of ~5-years, as is typical for this method. Although sediment quality is generally good across the fine scale sites, the 2020 survey has highlighted some anomalies or directional changes in key indicators (%mud, aRPD, richness, abundance) and the apparent loss of some sensitive species (from Paua-B), which are consistent with a decline in ecological condition. Furthermore, it appears likely that these changes are in part attributable to muddy sediment inputs. As such, it is recommended that the fine scale survey be repeated in January 2022, to determine whether the changes apparent in 2020 reflect an ongoing problem or are an anomaly. The latest broad scale survey (Stevens & Forrest 2020, in prep.) and a subtidal ecological survey planned for later in 2020, should also shed light on current ecological condition relative to earlier investigations.

Assuming an ongoing issue or a declining situation is revealed, subsequent considerations include how the changes in key indicators translate to wider effects on the ecological values of the harbour. These include shellfish beds, fish and bird values, and fringing rocky habitats (see photo next page). Simultaneously, the apparent recent 'blooms' of the green macroalga *Chaetomorpha ligustica* (see Section 4.1) suggest a need for investigations of wider harbour ecology and drivers of change.

In the meantime, in view of the combined results from the latest fine scale survey and the recent sediment plate monitoring, it is suggested that current and ongoing sources of muddy sediment inputs to the harbour are evaluated, and the scope for reducing inputs determined.

The broader fringing habitats of Te Awarua-o-Porirua Harbour include extensive rocky areas where mudflats and seagrass butt against diverse biogenic reefs formed by the tube worm *Spirobranchus cariniferus*

One of the considerations for the next fine scale monitoring survey is to review the extent that the current programme is fit-for-purpose, bearing in mind that there is great value in collecting a time series of data based on a repeated approach, even when only a snapshot in time. The current sites provide a broad representation of harbour conditions from the upper harbour to the entrance. They are sufficiently species-rich that changes over time can be adequately assessed, and given that the sites provide a dataset of five surveys over 12 years, it would be inadvisable to move them. However, broad scale survey results indicate the present sites may not represent the intertidal areas that appear to be most impacted by recent muddy sediment inputs (e.g. Kakaho Bay north of Paua-B). Supplementary sites in such areas may enable more direct assessment of sediment impacts to the harbour.

In terms of indicators, the current suite is fairly typical for routine monitoring and should be continued. Given the absence of ecologically significant nutrient and organic matter levels, there is no justification for broadening these indicators (e.g. to include a greater nutrient suite). However, given that past monitoring conducted by GWRC has revealed significantly elevated concentrations of non-metal contaminants (e.g. the historic pesticide DDT) at intertidal sites near point-source inputs around harbour margins, there would be value in a one-off analysis at the fine scale sites of a broader toxicant suite.

In the 2015 survey report it was suggested that vertical sediment profiles of oxidation-reduction potential (ORP; an indicator under development as part of the New Zealand ETI), be measured as a complement to aRPD. However, ORP values measured in 2020 (see Appendix 5 for results) were not particularly meaningful and did not correspond with the visible aRPD transition. Further, many ORP profiles were counter-intuitive in that values became increasingly positive (indicating more oxic conditions) with sediment depth. Published method limitations and comparisons between aRPD and ORP values describe marked core-to-core variability and inconsistency (Forrest & Creese 2006; Gerwing et al. 2013), consistent with many recent NEMP surveys (e.g. Forrest & Stevens 2019b; Forrest & Stevens 2019c, 2020). Such results undermine the utility of ORP for routine monitoring purposes, and its continued use in Te Awarua-o-Porirua Harbour is not recommended.

5.3 RECOMMENDATIONS

Based on the findings of this report, it is recommended that GWRC consider the following:

- A further fine scale survey in January 2022 to further evaluate whether the results from the 2020 survey reflect an ongoing state of decline in parts of Te Awarua-o-Porirua Harbour.
- Approaches for tracking recent and ongoing sediment inputs, such as using compound specific stable isotopes (e.g. Gibbs & Woodward 2017), to determine the origin of muddy sediments, especially in the Pauatahanui arm.
- Assess the broader ecological implications of changes in key indicators revealed by the present report, and recent (broad scale) or planned (subtidal) surveys.

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APPENDICES

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
Pauatahanui	Paua-A	Boatshed downstream	P_A1	1757240	5448655
Pauatahanui	Paua-A	Boatshed downstream	P_A2	1757266	5448601
Pauatahanui	Paua-A	Boatshed downstream	P_A3	1757242	5448587
Pauatahanui	Paua-A	Boatshed downstream	P_A4	1757212	5448645
Pauatahanui	Paua-B	Upstream	P_B1	1760353	5448353
Pauatahanui	Paua-B	Upstream	P_B2	1760356	5448294
Pauatahanui	Paua-B	Upstream	P_B3	1760386	5448298
Pauatahanui	Paua-B	Upstream	P_B4	1760382	5448353

Appendix 2. RJ Hill analytical methods

Summary of Methods

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

Sample Type: Sediment

Test	Method Description	Default Detection Limit	Sample No
Individual Tests			
Environmental Solids Sample Drying*	Air dried at 35°C Used for sample preparation. May contain a residual moisture content of 2-5%.	-	1-12
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 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	1-27
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 - 0.4 mg/kg dry wt	1-12
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	1-27
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	1-27
Fraction < 63 µm*	Wet sieving with dispersant, as received, 63 µm sieve, gravimetry (calculation by difference).	0.1 g/100g dry wt	1-27

These samples were collected by yourselves (or your agent) and analysed as received at the laboratory.

Dates of testing are available on request. Please contact the laboratory for more information.

Samples are held at the laboratory after reporting for a length of time based on the stability of the samples and analytes being tested (considering any preservation used), and the storage space available. Once the storage period is completed, the samples are discarded unless otherwise agreed with the customer. Extended storage times may incur additional charges.

This certificate of analysis must not be reproduced, except in full, without the written consent of the signatory.

Ara Heron BSc (Tech)
Client Services Manager - Environmental

Appendix 3. Sediment quality raw data for 2020

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**	0.6	87.5	11.9	0.34	<500	410	2 to 9	5.70	0.029	11.30	4.70	<0.02	8.80	5.80	48
	Y	0.7	87.8	11.5	0.28	<500	420	7 to 9	5.70	0.033	10.90	4.30	<0.02	8.30	5.40	47
	Z	1.3	89.1	9.7	0.29	<500	390	3 to 10	5.20	0.025	10.30	4.40	<0.02	8.30	5.40	44
Onep B	**X**	1.3	85.3	13.4	0.42	<500	240	8 to 13	3.40	0.062	7.60	7.30	<0.02	6.30	13.40	132
	Y	1.6	83.9	14.5	0.33	<500	270	9 to 17	3.50	0.057	8.60	7.40	0.02	17.90	13.40	134
	Z	3.9	81.7	14.4	0.34	<500	290	9 to 19	3.80	0.055	9.30	7.90	0.03	7.00	13.80	141
Paua A	**X**	2.3	84.0	13.8	0.32	<500	470	7 to 23	6.90	0.023	10.60	5.00	0.02	7.70	6.40	44
	Y	3.1	85.3	11.6	0.27	<500	430	15 to 20	7.10	0.022	10.60	4.60	<0.02	7.70	5.70	40
	Z	2.2	85.2	12.6	0.34	<500	460	3 to 10	7.50	0.025	10.70	4.80	<0.02	7.70	6.10	41
Paua B	**X**	1.6	78.8	19.6	0.57	500	210	5 to 18	3.00	0.029	5.90	4.10	0.03	4.50	6.50	33
	Y	1.3	77.7	21.0	0.50	500	210	5 to 20	2.90	0.030	5.90	3.70	0.03	4.50	6.20	31
	Z	1.0	80.5	18.5	0.47	<500	185	5 to 15	2.80	0.028	5.50	3.60	0.02	4.20	5.90	29
								DGV	20	1.5	80	65	0.15	21	50	200
								GV-high	70	10	370	270	1	52	220	410

Appendix 4. Macrofauna core raw data for 2020.

Cores 130mm diameter to 150mm deep, 0.013m² sample area, 2L core volume

Main group	Taxa	Habitat	EG	Onep A1	Onep A2	Onep A3	Onep A4	Onep A5	Onep A6	Onep A7	Onep A8	Onep A9	Onep A10	Onep B1	Onep B2	Onep B3	Onep B4	Onep B5	Onep B6	Onep B7	Onep B8	Onep B9	Onep B10
Anthozoa	Anthopleura aureoradiata	epibiota	III				1			1	1	3	4										
Anthozoa	Edwardsia sp. 1	epibiota	II											2	2		1	4	4	3			1
Gastropoda	Cominella glandiformis	epibiota	III		2	1			1			2	3				1	1	1				1
Gastropoda	Diloma subrostratum	epibiota	II																				
Gastropoda	Haminoea zelandiae	epibiota	I								1												
Gastropoda	Neoguraleus sinclairi	epibiota	NA		1																		
Gastropoda	Notoacmea spp.	epibiota	II			1				1		2		1				1					
Gastropoda	Philine sp. 1	epibiota	NA																				
Gastropoda	Turbonilla sp. 1	epibiota	I							1													
Gastropoda	Xymene plebeius	epibiota	I		1																		
Gastropoda	Zeacumantus lutulentus	epibiota	II		3				1		1												1
Amphipoda	Amphipoda sp. 1	infauna	II		1						3	1	1				1						1
Amphipoda	Amphipoda sp. 5	infauna	II											1									
Amphipoda	Phoxocephalidae sp. 1	infauna	II	2	1	3	6	2		2	3	4	3										
Bivalvia	Arthritica cf bifurca	infauna	IV				1			6			1		2	1			1	1	1		3
Bivalvia	Austrovenus stutchburyi	infauna	II	7	6	2	2	3	5	5	8	16	22	22	11	22	19	27	28	22	21	19	9
Bivalvia	Linucula hartvigiana	infauna	II	22	27	11	27	17	11	15	30	21	19										
Bivalvia	Macomona liliana	infauna	II	4	3	3	4	6	5	2	6	7	5	9	4	7	10	8	4	9	8	7	7
Bivalvia	Paphies australis	infauna	II													1	1						
Copepoda	Copepoda sp. 1	infauna	II																				
Cumacea	Colurostylis lemurum	infauna	I																				
Decapoda	Halicarcinus whitei	infauna	III																	1	4		1
Decapoda	Hemiplax hirtipes	infauna	V													1							
Decapoda	Paguristes pilosus	infauna	II			1																	
Decapoda	Unidentified decapod megalopa	larva	NA				1	1															
Holothuroidea	Taeniogyrus dendyi	infauna	I						1														
Mysidae	Tenagomysis sp. 1	infauna	II																1				
Nemertea	Nemertea sp. 1	infauna	III				1		1	1					1	2				4	1	1	1
Nemertea	Nemertea sp. 2	infauna	III			1	1																
Nemertea	Nemertea sp. 3	infauna	III																				
Nemertea	Nemertea sp. 4	infauna	III							1													
Oligochaeta	Oligochaeta	infauna	III				1														2		1
Ostracoda	Ostracoda sp. 1	infauna	I					1															
Ostracoda	Ostracoda sp. 2	infauna	I																				
Ostracoda	Ostracoda sp. 4	infauna	I																				
Polychaeta	Aonides trifida	infauna	I											21	13	97	96	81	90	85	99	97	95
Polychaeta	Armandia maculata	infauna	II						1														
Polychaeta	Axiothella serrata	infauna	II											1	1	4	2	2	3	1	4	2	2
Polychaeta	Boccardia (Paraboccardia) acus	infauna	II								1									1	3	4	
Polychaeta	Boccardia (Paraboccardia) syrtis	infauna	II	1	1			1															
Polychaeta	Capitella sp. 1	infauna	IV											1	1								
Polychaeta	Dorvilleidae sp. 1	infauna	II																				
Polychaeta	Glycera ovigera	infauna	III								1												
Polychaeta	Glycinde sp. 1	infauna	II																				
Polychaeta	Heteromastus filiformis	infauna	III	4	9	3	7	9	6	11	9	9	6			4			3		2	2	2
Polychaeta	Microspio maori	infauna	I															1		2		1	
Polychaeta	Nicon aestuariensis	infauna	III								1												
Polychaeta	Orbinia papillosa	infauna	I											11	6	10	7	14	12	3	10	7	15
Polychaeta	Paradoneis sp. 1	infauna	III							1		2				1	1	1		3	2	1	1
Polychaeta	Perinereis vallata	infauna	II							1					1								
Polychaeta	Polynoidae sp. 1	infauna	I																				
Polychaeta	Prionospio aucklandica	infauna	II	11	17	7	8	7	2	5	1	20	5	1		1	1	1		2	1	1	
Polychaeta	Scolecolepides benhami	infauna	IV			1				1	1	3			1		1		1				
Polychaeta	Scoloplos (Scoloplos) cylindrifer	infauna	I				1						1	23	18	20	17	30	19	17	19	15	12
Polychaeta	Syllidae sp. 1	infauna	II																				
Polychaeta	Nereididae (unidentified juv)	infauna juv	NA		2						1	1	1					2		1			1

Main group	Taxa	Habitat	EG	Paua A1	Paua A2	Paua A3	Paua A4	Paua A5	Paua A6	Paua A7	Paua A8	Paua A9	Paua A10	Paua B1	Paua B2	Paua B3	Paua B4	Paua B5	Paua B6	Paua B7	Paua B8	Paua B9	Paua B10
Anthozoa	Anthopleura aureoradiata	epibiota	III				1																
Anthozoa	Edwardsia sp. 1	epibiota	II	4	1	2	3	4	7	1		3	5	1	1	2	1	3	1	2		1	1
Gastropoda	Cominella glandiformis	epibiota	III			1	1										1	1			1	1	
Gastropoda	Diloma subrostratum	epibiota	II												1	2	1	1	1			4	
Gastropoda	Haminoea zelandiae	epibiota	I																			1	
Gastropoda	Neoguraleus sinclairi	epibiota	NA	1																			
Gastropoda	Notoacmea spp.	epibiota	II				1					1									1		
Gastropoda	Philine sp. 1	epibiota	NA														1						
Gastropoda	Turbonilla sp. 1	epibiota	I																				
Gastropoda	Xymene plebeius	epibiota	I																				
Gastropoda	Zeacumantus lutulentus	epibiota	II		2					1		1			1								
Amphipoda	Amphipoda sp. 1	infauna	II			9	2			3		1	7			1							
Amphipoda	Amphipoda sp. 5	infauna	II																				
Amphipoda	Phoxocephalidae sp. 1	infauna	II	1	5	1	2	4	2	1	1	1	1										1
Bivalvia	Arthritica cf bifurca	infauna	IV							1	1		2	1			1		1				
Bivalvia	Austrovenus stutchburyi	infauna	II	16	7	6	9	1	9	7	10	15	2	13	9	4	4	4	7	5	8	6	6
Bivalvia	Linucula hartvigiana	infauna	II	11	12	4	10	10	6	8	12	8	7	3	1	2		2	2		1		1
Bivalvia	Macomona liliana	infauna	II	3	5	3	7	4	8	2	3	6	5	8	10	5	3	4	5	8	4	9	3
Bivalvia	Paphies australis	infauna	II																				
Copepoda	Copepoda sp. 1	infauna	II																	1			
Cumacea	Colurostylis lemurum	infauna	I			1																	
Decapoda	Halicarcinus whitei	infauna	III	1								1	2	2			1			2			1
Decapoda	Hemiplax hirtipes	infauna	V																				
Decapoda	Paguristes pilosus	infauna	II																				
Decapoda	Unidentified decapod megalopa	larva	NA																				
Holothuroidea	Taeniogyrus dendyi	infauna	I	1	1	1	1			2	2		1	2	2		1			1	1		1
Mysidae	Tenagomysis sp. 1	infauna	II															1	4	1	1	2	2
Nemertea	Nemertea sp. 1	infauna	III		1			3	1		3		3		1		1			1			
Nemertea	Nemertea sp. 2	infauna	III	1																			
Nemertea	Nemertea sp. 3	infauna	III	1					1		1												
Nemertea	Nemertea sp. 4	infauna	III			1																	
Oligochaeta	Oligochaeta	infauna	III																				
Ostracoda	Ostracoda sp. 1	infauna	I				1	1			1												
Ostracoda	Ostracoda sp. 2	infauna	I							1			4										
Ostracoda	Ostracoda sp. 4	infauna	I	1																			
Polychaeta	Aonides trifida	infauna	I																				
Polychaeta	Armandia maculata	infauna	II	1	4	1	5	1	1	2	1	2			1						1		
Polychaeta	Axiothella serrata	infauna	II																				
Polychaeta	Boccardia (Paraboccardia) acus	infauna	II		1	1			4		3			3		1			2		7		2
Polychaeta	Boccardia (Paraboccardia) syrtis	infauna	II							1			1										
Polychaeta	Capitella sp. 1	infauna	IV																				
Polychaeta	Dorvilleidae sp. 1	infauna	II								1												
Polychaeta	Glycera ovigera	infauna	III																				
Polychaeta	Glycinde sp. 1	infauna	II						2								1			2			
Polychaeta	Heteromastus filiformis	infauna	III	1	8	2	4	12	13	2	20	4	19	10	13	15	13	3	15	12	6	10	6
Polychaeta	Microspio maori	infauna	I																				
Polychaeta	Nicon aestuariensis	infauna	III					2		1	1	2	2							1		1	
Polychaeta	Orbinia papillosa	infauna	I	1	2	1	2	3	5	1	1	1	5	5	1	3	1		2		1		
Polychaeta	Paradoneis sp. 1	infauna	III								7		4										
Polychaeta	Perinereis vallata	infauna	II														1						
Polychaeta	Polynoidae sp. 1	infauna	I								1												
Polychaeta	Prionospio aucklandica	infauna	II	3	10	10	11	14	15	11	28	13	16	9	5	8	10	3	1	3	4	2	
Polychaeta	Scolecolepides benhami	infauna	IV		1					1		2				3				4		1	
Polychaeta	Scoloplos (Scoloplos) cylindrifer	infauna	I	4	5	3	11	17	6	8	13	21	12			1							
Polychaeta	Syllidae sp. 1	infauna	II										2										
Polychaeta	Nereididae (unidentified juv)	infauna juv	NA	1	1		1	3	2	2	4	4	1	1	1		2		1	1		1	

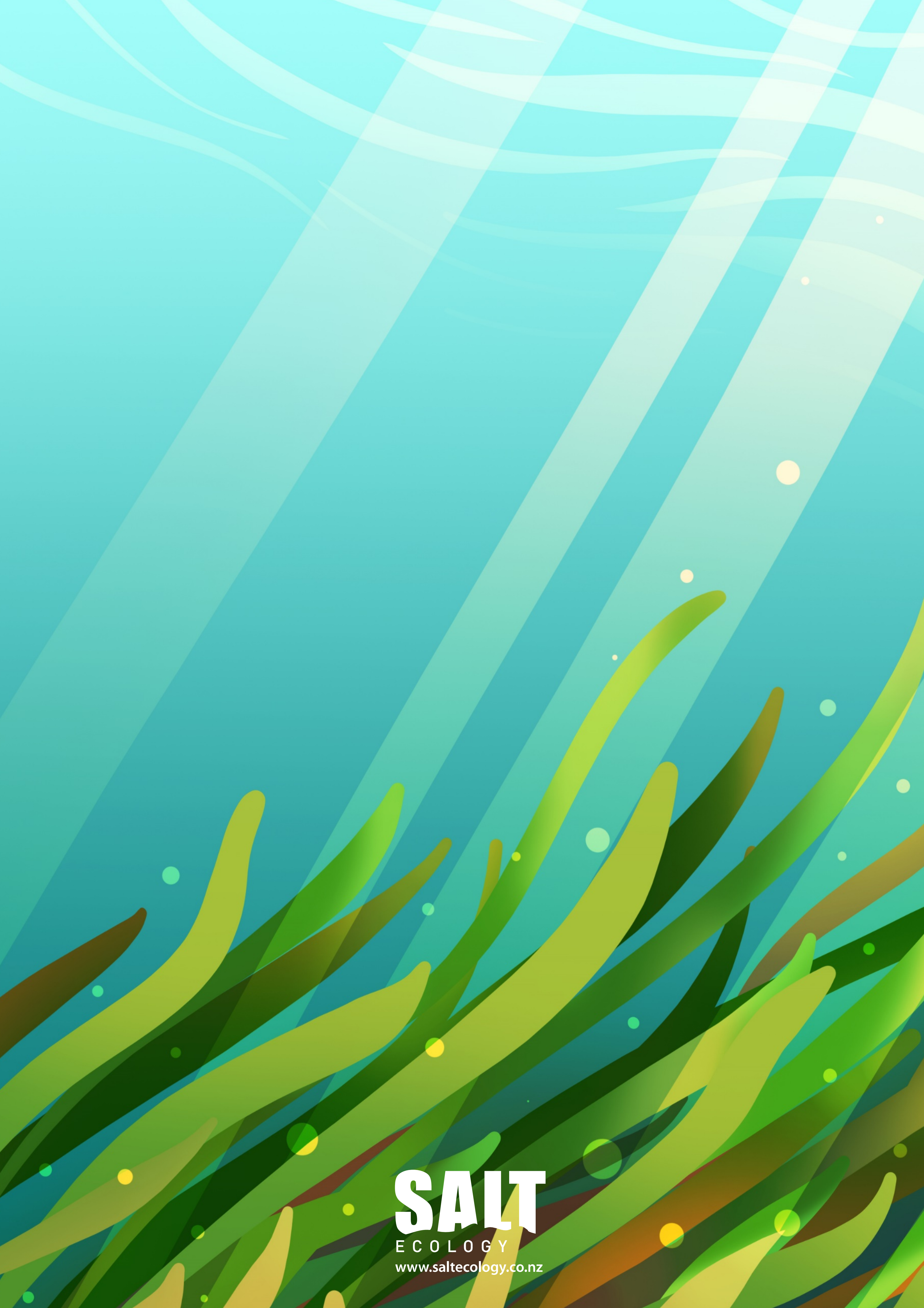
Appendix 5. Oxidation-reduction potential (ORP) profiles in sediment at fine scale sites

ORP was evaluated as a trophic state indicator to compare with aRPD. To provide sufficient data to enable comparison against results from a visual assessment of aRPD depth, in each of three plots (1X, 4Y and 7Z), a sediment core (120mm diameter, 150mm deep) was taken using a Perspex corer, and ORP was measured at five sediment depths (10, 30, 50, 70 and 100mm). ORP measurements were made using a YSI Pro10 ORP meter and YSI 1002 ORP (redox) sensor. The sensor probe was inserted horizontally into holes pre-drilled at the designated depth in the Perspex corer and, after allowing the probe to stabilise at each depth for a consistent 1-minute interval, ORP (mV) was measured.

There was a poor relationship between instantaneous ORP results from sediment pore water and more stable integrated measures of sediment aRPD. ORP data were considered unreliable due to identified method problems. These include a ~10mm probe diameter limiting the ability to obtain fine scale readings and to reliably measure ORP when aRPD was <10mm depth. There are also difficulties in measuring ORP under field conditions (e.g. flooding of core holes with water) and in free-draining sandy sediments. The occurrence of oxic zones throughout the core profile, such as caused by the mixing of surface and deeper sediments by bioturbation also contribute to high variability in results.

Table A5.1 ORP readings 14 and 15 January 2020. Readings could not be obtained for some cores due to their sandy free-draining nature.

Estuary	Site	zone	ORP method	Temp50mm °C	ORP10mm mv	ORP30mm mv	ORP50mm mv	ORP70mm mv	ORP100mm mv
Paua	B	X	Insitu_fullflood	14.3	-146	-179	-235	-236	-331
Paua	B	Y	Insitu_fullflood	14.9	-175	-189	-172	-166	-140
Paua	B	Z	Insitu_fullflood	15.1	-189	-226	-316	-265	-251
Onep	B	X	Insitu_fullflood	15.5	355	265	231	214	145
Onep	B	Y	Insitu_fullflood	15.6	168	128	112	164	214
Onep	B	Z	Insitu_partflood	16	201	205	196	149	117
Paua	A	Y	Tray	17.1	-19	-122	650	659	504
Paua	A	Z	Tray	17.2	1500	1414			
Paua	A	X	Tray	17.4	730		887		
Onep	A	Z	Insitu_fullflood	17.9	-256	-320	-289	-232	-238
Onep	A	Y	Insitu_partflood	18.1	-250	-298	-415	-436	-234
Onep	A	X	Insitu_fullflood	18.1	-141	-176	-264	-268	-360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