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Executive summary

Waikato Regional Council's Regional Estuary Monitoring Programme (REMP) focuses on monitoring intertidal benthic macroinvertebrates (i.e., animals that live in estuarine sediments) and sediment properties at 15 sites in three estuaries in the Waikato region: The Firth of Thames, Whāingaroa (Raglan) Harbour (both monitored since 2001) and Tairua Harbour (monitored since 2012). This report presents data collected over 17 years (from 2001 to 2018), summarises the state of, and trends in, estuarine health and provides recommendations for future monitoring.

Monitoring sites in the REMP vary in their general characteristics in terms of sediment mud content, macroinvertebrate community composition, sediment deposition rates, and elevation relative to tidal level, as well as their location within an estuary and geographic location within the Waikato Region. Estuarine health indices suggest most sites are currently moderately healthy, although two sites are in poor health and four sites are in good health.

Trends in 'indicator taxa'[1] and sediment properties suggest that health is declining at many REMP sites in all three estuaries. There are fewer trends at sites in Tairua Harbour (compared to the Firth of Thames and Whāingaroa Harbour), but this may be attributable to the shorter monitoring period (6 years compared with 17 years at the other estuaries) and therefore fewer data points that limits statistical power to detect trends. State and trend results for each site are summarised in the table on the following page.

Estuaries are the receiving environment for any contaminants delivered from their catchments and are subject to pressures from development around their margins, or activities within the estuary itself. This estuarine monitoring programme is not directly linked to monitoring of freshwater or land use change in catchments, making it difficult to ascertain whether changes in the sites monitored are linked to activities in the catchments or estuary. Nonetheless, the results suggest that estuarine health at ten out of fifteen monitoring sites is declining, which is cause for concern and indicates that management practices (on land and/or in the coastal marine area) have not been sufficient to safeguard estuarine health. This is perhaps not surprising given the widely documented declines in freshwater health over recent decades.

There are c. 30 estuaries in the Waikato region, and there is a need to assess state and trends across a wider range of locations than the three estuaries that were monitored over 2001 to 2018. Coromandel Harbour was added to the monitoring programme in spring 2019 by adopting a spatially nested approach in estuaries that have already been monitored for greater than 10 years (i.e., the Firth of Thames and Whāingaroa Harbour). A recommended sampling and reporting schedule for the four REMP estuaries (from 2019 to 2028) is included in this report. Sampling in other estuaries will occur through a marine sediment contaminant monitoring programme started in 2019, which aims to sample all major estuaries in the region on a 5-year cycle, and analyses sediment for heavy metals and organic contaminants, sediment properties (grain-size, organic matter content and chlorophyll *a*) and benthic macroinvertebrates. While not useful for assessing trends, this will provide a broader, region wide understanding of benthic health, and provide context for the data collected in the REMP estuaries.

Monitoring in the REMP has been focused on intertidal, unvegetated habitats at a fine scale and the results are site-specific. There has been some monitoring of estuarine water quality, vegetation, and sediment contaminants in the Waikato region over the past twenty years, but data has been collected infrequently and has not necessarily sampled the same estuaries or sites as the REMP, making it difficult to pull the information together to provide a coherent account of the state of Waikato estuaries. Furthermore, the lack of links between the state of estuarine health to relevant drivers (i.e., activities in the estuary or catchment) has limited the ability to attribute the observed state and trends to any particular cause. It is recommended that the sites

[1] 'Indicator taxa' are macroinvertebrates that are known to either be tolerant or intolerant to high mud, organic enrichment and/or sediment pollution levels.

and indicators monitored in the REMP become part of a broader Coastal Ecosystem Health Monitoring Programme, that collects data on connected and relevant indicators of drivers, pressures, and state. This will require that monitoring of Waikato estuaries be more closely integrated with monitoring in their catchments to improve our ability to attribute declines or improvements in estuarine health to activities on land.

Summary of results for each monitoring site:

Estuary and site	Summary of state and trends
Firth of Thames	
Gun Club	Estuarine health indices, mud content (c. 5%) and organic matter content (c. 2%) suggest this site is in **moderate to good health**. The lack of sedimentation (c. -0.4mm/yr) and three of four trends in indicator taxa (significant increasing trends in *Colurostylis lemurum, Paphies australis* and *Aonides trifida)* suggest health is **improving** at this site. Note that there were also significant increasing trends in organic matter content and in Capitellidae abundance, which suggest declining health.
Kaiaua	Estuarine health indices and organic matter content (c. 2 %) suggest this site is **moderately healthy**, but with elevated mud content (c. 19%). High rates of sedimentation (c. 3.6 mm/year) and indicator taxa (significant decreasing trends in *Austrovenus stutchburyi,* Phoxocephalidae*, Linucula hartivigiana and Magelona* cf. *dakini*) suggest health is **declining** at this site.
Kuranui Bay	Estuarine health indices and organic matter content (c. 2 %) suggest this site is **moderately healthy**, with c. 9% mud content. The site is experiencing net erosion (-4.9 mm/yr), but the possible increase in mud content (not statistically significant), significant increasing trend in organic matter content, significant trend in an Estuarine Health Index, and indicator taxa (significant decreasing trends in *Aonides trifida, Macomona liliana, Linucula hartigiana* and an increasing trend in Capitellidae) all suggest health is **declining** at this site.
Miranda	Estuarine health indices and organic matter content (c. 1.4 %) suggest this site is in **moderate to good health**, with c. 8% mud content. The site is experiencing net sediment erosion (-2.5 mm/yr), but there has been a significant increase in mud content and trends in an Estuarine Health Index, and in six indicator taxa (significant decreasing trends in *Macomona liliana*, *Aonides trifida,* and *Austrovenus stutchburyi,* and significant increasing trends in *Prionospio aucklandica, Pseudopolydora complex,* and Capitellidae) all suggest health is **declining** at this site.
Te Puru	Estuarine health indices, organic matter content (c. 1.6 %) and low mud content (c. 2.6%) suggest this site is in **good health**. Sedimentation rates are unknown, but there has been a significant increase in organic matter and a possible increase in mud content (not statistically significant). Significant trends in three out of four indicator taxa (significant decreasing trends in *Linucula hartivigiana* and *Notacmea* spp.*,* and a significant increasing trend in Capitellidae) suggest health is **declining** at this site.
Whāingaroa (Raglan) Harbour	
Haroto Bay	Estuarine health indices, organic matter content (c. 3 %) and mud content (c. 46%) suggest this site is in **poor health**. High rates of sedimentation (c. 2.3 mm/year), a significant increasing trend in organic matter, and indicator taxa trends (significant decreasing trend in *Austrovenus stutchburyi* and significant increasing trend in Nereididae) suggest health is **declining** at this site.
Okete Bay	Estuarine health indices and organic matter content (c. 2.4%) suggest this site is **moderately healthy**, although with relatively high mud content (c. 26%). Sedimentation rates were highly variable at this site but averaged c. 1.4 mm/year, and a significant increasing trend in organic matter, and several

	trends in indicator taxa (significant increasing trends in *Arthritica bifurca, Aricidea* spp., *Prionospio aucklandica* and Paraonidae) suggest health is **declining** at this site.
Te Puna Point	Estuarine health indices and organic matter content (c. 1.3%) suggest this site is in **good health**, with c. 14% mud. Sedimentation rates suggest net erosion (c. -1.3 mm/year) and one trend in indicator taxa (significant decreasing trend in *Arthritica bifurca)* suggests health is **improving** at this site.
Whatitirinui Island	Estuarine health indices and organic matter content (c. 1.6%) suggest this site is in **moderate to good health**, with c. 16% mud. Sedimentation rates suggest net erosion (c. -2.1 mm/year), and three out of four indicator taxa trends (significant increasing trends in *Anthopleura aureoradiata* and *Linucula hartvigiana,* and a significant decreasing trend in Capitellidae) also suggest health is **improving** at this site. Note that there were also significant decreasing trends in *Macomona liliana* and an Estuarine Health Index, (both for the most recent period of 2012 to 2018), which suggest declining health.
Ponganui Creek	Estuarine health indices and organic matter content (c. 1.7%) suggest this site is in **good health**, with c. 14% mud. There is little net sedimentation (c. 0.8 mm/year), but a possible increase in mud content (p = 0.053), and trends in indicator taxa (significant increasing trend in *Prionospio aucklandica* and significant decreasing trend in *Glycera* spp.) suggest health is **declining** at this site.
Tairua Harbour	
Gumdigger Gully	Estuarine health indices suggest this site is in **poor health**, despite low organic matter (c. 1.6 %) and mud content (c. 2%). Sedimentation rates are unknown, but one indicator taxa (significant decreasing trend in *Paphies australis*) suggest health is **declining** at this site.
Manaia Road	Estuarine health indices, mud content (c. 1%) and organic matter content (c. 1.2%) suggest this site is in **good health**. Sedimentation rates are unknown, but one indicator taxa (significant decreasing trend in *Aonides trifida*) suggest health is **declining** at this site.
Oturu Stream	Estuarine health indices, and organic matter content (c. 1.7%) suggest this site is **moderately healthy**, with c. 6% mud. Sedimentation rates are unknown, but one indicator taxa (significant increasing trend in Nereididae) suggest health is **declining** at this site.
Pauanui	Estuarine health indices, mud content (< 1%) and organic matter content (c. 1.1%) suggest this site is in **good health**. Sedimentation rates are unknown and the two trends in indicator taxa are inconclusive, as one indicates declining health and the other improving health.
Pepe Inlet	Estuarine health indices, and organic matter content (c. 1.8%) suggest this site is **moderately healthy**, though with relatively high mud content (c. 13%). Sedimentation rates are unknown, but there was a significant decreasing trend in mud content, and trends in indicator taxa (significant increasing trends in *Austrovenus stutchburyi* and *Macomona Liliana*) and an Estuarine Health Index all suggest health is **improving** at this site.

Note that sedimentation rates, mud and organic matter content represent the mean for the period 2001 to 2018 for the Firth of Thames and Whāingaroa Harbour, and for the period 2012 to 2018 for Tairua Harbour.

1 Introduction

There are around 30 estuaries in the Waikato region, ranging from the Firth of Thames, which is c. 730 km^2 in area, to small tidal lagoons less than 10 ha, such as at Miranda and Waiaro stream mouths (Hume et al. 2016). Estuaries in the Waikato region, as in the rest of New Zealand, are highly valued for environmental, economic, cultural, and social reasons. These highly productive ecosystems are subject to multiple pressures that are exacerbated by climate change (e.g., Kennish 2002). Increased loading of nutrients, sediments and other contaminants from catchment runoff, urban development around coastal margins, and the spread of invasive species all threaten biodiversity and ecosystem function in estuaries. Deposition of sediment and increased muddiness of estuarine habitats has long been recognised as a major issue for estuaries in New Zealand (e.g., Thrush et al. 2004), including in the Waikato region (Jones 2008). Deposition of large amounts of sediment smothers benthic communities, whilst elevated levels of suspended sediment detrimentally affect suspension feeding bivalves and reduce the productivity of benthic microalgae (e.g., Ellis et al. 2002, Norkko et al. 2006, Mangan et al. 2020).

As a result of their high value and the pressures upon them, estuaries require careful management to safeguard environmental health, and the economic, cultural, and social values which depend on healthy, functioning ecosystems. A critical aspect of managing the region's estuaries is State of the Environment (SOE) monitoring, which is employed by Regional Councils to meet their obligations under Section 35(2) (a) of the Resource Management Act (1991). SOE monitoring should allow for early detection of adverse environmental changes and provide an opportunity to initiate effective changes in management practices on land or in the coastal environment.

Intertidal sand- and mudflats comprise a large proportion of estuarine area within the Waikato region. These areas contain diverse macroinvertebrate communities (animals such as shellfish, crustaceans, and marine worms) that perform many important ecological processes such as nutrient recycling, sediment mixing and water filtration (Thrush et al. 2013). Sediment-dwelling macroinvertebrates are widely used as indicators of estuary health in environmental monitoring programmes in New Zealand, and elsewhere in the world, because certain species respond predictably to many common natural and man-made stressors (e.g., Hewitt et al. 2012). Changes in species, community composition or abundance may indicate impacts from local scale pressures, such as point-source pollution, or catchment scale pressure, such as increased sediment loading or nutrient input.

Waikato Regional Council's Regional Estuary Monitoring Programme (REMP) was initiated in April 2001 to determine the status and temporal changes in the state of selected estuaries in the region. Results have been used to analyse trends over the first five and ten years of monitoring (Felsing and Singleton 2008, Needham et al 2014). This report presents data and trends over 17 years (from 2001 to 2018), summarises the state of, and trends in, estuarine health, and provides recommendations for future monitoring.

2 Methods

2.1 General programme design

The Regional Estuary Monitoring Programme (REMP) focuses on monitoring intertidal benthic macroinvertebrates (i.e., animals that live in estuarine sediments) and sediment properties in estuaries in the Waikato region. The benthic macroinvertebrates and sediment properties are indicators of ecological health. Initially two estuaries were selected for the programme: the southern Firth of Thames and Whāingaroa (Raglan) Harbour. Tairua Harbour was added to the programme in 2012. Note that Coromandel Harbour was also added to the programme in 2019 but is not reported on here (as this report covers the period 2001 to 2018). Within each estuary, five monitoring sites were selected. At each site sampling was carried out between one and four times a year, depending on resourcing available. The key variables measured in the REMP are:

1) Twenty-six 'indicator taxa'[2] characteristic of intertidal benthic macroinvertebrate communities, selected to represent a variety of taxonomic groups and a range of life-histories, ecological niches, feeding methods and susceptibilities to fine sediments and organic enrichment (Hewitt et al. 2001).

2) Sediment properties (grain size, total organic carbon, total nitrogen, chlorophyll *a* and phaeophytin) that characterise the estuarine benthic habitat and may influence the distribution and abundance of benthic macroinvertebrates.

3) Rates of sediment deposition and erosion that may influence the distribution and abundance of benthic macroinvertebrates.

Other variables measured at REMP sites included sediment contaminants (heavy metals) and macroinvertebrate taxa other than indicator taxa. Results are analysed using various statistical methods (detailed in Section 2.3) to examine differences among sites within each estuary, differences between estuaries, and changes over time.

2.1.1 Monitoring locations and sampling frequency

The background to the selection of the estuaries is described in Turner (2001). The locations of the five monitoring sites in the Firth of Thames, Whāingaroa (Raglan) Harbour and Tairua Harbour are shown in Figure 1. At each site, a permanent monitoring plot (approximately 100 m × 100 m) was established. The monitoring sites were installed at approximately the mid-intertidal level.

Sampling was generally undertaken two or four times per year from April 2001 to October 2015, and then reduced to once per year (in Spring) after October 2015[3]. In 2003, in the Firth of Thames and Whāingaroa (Raglan) Harbour, between four and six concrete paving tiles were buried in the sediment close to the monitoring site to measure sediment deposition and/or erosion. For Tairua Harbour, concrete paving tiles were only installed at monitoring sites in 2019.

[2] 'Indicator taxa' are macroinvertebrates that are known to either be tolerant or intolerant to high mud, organic enrichment and/or sediment pollution levels. 'Taxa' is used here to indicate that some macroinvertebrates cannot reliably be identified to species level and that therefore some of the monitored 'taxa' may include more than one species.

[3] Sampling frequency at each site changed over the years from 2001 to 2015 in response to resourcing available and the expansion of the programme to Tairua Harbour in 2012.

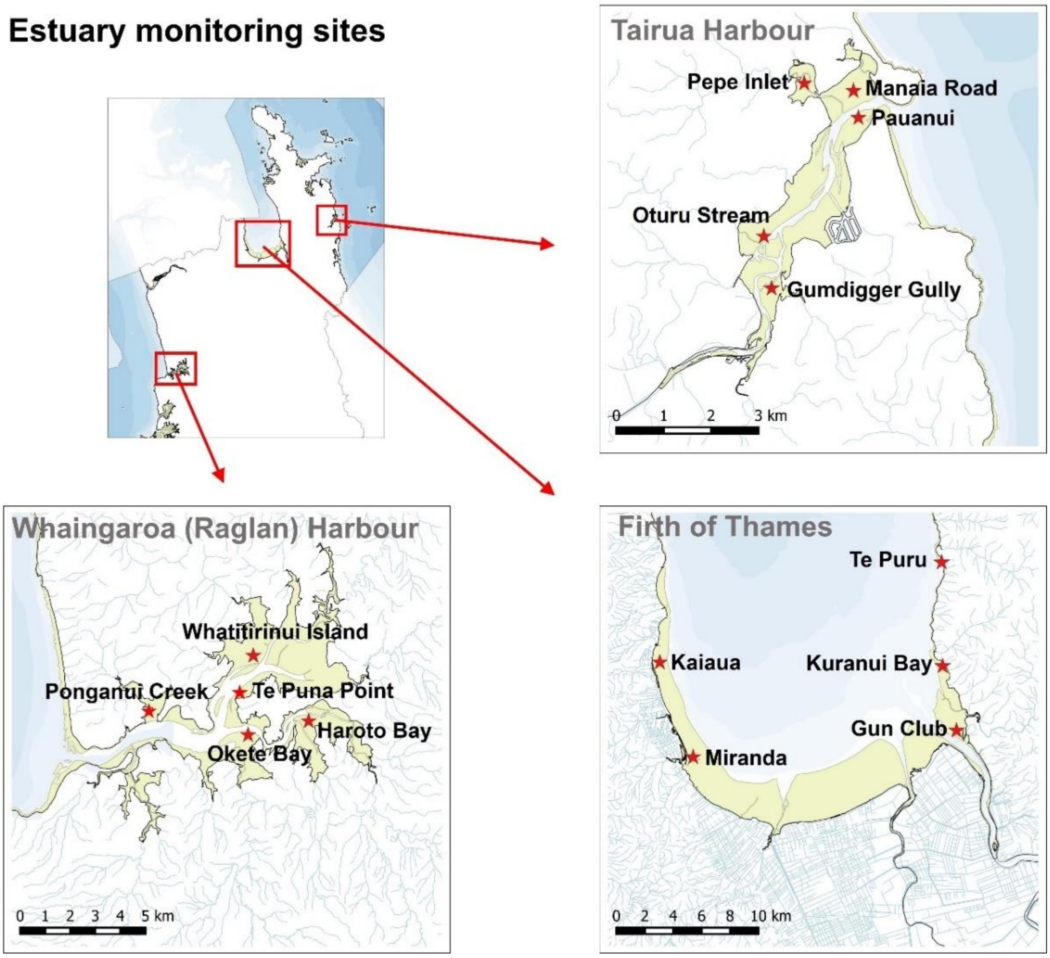

Figure 1: Location of monitoring sites in the REMP (2001 to 2018)

2.2 Sample collection and processing

2.2.1 Benthic macroinvertebrates

On each sampling occasion 10 or 12 core samples[4] (13 cm diameter, 15 cm deep) were collected from within each monitoring plot (Figure 2). Each site was divided into 10 or 12 equal-sized sectors and one core sample taken randomly (using randomly derived Cartesian co-ordinates) from within each sector. To minimise sample interdependence, samples were not positioned within a 5 m radius of each other. To avoid effects from previous sampling occasions, samples were not taken within 5 m of previous sampling positions over any 6-month period.

Cores were sieved (500 µm mesh), and the retained benthic macroinvertebrates preserved with 70% isopropyl alcohol and stained with 0.1% Rose Bengal. In the laboratory, the benthic macroinvertebrates were sorted, identified to the lowest possible taxonomic level, and counted (Figure 3). Twenty-six benthic macroinvertebrates were selected as ‘indicator taxa’, which are known to either be tolerant or intolerant of high mud, organic enrichment and/or sediment pollution levels. In general, they respond to changes in environmental conditions by either increasing or decreasing in numbers, depending on their tolerance levels. Indicator taxa include bivalves such as cockles (*Austrovenus stutchburyi*) and pipi (*Paphies australis*), whelks (*Cominella adspersa*), limpets (*Notacmea* spp.), cumacean shrimp (*Colurostylis lemurum*) and species of amphipod and polychaete worms. A full list of indicator taxa and their habitat preferences are included in Appendix A.

[4] See Hewitt et al. (2001) and Docs#3941055 for justification. In summary, 12 replicates were collected from 2001 to 2014 at Firth of Thames and Whāingaroa Harbour sites. This was reduced to 10 replicates in 2015 following statistical assessment that showed this had little effect on variance. 10 replicates have always been collected at Tairua Harbour.

Non-indicator taxa were identified to the lowest taxonomic level practicable. The remaining non-living material (shell material, gravel and coarse sand) was dried at 70°C for 48 hrs and weighed to determine the dry weight of each sample. In all samples shell material (hereafter referred to as shell hash) dominated the non-living material (typically over 90%).

Figure 2: Sampling on intertidal flats in the Firth of Thames

Figure 3: View through the microscope of sorted and stained benthic macroinvertebrates, including some indicator taxa (Photo: Barry O'Brien, University of Waikato).

2.2.2 Sediment properties

Two samples (5 cm diameter, 2 cm deep core) of surface sediment were collected in the vicinity of each core sample and combined into five composite samples for each site (reduced to three composite samples in October 2015). Samples were stored frozen, then defrosted, sub-sampled and analysed for grain-size, organic carbon and nitrogen as described below. Five surface sediment scrapes (3 to 5mm depth) were also collected at each monitoring plot for analysis of benthic microalgal biomass (represented by chlorophyll *a* and phaeophytin concentration). Samples were taken at the four corners and the centre of each site and were stored in black containers and frozen until analysis.

Sediment grain size

Grain size analysis was carried out by wet sieving. Samples were not pre-treated, and no dispersant was added (Hunt and Jones 2018). Samples were sieved through a stack of sieves (2000 µm, 500 µm, 250 µm, 125 µm and 63 µm) and the fractions remaining on the sieves dried at 60°C for 48 hours. Results were reported as the percent by weight of the total sample. Grain size data were grouped into the following grain size categories: mud (<63 µm), very fine sand (63-125 µm), fine sand (125-250 µm), medium sand (250-500 µm), coarse sand (500-2000 µm) and gravel (>2000 µm). Organic matter content was quantified by loss on ignition from subsamples taken prior to sieving.

Sediment organic carbon and nitrogen content

Sediments were dried and finely ground, then analysed for total organic carbon and total nitrogen content using an automated CHN analyser. Samples for total organic carbon analysis were pre-treated with acid to remove carbonate material prior to analysis.

Sediment chlorophyll a and phaeophytin content

Chlorophyll *a* was extracted from the sediment by boiling in 95% ethanol and the extract analysed using a spectrophotometer. Acidification was used to separate plant degradation products (phaeophytin) from chlorophyll *a*.

2.2.3 Sediment deposition and erosion measurements

In 2003, concrete paving tiles (referred to as 'sedimentation plates') were buried in the sediment close to the biological monitoring plots in the Firth of Thames and Whāingaroa Harbour. The layout of the plates differed in each estuary, with a shore perpendicular transect of six plates centred on the monitoring plots installed at sites in the Firth of Thames, and two clusters of two plates (i.e., four in total) installed around the monitoring plots in Whāingaroa Harbour. On each sampling occasion, measurements were made of the depth between the plate and the sediment surface, which over time allowed for the calculation of sedimentation erosion or deposition rates. A detailed description and analysis of the effectiveness of the plate methodology and the sedimentation trends observed over 2003 to 2015 is provided in Hunt (2019a). Here we use the sedimentation rates measured at the plates closest to the biological monitoring plots over the period 2003 to 2018 to assess the degree of sedimentation experienced by the macroinvertebrate communities at the monitoring sites. Note that there were no sediment plates installed at the Te Puru site in the Firth of Thames, and plates were only installed at sites in Tairua Harbour in 2019, so sedimentation rate measurements are not available for all sites.

2.2.4 Modifications to sampling protocol and analysis techniques

Since the beginning of the REMP, some modifications to sampling protocol and analysis techniques have been made based on the findings of previous trend reports (e.g., Felsing and Singleton 2008, Needham et al. 2014), critical assessment of the programme (e.g., Compton et al. 2011), changes to laboratory methods and logistical or financial constraints. These are briefly described below.

Site location and sampling

In October 2001, the Kaiaua site in the Firth of Thames was relocated 200 m up shore due to access difficulties (only data from October 2001 onwards are analysed in this report, so the shift will have no effect on trends reported here). Similarly, in April 2007 the Te Puru site was shifted approximately 70 m along shore and 30 m up shore due to access issues (there were no abrupt change in macroinvertebrate community composition or sediment properties noted after this shift, however). In Whāingaroa (Raglan) Harbour, a fifth monitoring site, Ponganui Creek, was added in October 2001. Sampling at Te Puna Point and Ponganui Creek was stopped in October 2008 and April 2011, respectively. These sites were re-instated in October 2015.

Taxonomic resolution of benthic macroinvertebrates

Taxonomic resolution of non-indicator taxa has changed throughout the monitoring programme. Although these changes have resulted in improved characterisation of macroinvertebrate community structure it means that it is not possible to look at changes in the full macroinvertebrate community structure over the entire monitoring period. From 2007 taxonomic resolution was increased for non-indicator taxa to enable more comprehensive descriptions of the community structure. From 2012 taxonomic resolution was again increased and aligned with that used by NIWA Hamilton and Auckland Council, in line with recommendations in Needham et al. (2014). This enabled the calculation of estuarine health indices such as the Benthic Health Model (BHM, e.g., Hewitt and Ellis 2010) and Traits Based Index (TBI; van Houte-Howes and Lohrer 2010, Lohrer and Rodil 2011) from the benthic macroinvertebrate data. These indices condense complex ecological information into univariate metrics that can be used to track estuarine health and are used in Auckland Council SOE reporting.

Sediment grain size analyses

Sediment grain size results reported here differs from previous REMP reports (e.g., Felsing and Singleton 2008, Needham et al. 2014). These contained sediment grain size data analysed by a Galai (CIS-100) stream-scanning laser particle sizer (up to October 2007) and a Malvern Mastersizer 2000 laser diffraction instrument (from October 2007 onwards). Issues were detected with these data including an abrupt change in measured mud content when the instrument changed, and issues with the pre-treatment used (Hunt and Jones 2018). To address these issues, archived sediment samples were re-analysed by wet sieving. Values and trends in this report may therefore differ to those in the ten-year trend report (i.e., Needham et al. 2014). See Appendix B for further information on sediment grain size analyses.

Sediment chlorophyll a and phaeophytin content

Sediment chlorophyll *a* and phaeophytin data in the ten-year trend report (Needham et al. 2014) were incorrect. Due to miscommunication with the laboratory used for analysis, chlorophyll *a* and phaeophytin data were corrected for dry weight twice (once by the lab and again by WRC). The mistake has now been rectified in this report. Values and trends in this report may therefore differ to those in the ten-year trend report.

2.3 Data analysis

2.3.1 Overview of data analysis techniques

Estuaries are dynamic environments. Natural variation in the community structure of benthic macroinvertebrates occurs in response to factors such as food availability, water temperature, and recruitment. It is important to identify these patterns and tease them apart from patterns that might indicate a decline in the health of the environment, and to do so data needs to be collected over long periods of time. Without long-term data, short-term patterns in community structure, such as annual or interannual cycles, could be misinterpreted. In this report, several data analysis techniques have been used to separate natural variation from potential changes in environmental health. The rationale for, and description of, these analysis techniques are outlined below.

2.3.2 Trend analysis

Trend analysis is the statistical tool used to formally separate cyclic patterns and natural variability from long-term trends that might indicate changes in the environmental health of the estuary. Trend analysis was used to determine if significant changes in benthic macroinvertebrate abundances, sediment characteristics, or Estuarine Health Indices (for data collected from 2012 to 2018) had occurred at each site over the monitoring period. Since the primary concern related to grain size changes in coastal ecosystems is an increase in fine sediments, especially mud (e.g., Thrush et al. 2004, Ministry for the Environment & Stats NZ 2019), trend analysis results of grain size data are only reported for the mud fraction.

Trends were also compared among sites to identify if benthic macroinvertebrates or sediment properties showed similar trends throughout the estuary or if changes only occur locally. Trends in benthic macroinvertebrates were also compared to trends in sediment properties.

Trend analysis was undertaken in R (Version 3.6.2), using averaged data from each sampling event for each type of monitoring data collected. The methodology followed that used to analyse trends in Auckland Council estuarine monitoring programmes (e.g., Hewitt and Carter 2020). Temporal changes were first visually assessed for step changes, multiyear cycles, or the potential for trends to have started or stopped part way through the monitoring period. If step changes were evident, then these were assessed for statistical significance by conducting a t-test (or Kruskal-Wallis test where data were not normally distributed). Otherwise, a linear regression of the response variable against time was performed, using log or square root transformations to include non-linear responses. Trends were tested to a significance level of $p = 0.05$, and where a statistically significant trend was detected then residuals were examined for cyclic patterns. To reduce the potential for autocorrelation, only data collected once per year (in Spring) were used in trend analysis.

Given the large number of tests (26 indicator taxa and 7 sediment variables, each multiplied by 15 sites) there is the potential for many false positives (Type I errors). Out of 495 trend tests, and with a significance level set at 5%, we would expect to obtain c. 25 'significant trends' purely by chance. A Bonferroni correction or controlling the false discovery rate using the Benjamini-Hochberg procedure can reduce the number of false positives, but this may also have the effect of increasing the number of false negatives, where there actually is a trend, but it is not detected as statistically significant (i.e., Type II errors). Rather than focusing only on statistical significance (i.e., the p value), the trend was used to calculate the predicted change over the monitoring period to help evaluate how meaningful a statistically significant trend might be.

2.3.3 Multivariate analyses

Macroinvertebrate community composition and relationship with environmental variables

Multivariate analysis techniques were used to visualise differences, and changes over time, in macroinvertebrate community composition. Patterns within sites, between sites and between estuaries were identified using non-metric multidimensional scaling ordination (MDS) plots in PRIMER v6 (Clarke and Gorley 2006). Data from the spring of each year were used for this analysis as this time of year showed fewer peaks in abundance due to recruitment than at other times. Previous trend reports (Felsing and Singleton 2006, Needham et al. 2014) analysed indicator taxa data only, as full macroinvertebrate community composition was not enumerated prior to 2012. Here full macroinvertebrate community composition is analysed using data from 2012 to 2018. Data were square root transformed to reduce the influence of numerically dominant taxa, then analysed using Bray-Curtis similarities based on mean abundance values (across replicates) from each sampling date.

Relationships between macroinvertebrate community composition and environmental variables (including sediment properties, sediment contaminants, and the elevation of the sampling plot), were investigated using a distance-based redundancy analysis based on Bray-Curtis similarities of square root transformed macroinvertebrate abundances and normalised environmental variables. Multi-collinearity in environmental variables was investigated using Pearson's correlation coefficient and where two variables were highly co-linear ($r > 0.9$), one was dropped from the analysis. Forward selection using Akaike's Information Criteria (AIC) was used to determine the most significant environmental predictors on macroinvertebrate community composition using the DISTLM routine in PERMANOVA+ for PRIMER v6 (Anderson et al. 2008). The analysis was restricted to data collected in 2018 only, as that is the only year in which all data (full macroinvertebrate community composition, sediment grain size, sediment chlorophyll, sediment contaminants, and plot elevation) were available. The DISTLM analysis was also conducted for sites where sedimentation rate measurements were available (i.e., for all sites in Whāingaroa Harbour, and for all sites except Te Puru in the Firth of Thames). Sedimentation rates at most sites were highly variable over short time scales, so the analysis used the average sedimentation rate calculated over the 5-year period prior to the macroinvertebrate sampling in 2018. This shorter period was of potentially higher relevance to the 2018 macroinvertebrate community structure than sedimentation rates calculated across the whole dataset.

Estuarine Health Indices

Estuarine health indices are designed to summarise complex multivariate information (i.e., macroinvertebrate community composition) into an easily understood and scientifically defensible univariate measure of estuarine ecosystem health. A Traits Based Index (TBI) was developed by NIWA for Auckland Council that uses the richness of taxa exhibiting particular traits (e.g., their feeding mode, degree of mobility, body size, etc.) that are reflective of their ability to perform certain ecosystem functions (van Houte-Howes and Lohrer 2010, Lohrer and Rodil 2011). The index value is calculated based on the numbers of taxa in seven functional trait groups (groups that have previously been shown to respond to mud and heavy metal contaminants). Areas with high numbers of taxa per functional trait group (and high index values) are thought to have a greater capacity to cope with species losses. This is a component of resilience that contributes to maintenance of ecosystem functions despite stress and environmental disturbance. Index values range between zero and one, with values near zero indicating highly degraded sites with low functional resilience, and values near one indicating more pristine environments with very high functional resilience. Scores less than 0.3 are thought to indicate "poor resilience", and scores greater than 0.4 indicate "good resilience" (Hewitt et al. 2012).

The Benthic Health Model was also developed by NIWA for Auckland Council and comprises two separate models (indices) for two key contaminants – sediment mud content and sediment heavy metal (copper, lead and zinc) concentrations (e.g., Anderson et al. 2006, Hewitt and Ellis 2010). The models describe the response of macroinvertebrate community composition to those contaminants and are based on data collected at 84 sites in Auckland estuaries. The scores are grouped into five categories, corresponding to "extremely good health", "good health", "moderate health", "poor health", and "unhealthy". Hewitt et al. (2012) recommend using all three indices (the TBI, BHM metals and BHM mud) to assess estuarine health at a site, as they provide complementary information on the composition, functionality, and resilience of the macroinvertebrate community. Given the geographical proximity of the Auckland and Waikato regions, and the similarity in estuarine types and habitats between these regions (and associated macroinvertebrate community composition) these indices are likely appropriate for Waikato estuaries[5].

[5] Note, however, that new National Benthic Health Models have recently been developed that could be used in future REMP data analysis and reporting (Clark et al. 2020).

These estuarine health indices were calculated using REMP data collected in spring of 2012-2018. Prior to 2012 taxonomic resolution was insufficient to calculate these indices. The index values can be compared between sites but combining health scores for sites across each estuary (e.g., to produce an average TBI value for the Firth of Thames) is not considered appropriate as the REMP sites do not sample all areas of each estuary proportionally. Many more sites (than the current five per estuary) would need to be sampled to produce an average health score for each estuary.

3 Results and discussion

3.1 General characteristics of monitoring sites

The general characteristics of each of the REMP sites are described below, in terms of location in the estuary (Figure 1), sediment composition, elevation of the site (relative to tidal level), net sedimentation rates (if known), and the dominant macroinvertebrate taxa. Summary data is provided in Appendix C. Monitoring sites vary considerably in their general characteristics: some sites are muddier than others, especially those that are in sheltered locations, such as Haroto Bay in Whāingaroa Harbour, and Pepe Inlet in Tairua Harbour (Figure 4). Some sites have experienced net accretion of sediment over the past 17 years (e.g., Haroto Bay) whereas others have experienced net erosion (e.g., Kuranui Bay and Miranda). Furthermore, although the intention when setting up this programme was to locate sites at mid tide level, recent measurements (using RTK GPS and LiDAR) show that there is significant variability in elevation of the biological monitoring plots relative to tidal level, and some sites are located close to low tide level (such as Okete Bay in Whāingaroa Harbour, and Kaiaua in the Firth of Thames), which will likely influence the general site characteristics.

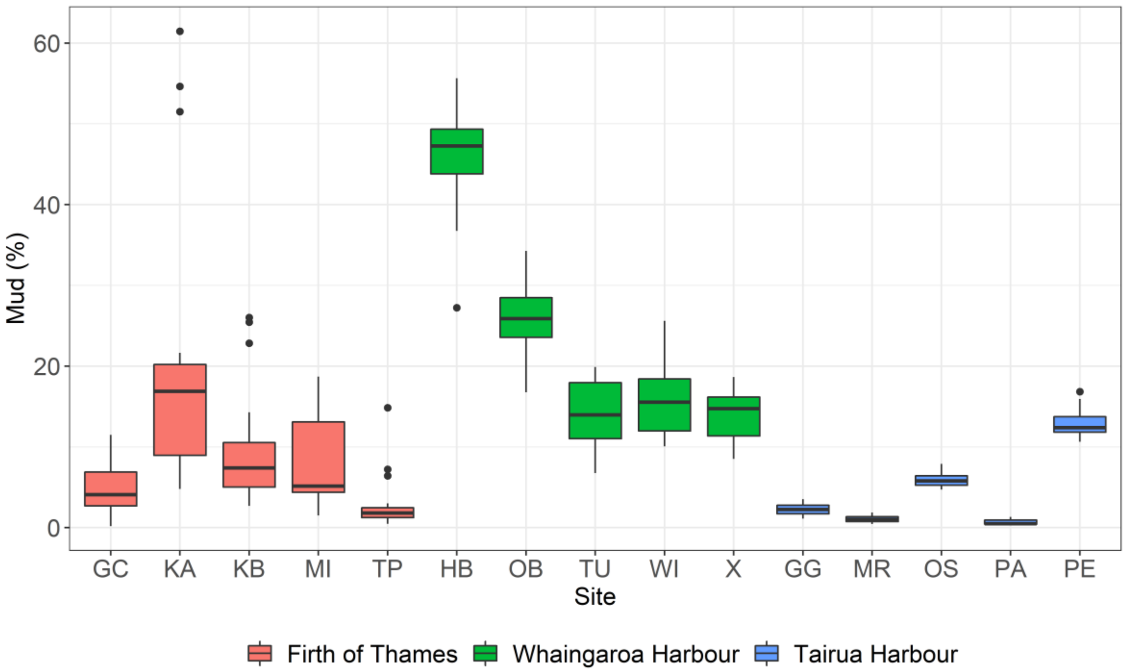

Figure 4: Sediment mud content at monitoring sites

Boxplot explanation: The solid horizontal line in each box corresponds to the median value (of all data collected between 2001 and 2018), the lower and upper hinges of each box correspond to the first and third quartiles, the whiskers extend from the hinge to the largest/smallest value or, at most, 1.5 * the inter quartile range, and black dots are outliers (i.e., data points that extend beyond the end of the whiskers).

Firth of Thames

Gun Club (abbreviated to 'GC')

This site is in the southeast of the Firth of Thames, close to the Waihou River mouth (Figure 1). The sediments are mostly sandy with small amounts of "gravel"[6] (c. 9%), less than 5% mud, c. 2.2% organic matter, c. 14 mg/kg chlorophyll *a* and 0.06% total nitrogen content (average values for the entire monitoring period). The biological monitoring plot is at 0.5 m below mean sea level (i.e., close to mid-tide level[7]). Sedimentation plates installed at the site indicate there is no net sedimentation occurring at the biological monitoring plot; rather there is a very slight trend of erosion with the rate averaging -0.4 mm/yr between 2003 and 2018. The macroinvertebrate community is dominated by polychaete worms (especially *Aonides trifida*).

Kaiaua (abbreviated to 'KA')

This site is in the northwest of the Firth of Thames, just south of the Kaiaua town. The sediments are mostly sandy, but with relatively high mud content (c. 18%), very little "gravel", c. 2.3% organic matter, c. 11 mg/kg chlorophyll *a* and 0.08% total nitrogen content. The biological monitoring plot is very low on the shore at 1.6 m below mean sea level (i.e., at low tide level). Sedimentation plates installed at the site indicate there is net deposition occurring at the biological monitoring plot, with a sediment accretion rate of approximately 3.6 mm/yr. The macroinvertebrate community is dominated by nut shells (*Linucula hartivigiana*) and polychaete worms (Capitellidae).

Kuranui Bay (abbreviated to 'KB')

This site is on the eastern side of the Firth of Thames, just north of Thames town. The sediments are mostly sandy, with c. 9% mud content, c. 7% "gravel", c. 2.1% organic matter, c. 11 mg/kg chlorophyll *a* and 0.10% total nitrogen content. The biological monitoring plot is quite low on the shore at 1.2 m below mean sea level (i.e., close to low tide level). Sedimentation plates installed at the site indicate there has been net erosion (rather than deposition) occurring at the biological monitoring plot, with a sediment erosion rate of approximately 4.9 mm/yr. The macroinvertebrate community is dominated by polychaete worms (Capitellidae) and cockles (*Austrovenus stutchburyi*).

Miranda (abbreviated to 'MI')

This site is in the southwest of the Firth of Thames and is in an area of very active chenier ridges, some of which have moved across the monitoring site over the past 17 years. The sediments are mostly sandy, with c. 4 % "gravel", c. 8% mud content (although this varied between 2 and 19 % over the monitoring period), c. 1.4% organic matter, c. 11 mg/kg chlorophyll *a* and 0.06% total nitrogen content. The biological monitoring plot is close to mid tide level, at 0.3 m below mean sea level. Sedimentation plates installed at the site indicate there has been net erosion (rather than deposition) occurring at the biological monitoring plot, with a sediment erosion rate of approximately 2.5 mm/yr although there has been net deposition occurring over the most recent part of the monitoring record (i.e., 2013 to 2018), which is likely to reflect the fact that this site is in an active Chenier plain and shell banks have moved around (or perhaps across) the site. The macroinvertebrate community is dominated by polychaete worms (especially *Aonides trifida* and Capitellidae).

Te Puru (abbreviated to 'TP')

This site is on the eastern side of the Firth of Thames, north of Gun Club and Kuranui Bay. The sediments are almost entirely sand (c. 97%), with little mud (c. < 3%), very little "gravel", c. 1.6% organic matter, c. 4.1 mg/kg chlorophyll *a* and 0.04% total nitrogen content. As at Kaiaua, the biological monitoring plot is located very low on the shore at 1.9 m below mean sea level (i.e., low tide level). There were no sedimentation plates installed at this site, so the sedimentation

[6] Note that this size fraction is composed of true gravel (i.e., made of rock) and gravel-sized shell pieces, hence it is referred to as "gravel".

[7] Tidal range in the Firth of Thames is c. 3.2 m at mean spring tides (https://www.linz.govt.nz/sea/tides/tide-predictions)

rate is unknown. The macroinvertebrate community is dominated by nut shells (*Linucula hartivigiana*) and pipi (*Paphies australis*).

Whāingaroa (Raglan) Harbour

Haroto Bay (abbreviated to 'HB')

This site is in the Waitetuna arm of Whāingaroa Harbour. The sediments contain elevated mud content (c. 46%), the rest being fine sands, with almost no "gravel", c. 3.2% organic matter, c. 15.6 mg/kg chlorophyll *a* and 0.11% total nitrogen content. The biological monitoring plot is at 0.1 m above mean sea level (i.e., mid-tide level[8]). Sedimentation plates installed at the site indicate there has been net deposition occurring at the biological monitoring plot, with a sediment accretion rate of approximately 2.3 mm/yr. The macroinvertebrate community is dominated by polychaete worms (Capitellidae and Nereididae) and a bivalve (*Arthritica bifurca*).

Okete Bay (abbreviated to 'OB')

This site is in the middle of Whāingaroa Harbour. The sediments contain relatively high mud content (c. 26%), the rest being fine sands, with almost no "gravel", c. 2.4% organic matter, c. 11.8 mg/kg chlorophyll *a* and 0.09% total nitrogen content. The biological monitoring plot is at 1.4 m below mean sea level (i.e., low tide level). Sedimentation plates installed at the site indicate there has been net deposition occurring at the biological monitoring plot, with a sediment accretion rate of approximately 1.4 mm/yr. The macroinvertebrate community is dominated by Polychaete worms (Capitellidae and *Cossura consimilis*).

Te Puna Point (abbreviated to 'TU')

This site is in the Waingaro arm of Whāingaroa Harbour. The sediments are mostly sandy, with c. 14% mud content, c. 6% "gravel", c. 1.3% organic matter, c. 19.1 mg/kg chlorophyll *a* and 0.08% total nitrogen content. The biological monitoring plot is at 0.3 m below mean sea level (i.e., mid tide level). Sedimentation plates installed at the site indicate there has been net erosion occurring at the biological monitoring plot, with a sediment erosion rate of approximately 1.3 mm/yr. The macroinvertebrate community is dominated by cockles (*Austrovenus stutchburyi*) and nut shells (*Linucula hartivigiana*).

Whatitirinui Island (abbreviated to 'WI')

This site is north of the site at Te Puna Point, in the Waingaro arm of Whāingaroa Harbour. As at Te Puna Point, the sediments are mostly sandy, with c. 16% mud content, c. 4% "gravel", c. 1.6% organic matter, c. 15.1 mg/kg chlorophyll *a* and 0.08% total nitrogen content. The biological monitoring plot is at 0.6 m below mean sea level (i.e., close to mid tide level). Sedimentation plates installed at the site indicate there has been net erosion occurring at the biological monitoring plot, with a sediment erosion rate of approximately 2.1 mm/yr. The macroinvertebrate community is dominated by cockles (*Austrovenus stutchburyi*) and nut shells (*Linucula hartivigiana*).

Ponganui Creek (abbreviated to 'X')

This site is in the small embayment on the northern side of Whāingaroa Harbour, close to the harbour mouth. The sediments are mostly sandy, with c. 14% mud content, c. 2% "gravel", c. 1.8% organic matter, c. 17.9 mg/kg chlorophyll *a* and 0.07% total nitrogen content. The biological monitoring plot is at 0.5 m below mean sea level (i.e., close to mid tide level). Sedimentation plates installed at the site indicate there has been little net sediment deposition occurring at the biological monitoring plot, with a sediment accretion rate of approximately 0.8 mm/yr. The macroinvertebrate community is dominated by cockles (*Austrovenus stutchburyi*) and nut shells (*Linucula hartivigiana*).

[8] Tidal range in Whaingaroa Harbour is c. 3.2 m at mean spring tides (https://www.linz.govt.nz/sea/tides/tide-predictions)

Tairua Harbour

Sedimentation rates at sites in Tairua Harbour are currently unknown as monitoring of sedimentation only began in 2019.

Gumdiggers Gully (abbreviated to 'GG')

This site is in the upper Tairua Harbour, close to where the Tairua River enters the estuary. The sediments are mostly medium or coarse sands, with small amounts of "gravel" (c. 2.5%) and mud (c. 2%), c. 1.6% organic matter, c. 11.9 mg/kg chlorophyll *a* and 0.03% total nitrogen content. The biological plot is at 0.06 m below mean sea level (i.e., mid tide level[9]). The macroinvertebrate community is dominated by polychaete worms (Capitellidae and Nereididae).

Manaia Road (abbreviated to 'MR')

This site is in the lower Tairua Harbour, between Tairua town and the harbour mouth. The sediments are mostly sandy, with very little mud (c. 1%), small amounts of "gravel" (c. 2.5%), c. 1.2% organic matter, c. 15.1 mg/kg chlorophyll *a* and 0.03% total nitrogen content. The biological plot is at 0.1 m above mean sea level (i.e., mid tide level). The macroinvertebrate community is dominated by cockles (*Austrovenus stutchburyi*) and polychaete worms (especially *Aonides trifida*).

Oturu Stream (abbreviated to 'OS')

This site is in the upper Tairua Harbour, just downstream of the site at Gumdiggers Gully. The sediments are sandy, with small amounts of "gravel" (c. 3%) and c. 6% mud content, c. 1.7% organic matter, c. 15.8 mg/kg chlorophyll *a* and 0.03% total nitrogen content. The biological plot is at 0.25 m below mean sea level (i.e., close to mid tide level). The macroinvertebrate community is dominated by amphipods (Corophiidae) and polychaete worms (Capitellidae).

Pauanui (abbreviated to 'PA')

This site is in the lower Tairua Harbour, close to the harbour mouth. The sediments are mostly sandy, with very little mud (c. <1%), small amounts of "gravel" (c. 3.5%), c. 1.1% organic matter, c. 15.0 mg/kg chlorophyll *a* and 0.03% total nitrogen content. The biological plot is at 0.1 m below sea level (i.e., mid tide level). The macroinvertebrate community is dominated by cockles (*Austrovenus stutchburyi*) and pipi (*Paphies australis*).

Pepe Inlet (abbreviated to 'PE')

This site is in a small, sheltered embayment where Pepe Stream enters the estuary. The sediments are mostly sandy, but with relatively high mud content (c. 13%), small amounts of "gravel" (c. <2%), c. 1.8% organic matter, c. 15.6 mg/kg chlorophyll *a* and 0.03% total nitrogen content. The biological plot is at mean sea level (i.e., mid tide level). The macroinvertebrate community is dominated by polychaete worms (Nereididae, *Prionospio aucklandica,* and Capitellidae).

[9] Tidal range in Tairua Harbour is c. 1.7 m at mean spring tides (https://www.linz.govt.nz/sea/tides/tide-predictions)

3.2 Macroinvertebrate community structure

Macroinvertebrate community structure differed between estuaries, sites, and years (Figure 5). There were distinct differences between the three estuaries, (i.e., the MDS ordination shows the sites from each estuary as separate clusters), and there was greater variability (dissimilarity) between sites in the Firth of Thames and Tairua Harbour, compared to Whāingaroa Harbour. In the Firth of Thames, the macroinvertebrate community structure at Te Puru (TP) and Gun Club (GC) were quite different from one another and the other sites in this estuary, indicated by the clear separation between these sites in Figure 5. In Whāingaroa Harbour, sites at Okete Bay (OB) and Haroto Bay (HB) were quite different from the other sites, and in Tairua Harbour there was a clear separation between the upper estuary (Gumdigger Gully, Oturu Stream and Pepe Inlet) and lower estuary sites (Manaia Road and Pauanui). Although there were differences between years at each site, close examination of the MDS plots indicated that there appeared to be no consistent directional change over 2012 to 2018, suggesting year-to-year variability rather than a shift in macroinvertebrate community structure. Some sites showed more between year variability than others; for example, high variability at Te Puru, indicated by the large space between the red circles in the MDS plot in Figure 5.

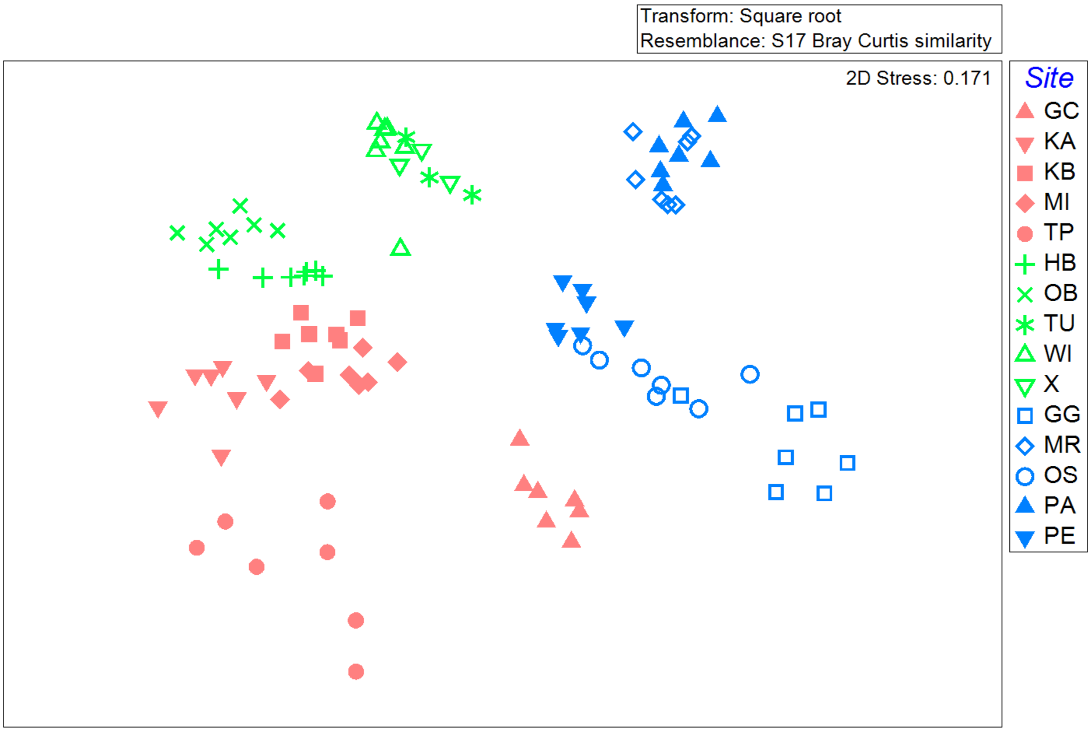

Figure 5: MDS plot showing the similarity in macroinvertebrate community structure between sites in the Firth of Thames (red symbols), Whāingaroa Harbour (green symbols) and Tairua Harbour (blue symbols). Data for each site for each year between 2012 and 2018, are displayed as separate points on the plot. The proximity of points indicates the degree of similarity in community structure between each sampling occasion.

The relationship between macroinvertebrate community composition and environmental variables was analysed using DISTLM. Many of the potential environmental predictor variables were highly correlated (see table in Appendix D), necessitating the exclusion of some to reduce redundancy in the analysis. Total organic carbon (TOC) and total nitrogen (TN) were excluded from the analysis as these two variables were both highly correlated with mud content ($r > 0.9$). Mud content was chosen over TOC and TN as mud is known to have a strong influence on macroinvertebrate communities. Although not highly correlated, many grain size fractions showed some degree of correlation with one another, which is to be expected given they are all fractions of a whole, and shell hash was highly correlated with coarse sand. For these reasons, shell hash was included, but grain size fractions other than mud content were excluded from the analysis. Many of the sediment trace elements were highly correlated with one another (e.g., copper was highly correlated with antimony, lead, mercury, and zinc). Copper, which is known to influence macroinvertebrate communities, was retained along with chromium, arsenic, and nickel, which were not highly correlated with anything else.

The environmental variables included in the DISTLM analysis in total explained 88% of the variability in macroinvertebrate community composition among all sites (Appendix D). Mud, site elevation and chlorophyll *a* collectively accounted for 47% of the variation, whereas copper, arsenic, nickel, and chromium had a relatively small influence on macroinvertebrate community structure. Note that concentrations of these trace elements are below guideline values at all the monitoring sites and so are unlikely to be a significant stressor on macrofauna communities[10]. Sedimentation rate was not found to be a significant predictor variable on macrofauna community composition (for those sites where sedimentation rates have been measured).

Results from the DISTLM analysis were visualised using a distance-based redundancy analysis (dbRDA) plot (Figure 6), which shows the predictor variables obtained from the model and their relationship to macroinvertebrate community composition at each site. This indicates that Haroto Bay (HB) and Okete Bay (OB) in Whāingaroa Harbour are influenced by mud. Most sites in the Firth of Thames are influenced by organic matter, except for Gun Club (GC), which is influenced by shell hash. Sites in Tairua are influenced by shell hash (Gumdigger Gully), and higher plot elevations (Manaia Road, Pauanui and Pepe Inlet) and less affected by mud and organic matter.

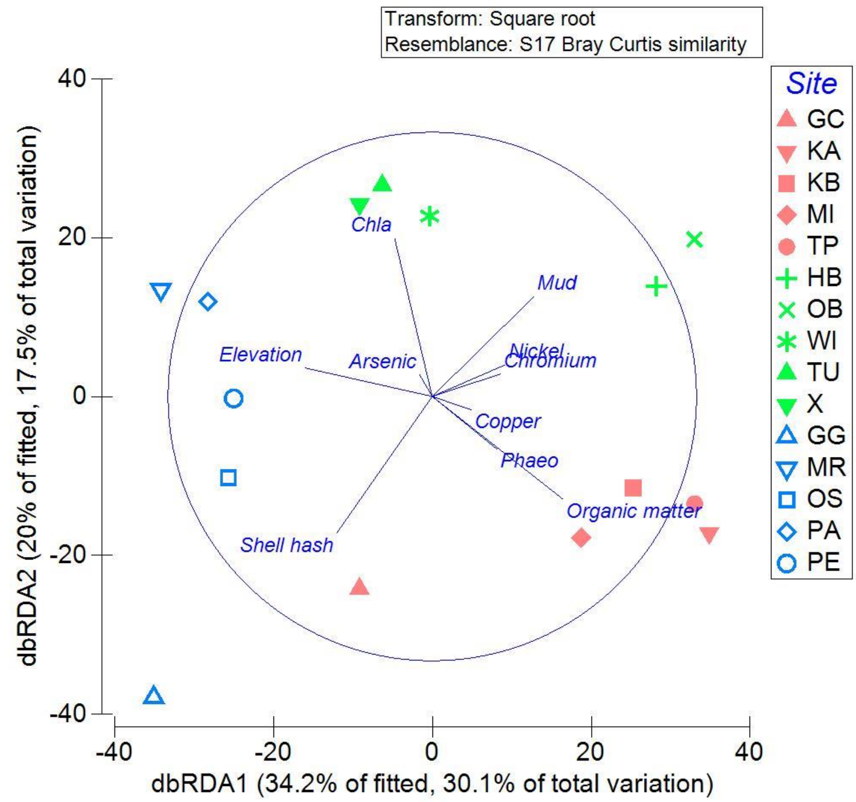

Figure 6: Distance-based redundancy analysis (dbRDA) of macroinvertebrate community composition at monitoring sites in spring 2018, overlaid with normalised environmental predictor variables (based on DISTLM analysis). Sites from the Firth of Thames are in red, Whāingaroa Harbour are in green, and Tairua Harbour are in blue.

[10] Waikato Regional Council 'Pollutants in sediments' Environmental Indicator: https://waikatoregion.govt.nz/environment/coast/coast-monitoring/pollutants-in-sediments-report/

3.3 Estuarine Health Indices

Estuarine health indices, calculated for each of the monitoring sites, are summarised in (Figure 7). Sites in the Firth of Thames had similar Traits Based Index (TBI) scores indicating that these sites are broadly similar in terms of functional resilience (and all were in the "moderate" category). Both Benthic Health Model (BHM) scores suggest that sites at Te Puru (TP), Miranda (MI) and Gun Club (GC) are healthier than those at Kaiaua (KA) and Kuranui Bay (KB).

All indices suggested that there were substantial differences in health and resilience between sites in Whāingaroa (Raglan) Harbour. Haroto Bay (HB) is in poor health and has poor resilience, whereas Whatitirinui Island (WI), Ponganui Creek (X), and Te Puna Point were in good health and had good resilience, although resilience was slightly lower at Te Puna Point. At Okete Bay (OB), the TBI score suggested good resilience, but the scores for both Benthic Health Models indicated moderate health.

The indices were generally consistent across sites in Tairua Harbour indicating Pauanui and Manaia Road had good health and resilience, whereas the sites at Pepe Inlet and Oturu Stream had moderate health and resilience, and Gumdigger Gully had moderate resilience and poor health (as measured by the BHM mud).

At most sites there is some variation from year to year in estuarine health scores (Appendix E); statistically significant trends through time are reported in Section 3.4 below.

3.4 Changes over time

Out of the 15 sites monitored only four (Gun Club, Whatitirinui Island, Te Puna Point and Pepe Inlet) displayed trends in indicator taxa that suggest the environment may be getting healthier (Table 1, and Figures 8, 15, 16 and 22). At these sites, there were increasing trends in taxa that prefer sandy sediments with low organic enrichment, e.g., *Colurostylis lemurum* and *Paphies australis* at Gun Club, *Anthopleura aureoradiata* and *Linucula hartivigiana* at Whatitirinui Island and *Austrovenus stutchburyi* and *Macomona liliana* at Pepe Inlet. There was a decreasing trend in *Arthritica bifurca*, which prefers moderately muddy habitats, at Te Puna Point. Note that at Gun Club and Whatitirinui Island there were also significant trends in indicator taxa, organic matter or estuarine health indices that suggest health may be declining, so the evidence for improving health is not unequivocal.

Trends in indicator taxa at ten sites suggest declines in environmental health (Table 1, and Figures 9 to 14, and 17 to 21), as taxa that prefer sandy sediments with low organic enrichment decreased in abundance (e.g., *Austrovenus stutchburyi* at Kaiaua, Miranda and Haroto Bay) and/or because taxa that prefer muddier, enriched habitats increased in abundance (e.g., Capitellidae at Kuranui Bay, Miranda, and Te Puru, and *Prionospio aucklandica* at Miranda, Okete Bay, and Ponganui Creek). In general, there were more trends detected at sites in the Firth of Thames and Whāingaroa Harbour, compared to Tairua Harbour, possibly because the shorter monitoring record at Tairua hinders the ability to detect change at those sites. It is also possible that the significant trends that were detected at sites in Tairua Harbour may be part of multiyear cycles that are not yet able to be detected in the relatively short time series. The long times series at Firth of Thames and Whāingaroa Harbour sites (17 years) suggest that multiyear cycles are common for several indicator taxa, such as Capitellidae, *Austrovenus stutchburyi* and *Linucula hartivigiana,* and similar monitoring in Auckland estuaries has shown that with less than 10 years of data multiyear cycles can be misinterpreted as trends in health (Hewitt and Carter 2020).

There were fewer data available for mud and organic matter content, due to the issues described in Section 2.2.4, limiting the power of statistical analysis, but the trends that were identified in these sediment properties were generally consistent with trends in indicator taxa. The increasing trend in mud content at Miranda is consistent with the significant trends in indicator taxa at this site, which included an increase in Capitellidae, a taxon that prefers muddier habitats, and a decrease in *Aonides trifida*, a species that prefers sandy sediments. Note that *Aonides trifida* has an optimum range of c. 0 to 5 % mud content, which was exceeded at Miranda around 2011 and this coincides with this species almost entirely disappearing from this site. Similarly, the increasing trend in mud content at Ponganui Creek was consistent with the increase in *Prionospio aucklandica,* a taxon that prefers moderately muddy habitats.

There was a significant increasing trend in organic matter at Te Puru in the Firth of Thames, which was consistent with an increasing trend in Capitellidae, which prefer organically enriched habitats, and a decreasing trend in *Linucula*, which are sensitive to organic enrichment. There was also a significant increasing trend in organic matter and Capitellidae at Gun Club in the Firth of Thames, suggestive of declining health, which is contrary to significant trends in other indicator taxa at this site, which suggest health is improving.

Significant decreasing trends in shell hash mostly occurred at sites where significant increasing trends in mud or organic matter were also detected. For example, at Kuranui Bay, Haroto Bay and Okete Bay there were significant decreasing trends in shell hash and significant increasing trends in organic matter, along with various significant trends in indicator taxa that all suggest declining health. Conversely, at Pepe Inlet, there was a significant decreasing trend in mud content, and significant increasing trend in shell hash, along with significant increasing trends in *Austrovenus stutchburyi* and *Macomona lilana* (both of which prefer sandy sediments), so all these trends suggest improving health.

Where significant trends in sediment properties other than mud, organic matter and shell hash were identified they were generally in the same direction (i.e., either increasing or decreasing) for each variable, regardless of the estuary or site. There were increasing trends in phaeopigment at four sites, and decreasing trends in total nitrogen at five sites, and total organic carbon at two sites. These trends are difficult to interpret in terms of estuarine health but may perhaps be driven by long-term climatic cycles.

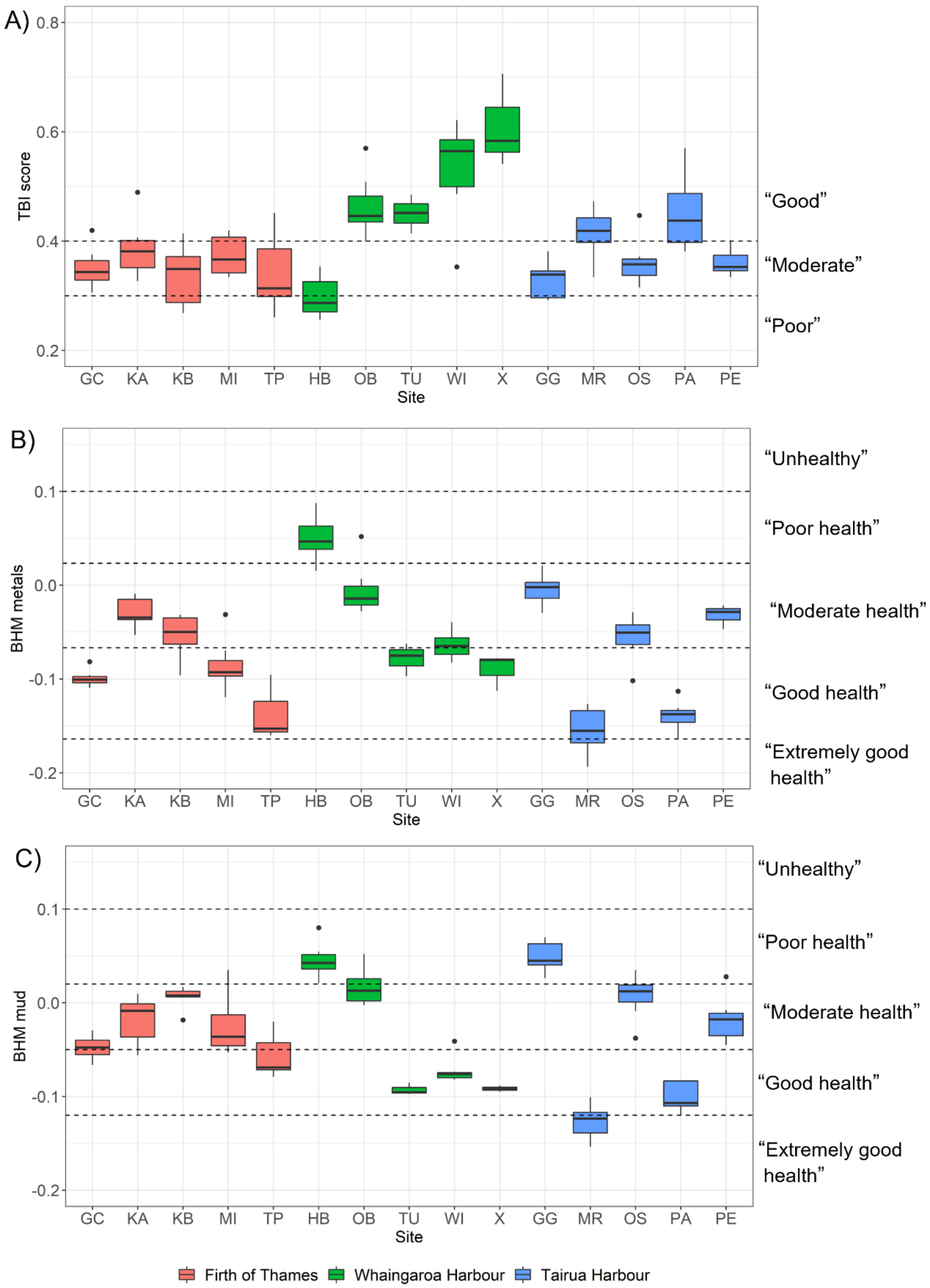

Figure 7: Estuarine Health Indices scores at REMP sites (summarised for 2012 to 2018 data). A) Traits Based Index (TBI), B) Benthic Heath Model (metals), and C) Benthic Health Model (mud). Categories corresponding to good, moderate and poor functional resilience (for the TBI), and a range in health (the BHMs) indicated by dashed horizontal lines.

Boxplot explanation: The solid horizontal line in each box corresponds to the median value (of all data collected between 2001 and 2018), the lower and upper hinges of each box correspond to the first and third quartiles, the whiskers extend from the hinge to the largest/smallest value or, at most, 1.5 * the inter quartile range, and black dots are outliers (i.e., data points that extend beyond the end of the whiskers).

Table 1: Statistically significant trends in indicator taxa, sediment properties and Estuarine Health Indices at REMP sites

Estuary	Site	Parameter	Trend	p value	Predicted change	Indicates health is
Firth of Thames	Gun Club (GC)	*Aonides trifida*	Step increase (in 2005)	0.003	109.6	Improving
		Capitellidae	Step increase (in 2005)	0.003	7.1	Declining
		Colurostylis lemurum	Increasing trend	<0.001	28.8	Improving
		Paphies australis	Step increase (in 2011)	0.001	50.8	Improving
		Organic matter	Increasing trend	0.040	1.1	Declining
		Shell hash	Decreasing trend	<0.001	-418.2	
		Total nitrogen	Decreasing trend	0.002	-0.05	
		Total organic carbon	Decreasing trend	0.016	-0.21	
	Kaiaua (KA)	*Austrovenus stutchburyi*	Step decrease (in 2007)	0.002	-4.8	Declining
		Linucula hartvigiana	Decreasing trend (after 2009)	<0.001	-159.4	Declining
		Magelona cf. dakini	Decreasing trend	0.003	-3.1	Declining
		Phoxocephalidae	Decreasing trend	0.010	-6.4	Declining
		Chlorophyll a	Increasing trend (after 2004)	0.039	5.5	
		Phaeophytin	Increasing trend (after 2004)	0.018	12.0	
		Shell hash	Decreasing trend	<0.001	-51.8	
	Kuranui Bay (KB)	*Aonides trifida*	Step decrease (in 2010)	0.001	-3.8	Declining
		Capitellidae	Step increase (in 2006)	0.021	28.1	Declining
		Linucula hartvigiana	Decreasing trend (until 2011)	<0.001	-2.5	Declining
		Macomona liliana	Decreasing trend	0.001	-2.0	Declining
		Organic matter	Increasing trend	0.045	1.4	Declining
		Phaeophytin	Increasing trend (after 2004)	0.032	13.7	
		Shell hash	Decreasing trend	0.004	-61.6	
		Total nitrogen	Decreasing trend	0.032	-0.05	
		Benthic Health Model (mud)	Increasing trend (2012 to 2018)	0.024	0.025	Declining
	Miranda (MI)	*Aonides trifida*	Decreasing trend (until 2010)	0.002	-52.9	Declining
		Austrovenus stutchburyi	Step decrease (in 2012)	0.010	-2.0	Declining
		Capitellidae	Increasing trend	0.001	62.5	Declining
		Magelona cf. dakini	Decreasing trend	<0.001	-3.6	Declining
		Prionospio aucklandica	Step increase (in 2006)	0.001	4.8	Declining
		Pseudopolydora complex	Increasing trend	0.016	1.6	Declining
		Mud	Increasing trend	0.014	9.3	Declining

		Shell hash	Decreasing trend (after 2007)	<0.001	-198.8	
		Benthic Health Model (metals)	Increasing trend (2012 to 2018)	0.023	0.064	Declining
	Te Puru (TP)	Capitellidae	Increasing trend	0.017	15.1	Declining
		Linucula hartvigiana	Decreasing trend (until 2011)	<0.001	-79.3	Declining
		Magelona cf. dakini	Increasing trend	<0.001	4.5	Improving
		Notoacmea spp.	Step decrease (in 2008)	<0.001	-1.0	Declining
		Organic matter	Increasing trend	0.028	1.0	Declining
		Phaeophytin	Increasing trend (after 2004)	0.039	3.7	
Whāingaroa Harbour	Haroto Bay (HB)	*Austrovenus stutchburyi*	Decreasing trend	0.023	-9.8	Declining
		Nereididae	Increasing trend	0.049	5.4	Declining
		Organic matter	Increasing trend	0.035	1.1	Declining
		Phaeophytin	Increasing trend (after 2004)	0.028	9.9	
		Shell hash	Decreasing trend	<0.001	-145.2	
		Total nitrogen	Decreasing trend	0.031	-0.04	
	Okete Bay (OB)	*Aricidea spp.*	Step increase (in 2010)	<0.001	1.86	Declining
		Arthritica bifurca	Increasing trend	0.003	3.6	Declining
		Paraonidae	Increasing trend	0.003	9.7	Declining
		Prionospio aucklandica	Increasing trend	0.001	7.6	Declining
		Organic matter	Increasing trend	0.047	0.9	Declining
		Shell hash	Decreasing trend	0.037	-10.4	
		Total nitrogen	Decreasing trend	0.018	-0.02	
	Te Puna Point (TU)	*Arthritica bifurca*	Decreasing trend	0.014	-6.8	Improving
	Whatitirinui Island (WI)	*Anthopleura aureoradiata*	Increasing trend	<0.001	5.1	Improving
		Capitellidae	Decreasing trend (after 2010)	0.001	-35.0	Improving
		Linucula hartvigiana	Increasing trend	0.005	56.9	Improving
		Macomona liliana	Decreasing trend (after 2009)	0.002	-9.7	Declining
		Total nitrogen	Decreasing trend	0.029	-0.03	
		Benthic Health Model (metals)	Increasing trend (2012 to 2018)	0.002	0.039	Declining
	Ponganui Creek (X)	*Glycera spp.*	Decreasing trend (after 2004)	<0.001	-1.9	Declining
		Prionospio aucklandica	Increasing trend	0.006	10.9	Declining
		Mud	Increasing trend?	0.053	6.1	Declining
Tairua Harbour	Gumdigger Gully (GG)	*Paphies australis*	Decreasing trend	0.039	-8.79	Declining
	Manaia Road (MR)	*Aonides trifida*	Decreasing trend	0.010	-19.72	Declining
		Shell hash	Decreasing trend	0.002	-13.2	

	Oturu Stream (OS)	Nereididae	Increasing trend	0.039	10.09	Declining
	Pauanui (PA)	*Aonides trifida*	Decreasing trend	0.028	-15.75	Declining
		Capitellidae	Decreasing trend	0.008	-7.53	Improving
	Pepe Inlet (PE)	*Austrovenus stutchburyi*	Increasing trend	0.015	5.44	Improving
		Macomona liliana	Increasing trend	0.005	1.93	Improving
		Mud	Decreasing	0.008	-4.3	Improving
		Shell hash	Increasing trend	0.029	39.0	
		Total organic carbon	Decreasing trend	0.004	-0.08	
		Benthic Health Model (mud)	Decreasing trend (2012 to 2018)	0.024	-0.055	Improving

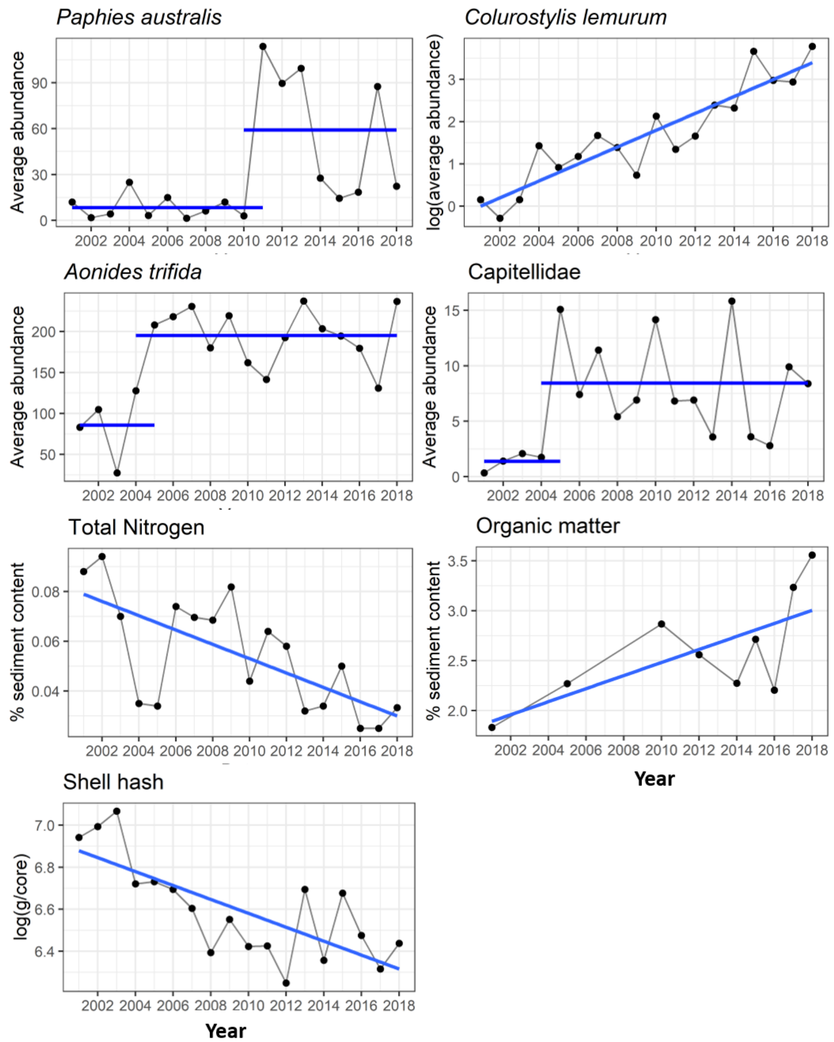

Figure 8: Statistically significant trends at Gun Club, Firth of Thames

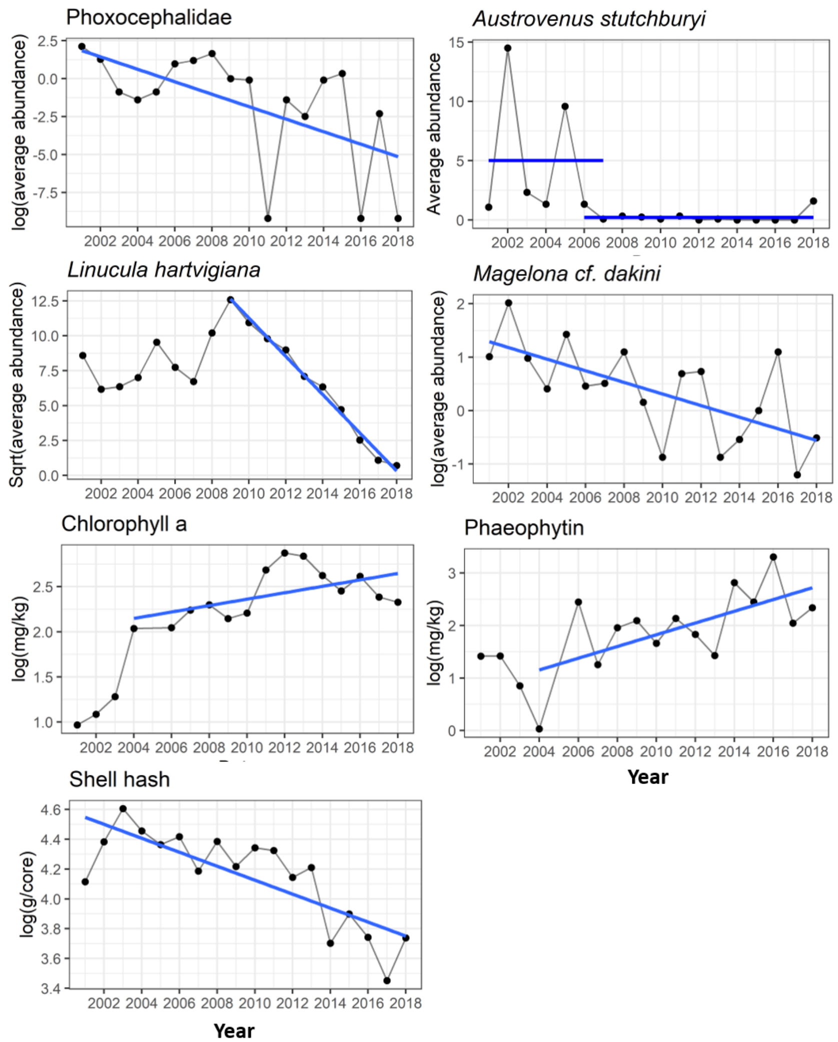

Figure 9: Statistically significant trends at Kaiaua, Firth of Thames

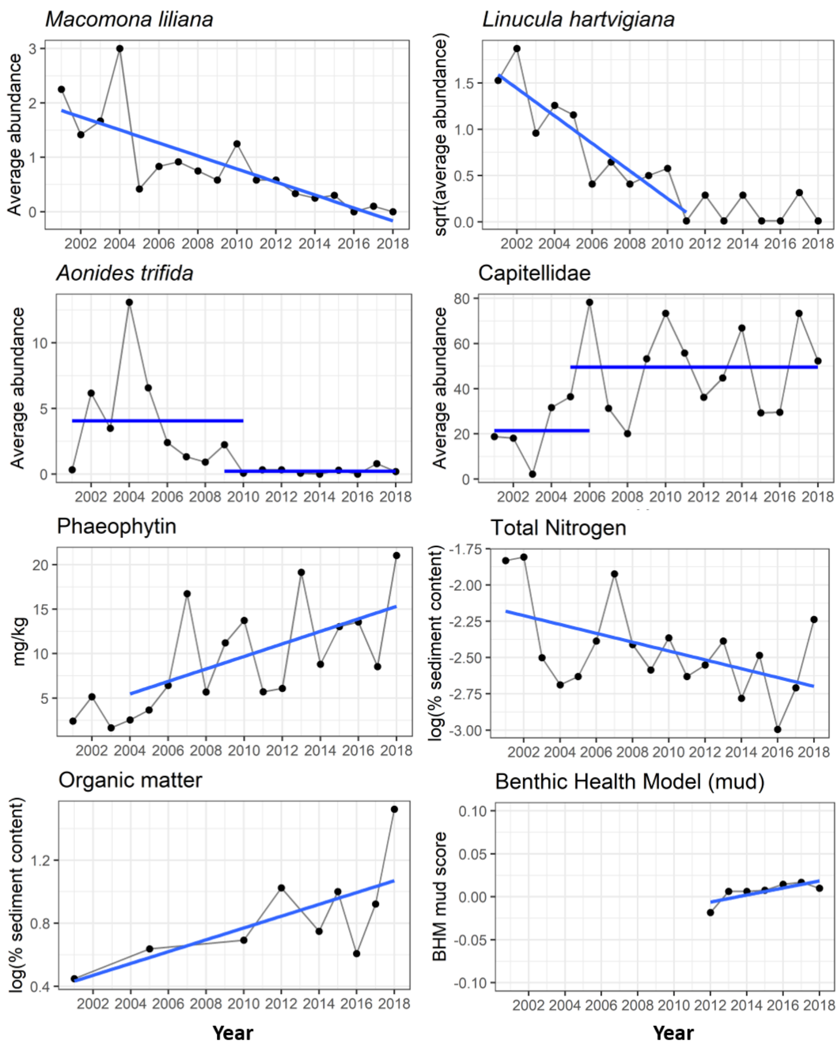

Figure 10: Statistically significant trends at Kuranui Bay, Firth of Thames

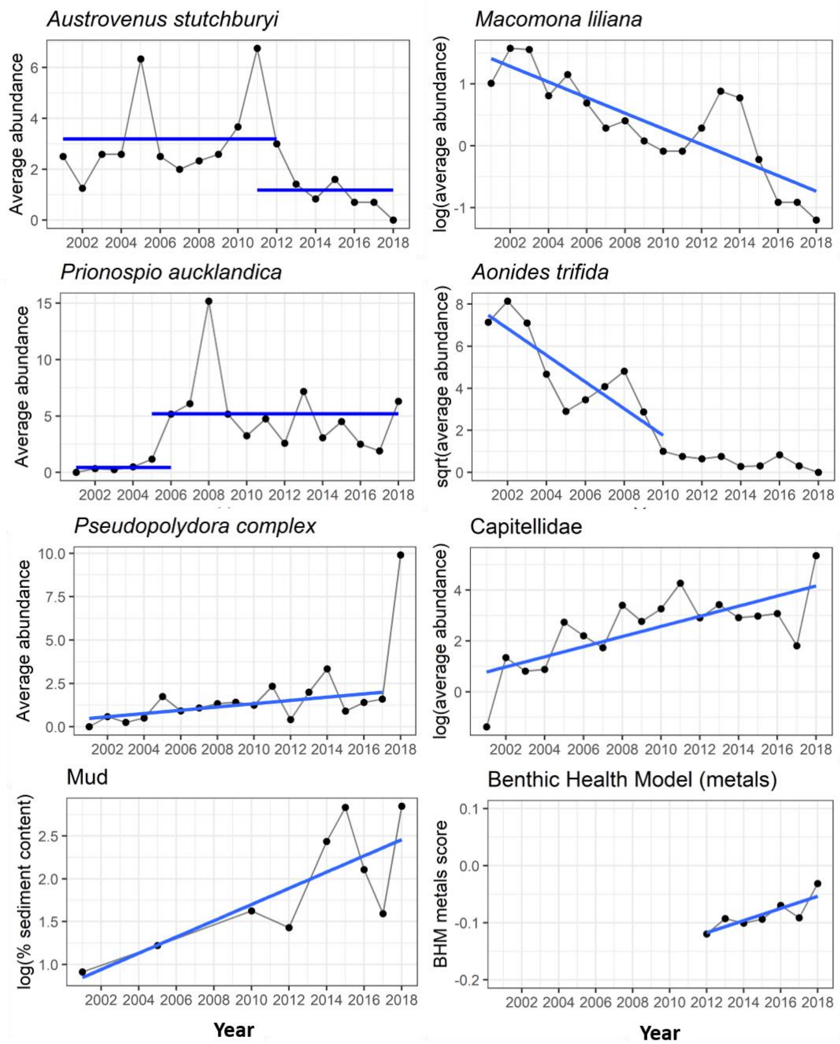

Figure 11: Statistically significant trends at Miranda, Firth of Thames

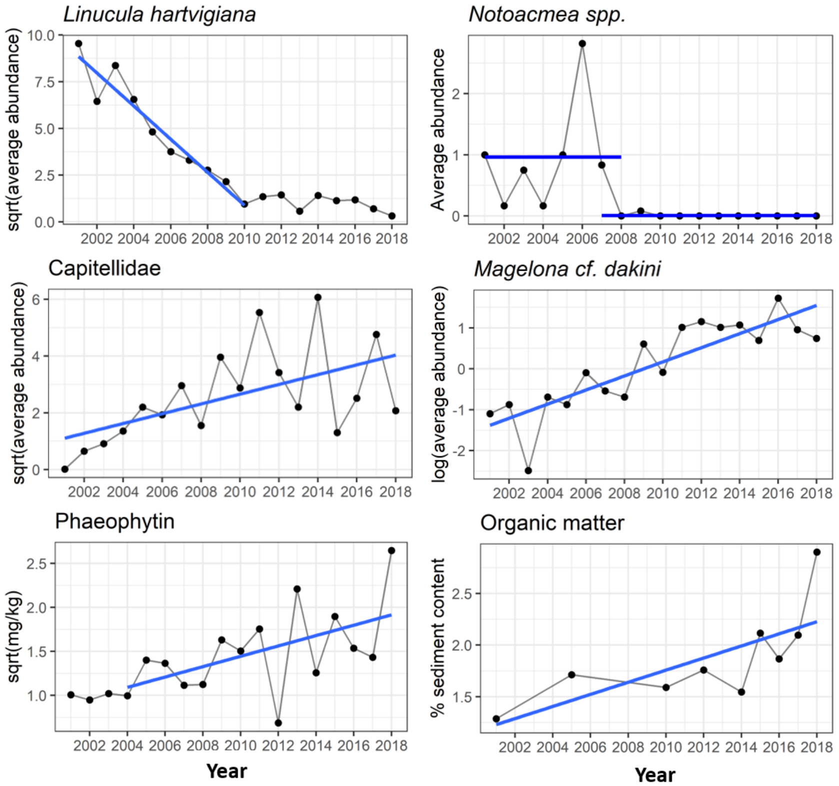

Figure 12: Statistically significant trends at Te Puru, Firth of Thames

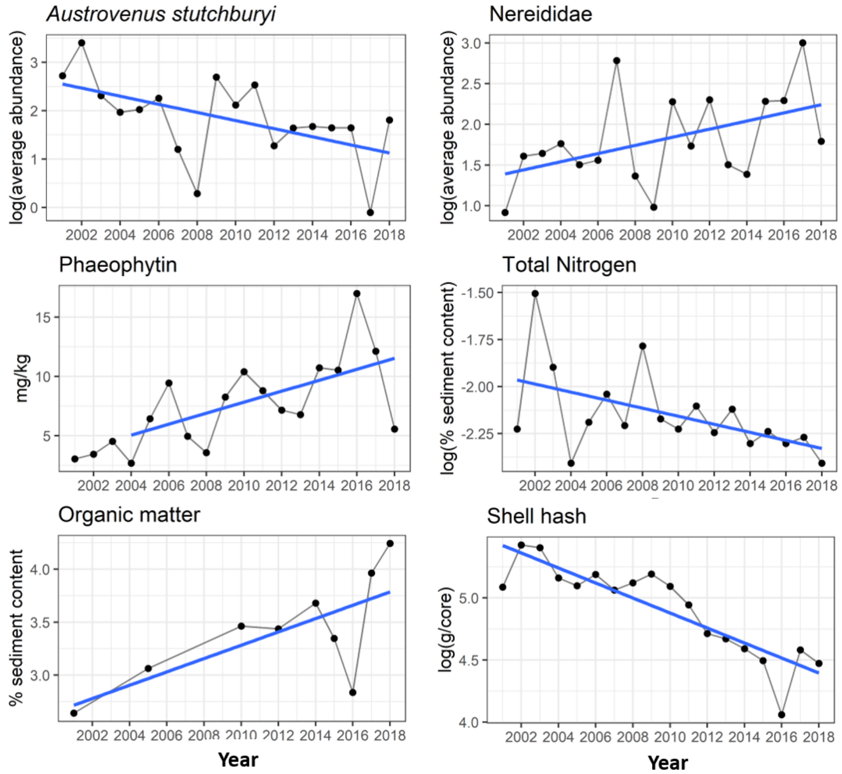

Figure 13: Statistically significant trends at Haroto Bay, Whāingaroa Harbour

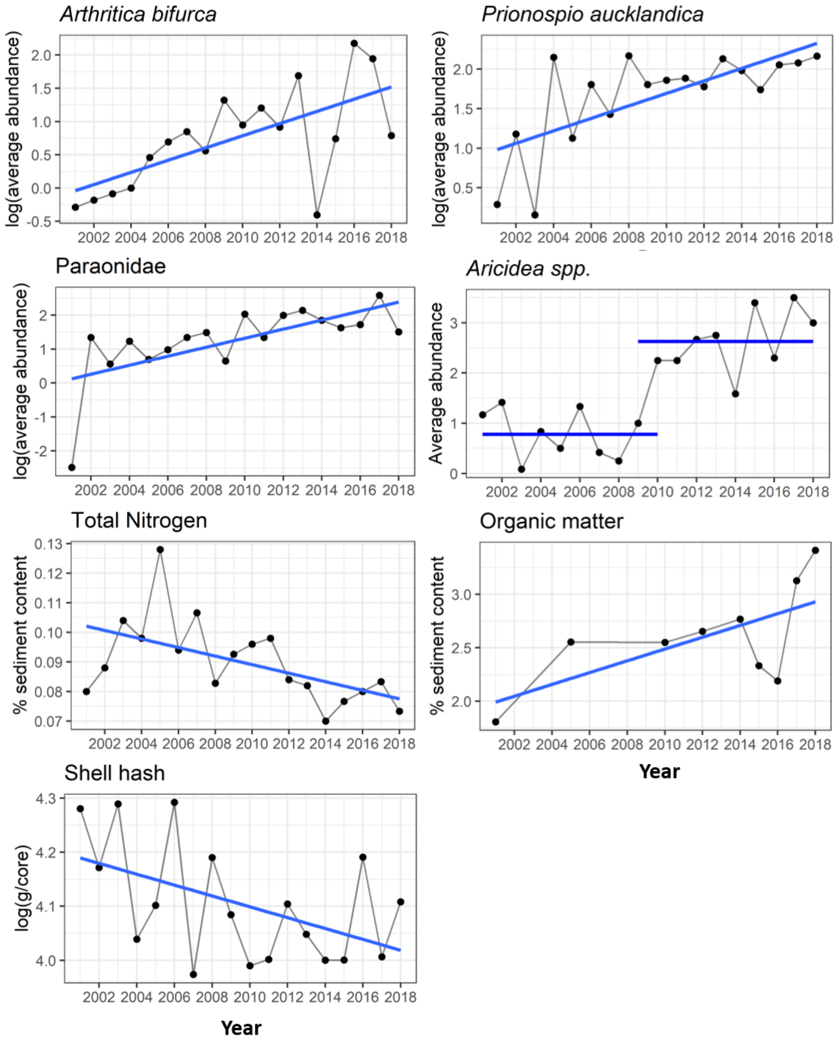

Figure 14: Statistically significant trends at Okete Bay, Whāingaroa Harbour

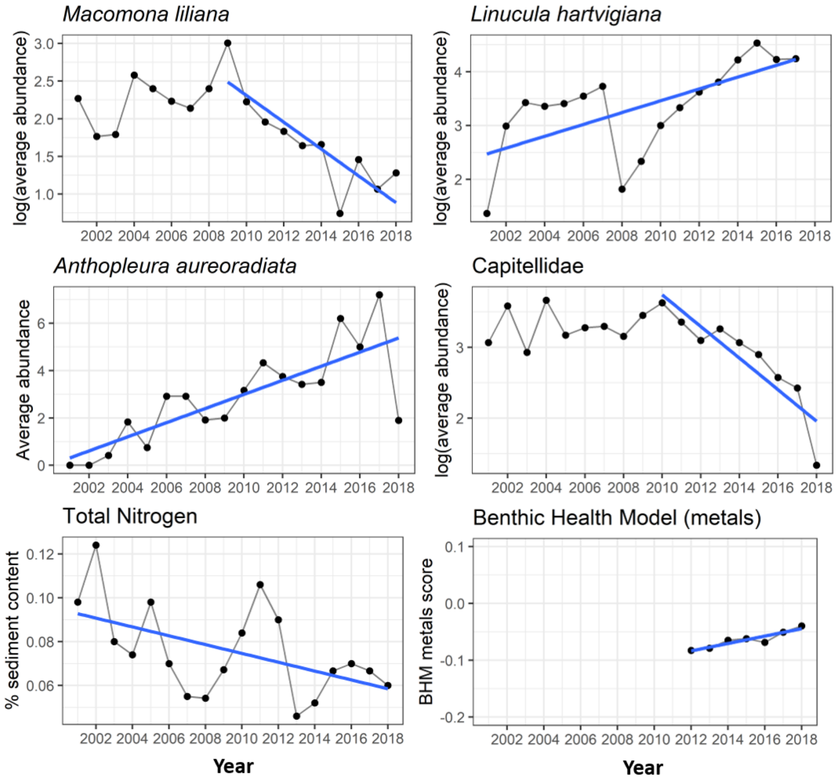

Figure 15: Statistically significant trends at Whatitirinui Island, Whāingaroa Harbour

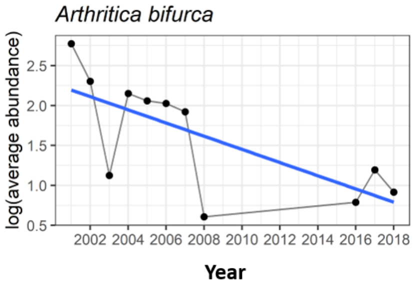

Figure 16: The only statistically significant trend at Te Puna Point, Whāingaroa Harbour

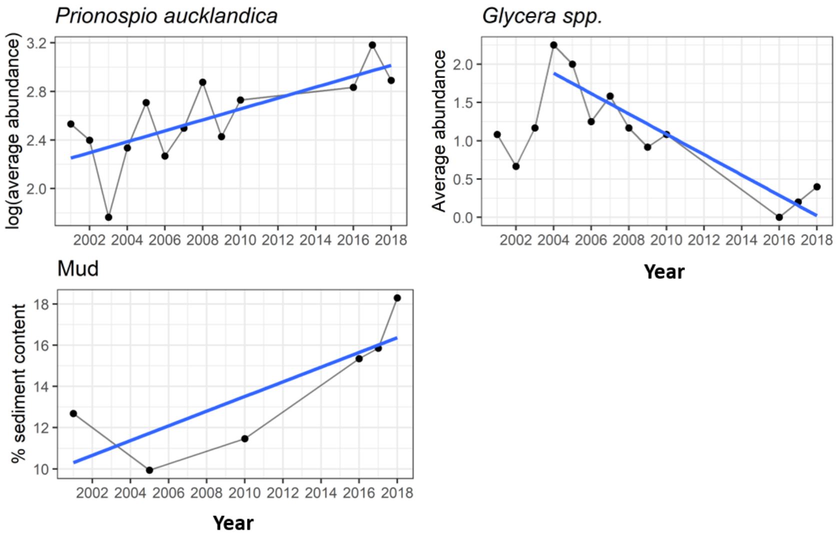

Figure 17: Statistically significant trends at Ponganui Creek, Whāingaroa Harbour

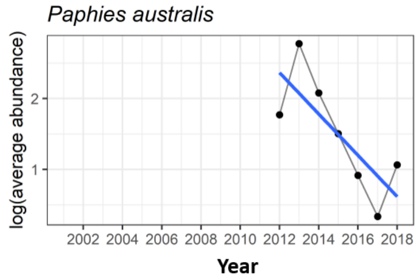

Figure 18: The only statistically significant trend at Gumdigger Gully, Tairua Harbour

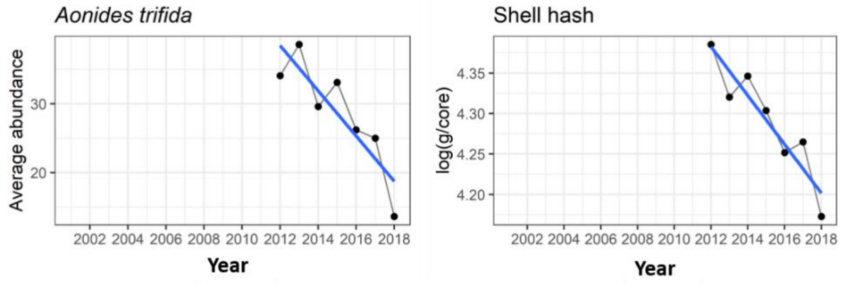

Figure 19: Statistically significant trends at Manaia Road, Tairua Harbour

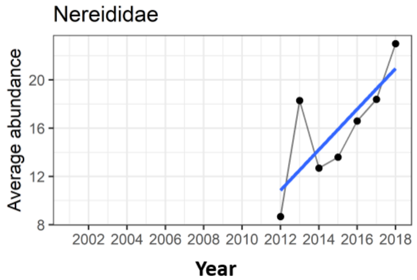

Figure 20: The only statistically significant trend at Oturu Stream, Tairua Harbour

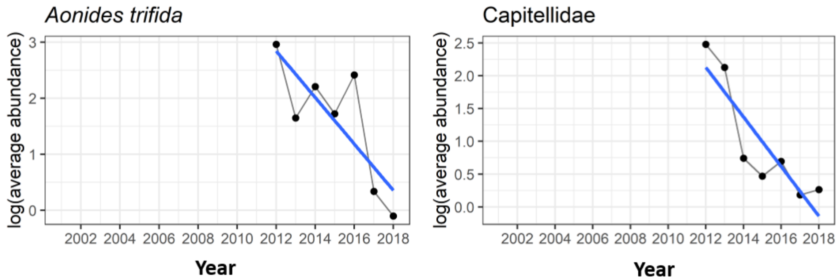

Figure 21: Statistically significant trends at Pauanui, Tairua Harbour

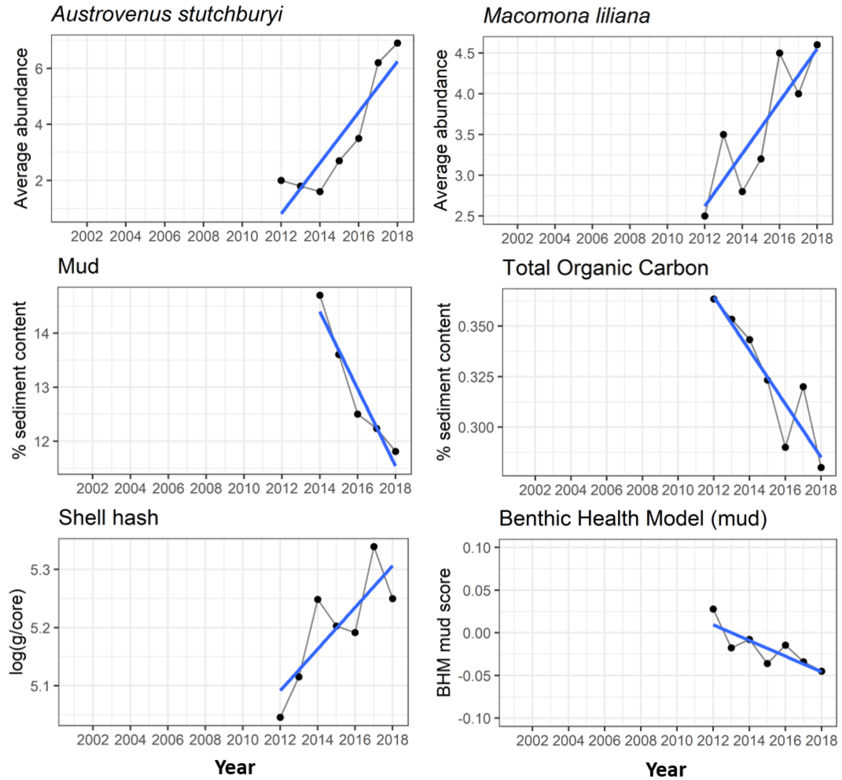

Figure 22: Statistically significant trends at Pepe Inlet, Tairua Harbour

3.5 Summary of state and trends in estuarine health

Monitoring sites in the REMP vary in their general characteristics in terms of sediment and macroinvertebrate community composition, sedimentation rates, and elevation relative to tidal level, as well as their location within an estuary and geographic location within the Waikato Region. Estuarine health indices suggest most sites are moderately healthy, although some are in poor health (e.g., Haroto Bay and Gumdigger Gully) and some are in good health (e.g., Ponganui Creek and Pauanui).

Overall, the trends in indicator taxa and sediment properties suggest that health is declining at many REMP sites in the Firth of Thames, Whāingaroa Harbour and Tairua Harbour. State and trend results for each site are summarised in Table 2. Many of the trends in indicator taxa and sediment properties identified here using 17 years of monitoring data were also identified in a previous trend report using 10 years of data (Needham et al. 2014). For example, both have identified increasing trends in sediment phaeopigment and decreasing trends in total organic carbon and total nitrogen at many sites. Many of the trends in indicator taxa detected in the earlier analysis were also identified using the longer, 17-year dataset. For example, increasing trends in Capitellidae at Miranda and Te Puru, Paraonidae at Okete Bay, and *Anthopleura* at Whatitirinui Island found in 2001 to 2011 data were still evident. Conversely, there were some trends identified using 10 years of data that were no longer significant when using 17 years of data, potentially due to the presence of multiyear cycles or other long-term variability.

Table 2: Summary of results for each monitoring site

Estuary and site	**Summary of state and trends**
Firth of Thames	
Gun Club	Estuarine health indices, mud content (c. 5%) and organic matter content (c. 2%) suggest this site is in **moderate to good health**. The lack of sedimentation (c. -0.4mm/yr) and three of four trends in indicator taxa (significant increasing trends in *Colurostylis lemurum, Paphies australis* and *Aonides trifida)* suggest health is **improving** at this site. Note that there were also significant increasing trends in organic matter content and in Capitellidae abundance, which suggest declining health.
Kaiaua	Estuarine health indices and organic matter content (c. 2 %) suggest this site is **moderately healthy**, but with elevated mud content (c. 19%). High rates of sedimentation (c. 3.6 mm/year) and indicator taxa (significant decreasing trends in *Austrovenus stutchburyi,* Phoxocephalida*e, Linucula hartivigiana and Magelona* cf. *dakini*) suggest health is **declining** at this site.
Kuranui Bay	Estuarine health indices and organic matter content (c. 2 %) suggest this site is **moderately healthy**, with c. 9% mud content. The site is experiencing net erosion (-4.9 mm/yr), but the possible increase in mud content (not statistically significant), significant increasing trend in organic matter content, significant trend in an Estuarine Health Index, and indicator taxa (significant decreasing trends in *Aonides trifida, Macomona liliana, Linucula hartigiana* and an increasing trend in Capitellidae) all suggest health is **declining** at this site.
Miranda	Estuarine health indices and organic matter content (c. 1.4 %) suggest this site is in **moderate to good health**, with c. 8% mud content. The site is experiencing net sediment erosion (-2.5 mm/yr), but there has been a significant increase in mud content and trends in an Estuarine Health Index, and in six indicator taxa (significant decreasing trends in *Macomona liliana*, *Aonides trifida,* and *Austrovenus stutchburyi,* and significant increasing trends in *Prionospio aucklandica, Pseudopolydora complex,* and Capitellidae) all suggest health is **declining** at this site.
Te Puru	Estuarine health indices, organic matter content (c. 1.6 %) and low mud content (c. 2.6%) suggest this site is in **good health**. Sedimentation rates are unknown, but there has been a significant increase in organic matter and a possible increase in mud content (not statistically significant). Significant

	trends in three out of four indicator taxa (significant decreasing trends in *Linucula hartivigiana* and *Notacmea* spp., and a significant increasing trend in Capitellidae) suggest health is **declining** at this site.
Whāingaroa (Raglan) Harbour	
Haroto Bay	Estuarine health indices, organic matter content (c. 3 %) and mud content (c. 46%) suggest this site is in **poor health**. High rates of sedimentation (c. 2.3 mm/year), a significant increasing trend in organic matter, and indicator taxa trends (significant decreasing trend in *Austrovenus stutchburyi* and significant increasing trend in Nereididae) suggest health is **declining** at this site.
Okete Bay	Estuarine health indices and organic matter content (c. 2.4%) suggest this site is **moderately healthy**, although with relatively high mud content (c. 26%). Sedimentation rates were highly variable at this site but averaged c. 1.4 mm/year, and a significant increasing trend in organic matter, and several trends in indicator taxa (significant increasing trends in *Arthritica bifurca, Aricidea* spp., *Prionospio aucklandica* and Paraonidae) suggest health is **declining** at this site.
Te Puna Point	Estuarine health indices and organic matter content (c. 1.3%) suggest this site is in **good health**, with c. 14% mud. Sedimentation rates suggest net erosion (c. -1.3 mm/year) and one trend in indicator taxa (significant decreasing trend in *Arthritica bifurca)* suggests health is **improving** at this site.
Whatitirinui Island	Estuarine health indices and organic matter content (c. 1.6%) suggest this site is in **moderate to good health**, with c. 16% mud. Sedimentation rates suggest net erosion (c. -2.1 mm/year), and three out of four indicator taxa trends (significant increasing trends in *Anthopleura aureoradiata* and *Linucula hartvigiana,* and a significant decreasing trend in Capitellidae) also suggest health is **improving** at this site. Note that there were also significant decreasing trends in *Macomona liliana* and an Estuarine Health Index, (both for the most recent period of 2012 to 2018), which suggest declining health.
Ponganui Creek	Estuarine health indices and organic matter content (c. 1.7%) suggest this site is in **good health**, with c. 14% mud. There is little net sedimentation (c. 0.8 mm/year), but a possible increase in mud content (p = 0.053), and trends in indicator taxa (significant increasing trend in *Prionospio aucklandica* and significant decreasing trend in *Glycera* spp.) suggest health is **declining** at this site.
Tairua Harbour	
Gumdigger Gully	Estuarine health indices suggest this site is in **poor health**, despite low organic matter (c. 1.6 %) and mud content (c. 2%). Sedimentation rates are unknown, but one indicator taxa (significant decreasing trend in *Paphies australis*) suggest health is **declining** at this site.
Manaia Road	Estuarine health indices, mud content (c. 1%) and organic matter content (c. 1.2%) suggest this site is in **good health**. Sedimentation rates are unknown, but one indicator taxa (significant decreasing trend in *Aonides trifida*) suggest health is **declining** at this site.
Oturu Stream	Estuarine health indices, and organic matter content (c. 1.7%) suggest this site is **moderately healthy**, with c. 6% mud. Sedimentation rates are unknown, but one indicator taxa (significant increasing trend in Nereididae) suggest health is **declining** at this site.
Pauanui	Estuarine health indices, mud content (< 1%) and organic matter content (c. 1.1%) suggest this site is in **good health**. Sedimentation rates are unknown and the two trends in indicator taxa are inconclusive, as one indicates declining health and the other improving health.
Pepe Inlet	Estuarine health indices, and organic matter content (c. 1.8%) suggest this site is **moderately healthy**, though with relatively high mud content (c. 13%). Sedimentation rates are unknown, but there was a significant decreasing trend in mud content, and trends in indicator taxa (significant increasing trends in *Austrovenus stutchburyi* and *Macomona Liliana*) and an Estuarine Health Index all suggest health is **improving** at this site.

Note that sedimentation rates, and mud and organic matter content represent the mean for the period 2001 to 2018.

4 Recommendations and conclusions

4.1 Pressures on estuaries in the Waikato region

Estuaries are the receiving environment for any contaminants delivered from their catchments and are subject to pressures from development around their margins, or activities within the estuary itself. The way that an estuary responds to these various pressures is dependent on the physical shape of the estuary, the influence of tides, wind, and freshwater flow, as well as the plant and animal communities that live in the estuary. The links between pressures on an estuary and the state and trends in estuarine health are thus complex and estuarine monitoring programmes are rarely able to quantify cause and effect at the scale of individual monitoring sites. This estuarine monitoring programme is not directly linked to monitoring of freshwater or land use change in catchments, making it difficult to ascertain whether changes in the sites monitored are linked to particular activities in the catchment or estuary. Nonetheless, the results from this monitoring programme suggest that estuarine health at many of the monitoring sites is declining, which is cause for concern and indicates that current management practices (on land and/or in the coastal marine area) are not sufficient to safeguard estuarine health. This is perhaps not surprising given the widely documented declines in freshwater health over recent decades (Ministry for the Environment & Stats NZ 2020).

In the Waikato region, there are no estuaries that are in a pristine state or a 'reference' condition. All estuarine catchments have experienced significant land use and landcover change, and many estuaries have been significantly modified around their margins by coastal development or reclamation (e.g., Jones 2008). Many of these changes occurred prior to the commencement of the monitoring programme in 2001. Sediment cores collected from several Waikato estuaries (including the Firth of Thames and Whāingaroa Harbour) show that sedimentation rates increased markedly c. 50 to 100 years ago, following settlement by Europeans and large-scale catchment deforestation (Hunt 2019b). Urban settlement on the margins of estuaries (e.g., at Raglan on Whāingaroa Harbour) often resulted in direct discharge of untreated sewage into the water (Parliamentary Commissioner for the Environment 2020), although improvements in wastewater treatment and other point source discharges have been made in recent decades. Diffuse contamination has been more difficult to manage, however, and monitoring of water quality in the Waikato region's rivers since 1980 has shown that total nitrogen and nitrate concentrations have increased in many rivers, likely related to widespread and intense pastoral farming in the region (Vant 2008 and 2018). These trends are also reflected in recent national reporting of coastal water quality, where there were more worsening than improving trends in total nitrogen and ammoniacal nitrogen at coastal sites over the time period 2008 to 2017 (Ministry for the Environment & Stats NZ 2019). Given this context of historical and ongoing pressure it is unsurprising that monitoring of estuarine health in the Waikato region has shown that many sites are in moderate to poor health and/or are showing signs of declining health.

Two of the four sites that do appear to be improving in health (Whatitirinui Island and Te Puna Point) are in the Waingaro arm of Whāingaroa Harbour. Sedimentation rates measured at these sites indicate erosion, rather than accretion, which is consistent with research showing that wind waves generated in this part of the harbour resuspend sediment (and remove it from the area), because the fetch is aligned with prevailing south-westerly winds (Hunt 2019a). In contrast, sites in the Waitetuna arm of the estuary (at Haroto and Okete Bay) appear to be declining in health and accumulating sediment. This is because of the fine sediment supply from the Waitetuna River (McKergow et al. 2010) and the restricted fetch for wave generation in and around the Waitetuna arm, which restricts the potential for wind waves to resuspend that sediment and move it away from these sites.

There was no monitoring site established in the Opotoru arm of Whāingaroa Harbour, and the area around this arm contains most of the urban development from the town of Raglan, including new subdivisions. In 2019, a new monitoring site was established in the Opotoru arm of the harbour in Kaitoke Bay to better capture any effects of urban development on the estuary.

The monitoring results for the Waingaro and Waitetuna arms of Whāingaroa Harbour highlight the increased susceptibility of some parts of estuaries, compared to others, with regards to catchment-derived inputs of sediment (and associated contaminants). The changes in health at estuarine monitoring sites are not just a function of their biological characteristics and the pressures exerted upon them but are highly dependent on the physical characteristics of the surrounding area.

4.2 Recommendations for future monitoring

This monitoring programme has assessed the state of, and trends in, estuarine health at sites in three estuaries in the Waikato region. Statistical analyses show that it is possible to detect trends with data collected once per year, although it likely requires c. 10 years of data to be able to do so. This is demonstrated by the greater number of trends detected in the Firth of Thames and Whāingaroa Harbour, which have been monitored for 17 years, compared to the 6 years for Tairua Harbour. This is also consistent with analyses in Hunt (2019a), which showed that annual monitoring at sedimentation plates was sufficient to detect trends if at least 10 years of monitoring were carried out. More frequent monitoring (e.g., two or four times per year), as carried out during the first 10 years or so of this monitoring programme, increases statistical power but was resource intensive and limited the number of estuaries included in the monitoring programme. There are c. 30 estuaries in the Waikato region, and there is a need to assess state and trends across a wider range of locations than the three estuaries that were monitored over 2001 to 2018. Recent progress has been made under a marine sediment contaminant monitoring programme started in 2019. This programme collects sediment for the analysis of heavy metal and organic (hydrocarbons, pesticides) contaminants, but has also paired this with sediment properties (grain-size, organic matter content and chlorophyll a) and benthic macroinvertebrates. Eleven estuaries have been sampled so far, with the plan to include all major estuaries on rotation over a 5-year cycle. While this data will not be useful for assessing trends, it will provide a broader, region wide understanding of benthic health, and potentially help identify estuaries in need of further monitoring. This data will also help to contextualise the trends and changes observed in the REMP estuaries.

The original intention of the REMP was to include four estuaries in the monitoring programme, covering four of the main estuary types in the region (Turner 2001):

- southern Firth of Thames (compound estuary – semi-enclosed bay)
- Coromandel Harbour (coastal embayment)
- an east coast Coromandel Harbour, e.g., Tairua Harbour (tidal lagoon – barrier enclosed lagoon)
- Whāingaroa (Raglan) Harbour (compound estuary – drowned river)

Note that there is another common estuary type in the Waikato region – tidal river estuaries (for example, Waikato, Waihou, Piako, Mokau and Awakino river estuaries) – which have not been a focus of state of the environment monitoring to date. These types of estuaries have specific characteristics, such as large subtidal areas, highly variable salinity, and shorter water residence times, and so REMP style monitoring may be challenging or may not be appropriate (for example, monitoring may need to include subtidal parts of these estuaries to be representative of estuarine health). However, these types of estuaries should be considered for inclusion in SOE monitoring, albeit with a potentially modified approach.

Tairua Harbour was added to the programme in 2012 with a reduction in sampling frequency for all estuaries by the end of 2015 to once per year. The need to include Coromandel Harbour in the programme meant a further reduction in sampling effort in the other estuaries. Previous reports (e.g., Compton et al. 2011, Hewitt and Thrush 2007) suggested adopting a spatially nested approach whereby after an initial period of monitoring all sites in an estuary, only two sites are monitored for a period of five years and then all are monitored again for the next two. Coromandel Harbour was added to the monitoring programme in spring 2019 by adopting this approach: the number of sites sampled in the Firth of Thames and Whāingaroa Harbour (which had been sampled for 17 years) were reduced from five to two and four new sites in Coromandel Harbour were added. The current plan is to sample all sites in each estuary for at least ten years before dropping down to two sites per estuary. As a result, all five sites in Tairua Harbour should be sampled until 2021, but then will drop to two sites in 2022 (with those two sites to be determined). Similarly, all four sites should be sampled in Coromandel Harbour until 2028. The two sites selected for continuous monitoring in the Firth of Thames were Miranda and Kuranui Bay, as these are located on different sides of the Firth and are both declining in health. The two sites selected for continuous monitoring in Whāingaroa Harbour were Whatitirinui Island and Okete Bay, which are in different arms of the harbour. Although health appears to be improving at Whatitirinui Island, this site is in the main arm of the harbour and so continuing monitoring here is important. Another monitoring site has also been established at Kaitoke Bay in the Opotoru arm of Whāingaroa Harbour (which is subject to pressures from urban development), so the total number of sites currently sampled in Whāingaroa Harbour is three. The locations of all the current monitoring sites are shown in Figure 23, and the sampling schedule for 2019 to 2028 is outlined in Table 3.

Table 3: Recommended sampling schedule for 2019 to 2028

Estuary	Site	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Firth of Thames	Gun Club						✓	✓			
	Kaiaua						✓	✓			
	Kuranui Bay	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Miranda	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Te Puru						✓	✓			
Whāingaroa Harbour	Haroto Bay						✓	✓			
	Okete Bay	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Te Puna Point						✓	✓			
	Whatitirinui Island	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Ponganui Creek						✓	✓			
	Kaitoke Bay	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tairua Harbour	Gumdigger Gully	✓	✓	✓						✓	✓
	Manaia Road	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Oturu Stream	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Pauanui	✓	✓	✓						✓	✓
	Pepe inlet	✓	✓	✓						✓	✓
Coromandel Harbour	McGregor Bay	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Coromandel Town	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Brickfield Bay	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Awakanae Stream	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Total number of sites sampled:	14	14	14	11	11	17	17	11	14	14

Trend analyses should be undertaken approximately every 5 years, with the next scheduled after sampling in 2023. At this point there will have been over ten years of data collected for Tairua Harbour and 5 years for Coromandel Harbour (and over twenty years for sites continuously monitored in Whāingaroa Harbour and Firth of Thames). More regular reporting of REMP data is currently carried out via the WRC website[11], and with annual updates of an environmental indicator that show the TBI score for each monitored site[12]. It is recommended that the newly developed National Benthic Health Models (Clark et al 2020) are investigated for inclusion in this annual reporting and analysis, as these may be useful indicators of estuarine health (as opposed to resilience).

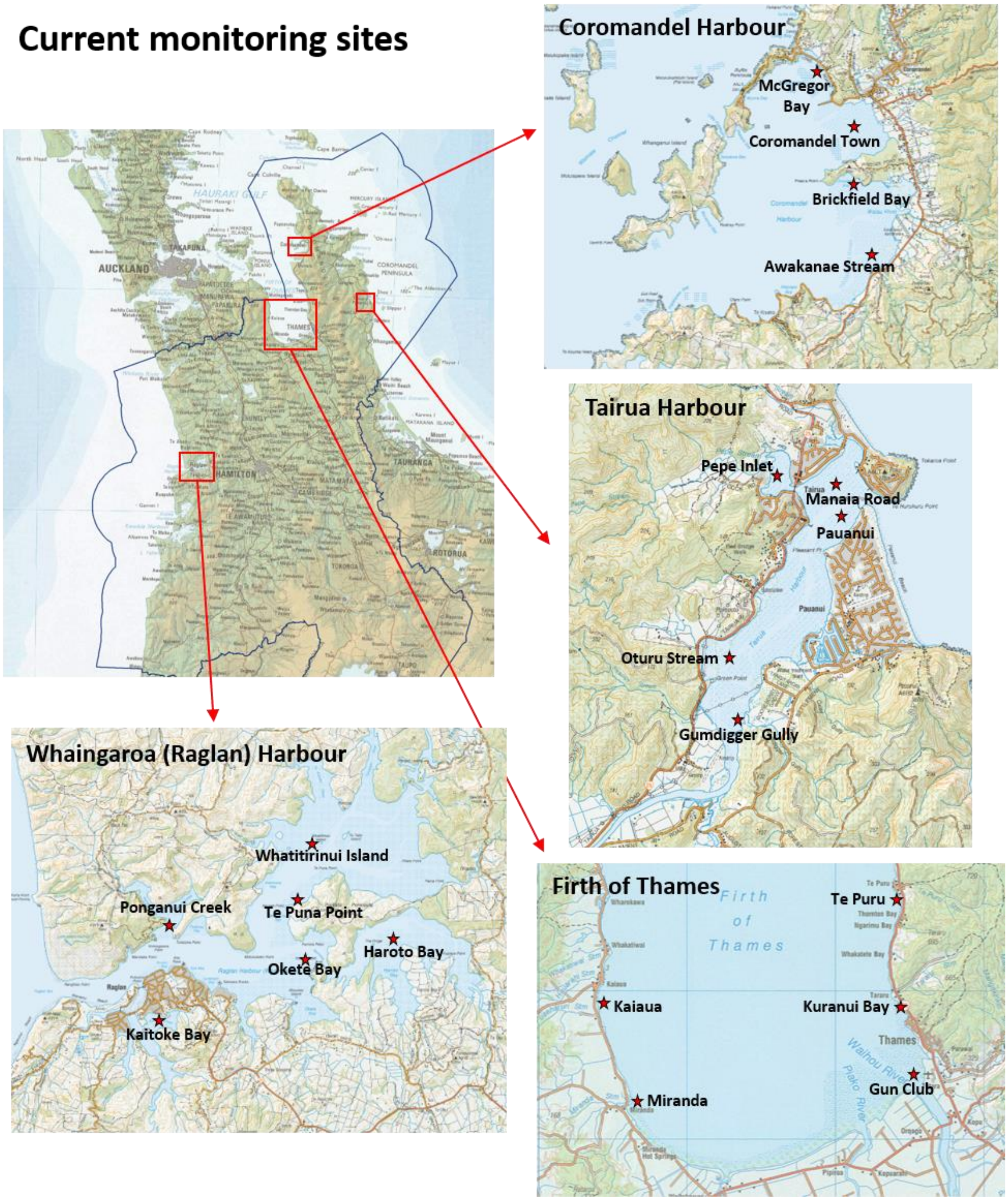

Figure 23: Current monitoring sites (i.e., as of 2019 onwards). Note that sampling at Ponganui Creek, Te Puna Point and Haroto Bay (Whāingaroa Harbour) and Kaiaua, Gun Club and Te Puru (Firth of Thames) has been paused between 2019 and 2023 as part of the spatially nested sampling design. Sites introduced in 2019 were Kaitoke Bay (Whāingaroa Harbour) and the four sites in Coromandel Harbour. Map source: LINZ NZ Topographic Series.

The variables monitored in the REMP have been focused on intertidal soft sediment macroinvertebrates and sediment characteristics at a fine scale, i.e., the results are site-specific. Although this monitoring has been able to detect trends in indicator taxa and sediment properties at a fine scale, it should ideally be part of a wider, more broad scale estuary

[11] https://waikatoregion.govt.nz/environment/coast/ecosystem-health/regional-estuary-monitoring-programme/
[12] https://waikatoregion.govt.nz/environment/coast/coast-monitoring/co1-report/

monitoring programme. There have been estuarine vegetation, water quality and sediment contaminant monitoring programmes in the Waikato region over the past twenty years (e.g., Graeme 2005, Felsing and Giles 2011, Graeme 2012), but these have collected data infrequently and haven't necessarily sampled the same estuaries or sites as the REMP, making it difficult to pull the information together to tell a coherent story about the state of Waikato estuaries. Furthermore, the lack of a link between monitoring the state of estuarine health in the REMP to drivers (i.e., activities) on land or in the estuary has limited the ability to attribute the observed state and trends to any particular cause.

Recent work has proposed a 'Coastal Ecosystem Health Monitoring Programme' as one of four coastal state of the environment monitoring programmes that would be both relevant to policy drivers and link to social value (Jones et al. 2019). Connected environmental indicators of drivers, pressures and state that should be included in an estuarine ecosystem health monitoring programme were identified and prioritised in Jones et al. (2020) and these are shown in Figure 24. Collecting data and reporting on these connected sets of indicators should allow for a clearer representation of the state of Waikato estuaries and the causes of any changes that are occurring. It is recommended that the sites and indicators monitored in the REMP become part of a broader Coastal Ecosystem Health Monitoring Programme. Macroinvertebrate community composition data would provide some information for state indicators focused on biodiversity and health of key habitats, whilst the sediment property data provides some information for a sediment quality indicator. Data collected in water quality monitoring (currently carried out in some Waikato estuaries, including Whāingaroa and Tairua Harbours) could be used to provide information for a water quality pressure indicator, and monitoring of trace elements in sediments (currently carried out on a somewhat ad hoc basis) could be combined with data collected on sediment mud and organic matter content to derive a more complete sediment quality indicator. Consideration will need to be given to the monitoring or information gathering required to collect data to derive other indicators (e.g., for catchment loading, coastal development, eutrophication, aquaculture). The design and implementation of a comprehensive Coastal Ecosystem Health monitoring programme is a key recommendation of this report.

The Parliamentary Commissioner for the Environment (2020) called for the mandatory inclusion of estuaries in freshwater management units (FMUs) under the National Policy Statement for Freshwater Management, which would go some way towards integrating management over the catchment and estuary. The PCE also recommended more robust monitoring in estuaries and catchments to better inform management decisions, which provides further justification for the recommended monitoring approach outlined above and in Figure 24. Monitoring of Waikato estuaries should be more closely integrated with monitoring in their catchments to improve our ability to attribute declines or improvements in estuarine health to activities on land. This will require collaborative work with freshwater and terrestrial science and monitoring teams.

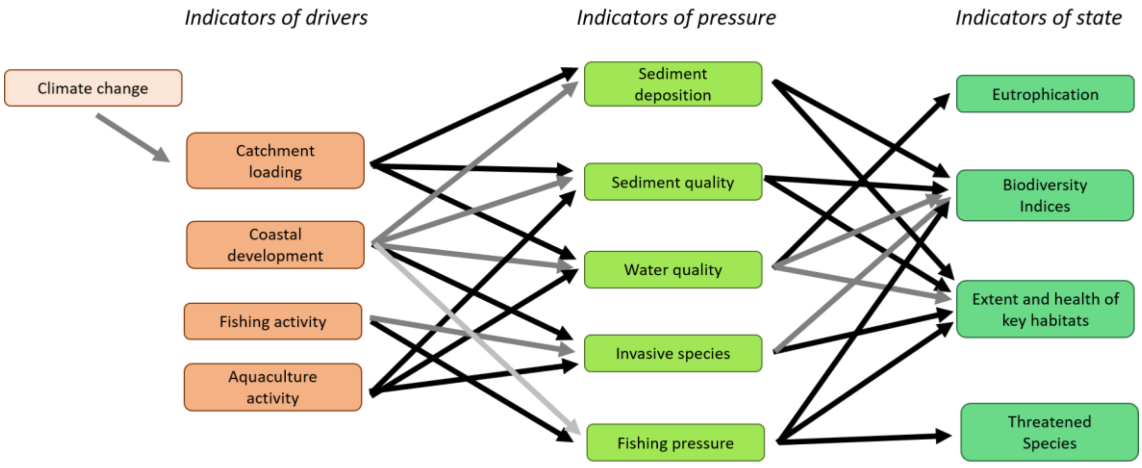

Figure 24: Indicators of drivers, pressure, and state relevant to a Coastal Ecosystem Health monitoring programme and focused on estuaries from Jones et al. (2020). Connections between indicators depicted by arrows with black, mid-grey and light-grey denoting strong, moderate, and minor influence, respectively.

4.3 Conclusions

The REMP has assessed the state of, and trends in, estuarine health at sites in three estuaries in the Waikato region. The data suggests that most sites in the REMP are moderately healthy, but health is declining at many sites in the Firth of Thames, Whāingaroa Harbour and Tairua Harbour. It is not possible to link the changes observed at the estuarine monitoring sites to particular activities in the catchments or estuary, but the results do indicate that management practices have been insufficient to safeguard estuarine health, which is perhaps not surprising given the widely documented declines in freshwater health.

There are c. 30 estuaries in the Waikato region, and there is a need to assess state and trends at more locations than have been able to be included in this monitoring programme to date, and to be able to link observed changes to specific drivers and pressures. It is recommended that the sites and indicators monitored in the REMP become part of a Coastal Ecosystem Health Monitoring Programme and that monitoring of Waikato estuaries be more closely integrated with monitoring in their catchments.

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Appendix A: Benthic macroinvertebrate indicator taxa

Group	Taxa	Habitat preference and relevance as indicator taxa*
Amphipods	Corophiidae	Corophiid amphipods tolerate a sediment mud content of 40-100%, with an optimum range of 95-100%. Therefore, they are usually found in very muddy habitats. Corophiid amphipods can also tolerate organic enrichment and pollution.
	Phoxocephalidae	Phoxocephalid amphipods are usually found in muddy sands, are intolerant of very high mud content, and are sensitive to pollution (e.g., lead contamination).
Bivalves	*Arthritica bifurca*	*Arthritica bifurca* tolerates a sediment mud content of up to 75% with an optimum range of 20-60%. Therefore, they prefer moderately muddy habitats.
	Austrovenus stutchburyi	*Austrovenus stutchburyi* (cockle, tuangi) tolerate mud content up to 85% with an optimum range of 0-10%. They are sensitive to long term exposure to high levels of mud. Therefore, they prefer sandy habitats with a small amount of mud. Cockles are also sensitive to copper contamination.
	Macomona liliana	*Macomona liliana* (wedge shell) tolerates mud content up to 75%, with an optimum range of 0-30%. Therefore, they prefer sandy habitats with some mud. *Macomona liliana* is also sensitive to copper contamination.
	Linucula hartvigiana	*Linucula hartvigiana* (nutshell) tolerates a sediment mud content up to 60%, with an optimum range of 0-5%. Therefore, they prefer sandy habitats. *Linucula hartvigiana* is also sensitive to organic enrichment and copper contamination.
	Paphies australis	*Paphies australis* (pipi) only tolerate a maximum sediment mud content of 5% and are very sensitive to high turbidity. Therefore, they are usually found in sandy habitats. Pipi are also sensitive to zinc contamination.
	Theora lubrica	*Theora lubrica* (Asian semele) is tolerant of mud, organic enrichment, and pollution. It can tolerate a mud content of up to 65% with an optimum range of 45-50%.
Cumaceans	*Colurostylis lemurum*	*Colurostylis lemurum* (Cumacean or hooded shrimp) tolerates a sediment mud content of up to 60%, with an optimum range of 0-5%. Therefore, they are usually found in sandy habitats. *Colurostylis lemurum* is also sensitive to lead contamination and other pollution.
Gastropods	*Cominella adspersa*	*Cominella adspersa* (Speckled whelk) is found in muddy sediments (the optimum range is unknown).
	Notoacmea spp.	*Notoacmea* (limpet) are highly sensitive to sediment mud content, with an optimum range of 0-5% and distribution range of 0-10%. Therefore, they are usually found in sandy habitats. *Notoacmea* can also be sensitive to pollution (particularly zinc).
Polychaetes	*Prionospio aucklandica*	*Prionospio aucklandica* tolerates a sediment mud content of up to 95%, with an optimum range of 20-70%. It is usually found in moderately to very muddy habitats but is less abundant in extremely muddy areas (>70% mud). *Prionospio aucklandica* is also sensitive to copper contamination.
	Aglaophamus spp.	*Aglaophamus* spp. generally prefer sandy habitats over muddy ones.
	Aonides trifida	*Aonides trifida* tolerates a sediment mud content up to 80% but has an optimum range of 0-5% and so is most abundant in sandy habitats. *Aonides trifida* is also sensitive to copper contamination.
	Aricidea spp.	*Aricidea* spp. tolerate a sediment mud content up to 70%, with an optimum range of 35-40%, and so are usually found in habitats that have a slightly greater proportion of sand than mud (e.g. muddy

		sands). *Aricidea* spp. have also shown sensitivity to lead and zinc contamination.
	Pseudopolydora complex	Polydorids generally live in sediments ranging from fine sand to sandy mud, while some are tolerant of muddier sediment (15-30%). Polydorids have also shown sensitivity to lead contamination.
	Cossura consimilis	*Cossura consimilis* tolerates a sediment mud content of 5 to 65%, with an optimum range of 20-25%. Therefore, it is usually found in habitats which are more sandy than muddy (e.g. muddy sand). *Cossura consimilis* has also shown sensitivity to copper contamination.
	Euchone spp.	*Euchone* spp. (fan or feather duster worms) are sensitive to copper and zinc contamination (but their sensitivity to mud is unknown).
	Goniada spp.	Goniadids tolerate a sediment mud content up to 60%, with an optimum range of 50-55%. Therefore, they are usually found in more muddy habitats with some sand. Goniadids have also shown sensitivity to copper contamination.
	Glycera spp.	Glycerids (blood worms) tolerate a sediment mud content up to 95%, with an optimum range of 10-15%. Therefore, they are usually most abundant in sandy habitats with some mud content. Glycerids are also sensitive to low levels of oxygen, which can occur in organically enriched estuarine sediments.
	Capitellidae	Capitellids tolerate a sediment mud content of up to 95%, with an optimum range of 10-40%. Therefore, they are usually found in moderately muddy habitats. Capitellid abundance is often high in organically enriched estuarine sediments.
	Magelona cf. dakini	Magelonids are highly sensitive to lead contamination and are usually more abundant in sandy habitats.
	Orbinia papillosa	*Orbinia papillosa* tolerates a sediment mud content up to 40%, with an optimum range of 5-10%, so is usually found in sandy habitats. *Orbinia papillosa* has been shown to be slightly sensitive to zinc contamination.
	Nereididae	Nereidids tolerate a sediment mud content of up to 100%, with an optimum range of 35-60%. Therefore, they are usually most abundant in moderately to very muddy habitats. Nereidids are not sensitive to copper, lead and zinc contamination and can be found in high densities in relatively contaminated sediments.
	Paraonidae	Paraonids generally prefer habitats with some mud (muddy sands) and some paraonids are known to tolerate mud content up to 70% with an optimum range of 35-40%.
Anthozoans	*Anthopleura aureoradiata*	*Anthopleura aureoradiata* tolerates a sediment mud content of up to 40%, with an optimum range of 0-10%. It is intolerant of high turbidity and so is usually found in more sandy habitats. This species is also very sensitive to copper contamination.

* Adapted from Needham et al. (2014) and references therein.

Appendix B: Sediment grain size analyses

Between 2001 and 2017 sediment grain size was analysed by laser diffraction or laser particle scanning, both of which give grain size fractions by volume. The specific instrument used to analyse grain size changed part way through the monitoring programme. Up to October 2007 samples were analysed using a Galai (CIS-100) stream-scanning laser particle sizer. From October 2007 to October 2017, samples were analysed using a Malvern Mastersizer 2000 laser diffraction instrument. However, the Galai and Malvern instruments analyse grain size distribution in different ways and have been shown to be poorly comparable (e.g., Goossens 2008, Roberson and Weltje 2014). The change in instrument is clearly visible in time series plots of the data; for example, as a substantial increase in percent mud content (Figure B1).

The difference in grain size fractions as measured by the two different instruments is partially due to differences in upper and lower detection limits. The lower detection limit was 10µm for the Galai and 5µm for the Malvern. Also, the Malvern analysis removed grains > 2 mm (by sieving and by hand-picking out large shell fragments), but the Galai only recorded the fraction > 1mm, with no upper limit given (and lab notes indicate the samples were sometimes sieved, but not the size of the sieve). This means that the grain size range as measured by the Malvern was 5 to 2000 µm, but for the Galai was 10 µm to an unknown (and possibly variable) upper limit. The grain size range in common between the Galai and Malvern was 10 to 1000 µm. Therefore, the grain size data was adjusted to be the percentage of the fraction between 10 and 1000 µm. Time series plots of the adjusted data do not show as much of a step change in measured grain size fractions when the instruments changed in 2007, compared to the raw data (Figure B2).

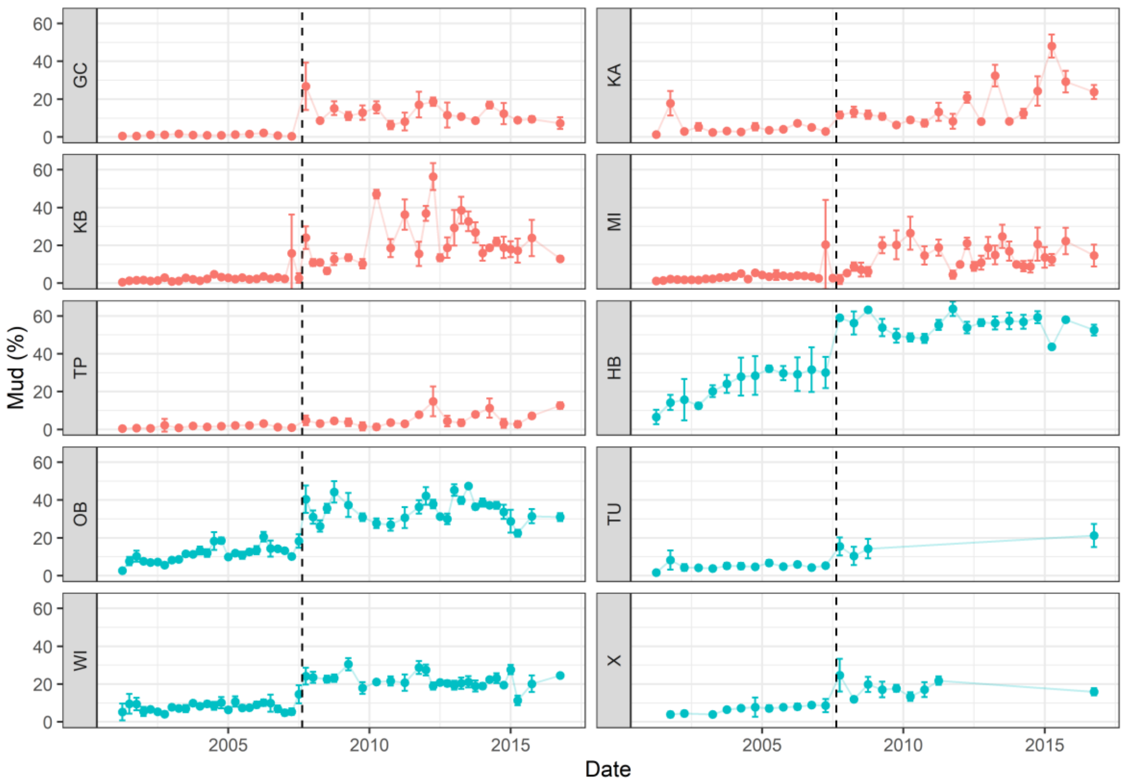

Figure B1: Percent mud content as measured by the Galai and Malvern instruments at REMP sites in the Firth of Thames (in red), and Whāingaroa Harbour (in blue). The timing of the change between instruments used for analysis (October 2007) is indicated by the dashed line.

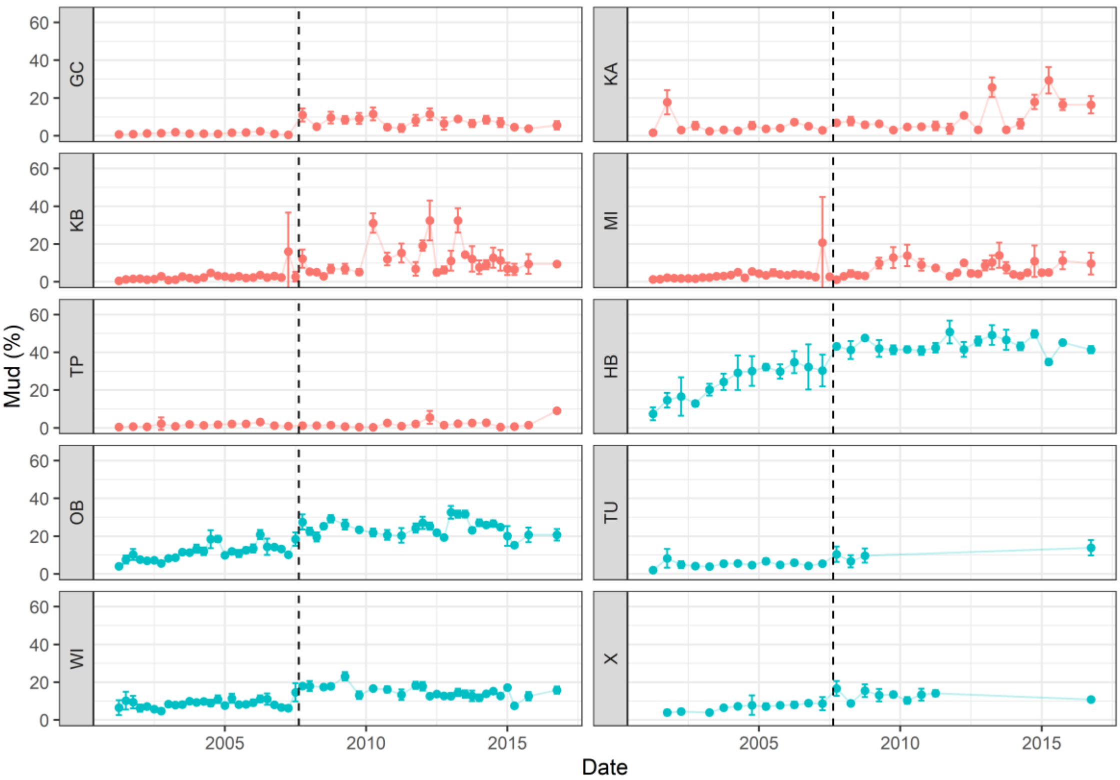

Figure B2: Adjusted percent mud content as measured by the Galai and Malvern instruments at REMP sites in the Firth of Thames (in red), and Whāingaroa Harbour (in blue). Mud content was adjusted to be the percentage of the fraction between 10 and 1000um (i.e., the grain size range in common between the two different instruments). The timing of the change between instruments used for analysis (October 2007) is indicated by the dashed line.

The Galai and Malvern use different methods to measure grain size, and so the differences between the two datasets are not surprising, but it does not make for a useful dataset for long-term monitoring. Although the adjustment made the Galai and Malvern datasets more comparable than the raw data, these data are not considered to be reliable for the following reasons. Firstly, mud content as measured by the Galai was extremely low (< 5%), even at sites that are known to be very muddy (e.g., Haroto Bay and Okete Bay in Whāingaroa Harbour), indicating that the data may not have been very accurate. Furthermore, sediment grain size analyses with both instruments used the same pre-treatment, which included addition of acid to remove carbonates. The acid has been shown to affect Whāingaroa and Firth sediment samples more than those from Tairua Harbour (Hunt and Jones 2018). Mud content is likely to have been affected by the acid pre-treatment, particularly in Whāingaroa samples, possibly because mud/siltstone is weathered by the acid and measured as mud by the instrument. This means that the mud content as measured by the Galai and Malvern may not have accurately quantified the mud that the benthic invertebrate communities were exposed to (and may therefore not be particularly relevant to an ecological monitoring programme).

To address the above issues archived sediment samples were re-analysed by wet sieving with no pre-treatment, and samples collected from 2018 onwards in the REMP are being analysed by this method. Wet sieving with minimal pre-treatment is considered an appropriate grain size analysis methodology for long term ecological monitoring programmes as it is simple, standardised and minimises modification to sediment characteristics (Hunt and Jones 2018). Only a subset of sediment samples was archived, but there were samples available for most sites for the spring (October or November) of 2001, 2005, 2010, 2012, 2014, 2015, 2016, 2017 and 2018, yielding sufficient data for trend analysis.

Appendix C: General characteristics of monitoring sites

Table C1: Sediment properties at each monitoring site

Numbers represent the mean of all samples taken for the monitoring period (i.e., 2001 to 2018 for sites in the Firth of Thames and Whāingaroa Harbour, 2012 to 2018 for sites in Tairua Harbour).

Estuary	Site	Chlorophyll a (mg/kg)	Phaeophytin (mg/kg)	Total nitrogen (%)	Total organic carbon (%)	Organic matter (%)	Mud (%)	Sand (%)	Gravel (%)	Shell hash (g/core)
Firth of Thames	Gun Club	14.27	3.85	0.064	0.383	2.23	4.64	86.63	8.73	769.1
	Kaiaua	10.72	9.55	0.082	0.458	2.34	18.63	80.86	0.51	157.7
	Kuranui Bay	11.08	10.16	0.097	0.489	2.08	9.33	83.96	6.70	170.8
	Miranda	10.71	7.20	0.060	0.321	1.37	8.36	87.51	4.12	198.8
	Te Puru	4.05	2.07	0.035	0.161	1.62	2.60	96.55	0.85	151.5
Whāingaroa (Raglan) Harbour	Haroto Bay	15.58	7.06	0.112	0.786	3.16	46.34	53.34	0.32	157.7
	Okete Bay	11.84	6.72	0.091	0.642	2.39	26.24	73.19	0.57	61.2
	Te Puna Point	19.17	5.94	0.076	0.436	1.32	14.15	79.77	6.08	136.7
	Whatitirinui Island	15.09	7.29	0.078	0.470	1.63	15.87	80.10	4.03	145.7
	Ponganui Creek	17.94	6.79	0.073	0.444	1.75	13.93	83.97	2.11	232.2
Tairua Harbour	Gumdiggers Gully	11.94	3.74	0.026	0.157	1.57	2.30	95.20	2.51	707.6
	Manaia Road	15.13	2.85	0.030	0.181	1.23	1.07	96.39	2.55	73.8
	Oturu Stream	15.77	4.44	0.032	0.368	1.67	5.93	90.78	3.29	334.9
	Pauanui	14.96	4.00	0.029	0.202	1.07	0.65	95.75	3.60	81.6
	Pepe Inlet	15.61	3.10	0.031	0.321	1.77	12.97	85.26	1.77	183.6

Table C2: Elevation (relative to mean sea level), rates of sediment deposition and dominant macroinvertebrate taxa at REMP sites.

For sites in the Firth of Thames and Whāingaroa Harbour, the elevation of the monitoring plots was obtained from RTK GPS measurements (Sandwell and Bryan, 2020); for Tairua Harbour elevation was obtained from LIDAR collected in 2012/2013 by WRC. The elevations in NZ Vertical Datum 2016 were converted to Mean Sea Level (MSL) using offsets from the closest gauging site as reported in MfE (2017). Sediment deposition rate is calculated from measurements made over buried sedimentation plates close to the monitoring plot from 2003 to 2018. The dominant macroinvertebrate taxa represent the numerically dominant indicator taxa (across all sampling events at each site).

Estuary	Site	Elevation (above MSL; m)	Sediment deposition rate (mm/yr) *	Dominant macroinvertebrate taxa
Firth of Thames	Gun Club	-0.464	-0.37	Polychaete worms (*Aonides trifida*)
	Kaiaua	-1.599	3.63	Nut shells (*Linucula hartivigiana*) and polychaete worms (Capitellidae)
	Kuranui Bay	-1.199	-4.93	Polychaete worms (Capitellidae) and cockles (*Austrovenus stutchburyi*)
	Miranda	-0.317	-2.54	Polychaete worms (*Aonides trifida* and Capitellidae)
	Te Puru	-1.886	NA	Nut shells (*Linucula hartivigiana*) and pipi (*Paphies australis*)
Whāingaroa (Raglan) Harbour	Haroto Bay	0.099	2.32	Polychaete worms (Capitellidae and Nereididae) and *Arthritica bifurca*
	Okete Bay	-1.361	1.41	Polychaete worms (Capitellidae and *Cossura consimilis*)
	Te Puna Point	-0.280	-1.25	Cockles (*Austrovenus stutchburyi*) and nut shells (*Linucula hartivigiana*)
	Whatitirinui Island	-0.626	-2.11	Cockles (*Austrovenus stutchburyi*) and nut shells (*Linucula hartivigiana*)
	Ponganui Creek	-0.527	0.78	Cockles (*Austrovenus stutchburyi*) and nut shells (*Linucula hartivigiana*)
Tairua Harbour	Gumdiggers Gully	-0.062	NA	Polychaete worms (Capitellidae and Nereididae)
	Manaia Road	0.102	NA	Cockles (*Austrovenus stutchburyi*) and polychaete worms (*Aonides trifida*)
	Oturu Stream	-0.251	NA	Amphipods (Corophiidae) and polychaete worms (Capitellidae)
	Pauanui	-0.098	NA	Cockles (*Austrovenus stutchburyi)* and pipi (*Paphies australis*)
	Pepe Inlet	0.004	NA	Polychaete worms (Nereididae, *Prionospio aucklandica*, and Capitellidae)

* Note that a negative number indicates sediment erosion, rather than deposition

References:

MfE 2017. Coastal Hazards and Climate Change: Guidance for Local Government. Report Appendices. Ministry for the Environment, Wellington, New Zealand.

Sandwell, D. Bryan, K. 2020. Real-Time Kinetic (RTK) elevation survey of sediment plates located in Raglan (Whāingaroa) and Firth of Thames for The Waikato Regional Council Regional Estuarine Monitoring Programme. Environmental Research Institute Report No. 137. Client report prepared for Waikato Regional Council. Environmental Research Institute, School of Science, The University of Waikato, Hamilton.

Appendix D: DISTLM analysis

Table D1: Pearson’s correlation coefficient (r) between environmental predictor variables used in DISTLM analysis. Data was collected in 2018. Highly correlated variables (r > 0.9) indicated by bold type and red fill. Moderately correlated variables (r > 0.8) indicated by yellow fill.

	TOC	TN	Chla	Phaeo	Mud	Very fine sand	Fine sand	Medium sand	Coarse sand	Gravel	Shell hash	Organic matter	Elevation	Antimony	Arsenic	Cadmium	Chromium	Copper	Lead	Mercury	Nickel	Silver	Zinc
TOC																							
TN	**0.927**																						
Chla	0.284	0.167																					
Phaeo	0.523	0.700	-0.161																				
Mud	**0.918**	0.830	0.284	0.257																			
Very fine sand	0.551	0.583	0.138	0.212	0.621																		
Fine sand	-0.413	-0.339	0.239	0.011	-0.465	-0.391																	
Medium sand	-0.496	-0.574	-0.476	-0.194	-0.601	-0.736	-0.066																
Coarse sand	-0.364	-0.372	-0.374	-0.199	-0.374	-0.489	-0.418	0.550															
Gravel	-0.472	-0.410	0.193	-0.378	-0.437	-0.450	0.260	0.231	0.043														
Shell hash	-0.349	-0.405	-0.353	-0.195	-0.414	-0.556	-0.419	0.706	**0.955**	0.093													
Organic matter	0.834	0.796	-0.115	0.621	0.717	0.271	-0.542	-0.054	-0.087	-0.424	-0.009												
Elevation	-0.304	-0.286	0.287	-0.503	-0.183	-0.216	-0.016	0.046	0.292	0.367	0.227	-0.449											
Antimony	0.353	0.393	-0.172	0.718	0.077	-0.212	0.098	0.218	-0.047	-0.227	0.031	0.520	-0.437										
Arsenic	0.498	0.455	-0.051	0.478	0.351	-0.111	-0.271	0.280	-0.071	-0.061	0.092	0.770	-0.393	0.701									
Cadmium	0.478	0.588	-0.035	0.825	0.171	-0.080	0.083	0.034	-0.116	-0.209	-0.053	0.568	-0.291	**0.916**	0.632								
Chromium	0.368	0.280	-0.148	0.200	0.380	0.113	-0.375	0.157	-0.162	0.006	-0.047	0.575	-0.432	0.406	0.795	0.202							
Copper	0.529	0.568	-0.218	0.747	0.287	-0.010	-0.149	0.154	-0.142	-0.168	-0.030	0.746	-0.561	**0.908**	0.858	0.852	0.643						
Lead	0.398	0.470	-0.355	0.765	0.126	-0.080	-0.173	0.331	-0.047	-0.160	0.103	0.734	-0.515	0.817	0.819	0.810	0.528	**0.929**					
Mercury	0.457	0.560	-0.131	0.827	0.146	-0.125	0.001	0.158	-0.058	-0.177	0.037	0.640	-0.343	**0.915**	0.726	**0.981**	0.300	**0.902**	**0.902**				
Nickel	0.515	0.441	-0.193	0.236	0.520	0.208	-0.621	0.100	-0.011	-0.054	0.090	0.754	-0.479	0.249	0.764	0.164	0.855	0.586	0.545	0.293			
Silver	0.405	0.502	-0.123	0.771	0.117	-0.086	0.113	0.090	-0.136	-0.256	-0.065	0.523	-0.301	**0.910**	0.585	**0.967**	0.168	0.827	0.807	**0.950**	0.111		
Zinc	0.564	0.654	-0.100	0.835	0.279	-0.020	-0.080	0.056	-0.098	-0.216	-0.018	0.712	-0.390	**0.918**	0.762	**0.972**	0.390	**0.938**	0.890	**0.984**	0.380	**0.928**	

Table D2: Results of DISTLM analysis. Macrofauna and environmental data collected in Spring 2018. Analysis conducted in PRIMER V6.1.15.

DistLM							
Distance based linear models							
Resemblance worksheet							
Name: Taxa (BC Resem)							
Data type: Similarity							
Transform: Square root							
Resemblance: S17 Bray Curtis similarity							
Predictor variables worksheet							
Name: Normalised EnvData							
Data type: Environmental							
Normalise							
Selection criterion: AIC							
Selection procedure: Forward							
VARIABLES							
1	TOC	Exclude					
2	TN	Exclude					
3	Chla	Trial					
4	Phaeo	Trial					
5	Mud	Trial					
6	Very fine sand	Exclude					
7	Fine sand	Exclude					
8	Medium sand	Exclude					
9	Coarse sand	Exclude					
10	Gravel	Exclude					
11	Shell hash	Trial					
12	Organic matter	Trial					
13	Elevation	Trial					
14	Antimony	Exclude					
15	Arsenic	Trial					
16	Cadmium	Exclude					
17	Chromium	Trial					
18	Copper	Trial					
19	Lead	Exclude					
20	Mercury	Exclude					
21	Nickel	Trial					
22	Silver	Exclude					
23	Zinc	Exclude					
Total SS(trace): 32866							
MARGINAL TESTS							
Variable	**SS(trace)**	**Pseudo-F**	**P**	**Prop.**			
Mud	6764	3.369	0.0010	0.206			
Organic matter	6543.4	3.232	0.0040	0.199			
Elevation	6204.5	3.025	0.0060	0.189			
Nickel	5252	2.473	0.0140	0.160			
Shell hash	5041.4	2.355	0.0130	0.153			
Phaeo	4685.3	2.161	0.0230	0.143			
Chromium	4648.8	2.142	0.0260	0.141			
Chla	4287.3	1.950	0.0380	0.130			
Copper	4267	1.940	0.0350	0.130			
Arsenic	3510.2	1.555	0.1450	0.107			
res.df: 13							
NO STARTING TERMS							
SEQUENTIAL TESTS							
Variable	**AIC**	**SS(trace)**	**Pseudo-F**	**P**	**Prop.**	**Cumul.**	**res.df**
+Mud	115.9300	6764	3.3688	0.002	0.20581	0.20581	13
+Elevation	114.69	5065.9	2.8898	0.003	0.15414	0.35995	12
+Chla	113.9	3564.3	2.244	0.008	0.10845	0.46839	11
+Chromium	113.53	2559.4	1.7163	0.061	7.79E-02	0.54627	10
+Shell hash	112.76	2512.6	1.8237	0.057	7.65E-02	0.62272	9
+Organic matter	111.85	2184.8	1.7111	0.078	6.65E-02	0.6892	8
+Arsenic	110.55	2018.3	1.7237	0.095	6.14E-02	0.75061	7
+Nickel	108.65	1877.2	1.7824	0.093	5.71E-02	0.80773	6
+Phaeo	107.23	1288.4	1.2805	0.262	3.92E-02	0.84693	5
+Copper	105.78	1033	1.0336	0.457	3.14E-02	0.87836	4
BEST SOLUTION							
AIC	**R^2**	**RSS**	**No.Vars**				
105.78	0.87836	3997.9	10				

Appendix E: Estuarine Health Indices

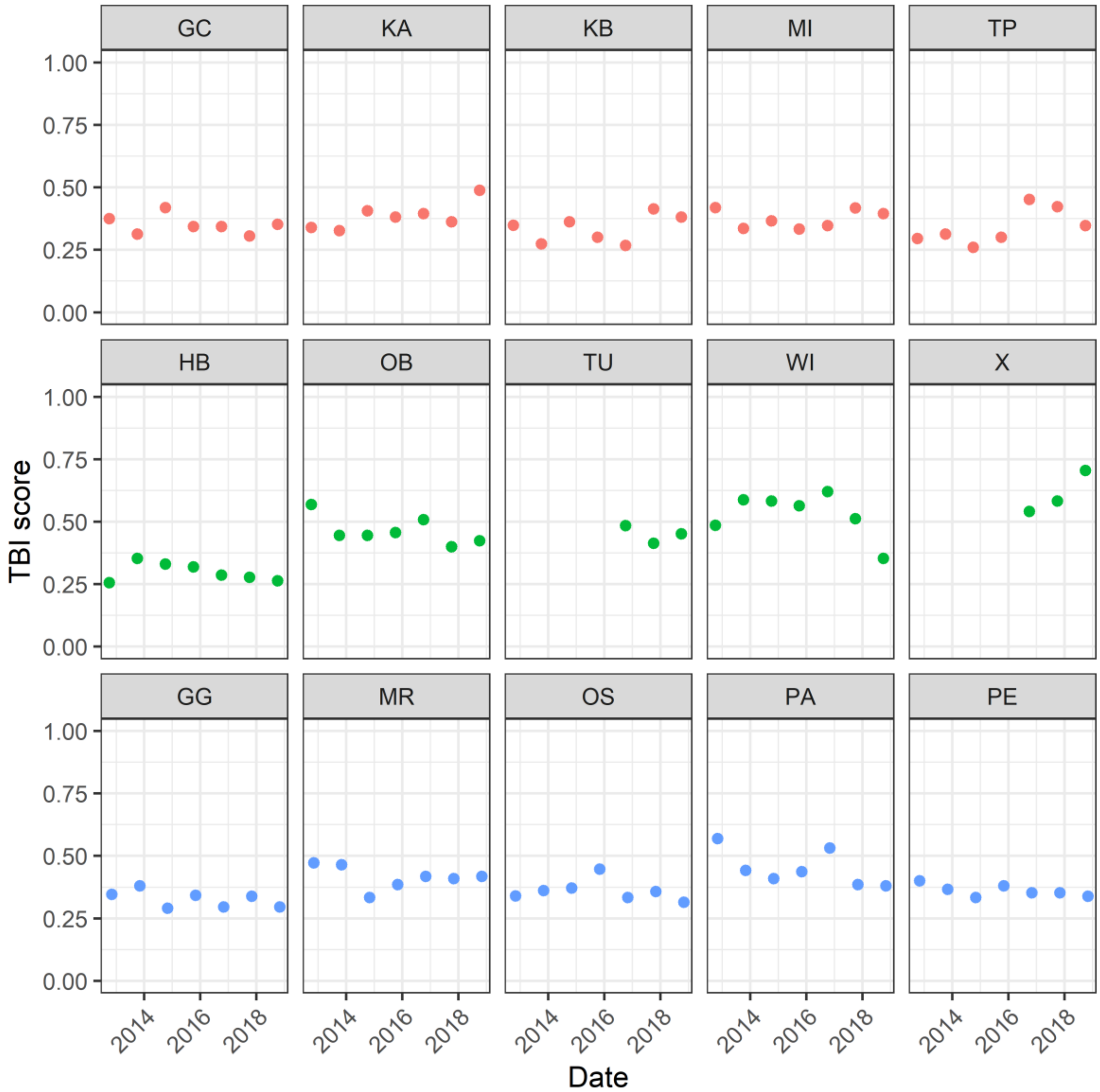

Figure E1: Traits Based Index (TBI) score at REMP sites, plotted against time from 2012 to 2018. Firth of Thames sites in top panel, in red. Whāingaroa Harbour sites in middle panel, in green, and Tairua Harbour sites in lower panel, in blue.

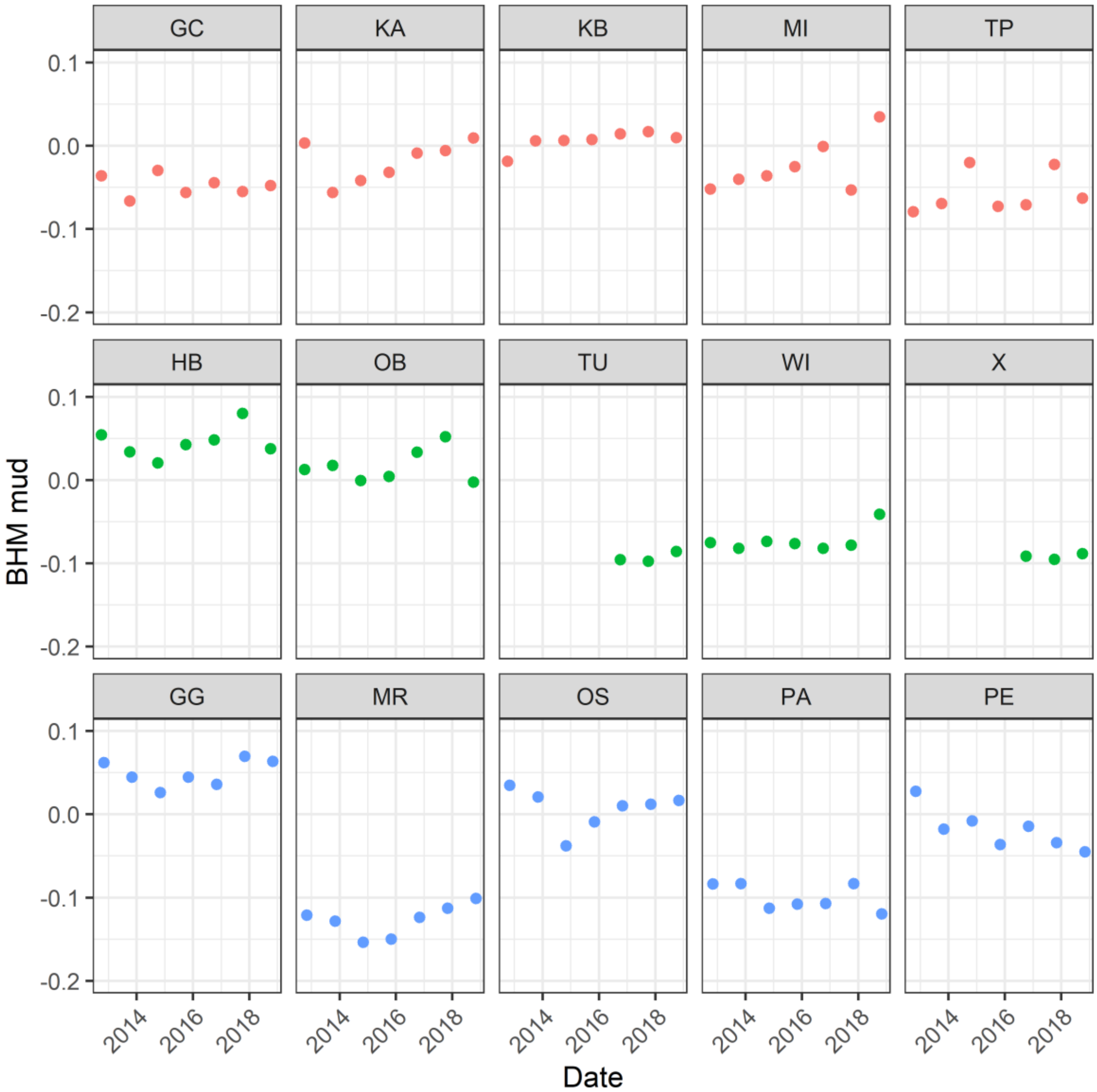

Figure E2: Benthic Health Model - mud (BHM mud) score at REMP sites, plotted against time from 2012 to 2018. Firth of Thames sites in top panel, in red. Whāingaroa Harbour sites in middle panel, in green, and Tairua Harbour sites in lower panel, in blue.

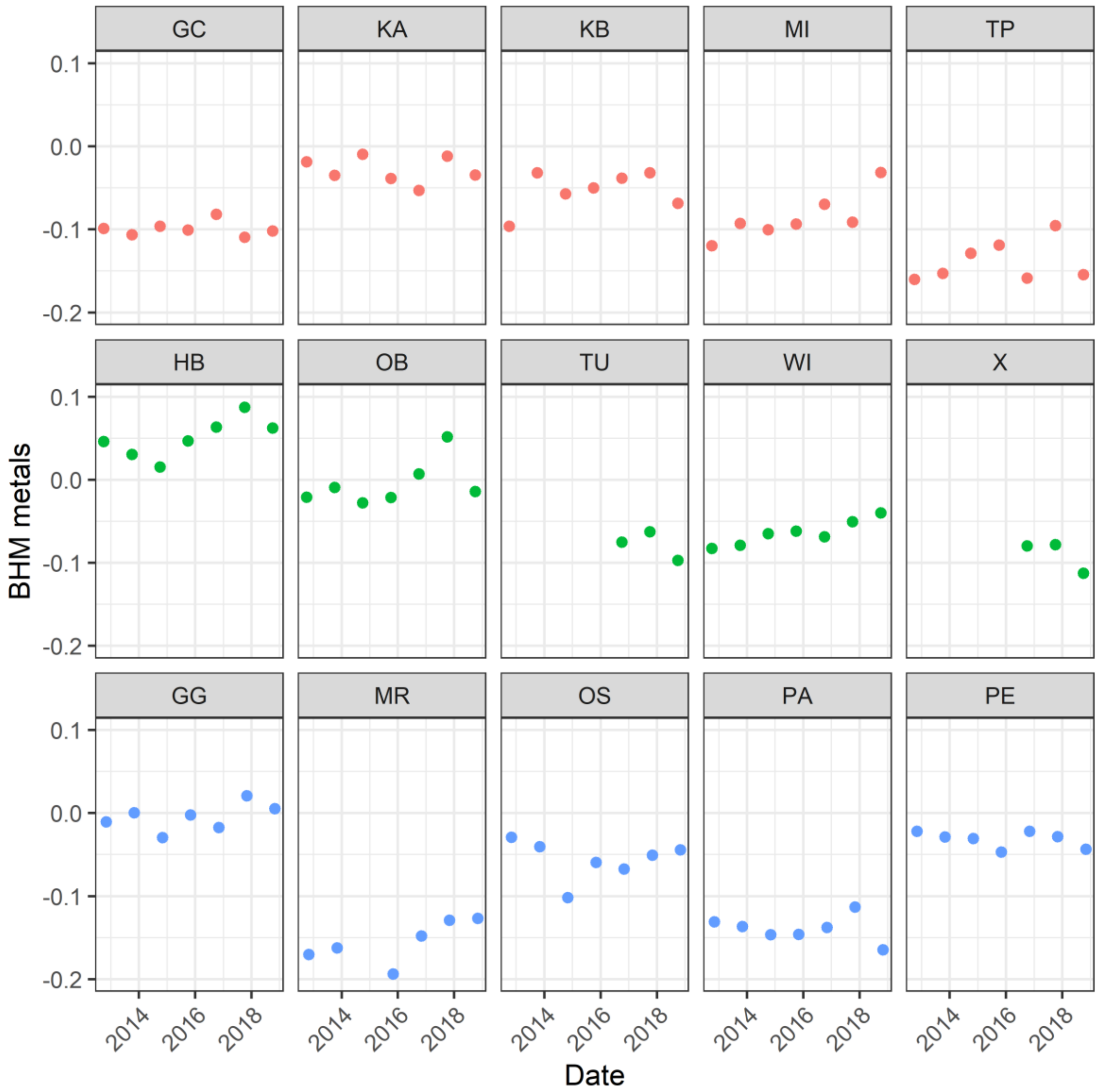

Figure E3: Benthic Health Model - metals (BHM metals) score at REMP sites, plotted against time from 2012 to 2018. Firth of Thames sites in top panel, in red. Whāingaroa Harbour sites in middle panel, in green, and Tairua Harbour sites in lower panel, in blue.