Marine Ecology State and Trends in Tāmaki Makaurau / Auckland to 2019. State of the Environment Reporting

Tarn P. Drylie

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Research and Evaluation Unit RIMU

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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Executive summary

The coastal marine environment is a defining feature of Tāmaki Makaurau / Auckland. Auckland Council conducts long-term monitoring of benthic (seafloor) ecology in estuaries around the region as part of its broader State of the Environment programme, enabling assessments of 'health' (i.e. state) and detection of changes through time (i.e. trends). This monitoring partly fulfils Auckland Council's obligations under the Resource Management Act 1991. The information gained is used to identify issues and inform policy development and environmental decision-making.

Benthic ecology monitoring focuses on surface sediment characteristics and macrofauna to assess the ecological health of intertidal sandflats. Healthy sandflats support ecosystem functions that allow Aucklanders to obtain a range of ecosystem services from estuaries (e.g. cultural and recreational opportunities, food production and disturbance regulation). This report presents the latest results from benthic ecology monitoring of all sampled estuaries (including the Kaipara, Manukau, Waitematā and Mahurangi Harbours and eight smaller east coast estuaries) together for the first time, providing a unique opportunity to identify patterns and pressures from 136 sites spanning the region. Results show 6% of sites have 'excellent', 22% have 'good', 22% have 'fair', 29% have 'marginal' and 21% have 'poor' overall health.

Impacts from increased sedimentation were detected in all estuaries. Although Kaipara Harbour has predominantly 'good' health (according to the combined health score), multiple trends consistent with recent sedimentation were found at all sites except Kaipara Flats. Likewise, all small east coast estuaries are affected by sedimentation with Okura, Mangemangeroa and Turanga exhibiting the greatest number of recent concerning trends (Whangateau, the northern-most estuary, has the fewest).

The tidal creeks of Manukau Harbour and Central Waitematā are very muddy and have mostly low health related to this pressure, but the open sandflats tend to have lower sediment mud content and better health. There are no concerning trends related to sedimentation in Manukau, but there are for some tidal creek and sandflat sites in Central Waitematā (namely around Meola Reef, Hobsonville, Whau River and Henderson Creek). There is no distinction between the tidal creek and open sandflat sites in the Upper Waitematā, however, with most having high mud content and 'marginal' health (three sites in the centre of the harbour are exceptions). Furthermore, trends indicative of increased sedimentation have begun within the last five years at five sandflat sites throughout Upper Waitematā, implying recent sedimentation impacts.

Heavy metal contamination is another region-wide pressure on estuarine benthic health but is less prevalent than sedimentation. Trends related to metals in the Kaipara and Mahurangi harbours require close observation as they may reflect recent contamination. In the

Manukau and Central Waitematā harbours, health in relation to metals again tends to be lower in the tidal creeks (mostly ‘fair’ or ‘marginal’) than the sandflats (mostly ‘excellent’ to ‘fair’), but there is no distinction between these areas in Upper Waitematā (all sites are ‘fair’ or ‘marginal’). Nevertheless, health related to metals is improving in Upper, Central and Outer Waitematā tidal creeks, suggesting historic rather than recent inputs.

Nutrient enrichment may be affecting benthic health in some restricted areas, including the eastern side of Mahurangi Harbour, throughout Upper Waitematā and the western side of Central Waitematā. This is implied from trends in sediment organic content and chlorophyll *a* concentration, which are expected to increase in response to elevated nutrients. These assertions need further investigation, however, and development of more rapid and sensitive indicators of nutrient enrichment is required.

According to the most recent available combined health score, Manukau is the only large harbour with a site scoring ‘excellent’ overall health (the sandflat site near Auckland Airport), while Puhoi, Orewa, Okura, Turanga and Waiwera all have at least one site in this category. Of the large harbours, all except Kaipara contain a site with ‘poor’ health (although these are confined to the tidal creeks in Manukau and Central Waitematā), whereas none of the smaller east coast estuaries have any sites that are considered ‘poor’.

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1.0 Introduction

1.1 Background

Tāmaki Makaurau / Auckland is characterised by its extensive and varied marine environments. The region boasts 3100km of coastline, split between the gentle east and rugged west coasts, and 11,117km^2 of ocean. There are three major harbours and numerous estuaries and embayments, including several on offshore islands. The ancestry and history of tangata whenua is etched into these seascapes, and coastal iwi have a deep sense of kaitiakitanga (guardianship) to ensure natural resources are available for future generations. Estuaries are semi-enclosed waterbodies where saltwater from the sea mixes with freshwater from the land (Pritchard, 1967), encompassing harbours, estuaries, fjords and more. This report assesses the health of seafloor (benthic) ecosystems within estuaries across the region and investigates changes that have occurred through time. The underpinning monitoring is carried out as part of Auckland Council's region-wide State of the Environment monitoring.

We focus on intertidal estuarine environments (those that are periodically covered and uncovered by the tides) because they are associated with abundant ecosystem services that provide benefits for people now and in the future (e.g. recreational and cultural values, climate regulation, food production, and nutrient and water cycling (Costanza et al., 1997 and 2014; Snelgrove et al., 2014)), and are highly susceptible to impacts from human activities (i.e. anthropogenic effects). This is because estuaries are affected by activities at sea, such as fishing, dredging and aquaculture, and are also receiving environments for freshwater drainage networks. They are therefore sensitive to the same effects of land use as streams and rivers, including pollution from excess sediments, nutrients, and contaminants like heavy metals. These pollutants can reduce the quality of the benthic environment and impact the sediment-dwelling animals living there (e.g. macrofauna).

Macrofaunal communities add complexity to sandflat habitats by building burrows, churning through layers of sediments, and pumping oxygen-rich seawater into deeper sediments. In doing so, they stimulate many of the ecological processes that underpin estuarine ecosystem services (Hillman et al., 2019; Karlson et al., 2020; Lohrer et al., 2016). Changes in the make-up of macrofaunal communities can therefore have detrimental effects on the functioning of the ecosystem, and their composition can provide a sensitive measure of ecosystem condition, or 'health'. Their relatively low mobility also makes them representative of local conditions. Furthermore, macrofauna in these coastal communities form a significant component of Auckland's regional biodiversity and provide an important food source for birds, fish, and people.

Ecological indicators are commonly used to assess and track changes in environmental condition and are most useful when reflective of a specific driver (Niemi & McDonald, 2004). For example, excessive sediment input to estuaries can lead to a muddying of sandflats as fine terrestrial sediments settle to the seafloor, causing predictable declines in macrofaunal biodiversity and ecosystem function as sediment mud content increases (Douglas et al., 2019; Pratt et al., 2014; Thrush et al., 2003). Sediment mud content is therefore a useful indicator of sedimentation and provides insight on the potential for sandflat habitats to support diverse macrofaunal communities with high functionality. Similarly, changes in the abundance of macrofauna with known sediment preferences (e.g. sand versus muddy sand) or sensitivities to given contaminants (such as heavy metals) can signal alterations in the physical environment, especially when multiple species show trends consistent with a single driver. Indicators based on the entire macrofaunal community are also common internationally (e.g. Borja, Franco, & Pérez, 2000; Grall & Glémarec, 1997; Simboura & Zenetos, 2002) and in New Zealand (Clark et al., 2019) and can provide a more holistic approach for detecting change. For instance, Auckland-specific benthic health models were developed to determine the extent to which macrofaunal community composition is affected by sediment mud content or heavy metal contamination (Anderson et al., 2006; Hewitt & Ellis, 2010; Hewitt, Lohrer, & Townsend, 2012); these have now been tested for their regional applicability and used by other councils (e.g. see Berthelsen et al., 2020). Further details on these indices are given in Section 2.3. Monitoring a suite of complementary indicators can help detect change in the environment, however further interpretation is required to determine whether such change is indicative of a driver that requires management intervention.

Change in environmental variables over time has three components: within-year cycles, multi-year cycles and consistent change (frequently called a trend). The purpose of monitoring estuarine benthic health is to identify trends that may be of concern, but this is complicated by broad-scale drivers of change that result in multi-year cycles that may be incorrectly interpreted as a trend. For example, the El Niño – Southern Oscillation is a recurring climate pattern that causes long-term cycles in the abundance of many benthic macrofauna (Hewitt, Ellis, & Thrush, 2016). As data records increase in length, however, it becomes increasingly possible to distinguish between this natural variability and trends that may be attributed to anthropogenic influences and/or persistent climate change, emphasising the importance of consistent, long-term monitoring.

1.2 Programme design

Managing the region's natural resources is a core function of Auckland Council set out in legislation. This includes monitoring and reporting on the state of all or part of the environment under section 35 of the Resource Management Act 1991. The benthic ecology programme is designed to monitor and report on the state of the region's marine environments and to provide information to enable Auckland Council to maintain and enhance the quality of the environment (Local Government Act, 2002). The information collected can help identify new and emerging issues and inform the development of responses. It also provides, baseline, regionally representative data to support the resource consent process and associated compliance monitoring.

Auckland's coastal marine area is very large and highly variable, with two very different coastlines, a strong exposure gradient from the inner to the outer Hauraki Gulf, three large harbours and many estuaries and embayments. The inherent complexity of the marine environment makes it very difficult to generalise across the region, so a comprehensive monitoring programme that covers the range of habitats and exposure gradients is required. The Benthic Health programme focuses on surface sediment characteristics and benthic macrofauna (plants and animals living in and on the sediment surface) to assess the ecological condition of monitored sites. Sediment characteristics can be directly and indirectly influenced by anthropogenic activities and determine the distribution of macrofaunal communities, while the macrofauna themselves provide an important link between seafloor and water column processes, have generally limited mobility, and respond predictably to anthropogenic pressures.

The Benthic Health programme draws data from two key State of the Environment programmes:

- Marine Ecology
- Regional Sediment Contaminants

The Marine Ecology programme is designed to provide a long-term, baseline understanding of the condition of regionally representative marine habitats. Monitoring began in 1987 in Manukau Harbour and has since been expanded to cover our larger harbours and eight smaller east coast estuaries (see Section 2.1). The Regional Sediment Contaminants Monitoring Programme (RSCMP) is designed to measure the quality of marine sediments against established guidelines and includes benthic ecology sampling at most sites. This programme focuses on sheltered tidal creeks to complement and increase the coverage of the Marine Ecology programme, which focuses on more open sandflats (Figure 1). The ecology data are utilised in the Benthic Health programme to assess ecological health, while results from the sediment contaminant sampling are presented in Mills (2020). Alongside these benthic programmes, monthly measurements of coastal water quality ensure a complete evaluation of Auckland's nearshore marine environments. The current state of coastal water quality, and any changes over the last 10 years (2010-2019), are reported in Ingley (2020).

1.3 Purpose and objectives

The ecological health of intertidal soft sediment sites across the Auckland region will be assessed to determine their current state and identify any changes occurring over time. The objective is to identify changes of concern and potential pressures influencing overall health. This is the first time data from all harbours and estuaries have been summarised in a single report (rather than individual harbour reports e.g. Greenfield, McCartain, and Hewitt (2019)), providing a unique opportunity to identify regional patterns and issues.

1.4 Wider reporting

Previous reports from all marine programmes can be obtained from Auckland Council's Knowledge Auckland website, www.knowledgeauckland.org.nz. For further enquiries and data supply, email environmentaldata@aucklandcouncil.govt.nz.

This report is one of a series concerning coastal and freshwater environments prepared to support the 2020 state of the environment report for the Auckland region:

- *Auckland river water quality: annual reporting and National Policy Statement for Freshwater Management current state assessment, 2019* – TR2021/11
- *Coastal and estuarine water quality 2019 annual report* – TR2020/016
- *Coastal and estuarine water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/02
- *Groundwater quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/03
- *Lake water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/04
- *Marine sediment contaminant state and trends in Tāmaki Makaurau / Auckland 2004-2019. State of the environment reporting* – TR2021/10[1]
- *River ecology state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/05
- *River water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/07

[1] Analyses for coastal benthic ecology (this report) and coastal sediment contaminants were completed for all data on record.

2.0 Methods

2.1 Sites

This report draws data from two key State of the Environment programmes with different focuses. The Marine Ecology programme monitors temporal changes in sediment characteristics and the abundance of benthic macrofauna in harbours and estuaries across the region, including Manukau, Central Waitematā, Upper Waitematā, Kaipara and Mahurangi Harbours, as well as eight smaller east coast estuaries: Whangateau, Puhoi, Waiwera, Orewa, Okura, Mangemangeroa, Waikopua and Turanga. Within the harbours, sites are located to be representative of the main anthropogenic influences of the harbour and in areas likely to show a transition from sand to mud. Hence, sites are largely sandy in nature and located in the main bodies of the harbours. Within the smaller estuaries a gradient design has been employed, with 10 sites (except Whangateau which has seven) located from the upper reaches (site 10) to the mouth of the estuary (site 1) encompassing low- and high-energy areas.

Since 2000, Marine Ecology monitoring has followed a robust and cost-effective sampling design to enable intense temporal sampling for trend detection without sacrificing spatial representativeness (Hewitt, 2000). Briefly, core sites are sampled continuously in each estuary while rotational sites are sampled periodically (e.g. for two years every five years). Trends occurring at the rotational sites can be contextualised using data from the core sites to identify local versus broad-scale change. Sampling frequency varies by harbour/estuary: Manukau and Central Waitematā Harbours are sampled every two months (bimonthly), Kaipara, Mahurangi and Upper Waitematā are sampled every three months (quarterly), and east coast estuaries are sampled twice a year.

Sites sampled for ecology under the RSCMP complement the Marine Ecology sites by including more low-energy tidal creeks. As this programme is focused on detecting contaminant inputs which are largely derived from urban sources, there are more sites in the Manukau and Waitematā Harbours. Sites additional to the main harbours are also sampled, namely the Outer Waitematā which includes Hobson Bay and Tamaki Estuary. Sampling occurs every two to five years, depending on the site, allowing time for sites to recover from sampling disturbance given they are often very muddy.

Sites vary in their last sampling date due to the rotational sampling design of the Marine Ecology programme and the two- to five-year sampling frequency of the RSCMP sites, however sites are only included in analyses if they have data from within the last five years. In total, 136 sites had data available for assessments of current state (Figure 1).

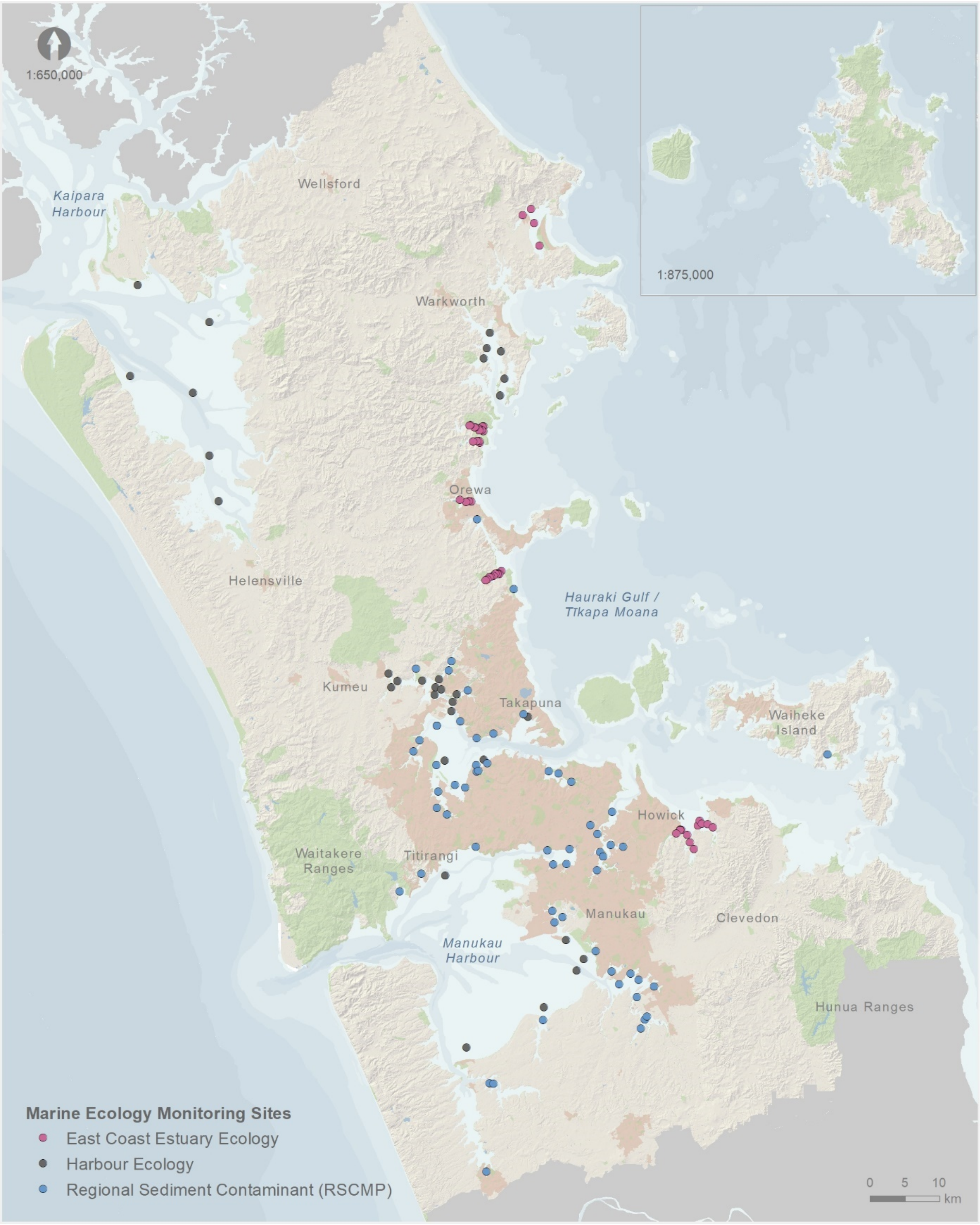

Figure 1. Location of sites featured in this report.

2.2 Ecology sampling

The field and laboratory methods for sampling surface sediment characteristics and benthic macrofauna have been described in detail by Greenfield et al. (2019) and Hewitt and McCartain (2017) and are covered here in brief.

2.2.1 Sediments

Composite samples of surface sediments are collected to characterise the site according to sediment grain size, organic content and chlorophyll *a* concentration (chl *a*; a proxy for the abundance of benthic microalgae). Sites are typically rectangular and 9000m^2 in area, but vary in dimension depending on, for example, the presence of vegetated habitats or the shape of the sandflat. Small cores (2cm diameter, 2cm deep) are collected randomly from across the site and split into two sample jars (one for grain size and organic content analyses, the other for chl *a*). Samples are then stored frozen in the dark prior to the following laboratory analyses.

<u>Grain size</u>

Samples are homogenised before taking a 5g subsample and digesting in 6% hydrogen peroxide to remove organic matter. Wet sieving and pipette analysis are used to separate size fractions (Gatehouse, 1971), before drying at 60 ºC until a constant weight. The results are presented as percentage composition of gravel/shell hash (>2 mm), coarse sand (500-2,000 µm), medium sand (250-500 µm), fine sand (125-250 µm), very fine sand (62.5-125 µm), silt (3.9-62.5 µm) and clay (<3.9 µm). Mud content is the sum of silt and clay content.

Proportions of mud and very fine sand are combined as an indicator of sedimentation for the east coast estuaries. This is because very fine sand has increased in most estuaries and is thought to have similar ecological effects to mud, therefore including this sediment fraction increases our ability to detect ecologically relevant changes. Very fine sand has only been measured in the harbour ecology programmes since 2017, so cannot be included in trend analyses.

<u>Organic content</u>

Approximately 5g of sediment is placed in a dry, pre-weighed foil tray and dried at 60 ºC until it reaches a constant weight. The sample is then combusted at 400 ºC for 5.5h and reweighed (Mook & Hoskin, 1982). The results are presented as a percentage composition.

Chlorophyll *a*

Within one month of sampling, the full sample is freeze-dried, weighed, then homogenised and a roughly 0.5g subsample taken for analysis. The pigments are extracted by boiling the sediment in 90% ethanol (using an acidification step to separate chl *a* from degradation products) and the extracts are processed using a spectrophotometer (Sartory & Grobbelaar, 1984). The results are presented as the concentration of chl *a* per gram of dry weight sediment: µg g^{-1} dw sediment.

2.2.2 Macrofauna

For analysis of macrofauna, large cores (13cm in diameter, 15cm deep) are collected and sieved *in situ* over a 500 µm mesh. The material remaining on the sieve is washed into sample jars, stored in 50% isopropyl alcohol, and stained with Rose of Bengal solution prior to sorting, identification and enumeration. The number of cores collected per site varies between programmes: 12 are collected from the major harbour sites, 10 from RSCMP sites, and six from the east coast estuary sites. A random sampling approach is used ensuring samples are not within a 5m radius of each other or any samples from the preceding 12 months.

For each harbour a specific set of species are selected for monitoring as they respond to particular stressors, are important for biodiversity or ecosystem functioning, and occur in sufficient abundance for changes to be monitored (hereafter "monitored species", see Appendix B). An exception is in October/November, when all harbours are sampled and the entire macrofauna community is identified for analysis with benthic health indices (see Section 2.3). Of the monitored species, 35 are common at monitoring sites across the region (Appendix C, hereafter "common species").

Only some of the common species have their abundances reported for the east coast estuaries as this programme was designed specifically to track effects of increased terrestrial sediment entering the small estuaries. Consequently, reporting focusses on a small number of species with defined responses to sedimentation. Thus, for these estuaries, information on only 11 of the common species were available (although the entire community is captured during October sampling and is reported in the programme-specific monitoring reports, e.g. Hewitt and Carter (2020)):

- The bivalves *Austrovenus stutchburyi*, *Macomona liliana* and *Linucula hartvigiana*
- the polychaetes *Aonides trifida*, *Aricidea* sp., *Prionospio aucklandica*, *Heteromastus filiformis* (+ *Barantolla lepte*) and Oligochaetes (+ Capitellids)
- the anemone *Anthopleura aureoradiata*

- the cumacean *Colurostylis lemurum*
- the gastropod *Notoacmea scapha.*

2.3 Health indices

2.3.1 Benthic Health Models

Benthic health models (BHM) were developed to assess the health of macrofaunal communities relative to stormwater contaminants (total sediment copper, lead and zinc; BHMmetals) and sediment mud content (BHMmud) (see Anderson et al. (2006) and Hewitt and Ellis (2010) for details). The models are based on data from 95 intertidal sites across the Auckland region encompassing tidal creeks, estuaries and harbours (but not exposed beaches) with a range of contaminant concentrations and mud content. Multivariate analyses of the variation in macrofaunal community composition related to each environmental variable were used to define scores of community composition related to that variable. The composition of new samples is compared to the model data to obtain a score which is then allocated to one of five groups related to health (Table 1). An increase in BHM score represents a degradation of health.

2.3.2 Traits-Based Index

Benthic ecosystem function is directly affected by benthic biodiversity (Belley & Snelgrove, 2016; Snelgrove et al., 2014; Thrush et al., 2006). To help understand these interactions, macrofauna can be categorised according to characteristics (traits) that are likely to influence function, e.g. their feeding mode (such as deposit or suspension feeding), mobility, size, living habit (such as free-living or tube dwelling), and so on. The Traits-Based Index (TBI) was developed based on the richness (count) of species exhibiting seven particular traits important for benthic ecosystem function: living in the top 2cm of sediment, having an erect structure or tube, moving sediment around within the top 2cm of the sediment column, being sedentary or only moving within a fixed tube, being a suspension feeder, being of medium size, or being worm shaped (Hewitt et al., 2012; Lohrer & Rodil, 2011; van Houte-Howes & Lohrer, 2010). The index calculation accounts for the number of macrofaunal cores collected so that differences in sampling effort between programmes do not influence the index score. Index values range from 0-1, with TBI scores <0.3 indicating low levels of functional redundancy and highly degraded sites, scores of 0.3-0.4 indicating intermediate conditions, and scores >0.4 indicating high levels of functional redundancy. A site with a high level of functional redundancy is considered ‘healthy’ as environmental changes that affect the macrofaunal community tend to have a lesser impact on ecosystem function than a site with low functional redundancy (Drylie et al., 2020; Hewitt et al., 2012). As such, an increase in TBI score represents an improvement in functional resilience and hence health.

2.3.3 Combined Health Score

The BHMs and TBI are combined into a single index, the combined health score, to provide a complementary assessment of health (see Hewitt et al. (2012) for details). This index ranges from 0-1 and an increase in score represents a degradation of health (Table 1). It is important to recognise that the score of the monitored sites cannot be generalised to the whole estuary, which may have locations with better or worse health.

Table 1. Conversion of BHM scores into health groups (1 is least healthy). The cut-off is equal or less than. These groups are then converted (along with TBI scores) into values of similar scale (0-1) that run in the same direction (higher values indicating more degraded conditions), to facilitate their combination into combined health scores.

Health Group	BHMmetals		BHMmud		TBI		Combined Health Score
	Cut-off	Value	Cut-off	Value	Cut-off	Value	
1	-0.164	0.2	-0.12	0.2	0.4	0.33	0.2 = Excellent
2	-0.067	0.4	-0.05	0.4	0.3	0.67	0.4 = Good
3	0.023	0.6	0.02	0.6		1.0	0.6 = Fair
4	0.100	0.8	0.10	0.8			0.8 = Marginal
5		1.0		1.0			1.0 = Poor

2.4 Statistical analyses

2.4.1 Trends over time

Changes in sediment characteristics, species abundances and health indices at each site were analysed to identify statistically significant trends during the monitoring period. Details of the statistical approaches are given in Appendix D and outlined briefly here. Trends were analysed for time series containing five or more data points only, as trends based on any fewer observations are likely to be unreliable. A total of 95 sites had sufficient data for trend analyses (see Appendix A) and there were 2369 unique site-variable combinations for analysis. In all cases, the complete time series was analysed to maximise our ability to detect cycles and patterns in the data that may influence trends.

Initially, scatterplots were inspected to identify suspected linear or non-linear trends, step changes, or other patterns. Only monotonic trends were investigated to focus on continuous, long-term change. Ordinary least squares regression was used to analyse trends in datasets with no temporal autocorrelation (detected using Durbin-Watson statistics), whereas generalised least squares regression was used when autocorrelation occurred. The slope of the regression indicated the trend magnitude (expressed in the units of the given variable), and the associated p-value was used to determine whether this was statistically significant ($p < 0.15$). For statistically significant trends, plots of residuals were inspected for any bias that might indicate multi-year cycles rather than long-term change and, in combination with scatterplots, used to identify the start and end of trends that occurred over only a portion of the time series. All trend analysis steps were performed in R Studio v4.0.2 (R Core Team, 2020).

Statistically significant trends were assigned a certainty score, as follows:

- If $p < 0.05$ and no multi-year cycles were observed, the trend was considered "certain" and assigned a score of 1.
- If p was between 0.05 and 0.1 or $p < 0.05$ but multi-year cycles were observed, the trend was "less certain" and assigned a score of 0.5.
- If p was between 0.1 and 0.15 the trend was "uncertain" and assigned a score of 0.25.

This approach allows potential emerging trends to be highlighted while at the same time acknowledging there is a lack of confidence associated with them. Statistical significance does not necessarily equate to ecological significance, however. Time series become increasingly sensitive to small numerical fluctuations as they increase in length, such that a minor increase in sediment mud content may be highly statistically significant but have no discernible impact on the benthic community. Thresholds have not been applied to dictate whether trend magnitudes are ecologically important (e.g. a 1 or 2% increase per year in mud content), as there is currently insufficient understanding on what rates of change are likely to have ecological consequences (although the levels of mud content expected to elicit change are known). Instead, statistically significant trends are reported and contextualised using information on current state and knowledge of activities occurring in the surrounding catchment.

2.4.2 Macrofauna community

For each estuary, macrofaunal community data (from October sampling) were plotted using non-metric multi-dimensional scaling (nMDS) ordinations to visualise the (dis)similarities in community composition between sites. Data from the last 10 years was plotted to identify any recent change in the composition of the community and highlight if sites were becoming more alike (and thus indicating an estuary-wide driver of change). Ordinations were based on square root-transformed data to reduce the influence of dominant species and Bray-Curtis similarity matrices. Trajectories showing the direction of change through time were overlaid for each site. All plots were created using the software PRIMER (v7) following Anderson, Gorley, and Clarke (2008).

3.0 Results and Discussion

In this section, the results of state and trend analyses are first presented for individual harbours and estuaries, i.e. separate receiving environments, then summarised at a regional level in Section 3.6.

3.1 Kaipara

The Kaipara Harbour is the largest harbour in New Zealand and covers an area of 947km^2, of which almost half is intertidal (409km^2) (Heath, 1975, 1976). The harbour is bound by two large sandspits (South Head and Pouto Point) and is highly dynamic with frequently shifting sandbanks. Only the southern half of the harbour falls within the Auckland region, and has a catchment area of 1420km^2. The catchment is dominated by rural land uses (66% of the area in 2018) with notable patches of native and exotic forest (17 and 15%, respectively).

The Kaipara Harbour monitoring programme was initiated in 2009 to track changes in the ecology of the southern half of the harbour. This is the youngest of the harbour ecology programmes, but now with 11 years of data we can be increasingly confident in any trends detected and multi-year cycles identified. Site Te Ngaio Point replaced Tapora Bank in 2014, after a period of sampling to check the comparability of site characteristics, as it was difficult to find sufficiently low tides to sample the original site.

Sediment characteristics

Kaipara Bank has been notably muddier than the other sites in the Kaipara Harbour (15% median mud content) and has shown reasonable variability over the monitoring period (Table 2, Figure 2). Mud content has been very low at Te Ngaio Point, Haratahi Creek and Kaipara Flats (<1%) and has exhibited little variability, whilst Kakarai Flat and Ngapuke Creek have had slightly higher mud content (2-3%) and variability. Mud content has increased significantly at Kaipara Bank, Ngapuke Creek and Te Ngaio Point and there is a less certain trend at Kaipara Flats (Table 3), with the rate of increase being much greater at Kaipara Bank than at the other sites. The increasing trends at Kaipara Bank and Ngapuke Creek began in 2015 with largely cyclical changes in mud content occurring prior to this (Figure 2); the proximity of these sites to the mouth of the Kaipara River suggests an increase in sediment input since 2015.

The relationship between sediment mud content, macrofaunal community composition and ecosystem function has been well studied in New Zealand. We understand that sandflat macrofaunal communities peak in abundance and richness ~3% mud content and decline linearly from here (Douglas et al., 2019), TBI decreases when mud content is >10% (Rodil et al., 2013), and threshold responses are observed when mud content surpasses 20% that result in a breakdown of the interactions maintaining benthic ecosystem function (Thrush, Hewitt, & Lohrer, 2012). In 2019, sediment mud content is 31% at Kaipara Bank, meaning the functionality and resilience of the community at this site is likely to be low, whilst mud content remains <10% at all other sites (Figure 3).

Organic content is generally low in Kaipara Harbour (<2% at all sites) and has shown little variability over the monitoring period (Table 2, Figure 2). Patterns between sites and significant trends largely reflect those of mud content, with Kaipara Bank having the highest organic content and the greatest rate of increase since 2009. This is consistent with terrestrially derived sediments usually containing more organic material than sandy sediments and may not necessarily indicate nutrient enrichment. Indeed, the median concentration of chl *a*, a proxy for the abundance of benthic microalgae, has been low and varies little between sites (ranging from 6 µg g^{-1} dw sediment at Te Ngaio Point to 9 µg g^{-1} dw sediment at Kakarai Flat). The only certain trend in chl *a* concentration has been an increase at site Te Ngaio Point, however as Te Ngaio Point has only been monitored for six years this trend could be identified as a long-term cycle with the addition of more data.

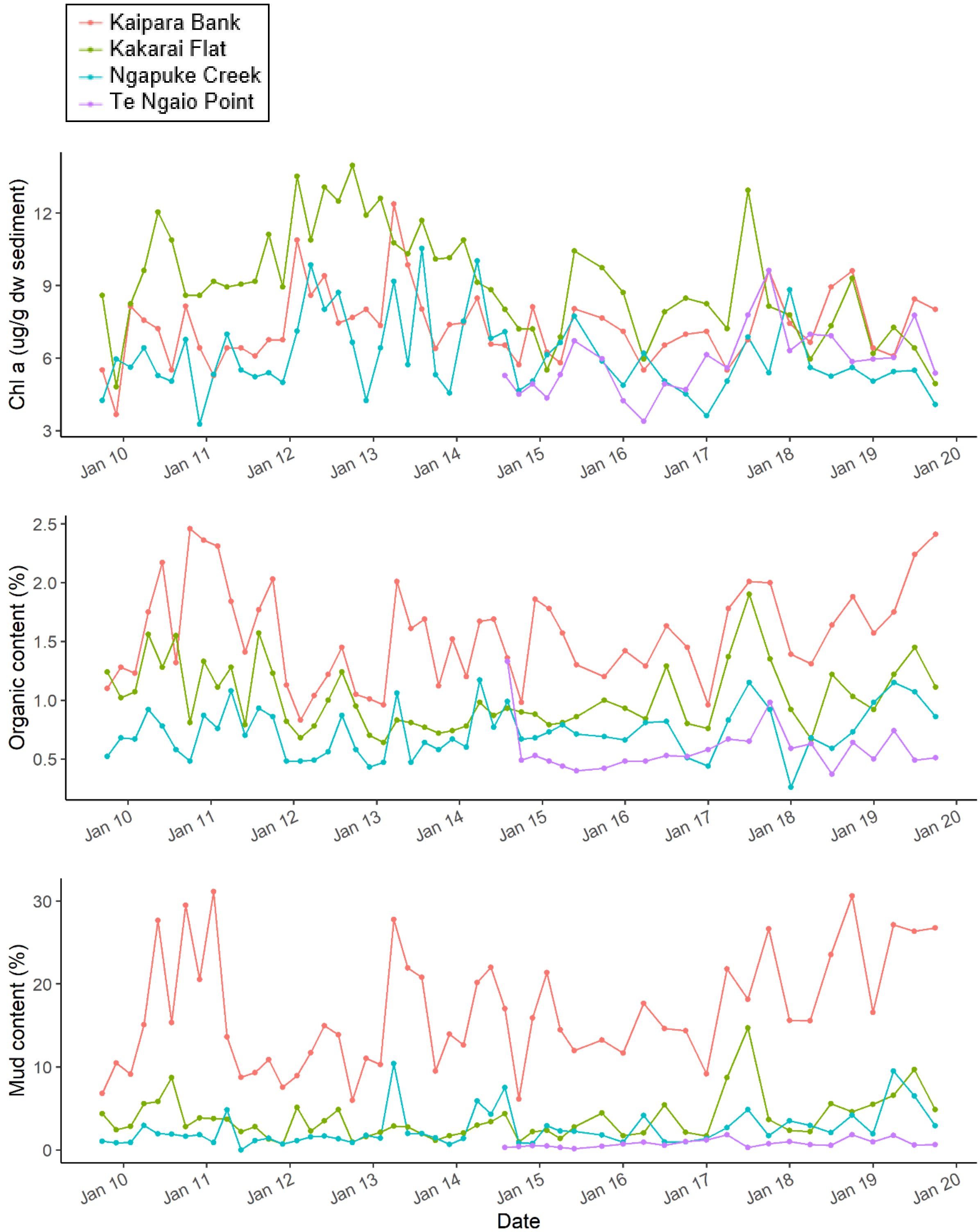

Figure 2. Surface sediment characteristics in core Kaipara sites between 2009 and 2019 (except Te Ngaio Point which is 2014-2019).

Table 2. Median and temporal variation (standard deviation) of surface sediment characteristics at Kaipara monitored sites between 2009 and 2019 (except Te Ngaio Point which is 2014-2019).

	Kakarai Flat		Ngapuke Creek		Kaipara Bank		Te Ngaio Point		Haratahi Creek		Kaipara Flats	
	Med	SD	Med	SD	Med	SD	Med	SD	Med	SD	Med	SD
Mud content (%)	2.85	2.50	1.81	2.17	15.21	7.11	0.61	0.68	0.59	0.44	0.33	0.19
Organic content (%)	0.75	0.31	0.77	0.31	1.65	0.64	0.63	0.26	0.75	0.26	0.62	0.22
Chl *a* (μg g^{-1} dw sediment)	9.02	2.30	6.03	1.63	7.35	1.50	5.85	1.33	8.70	2.04	8.40	2.88

Figure 3. Surface sediment mud content in Kaipara ecology sites in 2019.

Table 3. Direction of statistically significant trends in sediment characteristics in Kaipara between 2009 and 2019 (except Te Ngaio Point: 2014-2019). ▲ represents an increase (i.e. a positive relationship with time) and ▼ a decrease (i.e. a negative relationship) for the given variable. Grey cells indicate trends that are less certain or uncertain.

	Kakarai Flat	Ngapuke Creek	Kaipara Bank	Te Ngaio Point	Haratahi Creek	Kaipara Flats
Mud content (%)		▲	▲	▲		▲
Organic content (%)		▲	▲		▲	
Chl *a* (μg g^{-1} dw sediment	▼			▲	▼	▼

Species abundance

Of the 27 routinely monitored species, 26 are exhibiting trends at at least one site (all except *Travisia*). The abundance of *Aricidea*, *Aglaophamus* and *Magelona* has increased at multiple sites, whilst the abundance of *Hiatula* and *Taeniogyrus* have decreased at all sites except Kaipara Flats. Most species are exhibiting multi-year cycles at at least one site (Table 4).

Aricidea prefers slightly muddy sediments, therefore increases in this taxon are indicative of increased sedimentation. This is consistent with the trends of increasing sediment mud content at sites Kaipara Bank and Ngapuke Creek. There are another four species exhibiting trends consistent with sedimentation at more than one site (the polychaetes *Boccardia*, *Nicon* and *Prionospio*, and the amphipod *Waitangi*). The sites with the greatest number of trends consistent with sedimentation are Ngapuke Creek and Kaipara Bank, which is expected given the trends of increasing mud content at these sites. The only site with no trends consistent with sedimentation is the rotational site Kaipara Flats.

Magelona is highly sensitive to lead contamination, so increases in this species may be a promising sign of a decrease in lead at Kakarai Flat, Ngapuke Creek and Kaipara Bank. Nevertheless, *Torridoharpinia*, an amphipod sensitive to toxic contamination and pollution, has decreased in abundance at both Kaipara Bank and Ngapuke Creek, suggesting a contaminant other than lead may have an increasing effect at these sites. Te Ngaio Point is exhibiting the greatest number of trends consistent with metal contamination, however one of these trends is uncertain and others may be identified as long-term cycles with more data, so this is not currently of concern.

Table 4. Comparison of trends in abundance of monitored species at all Kaipara sites between Oct. 2009 and May 2019. An upward arrow represents an increase in abundance and a downward arrow a decrease. Grey cells indicate trends that are less certain or uncertain and sites exhibiting multi-year cycles (MY) are shown. Arrows are coloured to highlight trends consistent with a particular stressor: sedimentation (orange), metal contamination (blue) or both (green). Pref = sediment preference; SS = strong preference for sand, S = prefers sand, M = prefers some mud but not in high percentages, MM = strong mud preference.

Monitored species	Pref	Kakarai Flat	Ngapuke Creek	Kaipara Bank	Te Ngaio Point	Haratahi Creek	Kaipara Flats
Aricidea sp.	M	▲MY	▲MY	▲	▼	▲MY	▼MY
Boccardia syrtis	M	▲MY		▲MY	▼MY		
Cossura consimilis	M		▲	▼MY			
Macroclymenella stewartensis	M					▲	
Nicon aestuariensis	M			▲MY	▲		▼MY
Prionospio aucklandica	M	▼MY		▲MY	▲MY		
Torridoharpinia hurleyi	S		▼	▼	▲		
Scoloplos cylindrifer	S						▼
Anthopleura aureoradiata	S		▼MY	▲	▲MY		
Austrovenus stutchburyi	S		▼		▲MY		
Macomona liliana	S			▼MY	▼		
Linucula hartvigiana	S	▼	▲				
Orbinia papillosa	S	▲		▲	▼MY		
Owenia petersenae	S	▼MY					
Colurostylis lemurum	SS		▲MY				
Notoacmea scapha	SS		▼MY		▲		
Aonides trifida	SS				▲MY		▲
Waitangi brevirostris	SS		▼		▼MY	▲MY	
Travisia olens novaezealandiae	SS						
Aglaophamus macroura	-	▲	▲	▲	▼MY		▼
Euchone sp.	-	▼MY			▼		
Magelona dakini	-	▲MY	▲MY	▲MY	▼		
Exosphaeroma planulum	-	▼	▼MY				
Exosphaeroma waitemata	-	▼MY	▼MY				
Taeniogyrus dendyi	-	▼	▼	▼	▼MY	▼	
Hiatula siliquens	-	▼MY	▼MY	▼	▼MY	▼	
Arcuatula senhousia	-			▼MY			
Trends consistent with sedimentation		2	4	5	4	2	0
Trends consistent with metals		3	3	2	6	0	0

Community changes

Shifts in the composition of benthic macrofaunal communities through time can be indicative of environmental change. Such shifts are easily visualised using nMDS ordinations (see Figure 4) where the distance between points is relative to the dissimilarity between samples, i.e. the closer two points are to one another the more similar the macrofaunal communities are in these samples. The macrofaunal communities in the Kaipara Harbour monitored sites are largely distinct from one another, with site Te Ngaio Point being the most dissimilar to the other sites (Figure 4). There has been a reasonable degree of change in community composition over the last 10 years at all sites, and there have been comparable directional shifts at Kaipara Bank, Kakarai Flat, Ngapuke Creek and Haratahi Creek that may cause the communities at these sites to become more similar. Given mud content has increased at Kaipara Bank and Ngapuke Creek, and at least two species have displayed trends consistent with increased sedimentation at all four sites, it is likely sedimentation is driving these directional shifts.

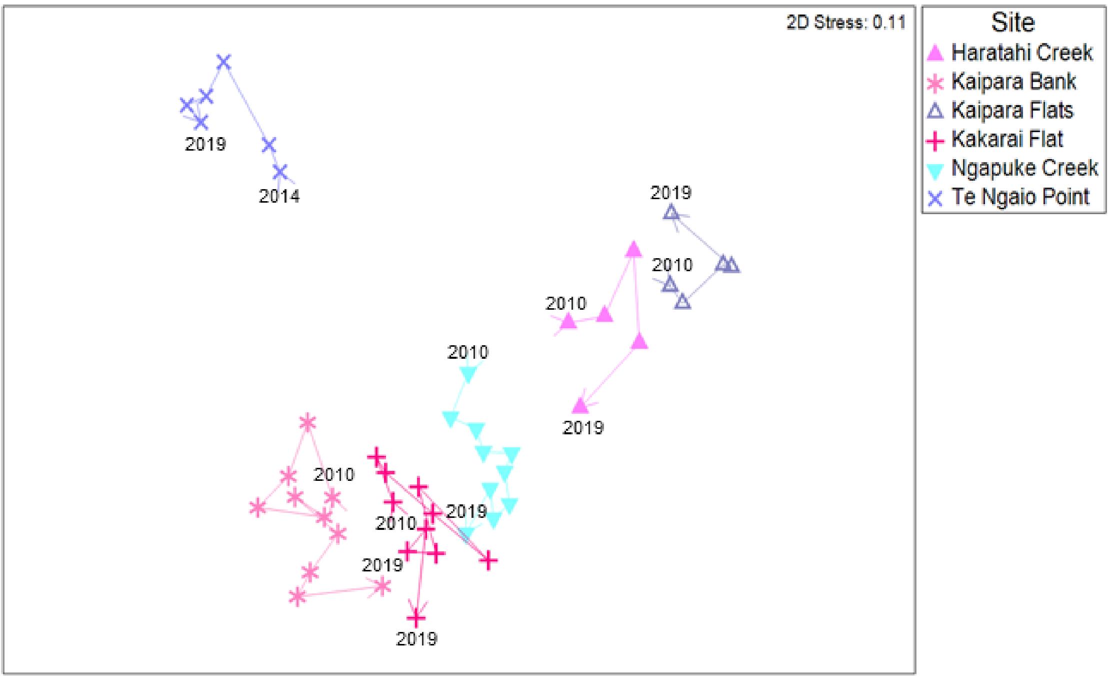

Figure 4. The similarity in macrofaunal community composition between Kaipara Harbour sites and changes over the last 10 years (2010-2019, based on October data).

Benthic health

There have been certain declines in health related to mud and metals at sites Ngapuke Creek and Kaipara Bank over the course of the monitoring period, as well as at site Te Ngaio Point with respect to metals (Table 5). These trends have resulted in sites Ngapuke Creek and Te Ngaio Point having ‘good’ health and Kaipara Bank ‘fair’ health in relation to both stressors in 2019. There have been no long-term changes in health at the other sites, with all scoring ‘excellent’ or ‘good’ (the only exception is Kakarai Flat, which has ‘fair’ health in relation to mud). No sites are in ‘excellent’ health in relation to mud, suggesting this is a greater stressor of the communities than metals. The functional resilience of the communities, indicated by TBI, is high at all sites and has improved significantly at Haratahi Creek, resulting in a shift from intermediate to high resilience between the last two sampling occasions. According to the combined health score, most sites in Kaipara Harbour are in ‘good’ health in 2019, except Kaipara Bank and Kakarai Flat which have ‘fair’ health (Figure 5).

Table 5. BHM and TBI groups at all Kaipara sites in 2019. BHMs: Group 1 = excellent, Group 2 = good, Group 3 = fair, Group 4 = marginal, Group 5 = poor. TBI: high, intermediate, low. Arrows show significant trends in index scores between Oct. 2009 and Oct. 2019: an upward arrow indicates an improvement and a downward arrow a degradation in health.

Index	Kakarai Flat	Ngapuke Creek	Kaipara Bank	Te Ngaio Point	Haratahi Creek	Kaipara Flats
BHMmetals		▼	▼	▼		
BHMmud		▼	▼			
TBI					▲	

Figure 5. Combined health score for Kaipara benthic ecology sites in 2019.

Summary

The regression analyses show that all sites except Kaipara Flats are exhibiting trends consistent with sedimentation; Kaipara Bank and Ngapuke Creek, which are strongly influenced by outflows from the Kaipara River, are of particular concern. There are also trends consistent with metal contamination at all sites except Haratahi Creek and Kaipara Flats. Although there is less than 10 years of data for site Te Ngaio Point, trends consistent with sedimentation and metal contamination here are supported by those occurring at other sites where more data is available. Despite several concerning trends, the Kaipara Harbour has good to fair benthic health at the monitored sites in 2019.

As expected with the increasing length of the time series, several of the trends in species abundance last reported by Hailes and Carter (2016) have now been identified as multi-year cycles. Previously, a decreasing step change in *Boccardia* abundance was recorded at Kakarai Flat (Hailes & Carter, 2016), but this has now been identified as part of a long-term cycle and in fact significant increases exceeding natural variation have occurred since October 2018. There are still the same number of sites exhibiting increasing trends in *Aricidea* abundance as last reported (four), but the identity of these sites has changed; an increasing trend at Kaipara Flats has now become a decreasing trend (with multi-year cycles confirmed), Tapora Bank is no longer monitored (and there is no trend at the replacement site Te Ngaio Point), and the increasing trends at Kakarai Flats and Haratahi Creek are new since Hailes and Carter (2016). Importantly, there is now greater evidence of harbour-wide and location-specific impacts of sedimentation that were not previously apparent.

3.2 Manukau

The Manukau Harbour is Auckland's (and New Zealand's) second largest harbour with an area of 365km^2, of which roughly 40% is intertidal (145km^2). The shallow harbour is generally well mixed and has three major inlets (Māngere, Pahurehure and Waiuku) that drain the 916km^2 catchment (Bell et al., 1998). The catchment is dominated by rural land uses (58% of the area in 2018) with notable urban and native vegetation areas (16 and 14%). Impacts from historic industry and urban development and treated sewage discharges from Māngere Wastewater Treatment Plant are likely the greatest anthropogenic pressures influencing harbour ecology.

The Manukau Harbour monitoring programme was initiated in October 1987 and is the longest running marine ecology programme, now boasting more than 30 years of data. There are six ecology sites on open sandflats for which data on sediment characteristics, species abundances and macrofaunal community composition are presented. The benthic health indices are presented for these six sites and an additional 24 RSCMP sites located in the tidal creeks and sheltered arms of the harbour that have data from within the last five years (a total of 29 sites have been sampled under the RSCMP since the start of monitoring, see Appendix A for full site list) (Figure 1).

<u>Sediment characteristics</u>

Mud content has been low at the Manukau sandflat sites over the course of the monitoring period, with medians ranging between <1% (at Auckland Airport) and 6% (at Elletts Beach) (Figure 6, Table 6). There has been substantial variability in mud content at Elletts Beach and Clarks Beach, however, with a maximum of 38% and 25% being recorded at each. There are very muddy areas shoreward of Elletts Beach which could easily be resuspended during a storm event and deposited on the site, and patches of seagrass occur across Clarks Beach trapping fine sediments, therefore mud content may vary between years depending on how many sediment cores are collected from within these patches. Nonetheless, the only trends in mud content have been decreases (certain at Cape Horn and less certain at Karaka Point) (Table 7). In 2019, sediment mud content is low at all sandflat sites (<10%; Figure 7) and is ≤3% at all except Elletts Beach. Mud content is higher in the tidal creeks than the sandflats, as expected due to their lower hydrodynamic energy, with all except Blockhouse Bay having >10% mud content and nine of the 24 sites having >80% (Figure 7).

The sandflats have been organically poor over the monitoring period (<1% median organic content at all sites except Clarks Beach), and patterns among sites reflect those of mud content (Table 6, Figure 6). There are only minor differences in median chl *a* concentration between sites (ranging from 7 to 12 $\mu g\ g^{-1}$ dw sediment at Karaka Point and Elletts Beach) and there has been little variability over the monitoring period. However, there have been a greater number of trends in organic content and chl *a* than mud. Both variables have decreased at Elletts Beach, Cape Horn and Karaka Point, whilst organic content has decreased at Auckland Airport and Puhinui Stream and chl *a* has at Clarks Beach (Table 7). An increase in organic content and chl *a* can indicate nutrient enrichment, provided light is not limiting, as nutrients fuel primary production and increase the amount of plant and algal material in the sediment. As such, these declining trends suggest nutrient enrichment is unlikely to be an issue at these sites.

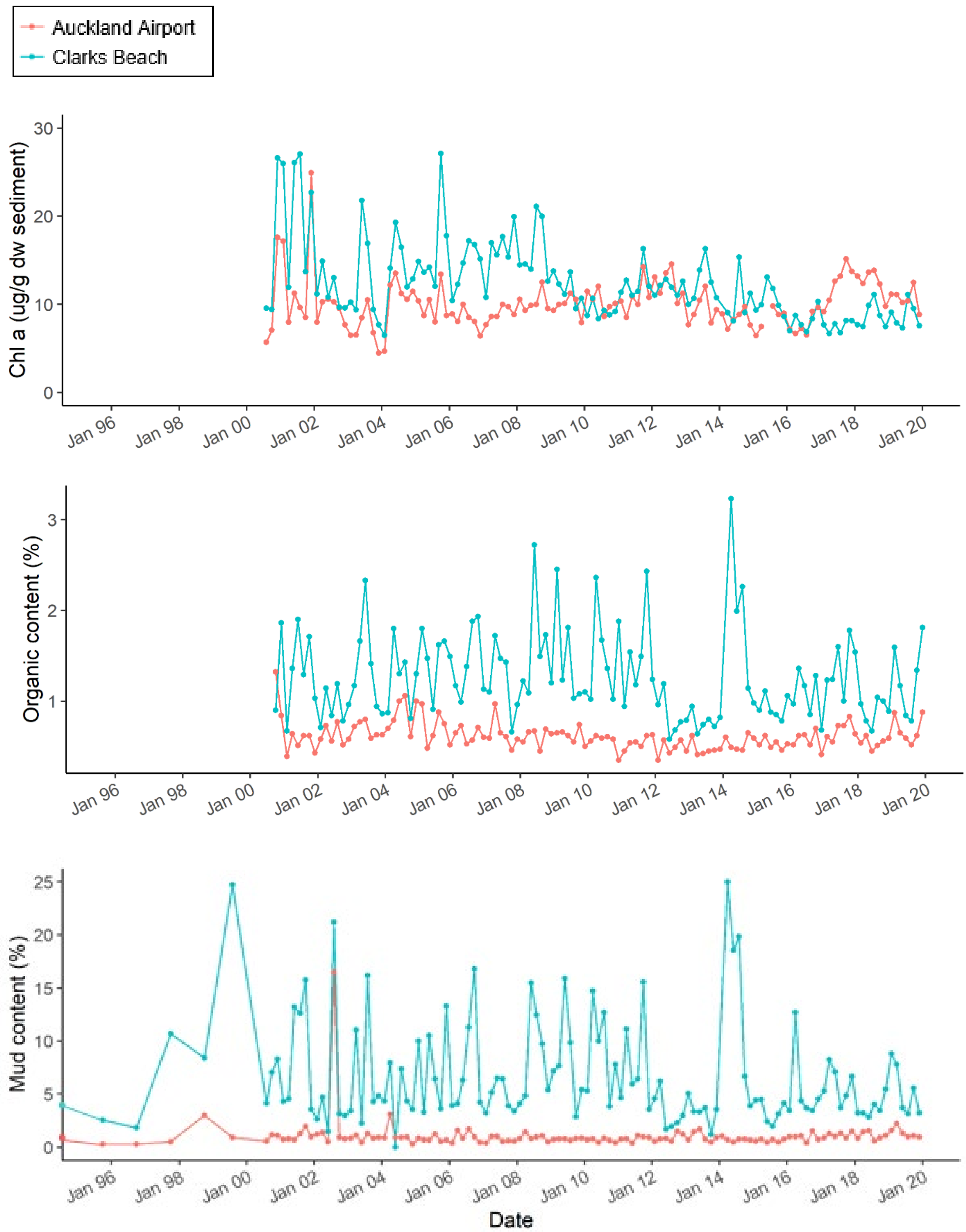

Figure 6. Surface sediment characteristics in core Manukau sites between 1987 (axis cut between 1987 and 1995) and 2019.

Table 6. Median and temporal variation (standard deviation) of surface sediment characteristics at Manukau monitored sites between 1987 and 2019.

	Auckland Airport		Clarks Beach		Elletts Beach		Cape Horn		Karaka Point		Puhinui Stream	
	Med	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**
Mud content (%)	0.84	1.47	4.61	4.90	5.91	7.16	0.90	3.17	2.34	3.55	1.14	1.77
Organic content (%)	0.60	0.16	1.17	0.50	0.95	0.63	0.70	0.45	0.78	0.23	0.59	0.20
Chl *a* (µg g^{-1} dw sediment)	9.86	2.71	11.12	4.61	11.55	3.49	7.80	4.26	7.07	3.08	9.17	3.46

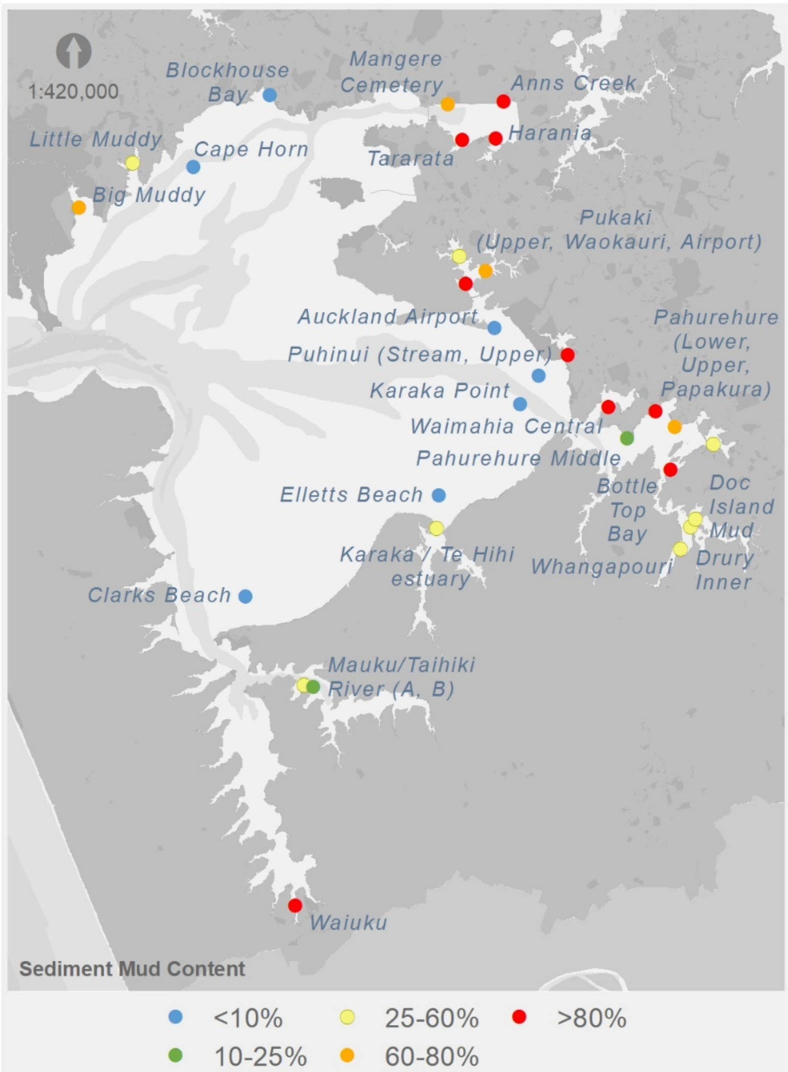

Figure 7. Most recent surface sediment mud content in Manukau ecology sites (measured between 2017-2019).

Table 7. Direction of statistically significant trends in sediment characteristics in Manukau between 1987 and 2019. Grey cells indicate trends that are less certain or uncertain.

	Auckland Airport	Clarks Beach	Elletts Beach	Cape Horn	Karaka Point	Puhinui Stream
Mud content (%)				▼	▼	
Organic content (%)	▼		▼	▼	▼	▼
Chl *a* (μg g^{-1} dw sediment)		▼	▼	▼	▼	

Species abundance

All 23 monitored species have exhibited a significant trend in abundance at least one site since 1987. The cockle *Austrovenus* has increased at all sites, and the cumacean *Colurostylis* and polychaete *Magelona* have increased at most (Table 8). *Austrovenus* influences several benthic ecosystem functions and is moderately sensitive to terrestrial sedimentation (Thrush et al., 2005), increases in suspended sediments (Nicholls, Hewitt, & Halliday, 2003) and stormwater contaminants (Hewitt et al., 2009). Both *Colurostylis* and *Magelona* are sensitive to lead, and *Colurostylis* also has a strong preference for sandy sediments (Anderson et al., 2007; Hewitt et al., 2009); therefore, the increases in abundance of these species across the harbour suggest the functionality and condition of the sandflats has improved over the monitoring period.

The abundance of the isopod *Exosphaeroma waitemata* has declined at several sites across the harbour, as has the polychaete *Aglaophamus*. There are no known sensitivities of these species to sedimentation or metal contaminants, although *Aglaophamus* is a key intermediate predator of the benthic community and both are important food sources for birds and small fish. As their declines cannot be linked to any particular stressor and increasing abundances have also been detected at some sites, these trends are not currently cause for concern.

Few trends in species abundance are consistent with terrestrial sedimentation at the sandflat sites (Table 8); Karaka Point has no such trends and Auckland Airport, Clarks Beach and Puhinui Stream have only one. Whilst Elletts Beach has the greatest number of species exhibiting trends indicative of sedimentation (three out of a possible eight), all are less than certain due to multi-year cycles in their abundance.

Eleven of the monitored species in the Manukau Harbour are sensitive to some form of metal contamination (see Appendix B), of these, three have declined in abundance at Cape Horn (the polychaetes *Boccardia* and *Aonides* and the bivalve *Macomona*) and Karaka Point (the polychaetes *Boccardia* and *Macroclymenella* and the anemone *Anthopleura*). Cape Horn is on the northern side of the harbour and is likely influenced by outflow from the Māngere Wastewater Treatment Plant. The declines in *Boccardia* and *Macomona* at Cape Horn occurred pre-2002 and there has been some recovery of both populations since 2013. Similarly, *Aonides* has occurred in low abundances throughout the monitoring period and was mostly absent between 1994 and 2010, but slight increases in its abundance have been recorded since. At Karaka Point, which is located at the mouth of the Pahurehure Inlet, trends in *Boccardia* and *Anthopleura* are likely reflecting multi-year cycles, whereas *Macroclymenella* abundance decreased notably between 2001 and 2006 and has remained low. These patterns in species abundance suggest that metal contamination was an historic rather than current stressor of Cape Horn and Karaka Point, but it will be important to continue observing populations at Karaka Point to see if contaminants from Pahurehure Inlet are being flushed into the wider harbour.

Table 8. Comparison of trends in abundance of monitored species at all Manukau sites between Oct. 1987 and Oct. 2019. An upward arrow represents an increase in abundance and a downward arrow a decrease. Grey cells indicate trends that are less certain or uncertain and sites exhibiting multi-year cycles (MY) are shown. Arrows are coloured to highlight trends consistent with a particular stressor: sedimentation (orange), metal contamination (blue) or both (green). Pref = sediment preference; SS = strong preference for sand, S = prefers sand, M = prefers some mud but not in high percentages, MM = strong mud preference.

Monitored species	Pref	Auckland Airport	Clarks Beach	Elletts Beach	Cape Horn	Karaka Point	Puhinui Stream
Boccardia syrtis	M			▲MY	▼MY	▼MY	
Macroclymenella stewartensis	M			▼		▼MY	▲MY
Prionopsio aucklandica	M	▲MY	▲MY	▲MY			
Anthopleura aureoradiata	S		▲MY	▲MY	▲	▼MY	
Austrovenus stutchburyi	S	▲MY	▲MY	▲MY	▲	▲MY	▲MY
Linucula hartvigiana	S	▼MY	▲MY	▲MY		▲MY	
Macomona liliana	S			▲MY	▼	▲MY	
Orbinia papillosa	S	▲	▼			▲	▲MY
Owenia petersenae	S		▲MY	▲MY	▼MY	▼MY	▲MY
Torridoharpinia hurleyi	S	▲MY	▲				
Aonides trifida	SS	▲			▼	▲MY	▲MY
Colurostylis lemurum	SS	▲MY		▲	▲MY	▲	▲
Notoacmea scapha	SS		▲	▲	▲		
Travisia olens novaezealandiae	SS					▲	
Waitangi brevirostris	SS			▼MY		▲MY	
Aglaophamus macroura	-	▼MY	▼	▼MY	▲MY	▲	▲
Exosphaeroma planulum	-		▲MY	▲MY		▼	
Exosphaeroma waitemata	-	▼MY	▼MY	▼MY		▲MY	
Glycinde trifida	-	▼MY	▼		▼	▼MY	▼MY
Hiatula siliquens	-		▼MY	▼MY			
Magelona dakini	-	▲MY		▲		▲	▲
Methalimedon sp.	-			▲	▲MY	▲	
Taeniogyrus dendyi	-	▲				▲MY	▲
Trends consistent with sedimentation		1	1	3	2	0	1
Trends consistent with metals		1	1	2	3	3	0

Community changes

The benthic macrofaunal communities are largely distinct between the sandflat sites, however there is some overlap in composition at Elletts Beach and Karaka Point (Figure 8). There has been no overall change in the community composition at Clarks Beach, Puhinui Stream or Auckland Airport over the last 10 years, however Elletts Beach and Karaka Point have shown some minor directional change and may be becoming more alike. Cape Horn has exhibited the largest degree of change over recent times, resulting in the community here being increasingly dissimilar to that at the other sandflat sites. Although several trends consistent with metal contamination were identified at Cape Horn, these appear to reflect historic inputs and the driver of the more recent change requires further investigation.

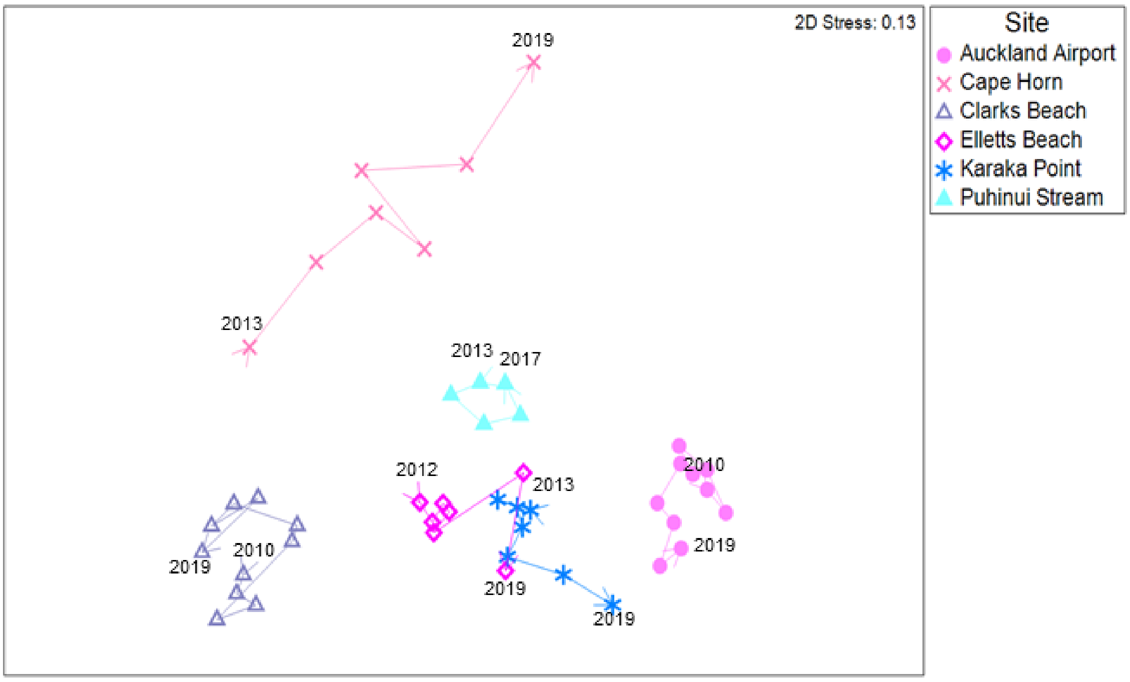

Figure 8. The similarity in macrofaunal community composition between Manukau Harbour sandflat sites and changes over the last 10 years (2010-2019, based on October data).

<u>Benthic health</u>

Of the tidal creek sites, only two have sufficient data to report on trends in health indices (Ann's Creek and Māngere Cemetery), but combined health scores are available for 24. There have been few spatially consistent trends in benthic health indices since the start of monitoring (Table 9). Health has degraded at Auckland Airport in relation to both metals and mud, but as of 2019 this site remains in the 'excellent' health category for both indices. Both Cape Horn and Karaka Point have improved in health related to metals (and score 'excellent' and 'good', respectively), supporting the theory that metals are not a current stressor of these sites. The tidal creek sites Ann's Creek and Māngere Cemetery have lower health related to metals (both 'marginal') than the sandflat sites (ranging from 'excellent' to 'intermediate') and have shown no significant change over time.

Health has improved in relation to mud at sandflat sites Elletts Beach and Cape Horn, and the tidal creek site Māngere Cemetery; this has resulted in 'good' health at both sandflat sites but remains 'marginal' at Māngere Cemetery. Generally, the health of the sandflat sites is 'good' regarding mud but is lower for the tidal creeks ('marginal' and 'poor'). The functional resilience of several sandflat sites has improved over the monitoring period and is high at all except Cape Horn, whilst both tidal creek sites have low functional resilience and have exhibited no significant trends. Although the trend at Elletts Beach resulted in an improvement from intermediate to high resilience between 2018 and 2019, the score at this site remains close to the boundary and is likely to fluctuate between these groups.

The latest combined health scores for all Manukau Harbour sites ranges from 'excellent' to 'poor', but the distribution of these scores can be separated spatially: tidal creeks are generally less healthy than open sandflats (Figure 9). The only site scoring 'excellent' is Auckland Airport, whilst all the sites scoring 'poor' are in tidal creeks. Clarks Beach remains in 'fair' overall health (this site had 'good' health until 1998 and has fluctuated between these categories since). As previously highlighted by Greenfield et al. (2019), the apparent decline in health at Clarks Beach has coincided with an increase in seagrass coverage and it is suspected the benthic health models, that were developed based on unvegetated reference sites, may not accurately reflect health in such cases.

Table 9. BHM and TBI groups at all Manukau sites in 2019 (except Ann's Creek and Māngere Cemetery where the score is from 2018). BHMs: Group 1 = excellent, Group 2 = good, Group 3 = fair, Group 4 = marginal, Group 5 = poor. TBI: high, intermediate, low. Arrows show significant trends in index scores between Oct. 1987 and Oct. 2019: an upward arrow indicates an improvement and a downward arrow a degradation in health.

Index	Auckland Airport	Clarks Beach	Elletts Beach	Cape Horn	Karaka Point	Puhinui Stream	Ann's Creek	Māngere Cemetery
BHMmetals	▼			▲	▲			
BHMmud	▼		▲	▲				▲
TBI	▲		▲			▲		

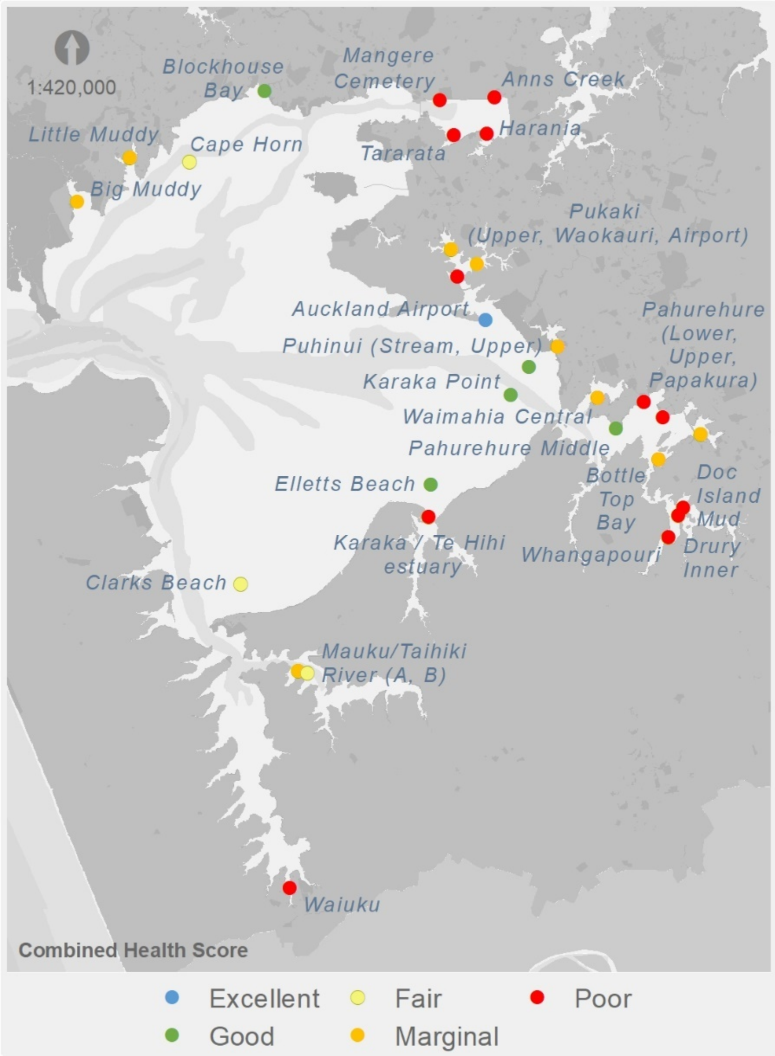

Figure 9. Combined health score for Manukau benthic ecology sites in 2019.

<u>Summary</u>

The health of Manukau Harbour sites varies according to how sheltered and close to urban influences they are; sites in or close to sheltered creeks with inputs from urban streams and rivers have the lowest health whilst more open sandflat sites are generally healthy. Multi-year cycles continue to be a common feature of species abundance time series at all sandflat sites, and there are no concerning trends related to sedimentation. Additionally, most impacts from metal contaminants appear to be related to historical inputs. There has been little change of concern in the tidal creek sites, however, there have not been any substantial improvements in health at these sites over the monitoring period either.

3.3 Mahurangi

The Mahurangi Harbour is formed by the Mahurangi River and opens into the Hauraki Gulf on the east coast. The harbour is characterised by numerous branching arms and creeks and has an area of 25km^2, the majority of which is intertidal (65%). This relatively small harbour drains a 128km^2 catchment, dominated by rural land uses (59% of the area in 2018) with notable areas of native vegetation (24%) and exotic forest (11%). The Mahurangi River winds through Warkworth, the major urban area within the catchment, and the Te Kapa River is another significant freshwater inflow to the harbour, draining Mahurangi East.

Monitoring in Mahurangi Harbour was initiated in July 1994 to track long-term changes in the health of benthic communities at three subtidal and five intertidal sites. In 2005, Dyers Creek was added to the programme in response to the implementation of catchment management plans around the harbour. Sampling at Cowans Bay was made rotational in 2011 after the site characteristics remained largely stable over the first 18 years of monitoring, and sampling of the subtidal sites was put on hold (see Halliday and Cummings (2012) and Cummings et al., (2016)). There is a clear transition from sandy to muddy sediments at the Te Kapa Inlet site, therefore separate samples are collected for analysis of sediment characteristics from each area.

Sediment characteristics

Sediment characteristics at the core Mahurangi Harbour sites have shown little overall change throughout the monitoring period (Figure 10). Mud content has been consistently high at Hamilton Landing (median 45%) and in the muddy part of the Te Kapa Inlet site (median 32%), whilst Jamieson Bay has had generally low mud content (<10%) (Table 10). Organic content has also been relatively high at Hamilton Landing and Te Kapa Inlet (muddy), with New Zealand sandflats typically having low (<2%) organic content (Pratt et al., 2014). It is likely terrestrial sediment inputs from the Mahurangi and Te Kapa rivers are responsible for the high levels of mud at the Hamilton Landing and Te Kapa Inlet sites, and a sewage outfall that discharges waste from Warkworth into the Mahurangi River may explain the high organic content measured at Hamilton Landing.

There has been substantial variation in chl *a* concentration between sites, with the lowest median value recorded at Jamieson Bay (4.5 µg g^{-1} dw sediment) and the highest at Cowans Bay (15 µg g^{-1} dw sediment); this variability seemingly reflects a gradient of nutrient availability, with higher chl *a* concentrations occurring at sites in the upper reaches of the harbour (close to river outflows) and lower concentrations occurring near the harbour mouth (where the influence of the sea is greater).

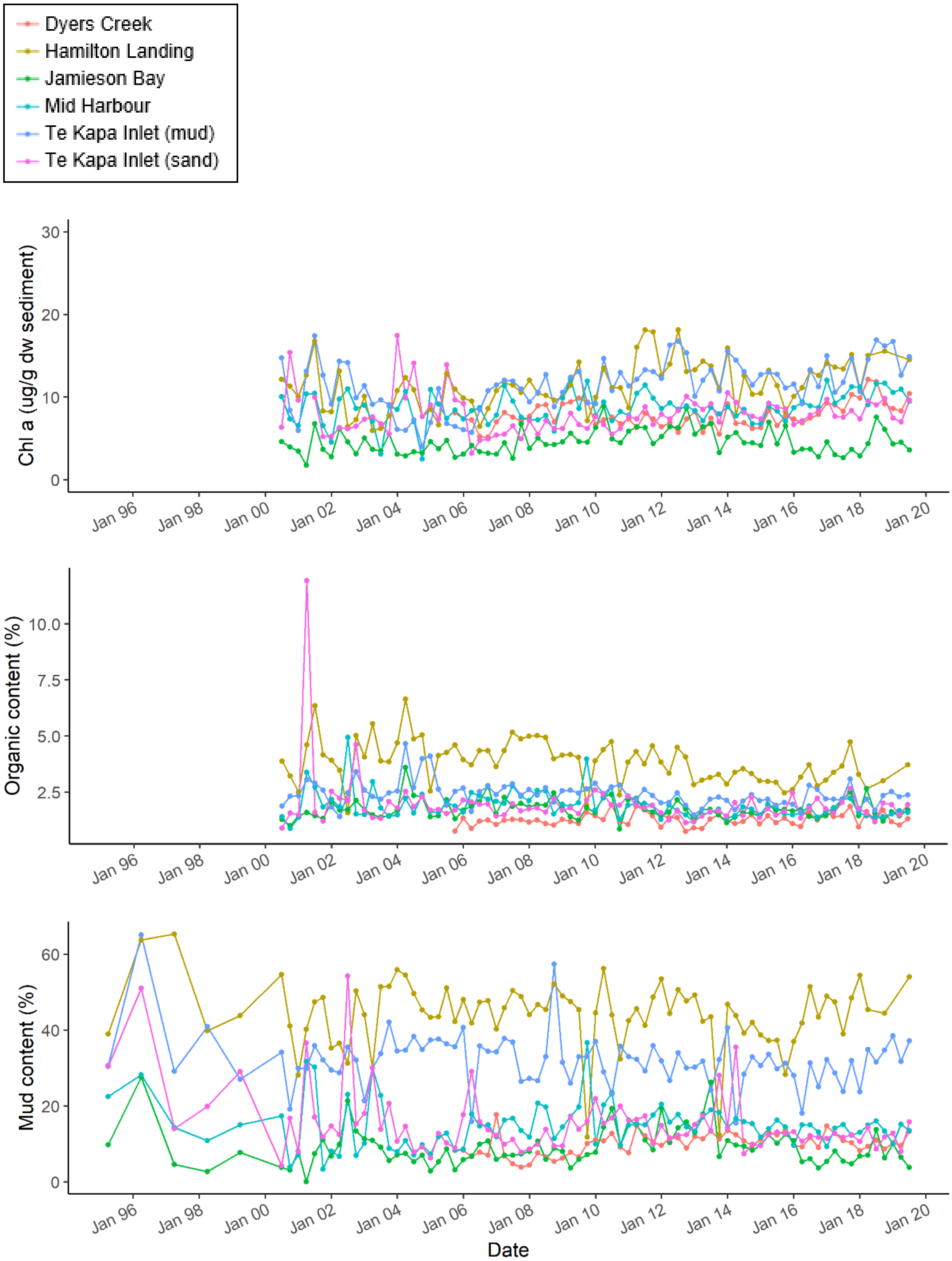

Figure 10. Surface sediment characteristics in core Mahurangi sites between 1994 and 2019.

Table 10. Median and temporal variation (standard deviation) of surface sediment characteristics at Mahurangi monitored sites between 1994 and 2019 (except Dyers Creek which is from 2005).

	Dyers Creek		Hamilton Landing		Jamieson Bay		Mid Harbour	
	Med	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**
Mud content (%)	10.07	2.79	44.92	8.61	8.01	4.90	14.49	6.02
Organic content (%)	1.26	0.29	3.87	0.93	1.70	0.46	1.82	0.61
Chl *a* (μg g^{-1} dw sediment)	7.56	1.50	11.12	2.89	4.46	1.45	8.71	1.91
	Te Kapa Inlet (muddy)		**Te Kapa Inlet (sandy)**		**Cowans Bay**			
	Med	**SD**	**Med**	**SD**	**Med**	**SD**		
Mud content (%)	32.13	7.08	13.21	8.53	26.31	6.09		
Organic content (%)	2.37	0.54	1.78	1.25	2.15	0.49		
Chl *a* (μg g^{-1} dw sediment)	11.68	3.00	7.60	2.33	14.56	2.57		

Figure 11. Most recent surface sediment mud content in Mahurangi ecology sites (measured in 2018 or 2019).

Over the last 15 years, sediment mud content, organic content and chl *a* have increased at Dyers Creek, suggesting fine sediment and nutrient inputs from the west of the catchment have increased (Table 11). There have been certain decreases in organic content and certain increases in chl *a* at Hamilton Landing, Mid Harbour and Te Kapa Inlet (muddy). Whilst these trends appear contradictory, if nutrients are elevated the increases in sediment organic content will lag those of chl *a*; therefore, these patterns may be signalling a recent increase in nutrient enrichment. This requires further investigation, however, as a decrease in grazing pressure or increased light availability would also favour an increase in the abundance of benthic algae (and hence chl *a* concentration). Indeed, the abundance of common deposit-feeding bivalves *Macomona* and *Linucula* has declined at all three sites over the monitoring period (see below), and water column turbidity has decreased in the upper reaches of the harbour over the last 10 years (Ingley, 2021), which may have improved light conditions at Hamilton Landing and Mid Harbour. No changes of concern have occurred at Te Kapa Inlet (sandy) or Cowans Bay, with some evidence that mud content has decreased at these sites, however they remain among the muddiest sites in 2019 (Figure 11).

Table 11. Direction of statistically significant trends in sediment characteristics in Mahurangi between 1995 and 2019 (except Dyers Creek which is from 2005). Grey cells indicate trends that are less certain or uncertain.

	Dyers Creek	Hamilton Landing	Jamieson Bay	Mid Harbour	Te Kapa Inlet (M)	Te Kapa Inlet (S)	Cowans Bay
Mud content (%)	▲					▼	▼
Organic content (%)	▲	▼		▼	▼	▼	
Chl *a* (μg g^{-1} dw sediment)	▲	▲		▲	▲		

<u>Species abundance</u>

Of the 19 monitored species, the abundance of all except the Polydorid group have changed significantly at least one site since the start of monitoring (Table 12). Several species have increased at all sites: the polychaetes Oligochaeta, *Aricidea* and *Cossura*, and the crab *Hemiplax*. These species all prefer muddy or slightly muddy sediments, suggesting there have been subtle impacts of sedimentation across the harbour that are not necessarily reflected in sediment mud content. Additionally, the mud-sensitive bivalves *Linucula* and *Macomona* decreased in abundance at all sites except Cowans Bay, and the limpet *Notoacmea* (which prefers sediments with <5% mud (Gibbs & Hewitt, 2004)) decreased in abundance at three sites. There are a high number of trends consistent with sedimentation at all sites except Cowans Bay, with the greatest occurring at Jamieson Bay (receiving outflow from Pukapuka Inlet) and Te Kapa Inlet (both nine out of a possible 12). There are few trends consistent with metal contamination across the harbour, with only one taxon displaying a certain trend at each of Dyers Creek, Hamilton Landing, Mid Harbour and Te Kapa Inlet out of a possible five (Table 12, and see Appendix B).

Table 12. Comparison of trends in abundance of monitored species at all Mahurangi sites between Jul. 1994 and May 2019. An upward arrow represents an increase in abundance and a downward arrow a decrease. Grey cells indicate trends that are less certain or uncertain and sites exhibiting multi-year cycles (MY) are shown. Arrows are coloured to highlight trends consistent with a particular stressor: sedimentation (orange), metal contamination (blue) or both (green). Pref = sediment preference; SS = strong preference for sand, S = prefers sand, M = prefers some mud but not in high percentages, MM = strong mud preference.

Monitored species	Pref	Dyers Creek	Hamilton Landing	Jamieson Bay	Mid Harbour	Te Kapa inlet	Cowans Bay
Oligochaeta	MM	▲	▲	▲	▲	▲	▲
Aricidea sp.	M	▲MY	▲MY	▲MY	▲MY	▲	▲MY
Arthritica bifurca	M	▲MY		▲	▲MY	▲MY	
Cossura consimilis	M	▲MY	▲MY	▲MY	▲MY	▲MY	▲MY
Hemiplax hirtipes	M	▲	▲	▲MY	▲	▲	▲
Heteromastus filiformis	M	▼MY	▲MY	▲		▲	
Nemertea	M		▲MY	▲MY	▲MY	▲MY	
Perinereis vallata	M		▼MY			▲MY	▼
Polydorids	M						
Prionopsio aucklandica	M	▲MY	▲	▲MY			
Austrovenus stutchburyi	S	▲MY	▼	▲	▲		▲MY
Linucula hartvigiana	S	▼MY	▼	▼MY	▼MY	▼	
Macomona liliana	S	▼MY	▼	▼	▼MY	▼	
Owenia petersenae	S			▼MY			
Paracalliope novizealandiae	S			▲MY	▲MY		
Scoloplos cylindrifer	S	▲MY	▼MY	▲MY	▲MY	▲MY	▲MY
Torridoharpinia hurleyi	S	▼MY		▲MY			
Aonides trifida	SS			▼MY	▲		
Notoacmea scapha	SS	▼MY			▼	▼	
Trends consistent with sedimentation		8	8	10	8	10	4
Trends consistent with metals		3	2	3	2	2	0

Community changes

The benthic macrofaunal communities are similar at Cowans Bay and Mid Harbour, but all other sites are largely distinct from one another (Figure 12). The community composition at Jamieson Bay has been the most variable over the last 10 years, but there has been little directional change here or at any other site. The communities at the monitored sites do not appear to be getting more similar despite the numerous species trends consistent with sedimentation.

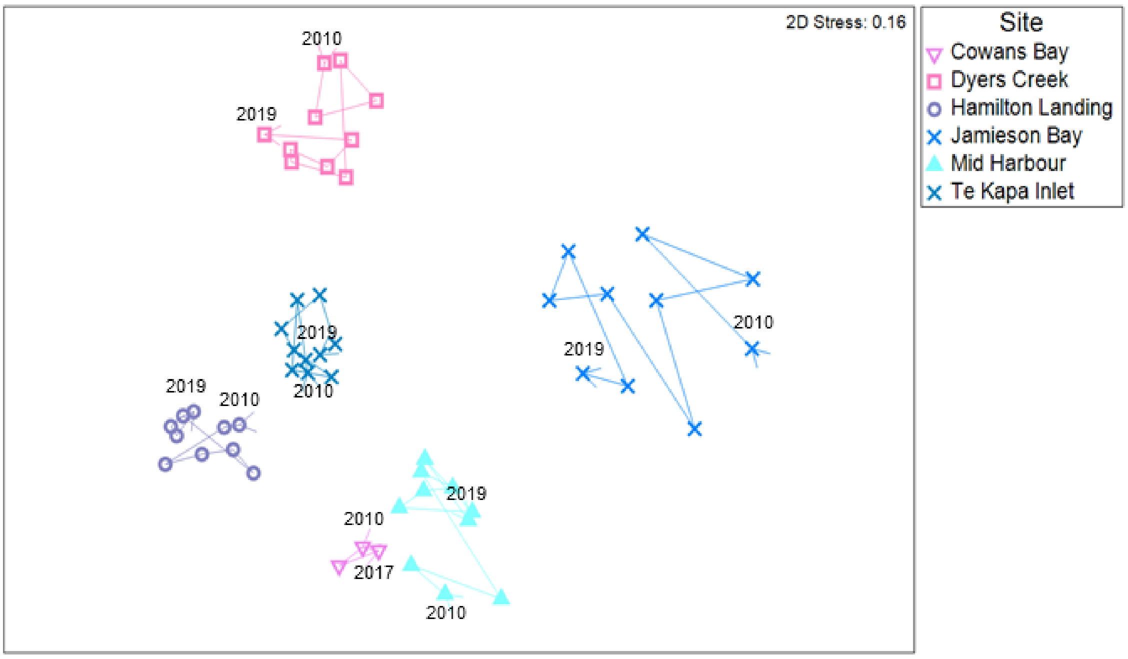

Figure 12. The similarity in macrofaunal community composition between Mahurangi Harbour sites and changes over the last 10 years (2010-2019, based on October data).

<u>Benthic health</u>

Health in relation to metals has degraded at all sites except Mid Harbour and Cowans Bay over the monitoring period (Table 13), and all currently have ‘fair’ or ‘marginal’ health. There have also been several degrading trends in relation to mud, and while those observed at Hamilton Landing stabilised in 2000, most sites are currently in ‘marginal’ health. Despite Jamieson Bay having a reasonably low sediment mud content (Table 10, Figure 11), the health of the community at this site has degraded and is now considered ‘fair’. There are also many species trends consistent with sedimentation at Jamieson Bay, therefore it will be important to monitor any further change at this site.

The functional resilience of the communities varies across the harbour but is high at 50% of sites (Table 13). Te Kapa Inlet currently has high resilience and has shown no change, but with health in relation to both metals and mud having degraded over the monitoring period, and the score in 2019 (0.41) being very close to the threshold between the high and intermediate categories (0.40), this site should be watched closely. Improving trends have occurred at Mid Harbour and Cowans Bay, resulting in a switch in category from low/intermediate to mostly high resilience since 2005. These sites are likely to switch between the intermediate and high categories, however, as their scores remain close to the threshold. The overall health of the intertidal Mahurangi Harbour sites ranges from ‘good’ (at Te Kapa Inlet and Cowans Bay) to ‘marginal’ (at Dyers Creek, Hamilton Landing and Mid Harbour) (Figure 13).

Table 13. BHM and TBI groups at all Mahurangi sites in 2019 (except Cowans Bay where the score is from 2017). BHMs: Group 1 = excellent, Group 2 = good, Group 3 = fair, Group 4 = marginal, Group 5 = poor. TBI: high, intermediate, low. Arrows show significant trends in index scores between Oct. 1994 and Oct. 2019 (except Dyers Creek which is from Oct. 2005): an upward arrow indicates an improvement and a downward arrow a degradation in health.

Index	Dyers Creek	Hamilton Landing	Jamieson Bay	Mid Harbour	Te Kapa inlet	Cowans Bay
BHMmetals	▼	▼	▼		▼	
BHMmud		▼	▼		▼	
TBI				▲		▲

Figure 13. Combined health score for Mahurangi benthic ecology sites in 2019 (except Cowans Bay which is 2018).

<u>Summary</u>

Overall, trends consistent with sedimentation have occurred at all sandflat sites, which are currently in good to marginal ecological health. Cowans Bay continues to be the most stable site, however changes occurring at Hamilton Landing, Dyers Creek, Jamieson Bay and Te Kapa Inlet are all of concern and require continued close observation. Metals do not appear to be an important stressor of the sandflats, but there are some signs that nutrient enrichment may be a developing issue; increases in chl *a* concentration are now apparent for three (possibly four) sites across the harbour whereas they were only recorded at Hamilton Landing by Carter and Hailes (2020).

Previous reporting for Mahurangi Harbour (based on data up to January 2018) found an increase in the number of trends consistent with sedimentation impacts at Mid Harbour and Te Kapa Inlet and suggested further investigation (Carter & Hailes, 2020). At Mid Harbour, nine trends in species abundance and a degrading trend in health related to mud were identified; with an additional seven data points the number of species displaying trends consistent with increased sedimentation has decreased to seven and a degrading trend in health could no longer be detected. At Te Kapa Inlet, nine species were also displaying trends consistent with sedimentation and all of these remain in the present analyses, plus a degrading trend in health related to mud is also now apparent.

3.4 Waitematā

The Waitematā Harbour has a total catchment area of 451km^2 but is broken down into Upper, Central and Outer for reporting to reflect differences in the physical characteristics of these areas (e.g. the Upper Waitematā is more sheltered than the Outer), and their surrounding land use types. The catchment is dominated by urban land use (50% of the area in 2018) with substantial rural areas (25%) and native vegetation (17%).

3.4.1 Upper

The Upper Waitematā catchment encompasses 185km^2 and drains to a small sub-estuary with a narrow outlet into the Central Waitematā. The catchment land use is mostly rural, but established urban areas are also undergoing substantial development. For example, the Auckland Unitary Plan highlights Albany East (on the Lucas Creek arm) and Whenuapai (on the Brigham Creek arm) as locations for special housing areas (with 360 and 1500 dwellings, respectively), and established special housing areas at Hobsonville Point were also approved for extension in 2016. The development of residential areas and associated increases in traffic (and hence pollution) are likely to exert increasing pressure on the adjacent receiving benthic environments.

Monitoring of the Upper Waitematā Harbour began in November 2005 to track any effects of urbanisation and catchment land use change on the ecology of the harbour. There are 10 intertidal sandflat sites for which sediment characteristics, species abundances and community composition data are reported. Benthic health indices are presented for these 10 sites and an additional four RSCMP tidal creek sites that have data from within the last five years (a total of 19 sites have been sampled under the RSCMP since monitoring began, see Appendix A) (Figure 1).

Sediment characteristics

The surface sediment characteristics have varied substantially between sandflat sites in the Upper Waitematā over the monitoring period (Figure 14). Mud content has been consistently high at Rangitopuni Creek, Brigham Creek and Upper Main Channel with sediments at these sites being majority mud (Table 14). Opposite Hobsonville, Hellyer's Creek, Lucas Creek and Central Main Channel have had high but relatively intermediate levels of mud content (from a median of 27 to 69%) and both Herald Island sites and the Outer Main Channel have had the lowest median mud content (13 to 18%). Since November 2005, there have been significant increases in mud content at one site representing each of these high, intermediate and low mud content groups: Rangitopuni Creek, Central Main Channel and Herald Island Waiarohia (Table 15). In 2019, sediment mud content in the sandflat sites ranges from 16-97% and in the tidal creek sites from 42-95% (Figure 15). Mud content is >10% at all sites and >20% at most, suggesting the resilience and functionality of these sandflats is likely to be degraded via negative effects on the macrofaunal community (Rodil et al., 2013; Thrush et al., 2012).

Sediment organic content is high in the Upper Waitematā sandflat sites (≥5% at four sites) and reflects spatial patterns in mud content (Table 14). There has been little change in organic content over the monitoring period (the only significant trend is an increase at Herald Island Waiarohia (Table 15)); the brief increases observed at all sites between January 2011 and January 2013 coincided with substantial land use changes across the catchment and large changes in climatic events (Townsend, McCartain, & Carter, 2020), but this does not appear to have had any lasting effect on sediment characteristics.

Contrastingly, sediment chl *a* concentration has increased at several sites across the harbour: Hellyer's Creek, Herald Island Waiarohia, Brigham Creek and Outer Main

Channel. The rate of increase has been much greater at Herald Island Waiarohia (0.22 µg g^{-1} dw sediment y^{-1}) than at the other sites (average increase of 0.08 µg g^{-1} dw sediment y^{-1}). These trends may be an indication of increasing nutrient availability across the harbour, and particularly from the Waiarohia Inlet.

Table 14. Median and temporal variation (standard deviation) of surface sediment characteristics at Upper Waitematā monitored sites between 2005 and 2019.

Characteristic	**Hellyer's Creek**		**Herald Island North**		**Herald Island Waiarohia**		**Lucas Creek**		**Rangitopuni Creek**	
	Med	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**
Mud content (%)	52.97	11.29	13.20	7.03	18.22	5.98	30.87	12.78	96.42	1.60
Organic content (%)	3.75	1.11	2.02	0.59	1.63	0.53	3.88	1.23	8.99	1.85
Chl *a* (µg g^{-1} dw sediment)	18.08	4.23	17.10	6.93	15.49	5.26	13.48	5.94	13.07	6.49
	Brigham Creek		**Opposite Hobsonville**		**CentralMain**		**Upper Main**		**Outer Main**	
	Med	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**
Mud content (%)	89.29	4.96	68.55	8.29	27.01	3.86	89.91	3.95	18.02	5.61
Organic content (%)	7.32	1.51	4.98	1.14	4.57	0.97	7.30	1.59	2.52	0.81
Chl *a* (µg g^{-1} dw sediment)	8.94	3.37	9.63	3.04	11.58	1.86	12.83	4.28	11.88	3.81

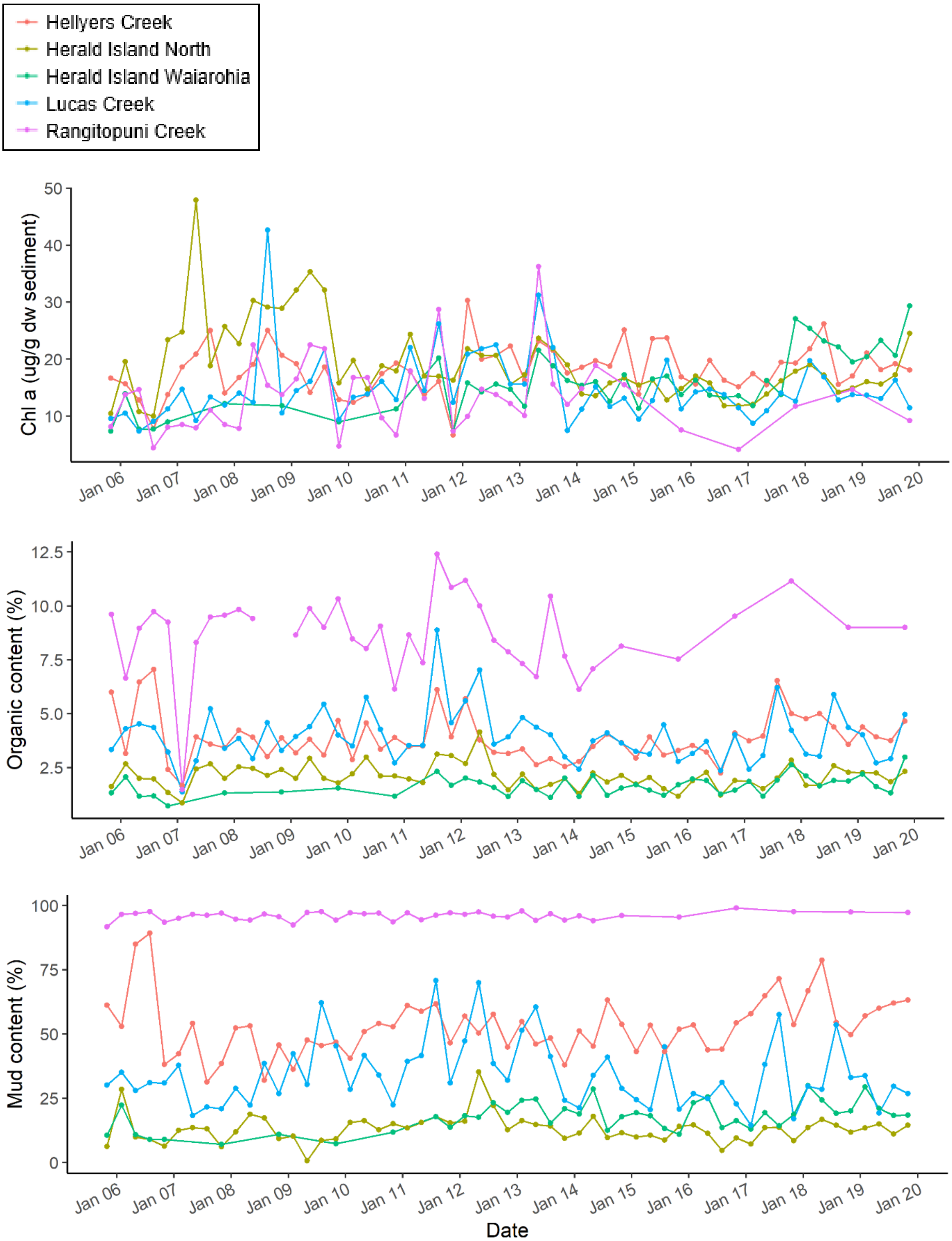

Figure 14. Surface sediment characteristics in core Upper Waitematā sites between 2005 and 2019.

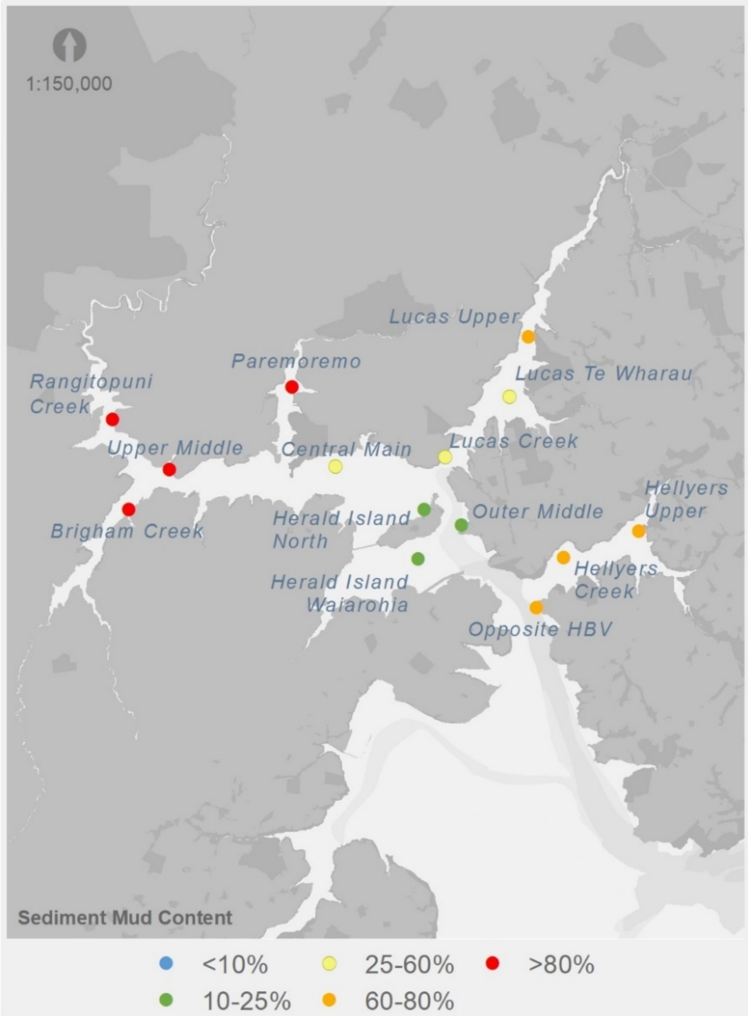

Figure 15. Most recent surface sediment mud content in Upper Waitematā ecology sites (measured in 2018 or 2019).

Table 15. Direction of statistically significant trends in sediment characteristics in Upper Waitematā between 2005 and 2019. Grey cells indicate trends that are less certain or uncertain.

	Hellyer's Creek	Herald Island North	Herald Island Waiarohia	Lucas Creek	Rangitopuni Creek
Mud content (%)			▲		▲
Organic content (%)			▲		
Chl *a* (µg g^{-1} dw sediment)	▲	▼	▲		
	Brigham Creek	**Opposite Hobsonville**	**Central Main**	**Upper Main**	**Outer Main**
Mud content (%)			▲		
Organic content (%)					
Chl *a* (µg g^{-1} dw sediment)	▲				▲

Species abundance

All monitored species are exhibiting trends at at least one site in the Upper Waitematā (Table 16). The polychaete *Prionospio* and the introduced gastropod *Tritia* are showing the greatest number of consistent trends, both having increased in abundance at eight sites. Additionally, the amphipod family Phoxocephalidae and bivalve *Macomona* have decreased in abundance at seven and six sites, respectively. The trends in *Prionospio* and *Macomona* may be indicative of sedimentation as *Prionospio* prefers slightly muddy sediments (and has an optimum range of 12-50% (Anderson et al., 2007; Gibbs & Hewitt, 2004; Thrush et al., 2003), and *Macomona* is moderately sensitive to smothering by sediments and has detrimental responses to increases in suspended sediment concentrations (Nicholls et al., 2003; Norkko et al., 2002; Thrush et al., 2005). The trends in these species are consistent with the increases in mud content observed at Central Main Channel and Herald Island Waiarohia, however there are numerous sites where the trends in species are not supported by those in surface sediment characteristics. This may be because increases in sediment mud content occurred prior to the start of monitoring and there has been a lag in the response of species abundances. Indeed, many of the trends in *Prionospio* and *Macomona* abundance appear to have started before monitoring began, although there have been increases in *Prionospio* abundance at Hellyer's Creek and Brigham Creek since 2015.

The declines in *Macomona* abundance are additionally concerning as this species is an important prey item for rays, birds and fish and contributes substantially to benthic ecosystem functions (Thrush et al., 2006; Volkenborn et al., 2012). The increases in *Tritia* may also affect benthic ecosystem interactions, as it is suspected this gastropod will compete with the native *Cominella* for food (Townsend, Marshall, & Greenfield, 2010). Population numbers are currently highest at Herald Island Waiarohia and Lucas Creek, with around 40 individuals recorded from 12 cores at both sites.

All sites are exhibiting at least one trend in species abundance that is consistent with sedimentation (Table 16). Central Main Channel, Herald Island Waiarohia and Brigham Creek have the greatest number of indicative trends and some of these began within the last five years, suggesting sedimentation is an ongoing pressure at these sites. For instance, the polychaete *Cossura* began increasing in abundance at both sites around 2017, and *Prionospio* and Oligochaeta have both been increasing at Brigham Creek since 2015. There are few trends across the Upper Waitematā that are consistent with metal contamination, and although the bivalve *Linucula* is somewhat sensitive to copper and has decreased at four sites, these decreases occurred prior to 2011 at Hellyer's Creek, Lucas Creek and Central Main Channel. More recent declines have occurred at Herald Island North (since 2016), which may be signalling a more recent issue.

Table 16. Comparison of trends in abundance of common monitored species at Upper Waitematā sandflat sites between Nov. 2005 and Nov. 2019. An upward arrow represents an increase in abundance and a downward arrow a decrease. Grey cells indicate trends that are less certain or uncertain and sites exhibiting multi-year cycles (MY) are shown. Arrows are coloured to highlight trends consistent with a particular stressor: sedimentation (orange), metal contamination (blue) or both (green). Pref = sediment preference; SS = strong preference for sand, S = prefers sand, M = prefers some mud but not in high percentages, MM = strong mud preference.

Monitored species	Pref	Hellyer's Creek	Herald Island North	Herald Island Waiarohia	Lucas Creek	Rangitopuni Creek	Brigham Creek	Opposite Hobsonville	Central Main	Upper Main	Outer Main
Oligochaeta	MM					▲	▲MY				
Aricidea sp.	M		▼MY	▲MY							▲MY
Arthritica bifurca	M					▼	▼				▲MY
Austrohelice crassa	M					▲MY		▼MY		▲	
Capitellidae	M									▲	
Cossura consimilis	M	▼MY			▼		▲MY		▲MY		
Heteromastus filiformis	M						▲	▲	▲MY		
Nereididae	M	▲	▲	▲MY					▲		▼
Prionospio aucklandica	M	▲MY	▲MY		▲		▲	▲	▲MY	▲	▲
Polydorids	M		▲MY	▲MY							
Austrovenus stutchburyi	S	▼	▲MY	▼	▲MY						▲
Linucula hartvigiana	S	▼	▼MY		▼MY				▼		
Macomona liliana	S	▼		▼	▼			▼	▼		▼
Corophiidae	-	▼			▼			▼	▼	▼	
Phoxocephalids	-	▼MY	▼MY	▼MY		▼MY	▼	▲	▼MY		▼MY
Paradoneis lyra	-	▼					▲MY				
Levinsenia gracilis	-			▼	▼						
Pseudopotamilla sp.	-	▼	▼			▲	▲			▲MY	
Arcuatula senhousia	-			▲MY		▼	▼	▼	▼	▼	
Tritia burchardi	-	▲	▲	▲	▲MY		▲	▲	▲MY		▲
Trends consistent with sedimentation		3	3	4	2	2	4	3	5	3	4
Trends consistent with metals		2	1	1	2	0	0	1	2	0	1

Community changes

The composition of the benthic macrofaunal communities at the sandflat sites can be roughly separated into three groups (Figure 16). The first group contains Brigham Creek, Upper Main Channel and Rangitopuni Creek (the sites with the highest mud content), another with Hellyer's Creek, Opposite Hobsonville and Central Main Channel (sites with intermediate mud content) and the final one containing Herald Island North, Herald Island Waiarohia, Outer Main Channel and Lucas Creek (sites with the lowest mud content, with Lucas Creek being a slight exception). The largest amount of change in community composition over the last 10 years has occurred at Brigham Creek and to a lesser extent Upper Main Channel, suggesting the adaptation of the communities to muddier sediments are ongoing. There does not appear to be sustained directional change of the community at any sites, but Herald Island Waiarohia may be becoming more alike the muddy sites.

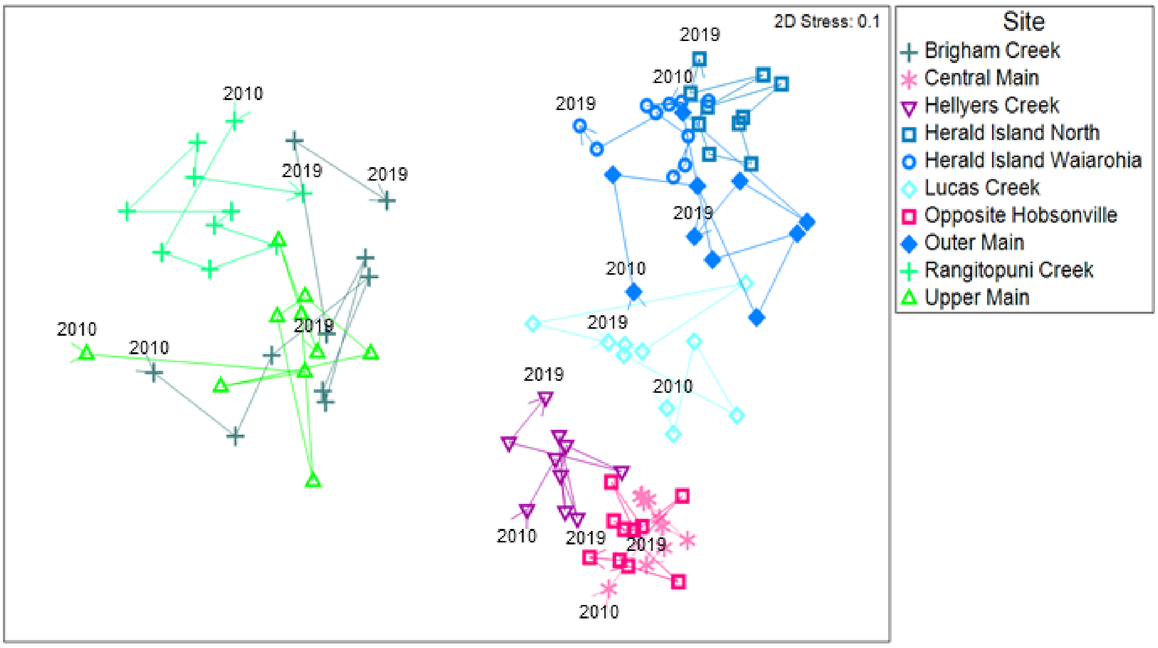

Figure 16. The similarity in macrofaunal community composition between Upper Waitematā Harbour sites and changes over the last 10 years (2010-2019, based on October data).

Benthic health

There are three tidal creek sites with sufficient data for trend analyses (Hellyer's Upper, Lucas Upper and Paremoremo) and the current state of an additional site (Lucas Te Wharau) is shown in the map of current combined health scores. Several of the sandflat sites in the mid-section of the Upper Waitematā have degraded in health in relation to metals: Hellyer's Creek, Herald Island North, Herald Island Waiarohia and

Lucas Creek (Table 17). In addition, the health of Herald Island North and Lucas Creek has also degraded in relation to mud and particularly so since 2015; these sites are influenced by outflow from Oteha Stream and the wider Lucas Creek. The health of the communities at the Opposite Hobsonville and Central Main Channel sites has also degraded in relation to mud. The trends demonstrated over the monitoring period, and activities preceding benthic ecology monitoring, have resulted in the communities in sandflat sites having 'fair' or 'marginal' health with respect to metals and mud, and most are defined by low functional resilience (the Outer Main Channel site is a notable exception with high resilience) (Table 17).

Whilst all three tidal creek sites have 'marginal' health in relation to metals, there are signs of improving health at both Lucas Upper and Paremoremo (Table 17). There has been no change in the health status of the tidal creek sites in relation to mud, however, and all scored 'marginal' in 2018. Similarly, all sites have low or intermediate resilience. Most monitored sites in the Upper Waitematā currently have 'poor' overall benthic health, and no distinction between the health of sandflat versus tidal creek sites is apparent (Figure 17). Indeed, the only site scoring 'good' health is the tidal creek site Lucas Te Wharau.

Table 17 A. BHM and TBI groups at Upper Waitematā sandflat sites in 2019 and **B.** tidal creek sites in 2018. BHMs: Group 1 = excellent, Group 2 = good, Group 3 = fair, Group 4 = marginal, Group 5 = poor. TBI: high, intermediate, low. Arrows show significant trends in index scores between Oct. 2005 and Oct. 2019: an upward arrow indicates an improvement and a downward arrow a degradation in health.

A. Index	**Hellyer's Creek**	**Herald Island North**	**Herald Island Waiarohia**	**Lucas Creek**	**Rangitopuni Creek**
BHMmetals	▼ [marginal]	▼ [fair]	▼ [marginal]	▼ [marginal]	[marginal]
BHMmud	[marginal]	▼ [fair]	[marginal]	▼ [marginal]	[marginal]
TBI	[low]	[intermediate]	[low]	[intermediate]	[low]
	Brigham Creek	**Opposite Hobsonville**	**Central Main**	**Upper Main**	**Outer Main**
BHMmetals	▲ [marginal]	[marginal]	[marginal]	[fair]	[fair]
BHMmud	[marginal]	▼ [marginal]	▼ [marginal]	▲ [marginal]	[fair]
TBI	[low]	[low]	[low]	[low]	[high]
B.	**Hellyer's Upper**	**Lucas Upper**	**Paremoremo**		
BHMmetals	[marginal]	▲ [marginal]	▲ [marginal]		
BHMmud	[marginal]	[marginal]	[marginal]		
TBI	[low]	[intermediate]	[low]		

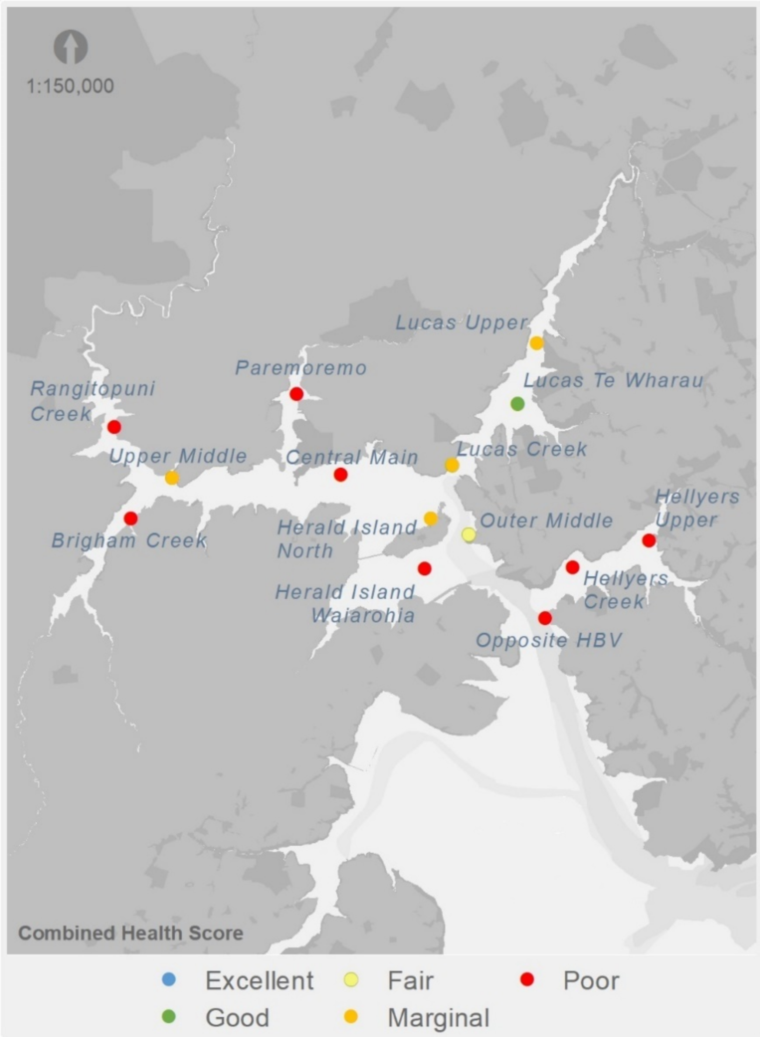

Figure 17. Combined health score for Upper Waitematā sites in 2019 (sandflat sites) and 2018 (tidal creek sites).

<u>Summary</u>

Sedimentation is the major pressure affecting the ecological health of the Upper Waitematā monitored sites. All sites show evidence of at least some impact from sedimentation, whether in tidal creeks or open sandflats. Some sites have very high sediment mud content and their ecological condition has worsened over the monitoring period (e.g. Rangitopuni Creek and Brigham Creek); it is unlikely that management intervention would enable significant recovery of these sites. The declines in the abundance of species sensitive to sedimentation and/or health at sites with comparatively low (i.e. Herald Island North) or intermediate (e.g. Lucas Creek, Central Main Channel and Opposite Hobsonville) sediment mud content are of greatest concern, however reducing sediment input to these sites could have the greatest positive outcomes. Metal contamination is a lesser concern, with most declines in sandflat health having occurred prior to 2011 and some improvements in the health of tidal creeks evident since 2005, although Herald Island North may be showing the effects of more recent contamination. Overall, the sandflats and tidal creeks of the Upper Waitematā are in poor ecological health and are either continuing to decline or are showing no signs of improvement.

The last report on the condition of the sandflat sites (based on data up to 2017; Townsend et al., 2020) found few persistent trends in the abundance of the monitored species. In the current analyses, several species displayed trends at multiple sites including *Prionospio*, *Tritia*, Phoxocephalidae and *Macomona*. Most of these new harbour-wide trends are consistent with impacts from sedimentation and signal recent impacts. The increasing trends in *Austrovenus* at the lower sandy sites previously reported are persisting, as are the increasing trends in *Heteromastus* at the mid-lower sites Central Main and Opposite Hobsonville. However, an increasing trend in *Heteromastus* was no longer detected at Lucas Creek while a new increasing trend is apparent at Brigham Creek.

3.4.2 Central

Long-term monitoring of benthic ecology in the Central Waitematā Harbour began in October 2000 (Hewitt, 2000). Initially six intertidal sites, five representing sandflats (Hobsonville, Henderson Creek, Whau River, Shoal Bay and Lower Shoal Bay) and one a rocky habitat (Meola Reef), were identified for sampling. In August 2014, the Shoal Bay sites were replaced with a new sandier site (Shoal Bay Upper) that would be better able to detect any effects of increased sedimentation (Parkes & Lundquist, 2018). In addition to these five sandflat sites, benthic health indices are presented for 17 tidal creek sites sampled under the RSCMP (16 of which have sufficient data for trend analysis) (Figure 1). A total of 27 tidal creek sites have been sampled under the RSCMP (see Appendix A).

<u>Sediment characteristics</u>

Sediment mud content has been relatively low at all sites since 2000 (median <10%; Figure 18, Table 18). There is high variability at Shoal Bay Upper and Meola Reef, however, with peaks of 18% (in February 2018) and 22% (in April 2007) being recorded, respectively. Whilst sediment mud content has increased significantly at Meola Reef (Table 19), most of these increases occurred between 2000 and 2010 and are associated with the expansion of seagrass across the site. Less certain increases in mud content have also occurred at Whau River and Henderson Creek. Mud content is highest at Meola Reef in 2019 (14%) but remains below 10% at all other sandflat sites (Figure 19). There is a greater range in mud content at the tidal creek sites, from 5% at Kendall Bay to 93% at Whau Lower, but most (11 out of 17) have >10% mud content (Figure 19).

There has been little variability in sediment organic content either between sites (median values range from 1% at Whau River to 2% at Henderson Creek) or over time within sites (Table 18). The concentrations at the monitored sites are typical of those found in sandflats throughout New Zealand (Pratt et al., 2014), and there have been no significant changes over time (Table 19). Sediment chl *a* has shown greater between-site variability, with Meola Reef having the lowest median concentration (8 µg g^{-1} dw sediment) and Henderson Creek the highest (26 µg g^{-1} dw sediment). Significant trends have occurred at several sites but these are not consistent across the sub-harbour; concentrations have decreased at Shoal Bay Upper and Meola Reef (to the east) and increased at Whau River and Henderson Creek (to the west). These increasing trends may be highlighting an increase in nutrient delivery from the Whau River and Henderson Creek catchments, which complements the trends of increasing mud at these sites given terrestrial sediments are often also rich with nutrients.

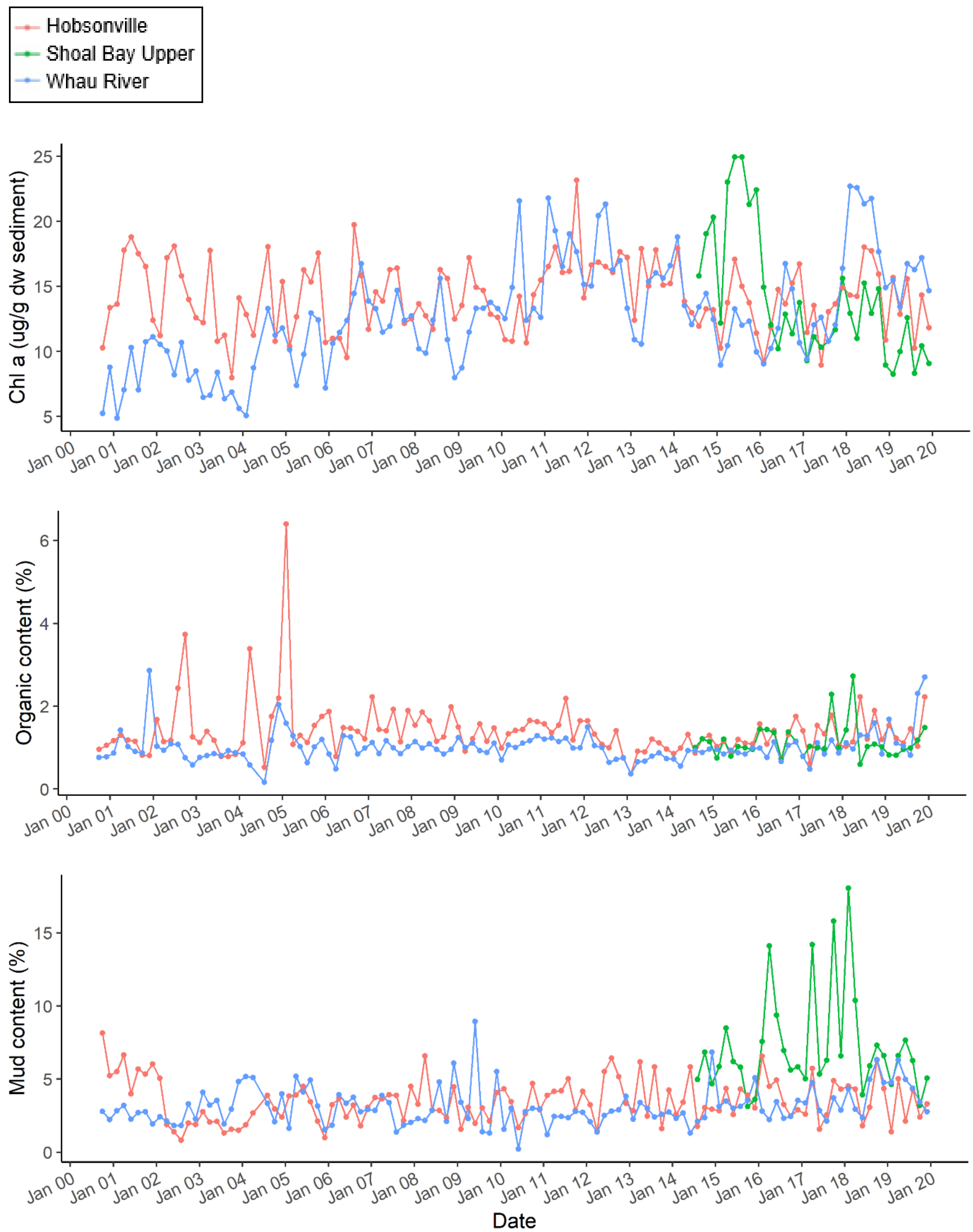

Figure 18. Surface sediment characteristics in core Central Waitematā sites between 2000 and 2019.

Table 18. Median and temporal variation (standard deviation) of surface sediment characteristics at Central Waitematā monitored sites between 2000 and 2019.

	Hobsonville		Shoal Bay Upper		Whau River		Henderson Creek		Meola Reef	
	Med	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**	**Med**	**SD**
Mud content (%)	3.26	1.47	6.22	3.56	2.85	1.32	6.25	2.85	7.65	3.89
Organic content (%)	1.25	0.68	1.02	0.43	0.97	0.38	2.18	0.64	1.48	0.80
Chl *a* ($\mu g\ g^{-1}$ dw sediment)	14.11	2.71	12.38	4.87	12.40	4.03	25.63	5.45	7.92	3.01

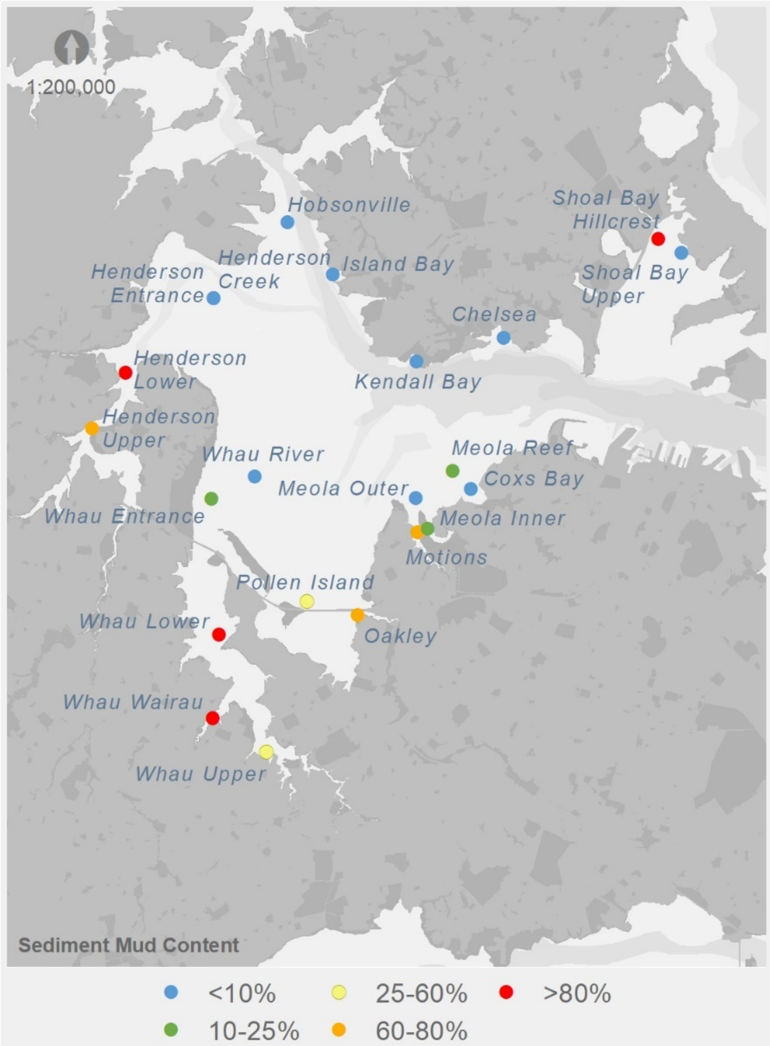

Figure 19. Most recent mud content in Central Waitematā ecology sites (measured in 2018 or 2019).

Table 19. Direction of statistically significant trends in sediment characteristics in Central Waitematā between 2000 and 2019. Grey cells indicate trends that are less certain or uncertain.

	Hobsonville	Shoal Bay Upper	Whau River	Henderson Creek	Meola Reef
Mud content (%)			▲	▲	▲
Organic content (%)					
Chl *a* (μg g^{-1} dw sediment)		▼	▲	▲	▼

<u>Species abundance</u>

Macrofaunal sampling in the Central Waitematā focuses on 20 key species. Of these, all except the polychaete *Glycera* have exhibited significant change in their abundance at at least one site. The anemone *Anthopleura* prefers sandy sediments and has increased in abundance at all sandflat sites (Table 20). Whilst this could be interpreted as evidence of improving sediment conditions, there are more species that are showing trends consistent with sedimentation at multiple sites. For instance, the polychaetes *Aricidea* and *Boccardia* have increased at all sites except Shoal Bay Upper and prefer slightly muddy sediments. Additionally, the polychaete *Heteromastus*, cumacean *Colurostylis*, gastropod *Diloma* and bivalve *Arthritica* prefer silty sediments and have increased in abundance at three sites, and the functionally important bivalve *Macomona* has a low tolerance for sedimentation and has decreased at three sites. The greatest number of trends consistent with sedimentation have occurred at Meola Reef and Whau River.

The small bivalve *Linucula* is somewhat sensitive to copper and prefers sediments with <12% mud content (Anderson et al., 2007; Hewitt et al., 2009; Thrush et al., 2003). The decreases in the abundance of *Linucula* at all sites except Shoal Bay Upper is a potential sign of metal contamination, but could also be reflecting increases in sediment mud content at Whau River, Henderson Creek and Meola Reef (Table 19).

Table 20. Comparison of trends in abundance of monitored species at all Central Waitematā sites between Oct. 2000 and Dec. 2019 (except Shoal Bay Upper which is from Aug. 2014). An upward arrow represents an increase in abundance and a downward arrow a decrease. Grey cells indicate trends that are less certain or uncertain and sites exhibiting multi-year cycles (MY) are shown. Arrows are coloured to highlight trends consistent with a particular stressor: sedimentation (orange), metal contamination (blue) or both (green). Pref = sediment preference; SS = strong preference for sand, S = prefers sand, M = prefers some mud but not in high percentages, MM = strong mud preference.

Monitored species	Pref	Hobsonville	Shoal Bay Upper	Whau River	Henderson Creek	Meola Reef
Aricidea sp.	M	▲		▲	▲MY	▲
Arthritica bifurca	M	▲MY		▲MY	▲	
Boccardia syrtis	M	▲MY	▼MY	▲MY	▲MY	▲
Heteromastus filiformis	M	▲MY	▼MY		▲MY	▲
Macroclymenella stewartensis	M				▼MY	
Prionopsio aucklandica	M	▲MY				▲MY
Anthopleura aureoradiata	S	▲MY	▲	▲MY	▲	▲MY
Austrovenus stutchburyi	S	▲		▲		▼MY
Linucula hartvigiana	S	▼MY		▼MY	▼MY	▼
Macomona liliana	S		▼	▼MY	▲MY	▼MY
Aonides trifida	SS			▼MY	▲	
Colurostylis lemurum	SS	▲MY		▲	▲MY	▼
Notoacmea scapha	SS					▲
Diloma subrostrata	-	▲MY		▲	▲MY	▼MY
Euchone sp.	-					▼MY
Exosphaeroma spp.	-	▼MY		▼		
Glycera americana	-					
Haminoea zelandiae	-		▼	▼MY		
Paphies australis	-	▲		▼		
Zeacumantus lutulentus	-		▼MY		▲MY	▼MY
Trends consistent with sedimentation		5	1	5	4	6
Trends consistent with metals		1	2	3	2	4

Community changes

The benthic macrofaunal communities at the Whau River and Henderson Creek sites are the most similar of the Central Waitematā sandflats (Figure 20), perhaps owing to their sediment characteristics trending in the same direction (Table 19). All other sites are distinct from one another, with Meola Reef showing the most dissimilar community composition. The community at the Whau River site has shown the greatest amount of change over the last 10 years, but there were also notable shifts at Meola Reef, and to a lesser extent Henderson Creek, between 2015 and 2016 that will be important to contextualise with the next scheduled sampling.

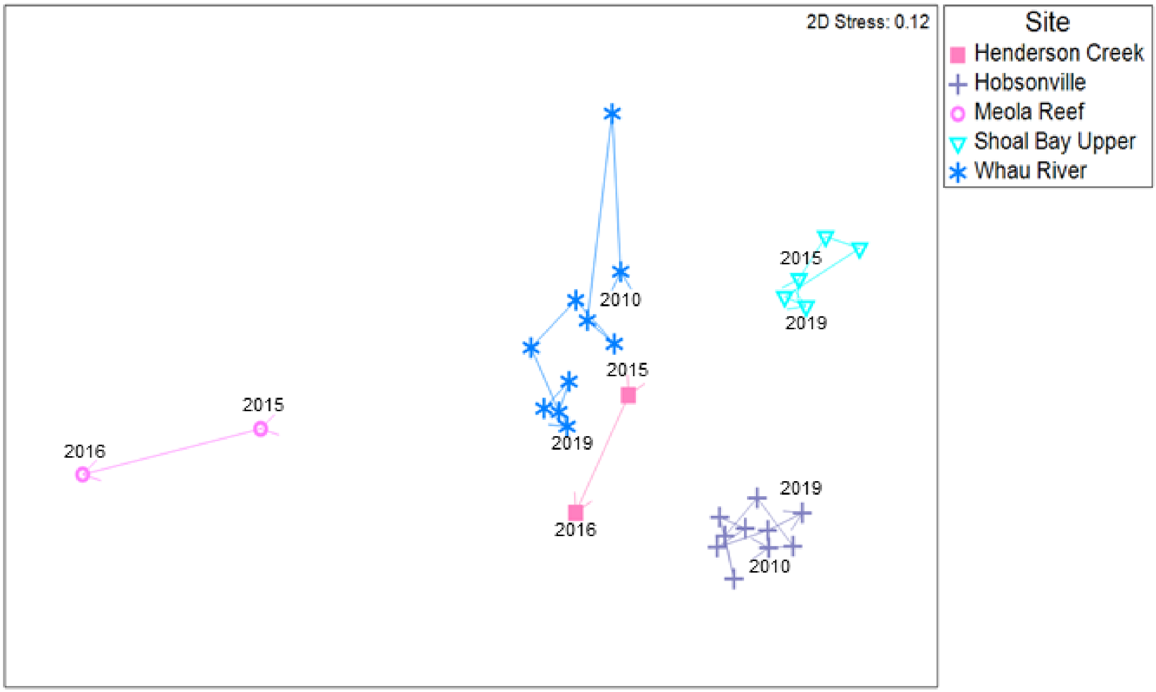

Figure 20. The similarity in macrofaunal community composition between Central Waitematā Harbour sites and changes over the last 10 years (2010-2019, based on October data).

<u>Benthic health</u>

In addition to the sandflat ecology sites, 16 tidal creek sites have benthic health data suitable for trend analysis and an additional two sites (Island Bay and Henderson Entrance) have combined health scores mapped (Figure 21).

Only two of the sandflat sites have exhibited significant trends in community health related to metals and these are in opposing directions: there has been an increase in health at Henderson Creek and a decrease at Meola Reef (Table 21A). Health has also declined in relation to mud at Meola Reef, in line with the numerous trends in species abundance consistent with sedimentation (Table 20), as well as at Hobsonville. Despite this, communities at all sandflat sites except Shoal Bay Upper have shown increases in their functional resilience over the course of monitoring. Currently, the health of the sandflat communities is 'good' or 'fair' in relation to metals and 'excellent' to 'fair' in relation to mud, and all sites have high functional resilience (improving trends have resulted in Whau River having high resilience since 2003 and Henderson Creek and Hobsonville since 2004).

There have been more consistent trends in community health in the tidal creeks, with seven sites having increased in health in relation to metals (including three sites within Whau Estuary (Whau Upper, Whau Wairau, Whau Lower) and two close to Meola Reef (Meola Inner and Motions)) (Table 21B). Each of the sites where health has improved currently have 'fair' or 'marginal' health, and the sites with no trends in relation to metals have 'good' to 'marginal' health. Contrastingly, the only trends in community health related to mud are declines (occurring at Coxs Bay, Meola Reef and Meola Outer). Although declines at three out of 16 sites is not initially alarming, eight out of the 16 sites are currently in 'marginal' health related to mud and are showing no improvement, and the three sites with declining health are currently considered 'good' or 'fair' and therefore represent a degradation of some of the best condition tidal creeks.

The functional resilience of the tidal creek communities is variable with no clear spatial pattern and little change over time. A significantly improving trend was detected at Whau Wairau and although the functional resilience remains low, the score at this site is now approaching the threshold of intermediate resilience (0.3); the average score over the last three sampling occasions was 0.26, compared to 0.16 over the first three. Overall, the monitored sandflat sites are in 'good' or 'fair' health, whilst the health of the tidal creek sites ranges from 'good' to poor' (Figure 21).

Table 21 A. BHM and TBI groups at Central Waitematā sandflat sites in 2019 (except Henderson Creek and Meola Reef which is 2016) and **B.** tidal creek sites in 2018 or 2019. BHMs: Group 1 = excellent, Group 2 = good, Group 3 = fair, Group 4 = marginal, Group 5 = poor. TBI: high, intermediate, low. Arrows show significant trends in index scores between Oct. 2000 and Oct. 2019: an upward arrow indicates an improvement and a downward arrow a degradation in health.

A. Index	**Hobsonville**	**Shoal Bay**	**Whau River**	**Henderson Creek**	**Meola Reef**			
BHMmetals				▲	▼			
BHMmud	▼				▼			
TBI	▲		▲	▲				
B.	**Coxs Bay**	**Meola Reef**	**Meola Inner**	**Meola Outer**	**Chelsea**	**Henderson Lower**	**Henderson Upper**	**Motions**
BHMmetals	▼		▲					▲
BHMmud	▼	▼		▼				
TBI								
	Oakley	**Pollen Island**	**Shoal Bay**	**Kendall Bay**	**Whau Wairau**	**Whau Upper**	**Whau Lower**	**Whau Ent.**
BHMmetals		▲	▲		▲	▲	▲	
BHMmud								
TBI					▲			

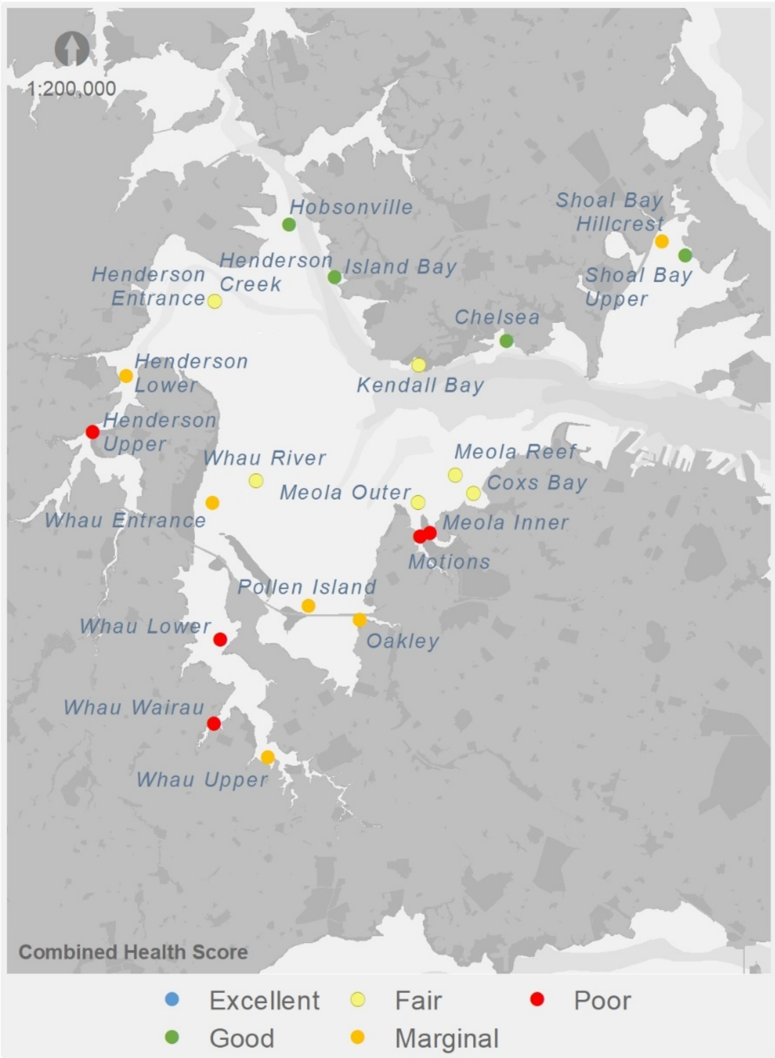

Figure 21. Most recent combined health score for Central Waitematā sandflat and tidal creek sites (scores are from 2018 or 2019).

Summary

Overall, sedimentation is the dominant driver of change for the intertidal benthic environments of the Central Waitematā. Open sandflat sites are characterised by low mud and organic content and their associated macrofaunal communities are in reasonable health. There have been concerning changes in ecology related to sedimentation at all sites except Shoal Bay Upper, and particularly at Meola Reef and Whau River (although much of the change at Meola Reef occurred prior to 2010). Nutrient enrichment from Whau River and Henderson Creek may be an issue and requires continued close monitoring. The tidal creek sites vary in their overall health, but many have shown improvements in relation to metal contaminants. Conversely, sedimentation continues to be a problem for these locations.

There has been no change in the number of species trends indicative of sedimentation at Hobsonville (five) or Henderson Creek (four) since last reported by Parkes and Lundquist (2018), but there has been an increase at Meola Reef (from five to six). Given the different macrofaunal community favoured by seagrass habitats (which now dominate the Meola Reef site), this increase is not necessarily of concern but should be monitored closely. When previously reported, trends associated with increased sedimentation were seemingly confined to areas around Meola Reef, Henderson Creek and Hobsonville, but there are now several such trends occurring at Whau River also.

3.4.3 Outer

There are 11 tidal creek sites from the Outer Waitematā with data available for state and trend analyses. These sites are from Hobson Bay (Purewa, Whakataka and Awatea) and Tamaki Estuary (Middlemore, Princes St., Otahuhu Creek, Pakuranga Upper, Pakuranga Lower, Bowden, Panmure and Benghazi) (see Figure 22). Sediment mud content is high at all sites, ranging from 23 to 90% (Figure 22A). There is some spatial distinction, though, as mud content is generally higher in Tamaki Estuary than Hobson Bay.

Community health related to metal contaminants has improved in both Hobson Bay (at Purewa) and Tamaki Estuary (at Middlemore, Pakuranga Upper and Panmure) (Table 22). As of 2019, all sites have ‘fair’ or ‘marginal’ health related to metals. In contrast, there have been very few trends in health related to mud in the Outer Waitematā, with a single degrading trend occurring at Middlemore; this site is currently in ‘marginal’ health with respect to mud. Health related to mud follows the pattern in sediment mud content, as Hobson Bay sites score ‘good’ or ‘fair’ whilst the Tamaki Estuary sites are predominantly ‘marginal’ (the two sites nearest the mouth of the estuary are exceptions).

There has been little change in the functional resilience of the Outer Waitematā sites. Purewa and Benghazi have exhibited significantly improving trends in TBI, resulting in these sites having mostly high functional resilience since 2010 and 2012 (both had mostly intermediate resilience prior to this) (Table 22). The remaining sites score variably, but most have ‘intermediate’ resilience. Overall, the Outer Waitematā tidal creek sites have ‘fair’ to ‘poor’ health (Figure 22B).

Table 22. BHM and TBI groups at all Outer Waitematā sites in 2019. BHMs: Group 1 = excellent, Group 2 = good, Group 3 = fair, Group 4 = marginal, Group 5 = poor. TBI: high, intermediate, low. Arrows show significant trends in index scores between Oct. 2000 and Oct. 2019: an upward arrow indicates an improvement and a downward arrow a degradation in health.

Index	Purewa	Whakataka	Awatea	Middlemore	Princes St.	Otahuhu Creek
BHMmetals	▲			▲		
BHMmud				▼		
TBI	▲			▼		
	Pakuranga Upper	**Pakuranga Lower**	**Bowden**	**Panmure**	**Benghazi**	
BHMmetals	▲			▲		
BHMmud						
TBI					▲	

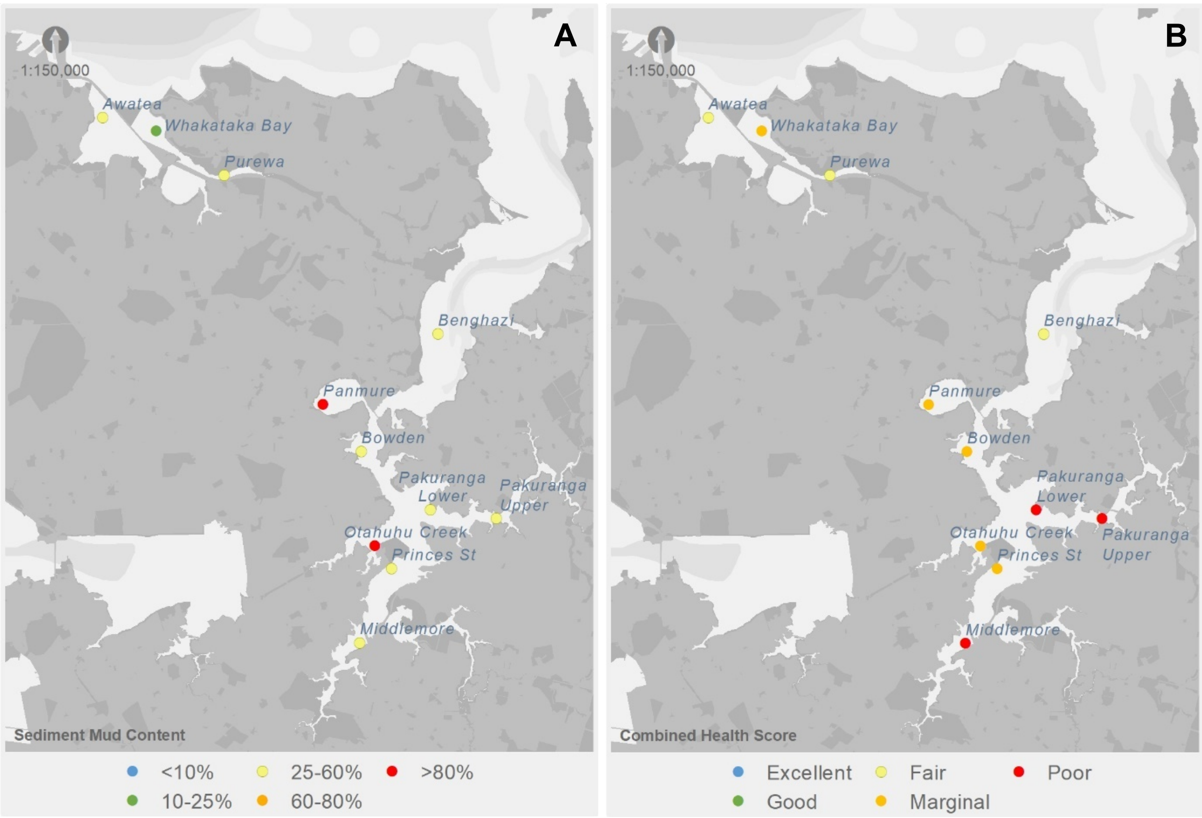

Figure 22. Most recent **A.** sediment mud content and **B.** combined health score in the Outer Waitematā sites (measured from 2016-2019).

3.5 East Coast Estuaries

The East Coast Estuaries monitoring programme was recently reported on with the inclusion of data up to April 2018 (see Hewitt and Carter (2020)). As the analyses undertaken for this report include only an additional three data points (October 2018, April 2019 and October 2019), changes to trends in sediment characteristics and macrofaunal indices are subtle and therefore only key findings will be summarised for each estuary. For more detailed discussion of trends and patterns in individual variables refer to Hewitt and Carter (2020).

3.5.1 Whangateau

Whangateau drains part of the North East catchment (according to Auckland Council's Consolidated Receiving Environments) which is dominated by rural land use types (60% of the area in 2018) and has significant areas of native (24%) and exotic (11%) forest. The estuary is characterised by two major branches, one draining the Omaha River and another longer arm that drains several small streams. Site 1 is in the upper and site 4 is in the middle of the longer arm, while site 7 is in the lower part of the Omaha River arm. The median very fine sand + mud content at all three sites is <20%, and the only significant trend has been a slight decrease at site 1 (Table 23 and Table 24). The sites have had low sediment organic content and intermediate concentrations of chl *a*, and there have been no significant changes in these variables.

The polychaetes *Heteromastus* + *Barantolla* have increased at all core sites and *Aricidea* has at sites 4 and 7, and each are indicative of increased sedimentation (Table 25). Both *Heteromastus* + *Barantolla* and *Aricidea* began increasing in abundance at site 4 in 2016 and continue to do so, whereas the abundance of *Heteromastus* + *Barantolla* has seemingly been decreasing at sites 1 and 7 since 2018, potentially signalling a return to more sandy conditions. In addition, the bivalve *Austrovenus* increased at all three sites and has a low tolerance for muddy sediments. Only one trend consistent with metal contamination was recorded (at site 1), although this is uncertain.

The macrofaunal community composition is distinctive between the core sites and has exhibited substantial change over the last 10 years at each (Figure 23). Whilst sites 4 and 7 are shifting in the same direction, and therefore likely due to sedimentation, the direction of change is more variable at site 1 and may also be reflecting metal contamination.

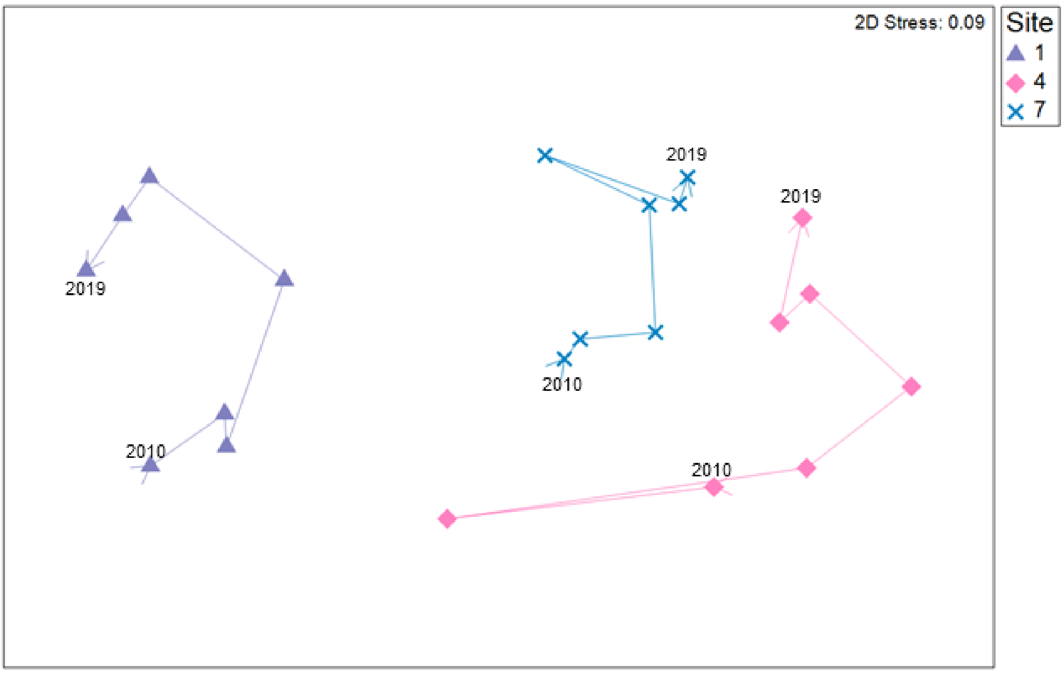

Figure 23. The similarity in macrofaunal community composition between Whangateau core sites and changes over the last 10 years (2010-2019, based on October data).

Health has been ‘good’ over the last five years in relation to both metals and mud at sites 1 and 4, but there has been a decline to ‘fair’ health at site 7 in the last two years (Table 26). This suggests outflows from the Omaha River may be affecting this site, and is consistent with the findings of Hewitt and Carter (2020) who reported a degradation at this site according to the east coast estuaries-specific metric referred to as CAPmud. Nonetheless, all core sites have high functional resilience in 2019 (Table 27). When summarising the health of the core sites according to the combined health score, sites 1 and 4 have ‘good’ health and site 7 is ‘fair’. Overall, all sites in Whangateau have ‘good’ or ‘fair’ benthic health (Figure 33).

3.5.2 Puhoi

Puhoi is a winding estuary within the Hibiscus Coast catchment that is sheltered by a large sandspit. The catchment is characterised by a variety of land use types: rural land uses comprised 38% of the total catchment area in 2018, while native vegetation and urban development each occupied 25%. The core sites, 1, 4 and 7, are located on sand banks in the centre of the channel in the outer, middle and upper parts of the estuary. Median very fine sand + mud has been lowest at site 1 (median value 7%) and highest at site 7 (40%) and has increased significantly at site 7 since 2004. Both organic content and chl *a* are low at the core sites (median values <1.5% and <10 µg g[1] dw sediment, respectively) and there have been no trends suggesting nutrient enrichment over the monitoring period (Table 23 and Table 24).

Multiple species are exhibiting trends consistent with increased sedimentation (Table 25), with at least one occurring at each site. While some of these trends do not reflect recent changes in sedimentation (e.g. the mud-sensitive polychaete *Aonides* has frequently been absent from site 4 samples since 2010, and the declines in *Colurostylis* at site 7 also occurred prior to 2010), some trends at site 7 have persisted since the start of monitoring (e.g. the increases in *Heteromastus* and *Prionospio*). The increase in *Aricidea* at site 1 is also indicative of recent changes in sediment condition as the polychaete prefers slightly muddy sediments and has been found in low numbers since 2015.

Four trends consistent with metal contamination were recorded at the core sites, with two each occurring at sites 4 and 7. Only one of these trends is certain, however, and none began within the last five years so it is unlikely they reflect a current contamination issue. The macrofaunal communities at sites 1, 4 and 7 are distinctive and there has been little change over the last 10 years at site 4, whereas sites 1 and 7 have been more variable with a large shift occurring recently at site 1 (Figure 24).

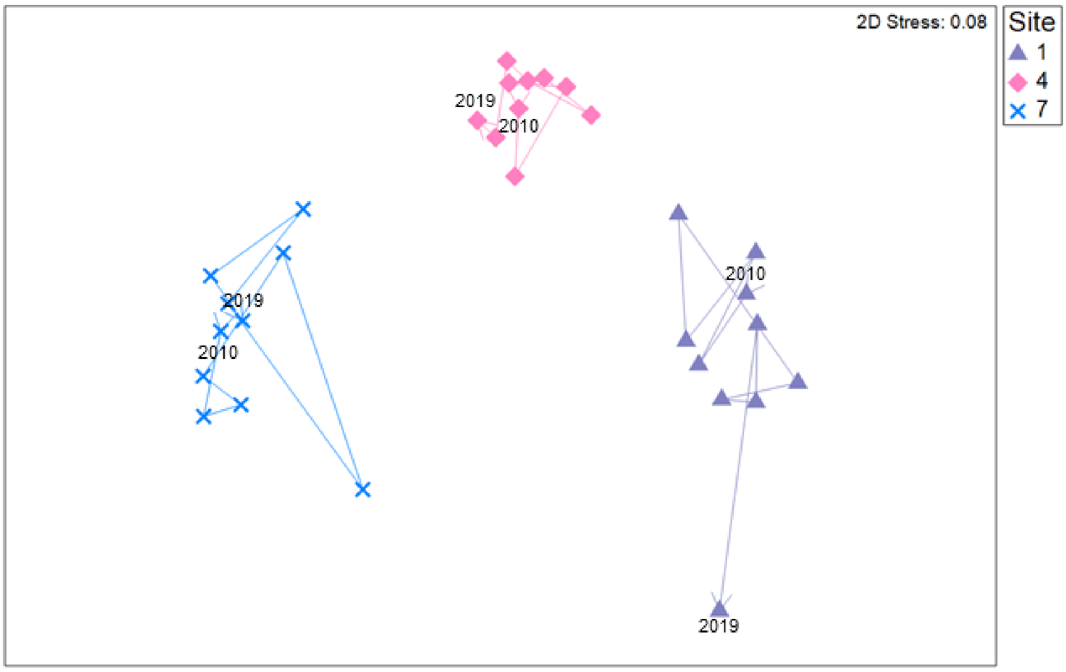

Figure 24. The similarity in macrofaunal community composition between Puhoi core sites and changes over the last 10 years (2010-2019, based on October data).

The core sites all have ‘good’ health with respect to metals in 2019, but site 1 has been mostly ‘excellent’ over the last five years (Table 26). Health has mostly been ‘good’ in relation to mud, but there are some spatial patterns with site 1, the most seaward site, scoring ‘excellent’ over the last three years and site 7, in the upper estuary, occasionally scoring ‘fair’. Conversely, functional resilience is low at site 1 and high at site 7 and has shown no significant change over time (Table 27).

Overall, sites 1 and 4 are in ‘good’ health while site 7 is ’fair’ regarding the combined health score. When considering all Puhoi sites, health ranges from ‘excellent’ to ‘marginal’ with five of the 10 sites scoring ‘marginal’ but no spatial pattern is apparent (Figure 33). There have been no notable changes in the state or trends observed at the core Puhoi sites since reported by Hewitt & Carter (2020).

3.5.3 Waiwera

Waiwera is also within the Hibiscus Coast catchment and the monitored core sites are sites 1, 3 and 8. Although site 1 is closest to the estuary mouth, it is in a sheltered arm fed by several small streams and has had a much higher proportion of very fine sand + mud than sites 3 and 8 (median of 47% at site 1 versus <10% at sites 3 and 8) (Table 23). The only certain significant change has been an increase in fine sediments at site 1 (Table 24).

None of the monitored species have exhibited changes at all three core sites (Table 25), although there has been at least one significant change consistent with increased sedimentation at each site. The greatest number of trends consistent with sedimentation have occurred at site 8 and while multi-year cycles mask the start of the trend for *Prionospio* and *Colurostylis*, the increases in *Heteromastus* + *Barantolla* and Capitellids + Oligochaeta began between 2011 and 2013. An uncertain increasing trend in the abundance of *Macomona* has reappeared at site 8 (this has been apparent previously but was not detected by Hewitt & Carter (2020)) and a new uncertain decreasing trend is evident at site 1, but these are both likely a result of multi-year cycles. The macrofaunal assemblages have been distinct over the last 10 years and although there has been considerable variability in all three, there is no consistency in the direction of change suggesting no estuary-wide stressor is affecting community composition (Figure 25).

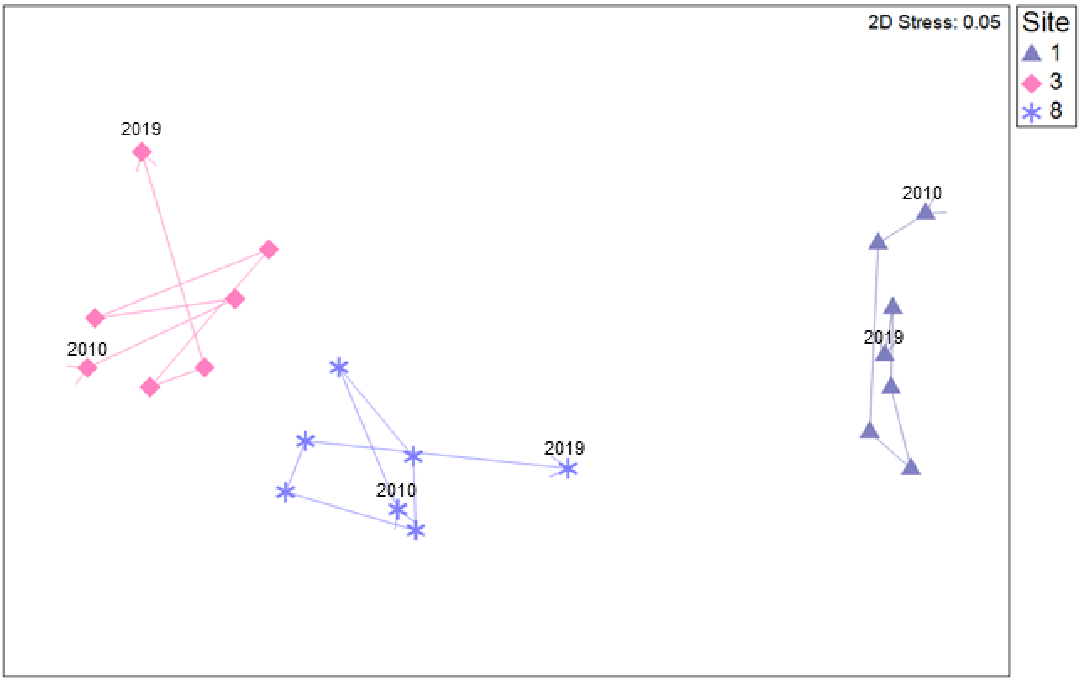

Figure 25. The similarity in macrofaunal community composition between Waiwera core sites and changes over the last 10 years (2010-2019, based on October data).

The most sheltered site, site 1, has had the lowest health of the core sites over the last five years, scoring ‘fair’ with respect to metals and ‘marginal’ with respect to mud (Table 26). Contrastingly, site 3 has been in mostly ‘good’ health in relation to both stressors and has increased to ‘excellent’ in the last two years, while the reverse pattern has occurred at site 8 which has had mostly ‘excellent’ health but has declined to ‘good’ in 2019 (Table 26). It will be important to see if the decline at site 8 persists, as this may be the start of a lasting degradation in health given the multiple trends associated with increased sedimentation at this site. Functional resilience is variable between the core sites, being intermediate at site 1, low at site 3 and high at site 8 (Table 27). Overall, health at site 1 is ‘marginal’, site 3 is ‘excellent’ and site 8 is ‘good’ according to the combined health score; this broad range in health is characteristic of the suite of sites in Waiwera (Figure 33).

3.5.4 Orewa

Orewa is also within the Hibiscus Coast catchment and the three core sites represent the outer (site 1), middle (site 4) and upper (site 8) parts of the estuary. Very fine sand + mud content and organic content have been lowest at site 1 and highest at site 8, whereas chl *a* has shown little variability between sites and is generally low (<5 µg g^{-1} dw sediment) (Table 23). There have been significant increases in very fine sand +

mud content and decreases in organic content and chl *a* at all three sites since 2004 (Table 24).

There are few significant trends in species abundance with none of the monitored species exhibiting trends at all three sites (Table 25). All of the trends consistent with sedimentation occur at site 4 (beginning between 2015 and 2017), and no trends indicative of metal contamination were detected. The macrofaunal community composition at sites 4 and 8 have moved in the same direction over the last 10 years, likely due to the effects of increased very fine sand + mud, yet remain distinct from one another. Site 1 has shown the least amount of change and is very dissimilar to the other core sites, possibly because the low organic content at this site is unable to support a diverse community (Figure 26).

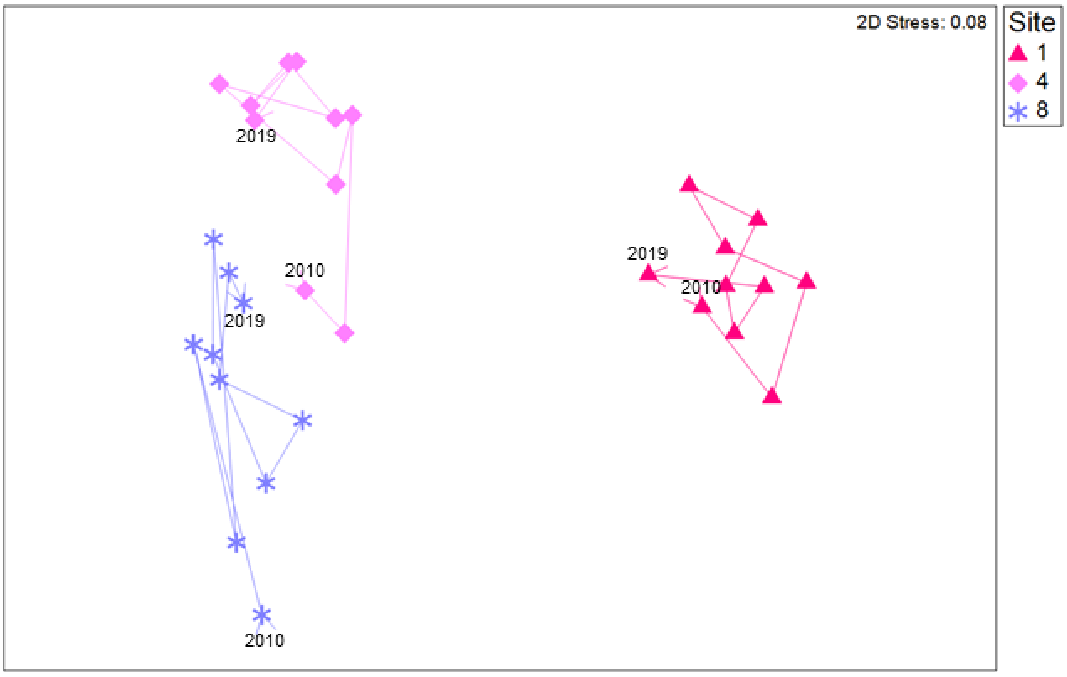

Figure 26. The similarity in macrofaunal community composition between Orewa core sites and changes over the last 10 years (2010-2019, based on October data).

There has also been little variation in BHM scores at the core sites, with all three scoring ‘excellent’ or ‘good’ with respect to metals and mud over the last four years (Table 26). Health is slightly lower with respect to mud (predominantly ‘good’) than metals (mostly ‘excellent’) and site 8 has generally lower health than sites 1 and 4. Functional resilience is high at site 4 in the mid-estuary, but is intermediate at sites 1 and 8 in 2019 (Table 27). Overall, there is a gradient in combined health score according to position in the estuary; health is ‘excellent’ at the outermost site (site 1), ‘good’ in the middle of the estuary (site 4) and ‘fair’ in the upper reaches (site 8). Most sites in Orewa have ‘good’ health (Figure 33).

3.5.5 Okura

Okura Estuary is an estuary within the Hibiscus Coast catchment that drains to Karepiro and Long Bay and is within the Long Bay-Okura Marine Reserve. All 10 sites have been monitored since 2014 following concerns that excess sediment from forestry operations and changes to land cover in the catchment could impact the estuary. Very fine sand + mud content tends to be lowest at sites nearest the estuary mouth and highest (and more variable) at sites in the upper reaches, except site 2 which is located on a depositional sandflat (Figure 27, Table 23). These very fine sediment fractions have increased at all sites since 2004 (Table 24), with the greatest rate of increase occurring at sites 9 and 10. Sediment organic content follows a similar gradient pattern as very fine sand + mud content, and the only certain trend that has occurred since 2004 is a decrease at site 4 (Table 23 and Table 24).

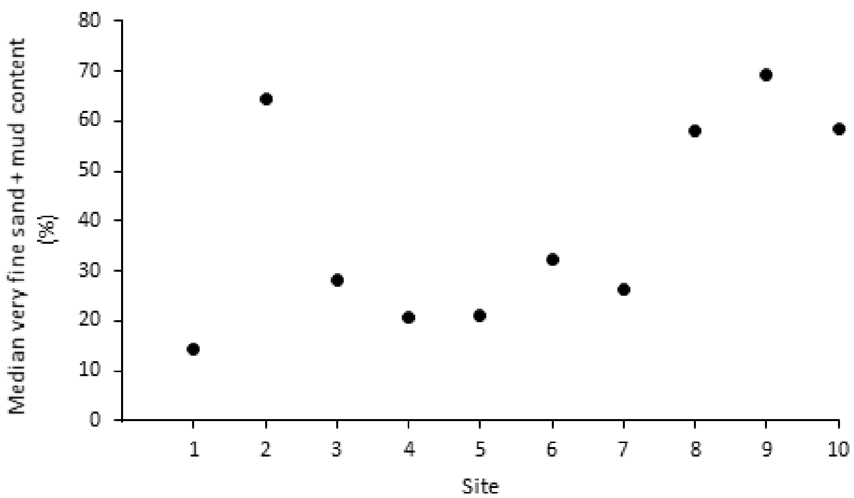

Figure 27. Median very fine sand + mud content (%) at Okura sites. Site 1 is located at the mouth of the estuary and 10 is in the upper reaches.

The Capitellids + Oligochaeta group has increased in abundance at nine of the 10 monitored sites and the polychaete *Prionospio* has at seven, while the polychaete *Aonides* has decreased at eight sites (Table 25). All of these trends are consistent with increased sedimentation and suggest an estuary-wide impact of this stressor, however many of these trends are only certain at the sites in the upper reaches of the estuary (sites 6-10) and are less certain at the outer sites (except site 2). There have also been numerous trends consistent with metal contamination and decreases in the abundance of three species sensitive to copper across the estuary are of concern (*Aonides*, *Linucula* and *Anthopleura*). Although the declines mostly occurred before 2016, there has been no recovery of these populations and *Anthopleura* continues to decline at sites 1 and 2.

The communities at each site have been mostly distinct from one another over the last 10 years, but there is some overlap in the outer estuary sites (1, 3 and 4; Figure 28A). Gradual shifts in composition are apparent according to position in the estuary reflecting proportions of very fine sediments, except for at site 2 where the community is more alike that of the sites in the upper estuary. When focusing on sites that represent the outer, middle and upper estuary (sites 1, 4 and 9) to identify changes through time, little change is apparent at sites 4 and 9 but there have been substantial shifts at site 1 (Figure 28B). All three sites are showing shifts in the same general direction, however, likely driven by sedimentation.

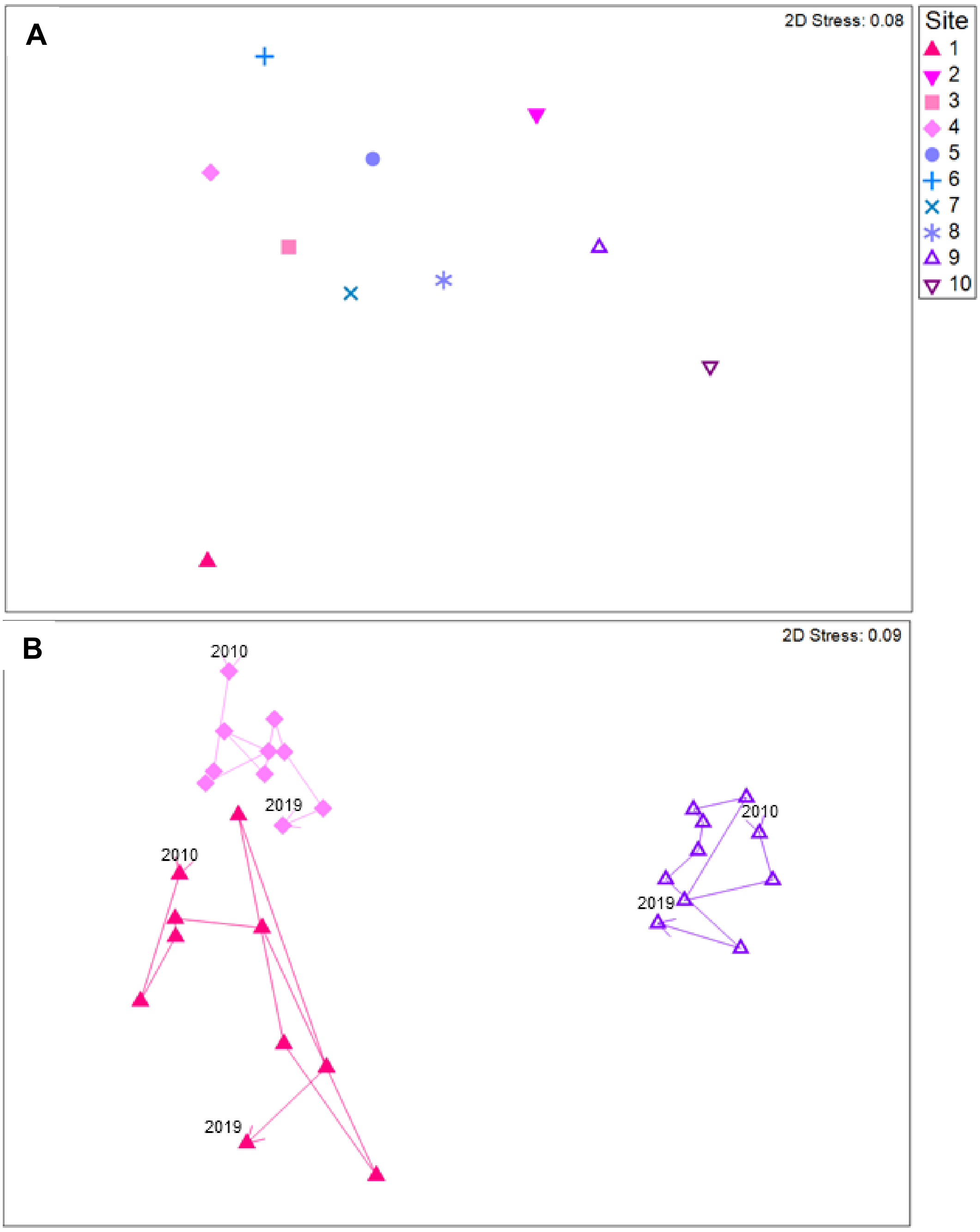

Figure 28. A. The similarity in macrofaunal community composition between Okura sites in 2019 and **B.** changes over the last 10 years (2010-2019, based on October data) at core sites.

A gradient in health according to position along the estuary is also apparent in relation to metals and mud. For instance, site 1 has had mostly 'excellent' health, site 4 has had mostly 'good' health and site 9 in the upper reaches has had generally 'fair' health (Table 26). Most sites (60%) have high functional resilience in 2019, with sites in the upper estuary being the major exception, and there has been no change at any site over the monitoring period (Table 27). Overall, sites in Okura range from ‘excellent’ to ‘fair’ health according to the combined health score, and most are ‘good’ (Figure 33).

There have been improvements from ‘good’ to ‘excellent’ health in relation to metals and mud at sites 1 and 4 since 2017 (as reported by Hewitt & Carter (2020)), and this has resulted in an improvement in their combined health score from ‘good’ to ‘excellent’. Site 4 has fluctuated between these scores since the start of monitoring, however, and site 1 has had ‘excellent’ health every year except 2017, so these improvements are unlikely to reflect a substantial improvement in health.

3.5.6 Mangemangeroa

Mangemangeroa is within the Tamaki catchment which is dominated by urban and rural land use types (55 and 28% of the total catchment in 2018). The core sites in Mangemangeroa are in the mid-lower part of the estuary. Site 3 is on the seaward side of a sandy spit and site 5 is on the sheltered estuary side, and site 6 is located on a sandbank in the centre of the channel. Very fine sand + mud content has been variable between the three sites (spanning a range of 47%), with the lowest median content occurring at site 3 and the highest at site 5. The proportion of these very fine sediments has been moderately high at all sites, however, and has increased significantly at sites 5 and 6 since 2004 (Tables 23 and 24). Median organic content is within the range typical of New Zealand sandflats whilst chl *a* concentrations are moderately high at all sites; neither variable has exhibited significant change over time (Table 23 and Table 24).

The opportunistic annelid group, Capitellids + Oligochaeta, has increased in abundance at all three sites (especially since 2009 at sites 5 and 6) (Table 25). These worms are known to be tolerant of muddy sediments and respond quickly to changes in sediment characteristics. The bivalve *Linucula* is somewhat sensitive to copper and sedimentation (Anderson et al., 2007; Hewitt et al., 2009; Thrush et al., 2003) and has also decreased at all three sites, although these trends are less certain and influenced by multi-year cycles. Nevertheless, the copper-sensitive anemone *Anthopleura* has also decreased at two of the core sites suggesting copper pollution could be affecting benthic health. Overall, there is at least one trend indicative of increased sedimentation and metal contamination at each of the core sites. Over the last 10 years the macrofaunal communities have been distinct between core sites, and while their composition has been variable through time, there has been little directional change (Figure 29).

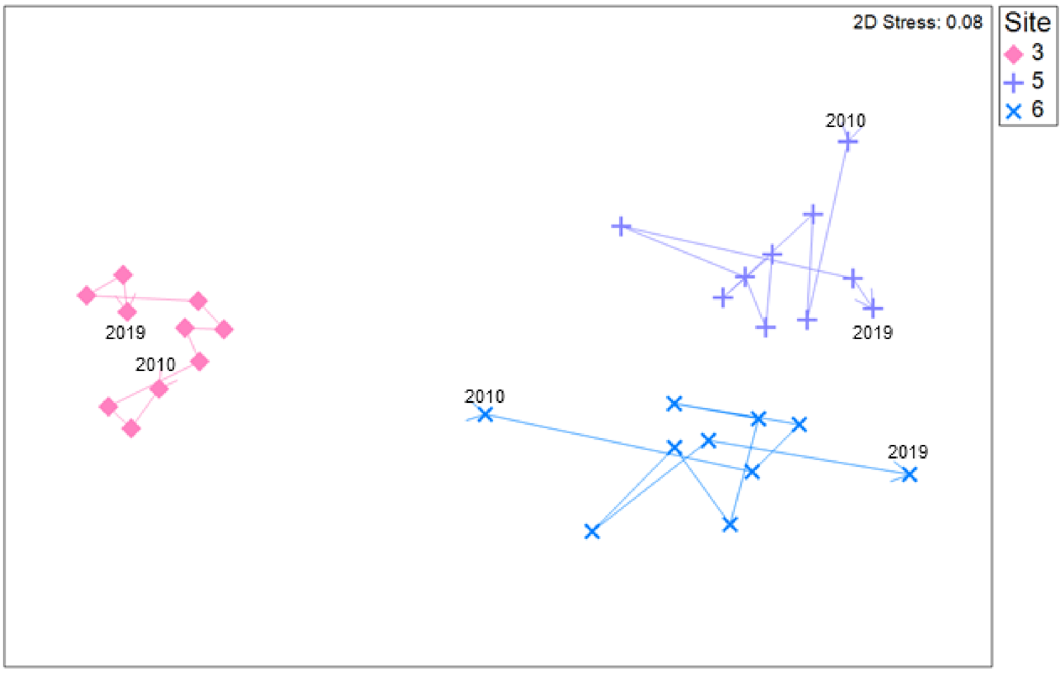

Figure 29. The similarity in macrofaunal community composition between Mangemangeroa core sites and changes over the last 10 years (2010-2019, based on October data).

When the entire macrofaunal community is considered via benthic health indices, site 3 has scored 'good' health in relation to both metals and mud over the last five years, while sites 5 and 6 have been in 'fair' health with respect to metals and mostly 'marginal' health with respect to mud. Although sites 5 and 6 have occasionally scored 'fair', it is important to consider that these indices are highly categorical and switches between groups that are not maintained may be a result of slight fluctuations in community composition, and not necessarily a meaningful change. While these fluctuations alert us to sites where the community is close to the threshold between groups, persistent shifts are more informative regarding changes in health. Functional resilience is high at sites 3 and 6 but low at site 5, and the improving trends in TBI at sites 3 and 5 reported by Hewitt and Carter (2020) were no longer detected (Table 27).

When the scores from the BHMs and TBI are combined into a 'combined health score', the exposed site 3 scores 'good' health while the more sheltered sites score 'fair' (site 6) and 'marginal' (site 5). When considering the most recent combined health score from the last five years, most Mangemangeroa sites have 'marginal' health (Figure 33).

3.5.7 Turanga

Turanga estuary is situated just south of Mangemangeroa in the Tamaki catchment and the three core sites are evenly spread along its length: site 1 is located on an exposed sandflat in the outer estuary and is minimally influenced by the outflow of Turanga Creek, site 4 is in the mid-estuary and site 7 is on a sandbank in the mid-upper estuary. The proportion of very fine sand + mud has been high at all sites (median >40%), particularly at sites 4 and 7 (medians of 80 and 70%) (Table 23), and significant increases have occurred at all sites since 2004 (Table 24). Significant decreases in organic content have occurred at the organically-poor site 1, and possibly at site 7, but there has been no change in chl *a* concentration at any site, therefore nutrient enrichment is unlikely to be affecting benthic health (Table 24).

Mud tolerant worms have increased in abundance at all core sites (Capitellids + Oligochaeta increased at all three and *Prionospio* increased at two (Table 25)), with most trends beginning in 2013. There are fewer trends indicative of metal contamination, however *Linucula* (sensitive to copper) and *Colurostylis* (sensitive to lead) have decreased in abundance at sites 1 and 7; the declines in *Linucula* occurred around 2018, while *Colurostylis* has been found in low numbers at site 7 since 2010. Sites 4 and 7 have had somewhat similar macrofaunal communities over the last 10 years and there have been shifts over time in roughly the same direction at these sites (Figure 30), suggesting a common environmental driver (likely mud) is causing these changes. The community composition is distinct at site 1, given it is in a more exposed part of the estuary and has had lower median very fine sand + mud content, and although there has been much change over the last 10 years, there is little difference in the assemblage between 2009 and 2019.

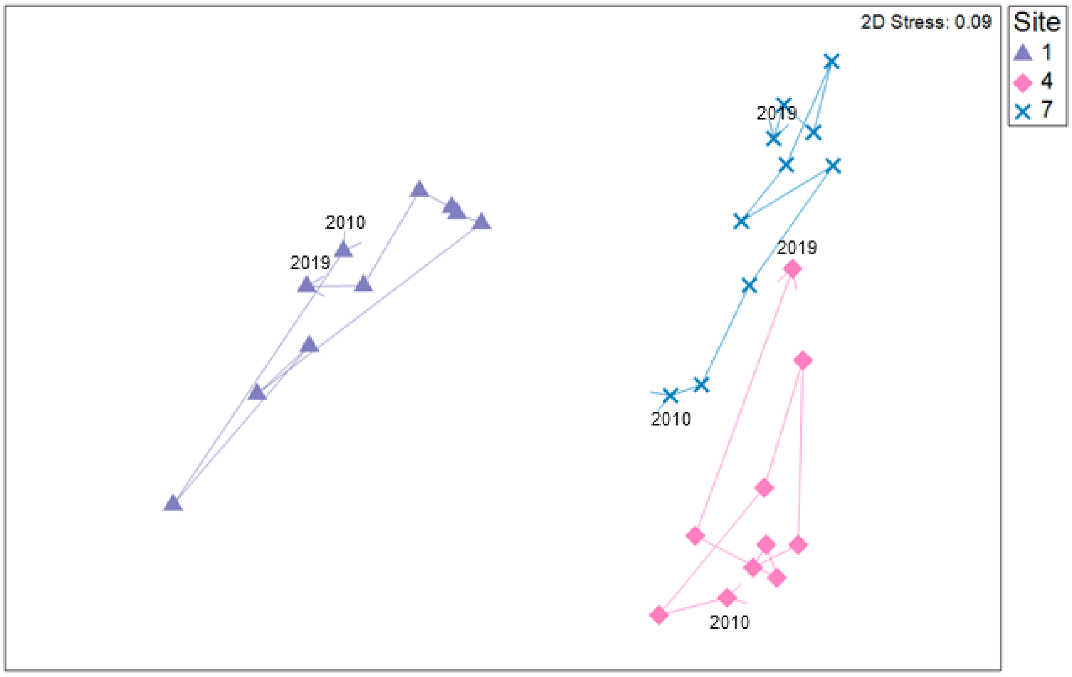

Figure 30. The similarity in macrofaunal community composition between Turanga core sites and changes over the last 10 years (2010-2019, based on October data).

The benthic community at site 1 has fluctuated between ‘excellent’ and ‘good’ health in relation to both metals and mud over the last five years, and scores ‘excellent’ in 2019 (Table 26). Despite this, the functional resilience of the community is intermediate and has not changed significantly over the monitoring period (Table 27), perhaps because the low organic content at this site cannot support a very diverse community. Health has been stable with respect to metals at sites 4 (‘fair’) and 7 (‘good’) over the last five years, and there has been little variation in health with respect to mud (site 4 is predominantly ‘marginal’ while site 7 is ‘fair’); both sites have high functional resilience in 2019 (Table 27). Overall, site 1 is in ‘excellent’ health and sites 4 and 7 are ‘fair’ according to the combined health score, and most sites in Turanga score ‘fair’ based on their most recent sampling (Figure 33). There has been no change in benthic health since reported in Hewitt and Carter (2020).

3.5.8 Waikopua

Waikopua is also within the Tamaki catchment (dominated by urban and rural land use types) and is a wide, open estuary with expansive wetlands at its head. The core sites (sites 1, 3 and 6) stretch from the outer to the mid-estuary. The proportion of very fine sediments at the core sites increases with distance from the estuary mouth (from a median of 19% at site 1 to 61% at site 6) and there have been significant increases over the monitoring period at all three sites. Organic content follows the same spatial pattern as very fine sand + mud and has been reasonably low (median <1.5% at core sites), with significant decreases recorded at site 1 (Table 23 and Table 24).

The Capitellids + Oligochaeta group have increased in abundance at all core sites, as has the ecologically important bivalve *Austrovenus* (Table 25). The increasing trends for these species appear contradictory, as increases in Capitellids + Oligochaeta are consistent with increases in sedimentation whereas *Austrovenus* is moderately sensitive to sediment deposition and suspended sediments. However, Capitellids + Oligochaeta abundances peaked between 2013 and 2016 and have been declining since at sites 1 and 6, whereas the increases in *Austrovenus* began more recently, which may be highlighting improvements in sandflat condition. Both trends consistent with metal contamination occurred at site 6, although the trend in polychaete *Aonides* is less certain owing to multi-year cycles in its abundance. Over the last 10 years, the communities at sites 1, 3 and 6 have been distinct from one another but all have exhibited large shifts over time that have caused them to become more similar (Figure 31), likely due to the increases in very fine sand + mud content.

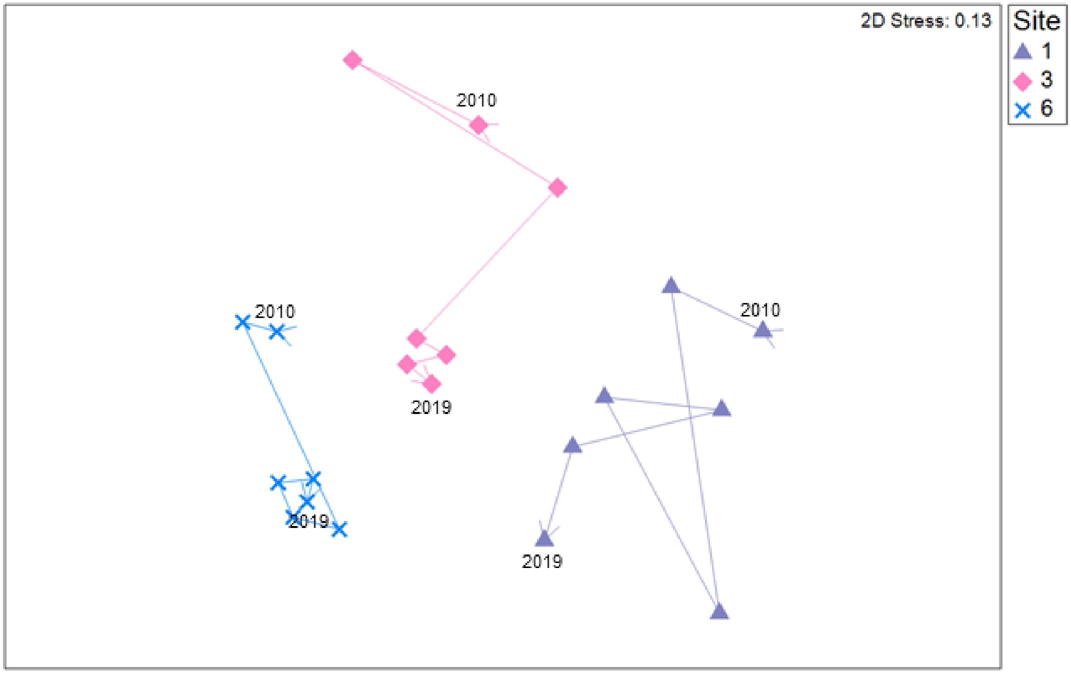

Figure 31. The similarity in macrofaunal community composition between Waikopua core sites and changes over the last 10 years (2010-2019, based on October data).

There is some evidence of a gradient in health along the estuary, decreasing from the mouth to the mid-estuary; sites 1 and 3 have had mostly 'good' health with regards to both stressors, while site 6 has been mostly 'fair' (Table 26). Between 2018 and 2019 site 1 decreased from 'good' to 'fair' health with respect to mud, and site 3 decreased from 'good' to 'fair' health with respect to metals. It will be important to see if these changes persist, however they are not supported by any trends in the monitored species and it is thus suspected they rather reflect small fluctuations around the group boundary. There have been no significant trends in TBI at the core sites and all have high functional resilience (Table 27). According to the combined health score, the outer and mid-estuary sites sampled in the last five years have 'good' or 'fair' health, while the sites in the upper reaches have 'marginal' health (Figure 33).

Table 23. Median and temporal variation (standard deviation) of surface sediment characteristics in the east coast estuary sites between 2004 and 2019, except Whangateau which is from 2009.

	Very fine sand + mud (%)		Organic content (%)		Chl *a* (µg g^{-1} dw sediment)	
	Med	**SD**	**Med**	**SD**	**Med**	**SD**
Whangateau						
1	14.19	11.03	0.78	0.17	5.32	1.17
4	8.85	13.78	0.86	0.23	9.14	1.11
7	19.89	7.19	1.01	0.40	9.40	1.69
Puhoi						
1	6.56	3.44	0.89	0.68	2.41	3.02
4	15.00	14.34	0.99	0.66	4.36	2.40
7	39.67	15.27	1.40	0.73	6.68	1.61
Waiwera						
1	47.12	11.20	2.47	1.53	10.68	1.99
3	2.49	5.74	0.81	0.47	4.06	0.49
8	6.46	6.51	1.38	0.72	7.96	1.84
Orewa						
1	14.88	12.86	0.63	0.52	4.27	0.52
4	45.48	18.29	1.04	0.67	4.31	0.84
8	62.36	19.45	1.26	0.78	4.76	1.16
Okura						
1	14.38	12.82	0.58	0.88	6.81	1.61
2	64.40	16.33	2.08	2.00	16.04	3.14
3	28.12	15.77	1.24	1.12	12.57	2.84
4	20.53	12.68	0.98	0.92	9.05	2.13
5	21.16	6.88	0.87	1.24	7.57	1.90
6	32.20	15.00	1.18	1.77	9.73	2.70
7	26.32	10.94	1.05	1.05	10.66	3.03
8	58.03	19.38	1.51	1.95	10.66	3.82
9	69.39	21.21	1.90	3.18	12.83	3.40
10	58.38	22.95	1.84	2.35	14.18	3.17
Mangemangeroa						
3	24.13	11.66	1.81	1.95	16.27	3.49
5	71.25	19.79	2.33	1.37	17.89	2.63
6	54.05	19.65	1.94	1.56	15.23	2.93
Turanga						
1	41.88	18.06	0.61	2.73	4.40	0.72
4	80.27	23.94	1.50	0.97	12.55	5.04
7	69.72	21.43	1.90	7.67	17.65	4.24
Waikopua						
1	18.72	11.46	0.66	0.53	5.65	2.06
3	50.11	17.23	0.97	1.31	7.98	1.42
6	60.79	19.10	1.21	0.72	11.91	1.98

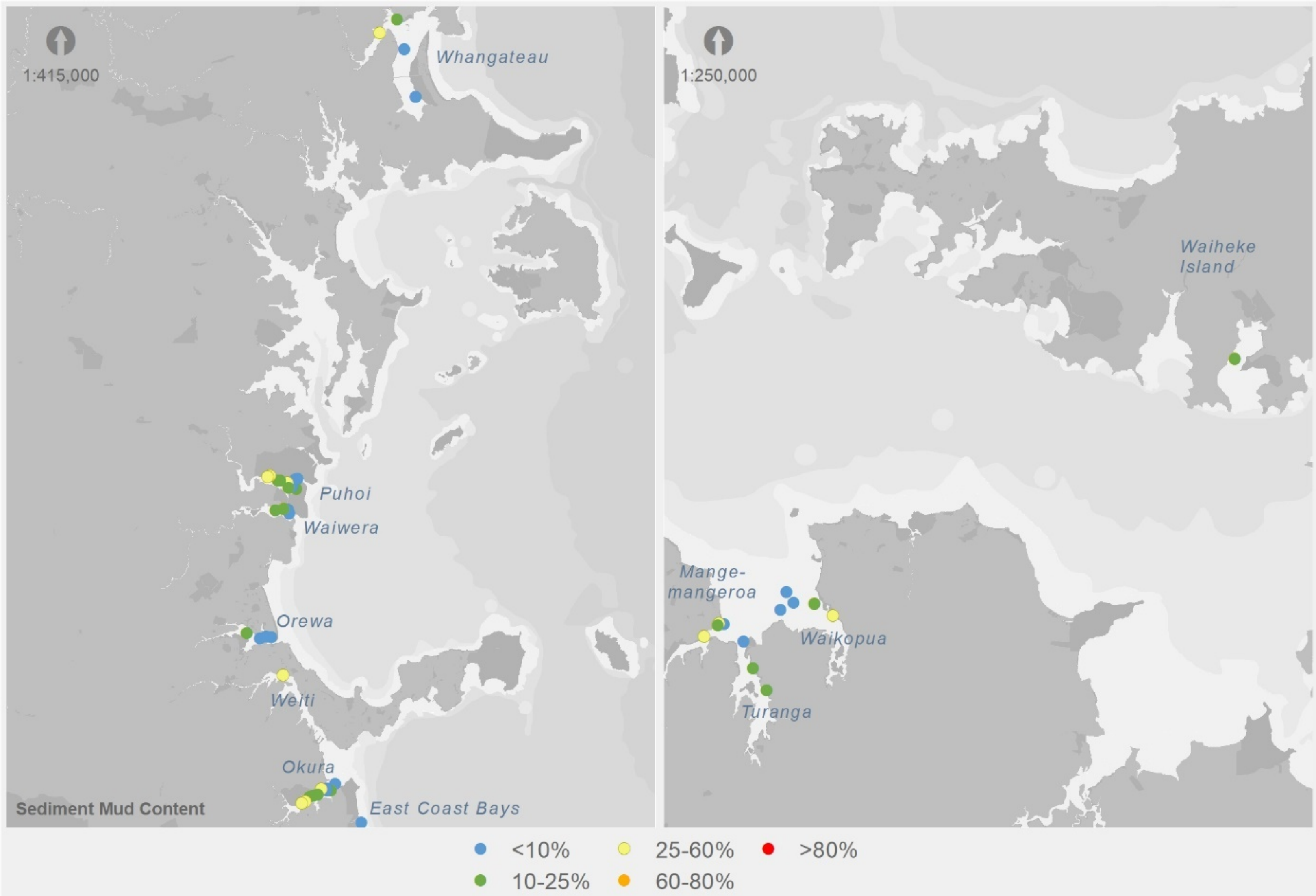

Figure 32. Most recent mud content in east coast estuary sites (measured in 2018 or 2019).

Table 24. Direction of statistically significant trends in sediment characteristics in core east coast estuary sites between 2004 and 2019, except Whangateau which is from 2009. Trends in organic content are analysed from 2009. Grey cells indicate less certain or uncertain trends.

		Very fine sand + mud (%)	Organic content (%)	Chl *a* (µg g^{-1} dw sediment)
Whangateau				
	1			
	4			
	7			
Puhoi				
	1		▼	
	4			▼
	7	▲		
Waiwera				
	1	▲		
	3			
	8		▼	
Orewa				
	1	▲	▼	▼
	4	▲	▼	▼
	8	▲	▼	▼
Okura				
	1			▲
	2	▲	▲	
	3	▲		
	4		▼	
	5	▲		
	6	▲		
	7	▲		
	8	▲	▼	
	9	▲	▲	
	10	▲		
Mangemangeroa				
	3			
	5	▲		
	6	▲		
Turanga				
	1	▲	▼	
	4	▲		
	7	▲	▼	
Waikopua				
	1	▲	▼	
	3	▲		
	6	▲		

Table 25. The number of trends in abundance of monitored species at monitored core east coast estuary sites up to Oct. 2019. The start of trend periods vary between estuaries: Okura = Oct. 2001; Mangemangeroa, Orewa, Waiwera and Puhoi = Aug. 2002; Turanga and Waikopua = Aug. 2004; Whangateau = Nov. 2009. Inc = increasing, Dec = decreasing. Note there are three monitored sites in all estuaries except Okura which has ten. Cells are coloured to highlight trends consistent with a particular stressor: sedimentation (yellow), metal contamination (blue) or both (purple). Pref = sediment preference; SS = strong preference for sand, S = prefers sand, M = prefers some mud but not in high percentages, MM = strong mud preference. See Appendix E for breakdown of trends per estuary.

Monitored species		Whangateau		Puhoi		Waiwera		Orewa		Okura		Mangemangeroa		Turanga		Waikopua	
	Pref	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec
Capitellids + Oligochaeta	MM	0	1	0	1	1	0	1	1	9	0	3	0	3	0	3	0
Aricidea sp.	M	2	0	1	1	0	0	1	0	1	0	1	0	0	0	1	0
Heteromastus filiformis + *Barantolla lepte*	M	3	0	2	0	2	0	1	1	0	4	2	0	1	0	1	1
Prionopsio aucklandica	M	0	1	1	0	1	0	1	0	7	0	1	0	2	0	1	0
Anthopleura aureoradiata	S	1	0	2	0	1	0	1	0	0	3	1	2	2	0	0	0
Austrovenus stutchburyi	S	3	0	2	0	1	1	2	0	6	4	0	1	2	0	3	0
Linucula hartvigiana	S	0	0	0	1	1	0	1	0	0	6	0	3	0	2	1	1
Macomona liliana	S	1	0	0	1	1	1	1	1	2	2	0	3	0	2	1	2
Aonides trifida	SS	0	0	0	1	0	0	1	1	0	8	0	1	0	0	0	1
Colurostylis lemurum	SS	0	0	0	1	0	2	1	0	2	2	0	0	0	1	0	0
Notoacmea scapha	SS	0	0	0	0	1	0	2	0	2	3	0	1	0	0	2	0
Trends consistent with sedimentation		**5**		**7**		**7**		**5**		**32**		**12**		**9**		**9**	
Trends per site		1.7		2.3		2.3		1.7		3.2		4		3		3	
Trends consistent with metals		**1**		**5**		**3**		**1**		**21**		**9**		**5**		**4**	
Trends per site		0.3		1.4		1		0.3		2.1		3		1.7		1.3	

Table 26. BHM and TBI groups in core east coast estuary sites over the last five years. BHMs: Group 1 = excellent, Group 2 = good, Group 3 = fair, Group 4 = marginal, Group 5 = poor. TBI: high, intermediate, low. Trends in TBI were analysed however none were statistically significant.

		Whangateau			Puhoi			Waiwera		
Index	**Year**	**1**	**4**	**7**	**1**	**4**	**7**	**1**	**3**	**8**
BHMmetals	2015	good	good	good	good	excellent	good	fair	good	excellent
	2016	good	good	good	excellent	good	good	fair	good	excellent
	2017	good	good	good	excellent	good	good	fair	good	excellent
	2018	good	good	fair	excellent	good	good	fair	excellent	excellent
	2019	good	good	fair	good	good	good	fair	excellent	good
BHMmud	2015	good	good	good	good	excellent	good	marginal	good	excellent
	2016	good	good	good	good	good	fair	marginal	good	excellent
	2017	good	good	good	excellent	good	good	marginal	good	excellent
	2018	good	good	fair	excellent	good	good	marginal	good	excellent
	2019	good	good	fair	excellent	excellent	fair	marginal	excellent	good
		Orewa			**Okura**			**Mangemangeroa**		
		1	**4**	**8**	**1**	**4**	**9**	**3**	**5**	**6**
BHMmetals	2015	excellent	excellent	good	excellent	good	fair	good	fair	fair
	2016	excellent	excellent	good	excellent	good	fair	good	fair	fair
	2017	excellent	excellent	good	good	good	fair	good	good	fair
	2018	excellent	excellent	good	excellent	excellent	fair	good	fair	fair
	2019	excellent	good	good	excellent	excellent	good	good	fair	fair
BHMmud	2015	good	excellent	fair	excellent	good	fair	good	marginal	marginal
	2016	good	excellent	good	excellent	good	fair	good	marginal	fair
	2017	good	excellent	good	good	good	marginal	good	fair	marginal
	2018	good	excellent	good	excellent	excellent	fair	good	marginal	marginal
	2019	good	excellent	good	excellent	excellent	fair	good	marginal	fair
		Turanga			**Waikopua**					
		1	**4**	**7**	**1**	**3**	**6**			
BHMmetals	2015	good	fair	good	good	good	fair			
	2016	good	fair	good	good	good	good			
	2017	excellent	fair	good	good	good	fair			
	2018	good	fair	good	good	good	good			
	2019	excellent	fair	good	good	fair	fair			
BHMmud	2015	excellent	marginal	fair	good	good	good			
	2016	good	marginal	fair	good	good	fair			
	2017	excellent	marginal	fair	good	fair	fair			
	2018	good	marginal	fair	good	good	fair			
	2019	excellent	fair	fair	fair	good	fair			

Table 27. TBI group at core east coast estuary sites in 2019: high, intermediate, low. Arrows show significant trends in TBI score from the start of monitoring to Oct. 2019. An increase in TBI equates to an increase in health.

	Whangateau			Puhoi			Waiwera			Orewa		
Index	**1**	**4**	**7**	**1**	**4**	**7**	**1**	**3**	**8**	**1**	**4**	**8**
TBI	high	low	high	intermediate	high	high	intermediate	high	intermediate	intermediate	low	high

	Okura									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
TBI	intermediate	high	high	high	high	high	intermediate	high	intermediate	intermediate

	Mangemangeroa			Turanga			Waikopua		
	3	**5**	**6**	**1**	**4**	**7**	**1**	**3**	**6**
TBI	high	high	high	low	intermediate	high	high	high	high

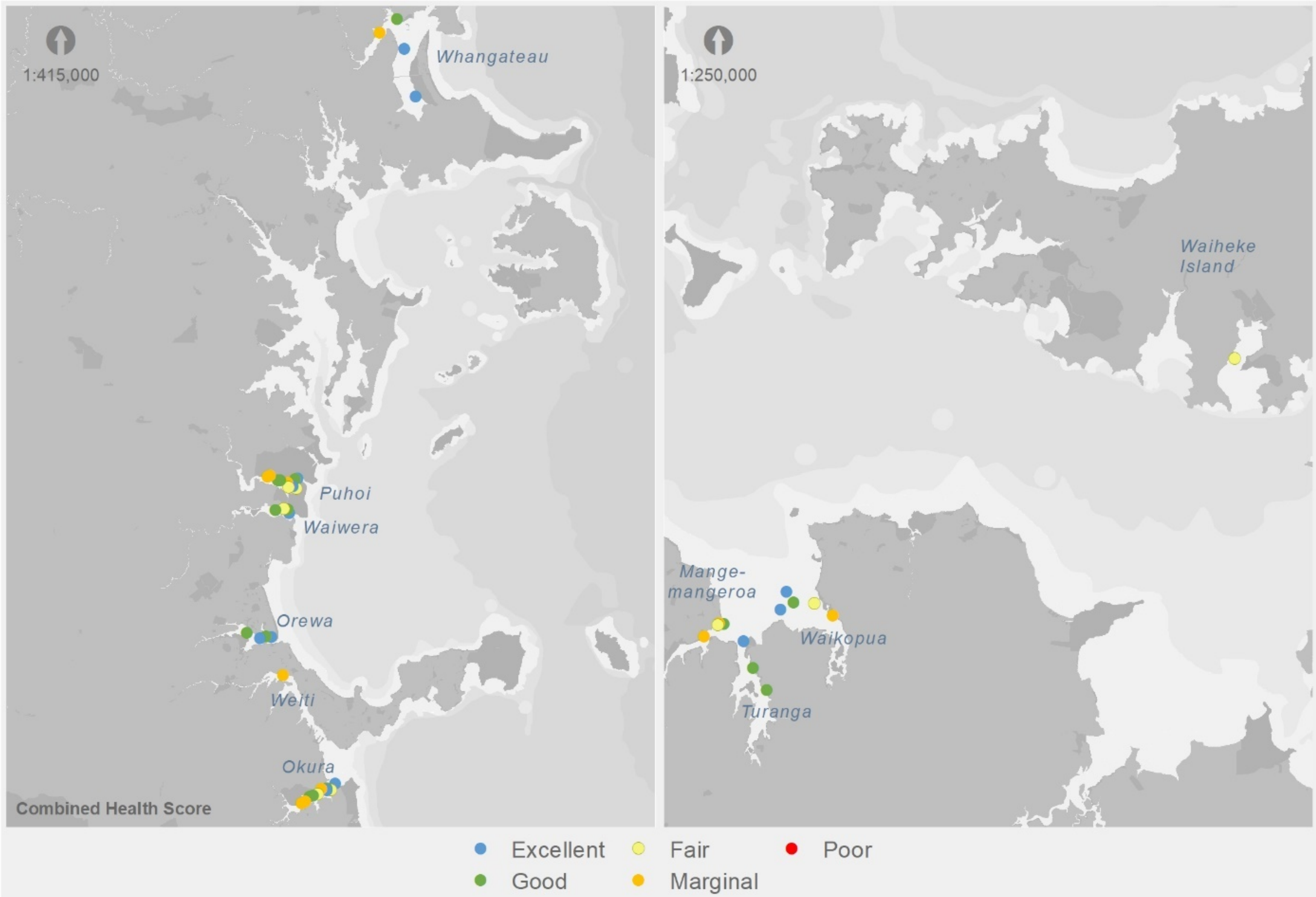

Figure 33. Most recent combined health scores for the east coast estuary sites (scores range from 2015-2019).

3.6 Regional summary

An understanding of the pressures acting upon Auckland's harbours and estuaries has been developed through analysing patterns in the sediment characteristics and benthic macrofaunal communities of regionally representative intertidal sandflats. Here, this understanding is summarised according to the major pressures to help paint a picture of benthic health across the region.

<u>Sedimentation</u>

Every monitored harbour and east coast estuary has been affected to some extent by increases in sedimentation (Table 28). This has resulted in very high sediment mud content in the tidal creeks throughout the Waitematā Harbour and on the sandflats of the Upper Waitematā, as well as in the sheltered creeks of the Manukau Harbour. In the east coast estuaries, proportions of very fine sand + mud are especially high in Turanga, Mangemangeroa, Waikopua and Orewa. Spatial patterns arise in relation to the impacts of sedimentation, with sheltered sandflats close to the outflows of streams and rivers tending to be most affected (as is observed in the Kaipara, Manukau, Waitematā, Okura and Waiwera harbours and estuaries, see Appendix H).

Of the common species monitored in all harbour and estuary sandflats (excluding tidal creeks), five are exhibiting trends consistent with sedimentation across the region. The polychaetes *Aricidea*, *Heteromastus* and *Prionospio* prefer slightly muddy sediments and have increased in abundance in all harbours and most east coast estuaries (Tables 25 and A6). Significant increasing trends have been recorded at more than 25 sites across the region for each of these species, but the greatest have been found for *Prionospio* which has increased at 33 sites. Region-wide declines in the abundance of two bivalves sensitive to sedimentation have also occurred; *Macomona* has decreased significantly in all harbours and estuaries except Whangateau, and *Linucula* has in all harbours and five estuaries (Tables 25 and A6). Both species have declined at 31 sites, and aside from indicating impacts of increased sedimentation, declines in *Macomona* are likely to have substantial negative consequences for the functioning of the sandflats they are being lost from (Hillman et al., 2020; Karlson et al., 2020; Thrush et al., 2006). The sandflats in the Central Waitematā and Mahurangi harbours have the greatest number of species trends per site that are consistent with increased sedimentation (Kaipara has the fewest; Table A6), and of the east coast estuaries, Mangemangeroa and Okura do (while Orewa and Whangateau have the fewest; Table 25).

The benthic health of Auckland's harbours and estuaries in relation to mud ranges from excellent to poor, both within waterbodies and across the region. Proximity to urban centres and/or areas of intense development has some ability to explain patterns in health, with Waitematā Harbour, the tidal creeks of Manukau Harbour, and Mangemangeroa having low health. However, there are also instances of low health and degrading trends in more rural areas (e.g. Mahurangi has mostly marginal health with respect to mud, and Kaipara is displaying several concerning trends). All instances of excellent health occur in open sandflats (in Manukau Harbour) or relatively undisturbed small east coast estuaries.

Metal contamination

The benthic health of most harbours and estuaries across the region has been affected by metal contamination (Table 28). Declines in the abundance of three species that are sensitive to metals and are monitored across the region have occurred: *Aonides*, *Anthopleura* and *Linucula*. All of these species are sensitive to copper and there has been a decline in the abundance of at least one in the sandflats of every harbour and estuary except Orewa, Waiwera and Whangateau (Table 25 and Table A6). The most declining trends are associated with *Linucula*, which has decreased at 31 sites across the region. It is important to note that these species are also somewhat sensitive to sediment mud content and may be responding to both stressors, and more analyses would be required to determine the key driver. Although not monitored in the east coast estuaries, there have also been declines in *Orbinia* (sensitive to zinc), *Magelona* and *Boccardia* (both sensitive to lead) in all of the major harbour sandflats except Mahurangi (Table A6). These species are not considered sensitive to mud and are more likely reflecting increases in contaminants.

Closer inspection of species trends, and those in the BHM for metals, often revealed that trends reflected historic rather than ongoing inputs of metals near the urban centres. This is evidenced by improving health in relation to metals in Manukau sandflats and Upper, Central and Outer Waitematā tidal creeks (Table 28). However, ongoing impacts are apparent in the rural Kaipara and Mahurangi harbours and sandflats of the Upper Waitematā, and while there are generally few trends of concern in the east coast estuaries, Mangemangeroa and Turanga (those closest to the city centre) are exhibiting more than one trend consistent with contamination.

No sites in the region have poor benthic health related to metals and most east coast estuaries and harbour sandflats are in good health, but despite some improving trends, health is mostly marginal in the tidal creeks near the city centre.

Nutrient enrichment

Excessive delivery of nutrients to enclosed coastal environments may stimulate algal blooms in the water column. These blooms can reduce the amount of light reaching benthic primary producers and, upon collapsing, settle to the seafloor where decomposition of the excess organic material has negative effects on sediment biogeochemistry (Cai et al., 2011; Drylie et al., 2019); a process termed eutrophication (Nixon, 1995). Monitoring sediment organic content and chl *a* is supposed to indicate nutrient enrichment (as well as the life-supporting capacity of a sandflat) as increases in organic content would be expected following algal bloom deposition, and chl *a* concentrations may increase with an increased availability of nutrients (given other necessary conditions are met, e.g. there is sufficient light).

There is very little evidence that nutrient enrichment has been a major pressure in Auckland's estuaries, as very few increasing trends in sediment organic content or chl *a* concentration have been identified (Table 28). These indicators are the end products of nutrient enrichment, therefore detecting increases in their concentration would be a late sign that this pressure was/is an issue. Furthermore, the activities of macrofauna stimulate organic matter remineralisation (Kristensen, 2000) such that measurements of organic content likely reflect what remains in the sediment rather than actual organic matter input. It stands, then, that we do not have adequate early indicators of nutrient enrichment in the benthic environment. Little is known about the sensitivities of macrofaunal species to nutrient enrichment, but this could be a useful avenue for research to improve our ability to monitor this pressure.

<u>Combined health</u>

Improvements in functional resilience (indicated by TBI) are occurring across the region. This seemingly contradicts otherwise degrading trends at some sites (e.g. significantly degrading health at Meola Reef with respect to metals and mud is not reflected by the significant increases in TBI). It may be that sandflats with 'intermediate' levels of mud have a greater number of species than either sand or mud-dominated flats, as they can support 'transitional' communities comprised of species preferring sandy and silty sediments, and therefore score highly in terms of functional traits. In such instances, species are likely to be living at the limits of their ecological niche and be highly stressed, which may impact on their ability to perform functionally. This implies that TBI could overestimate the functional resilience of such communities and is worth investigating further.

Overall, the east coast estuaries and the open sandflats of the major harbours (except in Upper Waitematā) are in good to fair health, with all instances of excellent heath being recorded here, whereas the tidal creeks in the urban harbours (Manukau and Waitematā) are in poor health. Of the 136 monitored sites with recent data, 6% have 'excellent', 22% have 'good', another 22% have 'fair', 29% have 'marginal' and 21% have 'poor' overall health (see Appendix H).

Table 28. Summary of benthic health across the region with a focus on potential pressures.

	Sedimentation	Metal contamination	Nutrient enrichment	Overall health
Kaipara	Sedimentation affects most sandflat sites, particularly those closest to river inflows.	All sites except those in exposed locations are affected by metal contamination.	No evidence of enrichment.	Good to Fair (predominantly Good)
Manukau	Sedimentation has little effect on sandflat sites, but tidal creeks have poor health.	Historic degradation of sandflats near urban outflows mostly recovered, while tidal creeks remain in marginal health.	No evidence of enrichment.	Excellent to Poor (tidal creeks have lower health than sandflats)
Mahurangi	Sedimentation affects all sites resulting in low health related to mud.	Most sites affected by metal contamination.	Potential enrichment at eastern sites.	Good to Marginal (predominantly Marginal)
Upper Waitematā	Sedimentation affects all sandflat and tidal creek sites.	Health has degraded at sandflat sites but improved in tidal creeks in relation to metals.	Potential enrichment at sites throughout.	Good to Poor (predominantly Poor)
Central Waitematā	Sedimentation affects all sandflat sites, but mud content remains low. The health of tidal creek sites has degraded and is poor.	Few sandflat sites are affected by metal contamination and health is improving at several tidal creek sites.	Possible evidence of enrichment at western sites.	Good to Poor (tidal creeks have lower health than sandflats)
Outer Waitematā	Tidal creek sites have good-poor health and have shown little change over time.	Health has improved at several sites.	N/A	Fair to Poor
Whangateau	Some species trends consistent with sedimentation.	No concerning evidence of contamination.	No evidence of enrichment.	Good or Fair
Puhoi	Trends consistent with increased sedimentation at all core sites but very fine sediment content remains low.	Some evidence of metal contamination, not within last five years.	No evidence of enrichment.	Excellent to Marginal (predominantly Marginal)
Waiwera	Some evidence of sedimentation affecting all core sites, especially in the upper estuary.	No evidence of contamination.	No evidence of enrichment.	Excellent to Marginal

	Sedimentation	Metal contamination	Nutrient enrichment	Overall health
Orewa	Sedimentation affects all core sites but few trends in indicator species.	No evidence of contamination.	No evidence of enrichment.	Excellent to Fair (predominantly Good)
Okura	Sedimentation affects all 10 sites, especially in the upper estuary.	Some evidence of copper contamination, not within last five years.	No evidence of enrichment.	Excellent to Marginal (predominantly Good)
Mangemangeroa	Sedimentation affects all core sites causing marginal health.	Some evidence of copper contamination at core sites.	No evidence of enrichment.	Good to Marginal (predominantly Marginal)
Turanga	Sedimentation affects all core sites causing excellent-marginal health.	Some evidence of copper and lead contamination.	No evidence of enrichment.	Excellent to Fair (predominantly Fair)
Waikopua	Sedimentation affects all core sites but some signs of recent recovery.	Some evidence of contamination at one site. Health is good/fair.	No evidence of enrichment.	Fair to Marginal (predominantly Fair)

4.0 Conclusions

Sediment input from streams and rivers continues to be the biggest pressure driving change in the benthic ecology and health of Auckland's harbours and estuaries. This is especially so in sheltered tidal creeks, and sedimentation has affected sites in both urban and rural catchments. A lesser but still important pressure is metal contamination, the impact of which seems to be decreasing in tidal creeks close to urban centres but may be increasing in sandflats further downstream, as well as in the rural Kaipara and Mahurangi harbours.

Although the effects of sedimentation are observed across the region, there are differences between estuaries in terms of the degree and timing of impacts. For example, the Kaipara Harbour is relatively healthy but has an increasing number of concerning trends which contrasts the Upper Waitematā Harbour, where the benthos is largely unhealthy but is fairly stable with few concerning current trends. Health also varies spatially within estuaries, with the tidal creeks of the urban harbours generally having lower health than the open sandflats. Despite this, there are some signs of improving health in the tidal creeks, particularly related to metals, while many sandflats are degrading in health (except for those in Manukau).

Multi-year cycles in species abundance are a common feature across the region. This has led to some previously identified trends being reclassified as long-term cycles. It is critical that future analyses continue to utilise long-term datasets for trend analyses to investigate these cycles. As the consequences of climate change are expected to develop over the coming decades, it will also be increasingly important to look for the effects of global warming, changes to rainfall, and seawater acidification on macrofaunal populations. It is therefore recommended climate variables (such as El Niño – Southern Oscillation indices, rainfall metrics and temperature) are built into linear regression models to determine their influence on species abundance trends. Such models would also improve confidence when attributing trends to local pressures, as the variation related to climate could be accounted for meaning any remaining relationship with time is more likely to be explained by local drivers.

Finally, when assessing benthic health, the state and trends of all indicators should be considered holistically. The importance of improving or degrading trends in one indicator may be determined from the current state of another; for example, management interventions may be less urgent for a site with increasing sediment mud content if it already has poor health according to the BHMmud than for a site with excellent health (provided the spatial extent of the mud-dominated habitat was not increasing). Seemingly contradictory trends in indicators can also identify phenomena worth investigating (like the improvements in functional resilience alongside degrading health related to metals and mud), act as possible early warnings (e.g. of nutrient enrichment, where chl *a* concentration increases but organic content does not), and highlight trends that may have ceased (e.g. where increases in the abundance of opportunistic polychaetes and sensitive bivalves apparently co-occur).

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Appendix A Monitored sites

Table A-1. Sites with sufficient data for trend analysis and length of time series.

	Programme	Site	Location	Series dates
1	RSCMP	Anns Creek	Manukau	2005-2018
2	RSCMP	Benghazi	Outer Waitematā	2004-2019
3	RSCMP	Bowden	Outer Waitematā	2004-2017
4	RSCMP	Chelsea	Central Waitematā	2004-2019
5	RSCMP	Coxs Bay	Central Waitematā	2004-2019
6	RSCMP	Henderson Lower	Central Waitematā	2004-2019
7	RSCMP	Henderson Upper	Central Waitematā	2005-2018
8	RSCMP	Kendall Bay	Central Waitematā	2004-2019
9	RSCMP	Lucas Upper	Upper Waitematā	2005-2018
10	RSCMP	Māngere Cemetery	Manukau	2005-2018
11	RSCMP	Meola Inner	Central Waitematā	2005-2018
12	RSCMP	Meola Outer	Central Waitematā	2004-2019
13	RSCMP	Meola Reef	Central Waitematā	2005-2019
14	RSCMP	Middlemore	Outer Waitematā	2005-2018
15	RSCMP	Motions	Central Waitematā	2005-2018
16	RSCMP	Oakley	Central Waitematā	2005-2018
17	RSCMP	Otahuhu Creek	Outer Waitematā	2004-2017
18	RSCMP	Pakuranga Upper	Outer Waitematā	2005-2018
19	RSCMP	Panmure	Outer Waitematā	2004-2019
20	RSCMP	Paremoremo	Upper Waitematā	2005-2018
21	RSCMP	Pollen Island	Central Waitematā	2005-2018
22	RSCMP	Princes St	Outer Waitematā	2004-2017
23	RSCMP	Purewa	Outer Waitematā	2004-2017
24	RSCMP	Shoal Bay	Central Waitematā	2004-2019
25	RSCMP	Whakataka Bay	Outer Waitematā	2005-2018
2	RSCMP	Whau Entrance	Central Waitematā	2006-2019
27	RSCMP	Whau Lower	Central Waitematā	2005-2018
28	RSCMP	Whau Upper	Central Waitematā	2005-2018
29	RSCMP	Whau Wairau	Central Waitematā	2005-2018
30	RSCMP	Awatea	Outer Waitematā	2006-2016
31	RSCMP	Hellyer’s Upper	Upper Waitematā	2007-2018
32-41	East Coast Estuaries	1-10	Okura	2001-2019

	Programme	Site	Location	Series dates
42-44	East Coast Estuaries	3, 5, 6	Mangemangeroa	2002-2019
45-47	East Coast Estuaries	1, 4, 8	Orewa	2002-2019
48-50	East Coast Estuaries	1, 4, 7	Puhoi	2002-2019
51-53	East Coast Estuaries	1, 4, 7	Turanga	2004-2019
54-56	East Coast Estuaries	1, 3, 6	Waikopua	2004-2019
57-59	East Coast Estuaries	1, 3, 8	Waiwera	2002-2019
60-62	East Coast Estuaries	1, 4, 7	Whangateau	2009-2019
63	Harbour Ecology	Auckland Airport (AA)	Manukau	1987-2019
64	Harbour Ecology	Clarks Beach (CB_MAN)	Manukau	1987-2019
65	Harbour Ecology	Karaka Point (KP)	Manukau	1987-2019
66	Harbour Ecology	Puhinui Stream (PS)	Manukau	1987-2019
67	Harbour Ecology	Cape Horn (CH)	Manukau	1987-2019
68	Harbour Ecology	Elletts Beach (EB)	Manukau	1987-2019
69	Harbour Ecology	Kaipara Bank (KAIB)	Kaipara	2009-2019
70	Harbour Ecology	Ngapuke Creek (NPC)	Kaipara	2009-2019
71	Harbour Ecology	Te Ngaio Point (TNP)	Kaipara	2014-2019
72	Harbour Ecology	Kakarai Flats (KKF)	Kaipara	2009-2019
73	Harbour Ecology	Haratahi Creek (HCK)	Kaipara	2009-2019
74	Harbour Ecology	Kaipara Flats (KAIF)	Kaipara	2009-2019
75	Harbour Ecology	Te Kapa Inlet (TK)	Mahurangi	1994-2019
76	Harbour Ecology	Hamilton Landing (HL)	Mahurangi	1994-2019
77	Harbour Ecology	Jamieson Bay (JB)	Mahurangi	1994-2019
78	Harbour Ecology	Mid Harbour (H)	Mahurangi	1994-2019
79	Harbour Ecology	Dyers Creek (DC)	Mahurangi	2005-2019
80	Harbour Ecology	Cowans Bay (CB)	Mahurangi	1994-2019
81	Harbour Ecology	Herald Island (HIN)	Upper Waitematā	2005-2019
82	Harbour Ecology	Waiarohia Inlet (HIW)	Upper Waitematā	2005-2019
83	Harbour Ecology	Lucas Creek (LUC)	Upper Waitematā	2005-2019
84	Harbour Ecology	Hellyer's Creek (HELL)	Upper Waitematā	2005-2019
85	Harbour Ecology	Rangitopuni Creek (RNG)	Upper Waitematā	2005-2019
86	Harbour Ecology	Brigham Creek (BRIG)	Upper Waitematā	2005-2019
87	Harbour Ecology	Upper Main (MAINU)	Upper Waitematā	2005-2019
88	Harbour Ecology	Central Main (MAINC)	Upper Waitematā	2005-2019
89	Harbour Ecology	Outer Main (MAINO)	Upper Waitematā	2005-2019
90	Harbour Ecology	Opposite Hobsonville (OHBV)	Upper Waitematā	2005-2019

	Programme	Site	Location	Series dates
91	Harbour Ecology	Hobsonville (HBV)	Central Waitematā	2000-2019
92	Harbour Ecology	Upper Shoal Bay (UPS)	Central Waitematā	2014-2019
93	Harbour Ecology	Whau River (WHAU)	Central Waitematā	2005-2019
94	Harbour Ecology	Henderson Creek (HC)	Central Waitematā	2005-2019
95	Harbour Ecology	Meola Reef (REEF)	Central Waitematā	2005-2019

Table A-2. Sites sampled for ecology but not within the last five years. RSCMP = Regional Sediment Contaminants Monitoring Programme.

	Programme	Site	Location	Last sampled
1	Harbour Ecology	Shoal Bay	Central Waitematā	2014
2	Harbour Ecology	Tapora Bank	Kaipara	2014
3-5	East Coast Estuaries	2, 3, 6	Whangateau	2014
6-7	East Coast Estuaries	7, 10	Waiwera	2011
8	East Coast Estuaries	4	Waiwera	2012
9-11	East Coast Estuaries	2, 5, 9	Waiwera	2014
12-14	East Coast Estuaries	7, 9, 10	Orewa	2013
15-17	East Coast Estuaries	2, 5, 6	Orewa	2014
18-20	East Coast Estuaries	1, 4, 8	Mangemangeroa	2012
21-23	East Coast Estuaries	2, 7, 10	Mangemangeroa	2014
24-26	East Coast Estuaries	2 ,5, 9	Turanga	2010
27-29	East Coast Estuaries	3, 6, 10	Turanga	2014
30	East Coast Estuaries	10	Waikopua	2009
31-35	East Coast Estuaries	2, 4, 5, 7, 8	Waikopua	2014
36	RSCMP	Meola Reef (Te Tokaroa)	Central Waitematā	2011
37	RSCMP	Newmarket	Outer Waitematā	2011
38	RSCMP	Victoria Ave	Outer Waitematā	2008
39	RSCMP	Hillsborough	Manukau	2008
40	RSCMP	Kaipatiki	Upper Waitematā	2009
41	RSCMP	Shoal Bay Lower	Central Waitematā	2009
42	RSCMP	Shoal Bay Upper	Central Waitematā	2008
43	RSCMP	Whau Outer	Central Waitematā	2004

Appendix B Monitored species

Table A-3. Routinely monitored species in each harbour ecology programme, their sediment preferences (SS = strong preference for sand, S = prefers sand, M = prefers some mud but not in high percentages, MM = strong mud preference) and sensitivity to metal contaminants, if known. KAI = Kaipara, MAN = Manukau, MAHU = Mahurangi, CWAI = Central Waitematā, UWAI = Upper Waitematā.

Order	Species	Pref	Metal	KAI	MAN	MAHU	CWAI	UWAI
Polychaete	*Aglaophamus macroura*	-		X	X			
Anthozoa	*Anthopleura aureoradiata*	S	✓	X	X		X	
Polychaete	*Aonides trifida*	SS	✓	X	X	X	X	
Bivalve	*Arcuatula senhousia*	-		X				X
Polychaete	*Aricidea sp.*	M		X		X	X	X
Bivalve	*Arthritica bifurca*	M				X	X	X
Decapod	*Austrohelice crassa*	M						X
Bivalve	*Austrovenus stutchburyi*	S		X	X	X	X	X
Polychaete	*Boccardia syrtis*	M	✓	X	X		X	
Polychaete	Capitellidae	M						X
Cumacea	*Colurostylis lemurum*	SS	✓	X	X		X	
Amphipod	Corophiidae	-						X
Polychaete	*Cossura consimilis*	M		X		X		X
Gastropod	*Diloma subrostrata*	S					X	
Polychaete	*Euchone sp.*	-	✓	X			X	
Isopod	*Exosphaeroma planulum*	-		X	X			
Isopod	*Exosphaeroma waitemata*	-		X	X			
Isopod	*Exosphaeroma spp.*	-					X.	
Polychaete	*Glycera americana*	M					X	
Polychaete	*Glycinde trifida*	-			X			
Gastropod	*Haminoea zelandiae*	-					X	
Decapod	*Hemiplax hirtipes*	M				X		
Polychaete	*Heteromastus filiformis*	M				X	X	X
Bivalve	*Hiatula siliquens*	-		X	X			
Polychaete	*Levinsenia gracilis*	-						X
Bivalve	*Linucula hartvigiana*	S	✓	X	X	X	X	X
Bivalve	*Macomona liliana*	S		X	X	X	X	
Polychaete	*Macroclymenella stewartensis*	M	✓	X	X		X	
Polychaete	*Magelona dakini*	-	✓	X	X			
Amphipod	*Methalimedon sp.*	-			X			
Polychaete	Nemertea	M				X		
Polychaete	Nereididae	M						X
Polychaete	*Nicon aestuariensis*	M		X				
Gastropod	*Notoacmea scapha*	SS		X	X	X	X	
Polychaete	Oligochaeta	MM				X		X
Polychaete	*Orbinia papillosa*	S	✓	X	X			
Polychaete	*Owenia petersenae*	S		X	X	X		

Order	**Species**	**Pref**	**Metal**	**KAI**	**MAN**	**MAHU**	**CWAI**	**UWAI**
Bivalve	*Paphies australis*	SS					X	
Amphipod	*Paracalliope novizealandiae*	S				X		
Polychaete	*Paradoneis lyra*	-						X
Polychaete	*Perinereis vallata*	M				X		
Amphipod	Phoxocephalids	-						X
Polychaete	Polydorids	M				X		X
Polychaete	*Prionospio aucklandica*	M	✓	X	X	X	X	X
Polychaete	*Pseudopotamilla* sp.	-						X
Polychaete	*Scoloplos cylindrifer*	S		X		X		
Holothuria	*Taeniogyrus dendyi*	-		X	X			
Amphipod	*Torridoharpinia hurleyi*	S	✓	X	X	X		
Polychaete	*Travisia olens novaezealandiae*	SS		X	X			
Gastropod	*Tritia burchardi*	-						X
Amphipod	*Waitangi brevirostris*	SS	✓	X	X			
Gastropod	*Zeacumantus lutulentus*	M					X	

Appendix C Common species across the region

Table A-4. Common species recorded in major harbours across the Auckland region.

Arthropoda: Amphipoda	**Annelida: Polychaeta**
Torridoharpinia hurleyi	*Aglaophamus macroura*
Waitangi brevirostris	*Aonides trifida*
Cnidaria: Anthozoa	*Aricidea* sp.
Anthopleura aureoradiata	*Boccardia syrtis*
Mollusca: Bivalvia	*Cossura consimilis*
Austrovenus stutchburyi	*Euchone* sp. (fan worm)
Macomona liliana	Glyceridae (blood worms)
Linucula hartvigiana	*Glycinde trifida*
Hiatula siliquens	*Heteromastus filiformis*
Arthritica bifurca	*Macroclymenella stewartensis*
Paphies australis	*Magelona dakini*
Arthropoda: Cumacea	*Nicon aestuarensis*
Colurostylis lemurum	*Orbinia papillosa*
Mollusca: Gastropoda	*Owenia petersenae*
Notoacmea scapha	*Prionospio aucklandica*
Diloma subrostrate	*Scoloplos cylindrifer*
Haminoea zelandiae	*Travisia olens novaezealandiae*
Zeacumantus lutulentus	Oligochaeta
Echinodermata: Holothuroidea	
Taeniogyrus (previously *Trochodota) dendyi*	
Arthropoda: Isopoda	
Exosphaeroma planulum (previously recorded as *E. chiliensis*)	
Exosphaeroma waitemata (previously recorded as *E. falcatum*)	

Appendix D Trend analysis method

Data

Due to changes in laboratory techniques and evolution of the ecology programmes, data on surface sediment characteristics are available from the following dates:

- Harbour Ecology
  - Sediment mud content – since the start of monitoring for each estuary
  - Organic content and chl *a* – October 2000
- East Coast Estuaries Ecology
  - Sediment mud content – August 2004
  - Organic content – September 2009
  - Chl *a* – September 2012

Macrofauna abundance data are available from the start of the monitoring period for all sites (see Appendix A).

Trends were only analysed for variables with five or more data points, as results based on fewer observations are likely to be unreliable. Climatic variables may also be important predictors of trends based on less than 10 years of data (Hewitt et al., 2016), so any such trends should be treated with caution unless supported by similar trends within the estuary.

Trend analysis

The statistical approaches largely follow those outlined by Hewitt et al., (2015) and Greenfield et al., (2019), and all trend analyses were performed in R Studio v4.0.2 (R Core Team, 2020). As a first step, visual assessments of data plotted over time were used to determine whether step changes, multi-year cycles, linear or non-linear patterns could be seen. Following that, for datasets with a within-year sampling frequency less than or equal to two (i.e. RSCMP and East Coast Estuaries sites):

- If a step change was indicated, analysis was conducted using a t-test with data grouped before and after the suspected step.
- Otherwise, an ordinary least squares regression with time was run, using log transformations to include monotonic non-linear responses. Polynomial non-linear responses were not investigated to maintain a focus on continuous, long-term trends.
- Where a statistically significant trend was observed ($p < 0.15$), residuals were examined for indications of multi-year cycles; where these indicated significant bias, the trend was considered a multi-year cycle. Inspection of residual plots also indicated whether trends occurred over the entire monitoring period or shorter time frames and enabled detection of their start and end points.

For datasets with a within-year sampling frequency greater than two (i.e. Harbour Ecology sites) and with more than 30 data points:

- Temporal autocorrelation was investigated using Durban-Watson statistics (up to six time lags is within-year, but this varies according to the frequency of sampling for the given programme) to check assumptions on the number of independent samples. The power to detect autocorrelation is low with fewer than 30 samples (Chatfield, 1980).
- Where autocorrelation was indicated:
    - Trends were investigated with generalised least squares regression, utilising autoregressive correlation structures (Choudhury et al., 1999).
    - Step trends were determined based on the significance of Yule-Walker parameter estimates on time series data points grouped before and after a suspected change.
- Plots of residuals were examined for significant trends as outlined above.

<u>Assigning “certainty”</u>

Statistically significant trends were assigned a certainty score based on the regression p-value and the presence of multi-year cycles as follows:

- If $p < 0.05$ and no multi-year cycles are observed, the trend is considered “certain” and is assigned a score of 1.
- If p is between 0.05 and 0.1 OR $p < 0.05$ but multi-year cycles are observed, the trend is “less certain” and assigned a score of 0.5.
- If p is between 0.1 and 0.15 the trend is “uncertain” and assigned a score of 0.25.

Due to the lower level of replication of macrofauna cores in the East Coast Estuaries Ecology programme, assignation of sites to benthic health categories varies randomly by 12-15%. Although this is less than a health category, and therefore does not affect our ability to assign a health status at a given time, it precludes analyses of trends through time as the ability to detect changes are vastly reduced. This is not an issue for the TBI as the number of replicates is accounted for during its calculation.

Appendix E East Coast Estuaries species trends

Table A-5. Trends in abundance of common monitored species at core east coast estuaries sites. Grey cells indicate trends that are less certain or uncertain and sites exhibiting multi-year cycles (MY) are shown. Pref = sediment preference; SS = strong preference for sand, S = prefers sand, M = prefers some mud but not in high percentages, MM = strong mud preference.

Monitored species	Pref	Mangemangeroa			Turanga			Orewa		
		3	5	6	1	4	7	1	4	8
Capitellids + Oligochaeta	MM	↑	↑	↑	↑	↑	↑ MY		↑ MY	↓
Aricidea sp.	M			↑ MY					↑ MY	
Heteromastus filiformis + Barantolla lepte	M	↑	↑			↑ MY			↑ MY	↓ MY
Prionospio aucklandica	M	↑ MY				↑ MY	↑ MY	↓ MY	↑ MY	
Anthopleura aureoradiata	S	↑ MY	↓ MY	↓ MY	↑		↑		↑ MY	
Austrovenus stutchburyi	S		↓		↑ MY		↑ MY		↑ MY	↑
Macomona liliana	S	↓	↓	↓		↓ MY	↓ MY	↓ MY	↑ MY	
Linucula hartvigiana	S	↓ MY	↓ MY	↓ MY	↓ MY		↓ MY		↑ MY	
Colurostylis lemurum	SS						↓		↑ MY	
Notoacmea scapha	SS		↓ MY						↑ MY	↑ MY
Aonides trifida	SS	↓ MY							↑ MY	↓ MY
		Waiwera			**Waikopua**			**Puhoi**		
		1	**3**	**8**	**1**	**3**	**6**	**1**	**4**	**7**
Capitellids + Oligochaeta	MM			↑	↑ MY	↑ MY	↑			↓ MY
Aricidea sp.	M					↑ MY		↑ MY		↓
Heteromastus filiformis + Barantolla lepte	M	↑ MY		↑ MY	↑ MY	↓ MY			↑ MY	↑ MY
Prionospio aucklandica	M			↑ MY	↑ MY				↑ MY	↑ MY
Anthopleura aureoradiata	S			↑					↑ MY	↑
Austrovenus stutchburyi	S		↓ MY	↑	↑ MY	↑	↑		↑ MY	↑ MY
Macomona liliana	S	↓ MY		↑ MY	↑ MY	↓ MY	↓ MY	↓ MY		
Linucula hartvigiana	S			↑	↑ MY		↓		↓ MY	
Colurostylis lemurum	SS		↓	↓ MY						↓ MY
Notoacmea scapha	SS			↑ MY	↑ MY	↑ MY				
Aonides trifida	SS						↓ MY		↓ MY	
		Whangateau								
		1	**4**	**7**						
Capitellids + Oligochaeta	MM		↓							
Aricidea sp.	M	↓ MY	↑ MY	↑ MY						
Heteromastus filiformis + Barantolla lepte	M	↑ MY	↑	↑ MY						
Prionospio aucklandica	M	↓ MY								
Anthopleura aureoradiata	S	↑ MY	↓ MY							
Austrovenus stutchburyi	S	↑ MY	↑	↑						
Macomona liliana	S			↑						
Linucula hartvigiana	S									
Colurostylis lemurum	SS									
Notoacmea scapha	SS									
Aonides trifida	SS									

Monitored species	Pref	Okura									
		1	2	3	4	5	6	7	8	9	10
Capitellids + Oligochaeta	MM	↑ MY	↑ MY	↑ MY	↑ MY		↑	↑	↑ MY	↑	↑
Aricidea sp.	M	↑							↓ MY		
Heteromastus filiformis + Barantolla lepte	M	↓							↓	↓	↓ MY
Prionospio aucklandica	M	↓ MY	↑ MY		↑ MY	↑ MY	↑ MY	↑ MY	↑ MY	↑ MY	
Anthopleura aureoradiata	S	↓ MY	↓ MY								↓
Austrovenus stutchburyi	S	↓ MY			↑ MY			↑	↓ MY		
Macomona liliana	S	↓ MY			↑ MY			↑	↓ MY		
Linucula hartvigiana	S	↓ MY	↓ MY	↓ MY	↓ MY	↑ MY				↓ MY	↓
Colurostylis lemurum	SS	↑				↑		↓ MY	↓ MY	↓ MY	↓ MY
Notoacmea scapha	SS		↓ MY				↑ MY		↑ MY	↓	↓
Aonides trifida	SS	↓ MY		↓ MY		↓ MY	↓	↓ MY	↓	↓ MY	↓

Appendix F Regional trends in common species

Table A-6. Significant trends in common species abundance at harbour sandflat sites. Dec = decrease in abundance, Inc = increase. Cells coloured to reflect trends consistent with increased sedimentation (yellow), metal contamination (blue) or both (purple).

Species	Kaipara		Manukau		Mahurangi		U. Waitematā		C. Waitematā	
	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec
Aglaophamus macroura	3	2	3	3	0	1	0	1	0	1
Aonides trifida	2	0	3	1	1	1	0	2	1	2
Aricidea sp.	5	2	3	1	6	0	2	1	5	0
Boccardia syrtis	2	1	1	2	0	0	0	0	4	1
Cossura consimilis	1	1	1	1	6	0	2	2	1	0
Euchone sp.	0	2	1	2	0	1	0	1	1	1
Heteromastus filiformis	2	0	4	1	2	2	3	0	4	1
Macroclymenella	1	0	1	2	2	0	3	0	0	1
**Magelona dakini*	3	1	4	0	0	0	0	1	1	1
Orbinia papillosa	3	1	3	1	3	0	1	2	1	1
Owenia petersenae	1	1	3	2	0	1	0	0	0	0
Prionospio aucklandica	2	1	3	0	3	0	8	0	3	1
Scoloplos cylindrifer	0	1	0	0	5	1	0	0	2	0
Oligochaeta	0	2	4	1	6	0	2	0	2	0
Austrovenus stutchburyi	1	2	6	0	4	1	3	2	3	2
Macomona liliana	0	3	2	1	0	5	0	6	2	4
Linucula hartvigiana	1	1	2	2	0	5	0	4	0	6
Hiatula siliquens	0	6	0	2	0	1	0	2	0	2
Arthritica bifurca	2	0	2	1	4	0	1	2	5	0
Paphies australis	1	1	4	0	0	0	0	1	1	2
Notoacmea scapha	1	1	3	0	0	3	1	0	1	1
Diloma subrostrata	1	1	2	2	0	3	1	0	3	2
Haminoea zelandiae	0	3	6	0	1	0	0	1	0	3
Zeacumantus lutulentus	1	0	3	1	0	1	0	2	1	2
Torridoharpinia hurleyi	1	2	2	0	1	1	0	0	0	0
Exosphaeroma planulum	0	2	2	1	0	2	3	0	0	0
Exosphaeroma waitemata	0	2	1	3	1	0	0	0	0	0
Anthopleura aureoradiata	2	1	3	1	0	2	1	2	6	0
Colurostylis lemurum	2	0	5	0	0	1	0	0	4	2
Trends consistent with sedimentation (per site)	17 (2.8)		20 (3.3)		34 (5.7)		29 (2.9)		33 (6.6)	
Trends consistent with metals (per site)	7 (1.2)		9 (1.5)		10 (1.7)		11 (1.1)		14 (2.8)	

Appendix G Summary of trends in harbour health indices

Table A-7. Number of increasing and decreasing trends in health indices in A. sandflat and B. tidal creek harbour sites. Trends that represent degrading health are highlighted and the number of sites per harbour are given in parentheses.

A.	Kaipara (6)		Manukau (6)		Mahurangi (6)		C. Waitematā (5)		U. Waitematā (10)	
Index	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec
BHMmetals	4	0	3	2	4	0	1	1	6	1
BHMmud	4	2	1	2	4	0	3	0	5	2
TBI	1	0	4	0	5	0	5	0	4	0

B.	Manukau (2)		C. Waitematā (16)		U. Waitematā (3)		O. Waitematā (10)	
Index	Inc	Dec	Inc	Dec	Inc	Dec	Inc	Dec
BHMmetals	0	1	1	8	0	2	1	4
BHMmud	0	1	4	0	1	0	1	0
TBI	0	0	4	0	0	1	2	2

Appendix H Regional state maps

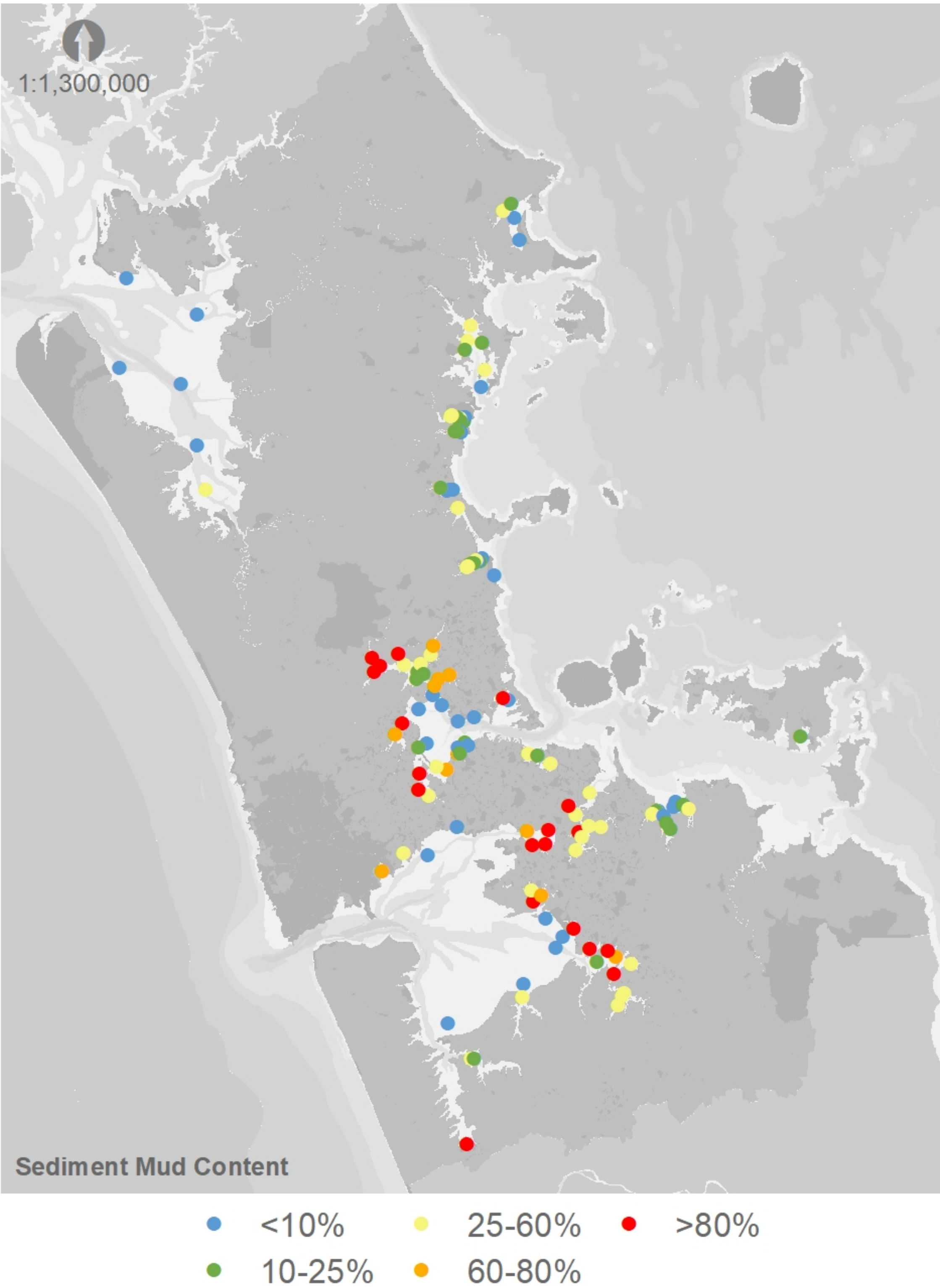

Figure A-1. Regional sediment mud content (measured within the last five years).

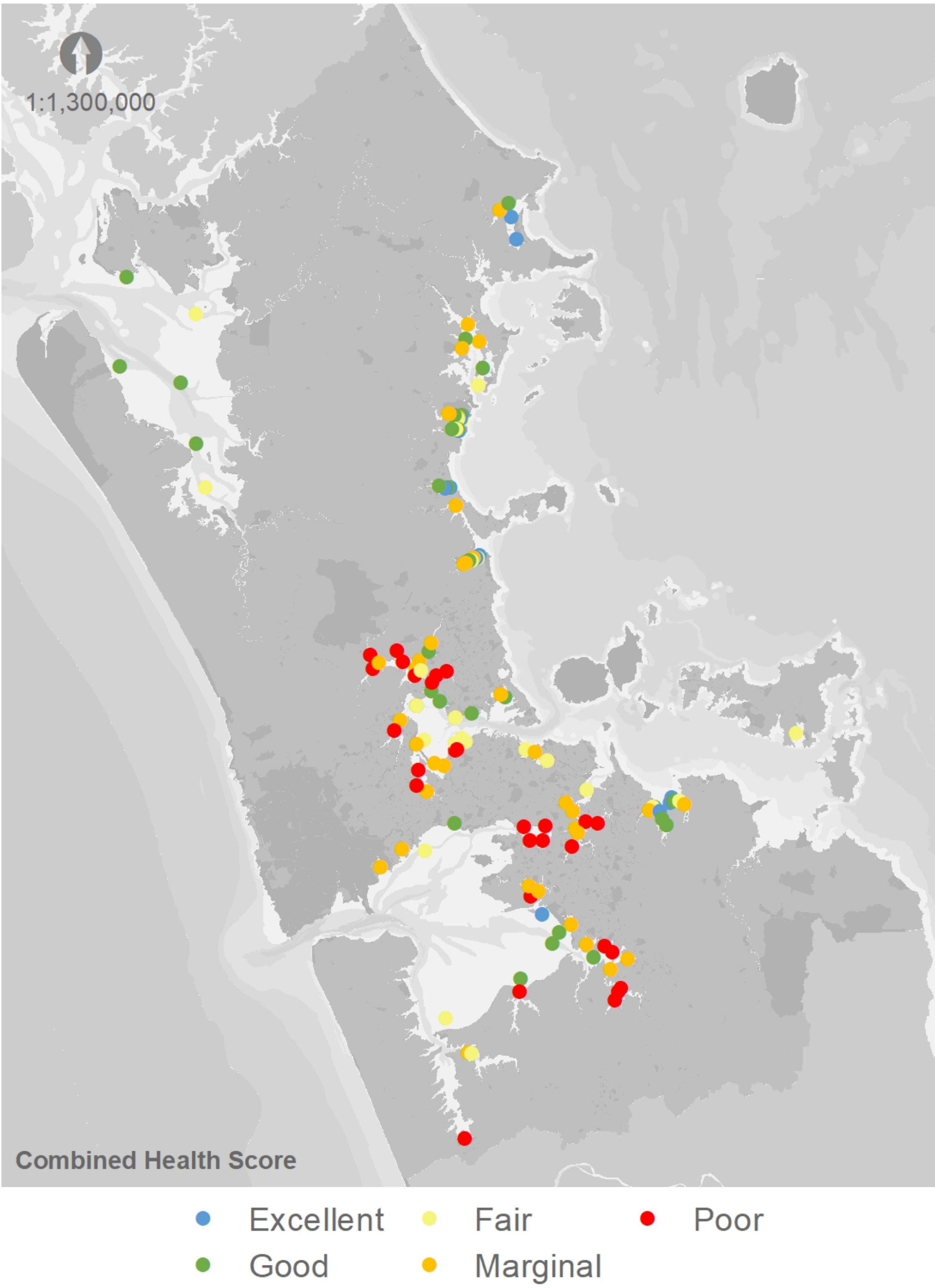

Figure A-2. Regional combined health score (measured within the last five years).

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