Arsenic and Mercury in Marine Sediment: State and Preliminary Trends in Tāmaki Makaurau / Auckland 2012-2021

H Allen

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Hamish Allen
Research and Evaluation Unit (RIMU)

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From Purewa bridge towards Auckland city, Hobson Bay, Waitematā Harbour.
Blockhouse Bay sediment contaminant monitoring site, Manukau Harbour.
Photographs by H Allen.

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Executive summary

Chemical contaminants such as mercury and arsenic can accumulate in the sediment of marine receiving environments. They can originate from both natural processes and man-made activities and are transported to the coast in numerous ways, including in stream and riverine systems, in wastewater and stormwater discharge and as leachate from decommissioned landfills. At elevated levels, these chemicals can be harmful, either directly or by contributing to already stressed ecosystems, affecting ecological health and functioning by reducing the number and/or the diversity of animals able to live in that environment. Identifying areas where concentrations of arsenic and mercury exceed what would occur naturally provides a useful indicator of land use impacts on marine receiving environments. Understanding the distribution of these contaminants in marine sediments, their effects on benthic ecology, and trends in contamination over time, is important for effective resource management of coastal areas.

Auckland Council regularly monitors contaminants in marine sediments at approximately 80 sites in the Regional Sediment Contaminant Monitoring Programme (RSCMP). The RSCMP assesses sediment contamination with regards to ecological impact, it does not assess chemical concentrations with regards to human health. The RSCMP data complement those obtained in other Auckland Council programmes (e.g., coastal water quality and benthic ecology), which together aim to provide consistent, long-term information on the quality of Auckland's coastal environment. Information gained is used to identify issues and inform policy development and environmental decision-making.

Previous sediment contaminant monitoring and reporting in Auckland has primarily focused on the metals associated with urban stormwater: copper (Cu), lead (Pb) and zinc (Zn). Intermittent testing of arsenic (As; a metalloid) and mercury (Hg) had shown that these contaminants were sometimes present at elevated concentrations in marine sediments. As sources and trends for these were unclear, routine monitoring was instituted in 2012 to obtain more information. It has now been ~10 years since this routine monitoring began, allowing current concentrations, spatial patterns of contamination and (at sites where data is sufficient) preliminary trends in concentration over time to be assessed.

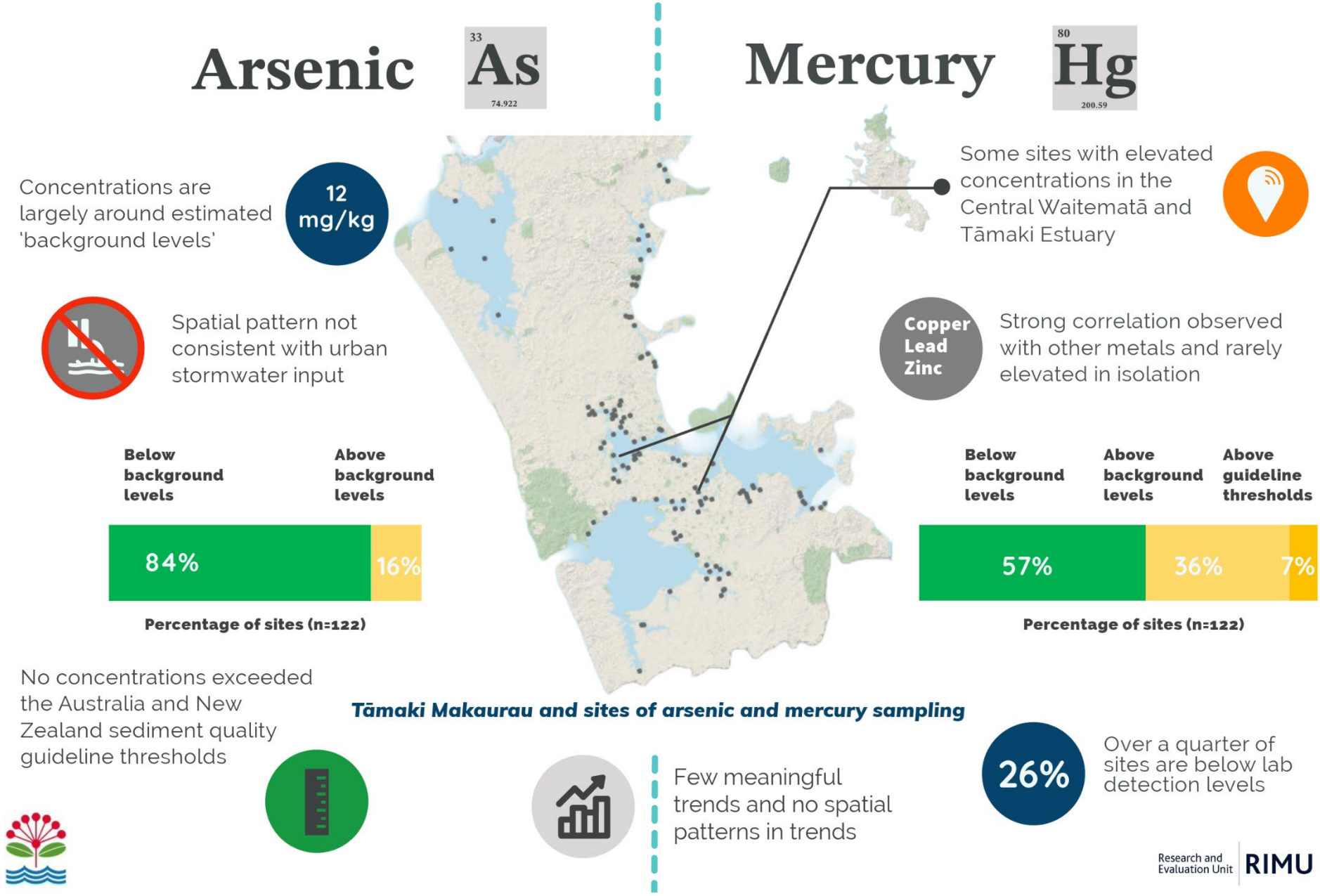
Key findings from the 122 sites assessed include:

- Concentrations of mercury are generally low across the region and based on sediment quality guidelines (a threshold based on the potential risk to benthic health), are below levels where impacts on benthic organisms would be expected. However, there are some sites with moderately elevated concentrations in the muddy, urbanised, inner estuary zones of the Central and Upper Waitematā Harbour and Tāmaki Estuary.
- Spatial patterns of mercury largely follow that of the metals associated with urban stormwater (i.e., Cu, Pb, and Zn), and concentrations are strongly correlated. This means that where mercury is elevated, generally other metals are too, and suggests mercury shares urban stormwater/wastewater as a common conduit into the marine environment.

- Arsenic concentrations are, for the most part, at levels close to or below what would be expected to be ‘natural’ for Auckland marine sediments.
- Arsenic concentration in marine sediment does not appear to follow any particular spatial pattern and differs from that of the other chemical contaminants monitored.
- There is some uncertainty with the risk assessment of arsenic, and interpretation of concentrations can be significantly influenced depending on which sediment quality guideline is applied.
- Relatively few sites showed meaningful trends for either chemical, and there does not appear to be any spatial patterns associated with increasing or decreasing trends.

In isolation, levels of arsenic and mercury currently pose only a low level of risk to benthic fauna, with the exception of a handful of sites where mercury levels are at higher concentrations. However, these chemicals are found at sites that may contain several other stressors and as such may be contributing to cumulative impacts, and even at slightly elevated concentrations may be negatively impacting benthic ecosystems.

Continual monitoring of arsenic and mercury in the RSCMP will provide insight into impacts of land use change on concentration levels, ensure that no widespread increases are occurring, and assess the effectiveness of remediation actions to limit emission. It will also enable a more comprehensive assessment of changes over time to be undertaken. This will support better decisions to be made regarding ongoing monitoring requirements.


Arsenic
33
As
74.922
Mercury
80
Hg
200.59
Concentrations are largely around estimated 'background levels'
12 mg/kg
Some sites with elevated concentrations in the Central Waitematā and Tāmaki Estuary
Spatial pattern not consistent with urban stormwater input
Copper
Lead
Zinc
Strong correlation observed with other metals and rarely elevated in isolation
Below background levels
Above background levels
84%
16%
Percentage of sites (n=122)
Below background levels
Above background levels
Above guideline thresholds
57%
36%
7%
Percentage of sites (n=122)
Tāmaki Makaurau and sites of arsenic and mercury sampling
No concentrations exceeded the Australia and New Zealand sediment quality guideline thresholds
Few meaningful trends and no spatial patterns in trends
26%
Over a quarter of sites are below lab detection levels
Research and Evaluation Unit
RIMU

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1 Introduction

1.1 Background

Chemical contaminants such as mercury and arsenic can accumulate in the sediment of our harbours, estuaries, and beaches (Mills et al., 2012). They can originate from both natural processes and man-made activities and can be transported into the marine environment in numerous ways, including in stream and riverine systems, in wastewater and stormwater discharge and as leachate from decommissioned landfills (Robinson et al., 2004; Chrystall and Rumsby, 2009). These chemicals can be harmful on their own (e.g., Neff, 1997; Nunes et al., 2008), but can also contribute to already stressed ecosystems, adding to the cumulative pressures of a cocktail of contaminants that can be present in some marine sediments. Where elevated, they can affect ecological health by reducing the fitness and number of animals and/or diversity of animals able to live in that environment. This can alter the ecological functioning of these ecosystems and result in degraded communities that are dominated by a few species that are able to tolerate higher contaminant levels. Identifying areas where concentrations of arsenic and mercury exceed what would occur naturally provides a useful indicator of the possible sources of these chemicals, and the impact of land use on marine receiving environments.

Auckland Council, and its predecessor the Auckland Regional Council (ARC), has undertaken marine sediment contaminant monitoring since 1998, aiming to assess the spatial distribution and temporal trends of chemical contaminants across the region. The main objectives of the 'Regional Sediment Contaminant Monitoring Programme' (RSCMP) are to assess the effects of catchment land use, in particular urbanisation, on marine environmental quality, and the effectiveness of resource management initiatives and policies that aim to mitigate adverse land use effects. Monitoring is carried out as part of legislative obligations, as well as providing evidence of how the council is maintaining and enhancing the quality of the region's coastal environment.

A summary of the monitoring undertaken and results from each RSCMP monitoring round are presented in an annual data report. Data are analysed every few years to assess the spatial distribution of contamination across the region (termed the contaminant 'state'), and how contaminant concentrations have changed over time (temporal trends). State and trend assessment was conducted for the period 1998-2010 (Mills et al., 2012), and 2004-2019 (Mills & Allen, 2021). Information is available for a wide range of end users and stakeholders and uses of the monitoring data include State of the Environment reporting, stormwater quality management, resource consenting, policy development and public education.

Previous sediment contaminant monitoring and reporting in Auckland has primarily focused on the metals associated with urban stormwater: copper (Cu), lead (Pb), and zinc (Zn). Mills

and Allen (2021) concluded that a clear picture of the spatial distribution of these chemical contaminants was provided by the monitoring programme. Highest concentrations were generally found in the muddy upper reaches of estuaries receiving run-off from older, intensively urbanised and/or industrialised catchments, particularly in the Tāmaki Estuary and Central Waitematā Harbour. Areas where concentrations were lower, but ecological effects were still possible, were also widely distributed throughout the Central and Upper Waitematā Harbour and in the Māngere Inlet (Manukau Harbour). Lowest concentrations were found in estuaries with largely rural/forested catchments and on open coastal beaches. Since the early 2000s, intermittent testing of arsenic and mercury had shown that these contaminants were sometimes present at elevated concentrations in marine sediments, and as sources and trends were unclear, routine monitoring was initiated in 2012 to obtain more information. It has now been ~10 years since this routine monitoring began, providing a platform for current concentration levels, spatial patterns of contamination and (where possible) preliminary trends in concentration over time to be assessed.

Along with data collected under the RSCMP, other marine monitoring programmes have also collected sediment contaminant data in recent years (including the East Coast Estuary Ecology and Harbour Ecology programmes). This has significantly expanded the spatial coverage of metal contaminant monitoring, particularly in more rural catchments.

1.2 This report

The objective of this report is to improve our current understanding of the potential risk of arsenic and mercury concentrations on benthic ecosystems, and begin to assess if these contaminants are increasing, decreasing, or remaining stable across the Auckland region. It provides a comprehensive state assessment and preliminary trend assessment, using monitoring data acquired from 2012 to 2021. This report does not address arsenic or mercury concentrations in marine life with regards to food safety for human consumption.

This report provides:

- assessment of spatial patterns in arsenic and mercury across the region and comparison of concentrations with sediment quality guidelines to assess the potential impacts on benthic ecosystem health, i.e., contaminant ‘state’,
- preliminary assessment of temporal trends in total recoverable arsenic and mercury concentrations at sites where sufficient data is available, and
- discussion of results and potential sources within an Auckland context.

1.3 Arsenic and mercury – sources and impacts

Arsenic (As) is a naturally occurring chemical element and can be found throughout the environment in air, land, and water. Unlike the other metal analytes tested in the RSCMP (Cu, Pb, Zn, and Hg), arsenic is a metalloid, a type of chemical which has properties in

between that of metals and nonmetals. Some natural processes such as geothermal activity have the potential to elevate concentrations, as super-heated water dissolves arsenic from surrounding volcanic rock and transports it to ground or surface water. This process can be particularly prevalent in areas that have high geothermal activity such as the North Island's central plateau (Robinson et al., 2004). Small quantities can also make their way out of rocks (all rocks contain some arsenic) and soil through erosion, dissolution, and weathering, entering streams or rivers and ultimately the receiving marine environment.

While natural processes contribute to the origin and distribution of arsenic, human activities can also release arsenic into the environment (Table 1-1). This can include through the treatment of timber (a process known as tanalising), where CCA (a chemical preservative which contains compounds of chromium, copper, and arsenic) is used to protect timber against insect and fungal attack. Arsenic can then be released through the treatment process, when the treated timber is burnt, or as the chemicals leach from timber into the adjacent environment. Arsenic has also historically been a common ingredient in fertilisers, herbicides, and pesticides, and can be released from various industrial processes such as glass and cement manufacturing and pulp and paper production. Arsenic can also be present in a number of domestic and industrial products (e.g., as a semiconductor in computer and electrical products). Therefore, there is the potential for arsenic to be present within landfill leachate[1] as previously discarded products breakdown over time (Ponthieu et al., 2007).

Once in aquatic ecosystems, arsenic can accumulate through trophic levels (e.g., from plants to invertebrates to fish) and can also undergo biomagnification, a process where a chemical progressively increases in concentration as it moves up the food chain (Ghosh et al., 2022). As with other contaminants, sediments can act as a sink for arsenic, and elevated levels have been shown to have a number of different effects, with different organisms having widely varying sensitivities to arsenic (Neff, 1997). In benthic marine environments, it can impact growth and reproduction of algae, alter feeding behaviour of some gastropod species (Ghosh et al., 2022), and affect size distribution and reproduction in amphipods (Visviki and Judge, 2020).

Long term exposure to arsenic can result in numerous human health issues, including cancer, cardiovascular disease, and impaired cognitive development (World Health Organization, 2022). This has led to the effect of arsenic on shellfish garnering special attention, due to the potential for human health impacts through consumption. Research has largely focused on accumulation rates and speciation (changes in the various forms of arsenic) in shellfish tissue, and research relating to impacts on invertebrate biology or ecological functioning are comparatively rare.

[1] Landfill leachate is caused by a process where liquid (usually rain) percolates through landfill waste, dissolving or entraining contaminants before it flows out of the waste material and seeps into ground water or the adjacent environment.

Arsenic in marine sediment undergoes complex interactions and can be present in various forms, driven by both biotic factors (such as the metabolic processes of organisms) and abiotic factors (such as the surrounding water or sediment chemistry). These interactions and the resulting form that arsenic takes, can have a significant impact on bioavailability, ecotoxicity and the impact it will have on organisms (Neff, 1997).

Mercury (Hg) is a naturally occurring metal that can be found across sediment, soil, water, and air. Mercury can take many chemical forms, and there are numerous pathways for it into the environment, both from natural and anthropogenic sources (Table 1-1). Major natural sources include emissions from volcanic activity, volatilisation (emissions to air from soils), and emissions from other geothermal sources to the atmosphere, soil, and water. Smaller amounts can also be emitted to the atmosphere through forest fires, as mercury present within plants is released into the atmosphere as they burn.

Generally, mercury is naturally found at very low concentrations, however, human activities such as the combustion of fossil fuels, geothermal power generation, mining activities, and the discharge of wastewater, can localise and elevate concentrations. Like arsenic, mercury is used in a number of consumer products such as fluorescent light bulbs, batteries, electrical fixtures and thermostats, also making it susceptible to being present in leachate from landfills. Once in the environment, either by natural or anthropogenic sources, mercury is capable of cycling between atmospheric, terrestrial, and aquatic reservoirs, and as a result, past emissions can continue to impact the environment for many decades (Amos et al., 2013).

Despite elevated concentrations of mercury having detrimental impacts on aquatic life, overall, there is a relative scarcity of papers relating directly to this in New Zealand. International research shows elevated mercury concentrations can cause reductions in amphipod feeding rates (Bundschuh et al., 2011), changes in gastropod growth rates and life span (Cardoso et al., 2013) and alterations in invertebrate community structure and composition (Horne, Finley and Sprenger, 1999; Nunes et al., 2008). While in New Zealand, mercury levels have been found to be elevated in the feathers of ōi / grey faced petrel (an oceanic seabird), potentially posing a risk to breeding performance (Lyver et al., 2017).

As with arsenic, multiple physical and biological factors affect the speciation of mercury, and a large amount of research has focused on understanding these complex transformations. Of particular importance is the conversion of inorganic mercury to methylmercury, a form produced as a result of the actions of microbes in aquatic ecosystems. Methylmercury is a highly toxic chemical that can accumulate in fish, shellfish, and animals (including humans) who eat fish. This can include accumulation in important mahinga kai species, limiting opportunities for the collection and consumption of traditional shellfish resources. Given the potential for human harm as a result of consuming methylmercury, it is this aspect of mercury speciation that has dominated research.

Table 1-1. Potential natural and man-made sources of arsenic and mercury.

	Natural Sources	Man-made sources
Arsenic	• volcanic activity • forest fires • weathering of rocks • ground water • hydrothermal vents	• timber treatment • agrichemical use • computing and electrical production • paper, pulp, cement, and glass manufacturing
Mercury	• volcanic activity • geothermal activity • weathering of rocks • forest fires • volatilisation – emission to air from soils	• extraction, refining and use of fuels and oil • waste disposal and wastewater discharge • consumer products such as light bulbs, batteries, electrical fixtures, thermostats

2 Monitoring methods

2.1 Programmes

Most of the data presented in this report are collected as part of the Regional Sediment Contaminant Monitoring Programme (RSCMP), which conducts regular monitoring at around 80 sites across the region's harbours and estuaries (see Mills and Allen (2021) for further detail on programme history).

The RSCMP aims to achieve the following objectives:

1. Provide assessment of the state of near shore marine sediment contamination.
2. Maintain regionally representative coverage, with an emphasis on areas undergoing change.
3. Provide data which allows the state and trends in sediment quality to be assessed over time for key contaminants using relevant guidelines where applicable.
4. Undertake studies to increase understanding and identify new and developing marine sediment contamination issues.

In addition to data collected as part of the RSCMP, this report also uses sediment samples taken in the East Coast Estuary Ecology and Harbour Ecology monitoring programmes. These programmes monitor benthic ecology, focusing on surface sediment characteristics and macrofauna to assess the ecological health of intertidal sandflats. Sampling for sediment contaminants at these sites is done less frequently than at RSCMP sites, and as such the data are not yet sufficient for trend analysis. However, they are suitable for inclusion in the 'state' assessment, broadening the spatial coverage of contaminant distribution across the region.

2.2 Sites

Monitoring sites are spread across the range of catchment land uses and histories found in Auckland. However, as a key focus of the RSCMP is to monitor the impacts of urban development, most of the sites are in areas receiving run-off from predominantly urban catchments such as the Manukau and Waitematā Harbours. Sites are in the intertidal zone and include a broad range of sediment textures. Many RSCMP sites can be described as 'muddy' with a significant proportion of silt and clay (particles <63 µm). The dominant representation of muddy sites reflects the accumulation of land derived fine sediment in many estuarine locations. These muddy zones tend to trap and accumulate contaminants, and hence they are useful as sentinel sites for assessing contaminant discharges from upstream catchments. There are a small number of firmer, sandier textured sites in the RSCMP (and considerably more when including the East Coast Estuary Ecology and Harbour Ecology programmes). Sandy sites, particularly those on beaches exposed to higher wave

and tidal energy, generally do not accumulate chemical contaminants to the same extent as muddier, low energy sites.

Overall, 122 sites were available for state assessment across the region. The location of sites and associated programmes are shown in Figure 2-1.

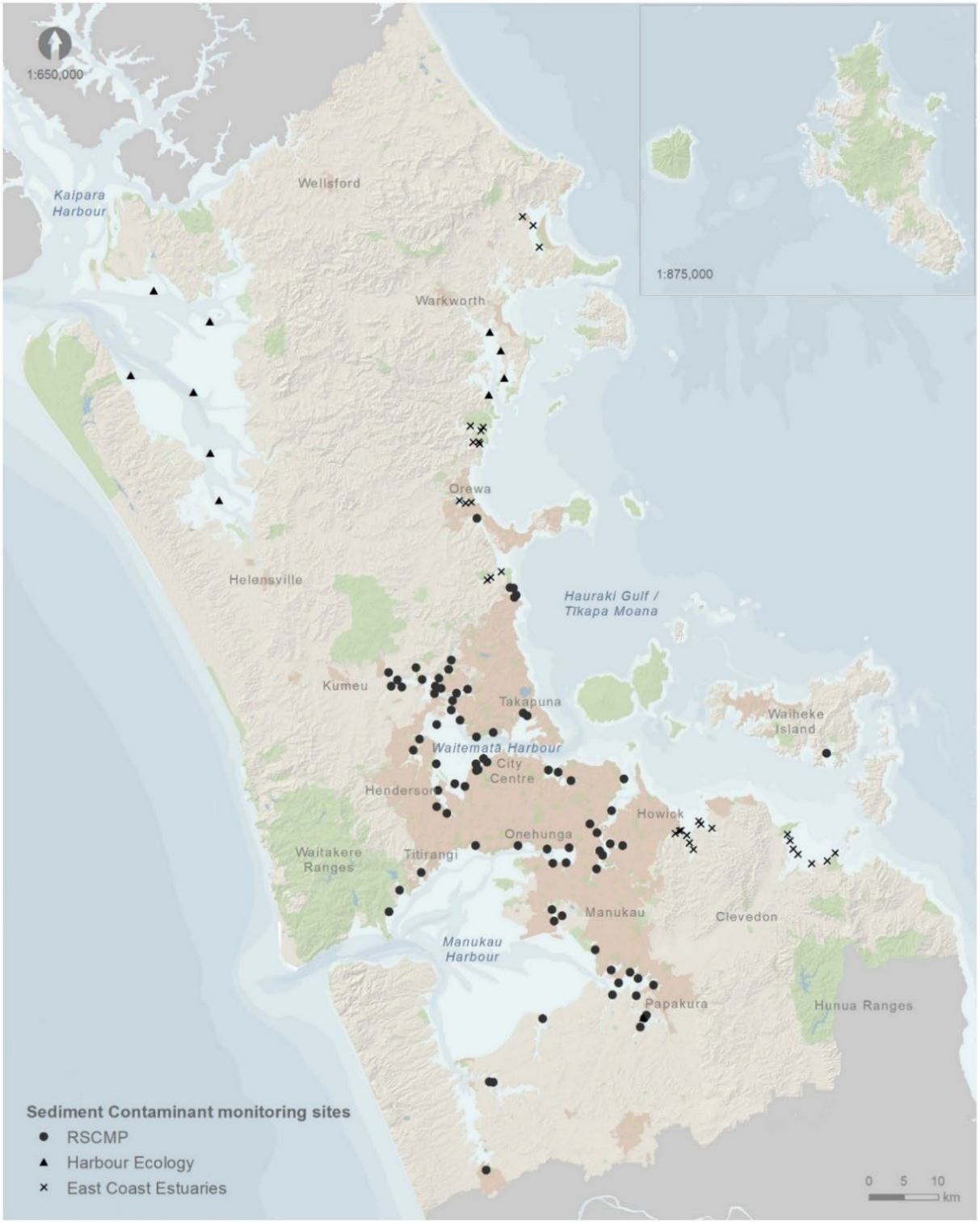

Figure 2-1. Locations and associated programmes of sediment contaminant monitoring sites featured in this report.

2.3 Sediment contaminant sampling

Sampling was carried out using protocols as described in the monitoring 'blueprint' document (ARC, 2004). Briefly, this involved taking replicate sediment samples from an approximately 50 x 20 m plot marked out at each monitoring site. The number of replicates analysed has varied slightly over time (three replicates were analysed at some sites prior to 2013), however five replicates at all sites have been analysed since 2015. Each replicate is made up from 10 sub-samples taken at regular intervals (approximately every 2 m) along two designated longitudinal transects within the sampling plot. The top 2 cm of sediment is sampled for laboratory analyses. Whilst it is possible contaminant concentrations may be higher at deeper levels in the sediment, particularly in areas where there may have been high historic input, sampling at this depth is a good compromise. It provides an integrated mixture of freshly deposited material and slightly older sediment from deeper in the profile, the sediments being mixed by biological and physical processes. This mixing is likely to 'smooth out' short-term variations in contaminant levels in the samples taken for analysis. Additionally, sampling at 2 cm depth is undertaken at all other regions in New Zealand where sediment contaminants are monitored by local authorities, allowing inter-regional comparisons to be made.

Sampling at several sites in the Upper Waitematā is undertaken using a different protocol, as described in Townsend et al. (2015). Briefly, this involves collection of replicate cores from four random locations across each site for muddier sites sampled by boat (to avoid disturbance of the substrate) or 12 random locations across sandier sites which are sampled on foot.

Currently, sampling frequency at RSCMP sites varies between three and six years. Sampling more regularly than this is not deemed critical, as concentrations have been shown to change relatively slowly over time (see Mills and Allen, 2021).

2.4 Sample extraction

Arsenic and mercury were extracted from the sediment by hot, strong acid digestion (HNO_3/HCl, USEPA Method 200.2). Samples were analysed on the <500 µm (<0.5 mm) fraction, which approximates the total sediment, with larger coarse particles – e.g., shell hash and gravel – removed to reduce data variability. Sample analysis has been conducted by Hill Laboratories (Hamilton).

The total recoverable metal results are used for state assessment by comparing concentrations with sediment quality guidelines (see section 3.2 for more details), which have generally been derived using metal concentrations of total sediment samples. Total recoverable metal results are also used for trend monitoring.

It is important to note that chemicals in marine sediment can be present in several different environmental compartments and forms, including in interstitial water (also called pore water), bound to organic carbon particles, or form insoluble precipitates with sulphides. Some of these forms are bioavailable to animals living in the sediment (i.e., able to be

absorbed and utilised in physiological reactions), and some (such as metals bound to organic carbon or precipitated with sulphide) are not. Laboratory analysis provides estimates of metal levels as a whole (i.e., analysis of total recoverable concentrations) and does not differentiate between the various forms. This means that only a portion of the total amount of the metal/metalloid measured is bioavailable and potentially pose biological risks.

2.5 Particle size distribution

Particle size distribution (PSD) is used primarily to assess whether there have been changes in sediment texture that may influence contaminant concentrations e.g., increasing amounts of fine muddy sediment could increase the total recoverable metal concentrations (and vice versa). It is also an integral component of the benthic ecology monitoring programmes because sediment texture is a key factor influencing benthic faunal assemblages and contaminant accumulation.

PSD of each sample is measured across several particle size ranges, from very fine clay (<3.9 µm) to very coarse gravel (>2 mm). The most important PSD data used in relation to contaminants is the 'mud fraction' (the sum of silt and clay particles; <63 µm fraction). This provides an integrative measure of changes in the proportion of the sediment where most contaminants are likely to be bound.

One composite sample, made up from 10 sub-samples of the top 2 cm of sediment, is analysed for PSD using standardised wet sieving/pipette analysis methodology by the National Institute of Water and Atmospheric Research (NIWA; Hamilton).

2.6 Quality assurance

Quality assurance (QA) is conducted to check that the contaminant data are 'fit for purpose' – i.e., suitable for reliably assessing state and temporal trends. The QA system has evolved over time and a set of QA 'acceptance guidelines' were developed (Mills, 2016). Current QA acceptance guidelines include measures for potential sample contamination, as assessed from procedural blanks, data accuracy from analysis of Certified Reference Materials (CRM)[2] and year to year data consistency as assessed from CRM and Bulk Reference Sediment (BRS)[3].

[2] Certified Reference Materials (CRM) are used to check data accuracy by comparing the lab-generated results with the certified concentrations and uncertainty limits for the reference materials. Three CRM samples (currently the CRM used is 'AGAL-10') are included in each analytical batch as 'unknowns' and analysed as for field samples. Note that the CRM analysis does not include the sediment preparation steps of sieving and drying prior to digestion and ICP-MS analysis, and therefore the CRM results may not completely reflect the total variation for field sediment sample analyses.

[3] Bulk Reference Sediment (BRS) are 'in-house' reference materials made up from bulk sediments sampled from two estuarine sites in 2011; one, more contaminated, muddy site from Middlemore (Tāmaki Estuary), and another, less contaminated, sandy site from Meola (Central Waitematā Harbour). Multiple replicates from each of these BRS are analysed with each batch of annual RSCMP monitoring samples and the results analysed to assess ongoing trends and variability. Details of BRS preparation are given in Mills (2016).

The application of the QA protocols, further detail on the process and yearly results can be found in annual RSCMP reports (e.g., Allen, 2023).

2.7 Summary of contaminant data used

For this state and trend update, the data used are as follows:

- data from 122 intertidal sites;
- median concentrations (from three or five replicates of surface sediment <2 cm depth) of total recoverable arsenic and mercury analysed on the <500 µm (<0.5 mm) fraction collected between 2012 and 2021;
- Mud content (% by weight <63 µm from sieve/pipette analysis), using a single composite sample result;
- Median concentrations (from three replicates of surface sediment <2 cm depth) of total recoverable arsenic and mercury analysed on the <500 µm (<0.5 mm) fraction from 23 intertidal sites sampled in 2005.

3 Data analysis and sediment quality guidelines

3.1 State assessment

The contaminant state is a measure of the current concentration of contaminants at a site. Concentrations are compared with sediment quality guideline threshold values to provide an indication of the potential risk of adverse ecological effects occurring on benthic organisms.

Multiple replicates have been analysed for each site, and median concentrations are used for state assessment. This provides a robust indicator of 'average' or 'typical' concentrations, the median value being less affected by occasional outlying values that can occur with environmental data.

State is assessed using the latest available data from each site. This is generally between the years 2016-2021. The rate of change is typically slow for contaminants in marine sediments (see Mills and Allen, 2021), so concentrations assessed several years previously remain useful and are likely to be at a relatively similar level today.

Tabulated data for site concentrations are provided in Appendix 9.1.

3.2 Sediment Quality Guidelines

Sediment Quality Guidelines (SQGs) provide a useful measure and means to interpret and present contaminant concentrations and are an important tool in assessing sediment quality. SQGs aim to identify concentration thresholds for chemicals in sediment below which ecological health is not impacted. While the initial intent of SQGs was to establish a rationale for taking corrective actions to protect aquatic life in contaminated sediments (Kwok et al., 2014), they provide a number of other helpful benefits, including as a trigger to prompt further investigations, allowing coarse comparisons to be made within a region, nationally and internationally, can help to guide management responses, can be utilised in regulatory applications, and are easily interpreted by a wide audience.

The derivation of SQGs is generally based on either empirical effects data for sediment contaminants (i.e., levels at which an observed adverse biological response occurs for a particular species), or mechanistic predictions using water quality guidelines and equilibrium partitioning, or a combination of both (Simpson, Batley and Chariton, 2013). Equilibrium partitioning accounts for the varying biological availability of chemicals in sediment (i.e., movement between pore water, sediment organic carbon and benthic organisms). If one of these concentrations is known, then the others can be predicted.

In order to derive SQGs, data from hundreds of studies including equilibrium-partitioning modelling, laboratory spiked-sediment bioassays, and field studies of sediment toxicity and benthic community composition have been critically evaluated and compiled into a biological effects database. Data for each chemical of concern are then incorporated into

data tables and sorted into an ‘effect’ data set and a ‘no effect’ data set, before the distributions of these data sets are divided above and below which effects are likely derived.

Ideally, SQGs would pinpoint the exact concentration in which contaminated sediments cause biological effects, however these effects are rarely clearly delineated, and include an area of uncertainty or ‘transition zone’ above and below thresholds for effects that are generally better understood (see Figure 3-1). This transition zone can cover a significant range of concentrations, caused by factors such as differences in bioavailability, differing responses by organisms and effects of unaccounted contaminants or other stressors (Simpson, Batley and Chariton, 2013).

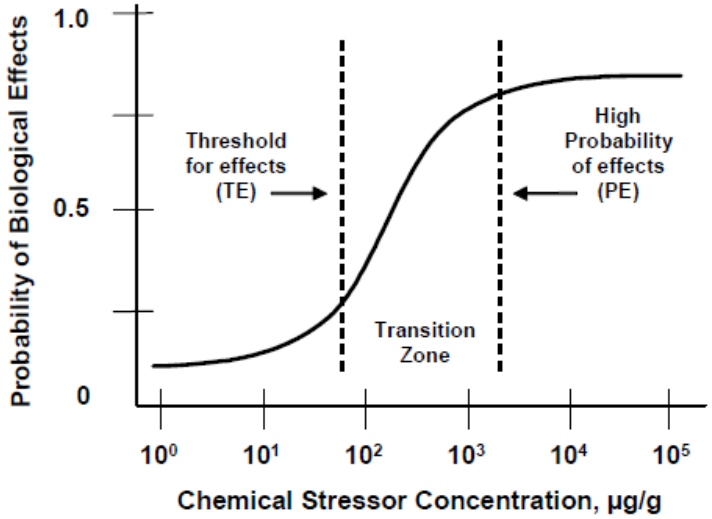

Figure 3-1. Generalised concentration-response relationship for contaminated sediments. Sourced from Simpson et al., 2013.

Currently, the SQGs used to assess the state of marine sediments in Tāmaki Makaurau are the Australian and New Zealand guidelines for fresh and marine water quality (ANZG, 2018) and the Auckland specific Environmental Response Criteria (ERC; ARC, 2004). The ERC, however, does not currently contain any values for arsenic or mercury. Given the ERC were largely derived from the Threshold Effect Level (TEL) and the Probable Effect Level (PEL) guidelines established by McDonald et al. (1996), these have been used in place of locally derived ERC for this assessment.

3.2.1 The Australian and New Zealand guidelines for fresh and marine water quality (ANZG)

When established in 2000, the ANZG values were deemed to be ‘interim’ guidelines, acknowledging that the science underpinning the values was developing, and that they would likely be revised in the future. A review of the guidelines took place in 2013 (with the values updated in 2018), resulting in a revised set of default guideline values (DGVs; the concentrations below which there is a low risk of ecological effects occurring). Table 3-1 shows the ANZG DGV and GV-high (concentrations where toxicity-related adverse effects

are likely to be occurring) values for arsenic and mercury. These values are stated to be derived primarily from the effects range low (ERL) and effects range median (ERM) values of Long et al. (1995), obtained using both field ecological and laboratory ecotoxicity-effects data from North America.

Table 3-1. Australia and New Zealand guidelines for fresh and marine water quality (ANZG) values for arsenic and mercury. Green reflects a low level of impact, Amber reflects a moderate impact where adverse effects may be beginning to appear, and Red reflects a higher level of impact where degradation has likely already occurred.

	ANZG (mg/kg)		
Metalloid/Metal	DGV		GV-high
Arsenic	<20	20 - 70	>70
Mercury	<0.15	0.15 - 1	>1

3.2.2 The Threshold Effect Level (TEL) and Probable Effect Level (PEL)

The TEL/PEL were established by McDonald et al. (1996). The TEL is a sediment contaminant concentration at which a toxic response has started to be observed in benthic organisms and is intended to estimate the concentration of a chemical below which adverse effects only rarely occur. Conversely, the PEL is intended to provide an estimate of the concentration above which adverse effects frequently occur to a large percentage of the benthic population. As with the ERL and ERM, which have been largely used to derive the ANZG, the TEL/PEL are derived from a biological effects database, albeit from an updated database with a modified and slightly more conservative quantitative approach (McDonald et al., 1996). TEL/PEL values for arsenic and mercury are presented in Table 3-2.

Table 3-2. Threshold Effect Level (TEL) and Probable effect level (PEL) guideline values for arsenic and mercury. Green reflects a low level of impact, Amber reflects a moderate impact where adverse effects may be beginning to appear, and Red reflects a higher level of impact where degradation has likely already occurred.

	TEL / PEL (mg/kg)		
Metalloid/Metal	TEL		PEL
Arsenic	<7.24	7.24 - 41.6	>41.6
Mercury	<0.13	0.13 - 0.7	>0.7

3.2.3 Sediment Quality Guideline variations

There can be considerable variation between SQGs reflecting the different criteria, factors and approaches used in deriving thresholds. This is particularly evident for arsenic (TEL <7.24 mg/kg compared with <20 mg/kg for the ANZG DGV). The guideline value for mercury is also more conservative under the TEL when compared with the ANZG DGV (<0.13 mg/kg vs <0.15 mg/kg), however with less disagreement. Because of these differences, the 'state' result can vary depending on what guideline is applied, and when concentrations from multiple sites fall between threshold values (i.e., above the TEL but below the ANZG DGV), the overall picture of potential estimated ecological impacts can change markedly.

3.2.4 Regionally specific guideline values

The establishment of 'regionally specific' guidelines is suggested in the ANZG, and region-specific guidelines are being increasingly encouraged internationally. In the absence of regionally specific guideline values for mercury and arsenic (i.e., no ERC values), this report will compare concentrations with two SQGs:

- the Australia and New Zealand Guidelines for fresh and marine water quality (ANZG) and,
- the Threshold Effect Level (TEL) and Probable Effect Level (PEL).

The ANZG are used widely across New Zealand, allowing national comparisons to be made, and the TEL/PEL offer more conservative thresholds in line with the ERC.

In addition, when regionally specific toxicant guidelines for sediment are unavailable, ANZG (2018) suggest adopting an interim 'reference site approach'. This involves taking the 80th percentile of concentrations from suitable 'reference sites' (i.e., sites located in largely native forested catchments with little urban impact). This provides a measure of what might be expected as natural 'background' levels, which can then be compared with concentrations from other potentially impacted sites. Accordingly, 80th percentile calculations at muddy reference sites 'Big Muddy' in the outer Manukau Harbour and 'Weiti' on the Hibiscus Coast, and a sandy reference site 'Te Matuku' on Waiheke Island have been calculated for arsenic and mercury. These sites spatially span the region, and the weighting towards muddier sediments better reflects the typical grain size observed at most RSCMP sites. The 80th percentile concentration derived from 49 samples (18 'sandy' and 31 'muddy')

are presented in Table 3-3. Background concentrations are discussed further in the Discussion section of this report.

Table 3-3. Probable 'background concentrations' of arsenic and mercury from three Regional Sediment Contaminant Monitoring Programme reference sites. Data (n=49).

Metalloid/ Metal	80th percentile concentration (mg/kg)
Arsenic	12.06
Mercury	0.048

3.2.5 Sediment Quality Guideline limitations

While a range of reports and research techniques have been incorporated into the effects database used in SQG development, many have been based on single-species laboratory-based toxicity measures (e.g., a 10-day amphipod survival test) rather than multiple species testing, which would provide more 'real world' relevance (Williamson et al., 2017). Additionally, the species used in SQG development are generally not the same as those present in the area where assessment is occurring, and laboratory conditions typically do not accurately reflect natural ecosystems (Hewitt et al., 2009). The effects database is also largely associated with muddy rather than sandy sediments. For the most part, this is in alignment with sites within the RSCMP, however it may mean that sandy sediments require stricter guidelines, due to partitioning to pore water (and as such bioavailability) being more prevalent in areas with sandier substrates (ANZG, 2018).

SQGs have been derived based on total sediment concentrations (the same fraction that is sampled in the RSCMP), as opposed to concentrations that are more readily bioavailable, such as those in pore water or the fine 'mud' fraction. This means that sediments can trigger thresholds for metals and be considered 'toxic' when in reality few biological effects are taking place.

Conversely, SQGs fail to account for the potential impact that cumulative effects of multiple metals at elevated concentrations may have on benthic ecology (i.e., will the impact on a site be worse with a single highly elevated metal concentration, or several slightly elevated concentrations?). Likewise, SQGs do not account for complex interactions which impact contaminant bioavailability, such as the presence of organic matter, organic carbon or sediment particle size. 'Effects' listed in effects databases are often a result of more than one chemical (i.e., a mixture of chemicals), however the effect range is ascribed to all chemicals, meaning some will be listed as causing impacts below actual effects thresholds (Simpson et al., 2013). Whilst this may provide more of a 'real world' effect (given sediments will contain more than one contaminant), it nevertheless has the potential to overestimate individual contaminant toxicity.

Databases typically used in SQGs are largely reliant on effects occurring because of acute toxicity. Analyses in recent reporting indicate that based on macrofaunal community

composition, some sites are showing degraded health in relation to metals despite concentrations being below ERC guideline values. This may be indicating chronic/and or cumulative toxicity effects (Drylie, 2021). Furthermore, research in the Auckland (Hewitt et al., 2009) and Tauranga (Tremblay et al., 2017) regions have observed changes to benthic community composition occurring along a contaminant gradient (for copper, lead and zinc) below both the ANZG and TEL thresholds. This could be a result of several factors, including simultaneous effects of multiple stressors, depth dependant responses, biological interactions between different species or differing susceptibility of species at various life stages (Hewitt et al., 2009). This emphasises the need to adopt conservative thresholds, and to ideally derive local SQGs, based off responses from native species which may behave differently to those from other parts of the world. Chronic toxicity measures may also provide a more realistic assessment, given the slow accumulation and persistent nature of contaminant concentrations observed in many Auckland marine sediments.

3.2.6 Multiple lines of evidence approach

SQGs are just one means by which impacts on benthic ecology can be assessed, and the ANZG (2018) recommends a 'multiple lines of evidence' approach is incorporated into sediment analysis to better assess ecosystem risk. This can include bioavailability measures, benthic ecology sampling or bioaccumulation analysis. A weight of evidence approach can then be used to evaluate these different lines of evidence. In line with this, sediment contaminant sampling in Tāmaki Makaurau has largely been undertaken in conjunction with benthic ecology sampling and particle size distribution, enabling these three lines of evidence to inform ecosystem health assessment. Despite the limitations discussed here, SQGs remain an important tool in the evaluation and dissemination of marine sediment quality.

3.3 Trend assessment

A key component of the RSCMP is the assessment of changes in contaminant concentrations over time. Trend assessment aims to determine whether contaminant concentrations in marine sediments are increasing, decreasing, or remaining constant, and the rate at which any changes are occurring. Assessment involves undertaking statistical analysis of the monitoring data to obtain the 'trend slopes' (magnitude of change per year, and the direction of change) and a measure of the likelihood of these changes over time being real (whether the changes are more likely to be attributable to chance, given the data variability in relation to the magnitude of the change).

The real-world relevance, or 'meaningfulness', of trends should also be assessed. For example, changes might be considered 'meaningful' if they are linked with changes in ecological health, if they can be associated with known changes in catchment land use or management, or if the rates of change exceed those required to trigger thresholds (e.g., SQGs) within time frames considered relevant for management purposes.

The trend analysis results presented in this report form only one part of the 'weight-of-evidence' for overall assessment of potential impacts on the marine environment. When combined with other information – e.g., trends in ecological health, catchment land use changes, contaminant management measures being implemented, targets or triggers for unacceptable rates of change in contaminant levels – a more complete evaluation of the 'meaningfulness' of the trends reported here can be made.

3.3.1 Considerations when assessing trends

A range of factors need to be considered when analysing and interpreting trends from monitoring data. These are discussed in detail by Mills and Allen (2021) for the most recent RSCMP trend assessment and are summarised briefly here.

The 'robustness' of trend results may be affected by factors associated with the monitoring itself – for example, sampling frequency, length of monitoring period, and consistency in sampling and analysis methods. Ideally, the trend monitoring data would be acquired at the same frequency, using the same sampling methodology, and the samples analysed by the same laboratory methods. However, this is rarely the case over the time scales required to build robust sediment contaminant data sets.

The numbers of samplings per site for the 2012-2021 arsenic and mercury data set ranged from one to five, as shown in Table 3-4. The number of data points in the time series record used for trend assessment in this report is still small due to the two yearly (or greater) sampling intervals. Only sites with four (or more) samples are included in trend analysis. As this number of data points is minimal, this trend assessment is deemed to be 'preliminary'. While this current assessment provides a good early indication of the general pattern of trends for arsenic and mercury, future analysis of these contaminants with an increased time series will provide a stronger analysis, and trends will be able to be assessed with greater confidence and reliability.

Table 3-4. Number of samples and number of sites for trend data used in this report. Sites with five or four samples only (48 in total) are used in trend assessment.

Number of samples	Number of sites
5	4
4	44
3	15
2	15
1	44

Trends have been analysed using median concentrations from each sampling round at each site. Three replicates per site (each composited from 10 sub-samples) were analysed for total recoverable metals from 2004 to 2013 (inclusive). From 2015 onwards (no monitoring took place in 2014 due to a programme review), five replicates per site were analysed at all sites. Therefore, for data used in this report, sampling at sites in 2012 (at 21 sites) and 2013 (at 38 sites) used the median of three replicates. Different numbers of replicates have no

effect on the calculated trend, however, the reliability of the median as a measure of the sample concentration improves with more replicates.

Particle size distribution (PSD) data are primarily used in the RSCMP to assess whether there have been changes in mud content that may affect interpretation of the total recoverable metals results. Because finer grained sediments (i.e., muddier) generally have higher metals' concentrations than coarser (i.e., sandy) material, trends in metals and PSD need to be considered together to assess the possible contribution of changing PSD to trends in metals over time. For consistency in this report, trend analysis of mud content has taken place over the same period and sampling events as for mercury and arsenic (i.e., from 2012 to 2021).

3.3.2 Data used for trend assessment

Trends for total recoverable arsenic, mercury, and PSD at 48 sites were analysed. The locations of these sites are shown in Figure 3-2. Additional detail on the data used and trend analysis results are presented in summary tables in Appendix 9.2. The majority of sites included in trend analysis are within the urban area of Auckland, with few 'rural' sites (such as those in the east coast estuaries), having had sufficient samplings to undertake analysis.

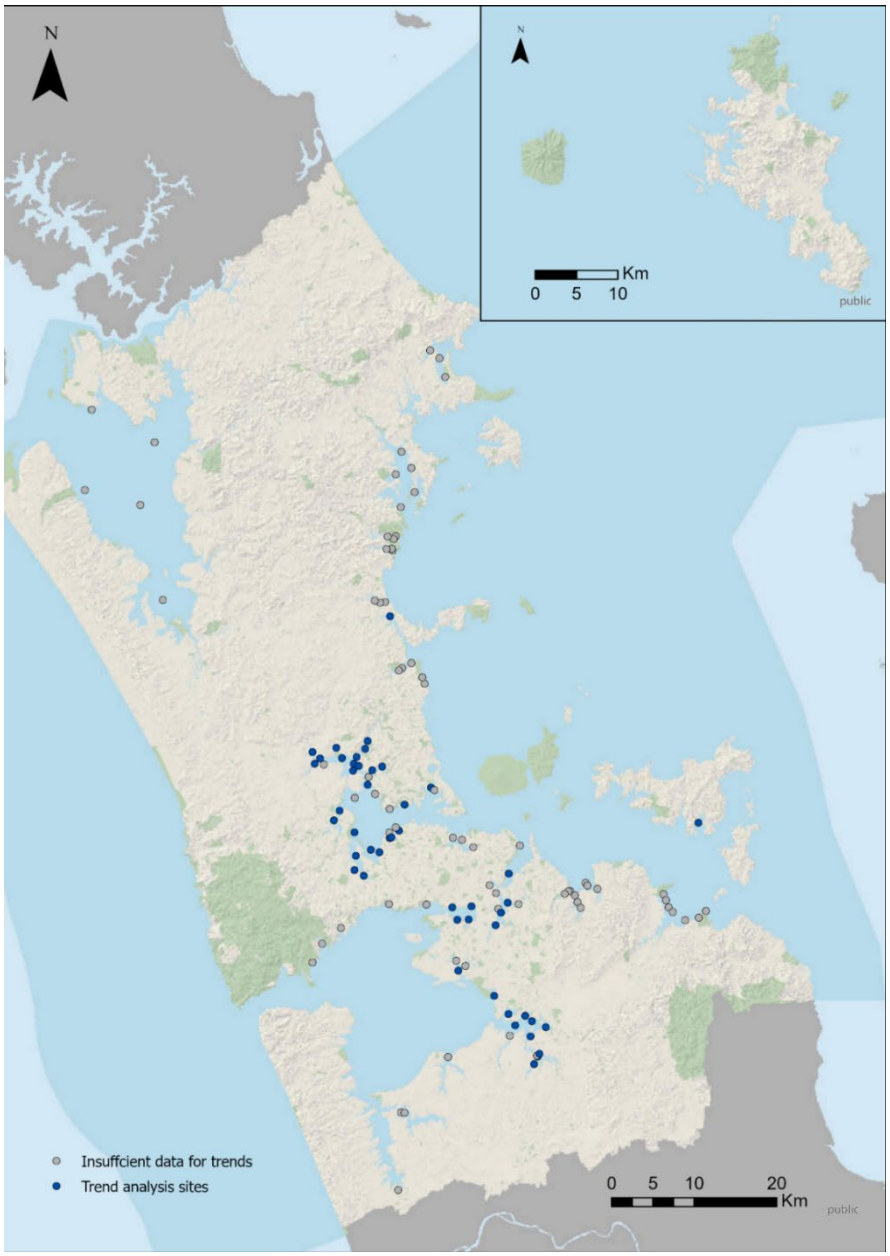

Figure 3-2. Locations of the 48 monitoring sites (blue dots) used for trend analysis of arsenic and mercury.

3.3.3 Comparisons with 2005 data

Sampling of arsenic and mercury took place at 27 sites in 2005, with results presented in Mills et al. (2012). From these 27 sites, a total of 23 have been sampled in recent times (between 2016 and 2021). Concentrations from 2005 and from the most recently available sampling are presented for each chemical, and a Pearson correlation used to determine the strength of the relationship between the two data sets.

It is important to note that there may be some discrepancy between results in 2005 and more recent values, due to concentrations in 2005 being obtained from a single composite sample, rather than the more robust method of using the median of three or five replicate composite samples as has been conducted between 2012 and 2021. However, these results remain useful as a coarse comparison over time.

3.3.4 Trend analysis

Significant linear trends in median concentrations were assessed with the non-parametric Mann-Kendall test and the magnitude (or 'rate of change') was obtained from the Sen Slope estimate. The Sen Slope is the median slope of all the slopes between all the data pairs in the data set (excluding ties, in values or in time). All analyses were performed in Time Trends v.6.30 (Jowett Consulting Ltd).

The likelihood of the trend being increasing or decreasing was assessed from the Sen Slope probability. Likelihood was categorised into five groups, as described by Land, Air and Water Aotearoa (LAWA, 2019) as follows:

- 'very likely' increasing or decreasing trends, where the Sen Slope probability is **90-100%**. For contaminants, an increasing trend reflects a degrading or worsening state, while a decreasing trend indicates improving conditions,
- 'likely' increasing or decreasing trends (Sen Slope probability **67-90%**). The lower certainty reflects the fact that while there is an indication of a trend, there is less statistical support for it,
- 'indeterminate' trends, where the Sen Slope probability is **<67%**, reflecting insufficient evidence to confidently determine if there is an improving or degrading trend.

This approach is consistent with that used for the most recent trend assessment for the RSCMP programme (Mills and Allen, 2021), for national water quality monitoring trend assessment and reporting (LAWA, 2019), and is the recommended method for analysis of temporal trends in environmental data, including for coastal and estuarine variables (Larned et al., 2021).

As for the previous trend assessment (Mills and Allen, 2021), trend magnitudes have been calculated as absolute values (in units of mg/kg per year for metals and %<63 µm per year for mud content) and a threshold of **±2%** of the median per year and '**very likely'** probability was used to define 'meaningfulness'. Trends meeting this threshold were considered to be reliable and have 'real world' significance.

4 Arsenic results

4.1 Arsenic state

The contaminant state of 122 monitoring sites, based on total recoverable arsenic concentrations in comparison with the ANZG DGV, TEL value, and regional 'background' concentration is shown in Figure 4-1. Individual site values are presented in Appendix 9.1.

Median concentrations of arsenic ranged between 17.63 mg/kg (site Lucas Upper in the Upper Waitematā Harbour) and 1.31 mg/kg at a site in the Whangateau Harbour. The majority of sites (103 out of 122; 84%) fell below 'background' concentrations, while no exceedances of the ANZG DGV threshold (20 mg/kg) were recorded, and consequently, no sites were remotely close to exceeding the ANZG GV-high value of 70 mg/kg.

Results using the more conservative TEL threshold limit (7.24 mg/kg) were more discriminating, with 79 out of 122 sites (65 %) exceeding this value. No sites exceeded the higher PEL (41.6 mg/kg). Exceedances of the TEL were widespread and observed at several sites that otherwise have very low levels of metal contamination (i.e., in the outer Manukau Harbour, East Coast Bays beach sites, and at numerous sites within east coast estuaries). The highest levels were recorded at a mixture of sites in the Upper and Central Waitematā Harbour, and in the Manukau Harbour. The lowest levels were recorded at sites in the Whangateau and Waikopua estuaries, and at several reasonably exposed sites in the Central Waitematā.

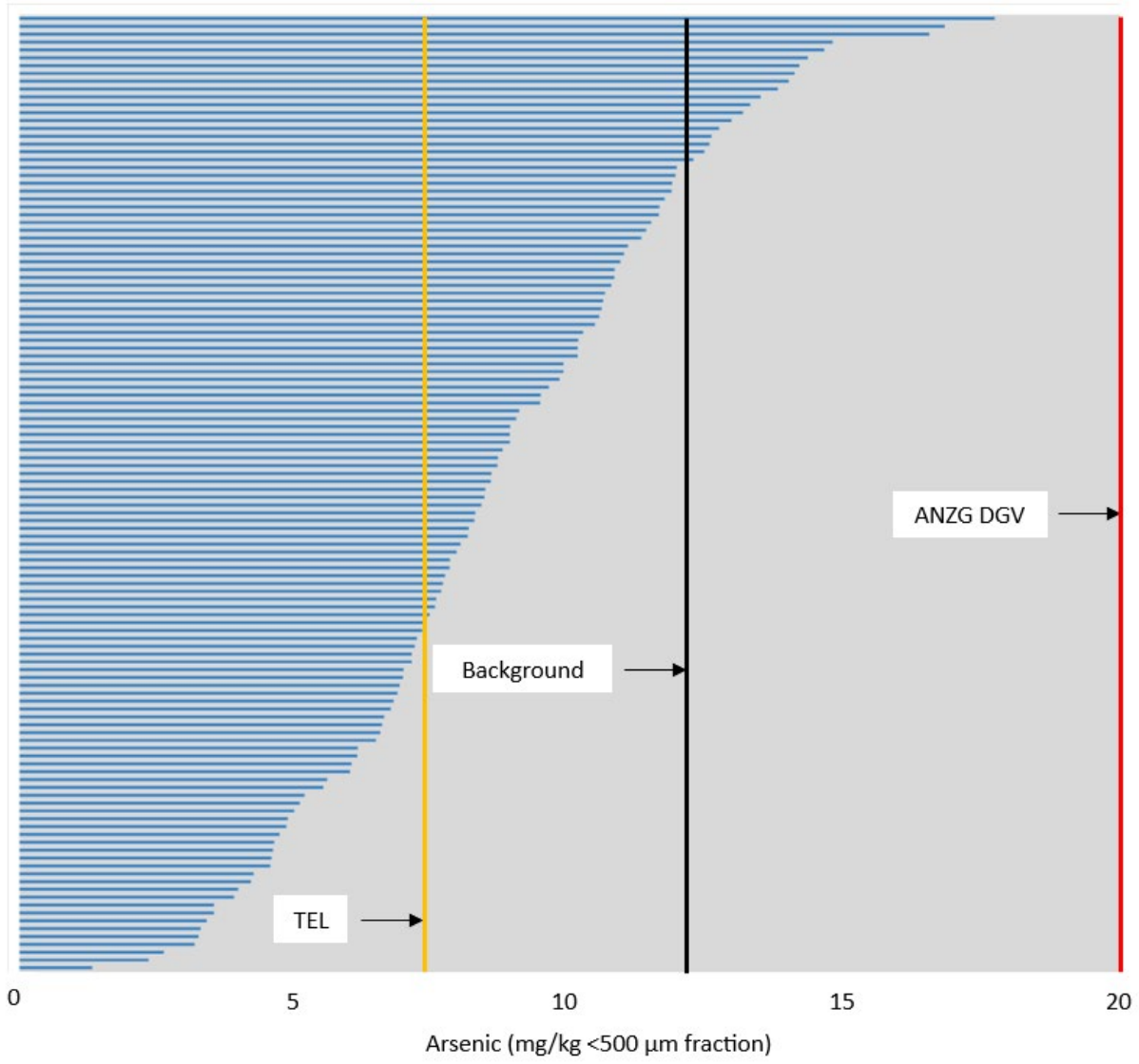

Figure 4-1. State for total recoverable arsenic for all sites. The yellow line is the Threshold Effects Level (TEL; 7.24 mg/kg), the red line is the ANZG default guideline value (ANZG DGV; 20 mg/kg), and the black line is the 'Background' level (12.06 mg/kg).

4.2 Spatial patterns of arsenic and state comparisons with other contaminants

Spatial patterns of arsenic using ANZG thresholds show nothing of concern, with levels across the region all below the DGV, and as such no figure is presented here. However, the spatial pattern of arsenic using the more conservative TEL/PEL guidelines shows regionwide elevated concentrations above the TEL value (Figure 4-2).

Previous spatial metal analyses associated with urban stormwater (i.e., Cu, Pb, and Zn) have shown that the highest concentrations are present at muddy upper estuary sites receiving run-off from the older urban and industrial catchments. This includes the areas of Henderson Creek to Cox's Bay along the southern shores of the Central Waitematā Harbour

(including Whau, Motions, and Meola estuaries), in Hobson Bay (Pourewa), the upper reaches and side-branches of the Tāmaki Estuary (e.g., Middlemore, Panmure, Ōtāhuhu, and Pakuranga) and, to a lesser degree, Māngere Inlet in the Manukau Harbour.

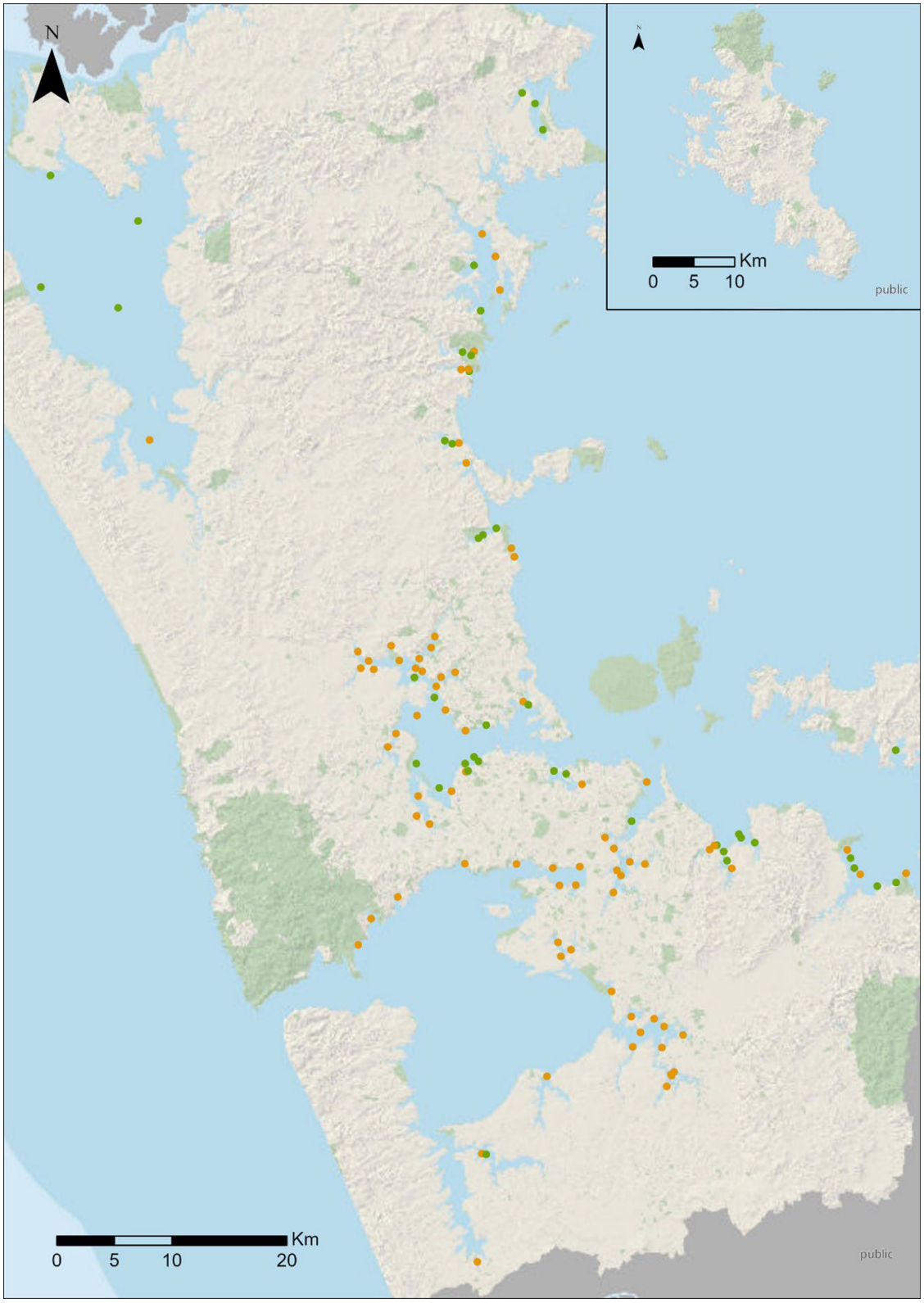

Figure 4-2. Map of total recoverable arsenic contamination state based on the Threshold Effect Level (TEL) sediment quality guidelines. Green sites are below the TEL (7.24 mg/kg), orange sites are above.

Pearson correlations between arsenic concentrations and that of metals copper, lead, mercury, and zinc, and mud content (particle size <63 μm) were examined. All correlations were statistically significant ($p<0.05$). The correlation between arsenic and mercury concentrations was fairly weak ($r^2 = 0.325$) indicating little relationship between these two contaminants. For the other metals, arsenic concentrations were shown to be moderately correlated (see Table 4-1), suggesting there may be some input from urban stormwater. However, it is unlikely to be largely stormwater-derived in the same way as copper, lead and zinc are generally considered to be. The relationship between muddiness and arsenic showed a slightly stronger relationship ($r^2 = 0.518$), suggesting particle size may be somewhat of an influencing factor in the spatial distribution and level of arsenic concentration.

Using the TEL to assess contamination, arsenic concentrations do not appear to follow any discernible spatial pattern, and do not follow a pattern similar to that of other metals tested in the RSCMP.

Table 4-1. Pearson correlation results for arsenic (As) concentrations (mg/kg dry weight <500μm fraction) with copper, lead, zinc, mercury, and mud (particle size <63 μm). *N* = 122.

Variables	R^2 value	P value
As and copper	0.396	<0.05
As and lead	0.439	<0.05
As and zinc	0.407	<0.05
As and mercury	0.325	<0.05
As and Mud	0.518	<0.05

4.3 Preliminary trends in arsenic

4.3.1 Arsenic trends at individual monitoring sites

Relatively few (seven; 15%) of the 48 trend sites showed 'meaningful' trends in arsenic ('very likely' probability (i.e., > 90%) and per cent annual change > ±2%), see Table 4-2.

Six sites had 'very likely' worsening arsenic concentrations in the following areas:

- two sites in the mid to lower reaches of the Pāhurehure Inlet (Pāhurehure Middle and Waimāhia Central) in the Manukau Harbour,
- three sites in the Upper Waitematā Harbour (Herald Island Waiarohia, Paremoremo and Lucas Te Wharau),
- one site (Weiti) located in the Weiti Estuary in the East Coast Bays.

One site (Drury Inner in the upper reaches of the Pāhurehure Inlet) had 'meaningful' improving arsenic concentrations.

Overall, trend results indicate that arsenic is worsening at more sites than it is improving (10 sites 'likely' or 'very likely' improving compared with 19 sites 'likely' or 'very likely' degrading). Results appear to be highly site specific, for example, sites relatively close to

each other in the Pāhurehure Inlet showed both meaningful increasing (Pāhurehure Middle) and decreasing (Drury Inner) trends.

Table 4-2. Summary of sites where meaningful (>2% per cent annual change, very likely probability >90%) increasing (▲) or decreasing (▼) trends in arsenic concentrations were recorded. PAC = per cent annual change. Concentrations are mg/kg dry weight <500µm fraction.

Site name	Samples	Sampling period	Median	Max	Min	PAC	Probability	Trend direction
Drury Inner	4	2015-2021	11.6	12.67	9.58	-3.79	0.91	▼
Herald Island Waiarohia	4	2013-2020	3.74	4.53	3.4	3.49	0.91	▲
Lucas Te Wharau	4	2013-2020	8.46	9.42	7.5	3.31	0.91	▲
Pāhurehure Middle	5	2012-2021	10.47	12.47	9.29	3.05	0.93	▲
Paremoremo	4	2013-2020	11.13	12.51	10.4	3.4	0.91	▲
Waimāhia Central	5	2012-2021	12.86	13.97	10.62	2.45	0.9	▲
Weiti	4	2013-2020	6.83	7.51	6.2	3.02	0.91	▲

4.3.2 Regional overview

There are no apparent spatial patterns observed in arsenic trends across the region (Figure 4-3). Meaningful increasing trends were observed in the Manukau Harbour, Upper Waitematā Harbour, and at a site in Weiti Estuary, while several other sites (eight in total) spread across the Tāmaki Estuary and Waitematā Harbour, showed trends that are 'likely' to be increasing (probability between 67 and 90%), with per cent annual change ranging from 2.66 to 7.61%. Indeterminate trends of varying magnitude and probability were also observed at sites dispersed across the areas where trend assessment could take place.

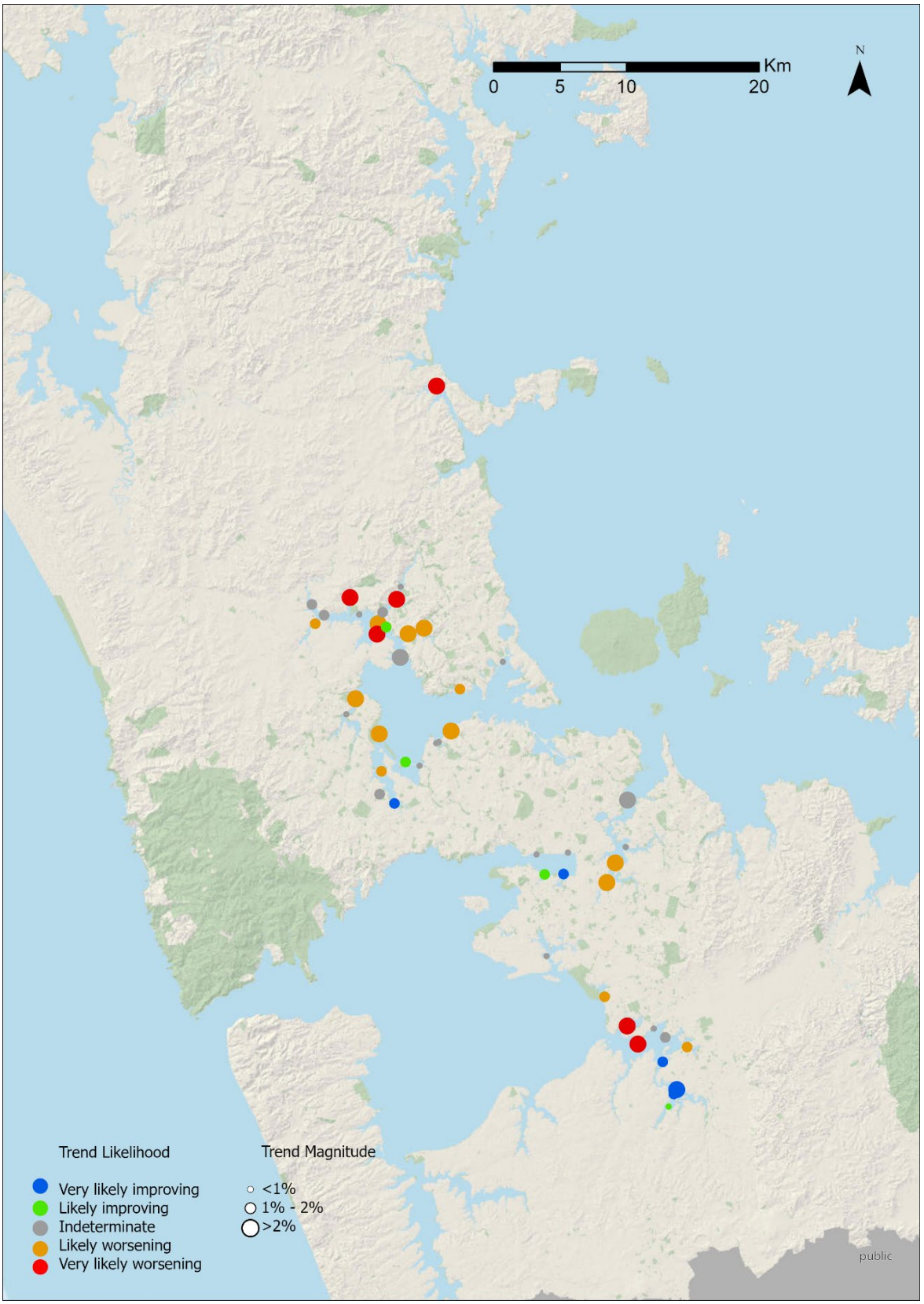

Figure 4-3. Distribution of trends in total arsenic concentrations from 48 sites across Auckland. Data from 2012-2021.

4.4 Arsenic state comparison with 2005 concentrations

Sampling of arsenic took place at 27 sites in 2005, with results presented in Mills et al. (2012). From these 27 sites, a total of 23 have been sampled in recent times (between 2016 and 2021). Comparisons between the two concentrations are shown in Figure 4-4.

Analysis showed a strong correlation (R^2 = 0.71; P value <0.05) of concentrations between the two sampling events, indicating that concentrations within this group of sites has in general remained relatively stable. The largest difference was observed at site Motions in the Central Waitematā, where arsenic showed lower concentration from sampling in 2020 (6.4 mg/kg) compared with 2005 (11 mg/kg).

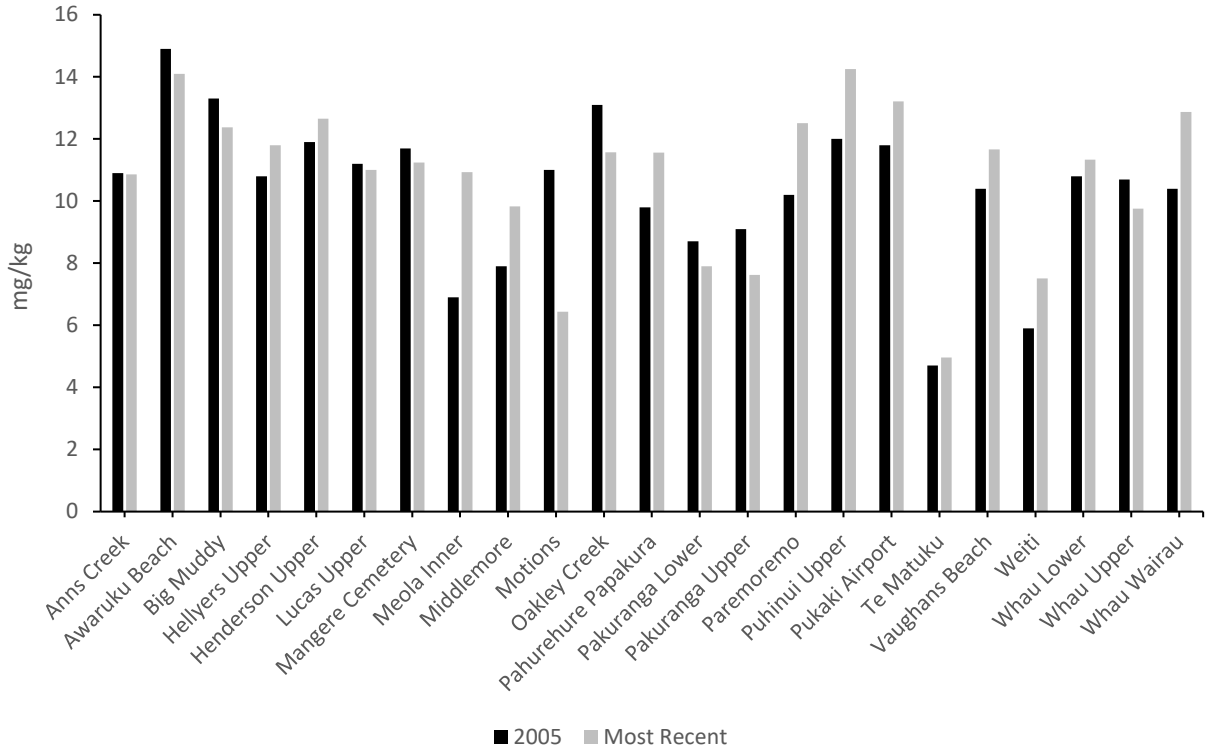

Figure 4-4. Concentrations of total recoverable arsenic at 23 sites sampled in 2005 and again recently. Concentrations are in mg/kg, <500 μm fraction.

5 Mercury results

5.1 Mercury state

The contaminant state of 122 monitoring sites, based on total recoverable mercury concentrations in comparison with the ANZG DGV, TEL value, and regional 'background' concentration are shown in Figure 4-1. Individual site concentrations are presented in Appendix 9.1.

Over half the sites (70 out of 122; 57%) recorded mercury values above estimated 'background' concentrations. From these, relatively few sites (8 out of 122; 7%) triggered the ANZG DGV for mercury (>0.15 mg/kg). These sites were located in the Central Waitematā (4 sites), Upper Waitematā (2 sites), and Tāmaki Estuary (2 sites). When compared with the slightly more conservative TEL (>0.13 mg/kg), a total of 19 sites (16%) triggered the guideline value, again these sites were split between the Central Waitematā (9 sites), Upper Waitematā (6 sites), and Tāmaki Estuary (4 sites). Encouragingly, no sites triggered either the ANZG GV-High (>1 mg/kg), or the PEL threshold (>0.7 mg/kg).

Several sites (32 out of 122; 26%) recorded mercury concentrations below the laboratory detection limit of 0.02 mg/kg. These sites have been listed as having concentrations of <0.02 mg/kg in the state table (Appendix 9.1). The majority of sites recording levels below laboratory detection were located in the outer reaches of the Manukau Harbour, the Kaipara Harbour, the East Coast Bays, and in the east coast estuaries (Ōrewa, Pūhoi, Waikopua, Waiwera and Whangateau). Values above detection limits ranged from 0.020 mg/kg (just above the detection limit) at site DOC Island Sand in the Pāhurehure Inlet, Manukau Harbour to 0.217 mg/kg at site Meola Inner in the Central Waitematā.

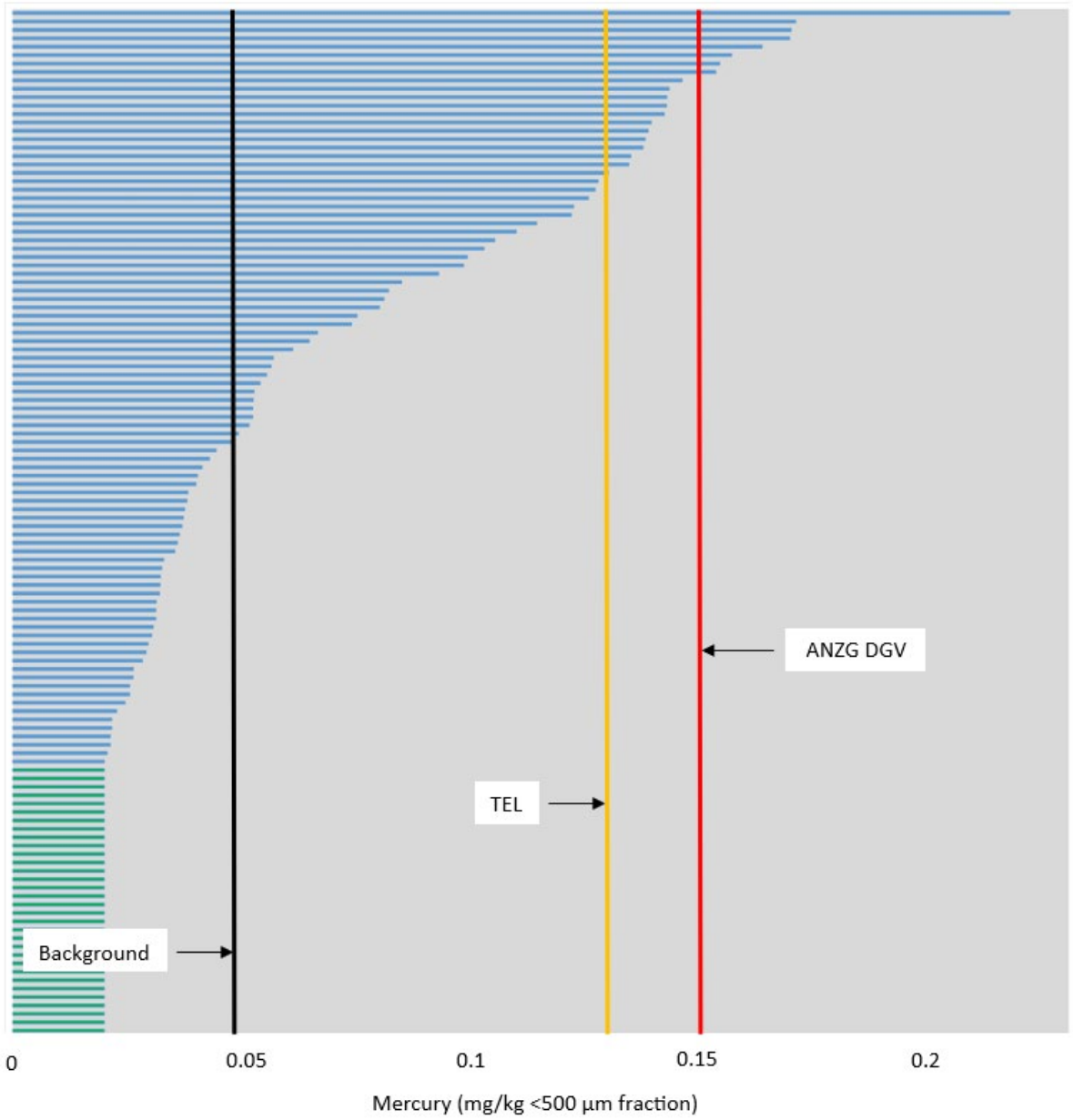

Figure 5-1. State for total recoverable mercury for all sites. Yellow line is the TEL (0.13 mg/kg), red line is the ANZG DGV (0.15 mg/kg), and the black line is the 'Background' level (0.048 mg/kg). Bars in green represent sites that were below the laboratory detection limit of 0.02 mg/kg.

5.2 Spatial patterns of mercury and state comparisons with other contaminants

The main areas showing elevated levels of mercury are located in the Upper and Central Waitematā, and the Tāmaki Estuary (see Figure 5-2). Patterns of mercury contamination (unlike arsenic), appear to follow the general spatial patterns observed with other metals within estuaries (i.e., higher concentrations in the upper reaches, decreasing with proximity to the estuary mouth). When compared with the ANZG DGV, mercury concentrations appear

to weakly follow this pattern, however it becomes more pronounced when using the slightly more conservative TEL.

Mercury levels at all sites in the Manukau Harbour, including those in the historically contaminated Māngere Inlet, are below both the ANZG DGV and TEL trigger values.

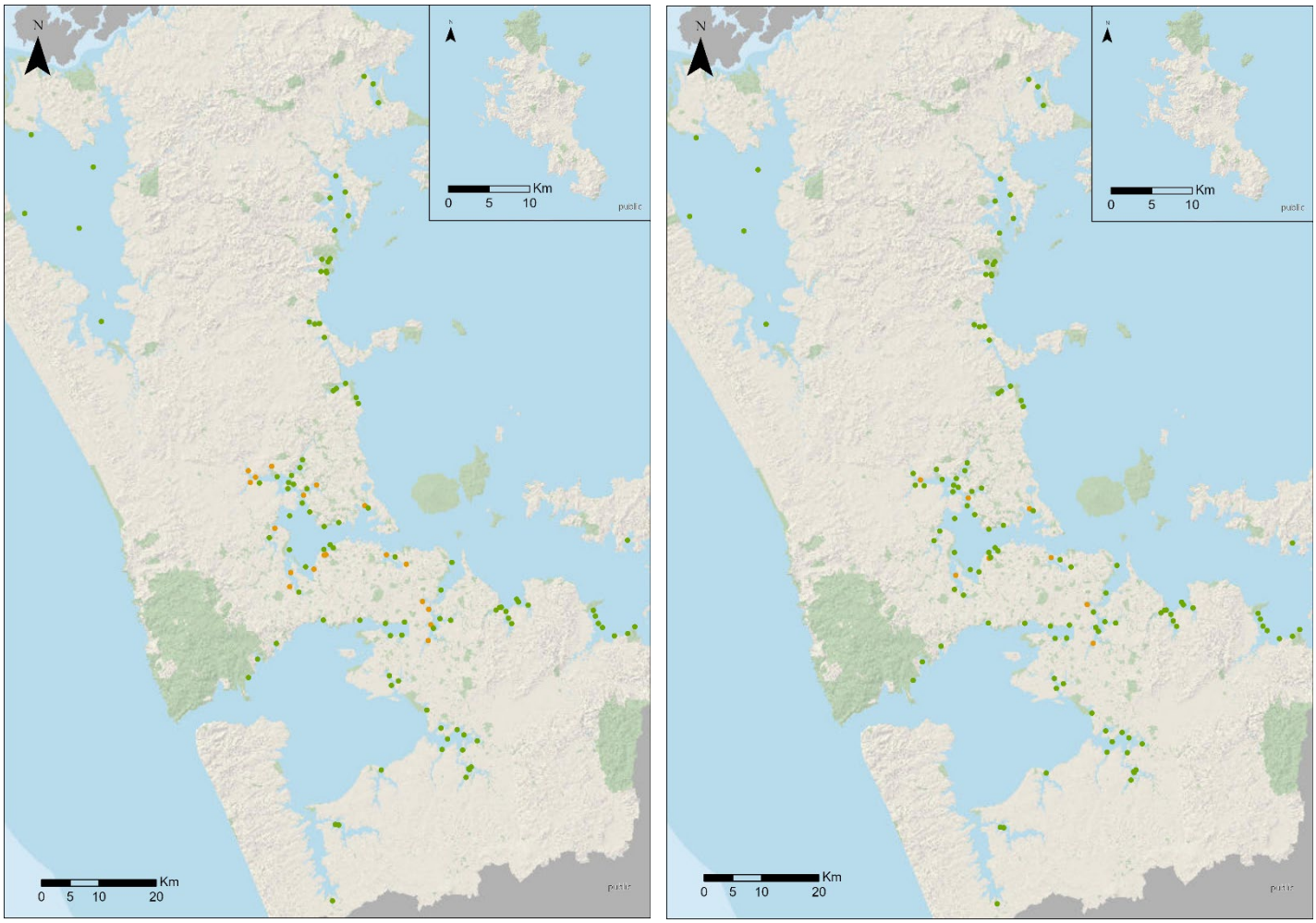

Figure 5-2. Map of mercury contamination state based the Threshold Effect Level (TEL; left) and the Australia and New Zealand guidelines for fresh and marine water quality (ANZG; right).

Pearson correlations between mercury concentrations and that of metals copper, lead, zinc, the metalloid arsenic, and mud content were examined (see Table 5-1).

All correlations were statistically significant ($p<0.05$). As demonstrated in Section 4.2, the correlation between mercury and arsenic concentrations is fairly weak ($r = 0.325$) indicating little relationship between these two contaminants. Conversely, mercury concentrations showed very strong relationships with copper, lead, and zinc. Mercury and mud showed a similar correlation to that of arsenic and mud ($r = 0.561$), indicating particle size may be having some influence on mercury concentrations.

Table 5-1. Pearson correlation results for mercury (Hg) concentrations (mg/kg dry weight <500μm fraction) with copper, lead, zinc, arsenic, and mud (particle size <63 μm). *N* = 122.

Variables	R^2 value	P value
Hg and copper	0.859	<0.05
Hg and lead	0.916	<0.05
Hg and zinc	0.829	<0.05
Hg and arsenic	0.325	<0.05
Hg and Mud	0.561	<0.05

Correlation analysis between mercury and other metals was conducted in 2005 (see Mills et al., 2012). The results presented here are largely in agreement with this earlier reporting, however stronger correlations are observed between mercury and other stormwater associated metals. The considerably larger data set available for this report (122 sites compared with 27 sites) reflects the extensive growth and development of the RSCMP over the past ~15 years, resulting in a more thorough correlation assessment being presented here.

Mercury was generally elevated alongside copper and/or zinc. Concentrations were elevated above TEL guidelines at just three sites (Shoal Bay Hillcrest and Opposite Hobsonville in the Central Waitematā, and at Awatea in Hobson Bay) which were not triggered by any other metal under the ERC.

5.3 Preliminary trends in mercury

5.3.1 Mercury trends at individual monitoring sites

Eleven of the 48 trend sites showed 'meaningful' ('very likely' probability > 90% and per cent annual change > ±2%) trends in mercury (Table 5-2). These were largely dominated by decreasing trends.

Ten sites had 'very likely' decreasing mercury concentrations >2% median per year with the following distribution:

- three sites in the Māngere Inlet in the Manukau Harbour,
- three sites in the Pāhurehure Inlet in the Manukau Harbour,
- four sites in the Central Waitematā Harbour.

Only one site (Waimāhia Central in the mid reaches of the Pāhurehure Inlet, Manukau Harbour) had very likely worsening mercury concentrations.

The improving sites in the Māngere Inlet agree with trends observed for other metals in this area (copper and lead) as reported in Mills and Allen (2021) and may reflect improving stormwater discharge as a result of modernising industry in the surrounding catchment, and/or burial of contaminated sediment by 'cleaner' sediment deposited in the inlet from elsewhere in the harbour.

Three of the four sites showing improving trends in the Central Waitematā are sites that are typically heavily contaminated (Motions, Whau Wairau and Oakley Creek). Sites Motions and Oakley Creek also show long-term improving trends in mud content (although not quite within the 'meaningful' criteria for site Motions; see Appendix 9.4).

Waimāhia Central is the only site showing meaningful worsening trends in mercury. This site is located in the lower reaches of the Pāhurehure Inlet in the Manukau Harbour and is also showing meaningful worsening trends for arsenic. This site is in relatively close proximity to sites in the upper reaches of the inlet that are showing improving mercury trends, emphasising the site-specific nature of contaminant concentrations. It is important to note that while this preliminary analysis indicates mercury is worsening at this site, concentrations are currently well below TEL or ANZG DGV thresholds.

Table 5-2. Summary of sites where meaningful (>2% median per year, very likely probability) increasing (▲) or decreasing (▼) trends in mercury concentrations were recorded. PAC = per cent annual change. Concentrations are mg/kg dry weight <500µm fraction.

Site name	Samples	Sampling period	Median	Max	Min	PAC	Probability	Trend direction
Anns Creek	4	2013-2021	0.062	0.074	0.050	-4.5	0.96	▼
Doc Island Mud	4	2015-2021	0.026	0.033	0.022	-6.6	0.98	▼
Drury Inner	4	2015-2021	0.041	0.048	0.036	-5.2	0.97	▼
Harania	4	2015-2021	0.057	0.058	0.052	-2.0	0.97	▼
Māngere Cemetery	4	2013-2021	0.057	0.059	0.042	-3.1	0.93	▼
Motions	4	2013-2020	0.174	0.21	0.137	-5.0	0.95	▼
Oakley Creek	4	2013-2020	0.147	0.167	0.134	-3.5	0.98	▼
Shoal Hillcrest	4	2012-2019	0.172	0.195	0.162	-2.7	0.93	▼
Whangapouri	4	2015-2021	0.033	0.040	0.029	-4.3	0.93	▼
Whau Wairau	4	2013-2020	0.153	0.174	0.141	-2.1	0.93	▼
Waimāhia Central	5	2012-2021	0.034	0.037	0.029	2.1	0.97	▲

5.3.2 Regional overview

Currently, mercury contamination appears to demonstrate a pattern of decreasing trends in the upper reaches of estuaries (i.e., Pāhurehure Inlet and Māngere Inlet in the Manukau Harbour, and the Upper Waitematā Harbour). However, these areas can be interspersed with sites showing 'likely' worsening and/or 'indeterminate' trends (Figure 5-3).

The magnitude of change was high for mercury at a number of sites. Twenty-two sites in total showed annual change >2% per year. Most of these (14 sites) showed decreasing trends of either 'very likely' or 'likely' probability.

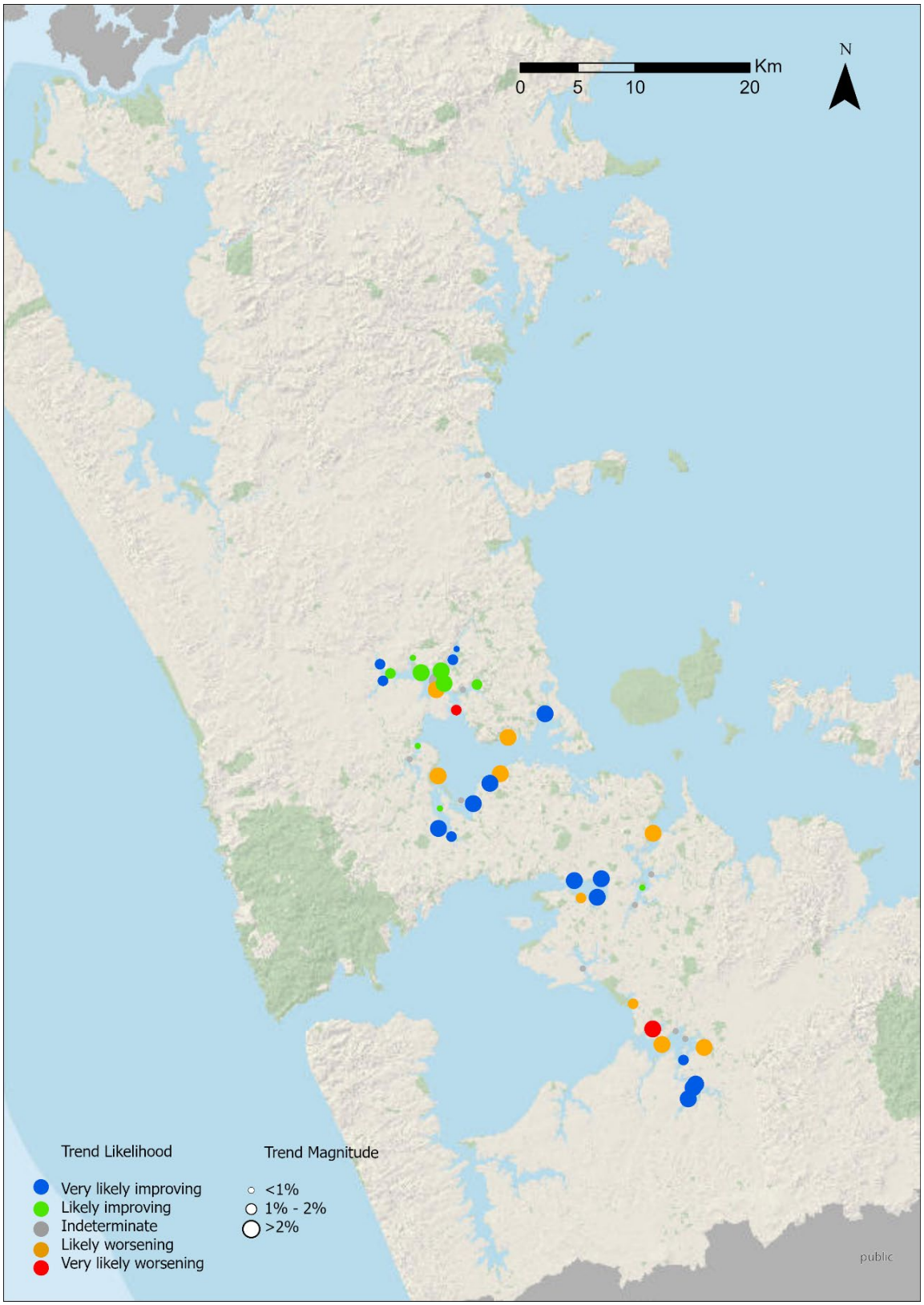

Figure 5-3. Distribution of trends in total mercury concentration from 48 sites across Auckland. Data from 2012-2021.

5.4 Mercury state comparison with 2005 concentrations

Sampling of mercury took place at 27 sites in 2005, with results presented in Mills et al. (2012). From these 27 sites, a total of 23 have been recently sampled between 2016 and 2021. Comparisons between the two datasets are summarised in Figure 5-4.

Analysis showed a strong correlation (R^2 = 0.84; P value <0.05) of concentrations between the two sampling events, indicating that concentrations over time within this group of sites have in general remained relatively stable.

The largest differences were observed at site Motions, which showed considerably lower mercury concentrations from sampling in 2020 (0.14 mg/kg) compared with 2005 (0.31 mg/kg). This agrees with the statistically significant and 'meaningful' reduction in mercury observed in trend analysis between 2012 and 2021, as well as decreasing copper and lead trends (from 2004 to 2019) reported for this site in Mills and Allen (2021). This site is located on the southern shore of the Central Waitematā Harbour, on a narrow, mangrove lined mudflat in the mid reaches of Motions Creek and receives run off from a highly urbanised catchment. Motions has constantly had relatively high levels of metal contamination (particularly zinc) since monitoring began in 1998 and is one of the more contaminated sites regularly monitored (Mills and Allen, 2021). The specific reason for the observed reductions is currently unclear, however levels of mud have been decreasing at site Motions, and this is likely a contributing factor to decreasing mercury concentrations over time.

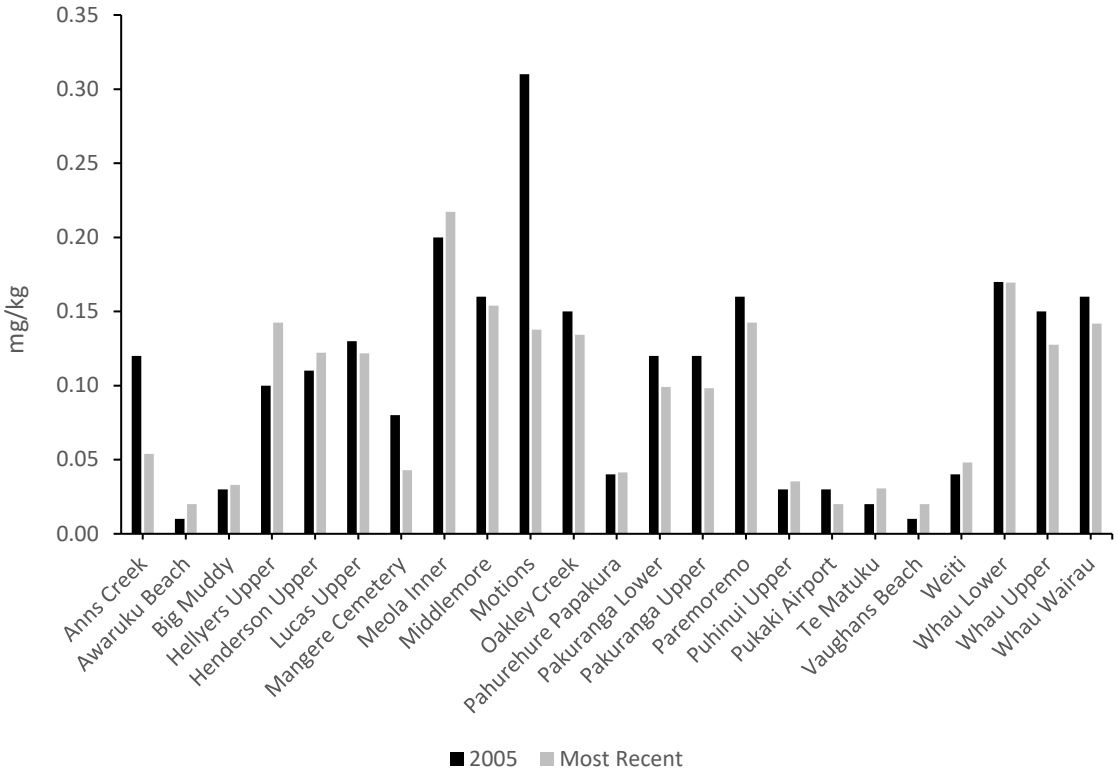

Figure 5-4. Concentrations of total recoverable mercury at 23 sites sampled in 2005 and again recently. Concentrations are in mg/kg, <500 μm fraction.

6 Discussion and Tāmaki Makaurau / Auckland context

Tāmaki Makaurau is a predominately marine region, surrounded by harbours, inlets, and exposed coastline. It is densely populated in parts, being home to approximately one third of New Zealand's population, with large and expanding urban areas. Historic and current land use practices and marine activities have placed significant pressure on coastal environments. This has resulted in areas where contaminants in marine sediments are elevated to levels where they are likely to be impacting ecological health.

Raw concentrations of arsenic and mercury have been reported in annual data reports for the RSCMP since 2012. However, since a brief analysis of one-off data collected from 27 sites in 2005 was conducted (see Mills et al., 2012), no further spatial analysis has taken place, and this is the first assessment of changes over time (trends) for these chemicals. This section will discuss the current results and potential sources of arsenic and mercury in Auckland marine sediments. It will compare observed concentrations with those reported elsewhere in Aotearoa and discuss relationships with levels of other metals (namely copper, lead, and zinc), providing context for the results presented in this report.

6.1 Arsenic

Arsenic concentrations in marine sediment vary across the region and based on the current concentrations do not appear to be having a significant or widespread effect on benthic ecological health. This is contrary to what may be inferred based on comparisons with the TEL, and the use of this sediment quality guideline in relation to arsenic needs careful consideration. In general, sites are at (or close to) what would typically be expected as background levels, with relatively few sites (19; 16%) above what might be expected naturally, and no sites above the ANZG DGV of 20 mg/kg.

Within an estuary, metal and mud concentrations typically follow a gradient that extends from the inner estuary (usually muddy settling zones) where concentrations are generally highest, decreasing (in both mud and metal contamination) as you move towards the estuary mouth. While arsenic appears to loosely follow a similar pattern in some instances, there are also numerous locations where no such spatial gradient exists. For example, in the Tāmaki Estuary, the typical pattern explained above is strongly evident for metals, with highly contaminated areas present in the mid to upper reaches, decreasing as you move towards the headwater. Conversely, arsenic levels in Tāmaki Estuary remain relatively stable from the upper reaches to the mouth, ranging in concentration from 7.18 mg/kg at site Benghazi in the lower reaches, to 10.76 mg/kg at site Bowden in the middle of the estuary.

Overall, very few sites (seven in total; 6% of sites) showed meaningful trends in total recoverable arsenic (i.e., greater than ±2% of the median per year and 'very likely'

probability). At sites with meaningful trends, these were mostly increasing. Trend direction and magnitude appear to be somewhat site specific, with sites in the Pāhurehure Inlet showing both meaningful increasing and decreasing trends. There does appear to be a concentration of increasing trends in the Upper Waitematā Harbour, however again, sites in this region are also showing indeterminate and likely improving trends. Despite there being more trends increasing than decreasing, the overall low number of meaningful trends means that at this stage there is no widespread concern for increasing arsenic concentrations across the region.

Interpretation of arsenic levels can be significantly influenced by which sediment quality guideline is applied. Levels appear to be widely elevated when compared with more conservative thresholds (i.e., the TEL). The Manukau Harbour has previously recorded largely low levels of metal contamination (for Cu, Pb, and Zn; sites largely in the ERC green category). This is thought to be due to a combination of factors, including the harbours large size and high level of tidal mixing, and a relatively small proportion of urban area within the catchment. However, when applying the TEL guidelines, arsenic concentrations appear elevated across the entire harbour, triggering all but one of the 28 sites monitored. Similarly, elevated levels above the TEL are observed at several sites in East Coast Estuaries where metal contamination is otherwise very low (i.e., in the ERC green category). Conversely, none of the 122 sites monitored trigger the higher ANZG DGV threshold.

Regardless of sediment quality guideline differences, arsenic appears to be ubiquitous in Auckland marine sediments, so the questions remain: where has it come from; are current concentrations impacting benthic ecology; and how much have human activities contributed to current concentrations?

Arsenic has been used in several agrichemical products. Some have been used extensively, sprayed or distributed across areas to control unwanted vegetation, or added to livestock dips to control ticks, fleas, and lice. Despite large scale use of these products no longer occurring, levels of contamination can remain high in both surface soil and soil deeper within the profile where long-term routine use has been undertaken (Gaw et al., 2006). Whilst the volume and regularity of the use of such products in the Auckland region over time cannot be quantified, it can be assumed that it was used to some extent. The coastal receiving environments of historical (and present day) rural catchments in Auckland show a range of arsenic concentrations in marine sediments (e.g., sites in Upper Waitematā catchment range from 4.53 to 17.63 mg/kg, the highest level observed in the region). Regional terrestrial soil monitoring shows that very few of the 157 sampling sites spread across Auckland exceed the background range for arsenic concentrations and exhibit no significant difference across land use types (between forestry, horticulture, native forest, dairy and dry stock), however they were found to be higher in urban areas compared with rural sites (Curran-Cournane, 2020). No discernible differences in concentrations based on catchment land use were observed in coastal sediments, and given the varying range observed in rurally dominated catchments across the region, it is unlikely that agrichemical use is a widespread or substantial source of arsenic to the marine environment.

Arsenic may also enter the marine environment from timber treated with CCA (copper chromium arsenate), a preservative that lengthens the life of wood by making it resist decay and insect and fungal attack. Timber in New Zealand is commonly treated with CCA, and when (illegally) burnt releases toxic chemicals in its smoke and ash. In 2018, a winter monitoring programme at four sites across the region found arsenic to be present in smoke plumes emitted from home fireplace burning, and potentially from industrial sources, often exceeding health-based ambient air quality guideline values (Talbot et al., 2020). Depending on weather conditions, ash (containing arsenic) from these fires may make its way into the marine environment. Additionally, studies have shown that low levels of arsenic can leach out of timber treated with CCA into surrounding soils (Schultz et al., 2002) or water (Archer and Preston, 1994). Auckland has a large number of timber posts embedded into marine sediment, for use as breakwaters, jetties and wharves, the majority of which are treated with CCA. There is a mild relationship observed between copper and arsenic in estuarine sediment ($r^2 = 0.396$). Whilst this suggests that a common source for these two contaminants is unlikely, a low correlation may be influenced in part by several factors, including there being more sources of copper than arsenic in the marine environment (namely copper based antifouling paints on vessel hulls), and arsenic seemingly having more of an affinity to accumulate in coarser sediment, meaning varying rates of accumulation dependent on sediment particle size. While both CCA treated timber embedded in marine sediment and emitted as ash from residential fireplaces will be contributing (to some degree) to overall arsenic loads entering the marine environment in Auckland, they are not likely to be prominent sources.

In addition to arsenic that may occur in soil from human input, Tāmaki Makaurau consists of approximately 50 small and localised basalt volcanic centres. As a result, volcanically derived soils and rock which can contain high concentrations of arsenic (Murray et al., 2023) cover much of the region. The natural weathering of these rocks and percolation through this soil type will result in small incremental amounts of arsenic being transported in waterways and ultimately into the marine receiving environment. Auckland is also home to several natural geothermal springs, including at Waiwera on the region's north-east coast and at Parakai, at the southern end of the Kaipara Harbour. Geothermal fluids can contain arsenic (and mercury), and while sites in the vicinity of Waiwera and Parakai do not show particularly elevated concentrations of either chemical, there is likely to be some natural contribution from these areas to the surrounding environment.

Typically, metal contaminant accumulation at beach sites is low due to the relatively high wave and tidal energy, which tend to disperse both fine sediments and contaminants. This does not apply to arsenic, with sandy beach sites in the East Coast Bays recording concentrations greater than many sheltered, muddy, highly urbanised locations. Studies in an estuary in New Zealand's north-east have shown arsenic to have a tendency to accumulate in sediments rich in calcareous substances, as opposed to metals which were more elevated in finer grained sediment containing organic matter (Bastakoti, Robertson and Alfaro, 2018). Arsenic accumulation in carbonate rich sands is likely due to sorption and/or co-precipitation processes (Romero et al., 2004). Whilst the exact carbonate

concentrations in sediments at sites sampled in Auckland is not known, this general theory may help to explain arsenic's relatively low correlation with muddiness and elevated concentrations at some sandier sites such as those on the East Coast Bays.

As is the case in Auckland, concentrations of arsenic in marine sediments are generally below ANZG thresholds across Aotearoa. Samples from 18 muddy intertidal sites in Canterbury showed arsenic to be between 2.1 and 5.6 mg/kg (Bolton-Richie and Lees, 2012). This is regarded to be within 'natural' concentrations, with background soil levels for the region between 0.9 and 8.7 mg/kg (Tonkin and Taylor, 2007). This background soil range is narrower than that given for the Auckland region (between 0.4 and 12 mg/kg; ARC, 2001), reflecting the variability between regions dependent on contributions from natural sources and predominant catchment soil type. Closer to Tāmaki Makaurau, five-yearly mean concentrations for over 90 marine sediment sites across the Bay of Plenty saw several sites above the TEL (7.24 mg/kg) however just one site was above 10 mg/kg (Crawshaw, 2021). In the Waikato region, in general sites show comparable levels to those observed in Auckland, although several sites do trigger the ANZG DGV threshold. This is particularly evident at sites in Port Waikato, where elevated levels are thought to be derived from geothermal sources (Waikato Regional Council, 2020).

The most appropriate approach for assessing arsenic concentrations in Auckland is to compare them with what would be expected naturally as 'background' concentrations. 'Background' levels have been calculated at 12.06 mg/kg (see section 3.2.4). This falls within literature values for background arsenic (albeit at the top end) in uncontaminated nearshore marine sediments of between 5-15 mg/kg (Moore and Ramamoorthy, 1984), is relativley close to the value assigned to sediments in the Bohai and Yellow Seas of 10 mg/kg (Luo et al., 2010), and falls between previousily derived concentrations for the Manukau (12.6 mk/kg) and Waitematā Harbour (11.0 mg/kg) (Pritchard et al., 2016). Neff (1997) suggests that the Effects Range Low (ERL) guideline value of 8.2 mg/kg (close to the TEL guideline value of 7.24 mg/kg used in this report) is low for marine sediments given background level estimates and proposes that this may be a result of guideline values being determined from freshwater or low salinity estuarine sediments which alter arsenic speciation and toxicity levels.

6.2 Mercury

Mercury contamination is generally low across Tāmaki Makaurau, with a total of 32 sites (26%) recording concentrations below laboratory detection levels. There are a few isolated pockets where levels are close to, or slightly above, those where impacts on benthic ecology may be occurring. These areas are in the muddy upper reaches of the Tāmaki Estuary, tidal creeks and inlets off the Central Waitematā, and at some sites in the Upper Waitematā. The spatial patterns largely follow that of the metals associated with urban stormwater (Cu, Pb, and Zn). The very strong correlation observed between mercury and these metals suggests that this contaminant shares urban stormwater as a common conduit into the marine

environment and a similar pattern of accumulation (i.e., elevated levels in the upper muddy reaches of estuary sites receiving run-off from the older urban and industrial catchments).

Overall, relatively few sites showed meaningful trends in total recoverable mercury (i.e., greater than ±2% of the median per year and 'very likely' probability). At the small number of sites with meaningful trends, these were mostly decreasing. Whilst not much can be read into these results given the short dataset, it does provide assurance that widespread increases in mercury are not currently occurring.

Mercury has been found to be well correlated with the mud fraction in other studies (see Coelho et al., 2016), and in Auckland showed a moderate correlation (r = 0.561), indicating that along with other contaminants, particle size can be an influencing factor in mercury accumulation. Decreasing trends for mercury at two sites (Oakley Creek and Drury Inner) correspond with meaningful decreasing mud trends (a further five sites are showing corresponding mercury and mud decreases, but do not fit the 'meaningful' criteria). Metals tend to accumulate in mud due in part to the large surface area of numerous very small particles (i.e., particle size <63µm) providing more space for contaminants to adhere to, and metals strong attraction to ionic exchange sites that are associated with the iron and manganese coatings common on clay and silt particles which make up the mud fraction (Ongley, 1996).

Landfills are acknowledged as a source and aquatic ecosystems a receptor of mercury in New Zealand (Bingham and Simpson, 2022). There are over 150 closed landfills in the Auckland region. Many of these were developed prior to the 1980s, and unlike more modern landfills, contained little in the way of lining or capping, and as such have the potential for contaminants to seep out into the adjacent environment. This is of particular concern at sites that are located on highly permeable ground, in areas adjacent to fresh water sources such as springs or streams, or those located adjacent to sensitive coastal environments.

Of the 19 sites that are considered to have elevated mercury concentrations under the TEL, 12 are in relatively close proximity to closed landfill sites (i.e., the site is either directly adjacent to a closed landfill or is located in the receiving environment of a catchment with multiple closed landfills). Several of the most contaminated sites such as Meola Inner, Shoal Bay Hillcrest and Whau Lower are located in the proximity of closed landfills deemed to be 'high-risk', due to the type of waste disposed, the potential for hazards when undertaking works, and general stability of the site. Mercury cycling and speciation in landfills is a complex and not completely understood process. Concentrations are typically not monitored under landfill consent conditions, however when they are, they are typically found at low levels (Chrystall and Rumsby, 2009). Whilst there may be some connection between closed landfills and elevated mercury in Auckland, further, more targeted investigation is required to better understand this relationship. This is particularly pertinent given the potential for increased erosion in both coastal and freshwater systems (and consequently the potential for some closed landfills to become compromised), as climate change causes sea levels to rise and storm events to become more intense and frequent.

Mercury may also enter the marine environment through wastewater discharge. While wastewater treatment processes can effectivley remove a significant proportion of mercury, retained and disposed of in sewage sludge (Watercare, 2015), untreated wastewater can at times overflow from gully traps, manholes, pump stations or engineered overflow points, often during high rainfall when networks are above capacity. Untreated wastewater can contain high levels of mercury, originating from its use in various products and processes, and is considered to be an important source of mercury to the environment (Wang and Mao, 2019; Suess et al., 2020; Bingham and Simpson, 2022). Whilst the concentrations of mercury in untreated wastewater is unknown, it is likely that it is contributing to elevated levels in urban areas affected by episodic untreated wastewater disharge. Along with wastewater, stormwater can also carry mercury to the coast, entraining atmospheric mercury when it rains and discharging it in marine receiving environments.

Intentional use of mercury in industrial processes in New Zealand is now largely historic. It is still utilised in some processes such as cement production and pulp and paper manufacturing, however emissions from these sources are likely to be small and mostly associated with fuels used in various production processes (Bingham and Simpson, 2022). Several sites with elevated mercury are located in urban areas with catchments that have a long history of industrial use, and it is possible that some amount of mercury found in these areas may be remnant from historic activities and practices.

Natural sources such as geothermal activity, volcanic activity and volatilisation from soils are estimated to provide approximately 50% of the overall proportion of mercury to the environment in New Zealand (Chrystall and Rumsby, 2009). However, for urban areas in Auckland where we see elevated mercury levels (such as the Tāmaki Estuary and estuaries off the Central Waitematā Harbour), these natural sources are not likely to be contributing above what would be expected as ‘background’ levels. ‘Background’ levels for mercury in Auckland sediments have been calculated at 0.048 mg/kg (see section 3.2.4). Based on this, 38 out of 122 (31%) sites sampled have concentrations above this value, indicating some other (i.e., anthropogenic) influence is occurring. Landfilling and wastewater treatment and disposal are the dominant sources of mercury nationally, contributing 96% of relative mercury outputs to water in New Zealand (Bingham and Simpson, 2022). It is likely to be a similar story here, with a combination of stormwater and wastewater discharges (and to a lesser extent landfill leachate and historic industrial practices) contributing to the observed elevated levels in pockets of Auckland’s urban marine environment.

In general, mercury results in Auckland are comparable with other sites across the country. Mercury exceedances of the ANZG DGV have been observed at several subtidal sites within Wellington Harbour (Cummings et al., 2022), while at intertidal muddy sites in Canterbury, mercury values ranged from below detection limits to levels just below the ANZG DGV (Bolton-Richie and Lees, 2012). The five-yearly mean concentrations for over 90 marine sites across the Bay of Plenty showed mercury levels were generally low, with no sites exceeding the ANZG DGV (Crawshaw, 2021). A small number of sites in the Waikato show slightly elevated levels of mercury. Sites in the Firth of Thames with concentrations exceeding the

ANZG DGV are attributed to both natural geochemical processes, and from mine tailings and industrial fill used in historic land reclamation (Waikato Regional Council, 2022).

Mercury levels have been of global concern for some time. In the 1950s large scale poisoning occurred in the Japanese city of Minamata, following decades of mercury laced industrial wastewater being discharged into the adjacent bay. Mercury subsequently bioaccumulated and biomagnified in fish and shellfish, which when eaten by residents, caused many to suffer what became known as Minamata disease (now known as methylmercury poisoning). Mercury levels in the environment, and particularly in fish, continue to be of concern (see the World Health Organization and Ministry for Primary Industries), and in 2013 this led to the development of a global treaty to protect human health and the environment from its adverse effects. Developed under the umbrella of the United Nations Environment Programme, the 'Minamata Convention' called for a reduction in the use of mercury and mercury compounds and a phasing out of its use in a wide range of products. It also set limits on specific sources such as mining, and controls on mercury added products and manufacturing processes. New Zealand initially signed on to the treaty but is yet to ratify the convention (as of 2023, 128 other countries have), however steps are being taken and domestic measures developed for this to take place (Ministry for the Environment, 2020). New Zealand's intentions to ratify the convention will have unknown, but presumably positive effects on environmental mercury concentrations in future years. Monitoring of mercury in marine sediments (and in other domains), will be essential if we are to understand the impact any changes introduced by this convention will have on environmental concentrations.

7 Summary and conclusions

Concentrations of arsenic and mercury were assessed at 122 intertidal sites spread across the harbours, estuaries, and beaches of Tāmaki Makaurau.

Concentrations of mercury are moderately elevated at some sites in the muddy, highly urbanised, inner estuary zones of the Central and Upper Waitematā Harbour and Tāmaki Estuary. At sites in predominantly rural catchments, or at open coastal sites, mercury concentrations are low. This suggests that urban activities are contributing to some degree to elevated levels, and that the stormwater network is a likely conduit for mercury into the marine receiving environment.

Arsenic concentrations are for the most part at levels close to or below what would be considered 'natural' for Auckland marine sediments. Some level of arsenic will enter the marine environment naturally, via groundwater or in stream or riverine systems. A lack of correlation with other contaminants known to be present and derived from stormwater, indicates that current land use and activities are not contributing significantly to arsenic levels in marine sediment. Notably, arsenic was elevated at several locations with an otherwise low level of metal and mud contamination.

Concentrations of arsenic and mercury were generally similar to those reported previously from monitoring undertaken in 2005, and relatively few sites showed meaningful trends over the time period analysed here (2012-2021). These results suggest there has been little meaningful change at most sites, although a small general improvement in mercury contamination might be inferred from decreases at most of the sites where meaningful change was measured. The overall lack of change observed at most sites is encouraging given the increasing intensity of urban activity in Auckland over the monitoring time frame (e.g., increased numbers of motor vehicles, ongoing land development and residential intensification). This may be due to increasing pressures being offset by improvements in stormwater management and improving industrial practices.

The preliminary trend results presented here indicate a highly site-specific nature of trend occurrences, and no broad spatial patterns can be inferred from these results for either arsenic or mercury. As this is the first assessment of trends for these contaminants, no comparisons with previous reporting can be made. Whilst these results serve as a useful preliminary assessment, the sample size is too small to be considered robust, and further analyses are required to have a more definitive understanding of trend direction and magnitude for these chemicals.

It is important to note that the contaminant data presented here represent only one part of the overall environmental picture required to assess ecological effects in the marine environment. While most of the monitored sites have contaminant concentrations in the 'green' range (except for arsenic under some sediment quality guidelines), Auckland Council's Benthic Health Model (see Anderson et al., (2006) and Hewitt et al., (2009))

indicates that adverse effects on benthic community health are being found even in the conservative ERC 'green' range. Because of this, conclusions on ecological effects based solely on comparisons with sediment quality thresholds must be treated with some caution. As intended by the ANZG, guidelines are just one 'line of evidence' and, rather than representing 'pass/fail' thresholds, they represent a measure of relative risk which should be used to trigger or guide further investigations at locations considered to be at higher risk of unacceptable ecological impacts. Contaminant monitoring in Tāmaki Makaurau has been undertaken alongside particle size distribution and largely in conjunction with benthic ecology sampling, enabling these three lines of evidence to inform ecosystem health assessment.

Based on the assessment in this report, in isolation, levels of arsenic and mercury in Auckland's marine sediments currently pose only a low level of risk to benthic fauna, with the exception of a handful of sites where mercury levels are at higher concentrations. However, even at slightly elevated concentrations, these chemicals can be contributing to cumulative and multiple stressor impacts and may be negatively impacting benthic ecosystems.

7.1 Future monitoring and reporting of arsenic and mercury

The use of SQGs in the interpretation of results for arsenic needs to be carefully considered. Comparing arsenic using the TEL is problematic, painting a picture of widespread elevation, when concentrations are for the most part close to (or below) what would be expected to occur naturally. It is therefore suggested that for arsenic, the use of ANZG guidelines is better suited for Auckland marine sediments. For mercury, using the TEL (as a slightly more conservative guideline, in line with the ERC used for metals copper, lead and zinc), along with the ANZG for national comparisons, is deemed suitable and should be continued. These guidelines (TEL and ANZG for mercury; ANZG for arsenic) can be used to present 'state' in future RSCMP reporting alongside the other contaminants analysed.

In future years, it is possible that the current spatial patterns of contamination observed in Auckland will change somewhat. As estuaries infill with sediment over time, a higher proportion of stream and river derived sediment (and associated contaminants) will be exported into the middle and lower reaches of estuaries, as opposed to settling in the upper reaches as occurs in most locations currently. Additionally, predicted climate changes may also impact future contaminant levels and distribution, as more frequent storm events and sea level rise increase rates of erosion in both freshwater and coastal systems, increasing sediment loads and potentially exposing older buried contaminants. This is of particular concern for vulnerable environments around closed landfills, which may contain and leach a range of contaminants (including arsenic and mercury). Increased high intensity rain events and associated flooding may also impact contaminant loads in coastal environments,

mobilising and entraining pollutants from urban areas that would have otherwise stayed contained. Maintaining a broad spatial monitoring coverage is important to track and better understand these potential shifts in contaminant accumulation.

There are numerous reasons for the continuation of arsenic and mercury monitoring that go hand in hand with the rationale for monitoring other contaminants in marine sediments. This includes (but is not limited to) legislative requirements to monitor and report on the state of the environment, assessment of policy and infrastructure upgrades, and to provide real world ground truthing for contaminant models and predictions. Ultimately, improving our understanding of the distribution, change over time, and potential effects on marine ecology of chemical contaminants is important for effective resource management of coastal areas. Monitoring of arsenic and mercury should continue at sites within the RSCMP to:

- strengthen our understanding of arsenic and mercury concentrations, changes over time, and distribution;
- provide information to more fully assess the impact of changes in legislation, land use and upgrades to infrastructure (e.g., completion of the central interceptor wastewater tunnel); and
- ensure that no widespread (or otherwise) increases are occurring.

8 References

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9 Appendix

9.1 State table for total recoverable arsenic (As) and mercury (Hg).

Concentrations (mg/kg) are medians of the last sample. Concentrations above the TEL are highlighted yellow, concentrations above the ANZG DGV are highlighted amber.

Site Name	Location	Programme	Last Sample	Arsenic (mg/kg)	Mercury (mg/kg)
Anns Creek	Manukau Harbour	RSCMP	2021	10.86	0.0539
Awaruku Beach	East Coast Bays	RSCMP	2018	14.1	<0.02
Awaruku Stream	East Coast Bays	RSCMP	2018	8.1	0.0664
Awatea	Waitematā Harbour	RSCMP	2016	7.09	0.1632
Benghazi	Tāmaki Estuary	RSCMP	2019	7.18	0.0847
Big Muddy	Manukau Harbour	RSCMP	2021	12.38	0.0329
Blockhouse Bay	Manukau Harbour	RSCMP	2021	7.29	<0.02
Bottle Top Bay	Manukau Harbour	RSCMP	2021	11.79	0.038
Bowden	Tāmaki Estuary	RSCMP	2017	10.76	0.1458
Brigham Creek	Waitematā Harbour	UWH	2020	10.58	0.143
Central Main Channel	Waitematā Harbour	UWH	2020	14.7	0.1141
Chelsea	Waitematā Harbour	RSCMP	2019	6.71	0.0492
Coxs Bay	Waitematā Harbour	RSCMP	2019	3.27	0.0799
Doc Island Mud	Manukau Harbour	RSCMP	2021	8.86	0.0227
DOC Island Sand	Manukau Harbour	RSCMP	2015	16.45	0.02
Drury Inner	Manukau Harbour	RSCMP	2021	10.55	0.0375
Dyers Creek	Mahurangi Harbour	Harbour Ecology	2016	4.6	<0.02
Hamilton Landing	Mahurangi Harbour	Harbour Ecology	2016	12.18	0.0363
Harania	Manukau Harbour	RSCMP	2021	10.7	0.0524
Haratahi Creek	Kaipara Harbour	Harbour Ecology	2019	6.76	<0.02
Hellyers Creek	Waitematā Harbour	UWH	2020	7.77	0.1254
Hellyers Upper	Waitematā Harbour	RSCMP	2020	11.8	0.1424
Henderson Creek	Waitematā Harbour	Harbour Ecology	2019	14.01	0.0523
Henderson Lower	Waitematā Harbour	RSCMP	2019	11.88	0.1346
Henderson Upper	Waitematā Harbour	RSCMP	2020	12.65	0.1222
Herald Island North	Waitematā Harbour	UWH	2020	8.87	0.0646
Herald Island Waiarohia	Waitematā Harbour	UWH	2020	4.53	0.0568
Hillsborough	Manukau Harbour	RSCMP	2021	9.41	0.0216
Hobsonville	Waitematā Harbour	Harbour Ecology	2019	3.38	0.0255
Island Bay	Waitematā Harbour	RSCMP	2018	10.4	0.0563
Jamieson Bay	Mahurangi Harbour	Harbour Ecology	2016	6.94	<0.02
Kaipara Bank	Kaipara Harbour	Harbour Ecology	2019	8.52	<0.02
Kaipara Flats	Kaipara Harbour	Harbour Ecology	2019	5.15	<0.02
Kakarai Flats	Kaipara Harbour	Harbour Ecology	2019	6.11	<0.02
Karaka/ Te Hihi Estuary	Manukau Harbour	RSCMP	2021	8.12	<0.02
Kendall Bay	Waitematā Harbour	RSCMP	2019	8.65	0.0295
Little Muddy	Manukau Harbour	RSCMP	2021	16.73	0.0359
Lucas Creek	Waitematā Harbour	UWH	2020	17.63	0.1027
Lucas Te Wharau	Waitematā Harbour	RSCMP	2020	9.42	0.105
Lucas Upper	Waitematā Harbour	RSCMP	2020	11	0.1217
Mangemangeroa 3	Mangemangeroa	East Coast Estuaries	2016	6.83	0.0322
Mangemangeroa 6	Mangemangeroa	East Coast Estuaries	2016	8.22	0.0403
Mangemangeroa 9	Mangemangeroa	East Coast Estuaries	2016	8.42	0.0553
Māngere Cemetery	Manukau Harbour	RSCMP	2021	11.24	0.0429
Mauku/Taihiki River A	Manukau Harbour	RSCMP	2021	7.69	<0.02
Mauku/Taihiki River B	Manukau Harbour	RSCMP	2021	6.52	<0.02
Meola Inner	Waitematā Harbour	RSCMP	2020	10.93	0.2172
Meola Outer	Waitematā Harbour	RSCMP	2019	3.51	0.0312
Meola Reef	Waitematā Harbour	Harbour Ecology	2019	4.58	0.075
Mid Harbour	Mahurangi Harbour	Harbour Ecology	2016	10.52	0.0213
Middlemore	Tāmaki Estuary	RSCMP	2020	9.83	0.154
Mill Bay	Manukau Harbour	RSCMP	2021	13.08	<0.02
Motions	Waitematā Harbour	RSCMP	2020	6.44	0.1378
Motu Manawa/Pollen Island	Waitematā Harbour	RSCMP	2020	6.93	0.0928
Oakley Creek	Waitematā Harbour	RSCMP	2020	11.57	0.1342

State table for total recoverable arsenic (As) and mercury (Hg) cont.

Site Name	Location	Programme	Last Sample	Arsenic (mg/kg)	Mercury (mg/kg)
Okura 1	Okura	East Coast Estuaries	2016	4.82	<0.02
Okura 7	Okura	East Coast Estuaries	2016	4.7	<0.02
Okura 9	Okura	East Coast Estuaries	2016	5.97	0.032
Opposite Hobsonville	Waitematā Harbour	UWH	2020	11.42	0.1692
Ōrewa 1	Ōrewa	East Coast Estuaries	2016	7.53	<0.02
Ōrewa 4	Ōrewa	East Coast Estuaries	2016	6.1	<0.02
Ōrewa 8	Ōrewa	East Coast Estuaries	2016	5.56	<0.02
Ōtāhuhu	Tāmaki Estuary	RSCMP	2017	7.41	0.1391
Outer Main Channel	Waitematā Harbour	UWH	2020	9.57	0.0738
Pāhurehure Middle	Manukau Harbour	RSCMP	2021	12.47	<0.02
Pāhurehure Papakura	Manukau Harbour	RSCMP	2021	11.56	0.0413
Pāhurehure Upper	Manukau Harbour	RSCMP	2021	13.71	0.0399
Pakuranga Lower	Tāmaki Estuary	RSCMP	2020	7.9	0.099
Pakuranga Upper	Tāmaki Estuary	RSCMP	2018	7.62	0.0982
Panmure	Tāmaki Estuary	RSCMP	2019	8.86	0.1566
Papakura Lower	Manukau Harbour	RSCMP	2021	10.1	0.0369
Paremoremo	Waitematā Harbour	RSCMP	2020	12.51	0.1425
Princes St	Tāmaki Estuary	RSCMP	2020	8.98	0.1297
Puhinui Upper	Manukau Harbour	RSCMP	2021	14.25	0.0353
Puhoi 1	Puhoi	East Coast Estuaries	2016	9.03	<0.02
Puhoi 4	Puhoi	East Coast Estuaries	2016	6.87	<0.02
Puhoi 8	Puhoi	East Coast Estuaries	2016	5.49	<0.02
Pukaki Airport	Manukau Harbour	RSCMP	2021	13.21	0.0303
Pukaki Upper	Manukau Harbour	RSCMP	2021	7.78	<0.02
Pukaki Waokauri	Manukau Harbour	RSCMP	2021	8.73	0.0216
Purewa	Waitematā Harbour	RSCMP	2017	13.91	0.1384
Rangitopuni Creek	Waitematā Harbour	UWH	2020	10.75	0.1373
Rarawaru	Waitematā Harbour	RSCMP	2020	10.48	0.1269
Roberta Reserve	Tāmaki Estuary	RSCMP	2015	7.28	0.0263
Shoal Bay Hillcrest	Waitematā Harbour	RSCMP	2019	8.64	0.1705
Shoal Bay Upper	Waitematā Harbour	Harbour Ecology	2018	3.51	0.0206
Tararata	Manukau Harbour	RSCMP	2021	9.83	0.0443
Te Kapa Inlet	Mahurangi Harbour	Harbour Ecology	2016	8.53	<0.02
Te Matuku	Te Matuku	RSCMP	2020	4.96	0.0306
Te Ngaio Point	Kaipara Harbour	Harbour Ecology	2019	4.23	<0.02
Turanga 4	Turanga	East Coast Estuaries	2016	4.85	0.0313
Turanga 7	Turanga	East Coast Estuaries	2016	6.59	0.0526
Turanga 8	Turanga	East Coast Estuaries	2016	8.4	0.061
Upper Main Channel	Waitematā Harbour	UWH	2020	11.86	0.1531
Vaughans Beach	East Coast Bays	RSCMP	2018	11.66	<0.02
Vaughans Stream	East Coast Bays	RSCMP	2018	3.95	0.0283
Waikopua 1	Waikopua	East Coast Estuaries	2016	2.33	<0.02
Waikopua 3	Waikopua	East Coast Estuaries	2016	3.16	0.0245
Waikopua 9	Waikopua	East Coast Estuaries	2016	5.06	0.0255
Waimāhia Central	Manukau Harbour	RSCMP	2021	13.4	0.0372

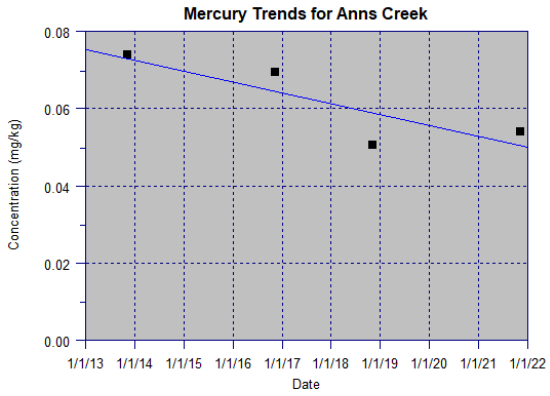
State table for total recoverable arsenic (As) and mercury (Hg) cont.

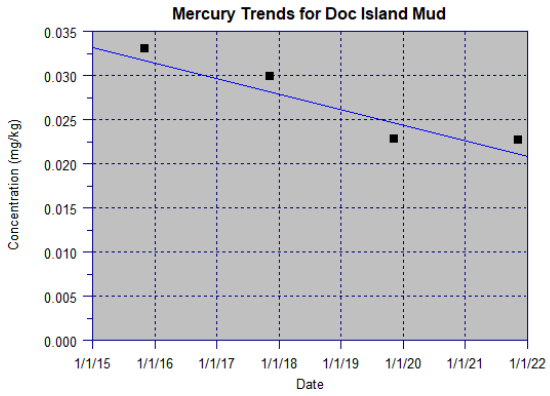
Site Name	Location	Programme	Last Sample	Arsenic (mg/kg)	Mercury (mg/kg)
Wairoa 1	Wairoa	NA	2018	10.19	0.0325
Wairoa 2	Wairoa	NA	2018	4.55	0.0262
Wairoa 3	Wairoa	NA	2018	4.18	0.0321
Wairoa 4	Wairoa	NA	2018	6	0.0312
Wairoa 5	Wairoa	NA	2018	7.65	0.0382
Wairoa 6	Wairoa	NA	2018	8.35	0.0809
Wairoa 7	Wairoa	NA	2018	6.55	0.0819
Waiuku	Manukau Harbour	RSCMP	2021	14.55	0.0523
Waiwera 1	Waiwera	East Coast Estuaries	2016	7.09	0.0213
Waiwera 3	Waiwera	East Coast Estuaries	2016	10.09	<0.02
Waiwera 8	Waiwera	East Coast Estuaries	2016	7.97	<0.02
Weiti	East Coast Bays	RSCMP	2020	7.51	0.0481
Whakataka Bay	Waitematā Harbour	RSCMP	2020	7.14	0.1097
Whangamaire	Manukau Harbour	RSCMP	2021	8.24	<0.02
Whangapouri	Manukau Harbour	RSCMP	2021	10.09	0.0291
Whangateau 1	Whangateau	East Coast Estuaries	2016	1.31	<0.02
Whangateau 4	Whangateau	East Coast Estuaries	2016	2.6	<0.02
Whangateau 5	Whangateau	East Coast Estuaries	2016	3.23	<0.02
Whau Entrance	Waitematā Harbour	RSCMP	2019	3.87	0.0515
Whau Lower	Waitematā Harbour	RSCMP	2020	11.33	0.1695
Whau Upper	Waitematā Harbour	RSCMP	2020	9.76	0.1275
Whau Wairau	Waitematā Harbour	RSCMP	2020	12.87	0.1419

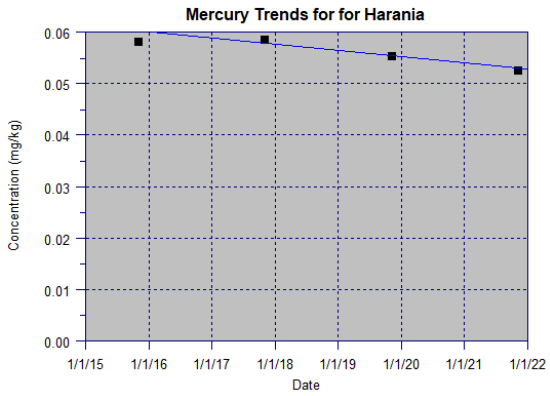
9.2 Preliminary trend data table for total recoverable mercury. Data are median annual rates of change (% median per year). Trend likelihood is assessed from Sen Slope probabilities and categorised as 'very likely' (>90%), 'likely' (67-90%), and 'indeterminate' (<67%).

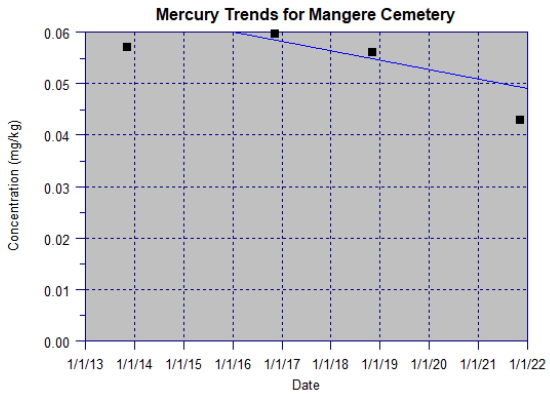
Site	Samplings	Start year	End year	Median value (mg/kg)	Percent annual change (%)	Sen Slope Probability	Trend likelihood LAWA category
Anns Creek	4	2013	2021	0.0617	**-4.55**	**0.96**	**Very likely improving**
Benghazi	4	2012	2019	0.0715	2.63	0.71	Likely worsening
Bottle Top Bay	4	2015	2021	0.0392	-1.07	0.93	Very likely improving
Brigham Creek	4	2013	2020	0.1543	-1.91	0.98	Very likely improving
Central Main Channel	4	2013	2020	0.1346	-2.49	0.84	Likely improving
Chelsea	4	2012	2019	0.0473	3.09	0.79	Likely worsening
Coxs Bay	4	2012	2019	0.067	8.62	0.81	Likely worsening
Doc Island Mud	4	2015	2021	0.0264	**-6.67**	**0.98**	**Very likely improving**
Drury Inner	4	2015	2021	0.0408	**-5.27**	**0.97**	**Very likely improving**
Harania	4	2015	2021	0.0566	**-2.06**	**0.97**	**Very likely improving**
Hellyers Upper	4	2013	2020	0.1412	-1.03	0.87	Likely improving
Hellyers Creek	4	2013	2020	0.1272	-0.12	0.65	Indeterminate
Henderson Lower	4	2012	2019	0.1344	-0.43	0.88	Likely improving
Henderson Upper	4	2013	2020	0.1213	0.03	0.63	Indeterminate
Herald Island North	4	2013	2020	0.0634	2.14	0.66	Indeterminate
Herald Island Waiarohia	4	2013	2020	0.0518	4.48	0.83	Likely worsening
Hobsonville	4	2012	2019	0.0229	1.47	0.91	Very likely worsening
Lucas Te Wharau	4	2013	2020	0.1099	-1.75	0.92	Very likely improving
Lucas Upper	4	2013	2020	0.1252	-0.68	0.98	Very likely improving
Lucas Creek	4	2013	2020	0.1089	-2.07	0.88	Likely improving
Mangere Cemetery	4	2013	2021	0.0565	**-3.20**	**0.93**	**Very likely improving**
Meola Inner	4	2013	2020	0.2186	-0.40	0.79	Likely improving
Middlemore	4	2013	2020	0.1502	0.31	0.53	Indeterminate
Motions	4	2013	2020	0.1744	**-5.09**	**0.95**	**Very likely improving**
Oakley Creek	4	2013	2020	0.1466	**-3.54**	**0.98**	**Very likely improving**
Outer Main Channel	4	2013	2020	0.1128	-6.16	0.87	Likely improving
Pahurehure Middle	5	2012	2021	<0.0200	-6.16	0.87	Likely improving
Pahurehure Papakura	4	2013	2021	0.0421	3.04	0.68	Indeterminate
Pahurehure Upper	5	2012	2021	0.0399	0.33	0.52	Indeterminate
Pakuranga Lower	4	2013	2020	0.1142	0.69	0.58	Indeterminate
Papakura Lower	5	2012	2021	0.0392	0.73	0.59	Indeterminate
Paremoremo	4	2013	2020	0.1442	-0.47	0.85	Likely improving
Motu Manawa	4	2013	2020	0.0904	0.05	0.62	Indeterminate
Princes St	4	2012	2020	0.1358	-0.67	0.79	Likely improving
Puhinui Upper	4	2015	2021	0.0344	1.28	0.82	Likely worsening
Pukaki Airport	4	2015	2021	0.0304	-0.05	0.66	Indeterminate
Rangitopuni Creek	4	2013	2020	0.1454	-1.45	0.93	Likely improving
Shoal Hillcrest	4	2012	2019	0.1724	**-2.79**	**0.93**	**Very likely improving**
Tararata	4	2015	2021	0.0536	-1.12	0.71	Likely improving
Te Matuku	4	2013	2020	0.0341	0.57	0.59	Indeterminate
Upper Main Channel	4	2013	2020	0.1541	-1.32	0.76	Likely improving
Waimahia Central	5	2012	2021	0.0347	**2.11**	**0.97**	**Very likely worsening**
Weiti	4	2013	2020	0.047	0.23	0.56	Indeterminate
Whangapouri	4	2015	2021	0.0333	**-4.34**	**0.93**	**Very likely improving**
Whau Entrance	4	2012	2019	0.0347	5.13	0.80	Likely worsening
Whau Lower	4	2013	2020	0.1718	-0.75	0.79	Likely improving
Whau Upper	4	2013	2020	0.137	-1.88	0.93	Very likely improving
Whau Wairau	4	2013	2020	0.1534	**-2.11**	**0.93**	**Very likely improving**

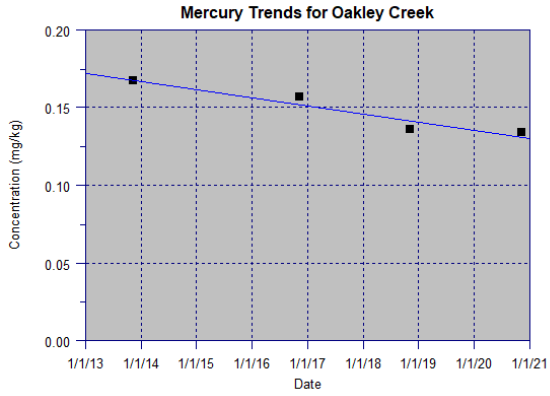
9.2.1 **Plots for sites with meaningful trends in mercury.** (>±2% median per year and very likely probability). The data plotted are median values from each sampling. The trend line is the Sen Slope.

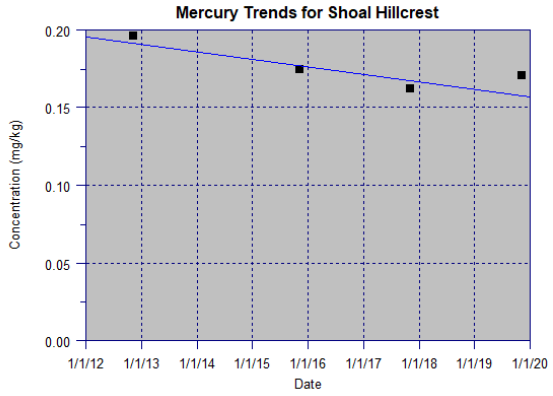


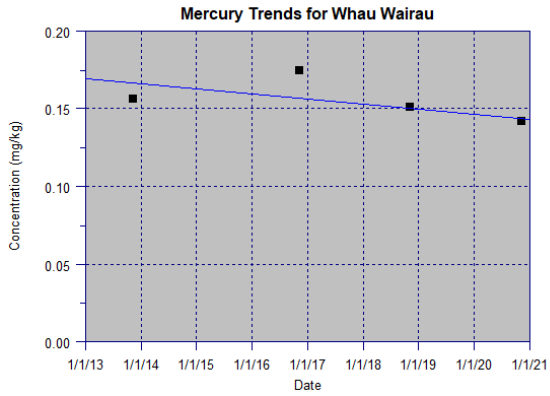


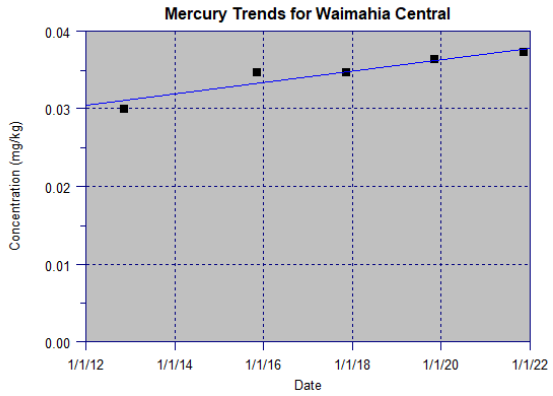




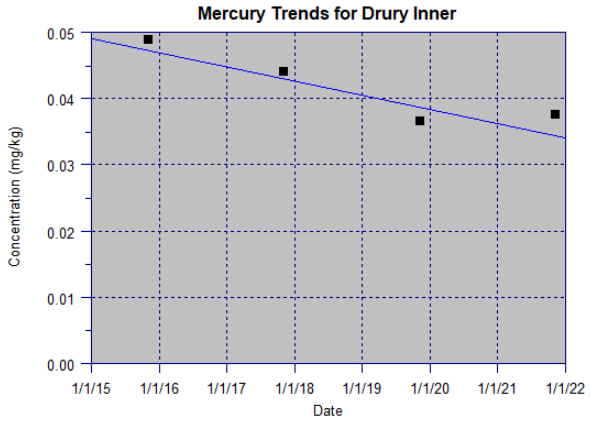


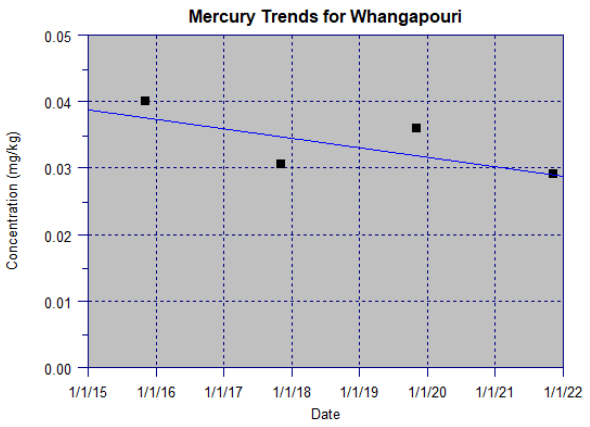


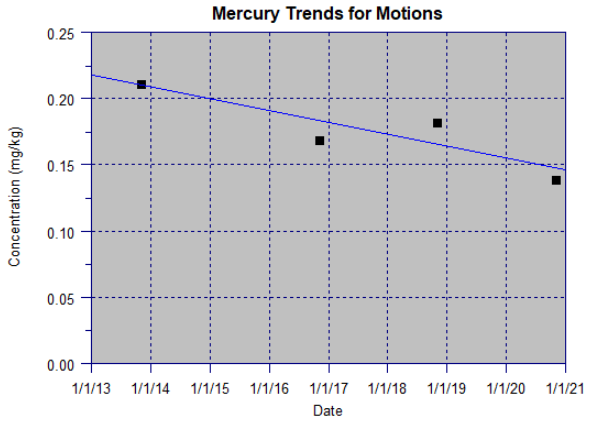




Plots for sites with meaningful trends in mercury cont.



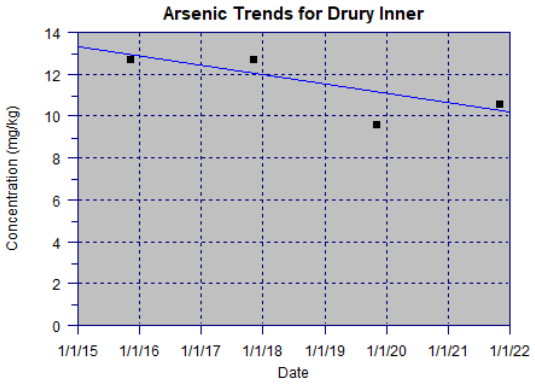


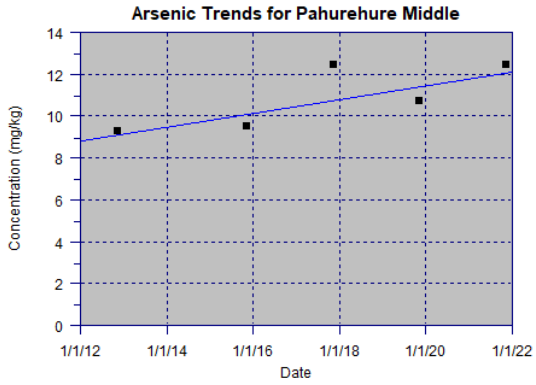


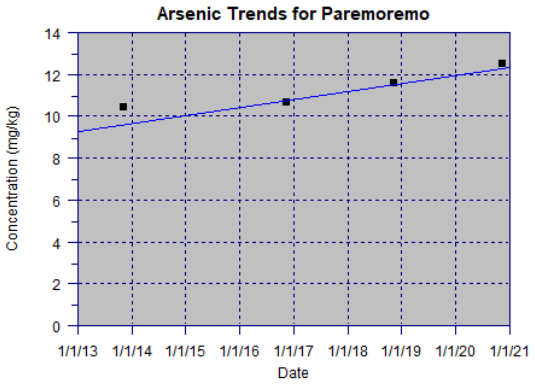
9.3 Preliminary trend data table for total recoverable arsenic. Data are median annual rates of change (% median per year). Trend likelihood is assessed from Sen Slope probabilities and categorised as 'very likely' (>90%), 'likely' (67-90%), and 'indeterminate' (<67%).

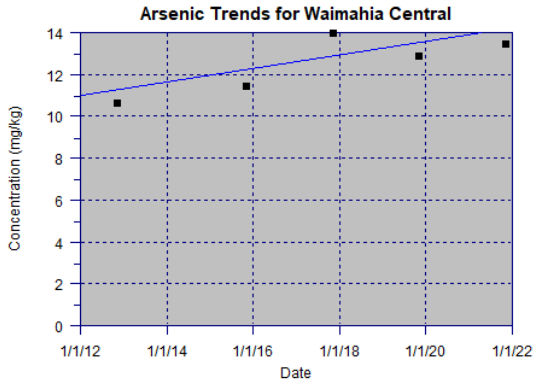
Site	Samplings	Start year	End year	Median value (mg/kg)	Percent annual change (%)	Sen Slope Probability	Trend likelihood LAWA category
Anns Creek	4	2013	2021	10.63	0.68	0.53	Indeterminate
Benghazi	4	2012	2019	6.76	2.82	0.67	Likely worsening
Bottle Top Bay	4	2015	2021	12.61	-1.68	0.92	Very likely improving
Brigham Creek	4	2013	2020	9.95	1.82	0.78	Likely worsening
Central Main Channel	4	2013	2020	14.6	0.31	0.63	Likely worsening
Chelsea	4	2012	2019	6.53	1.79	0.82	Likely worsening
Coxs Bay	4	2012	2019	3.09	3.71	0.8	Likely worsening
Doc Island Mud	4	2015	2021	9.11	-1.22	0.92	Very likely improving
Drury Inner	4	2015	2021	11.6	**-3.79**	**0.91**	**Very likely improving**
Harania	4	2015	2021	12.15	-1.3	0.98	Very likely improving
Hellyers Upper	4	2013	2020	10.35	3.58	0.85	Likely worsening
Hellyers Creek	4	2013	2020	7.35	2.66	0.85	Likely worsening
Henderson Lower	4	2012	2019	11.64	2.72	0.84	Likely worsening
Henderson Upper	4	2013	2020	12.48	0.59	0.61	Likely worsening
Herald Island North	4	2013	2020	7.71	4.07	0.89	Likely worsening
Herald Island Waiarohia	4	2013	2020	3.74	**3.49**	**0.91**	**Very likely worsening**
Hobsonville	4	2012	2019	3.68	6.28	0.59	Indeterminate
Lucas Te Wharau	4	2013	2020	8.46	**3.31**	**0.91**	**Very likely worsening**
Lucas Upper	4	2013	2020	10.95	0.21	0.59	Indeterminate
Lucas Creek	4	2013	2020	17.69	1.71	0.52	Indeterminate
Mangere Cemetery	4	2013	2021	11	0.34	0.59	Indeterminate
Meola Inner	4	2013	2020	10.08	0.62	0.58	Indeterminate
Middlemore	4	2013	2020	8.23	4.73	0.78	Likely worsening
Motions	4	2013	2020	6.21	0.36	0.54	Indeterminate
Oakley Creek	4	2013	2020	11.06	0.17	0.58	Indeterminate
Outer Main Channel	4	2013	2020	12.04	-1.68	0.85	Likely improving
Pahurehure Middle	5	2012	2021	10.74	**3.05**	**0.93**	**Very likely worsening**
Pahurehure Papakura	4	2013	2021	10.78	1.38	0.84	Likely worsening
Pahurehure Upper	5	2012	2021	12.45	1.36	0.64	Indeterminate
Pakuranga Lower	4	2013	2020	7.75	0.71	0.5	Indeterminate
Papakura Lower	5	2012	2021	11.11	-0.14	0.62	Indeterminate
Paremoremo	4	2013	2020	11.13	**3.4**	**0.91**	Very likely worsening
Motu Manawa	4	2013	2020	7.14	-1.31	0.73	Likely improving
Princes St	4	2012	2020	8.25	3.33	0.88	Likely worsening
Puhinui Upper	4	2015	2021	13.41	1.15	0.76	Likely worsening
Pukaki Airport	4	2015	2021	13.01	0.41	0.51	Indeterminate
Rangitopuni Creek	4	2013	2020	11.22	1.49	0.51	Indeterminate
Shoal Hillcrest	4	2012	2019	8.65	0.31	0.51	Indeterminate
Tararata	4	2015	2021	10.81	-1.87	0.77	Likely improving
Te Matuku	4	2013	2020	4.98	-0.52	0.76	Likely improving
Upper Main Channel	4	2013	2020	11.53	1.57	0.56	Indeterminate
Waimahia Central	5	2012	2021	12.86	**2.45**	**0.9**	**Very likely worsening**
Weiti	4	2013	2020	6.83	**3.02**	**0.91**	**Very likely worsening**
Whau Entrance	4	2012	2019	2.94	7.61	0.87	Likely worsening
Whau Lower	4	2013	2020	10.41	1.07	0.73	Likely worsening
Whau Upper	4	2013	2020	10.18	-1.75	0.98	Very likely improving
Whau Wairau	4	2013	2020	12.54	1.07	0.63	Indeterminate
Whangapouri	4	2015	2021	11	-0.4	0.7	Likely improving

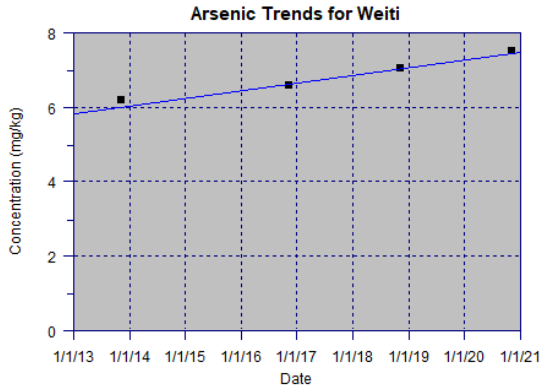
9.3.1 Plots for sites with meaningful trends in arsenic. (>±2% median per year and very likely probability). The data plotted are median values from each sampling. The trend line is the Sen Slope.

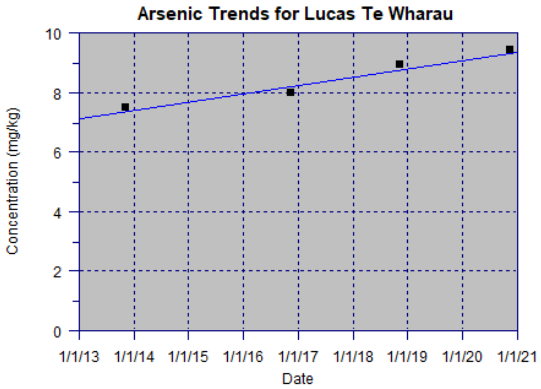


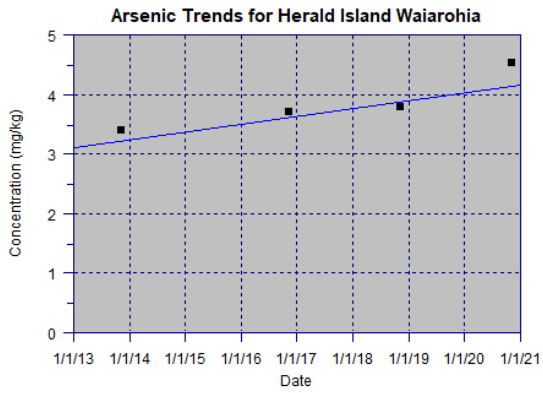








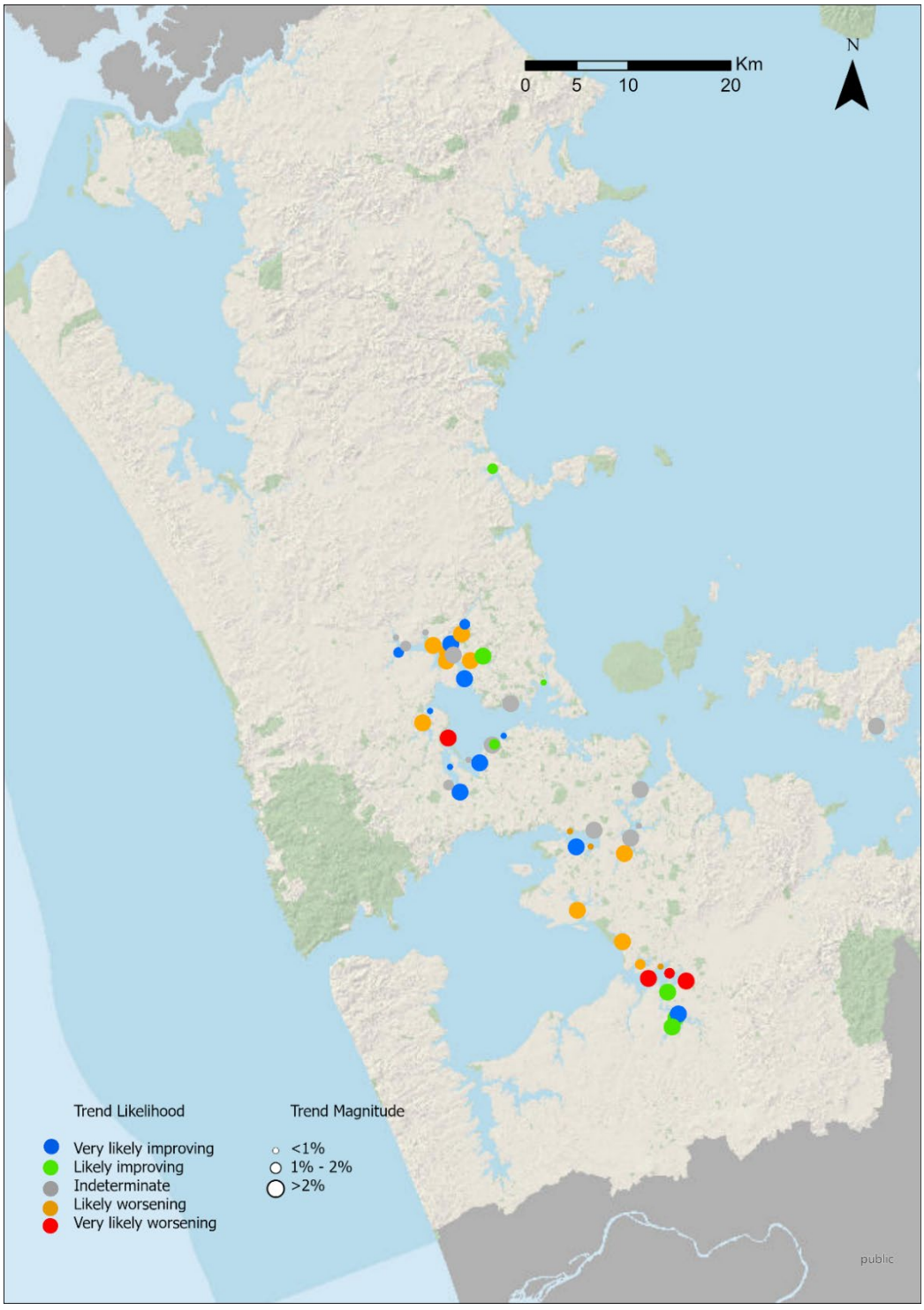




9.4 Preliminary trends in mud content

Note: For consistency with the data presented in this report, mud trends have been analysed for the same period as for arsenic and mercury (i.e., 2012-2021). Regional overview

Distribution of trends of mud concentrations (<63 µm; the sum of silt and clay) from 48 sites across Auckland. Data from 2012-2021.



9.4.1 Mud trends at individual monitoring sites

Generally, few sites showed meaningful trends (9 out of 48). These sites were in the Waitematā (5 sites) and Manukau (4 sites) Harbours. Overall, six sites showed meaningful decreasing/improving trends, while three sites showed increasing/worsening trends. The Pāhurehure inlet featured two sites that showed increasing trends, however it also had sites with decreasing trends. This demonstrates the site-specific nature of sediment accumulation and the fine scale dynamics that can occur within an estuary.

9.5 Preliminary trend data table for mud content (% <63 µm by weight).

Data are median annual rates of change (% median per year). Trend likelihood is assessed from Sen Slope probabilities and categorised as 'very likely' (>90%), 'likely' (67-90%), and 'indeterminate' (<67%)

Site	Samplings	Start year	End year	Median (% <63µm)	Percent annual change (%)	Sen Slope Probability	Trend Likelihood LAWA category
Anns Creek	4	2013	2021	84.8	2.29	0.61	Indeterminate
Benghazi	4	2012	2019	26.4	2.99	0.63	Indeterminate
Bottle Top Bay	4	2015	2021	81.8	-2.92	0.85	Likely improving
Brigham Creek	4	2013	2020	86.8	-1.06	0.98	Very likely improving
Central Main Channel	4	2013	2020	30.9	3.48	0.71	Likely worsening
Chelsea	4	2012	2019	9.9	3.29	0.55	Indeterminate
Coxs Bay	4	2012	2019	8.2	-0.27	0.92	Very likely improving
Doc Island Mud	4	2015	2021	30.9	-2.26	0.76	Likely improving
Drury Inner	4	2015	2021	49.2	**-3.17**	**0.93**	**Very likely improving**
Harania	4	2015	2021	88.1	0.60	0.80	Likely worsening
Hellyers Creek	4	2013	2020	52.1	2.70	0.79	Likely worsening
Hellyers Upper	4	2013	2020	75.9	-2.36	0.79	Likely improving
Henderson Lower	4	2012	2019	89.3	-0.49	0.98	Very likely improving
Henderson Upper	4	2013	2020	72.0	2.35	0.80	Likely worsening
Herald Island North	4	2013	2020	13.8	13.63	0.77	Likely worsening
Herald Island Waiarohia	4	2013	2020	22.2	6.17	0.84	Likely worsening
Hobsonville	4	2012	2019	3.5	**-3.83**	**0.96**	**Very likely improving**
Lucas Creek	4	2013	2020	31.2	**-6.84**	**0.92**	**Very likely improving**
Lucas Te Wharau	4	2013	2020	42.7	3.83	0.88	Likely worsening
Lucas Upper	4	2013	2020	66.6	-1.94	0.96	Very likely improving
Mangere Cemetery	4	2013	2021	81.4	0.86	0.76	Likely worsening
Meola Inner	4	2013	2020	63.9	4.08	0.64	Indeterminate
Middlemore	4	2013	2020	58.1	3.58	0.73	Likely worsening
Motions	4	2013	2020	21.8	-1.80	0.78	Likely improving
Motu Manawa	4	2013	2020	33.2	0.67	0.61	Indeterminate
Oakley Creek	4	2013	2020	75.8	**-2.32**	**0.94**	**Very likely improving**
Outer Main Channel	4	2013	2020	17.3	3.36	0.55	Indeterminate
Pahurehure Middle	5	2012	2021	13.8	**11.40**	**0.90**	**Very likely worsening**
Pahurehure Papakura	4	2013	2021	50.4	**6.43**	**0.91**	**Very likely worsening**
Pahurehure Upper	5	2012	2021	75.0	1.13	0.93	Very likely worsening
Pakuranga Lower	4	2013	2020	41.3	0.94	0.53	Indeterminate
Papakura Lower	5	2012	2021	89.8	0.71	0.77	Likely worsening
Paremoremo	4	2013	2020	95.3	0.04	0.50	Indeterminate
Princes St	4	2012	2020	43.5	2.24	0.52	Indeterminate
Puhinui Upper	4	2015	2021	86.0	2.93	0.77	Likely worsening
Pukaki Airport	4	2015	2021	80.7	3.27	0.83	Likely worsening
Rangitopuni Creek	4	2013	2019	97.3	0.00	0.63	Indeterminate
Shoal Bay Hillcrest	4	2012	2019	86.8	-0.29	0.80	Likely improving
Tararata	4	2015	2021	91.9	**-4.02**	**0.90**	**Very likely improving**
Te Matuku	4	2013	2020	14.8	6.48	0.60	Indeterminate
Upper Main Channel	4	2013	2020	87.1	1.10	0.61	Indeterminate
Waimahia Central	5	2012	2021	85.8	1.94	0.79	Likely worsening
Weiti	4	2013	2020	26.4	-1.74	0.85	Likely improving
Whangapouri	4	2015	2021	43.4	-2.51	0.82	Likely improving
Whau Entrance	4	2012	2019	14.3	**7.12**	**0.91**	**Very likely worsening**
Whau Lower	4	2013	2020	93.2	-0.51	0.94	Very likely improving
Whau Upper	4	2013	2020	58.3	**-3.04**	**0.96**	**Very likely improving**
Whau Wairau	4	2013	2020	74.7	1.66	0.56	Indeterminate

Find out more: rimu@aucklandcouncil.govt.nz
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