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Tairua Estuary
Shellfish and Benthic Habitat Mapping and Assessment of Sediment Contamination (2009/10)

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Executive Summary

Shellfish are major components of estuarine communities. Apart from their value as a food resource, shellfish perform important ecosystem services. Although relatively resilient compared to other types of intertidal biota, shellfish populations may be sensitive to a number of pressures associated with human activities, including sediment contamination. This project aimed to map the distribution and abundance of three species of shellfish in Tairua Estuary: the cockle (*Austrovenus stutchburyi*), the pipi (*Paphies australis*) and the wedge shell (*Macomona liliana*). The distributions of estuary sediment types, estuarine vegetation and sediment trace elements and organic compounds were also mapped.

At 275 sampling sites shellfish were counted and categorised into three size classes. Surface sediments were subjectively classified into substrate types. Vegetation cover was also recorded, as was the approximate depth of the Redox Potential Discontinuity (RPD). Samples for grain size analyses were collected at approximately every second site. Trace elements and organic compounds were analysed in twenty-nine composite samples representing most of the intertidal area of Tairua Estuary.

Using the qualitative substrate classification, the vast majority (82%) of sites were classified as ‘Firm sand’ or ‘Soft sand’, and the grain size data showed fine and medium sands to dominate in the estuary. Statistical analyses showed only limited correlations between the substrate categories and sediment grain size. Extensive *Austrovenus* beds were found in the estuary. The average abundance of *Austrovenus* was equivalent to 470/m^2, and the maximum abundance was 3600/m^2. A population of this size filters about 5.5 per cent of the estuary volume every tidal cycle. *Macomona* were present in the same areas but at much lower abundances (average 234/m^2, maximum 560/m^2), which is similar to findings from other estuaries in the region. The highest abundance of *Paphies* was equivalent to 7072/m^2. The dense populations of *Paphies* were located adjacent to subtidal main channels. Seagrass (*Zostera* sp.) beds were extensive throughout the estuary, while mangroves were only found at few sites. Trace element and organic compound concentrations were low, indicating that the likelihood of toxic effects from sediment contamination on aquatic organisms is very low.

Statistical analyses showed both *Austrovenus* and *Macomona* to be present in highest abundances at sites with shallower RPDs which were also classified as ‘Firm sand’. For *Paphies*, the results showed a higher probability of being present in ‘Mobile sands’ than in all other substrate categories. Of the measured environmental variables, sediment median grain size, medium sand content, mud content, and RPD depth had the biggest influence on the shellfish community. However, much of the variation in shellfish community composition remained unexplained, indicating the influence by environmental variables other than those measured in this study.

Some modifications to the sampling could be done to ensure maximum value for effort. These include improvements of the substrate classification system, sampling the edges of subtidal channels and determining shellfish biomass.

Habitat maps potentially provide an important tool for evaluating whether shellfish beds are declining, and for assessing the health of shellfish beds. Because it is so labour intensive, habitat mapping may not be feasible to carry out for all the estuaries in the Waikato region. However, because of the functional importance of shellfish, it would be useful to map shellfish beds in selected estuaries to obtain an inventory of resources. Repeat surveys in vulnerable estuaries would provide important information on estuary-wide trends in shellfish distribution and abundance, which could be used in state of the environment reporting or evaluations of the efficiency of policy.

1 Introduction

1.1 Benthic shellfish and habitat mapping project background

Estuaries are some of the most sensitive and diverse coastal areas within the Waikato Region. As interfaces between land and sea, they perform important ecological and biogeochemical functions. Estuaries support diverse ecological communities, and are spawning and nursery areas for many species of fish. Intertidal shellfish beds provide important food sources for birds, fish and other estuarine animals, as well as humans. Bivalves also provide important ecosystem services by filtering water, thereby improving water clarity and removing sediments and nutrients from the water column.

Estuaries are also among the most heavily used coastal areas within the Waikato Region, and are under increased pressure because of population growth, increased development in catchments with ensuing runoff of nutrients and sediments, and coastal developments such as marinas and marine farms that use estuarine space.

Intertidal biota are sensitive to the changes in habitat that accompany many of the external pressures facing estuaries, and the community composition of benthic fauna is thus often used to indicate the state of their environment. Shellfish form an important part of the intertidal biota, and are valued food resources for birds, fish, invertebrates and humans. Most of the familiar edible shellfish belong to a group of molluscs known as bivalves. In this report the terms shellfish and bivalves are used interchangeably. Although bivalves are more resilient to environmental change than many other intertidal species, they are still vulnerable to smothering by terrigenous sediments, displacement by activities such as dredging and other types of habitat modification, and habitat and water quality changes resulting from increases in nutrient runoff from land.

Waikato Regional Council has a statutory obligation to protect the Region’s natural coastal resources. Because of their cultural and ecological importance, the presence of extensive shellfish beds was included as a criterion when the Region’s Areas of Significant Conservation Value (ASCVs) were identified. The ASCVs include parts or all of most of the Region’s estuaries, and the Waikato Regional Coastal Plan stipulates that important conservation values within these areas should be protected against adverse effects arising from human development and activities.

In order to protect shellfish beds, or detect any changes to them arising from human activity, it is essential to know their extent – i.e. to map where they are found, and how large and dense the beds are. The current project focuses on three species of bivalve that are found in all the Region’s estuaries: the cockle (Austrovenus *stutchburyi*), the pipi (*Paphies australis*) and the wedge shell (*Macomona liliana*).

Austrovenus is endemic to New Zealand, and is an important food species for humans. They are surface suspension feeders, burrowing just below the sediment surface, and are found in muddy and sandy intertidal substrates. They grow up to 50 mm in shell length, and are sexually mature above about 18 mm.

Paphies are also surface suspension feeders, which generally burrow just below the sediment surface. Juvenile *Paphies* are normally found higher on the shore than adults, with most adult size *Paphies* beds found in areas of high water flow such as channels. *Paphies* are extensively harvested by humans.

Macomona are deposit feeders, which are normally found in 5 to 15 cm of sediment. They grow to a maximum size of about 70 mm in shell length, and reach sexual maturity at about 22 mm shell length. *Macomona* are not generally eaten by humans, but are important food resources for birds and fish.

1.2 Benthic shellfish and habitat mapping project objectives

The objectives of this estuary benthic shellfish and habitat mapping project are to:

- provide baseline information on the location of shellfish beds, substrate type and vegetation cover within the intertidal area of Tairua Estuary; and
- provide information to assist ecologically sound resource consent decision making, policy setting and to support the sustainable management of estuaries in the Waikato Region.

1.3 Assessment of sediment contamination

Weathering of catchment rocks containing trace elements represents a natural source of trace elements to estuary sediments. Human activities in catchments can also supply trace elements and organic compounds to the sediments of intertidal sand and mudflats. Potential man-made sources of trace elements and organic compounds to estuaries can include:

- drainage from tailings associated with historic mining operations;
- stormwater, carrying urban runoff;
- sewage effluent;
- combustion processes, including vehicles and home heating (coal and wood burning);
- agricultural runoff;
- land-use impacts such as forest clearance and development of subdivisions in the catchment increases erosion; and
- wood preservatives.

Enriched sediments become a source of trace elements and organic compounds to plants and animals in the sediment and overlying water column. At high concentrations trace elements and organic compounds such as organochlorine pesticides, pentachlorophenol, tributyl tin and polycyclic aromatic hydrocarbons (PAHs) can have toxic effects on aquatic organisms (Table 1). In these instances sediments are considered contaminated.

1.4 Tairua Estuary

Tairua Estuary is recognised as an Area of Significant Conservation Value in the Waikato Regional Coastal Plan. The estuary is a significant site to Hauraki Iwi, and is known to support important ecological communities including saltmarsh, and seagrass (*Zostera* sp.) and shellfish beds. Tairua Estuary also provides habitat for rare and threatened wading and coastal bird species, and important whitebait spawning habitat.

The estuary covers 605 ha (NIWA estuaries dataset), and has a catchment area of 28,044 ha (NIWA REC catchments dataset). Approximately 51% of the estuary is intertidal (NIWA estuaries dataset), and the intertidal area supports extensive vegetation, including 2.7% mangroves, 10% seagrass (*Zostera* sp.) and 15% saltmarsh (Graeme, 2008).

Figure 1 shows a map of Tairua Estuary and the vegetation found there in a 2008 survey (Graeme, 2008).

Table 1: Potential problems caused by trace elements and organic compounds in sediments.

Element or compound	**Potential problems**
Antimony Arsenic Beryllium Cadmium Chromium Copper Lead Mercury Nickel Selenium Silver Thallium Zinc	All of these elements can occur naturally. Some are essential to living animals and plants. For example, copper is important for the gills of shellfish. However, at high levels all trace elements are toxic. Their toxicity increases as their concentration increases. Within animals and plants some of these elements can accumulate, this is called bioaccumulation. For example, copper can accumulate in shellfish. In a marine community, as each animal eats the next animal or plant in the food chain and trace element levels (such as mercury) increase inside them, the levels of some trace elements can potentially increase up the food chain. This is called biomagnification. Trace elements affect plants and animals by interfering with metabolic processes. For example, antimony and arsenic interrupt the making of adenosine triphosphate (ATP) which is needed as a source of energy to help muscles in the body work.
Organochlorines	Man-made, at high concentrations cause problems to animals higher in the food chain. Build up in some tissues in the body and stay there for a long time. Have the potential to bioaccumulate, for example in shellfish. Biomagnify up the food chain. More organochlorines are found in animals at the top of the food chain.
PAHs	Emitted from combustion processes both natural (such as volcanic and wild forest fires) and man-made (vehicles, burning wood and coal, forest fires). Attach to sediment particles. Levels can be higher in plants and animals than the soil. Effects on marine animals that live in the sediment is not well known, but PAHs are potentially lethal to some marine animals and plants.

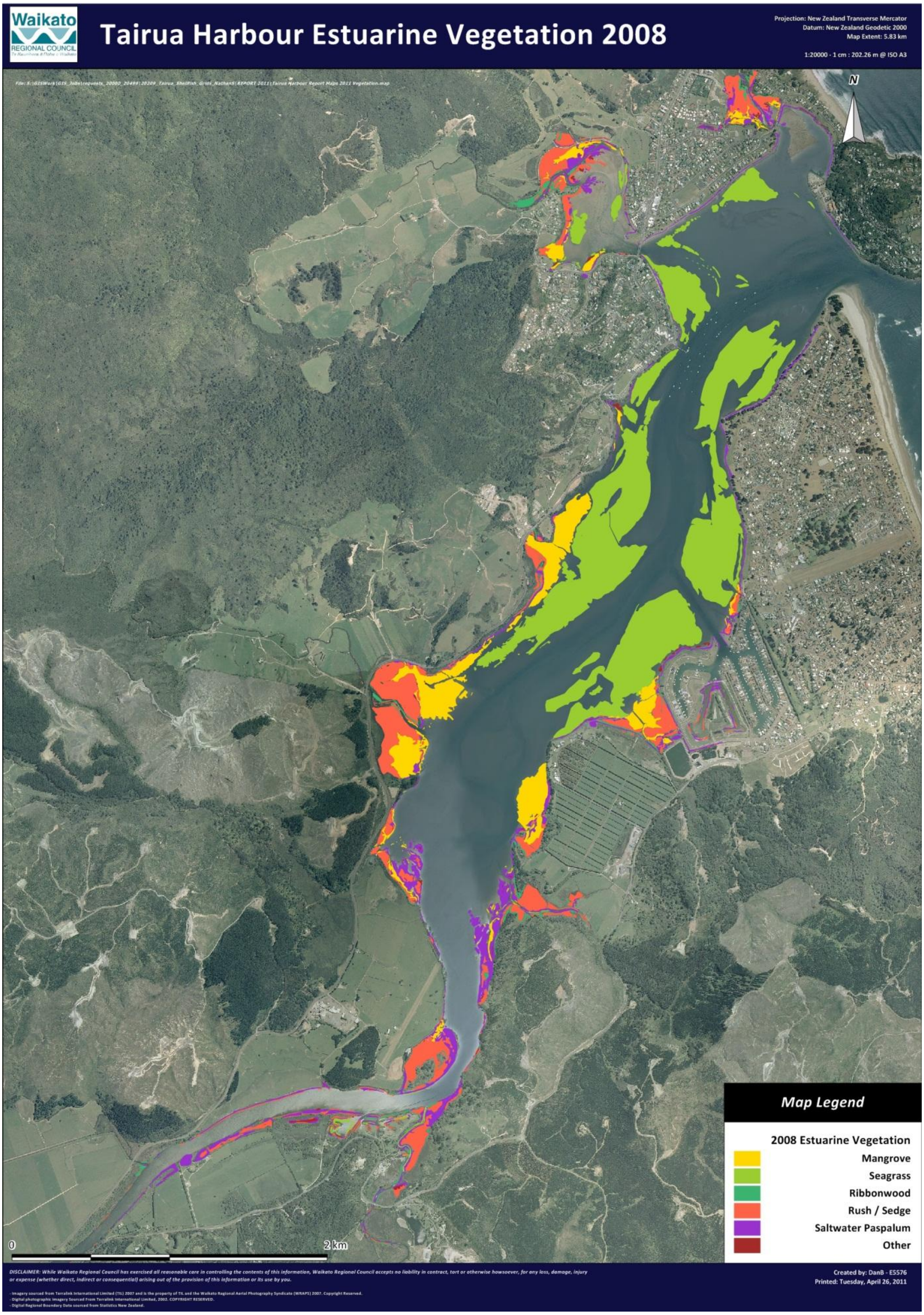

Figure 1: Map of Tairua Estuary intertidal vegetation. Source: Graeme (2008).

2 Methodology

2.1 Benthic shellfish and habitat mapping

2.1.1 Sampling and sample analyses

Sampling sites were located on the intersection points of a 150 m grid laid over the whole of Tairua Estuary. The grid was placed within the area outlined by the shoreline from the LINZ 1:50000 database. Sites near channels were sampled at low tide to ensure best possible coverage of the intertidal area. Where sampling points fell in channels they were shifted back to the closest channel edge.

Sampling was carried out between November 2009 and March 2010. For each sampling location, the following was documented:

- Characteristics of surface sediment (e.g. ‘Soft sand’, ‘Firm sand’, ‘Mobile sand’)
- Type and extent (%) of vegetation cover
- Diversity and density of epifaunal organisms
- Shellfish diversity and density
- Approximate Redox Potential Discontinuity (RPD) layer depth – an indication of sediment oxygenation

Surface sediments were categorised into substrate classes in a subjective manner, following the categories listed in Robertson & Peters (2006), shown in Table 2 below. The substrate classes are defined by sediment texture, visual features and a ‘sink-ability’ index (the amount an average adult would sink). Note that the category ‘Firm mud / sand’ from Robertson & Peters (2006) was omitted in this survey.

Sediment samples were also collected at roughly every second site (to ensure even coverage of the estuary) for grain size analysis. Three surface grabs (2 cm sediment depth) were collected roughly 1 m apart and combined into one sample bag, returned to the lab and frozen until analysis was undertaken. Prior to analysis, samples were pre-treated with 10% hydrogen peroxide to remove organic material, and 1M HCl to remove carbonate material. Calgon was added as a dispersant and samples were placed in an ultrasonic bath for 10 minutes to aid disaggregation. Samples were analysed with a Malvern Mastersizer 2000 sediment analyser.

The depth at which the sediment colour changed from brown to grey / black was recorded (following Robertson & Stevens, 2008) as an approximation of the redox potential discontinuity (RPD) layer. The RPD layer indicates the start of anoxic sediment and the lower limit of depth distribution for many species. The percentage cover of shell hash was estimated at each site.

Table 2: **Substrate categories (from Robertson & Peters, 2006).**

Category	Description
Firm sand	Will feel granular between your fingers; you will sink no more than 2 cm
Soft sand	Contains over 99% sand. You will sink more than 2 cm
Mobile sand	Granular sand that is rippled. You will sink less than 1 cm.
Soft mud / sand	A mix of mud and sand, surface appears brown and may have a black anoxic layer. You will sink 2-5 cm.
Very soft mud / sand	A mix of mud and sand, surface brown and may have a black anoxic layer below. You will sink more than 5 cm
Shellbed	The surface is dominated by shell material
Gravelbed	Surface is dominated by gravel and cobble sized grains

At each sampling point one 25 cm x 25 cm quadrat was randomly placed and all epifauna recorded. Per cent coverage of macroalgae, microalgae and other vegetation (seagrass and mangroves) were also recorded. After epifauna were recorded, the sediment within each quadrat was dug to a depth of 15 cm and sieved through a 0.5 mm sieve. All live bivalves were retained, identified and counted on site, then returned to the shallows to allow them to reburrow.

Austrovenus and *Macomona* were separated into three size categories:

small: 0 – 20 mm (this size class represents juveniles)
medium: 20 – 30 mm
large: >30 mm

The size categories used for *Paphies* were:

small: 0 – 20 mm
medium: 20 – 40 mm
large >40 mm (this size class represents adults)

The sampling points can be seen in Appendix 1, and the field sheets used are shown in Appendix 2.

2.1.2 Statistical analysis

Exploration of data and statistical analyses were carried out using R (http://www.r-project.org) and the multivariate statistical program MVSP (v. 3.2, Kovach Computing Services, UK, 2010).

In order to determine whether the subjective substrate data provides an indication of sediment grain size, the substrate data were compared to the results from the grain size analysis for the 111 sampling points where both sets of data were available. For the purposes of this and following analyses, the grain size analysis data was grouped into the following grain size categories: mud (<63 um); fine sand (63-250 um); medium sand (250-500 um); coarse sand (500-1000 um); and very coarse sand (>1000 um) (from the Wentworth sediment classification, see Appendix 3). The substrate data exhibited very different group sizes, and the grain size data did not meet assumptions of homoscedasticity, and untransformed and transformed data was often not normally distributed. As a result, the non-parametric Kruskal-Wallis test was used (using R) to test for differences between the grain size data of different substrate groups. Post-hoc pairwise comparisons were done using multiple Wilcoxon-Mann-Whitney rank sum tests (at $\alpha<0.05$); p-values were adjusted using the Bonferroni correction to control for family wise type 1 error.

Relationships between the substrate data and the sediment redox potential discontinuity depth (RPD) were explored in a similar manner, using Kruskal-Wallis tests followed by post-hoc comparisons using Wilcoxon-Mann-Whitney tests, Bonferroni corrected. For the purposes of this and subsequent analysis, for sites where the RPD was not recorded (because it was deeper than the 15 cm excavated, which occurred at 72 sites of a total of 275 sites), it was set to 16 cm.

Untransformed and transformed count data for the three bivalve species (*Austrovenus*, *Macomona* and *Paphies*) also failed to meet criteria for parametric analyses. As a result, abundances of bivalves at sites belonging to different substrate classes, and sites with different percentage of seagrass cover (for this purpose, seagrass cover was classified into the following categories: 0%; 1-10%; 11-30%; 31-50%; 51-70%; 71-90%; 91-100%), were compared using Kruskal-Wallis tests. Once again, post-hoc comparisons were carried out using multiple Wilcoxon-Mann-Whitney rank sum tests with adjustment of p-values done using the Bonferroni correction.

Potential relationships between the abundance of individual species of bivalve and environmental parameters (substrate type, RPD depth, percentage seagrass cover, number of mangrove pneumatophores) were explored using classification and regression tree (CART) analyses (Breiman *et al*., 1984). This method was chosen because the analysis makes no assumption about the distribution of the underlying data (i.e. is non-parametric), it is robust to outliers, and can handle a mixture of categorical and continuous predictors (in this case, the substrate data was categorical, and the RPD and vegetation data continuous). Classification and regression trees were constructed using the rpart routine in R (documented in Therneau & Atkinson, 1997). Optimal trees were generated using pruning based on a complexity parameter; tree sizes were selected to minimise cross-validated errors.

Relationships between bivalve community structure and environmental variables were explored using canonical correspondence analysis (ter Braak, 1986; 1987) (using CCA in MVSP) on the data from the subset of sites for which grain size analysis had been carried out. CCA is a multivariate direct gradient analysis method in which the species data is related directly to the environmental data; using a form of correspondence analysis, modified to allow environmental data to be incorporated into the analysis. In CCA the species ordination is constrained by the environmental variables, resulting in final ordination axes that are linear combinations of the environmental variables and the species data, thus directly linking the two data sets.

2.2 Assessment of sediment contamination

A selection of sediment samples were also examined for the presence of contaminants. Of the 275 samples collected in the estuary, 65 were selected and composited into 22 samples for analysis (Figure 2). Seven additional sites in the upper estuary and Tairua River were sampled in August 2010. Sampling sites and composite samples were chosen to represent areas of special interest or public concern and provide a good spread throughout the estuary.

Sediment samples were analysed by Hill Laboratories, Hamilton, for total organic carbon (TOC), thirteen trace elements (antimony, arsenic, beryllium, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver, thallium, zinc), organochlorine pesticides (organochlorines), pentachlorophenol, tributyl tin and polycyclic aromatic hydrocarbons (PAHs).

Results for organochlorines and PAHs were normalised to 1 % TOC assuming the concentration of the organic contaminant is linearly correlated with TOC content. Normalisation was not carried out for samples with TOC <= 0.2% because other effects (e.g. particle size and sorption onto non-organic mineral surfaces) become more important in sediments with lower TOC content, resulting in departure from linearity (ANZECC, 2000; DiToro et al., 1991).

In order to assess the likelihood of toxic effects on aquatic organisms, results were compared to guidelines derived by the Australian and New Zealand Environment and Conservation Council (ANZECC). For each trace element and organic compound, ANZECC has derived a low interim sediment quality guideline value (ISQG-Low) and a high interim sediment quality guideline value (ISQG-High). The ISQGs relate to the likelihood of toxic impact of trace elements and organic compounds on sediment-dwelling organisms. At concentrations below the ISQG-Low value adverse effects on organisms living in the sediment are very unlikely to occur. The ISQG-High value is a level at which adverse effects are expected in half of the exposed organisms. Concentrations above the ISQG-High value are interpreted as being reasonably likely to cause significant adverse effects on aquatic organisms. Concentrations between the ISQG-Low and ISQG-High values are thought to pose a moderate level of risk to aquatic organisms.

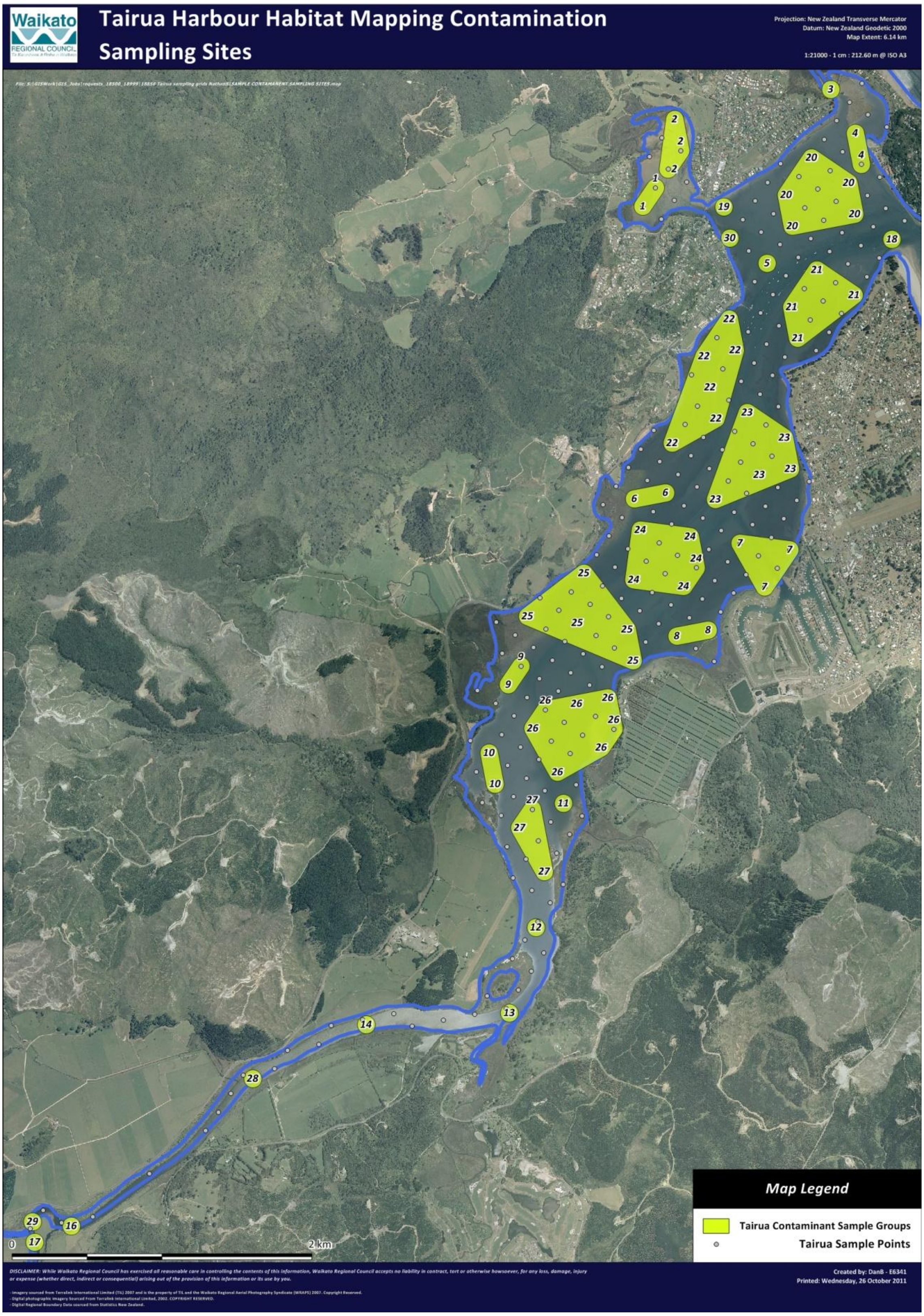

Figure 2: **Sites selected for analysis of trace elements and organic compounds. Numbered sites represent those included in the analyses. Sediment samples from identically numbered sites were composited and analysed as one sample.**

3 Results

3.1 Overview

In total 275 sites were sampled in Tairua Estuary, and sediment grain size analysis was carried out on 111 samples. An additional three intertidal sites were visited but not sampled, as they contained the invasive weed *Paspalum* and nothing else. Table 3 provides a summary of the organisms and vegetation found. Of the 52 sites where no bivalves were found, 15 sites contained seagrass, and five mangrove pneumatophores. Bivalves were numerically dominant to gastropods, and also found at more sites. Of the bivalves, *Austrovenus* were most abundant with a total of 5604 individuals counted. *Austrovenus* were also found at most sites (69%), compared to just over half of the sites sampled for *Macomona*, and less than 30% for *Paphies*. The majority of the bivalves sampled were classified as small.

3.2 Sediments

3.2.1 Substrate classification and grain size analysis data

The distribution of the different substrate categories within Tairua Estuary can be seen in Figure 6, and the results from 111 sites for which grain size analysis data were available are shown in Figure 7.

Within the estuary, only five substrate categories were present: ‘Firm sand’, ‘Mobile sand’, ‘Soft sand’, ‘Soft mud / sand’, and ‘Very soft mud / sand’. The relative abundance of the substrate classes differed widely, and the vast majority (82%) of sites were classified as ‘Firm sand’ and ‘Soft sand’ (Figure 3). The majority of the sites classified as ‘Mobile sand’ were found near the channel, whereas the ‘Very soft mud / sand’ and the ‘Soft mud / sand’ categories were scattered throughout the estuary.

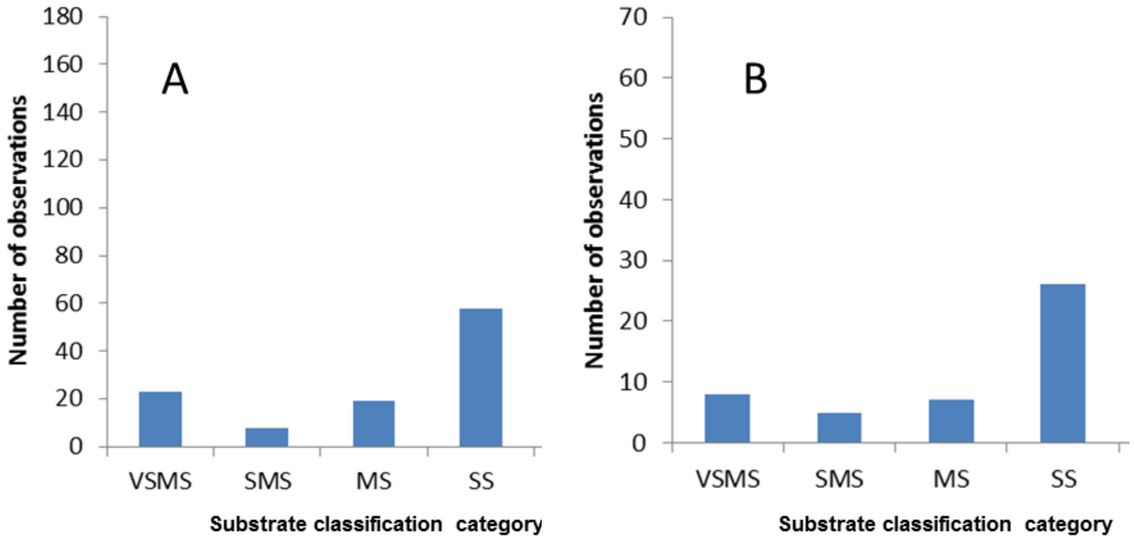

Figure 3: Number of sites classified into the different substrate categories for (A) all sites; (B) the subset of sites for which grain size analysis data were available. Substrate categories from Robertson & Peters (2006): FS = Firm sand; MS = Mobile sand; SMS = Soft mud / sand; SS = Soft sand; VSMS = Very soft mud / sand.

Table 3: Overview of abundance of bivalves, gastropods and vegetation found in Tairua Estuary. Average densities represent calculated averages for sites where species was present only, not average of all sites surveyed.

Species	**Total no. of individuals**	**Average density +/- SD (no. m^{-2})**	**Maximum density (no. m^{-2})**	**Per cent of sites found at**	**Size (%)**		
					Small	**Medium**	**Large**
Bivalves							
Austrovenus stutchburyi (cockle)	5604	472 ± 617	3600	69.1	76.1	22.6	1.3
Macomona liliana (wedge shell)	1227	134 ± 119	560	53.5	50.7	39.6	9.7
Paphies australis (pipi)	1443	282 ± 913	7072	29.8	85.0	14.5	0.6
Total bivalves	8274			81.8			
Gastropods							
Cominella sp.	217	36 ± 27	160	35.3			
Diloma sp.	219	52 ± 62	384	24.7			
Zeacumantus sp.	102	39 ± 32	134	15.3			
Total gastropods	538			48.4			
Vegetation							
Seagrass (*Zostera* sp.)				29.1			
Mangrove				4.4			
Ulva				2.2			
Total vegetation				33.8			

The sediment grain size analysis data showed fine sand (63-250 µm) and medium sand (250-500 µm) to dominate in the estuary. The majority (55%) of samples contained 40% or more fine sand, and 24% of sites contained 50% or more fine sand. Similarly, 50% of samples contained 40% or more medium sand, and 14% of samples contained 50% or more medium sand. Mud (grain size <63 µm) was found in 60% of the samples, with the majority of samples (70% of those which contained mud) containing less than 10% mud. The highest proportion of mud found was 85%, and only one other sample contained 50% or more mud.

3.2.2 Comparison of the two sediment assessment methods

Full grain size analysis is costly, and the use of a subjective descriptive method provides a potential to cut costs if such a method can be shown to provide a consistent and meaningful description of surface sediments. The extent to which the subjective substrate classes identified in this survey represent sediment grain size categories was determined by comparing the descriptive categories to the sediment grain size data for the 111 sites where both are available.

The results from grain size analysis offers a full picture of the sediment composition by providing single measures, such as median grain size, but also detailed information about the full composition of the sediment in terms of the relative amounts of different grain sizes. In comparison, the single descriptive term used for the subjective sediment categories provides only restricted information. Therefore a more comprehensive comparison of the two methods is to establish whether the descriptive sediment categories correspond to different relative amounts of different grain sizes (grain size distribution), or different median grain sizes.

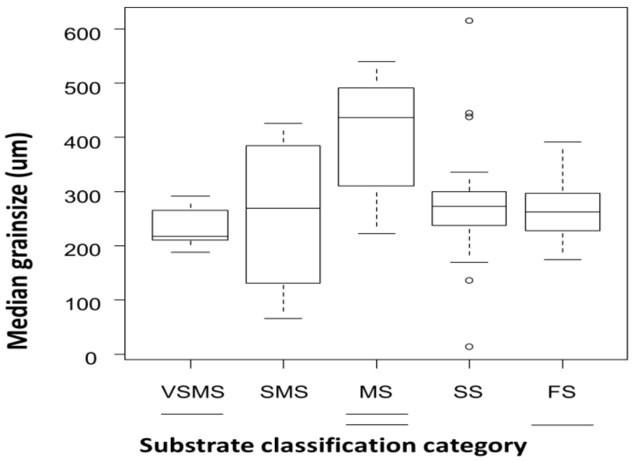

Figure 4: **Boxplot[1] showing median sediment grain size for different substrate categories: FS = Firm sand; MS = Mobile sand; SMS = Soft mud / sand; SS = Soft sand; VSMS = Very soft mud / sand. Statistically significant differences between substrate categories are denoted by solid lines under substrate categories. Lines at identical heights indicate that categories are different.**

The two sediment assessment methods were compared by (1) comparing the median grain sizes[2] of substrate classes and (2) comparing the relative amounts of different grain sizes (grain size distribution) of the substrate classes.

Median grain size of the substrate categories are shown in Figure 4. The median grain sizes of substrate categories ‘Very soft mud / sand’, ‘Soft mud / sand’, ‘Soft sand’ and ‘Firm sand’ were very similar (233 to 276 µm) and not statistically different. Median grain size of substrate category ‘Mobile sand’ was highest (401 µm) and significantly different from grain size of categories ‘Very soft mud / sand’ and ‘Firm sand’.

Statistical analyses (see Appendix 4) showed only limited correlations between the substrate categories and sediment grain size distribution. A difference in grain size between the ‘Very soft mud / sand’, ‘Soft mud / sand’ and ‘Mobile sand’ categories was detected, with a general decrease in the amount of fine sediments over the three categories, and an increase in the amount of coarse sediments. However, these differences were not always statistically significant. The muddy categories ‘Very soft mud / sand’ and ‘Soft mud / sand’ contained significantly higher levels of mud than other categories, but, statistically, could not be distinguished from one another in terms of grain size. The only substrate category that correlated to a discreet range of sediment grain size was ‘Mobile sand’. This category was significantly coarser than other substrate categories.

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[1] Boxplot: Lower and upper hinges represent 25th and 75th percentiles, respectively; the line across the box denotes the median; the ends of the vertical lines indicate the minimum and maximum data values, unless outliers are present in which case the whiskers extend to a maximum of 1.5 times the inter-quartile range; the points outside the ends of the whiskers are outliers or suspected outliers.

[2] Median grain size is the midpoint of the grain-size distribution, where 50% of the sediment is coarser and 50% is finer than the median grain size. Here 50% refers to 50% by volume.

3.2.3 Comparison of substrate categories with redox potential discontinuity layer

The depth of the RPD within the different substrate categories is shown in Figure 5. The difference in RPD depth of the substrate categories were found to be statistically significant (Kruskal-Wallis rank sum test: chi-squared = 18.1175, p = 0.001), and the post-hoc analyses (results from which are shown in Figure 5) indicate that the 'Mobile sand' category was associated with significantly higher RPD depths than most other categories.

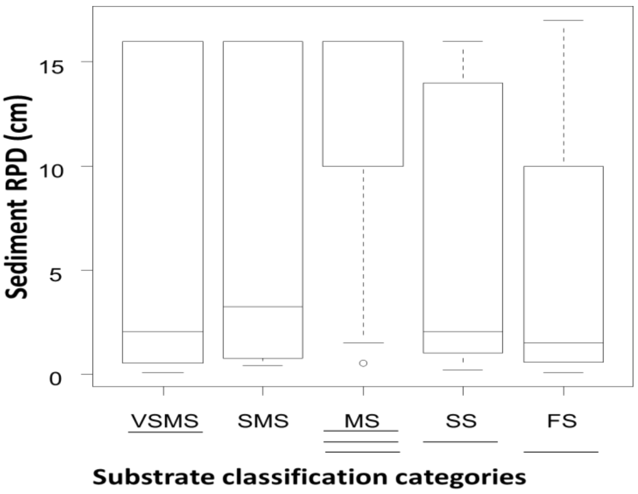

Figure 5: Boxplot[3] showing sediment redox potential discontinuity layer depth (RPD) for different substrate categories: FS = Firm sand; MS = Mobile sand; SMS = Soft mud / sand; SS = Soft sand; VSMS = Very soft mud / sand. Statistically significant differences between substrate categories are denoted by solid lines under sediment categories. Lines at identical heights indicate that categories are different, e.g. VSMS and MS.

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[3] Boxplot: Lower and upper hinges represent 25th and 75th percentiles, respectively; the line across the box denotes the median; the ends of the vertical lines indicate the minimum and maximum data values, unless outliers are present in which case the whiskers extend to a maximum of 1.5 times the inter-quartile range; the points outside the ends of the whiskers are outliers or suspected outliers.

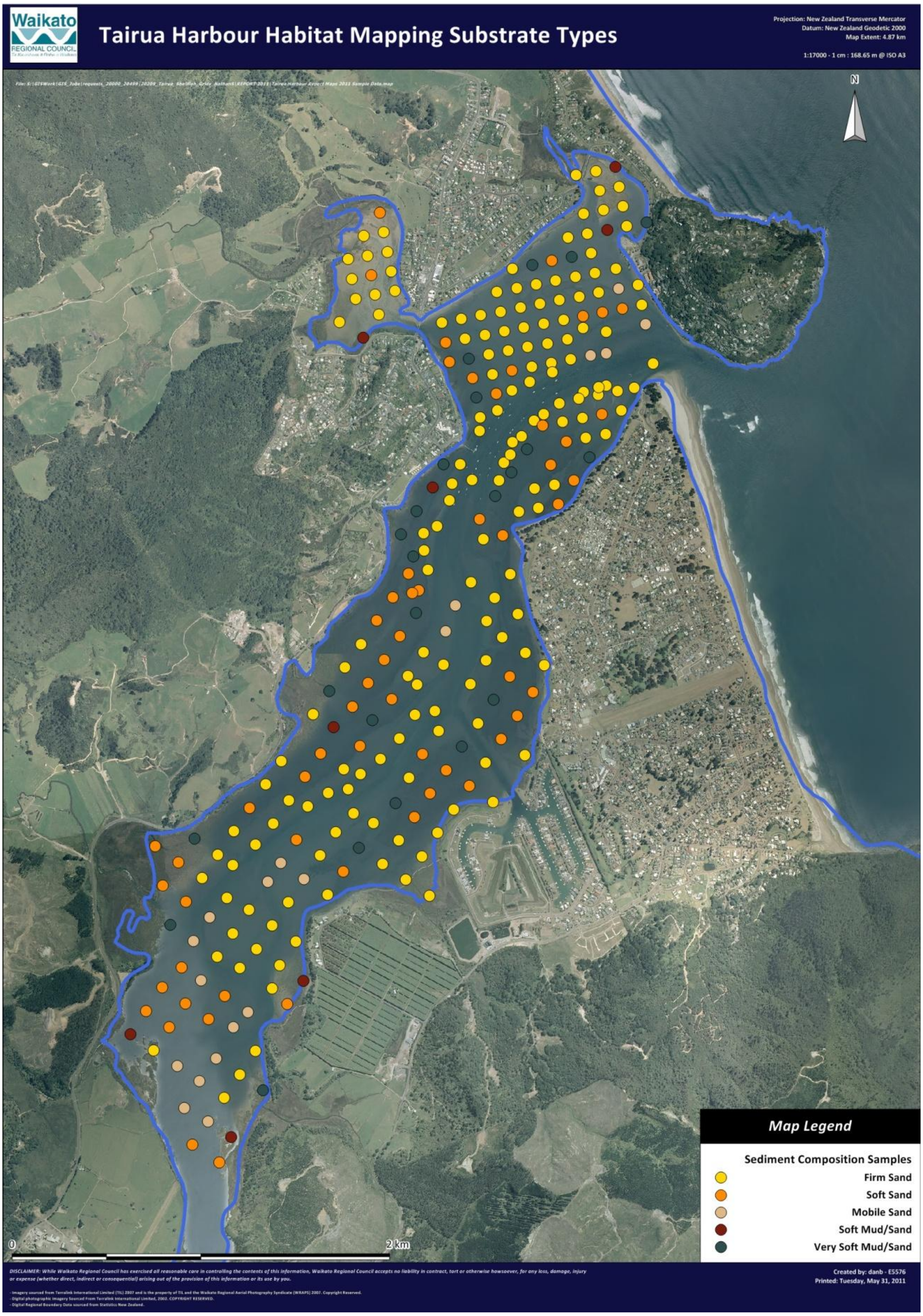

Figure 6: **Substrate classification results for Tairua Estuary. Substrate categories are those listed in Table 2 and Robertson & Peters (2006).**

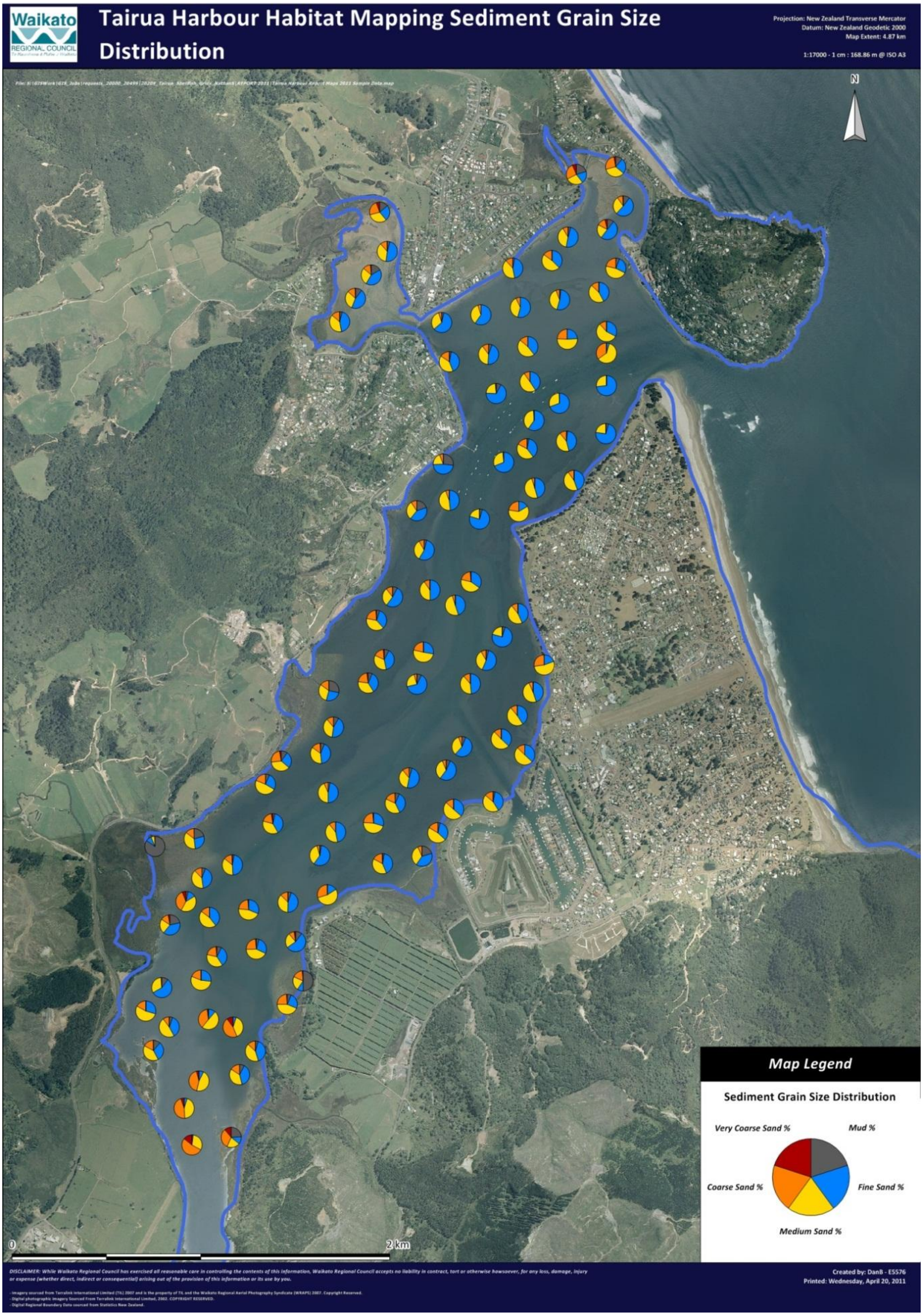

Figure 7: Results from grain size analyses, for the 111 sampling points within Tairua Estuary where sediment grain size analysis was carried out.

3.3 Bivalves

3.3.1 Bivalve abundance and distribution

Figures 8 to 10 show maps of the distribution of the different species of bivalves.

Extensive *Austrovenus* beds were present in the estuary. The densest beds (>1000/m^2) were found on the intertidal flats either side of the main channel due east of Tairua township, extending from just south of Paku Bay to just north of Cemetery Point. Given that sampling points were 150 m apart, it is hard to estimate the exact size of the beds, but in many places, the high density *Austrovenus* beds extended for a few adjacent sample points, indicating beds of reasonable size, interspersed with areas where *Austrovenus* were present in lower densities. For all sites surveyed, the average abundance of *Austrovenus* was equivalent to 326 individuals per m^2. If this average is extended to the entire intertidal area not covered by mangroves or saltmarsh (~254 ha, or just over 2.5 million m^2), the predicted total number of *Austrovenus* in Tairua Harbour is close to 828 million.

The populations of *Macomona* were sparse compared to *Austrovenus*, but the highest densities (>300/m^2) were found in similar areas. The distribution of *Macomona* was also slightly more restricted than that of *Austrovenus*, particularly in the upper estuary.

The densest *Paphies* beds were found near the main channel, and it seems that the estuary contains two main areas of *Paphies* beds: along the channel just inside the Tairua Harbour entrance, and in the upper estuary, approximately level with Tangitarori Lane on the Pauanui side of the estuary.

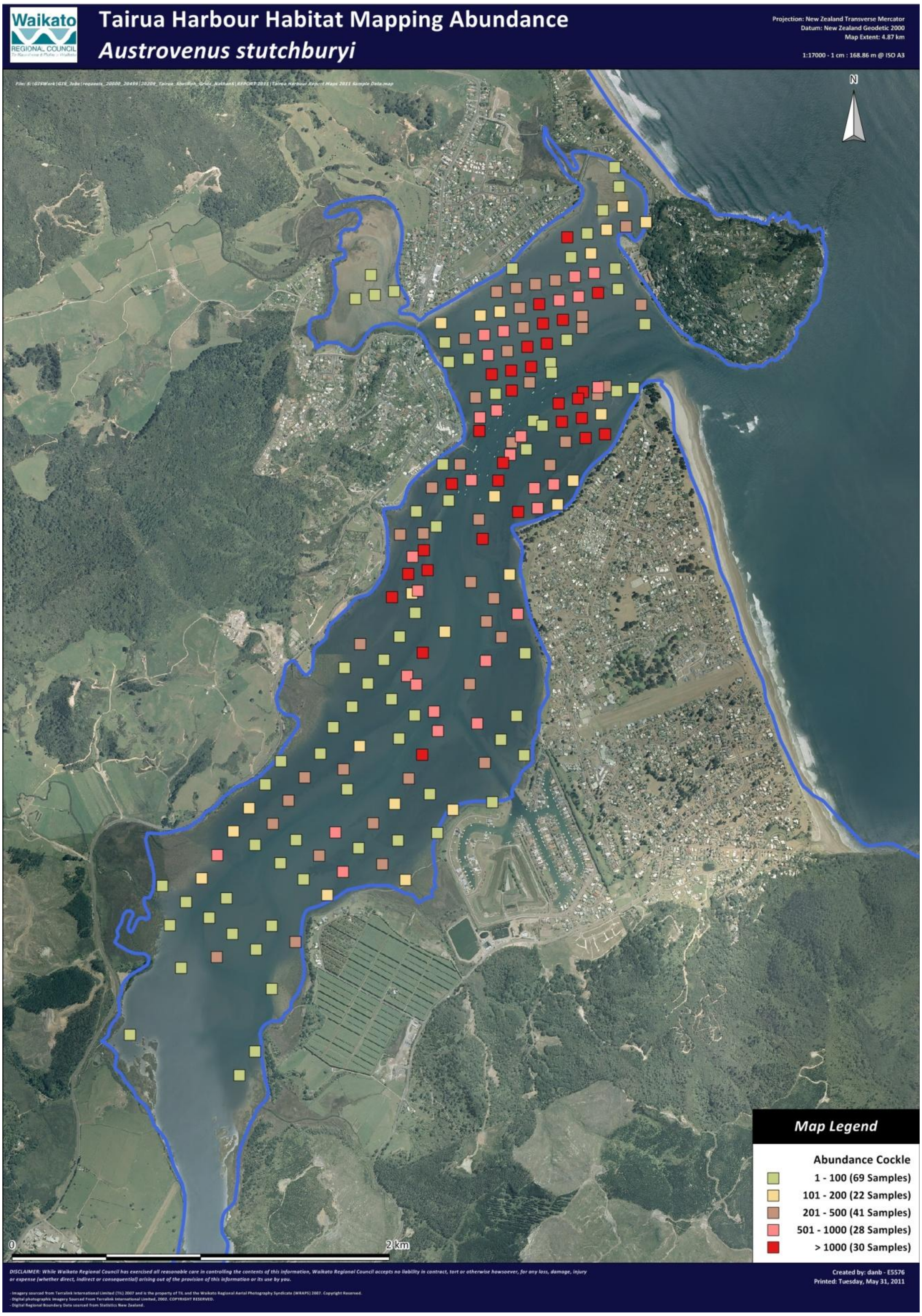

Figure 8: Abundance (individuals/m^2) and distribution of the cockle, *Austrovenus stutchburyi*, at the sample sites within Tairua Estuary. Note that sites at which no Austrovenus were found are not shown; for a map of all sampling sites, see Appendix 1.

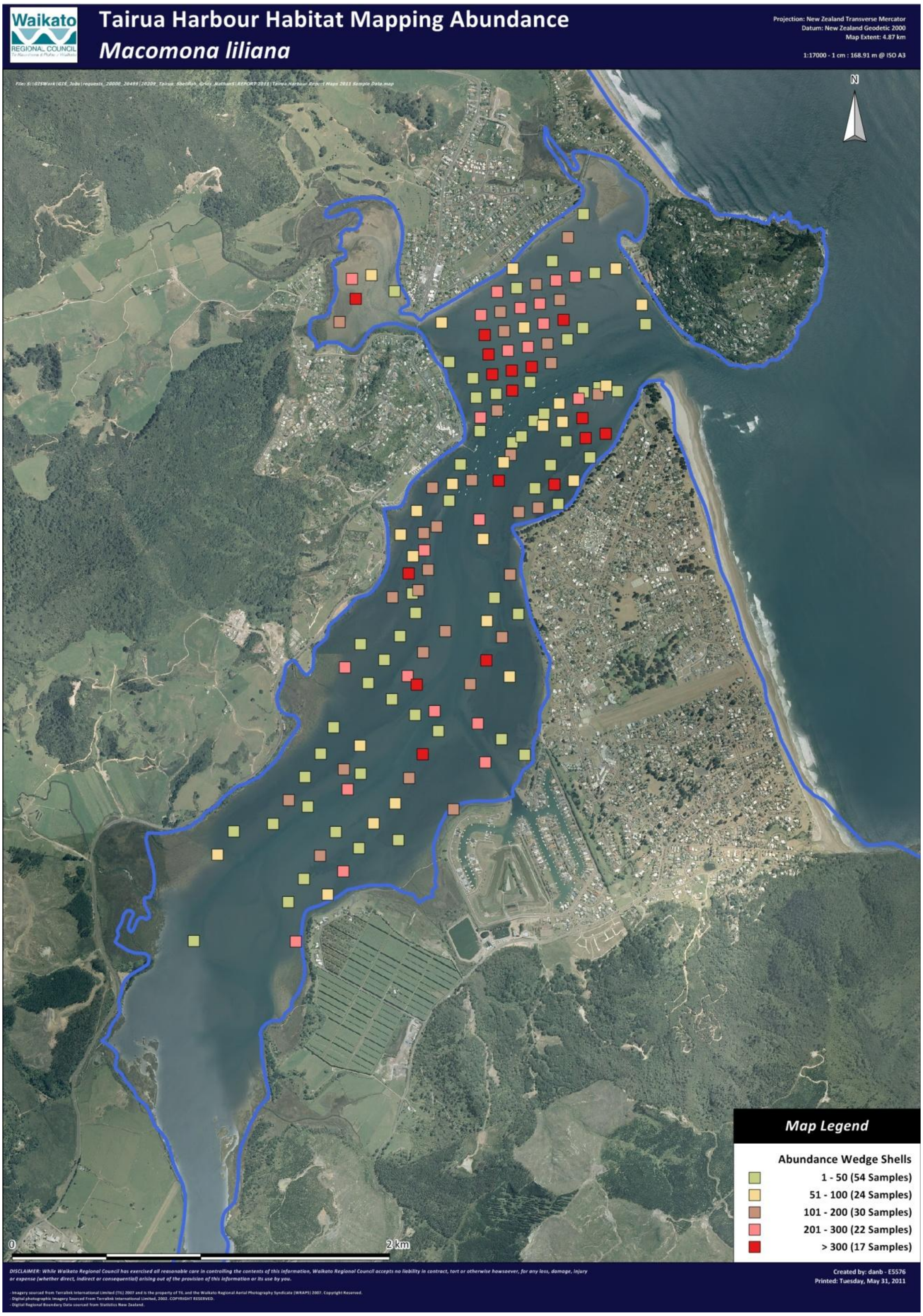

Figure 9: **Abundance (individuals/m^2) and distribution of the wedge shell, *Macomona liliana*, at the sample sites within Tairua Estuary. Note that sites at which no Macomona were found are not shown; for a map of all sampling sites, see Appendix 1.**

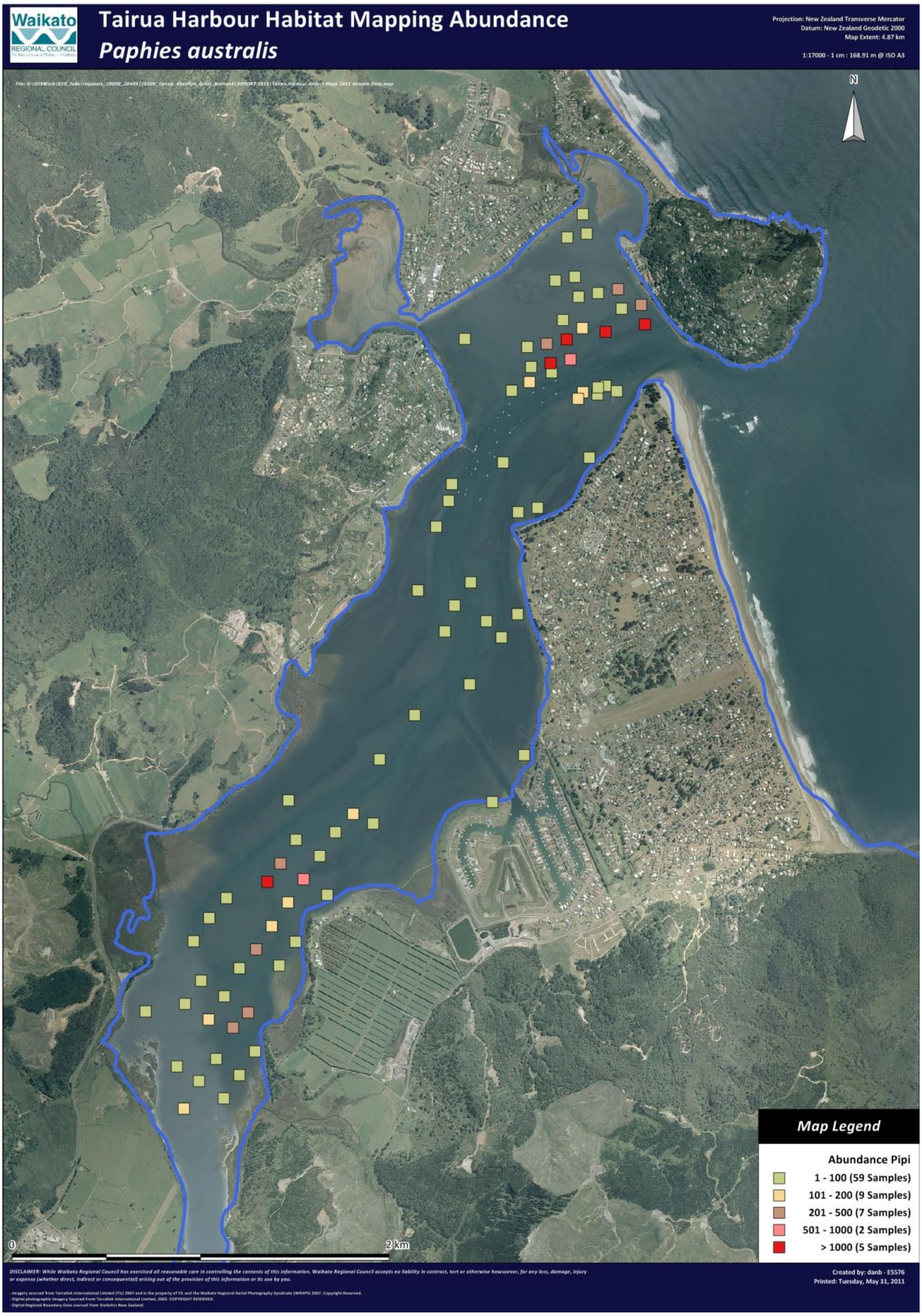

Figure 10: **Abundance (individuals/m^2) and distribution of the pipi, *Paphies australis*, at the sample sites within Tairua Estuary. Note that sites at which no *Paphies* were found are not shown; for a map of all sampling sites, see Appendix 1.**

3.3.2 Bivalve size classes

Figures 11 to 13 show the distribution of the different size classes of bivalves.

Of the 5604 *Austrovenus* sampled in total, the majority (4266) were juveniles (small size: 0-20 mm shell length), compared to 1265 medium size (20-30 mm shell length) and 73 large (>30 mm shell length). Only 27 sites (of 275 sites sampled) contained large *Austrovenus*. Of these sites, nine contained only one large *Austrovenus*, and nine only two, making the large *Austrovenus* only a small proportion of the total *Austrovenus* found at the site. The highest number of large *Austrovenus* found in one quadrat was 10, out of a total of 184 found at that site. Medium sized *Austrovenus* constituted half or more than the total *Austrovenus* sampled at only 41 sites; and 22 of these contained a total of less than ten *Austrovenus*. *Austrovenus* were found at 190 sites in total; the highest number of *Austrovenus* found within a quadrat was 225 (equivalent to 3600/m^2), and a total of 11 sites contained more than 100 *Austrovenus* (>1600/m^2).

A comparison between Figures 8 and 11 indicates one site where juveniles were present in reasonably high densities (>300/m^2). This is the large intertidal flat due east of Tairua township, north of Pepe inlet, where only juvenile *Austrovenus* were found at more than 20 sites, in some cases reaching densities of > 1000/m^2. It is possible that this site represents a site of *Austrovenus* recruitment.

In total 1227 *Macomona* were found at 147 sites. Of these 622 were small (<20 mm shell length), 486 were medium (20-30 mm shell length) and 119 large (>30 mm shell length). Only few sites (17) contained just small individuals, and eight sites contained only large *Macomona* (although of the latter, six sites contained only one individual). The highest number of *Macomona* found at one site was 35 (~560/m^2), and 20 or more individuals (320/m^2) were found at 12 sites. Figure 12 does not indicate any particular recruitment areas containing high densities of juvenile *Macomona*.

Numerically, *Paphies* were more abundant than *Macomona*, with a total of 1443 individuals found in Tairua Estuary. Of these, the vast majority (1226) were juveniles (<20 mm shell length), 209 were medium sized (20-40 mm shell length) and only eight were large (>40 mm shell length). *Paphies* were found at 82 sites in total, and at the majority of sites (62, or 76%) only small individuals were present. The density of *Paphies* varied widely within the estuary: the highest number of *Paphies* found in one quadrat was 442 (~ 7072/m^2), and at three sites more than 100 individual *Paphies* were counted within a quadrat (>1600/m^2).

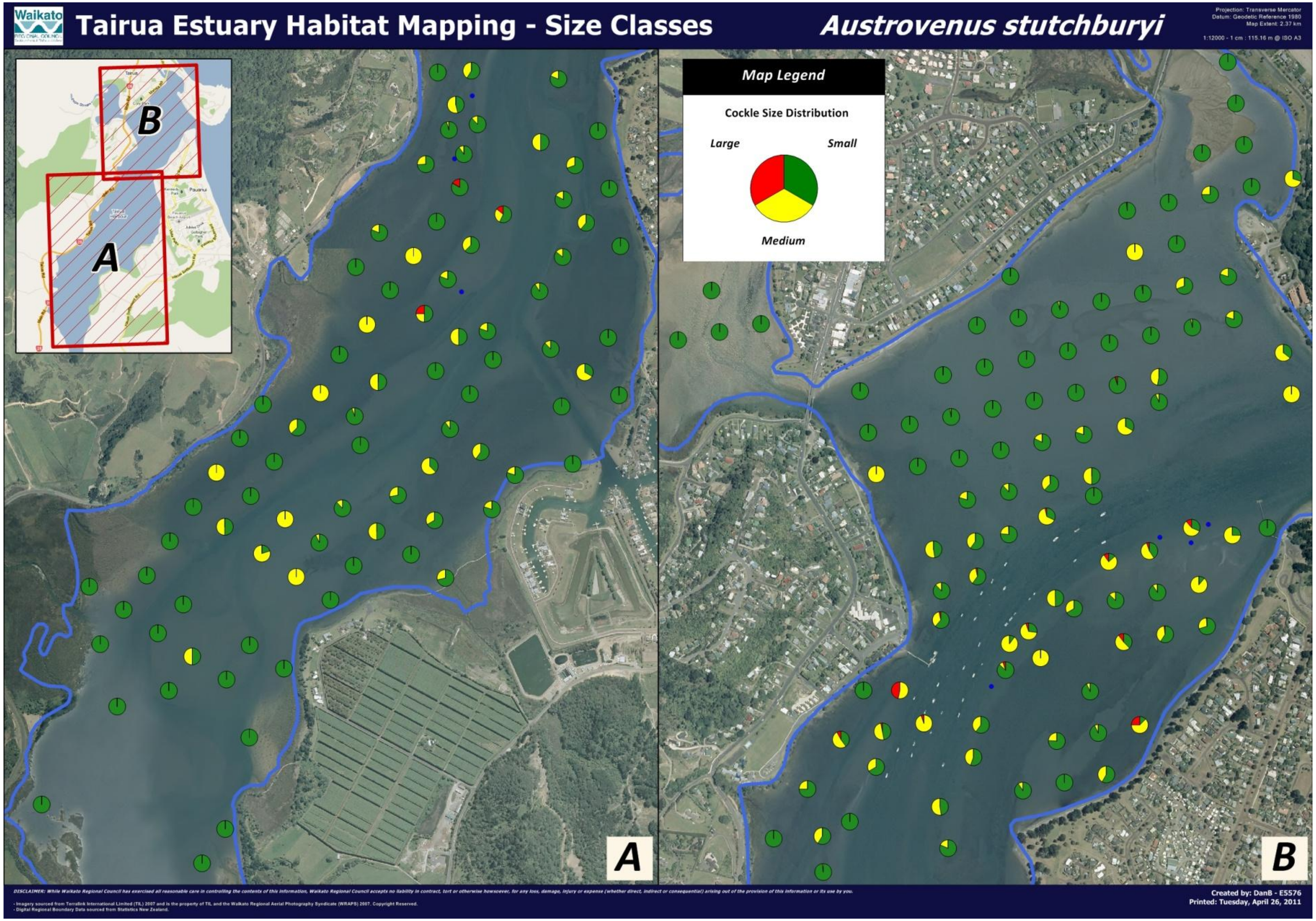

Figure 11: Distribution of the different size classes of cockles, Austrovenus stutchburyi, at the sampled sites within Tairua Estuary. Note that sites at which no Austrovenus were found are not shown; for a map of all sampling sites, see Appendix 1. In some cases symbols had to be moved to avoid overlap. In these instances blue dots represent actual sampling sites.

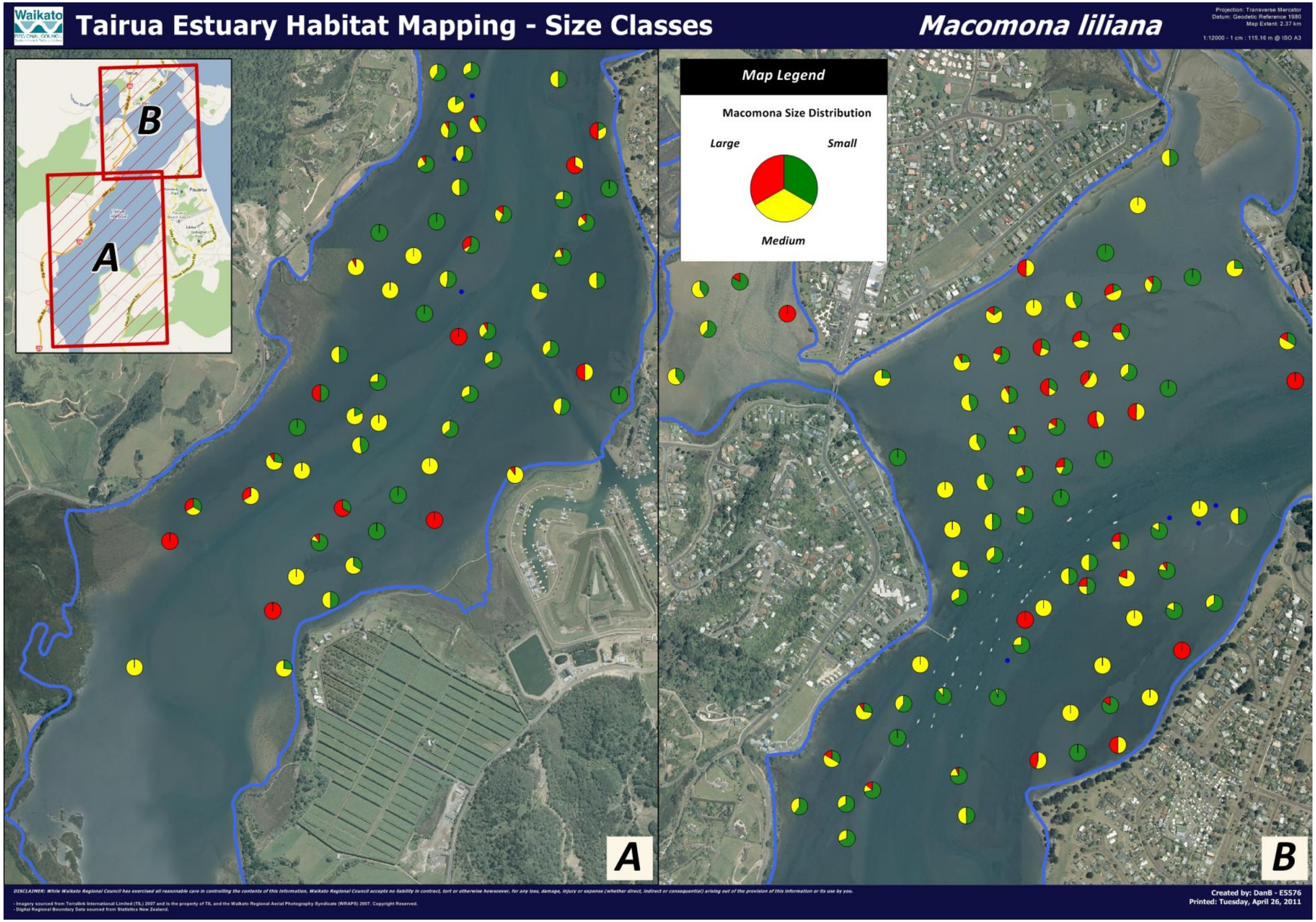

Figure 12: **Distribution of the different size classes of wedge shells, Macomona liliana, at the sampled points within Tairua Estuary. Note that sites at which no Macomona were found are not shown; for a map of all sampling sites, see Appendix 1. In some cases symbols had to be moved to avoid overlap. In these instances blue dots represent actual sampling sites.**

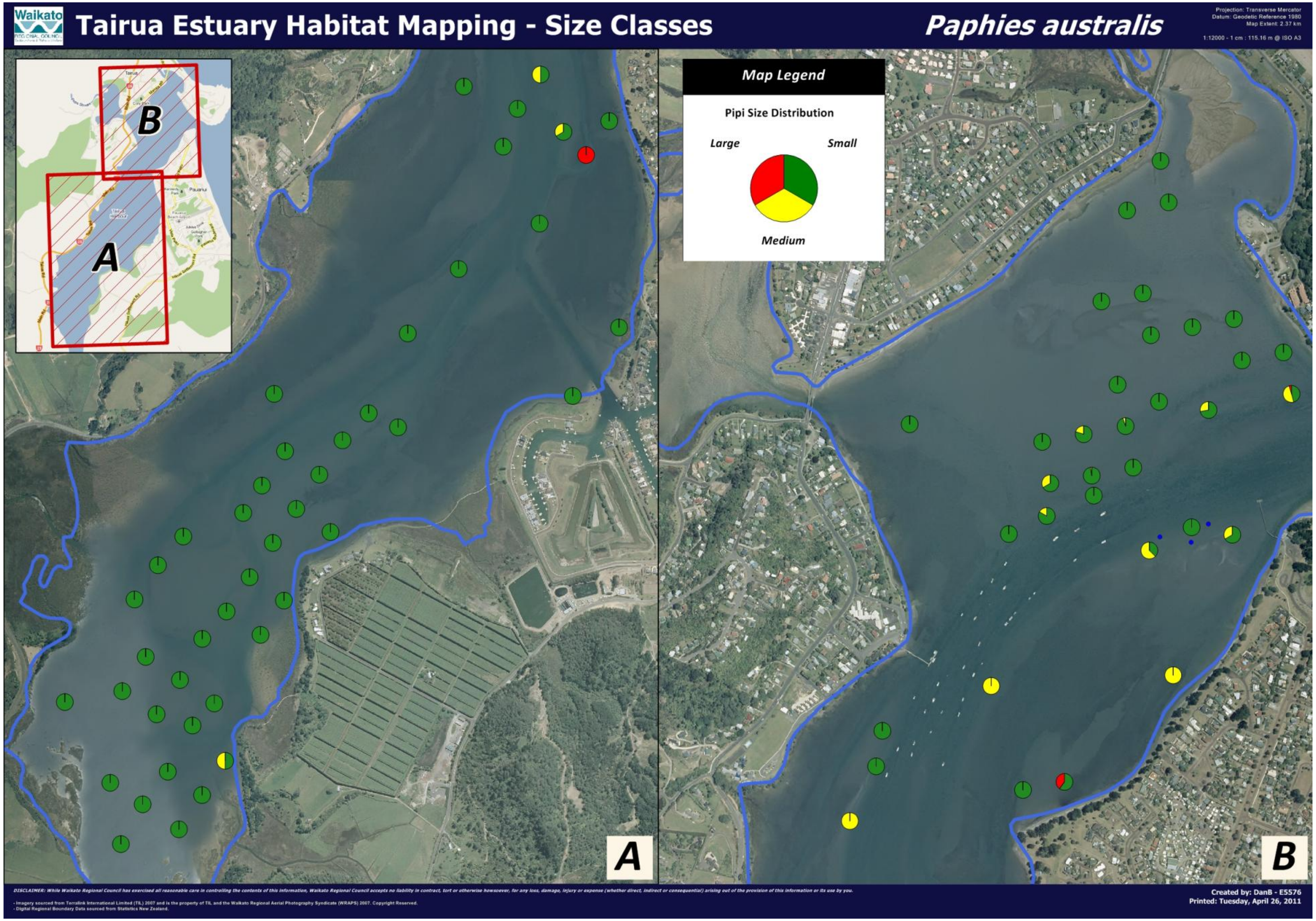

Figure 13: **Distribution of the different size classes of pipi, Paphies australis, at the sampled points within Tairua Estuary. Note that sites at which no Paphies were found are not shown; for a map of all sampling sites, see Appendix 1. In some cases symbols had to be moved to avoid overlap. In these instances blue dots represent actual sampling sites.**

3.4 Estuary vegetation

Figure 14 shows the distribution of seagrass (*Zostera* sp.) and mangrove pneumatophores, which were the most commonly found types of estuarine vegetation.

Seagrass was found at 82 of the 275 sites, and the map shows that the seagrass beds in Tairua Estuary are extensive. The densest seagrass beds were found near the estuary channel, and what appears to be the largest beds were found in the outer (closest to the sea) and middle parts of the estuary, with little seagrass in the upper estuary. A comparison of Figures 1 and 14 show that the seagrass beds were present in much the same areas of the estuary in 2010 as in 2008, but suggests that the beds have increased to cover larger areas within the Pepe Stream inlet, and that the exact location of the beds have shifted within the central part of the estuary just inside the harbour mouth, as well as further upstream. Although not directly comparable, Figure 14 and Table 3 indicate that the total area covered in seagrass beds may have increased between 2008 and 2011: in 2008, seagrass beds covered 15% of Tairua Estuary, whereas in 2011 seagrass was found at 29% of sites.

Only 12 of the 275 sites sampled were found to be colonised by mangroves, and in most of the locations where pneumatophores were found, they were quite dense (nine sites contained 10 or more pneumatophores per quadrat). Once again, a comparison between Figures 1 and 14 suggest that some areas that used to be covered in mangroves now support seagrass beds, whereas other areas have changed from seagrass into mangrove pneumatophores.

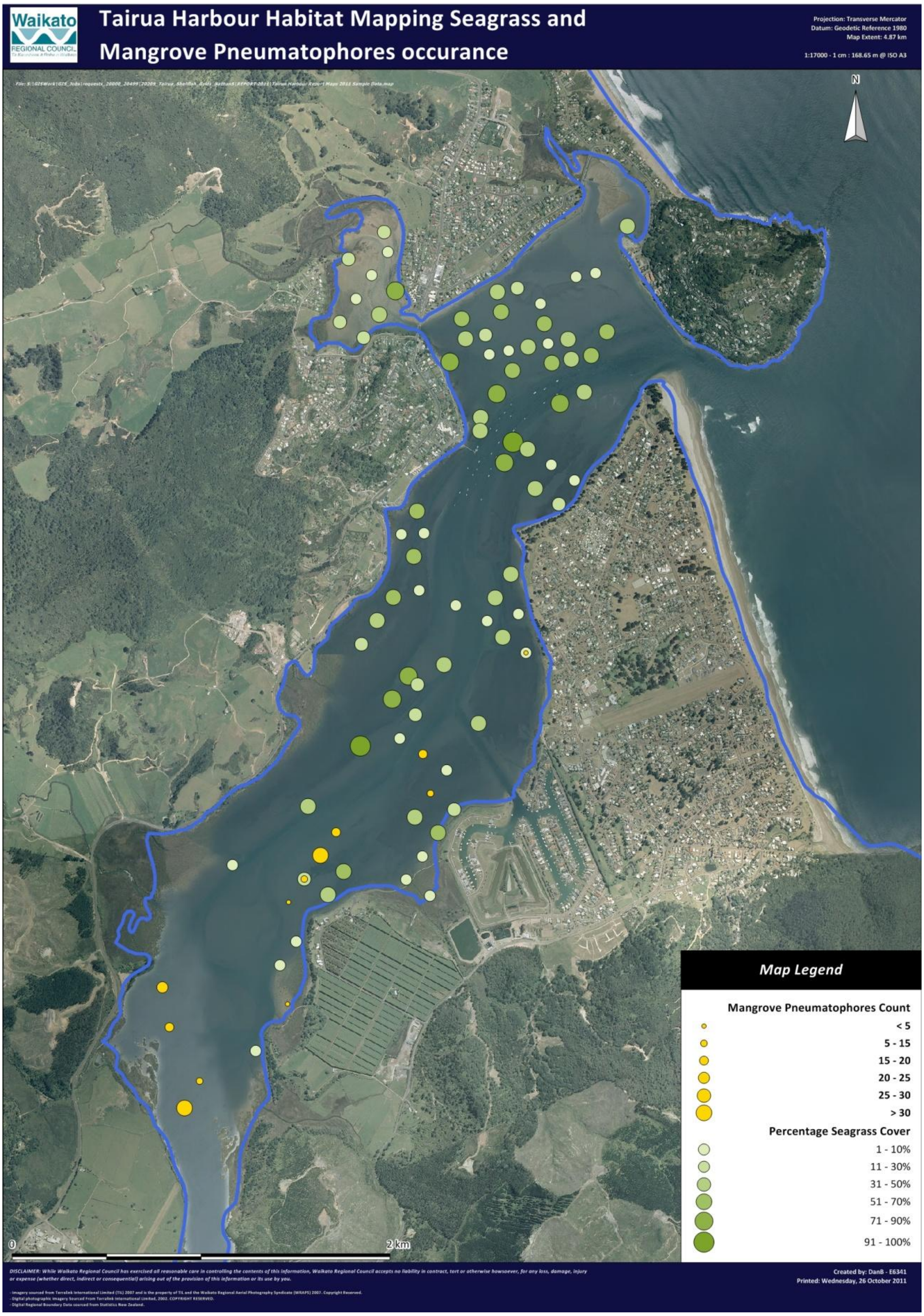

Figure 14: Map showing location and abundance of seagrass (Zostera sp.) and mangrove pneumatophores found in Tairua Estuary.

3.5 Relationships between sediment properties, vegetation and bivalve presence and densities

3.5.1 Bivalve abundance at sites with different sediment properties and vegetation cover

Relationships between bivalve abundances and sediment characteristics and estuarine vegetation were explored graphically. Figure 15 shows the abundance of *Austrovenus*, *Macomona* and *Paphies* at sites with different percentage seagrass cover. *Paphies* were only found at 21 sites where seagrass grew, but all three sites with abundances of more than 100 *Paphies* per quadrat (>1600/m^2) were at sites with more than 30% seagrass cover.

No significant differences were found between bivalve abundances at sites with different percentage seagrass cover (Kruskal-Wallis rank sum tests: *Austrovenus*: chi-squared = 7.873, p = 0.248; *Macomona*: chi-squared = 10.8036, p = 0.095; *Paphies*: chi-squared = 3.6605, p = 0.723).

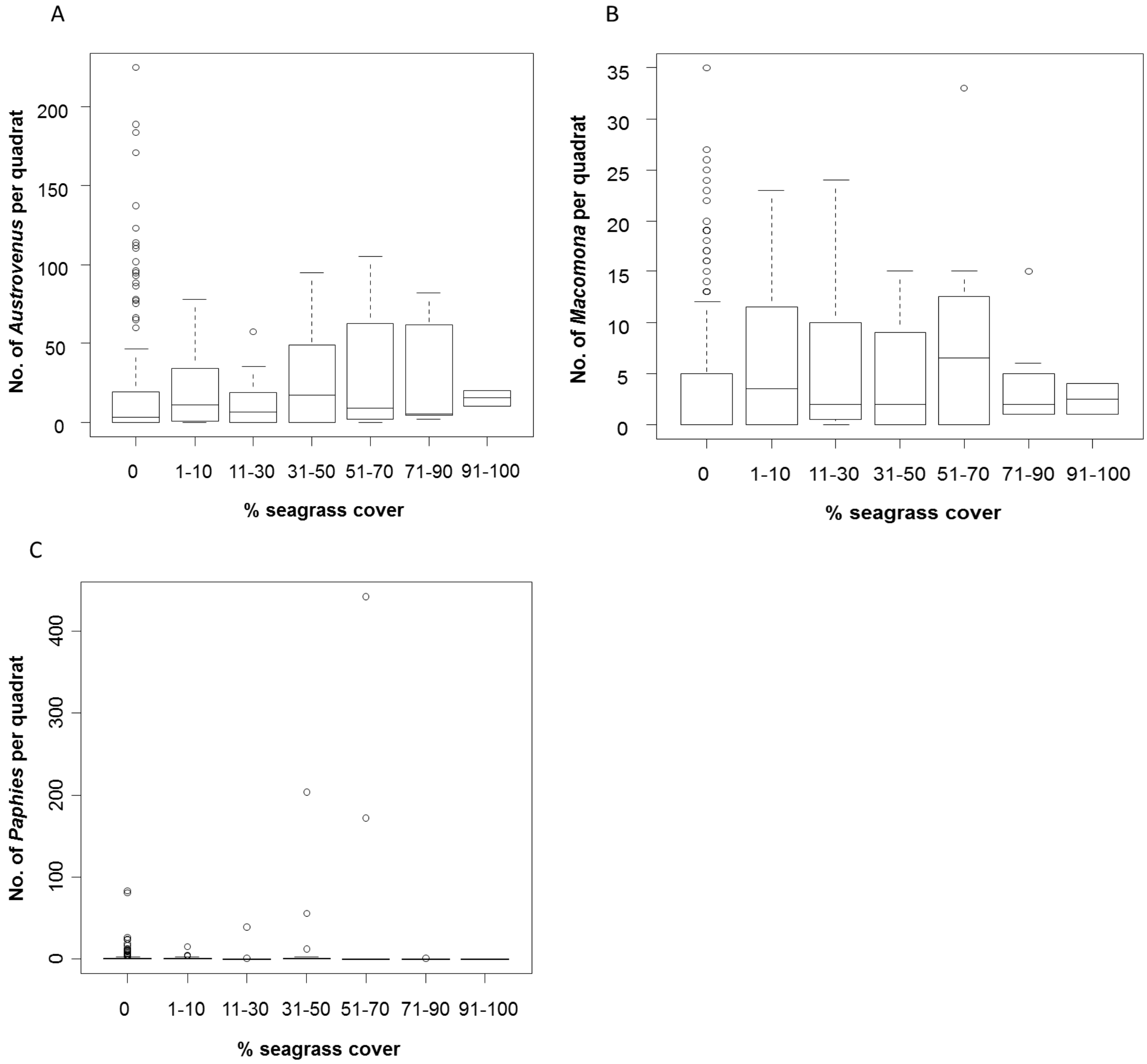

Figure 15: Boxplots[4] showing relative abundance of (A) cockles (Austrovenus stutchburyi); (B) wedge shells (Macomona liliana); and (C) pipi (Paphies australis) at sites with different percentage seagrass cover.

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[4] Boxplots: Lower and upper hinges represent 25th and 75th percentiles, respectively; the line across the box denotes the median; the ends of the vertical lines indicate the minimum and maximum data values, unless outliers are present in

Figure 16 shows the relative abundance of bivalves at the sites classed as belonging to different substrate classes. Kruskal-Wallis tests found significant differences between bivalve abundances at the different substrate categories (Table 4), and the results from post-hoc tests (shown in Figure 16) show that all three species of bivalves were significantly more abundant in ‘Firm sand’ than all other categories apart from ‘Soft mud / sand’, and that *Paphies* in addition were significantly more abundant in ‘Mobile sand’ than all other categories.

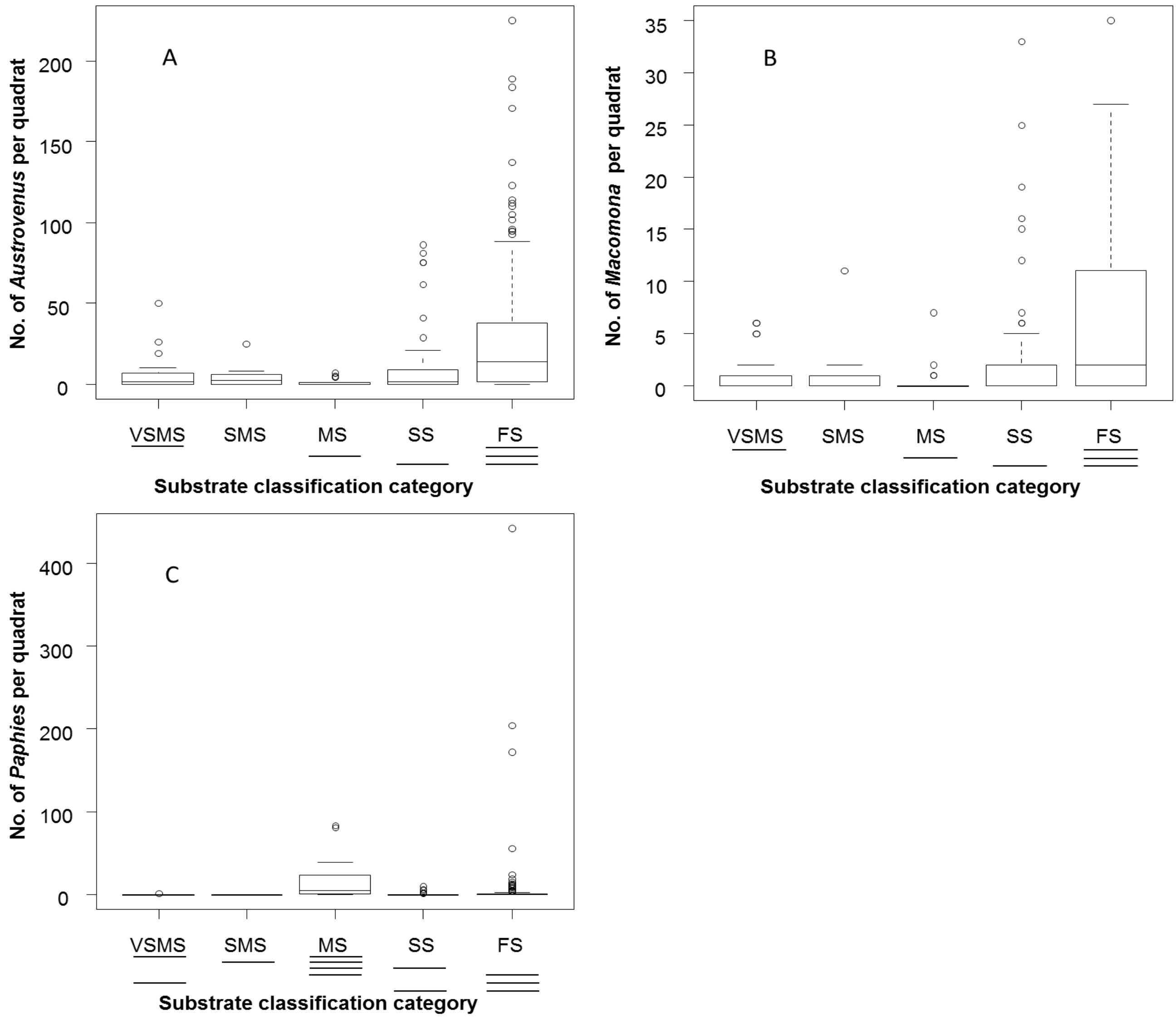

Figure 16: Relative abundance of (A) cockles (Austrovenus stutchburyi); (B) wedge shell (Macomona liliana); and (C) pipi (Paphies australis) at sites classified into different substrate categories. Statistically significant (at α<0.05) differences between means of pairs of substrate categories (determined using pairwise Wilcoxon-Mann-Whitney rank sum tests, p-value adjusted using Bonferrori correction) are denoted by solid lines under relevant substrate categories.

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which case the whiskers extend to a maximum of 1.5 times the inter-quartile range; the points outside the ends of the whiskers are outliers or suspected outliers.

Table 4: Results from Kruskal-Wallis tests for bivalve abundance differences between the different substrate categories VSMS, SMS, MS, SS, FS (for definition of substrate categories, see Table 1 and Figure 2 caption).

Bivalve species	Kruskal-Wallis chi-squared	p
Cockles (*Austrovenus stutchburyi*)	39.5431	<0.001
Wedge shells (*Macomona liliana*)	29.2912	<0.001
Pipi (*Paphies australis*)	53.6568	<0.001

Figure 17 shows the relative abundance of the three bivalve species at sites with different Redox Potential Discontinuity layer (RPD) depths. The figure shows that a large proportion of sites with high numbers of *Austrovenus* and *Macomona* coincided with shallow RPD depths; however, the spread of abundance of both species was great at low RPD depths, which constituted the majority of sites.

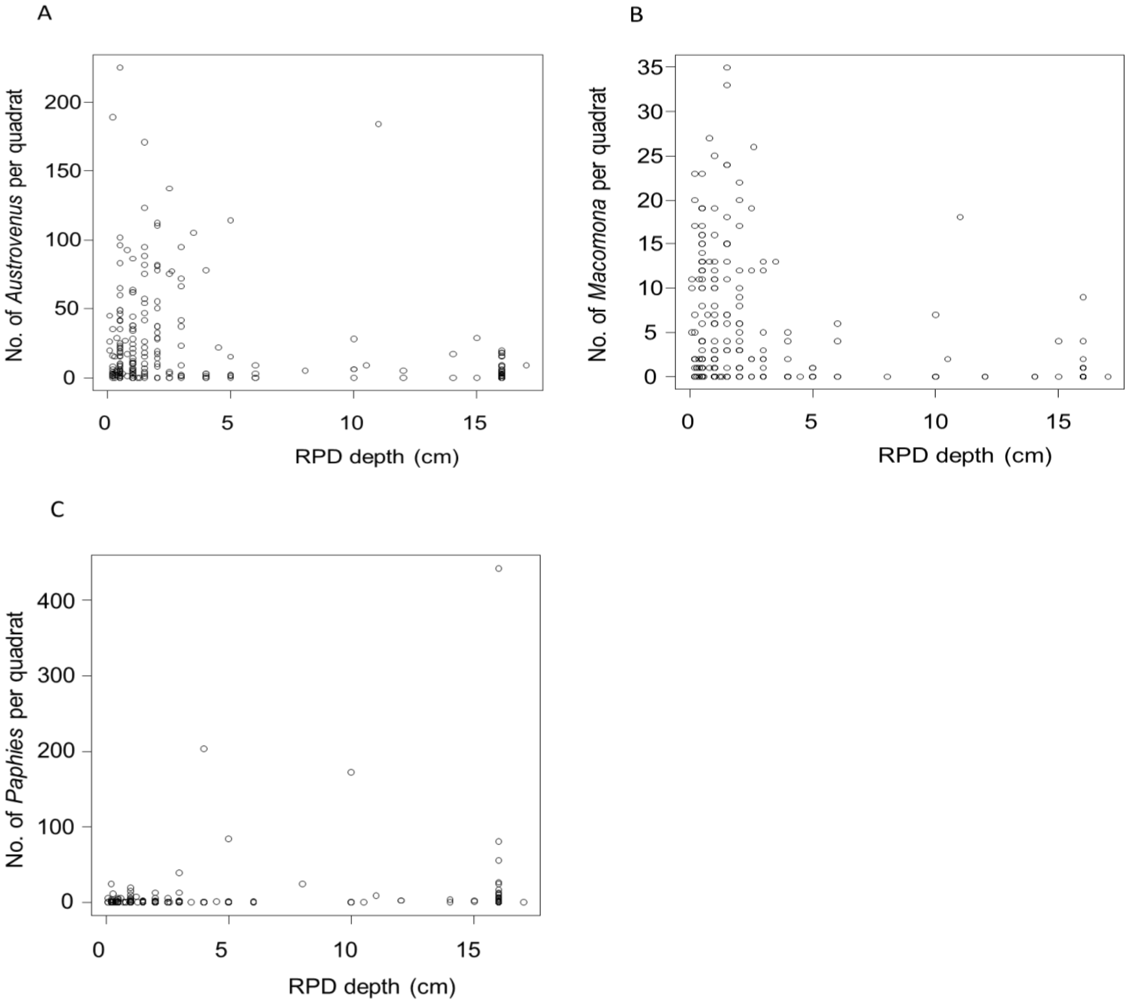

Figure 17: Relative abundance of (A) cockles (Austrovenus stutchburyi); (B) wedge shell (Macomona liliana); and (C) pipi (Paphies australis) at sites with different Redox Potential Discontinuity layer (RPD) depths.

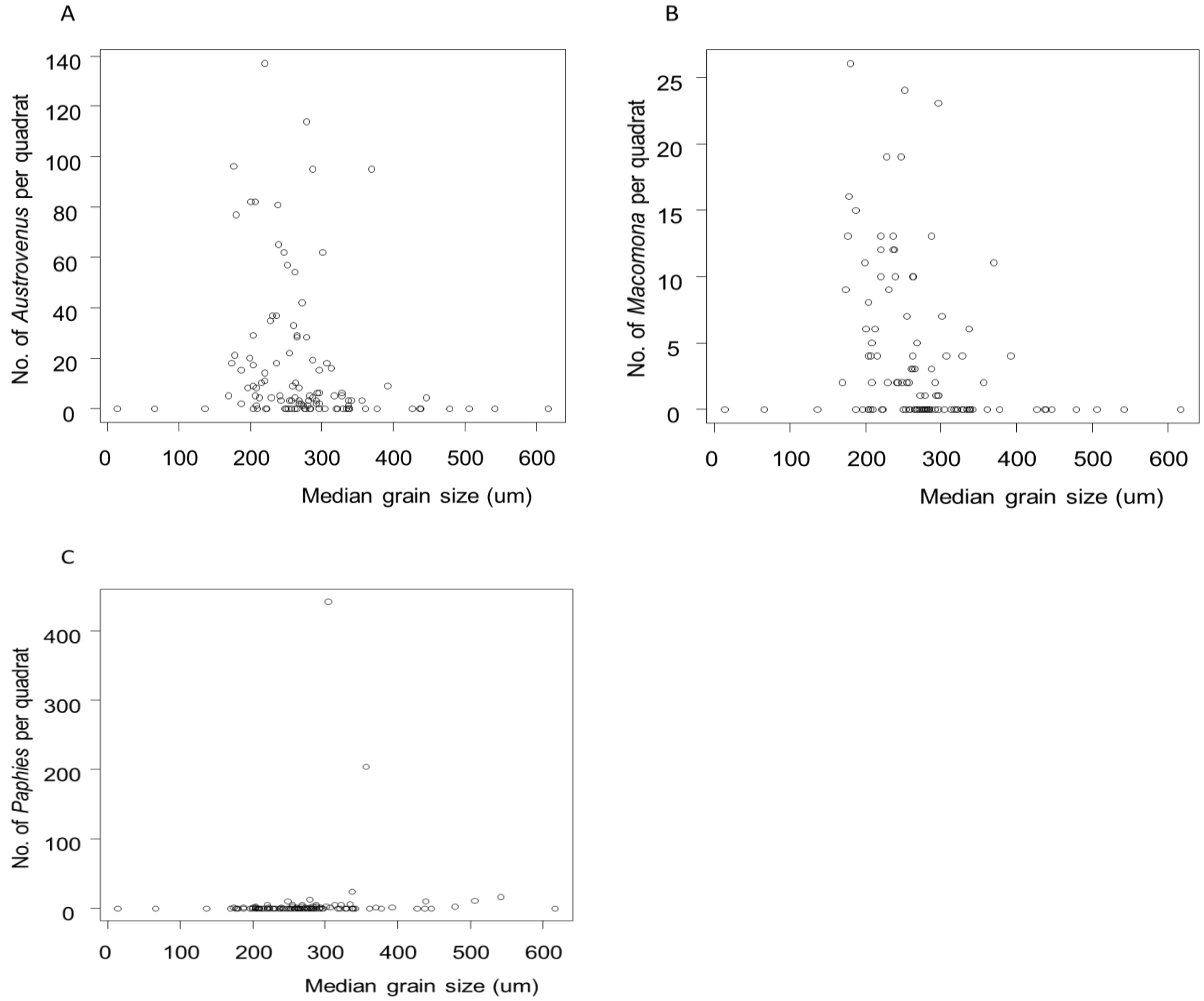

Figure 18: Relative abundance of (A) cockles (Austrovenus stutchburyi); (B) wedge shell (Macomona liliana); and (C) pipi (Paphies australis) at sites with different sediment median grain size.

Figure 18 shows the relative abundance of the three species of bivalves versus sediment median grain size for the 111 sites where grain size data were available. The majority of sites had median grain sizes of about 180 to 350 um, and it is within this range that the majority of sites with high *Austrovenus* and *Macomona* abundances were found. The highest abundances of *Paphies* were found at sites with median grain sizes between 300 and 400 um.

3.5.2 Regression trees to predict shellfish abundance from environmental data

The purpose of regression trees is to determine a set of if-then logical conditions that permit accurate prediction or classification of cases. Regression trees were used to explore relationships between abundance of *Austrovenus* and *Macomona* and environmental data (substrate categories, sediment RPD depth, percentage seagrass cover and number of mangrove pneumatophores). For *Paphies*, cross-validated errors were too large to leave a regression tree following statistical pruning, and as a result a classification tree based on presence / absence of *Paphies* (which withstood statistical pruning) was constructed instead. The results are shown in Figures 19 to 21.

For *Austrovenus*, RPD depth and substrate type were found to be the most important factors, and the regression tree indicates that abundances of *Austrovenus* were highest (average predicted abundance 36 / quadrat) in sediments with an RPD depth of less than 11.5 cm that were also classified as ‘Firm sand’ (Figure 19). Predicted average abundances in sediments with RPD depths shallower than 11.5 cm that classified as all other substrate categories was 11 *Austrovenus* per quadrat, and average abundance predicted for sediments with an RPD depth exceeding 11.5 cm was 3 *Austrovenus* per quadrat.

The same predictors were found to be important for *Macomona*, which the regression tree analysis predicted to be present in highest abundances (just over 8 *Macomona* / quadrat) in sediments with an RPD of less than 3.75 cm which were classified as 'Firm sand' (Figure 20). Sites with RPD depths of more than 3.75 cm were predicted to contain the lowest abundances (<1 *Macomona* / quadrat); whereas non-'Firm sand' sites with RPD depths exceeding 3.75 cm were predicted to contain just under 4 *Macomona* per quadrat.

For *Paphies*, the classification tree analysis indicated that the substrate class was the best predictor of presence / absence, with a higher probability (84%) of *Paphies* being present in 'Mobile sand' than in all other substrate categories (26%).

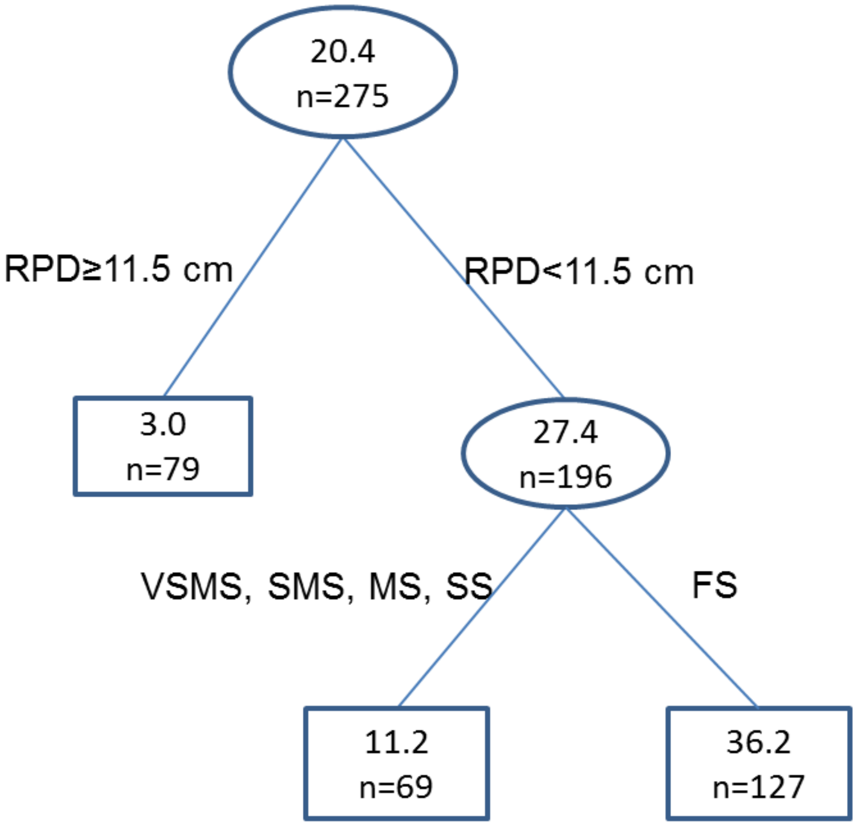

Figure 19: **Regression tree based on abundance data for cockles (Austrovenus stutchburyi). Ovals indicate more splits are possible, and rectangles that no further split is possible. Numbers represent predicted abundance of Austrovenus (per quadrat) in node. n=no. of observations (sites) in node. Analysis included the following potential predictors: substrate categories, sediment RPD, percentage seagrass cover, and number of mangrove pneumatophores per quadrat.**

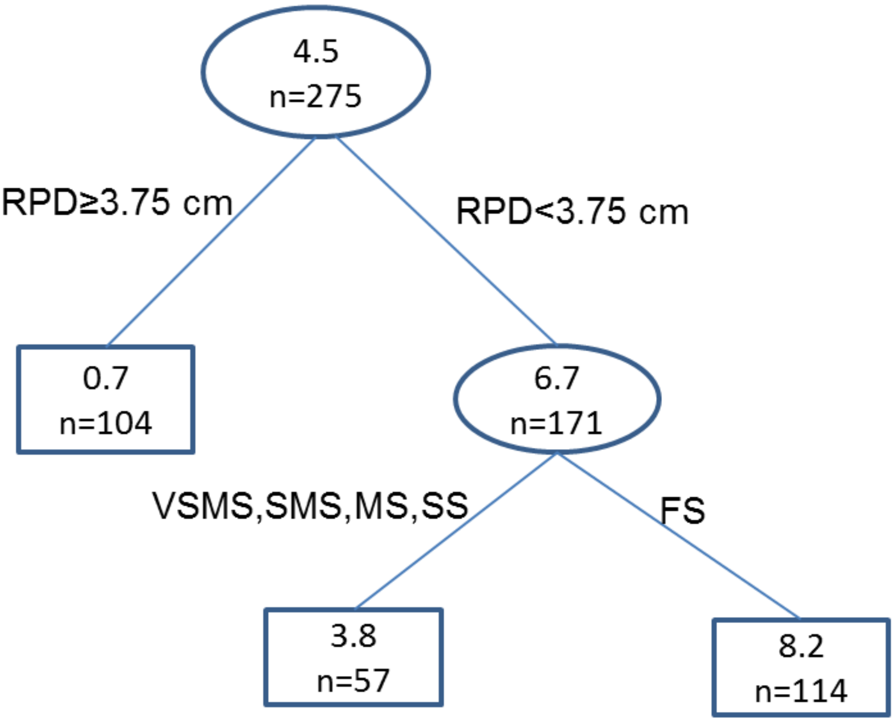

Figure 20: Regression tree based on abundance data for wedge shells (Macomona liliana). Ovals indicate more splits are possible, and rectangles that no further split is possible. Numbers represent predicted abundance of Macomona (per quadrat) per node, n=number of observations (sites) in node. Analysis included the following potential predictors: substrate categories, sediment RPD, percentage seagrass cover, and number of mangrove pneumatophores.

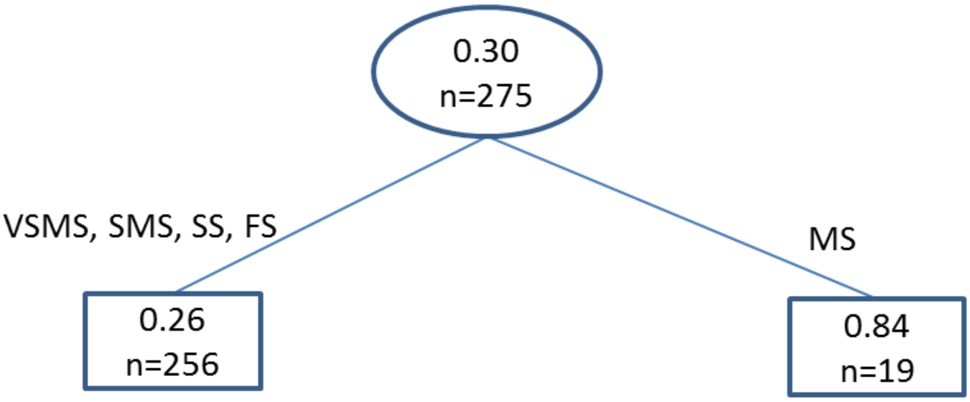

Figure 21: Classification tree based on presence / absence data for pipi (Paphies australis). Ovals indicate more splits are possible, and rectangles that no further split is possible. Analysis included the following potential predictors: substrate categories, sediment RPD, percentage seagrass cover, and number of mangrove pneumatophores. Numbers represent predicted probability of presence of Paphies in node (at site), n=number of observations (sites) in node.

3.5.3 Relationships between bivalve community structure and environmental variables

Canonical correspondence analysis (CCA) relates species data directly to the environmental data and therefore examines if bivalve community composition at sampling sites can be explained by differences in the various sediment properties or vegetation cover.

Figure 22 shows the results from the CCA for the sites where sediment grain size data were available. Axis 1 represents the main explainable variation in the bivalve community; this was strongly (long arrows in Figure 22) positively (arrows pointing to the right) correlated with sediment median grain size, sediment medium sand content and RPD depth, and strongly negatively (arrow pointing to the left) correlated with sediment mud content. In comparison, estuarine vegetation and sediment very coarse sand content showed only limited correlation (shorter arrows) to bivalve community composition.

Sampling sites are positioned on the CCA plot (Figure 22) according to their environmental variables. For example, sites on the far right have a high median grain size (near the end of the 'median grain size' arrow) but low mud content (opposite the '% mud' arrow). Sites without letters contained a mixture of two or more of the three species. Sites marked P contained only *Paphies*, sites marked M only *Macomona* and sites marked A only *Austrovenus*.

Axis 1 correlated positively with *Paphies*, and negatively with *Austrovenus* and *Macomona*: sites situated at the higher end of Axis 1 contained predominantly *Paphies*, whereas those at the lower end contained mainly *Austrovenus* and *Macomona*. Axis 2 correlated positively with *Paphies* and *Macomona*, and negatively with *Austrovenus*: sites situated towards the higher end of Axis 2 contained mainly *Macomona*, whereas those situated towards the lower end were dominated by *Austrovenus*; sites with high abundances of both *Austrovenus* and *Macomona* were located midway along Axis 2. Axis 2 was only weakly correlated to the environmental parameters, indicating that the bivalve community composition was likely influenced by environmental variables other than those measured in this study. Not unexpectedly, the analysis shows the 'Mobile sand' sites (green circles on Figure 22) to group towards the high end of Axis 1, correlating with presence of *Paphies*, increasing median grain size, increasing percentage medium (250-500 um) sand, and increasing RPD depth. In contrast, the 'Very soft mud / sand' (black circles) and 'Soft mud / sand' (blue circles) sites group towards the lower end of Axis 1, correlating with higher sediment mud (<63 um) content.

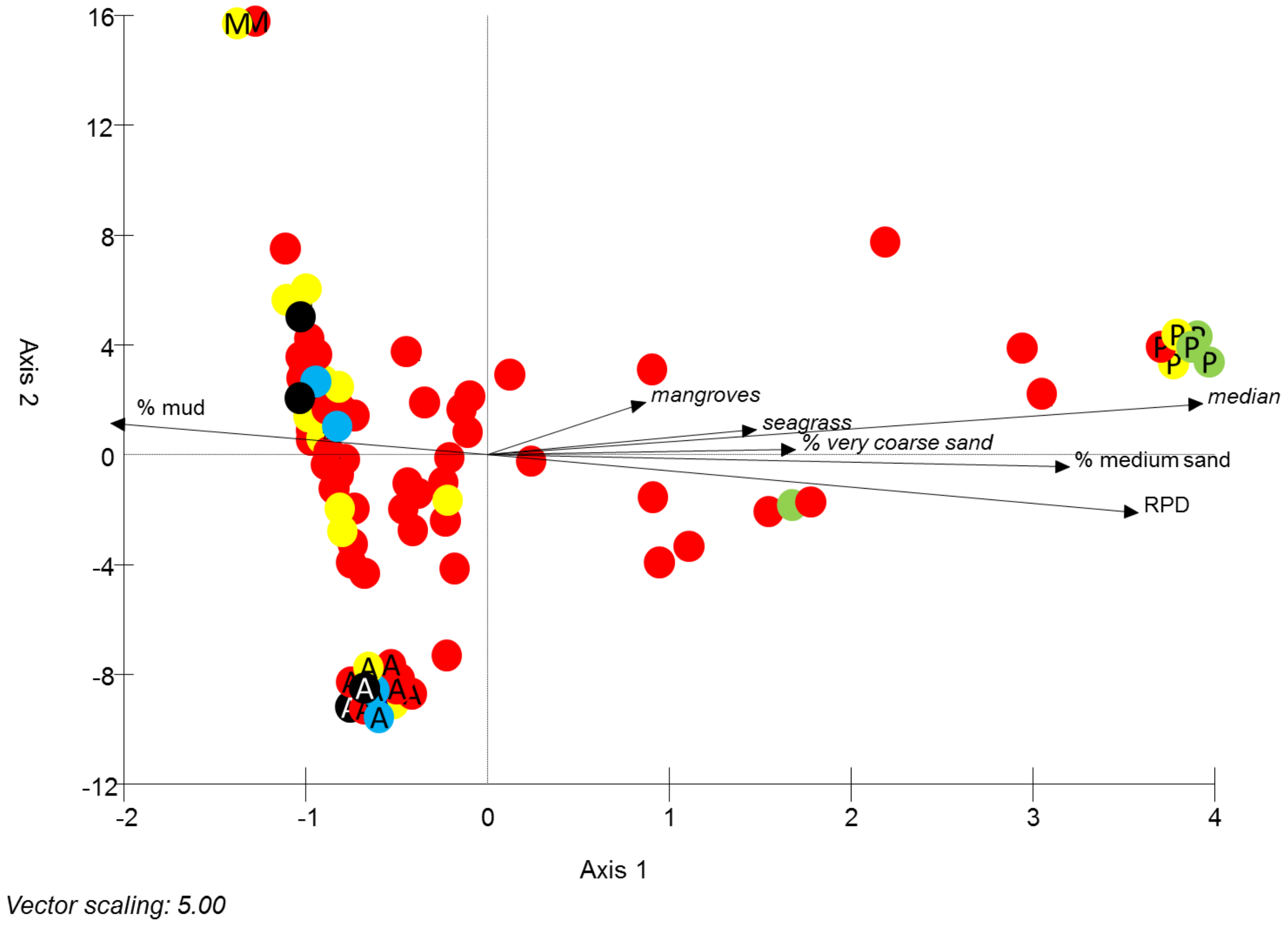

Figure 22: Biplot from canonical correspondence analysis of the bivalve (Austrovenus, Macomona and Paphies) abundance data. Analysis conducted on data from 87 sites (24 out of the 111 sites for which grain size data was available were dropped from analysis because combined abundance of all three species of bivalves was zero). Substrate categories are shown in different colours: VSMS = black; SMS = blue; MS = green; SS = yellow; FS = red. Sites marked P contained only Paphies; sites marked M only Macomona; sites marked A only Austrovenus; all remaining sites contained a mixture of two or more of the three species. Super-imposed on the plot are the vectors for environmental variables: mud = sediments < 63 um; medium sand = sediments 250-500 um; very coarse sand = sediments > 1000 um; median = sediment median grain size; RPD = sediment Redox Potential Discontinuity depth in cm; mangroves = no. of mangrove pneumatophores; seagrass = % seagrass cover. The arrows representing the environmental variables indicate the direction of maximum change of that variable across the diagram; the length of the arrow is proportional to the rate of change, the longer the arrow, the stronger the correlation with the ordination axes (and thus with bivalve community variation shown). Eigenvalues: axis 1 = 0.316, axis 2 = 0.009. Percentage of total variance explained: axis 1 = 42.1; axis 2 = 1.3

3.6 Assessment of sediment contamination

All results of pentachlorophenol and tributyl tin analyses revealed concentrations below the method detection limits. For this reason, results are not reported.

Results for ten trace elements, two of the most important organochlorine pesticides (total DDT and dieldrin), PAHs and sediment organic carbon are shown in Appendix 5. Table A5.1 provides measured trace level and organic compound concentrations. Figure A5.1 shows the likelihood of toxic effects of the measured compounds on aquatic organisms based on the ANZECC interim sediment quality guidelines. All results were well below the ISQG-Low values, indicating low risk on aquatic organisms.

No sediment quality guidelines exist for selenium, thallium and beryllium and therefore these trace elements are not included in Figure A5.1. Selenium could not be detected in the sediment samples. Thallium levels were similar to natural background soil levels (Matthew Taylor, pers. comm.). No local beryllium measurements were available for comparison but values measured in this study are in the range of various geochemical surveys conducted elsewhere and are considered not elevated (Environmental Contaminants Encyclopedia, 1997).

In general, trace elements and organic compounds in the sediments of Tairua Estuary occurred at very low levels. These results demonstrate that the analysed sediments are not contaminated and indicate that trace elements and organic compounds are unlikely to pose a risk to aquatic organisms in Tairua Estuary.

4 Summary and discussion

4.1 Sediments

The sediment grain size data suggests that most sites within Tairua Harbour are sandy, but that within that, great variation in percentage fines and median grain size is found throughout the estuary. The sediment mud content found was similar to that of Otahu Estuary (Singleton & Ross, in prep.) and Raglan Harbour (Felsing & Singleton, 2008).

The substrate classification was developed as part of the community estuaries toolkit ‘Turning the Tide’ published by the New Zealand Landcare Trust. The intention of the classification system is to provide an inexpensive tool that communities can use to classify estuarine sediments, so that they over time can detect whether they are changing, particularly if they are getting muddier, potentially as a result of catchment activities (Robertson & Peters, 2006). The substrate classes are defined by sediment texture, visual properties and a ‘sink-ability’ index. Category descriptions refer to the relative content of sand and mud, indicating that they are meant to represent different grain size distributions. However, it is not clear whether they were ever tested against actual sediment grain size data.

The analyses show the substrate classification to be quite unreliable as a measure of sediment grain size in Tairua Estuary. The only substrate category that separated out from the others in terms of median grain size was ‘Mobile sand’, which was found to be significantly coarser than both ‘Very soft mud / sand’ and ‘Firm sand’. Although they were not distinguishable in terms of median grain size, the muddy categories ‘Very soft mud / sand’ and ‘Soft mud / sand’ did contain significantly higher levels of mud (grain size < 63 um) than other categories, indicating that the presence of mud was recognised in the classification. The comparison with the Shepard sediment classification system shows that all samples were very sandy, even though they clearly appeared to field workers to vary a lot in terms of grain size. This similarity in sediments has likely contributed to the difficulties in separating out the sediment categories. ‘Mobile sand’ was the only substrate category that could be distinguished in terms of sediment Redox Potential Discontinuity layer (RPD) depths, with a statistically significant increase in RPD depth at 'Mobile sand' sites compared to most other sites.

It is possible that the correlation between substrate classes and grain size data could be improved if the classification system was modified. A noticeable difference between the Robertson & Peters (2006) framework and that used in the Waikato Regional Council field sheets (see Appendix 2) was the order of the different substrate classes. In the original reference, the sediments are listed in the order 'Firm mud / sand'; 'Soft mud / sand'; 'Very soft mud / sand'; 'Firm sand'; 'Soft sand'; and 'Mobile sand', likely implying a coarsening of sediments from the first to the last category. In the Waikato Regional Council field sheets, the 'Firm mud / sand' category was omitted, and the order of the remaining categories were 'Very soft mud / sand'; 'Soft mud / sand'; 'Mobile sand'; 'Soft sand'; and 'Firm sand', and the field workers assumed a coarsening of sediments over that order of categories (Nathan Singleton, pers. comm.). Whether the change of order of categories confused the categorisation is difficult to say, but the field workers did find that the easiest category to identify was 'Mobile sand' because of the presence of ripples (Nathan Singleton, pers. comm.). Perhaps not co-incidentally, that was the only category that could be distinguished statistically in terms of median grain size. The generally higher median grain sizes of 'Mobile sand' are probably related to the greater RPD depths recorded at these sites, as coarser sediments generally have deeper RPDs because they have better water circulation and hence better oxygenation.

Rather than just providing an indication of grain size, the substrate categories may indicate a mixture of sediment grain sizes and hydrodynamic environment. The sediments found at a specific site in an estuary represent a mixture of the source of sediment (e.g. the proximity of rivers / streams inputting fine sediments of terrestrial origin, or oceanic sources of coarser sediments) and the hydrodynamics at the site (where faster currents will tend to mobilise coarser sediments, so the finer the sediments the slower the prevailing currents). Because shellfish may be influenced by both, it may still be perfectly valid to use the substrate classification system to categorise shellfish habitats; this is explored further in Section 4.3.

4.2 Bivalve abundances

The density of *Austrovenus* in the densest beds (>3000/m^2) is high, but somewhat lower than the highest densities found in Otahu Estuary also on the Coromandel east coast, where several samples contained about 4500/m^2 (Singleton & Ross, in prep.). In the Department of Conservation surveys of Kawhia and Aotea Harbours on the west coast of the Waikato Region, the highest density of *Austrovenus* enumerated was >30 per quadrat (equivalent to >480/m^2), after which the surveyors stopped counting, and so it is not known how dense the densest beds found there were (Hillock & Rohan, in prep.). From the information available (i.e. samples from grid points), it seems that the size of *Austrovenus* beds are roughly similar in Tairua to Otahu, Kawhia and Aotea – in many cases dense beds extend about 500 or so metres in one direction. However, given the fine scale spatial and temporal variability of bivalve abundances reported for other estuaries in the Waikato Region (e.g. Felsing & Singleton, 2008), it is unlikely that the beds are uniformly dense over such distances.

The spatial distribution of *Macomona* was somewhat more restricted than that of *Austrovenus* in Tairua Estuary, similar to the findings from Otahu Estuary (Singleton & Ross, in prep.), and Kawhia and Aotea (Hillock & Rohan, in prep.). The densities of *Macomona* found in Tairua were similar to those found in both Otahu Estuary (Singleton & Ross, in prep.), and Kawhia and Aotea (Killock & Rohan, in prep.), with few quadrats containing more than 20 individuals (~320/m^2).

The distribution of *Paphies* differed completely from that of *Austrovenus* and *Macomona*. This was expected because *Paphies* prefer higher flow rates and therefore are mainly present in fast flowing channels, of which only some of the edges were sampled in this survey. The distribution (i.e. adjacent to channels) and densities of *Paphies* found in this survey were similar to those found for Otahu Estuary (Singleton & Ross, in prep.). The majority of *Paphies* found in Tairua Estuary were small, in contrast to findings from Otahu Estuary, where medium sized *Paphies* were more common, however, the size categories used in the Otahu survey were different than those used in Tairua, which may account for the differences (the Otahu survey classified shellfish into small: 0-15 mm shell length; medium: 15-30 mm shell length; large: >30 mm shell length). It should be noted that the Tairua survey design was not optimal for the mapping of *Paphies* beds, as such a survey should concentrate on areas adjacent to and within subtidal channels.

The majority of *Austrovenus* found in Tairua Estuary were small (<20 mm shell length), but a lot of sites contained medium (20-30 mm shell length) *Austrovenus* as well. Large (>30 mm shell length) *Austrovenus* were rare, and no sites contained only large individuals. This is similar to Otahu Estuary, where a recent survey found more small *Austrovenus* than medium sized ones, and very few large individuals (Singleton, in press); however, once again direct comparisons are difficult because of the different size classes used for small and medium *Austrovenus*. Similar relative scarcity of large sized *Austrovenus* was presented for Kawhia and Aotea estuaries in Hillock & Rohan (in press). In Otahu Estuary, large *Austrovenus* were mainly found near channels, whereas in Tairua, Kawhia and Aotea, a number of sites supporting large *Austrovenus* were on large intertidal flats, some distance from the main channel.

The scarcity of large *Austrovenus* reported for this and other estuaries (Singleton & Ross, in prep.; Hillock & Rohan, in press) may be because the (relatively coarse grid) sampling missed them. Alternatively, or in addition, it may be caused by selective human harvesting of larger individuals, driving down the average size of the populations, or by other environmental pressures (e.g. runoff of sediments and nutrients from the catchment), which adversely affects *Austrovenus* growth rates. As *Austrovenus* reach maturity at about 18-20 mm shell length, less than 25% of the *Austrovenus* enumerated in the current survey (i.e. medium or large sized *Austrovenus*) were likely to be reproductively active. Areas where only juvenile *Austrovenus* were present may indicate sites of juvenile recruitment, areas where large *Austrovenus* are selectively removed by humans, or a combination of both.

A reasonably high proportion of the population of *Macomona* were medium and large sized individuals, which is similar to the findings from Otahu (Singleton & Ross, in prep.) and Kawhia and Aotea estuaries (Hillock & Rohan, in press). However, note again that both these studies used different size classes for *Macomona*, and that direct comparison of results is therefore difficult. Several sites supported only large *Macomona*, and similar to in Otahu Estuary, large individuals were distributed throughout the estuary.

4.3 Relationship between bivalve presence and abundances and sediments and estuarine vegetation

Despite the limited correlation between the substrate classes and the grain size data, the substrate classes did show some relationship to bivalve abundances. The abundances of *Austrovenus* and *Macomona* were highest in ‘Firm sand’, and the regression tree analyses indicate an interaction effect between sediment RPD depth and substrate type.

Both *Austrovenus* and *Macomona* were most abundant in ‘Firm sand’ sediments with shallow RPD depths. The fact that the abundance of the two species correlate with the same factors fits well with the generally accepted notion that *Austrovenus* and *Macomona* mostly favour the same type of habitat (sandy to muddy sediments). Similar preference for habitat was found in the DoC survey in Aotea Harbour, which recorded higher abundances of both *Austrovenus* and *Macomona* in sandy sediments than in muddy ones (Hillock & Rohan, in press). It is curious that in Tairua the presence of *Austrovenus* could be related to more oxygenated sediments (i.e. those with deeper RPD) than that of *Macomona*, since *Macomona* is thought to be more sensitive to increased sediment mud content than *Austrovenus* (Norkko *et al*., 2001; Thrush *et al*., 2004), and sediment RPD depth generally decreases with mud content. The potential importance of RPD depth is supported by the strong correlation between sediment RPD and ordination axis 1 in the CCA analysis. The results suggest that the general coarsening of sediments associated with deeper RPDs could be equally important in terms of structuring the bivalve community. However, the CCA also shows that the majority of the variation in bivalve community composition at the sites which contain only *Austrovenus* and *Macomona* (i.e. the variation along ordination axis 2) was poorly explained by the environmental variables measured in the study. It is, of course, important to note that patterns revealed by regression tree analyses and CCA provide only an indication of which environmental parameters may be important in contributing to the biological pattern, rather than prove cause-and-effect. A number of potentially important variables structuring bivalve communities were not measured in this study, including current velocities during times of submersion, degree of tidal inundation at site, water turbidity, competition from other species, recruitment preferences of individual species, predation by fish, invertebrates, birds and humans, and sediment pollution by e.g. heavy metals.

Paphies abundances were highest in the substrate category ‘Mobile sand’, which makes sense since *Paphies* are known to prefer fast-flowing waters, and ‘Mobile sands’ were related to higher median grain sizes and therefore likely higher flow rates. This is in agreement with the CCA results, which show a trend of higher probability of presence of *Paphies* in coarser sediments with very low mud contents. The preference of *Paphies* for areas of low turbidity and sediments with low mud content is well documented (e.g. Norkko *et al*., 2001; Thrush *et al*., 2004).

Limited relationship was found between estuarine vegetation (percentage seagrass cover, and number of mangrove pneumatophores) and bivalve presence / absence or abundances. This is in contrast to the findings from Aotea and Kawhia Harbours, where a positive interaction between sediment type and seagrass presence was found to correlate with *Austrovenus* presence (Hillock & Rohan, in press).

4.4 Evaluation of habitat mapping and suggestions for improvement of methods

4.4.1 Bivalves

The estuary habitat mapping proved successful in mapping abundances of bivalves and estuary vegetation in Tairua Harbour. Although the exact spatial extent of bivalve and seagrass beds were not mapped, the sampling at 150 m grid points provides adequate information to produce rough maps of abundances of *Austrovenus*, *Macomona* and *Paphies*, as well as seagrass. The maps indicate that *Austrovenus* and *Macomona* are relatively abundant, and widely distributed in the estuary.

For *Paphies*, the mapping is somewhat incomplete, as *Paphies* are known to prefer channel habitats. However, the maps of *Paphies* abundance show where subtidal beds are likely to be present (i.e. in the channel next to intertidal areas of high abundance). If more detailed information is required about any particular potential *Paphies* bed in Tairua, the information presented in this report is likely to make more detailed surveys easier. In future surveys, for a more complete map of *Paphies* beds, sampling should include the edges on both sides of subtidal channels (e.g. at sites 150 m apart).

In the past, concern has been raised that bivalve (including *Austrovenus*, *Macomona* and *Paphies*) abundances are declining within the Hauraki Gulf. These concerns were addressed in a comprehensive report of the available data on changes in bivalve abundances over time which was published in 2003 (Grant & Hay, 2003). The report concluded that at the few sites where bivalve abundances had been robustly monitored over time, there was evidence of decline in abundances. However, at the time there was insufficient information to assess whether these results could be generalised to the entire Hauraki Gulf. As a result, the authors recommended that efforts to survey bivalve beds be increased, to establish whether declines in abundances were widespread and continuing.

Mapping of bivalve beds potentially provide an important tool for addressing this issue. Initial maps provide inventories of resources, and repeat surveys (of entire estuaries, or selected areas of high bivalve abundances) could provide information on general trends in bivalve abundances, as well as important information relating to temporal variability at individual sites. Other estuarine surveys (e.g. Gibberd, 2010; Felsing & Singleton, 2008) show that temporal variability in *Austrovenus* and *Macomona* abundances within individual monitoring sites can be very large (e.g. at one 100 m * 100 m site in the Firth of Thames, average (of 12 cores) *Austrovenus* abundances varied between less than 5 and 115 individuals over the course of five years, mainly due to periodic influxes of large numbers of juveniles). Given this variability within individual sites and the limited quantitative information available on pressures related to human activities, repeat mapping of large areas is currently one of the most accurate methods to estimate overall trends in total bivalve populations within an estuary.

Because of its widespread distribution and high abundance in New Zealand estuaries, *Austrovenus* is thought to provide important ecosystem services. Aside from their value as a food resource, and their bioturbation-mediated role in nutrient recycling, suspension feeders such as *Austrovenus* filter sediments, phytoplankton and other suspended particulates from the water column (Townsend *et al*., 2009), and as a result increase water clarity. It has been estimated that *Austrovenus* filters about 0.3 l h^{-1} per animal (Jones et al., 2011; McClatchie, 1992; H. Jones, pers. comm.). If it is assumed that filtration occurs at approximately one and a half hours either side of high tide (H. Jones, pers. comm.), the estimated total population of *Austrovenus* within Tairua Harbour of 828 million individuals will filter close to three quarters of a million cubic metres of water every tidal cycle. This represents 5.5 per cent of the total volume of water in the estuary at high tide or close to 10 per cent of the spring tidal prism, i.e. the volume of water entering the estuary on an incoming spring tide. Whilst obviously imprecise in nature because of the limited information that it is based on, this estimate nevertheless indicates the potential importance of filter feeding by *Austrovenus* on the water quality of the estuary.

Given this potential ecological importance, estuary wide declines in distribution and abundance of *Austrovenus* could have important consequences for estuarine function, as well as on parameters such as water quality which is highly valued by humans. Although mapping of bivalve beds is resource intensive, it provides one of only few methods to estimate total bivalve populations within an estuary, and as such may be an important tool to use for estuaries where bivalves are thought to be of particular importance (e.g. where high numbers are known to exist, or where they are of special importance to e.g. humans or bird populations), and / or where there is concern that anthropogenic factors, such as sediment or nutrient inputs from the catchment, may adversely affect bivalve populations.

Maps of bivalve beds will also potentially aid decision-making for resource use consents. For example, if an application for consent to carry out an activity that might adversely affect bivalve beds at some location in the estuary is lodged (e.g. dredging through a bed, construction of a marina nearby, etc.), the likelihood and potential severity of impact on the bivalve populations of the estuary can be estimated based on the relative proximity of the activity to beds of high abundance. If a bivalve bed is likely to be adversely affected by developments or activities, the percentage of the total area of bivalve beds that the affected area constitutes can now be estimated for the first time, providing an important indication of severity of impact. The rough maps of bivalve beds presented in this report can be refined if needs be, by resampling areas of high abundance, or areas thought to be important for e.g. juveniles.

Although correlations between bivalve abundances and environmental factors were found to be limited in this study, it would be interesting to explore whether similar correlations exist in other estuaries. If they did, it is possible that predictive models of bivalve presence or abundance based on environmental data could be developed which may allow more targeted sampling when bivalve beds are mapped.

Bivalve biomass is likely to be a better indicator of the functionality (e.g. as a food resource, or in terms of filtering capacity) of bivalve populations than just abundances, and as such it is likely worthwhile estimating bivalve biomass in estuaries where habitat mapping is carried out. Biomass can be estimated from shell length (Carolyn Lundquist, NIWA, pers. comm.), but for estimates to be reasonably accurate, exact shell lengths or smaller size categories need to be recorded rather than abundances of bivalves in only three size categories. In the present survey, the exact length of each bivalve was measured in order to assign it to the appropriate size category; however, only abundances per size category were recorded. Recording the measured length of each bivalve would not take much longer than assigning it to a size category and recording the result, and so it is recommended that exact shell lengths of bivalves be recorded in future surveys, and that the spatial distribution of biomass of the bivalve species be explored in future reports.

4.4.2 Vegetation

Mapping of vegetation within Waikato estuaries is already carried out as part of a separate Waikato Regional Council project, the Estuarine Vegetation Mapping project. This project generates more detailed presence / absence maps of estuarine vegetation than that provided by this survey (for the vegetation mapping, the exact extent of patches of vegetation is mapped by a fieldworker walking the perimeter of the patch, logging it onto a handheld GPS), but not data on the density, or percentage cover, of vegetation. In the current project, both type and density of vegetation was reported in case this could be related to bivalve presence or abundances. Because *Austrovenus* abundance is known to be correlated to the presence of seagrass (Alfaro, 2006), future habitat mapping exercises should continue to record information on estuarine vegetation. Although quite different techniques are used, it is possible that cost savings can be made by combining habitat and vegetation mapping projects, to avoid carrying out two separate field-work intensive exercises in the same estuary.

4.4.3 Sediments

Sediment grain size is an important parameter known to shape intertidal communities, and the CCA analyses suggest that bivalve community composition correlates with sediment grain size. In addition, because estuaries are vulnerable to adverse effects resulting from terrigenous sediment runoff, maps of sediment grain size would provide useful state of the environment information for estuaries, particularly if they could be repeated and changes in sediments (such as increase in percentage mud) could be detected over time. However, grain size analysis is expensive, and the use of proxies for grain size data in future surveys could provide cost savings.

In this regard, efforts should be made to either improve the substrate categories used in this survey or to develop a new classification system to better represent sediment grain size distribution.

In terms of the substrate categories used in this survey, the main aspects to consider for future surveys are:

- The category ‘Mobile sand’ was the one that the field workers found easiest to recognise. This is doubtless because of the presence of ripples, making assessment of this category less subjective than decisions about the relative ‘sinkability’ (which would vary with weight and shoe size of field worker).

- The ‘Mobile sand’ category was also the one that best related to a discrete range of median grain size, and sediment RPD depths. As this category also correlated with presence / absence of *Paphies*, it should be retained.
- The two mud categories (‘Very soft mud / sand’ and ‘Soft mud / sand’) contained significantly higher levels of mud than the sandy categories, suggesting that field workers were able to recognise the presence of mud. However, in terms of grain size these two categories were indistinguishable from one another, indicating that they could potentially be combined to form one ‘Soft mud / sand’ category.
- The ‘Firm sand’ category was the most commonly recorded category in Tairua Estuary. This category correlated with abundance of *Austrovenus* and *Macomona*, and so should probably be retained. However, ‘Firm sand’ encompassed a great variety of grain sizes, and the statistical analysis showed it to be indistinguishable from ‘Soft sand’ in terms of grain size. The ‘Firm sand’ and ‘Soft sand’ categories could be combined, however they were the two most common substrate categories, and a combined category would encompass 225 of the 275 sites (82%) in Tairua Estuary, making it rather broad (which is not necessarily a problem, if this reflects the substrate type accurately).
- Thus, it is recommended that substrate mapping used in future habitat mapping exercises should either be modified to contain fewer, more meaningful (in terms of grain size) categories, e.g. ‘Mud / sand’ (any substrate containing mud); ‘Mobile sand’ (ripples present) and ‘Other sand’ (any sandy substrate with no ripples), or improved so individual categories correspond better to discrete grain sizes (suggestions for how to achieve this are outlined below).

An example of a substrate classification system potentially better related to sediment grain size parameters has been used by the Department of Conservation in their surveys of Aotea and Kawhia Harbours (Hillock & Rohan, in press). Their system recognises the following categories:

- Mud (no grains of sand)
- Sandy mud (more mud than sand present)
- Muddy sand (more sand than mud present)
- Sand (no mud present)
- Gravel / cobbles
- Rock platform

Here, the first four categories were identified by rubbing the sediment between fingers. However, this classification system was not tested against grain size data, and there is therefore not known if it would perform any better than that used in Tairua.

Other substrate classification systems undoubtedly exist (e.g. in the NIWA estuary toolkit, Ngā Waihotanga Iho). This survey has illustrated the importance of trialling and verifying the chosen substrate classification system prior to conducting substrate mapping surveys to ensure that (1) field workers classify substrates reliably and (2) the system meets the objectives of the survey (e.g. to represent grain size distribution).

In Tairua, the approximate RPD depth was found to correlate with *Austrovenus* and *Macomona* presence. If an undisturbed face of sediment is used to record the RPD depth, the quality of data obtained should be good, and given its correlation to presence and abundance of bivalves, this parameter should definitely be retained in future surveys.

The substrate classification system could potentially be improved by implementing one or more of the following practical changes:

- Including the ‘Firm mud / sand’ category originally present in the classification, and, in information provided to field workers, re-arranging the order of substrate categories so that they read in order from finest to coarsest sediment;

- Improved training of field workers on how to recognise different substrate categories;
- Cross-validation of results from individual and different field workers, to maximise consistency;
- Portable examples of the different substrate types that field workers could use for comparison.

However, it is important to note that even if substrate categories were developed which could be accurately assigned and independently verified by fieldworkers, such subjective measures of substrate are of limited value if they don’t correlate with grain size data or some other ecological indicator, because we won’t know what they mean. In order to aid interpretation, it is therefore essential that any modified substrate classification system is validated prior to use.

4.5 Assessment of sediment contamination

Trace elements and organic compounds occurred at very low levels, ranging between non-detectable concentrations to 63 per cent of the low ANZECC interim sediment quality guideline value (ISQG-Low). At such low levels the likelihood of toxic effects on aquatic organisms is very low.

However, in this survey only the top 2 cm of the sediment was sampled. It is possible that trace element and organic compound levels are greater in deeper sediment layers. This is particularly relevant at locations where concentrations might have been elevated because of past human activities. In these instances, sediments containing elevated historic concentrations of trace elements and/or organic compounds might have been covered by more recent sediment.

The sites included in the sediment contamination assessment covered a large area of Tairua Estuary. However, it is still possible that there are areas of localised contamination that have been missed in this study.

5 Conclusion

The Tairua habitat mapping proved successful in generating rough maps (grid points 150 m apart) of the distribution and abundances of three species of bivalves (cockles, *Austrovenus stutchburyi*; wedge shells, *Macomona liliana*; and pipi, *Paphies australis*), sediment type, and type and extent of cover of estuarine vegetation.

Bivalves are known to provide important ecosystem services. They are important as food for fish, birds, invertebrates and humans, their bioturbation increases nutrient recycling, and as suspension feeders they filter large quantities of water, improving water quality. Although generally resilient, bivalves are vulnerable to impacts arising from human activity, including runoff of terrestrial sediments and nutrients, habitat modification, and effects from fishing. Given their ecological importance, estuary wide declines in distribution and abundance of *Austrovenus* could have important consequences for estuarine function.

Maps of the distribution and abundance of bivalves form an important tool for the management of these important resources. Initial maps provide an inventory of resources that will help identify estuaries, and areas within estuaries, of particular significance to bivalves. Repeat mapping (of entire estuaries, or selected areas therein) has the potential to generate important information on estuary-wide trends in bivalve abundances.

Two measures of sediment types were mapped in this study. A subjective substrate classification system was used to classify sediments into qualitative types, and samples for grain size analysis were collected as well. Limited correlation was found between the two methods, which demonstrates that the subjective substrate classification system is not a good proxy for grain size distribution.

The habitat mapping methodology could be improved as follows:

- Before it is used in further habitat mapping, the subjective substrate classification should be improved. Detailed suggestions for how to improve it are provided in Section 4.5.3.
- To enable bivalve biomass estimates, it is recommended that accurate shell length data be recorded.
- To provide a better map of *Paphies* beds, it is recommended that sampling points be located every 150 m either side of main subtidal channels.

Because it is so labour intensive, habitat mapping may not be feasible to carry out for all the estuaries in the Waikato Region. However, because of the ecological and cultural significance of bivalve species such as *Austrovenus*, *Macomona* and *Paphies*, mapping of bivalve populations is an important tool to use for estuaries where bivalves are thought to be of particular importance (e.g. where high numbers are known to exist, or where they are of special importance to e.g. humans, or bird populations), and / or where there is concern that anthropogenic factors, such as sediment or nutrient inputs from the catchment, may adversely affect bivalve populations. Repeat surveys in vulnerable estuaries would provide important information on estuary-wide trends in bivalve distribution and abundance, which could be used in state of the environment reporting and evaluations of the efficiency of policy.

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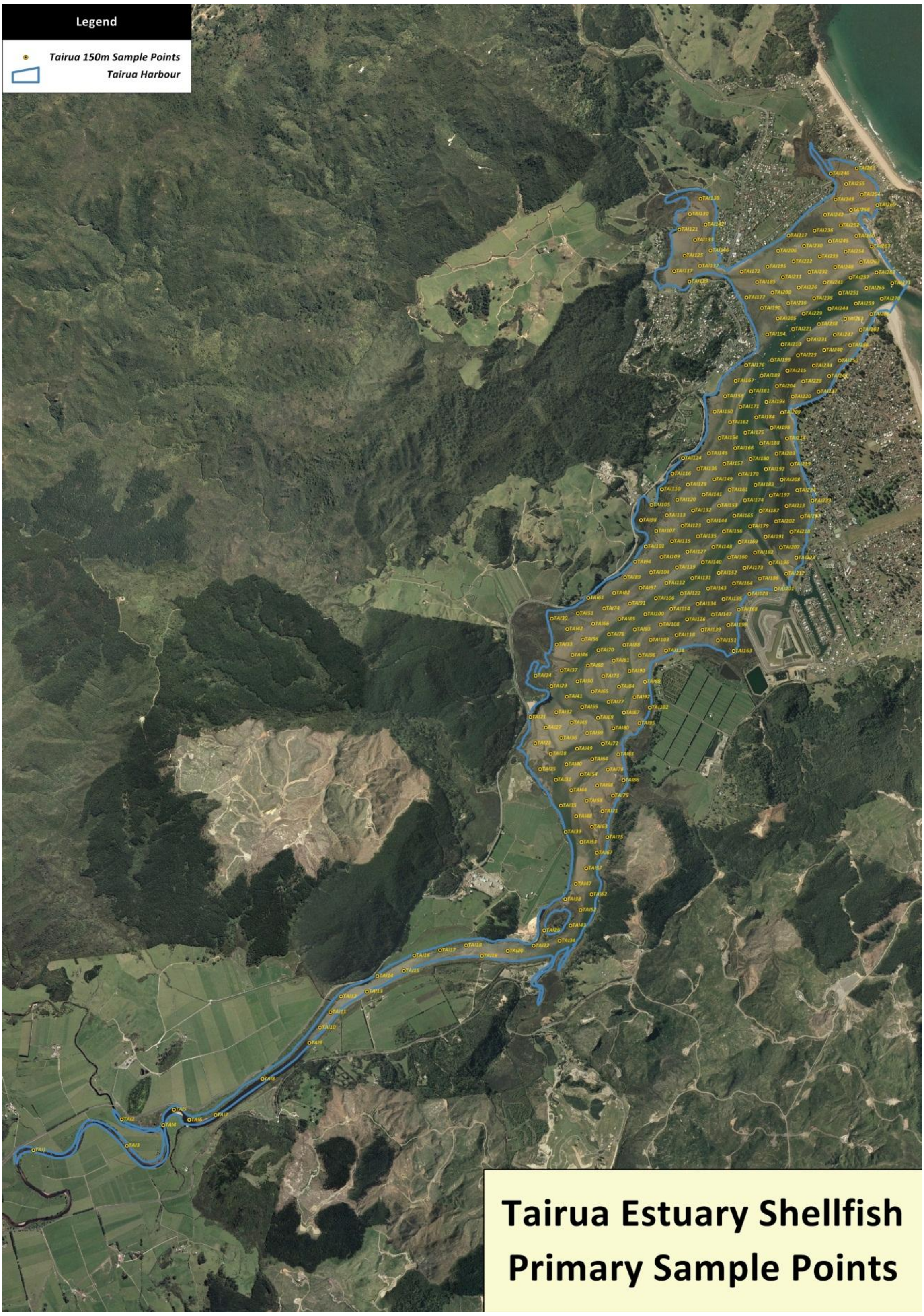
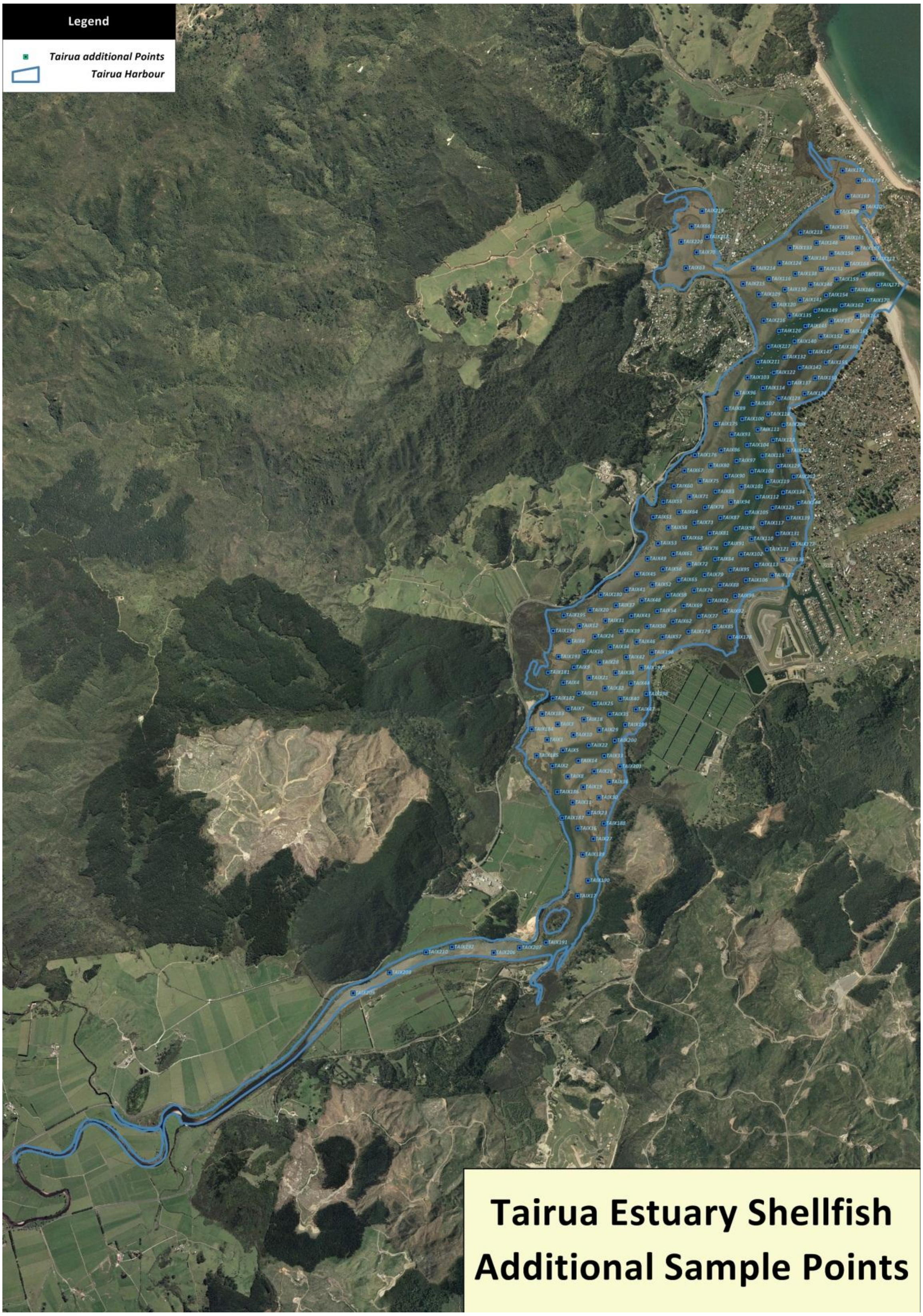
Appendix 1 – Sample point maps





Tairua Estuary Shellfish Additional Sample Points

Appendix 2 – Field sampling sheet

Date:	Location:	Observers:
Low tide time:	Low tide (m):	

SITE	Time (NZST)	Sediment	Vegetation (% cover)	RPD depth	Cockle 0-20	Cockle 20-30	Cockle 30+	Pipi 0-20	Pipi 20-40	Pipi 40+	Maco 0-20	Maco 20-30	Maco 30+	Cominella	Zeacum	Diloma	Other species

Appendix 3 – Wentworth sediment classification

Millimeters (mm)	Micrometers (µm)	Wentworth size class		Phi (Φ)
256 to 4096	>256000	Boulder	Gravel	-12 to -8
>64	>64000	Cobble		<-6
>4	>4000	Pebble		<-2
>2	>2000	Granule		<-1
>1	>1000	Very coarse sand	Sand	<0
>1/2	>500	Coarse sand		<1
>1/4	>250	Medium sand		<2
>1/8	>125	Fine sand		<3
>1/16	>63	Very fine sand		<4
>1/32	>31	Coarse silt	Mud	<5
>1/64	>15.6	Medium silt		<6
>1/128	>7.8	Fine silt		<7
>1/256	>3.9	Very fine silt		<8
<1/256	<3.9	Clay		>8

Appendix 4 – Statistical analyses used to compare substrate categories and sediment grain size

This appendix contains the results of statistical analyses conducted to examine correlations between the substrate categories and sediment grain size.

The outcomes from Kruskal-Wallis rank sum tests for grain size differences among different substrate categories are shown in Table A4.1. This analysis reveals that grain sizes are significantly different among substrate categories. Figure A4.1 illustrates the results from post hoc analyses in the form of boxplots of the data.

As can be seen in Figure A4.1 most of the substrate categories were associated with a wide range of different sediment grain sizes. A difference in grain size between the ‘Very soft mud / sand’, ‘Soft mud / sand’ and ‘Mobile sand’ categories was detected, with a general decrease in the amount of fine sediments over the three categories, and an increase in the amount of coarse sediments. However these differences were not always statistically significant, and the median grain sizes of the ‘Very soft mud / sand’ and ‘Soft mud / sand’ were not significantly different. As expected, the ‘Very soft mud / sand’ and ‘Soft mud / sand’ categories contained significantly more mud (sediment <63 um) than the other substrate categories. The ‘Soft sand’ and ‘Firm sand’ categories were very similar in terms of grain size, and apart from the mud content, there were no significant differences between the ‘Very soft mud / sand’ category and the ‘Soft sand’ and ‘Firm sand’ categories, indeed the three categories had very similar median grain sizes. The coarsest substrate category was ‘Mobile sand’, which had the highest median grain size, very low levels of mud, and high levels of medium and coarse sand.

An alternative way of reducing the grain size analysis data to a single measure for comparison to the descriptive categories is to fit it into a descriptive framework. Shepard (1954) devised a ternary classification system for sediment samples which comprises ten classes (shown in Appendix 5). When classified according to this system, all but four of the sediment samples classified as 'sand' (containing more than 75% sand). Of the remainder, three classified as ‘silty sands’, and one as ‘clayey silt’. The relative proportion of each of the substrate categories corresponding to the Shepard categories can be seen in Figure A4.2.

Figure A4.2 shows the degree of overlap of the substrate categories. ‘Firm sand’ and ‘Mobile sand’ were exclusively used for sandy sediments, whereas the categories ‘Very soft mud / sand’, ‘Soft mud / sand’ and ‘Soft sand’ were used for Shepard classification ‘sand’, as well as ‘silty sand’ or ‘clayey silt’.

Table A4.1: Results from Kruskal-Wallis tests for grain size differences between the different substrate categories VSMS, SMS, MS, SS, FS (for definition of substrate categories, see Table 1 and Figure 2 caption).

Grain size category	Kruskal-Wallis chi-squared	p
Mud (<63 um)	32.8687	<0.001
Fine sand (63-250 um)	12.6921	0.013
Medium sand (250-500 um)	18.7481	<0.001
Coarse sand (500-1000 um)	9.9675	0.041
Very coarse sand (>1000 um)	12.0389	0.017
Median grain size	13.5853	0.009

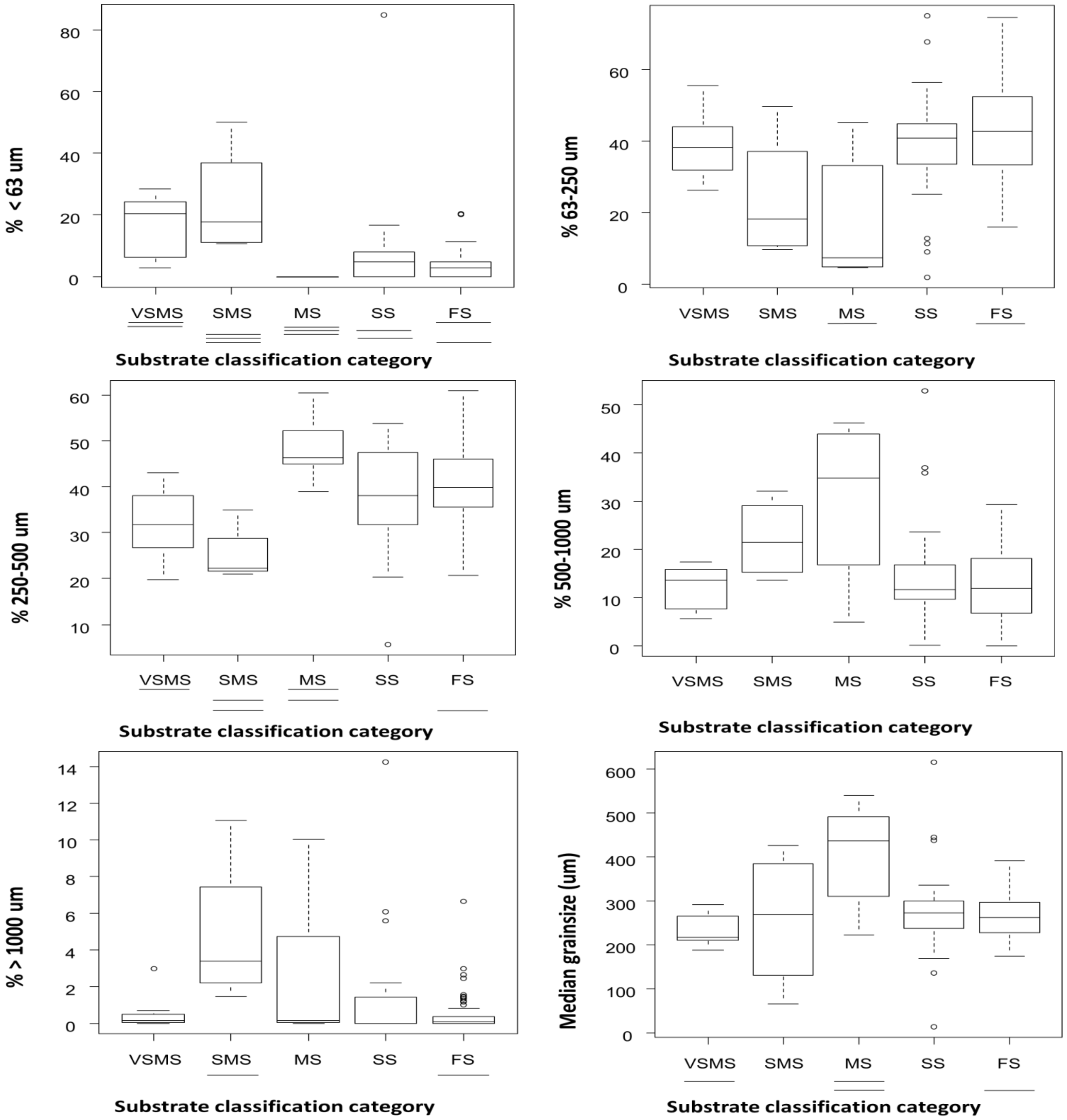


Figure A4.1: **Boxplots[5] showing sediment grain size characteristics for different substrate categories: FS = Firm sand; MS = Mobile sand; SMS = Soft mud / sand; SS = Soft sand; VSMS = Very soft mud / sand. Statistically significant differences between substrate categories are denoted by solid lines under substrate categories. . Lines at identical heights indicate that categories are different.**

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[5] Boxplots: Lower and upper hinges represent 25th and 75th percentiles, respectively; the line across the box denotes the median; the ends of the vertical lines indicate the minimum and maximum data values, unless outliers are present in which case the whiskers extend to a maximum of 1.5 times the inter-quartile range; the points outside the ends of the whiskers are outliers or suspected outliers.

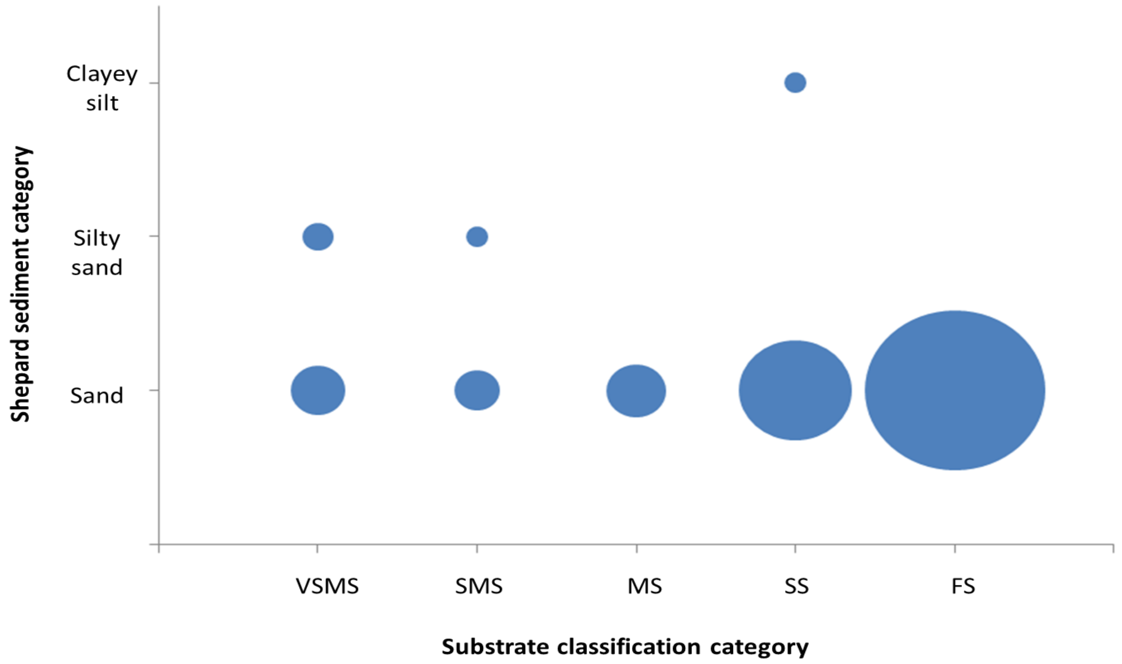
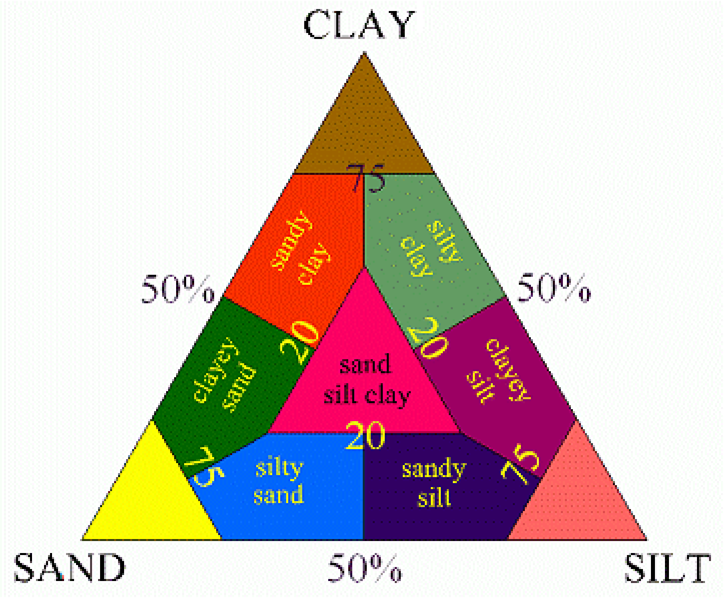


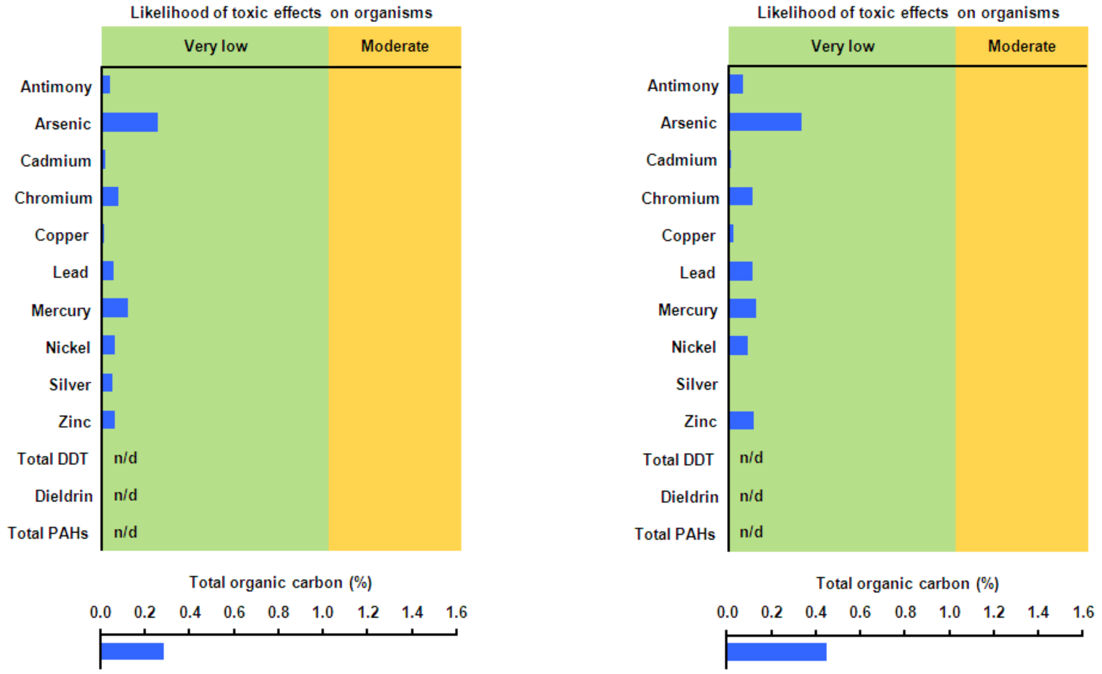
Figure A4.2: Bubble diagram of sediment category according to Shepard's classification system (Shepard, 1954) versus the descriptive substrate category of Robertson & Peters (2006). Size of bubble is proportional to the number of sites corresponding to the sediment categories (N=111).

Appendix 5 – Shepard's diagram for sediment classification

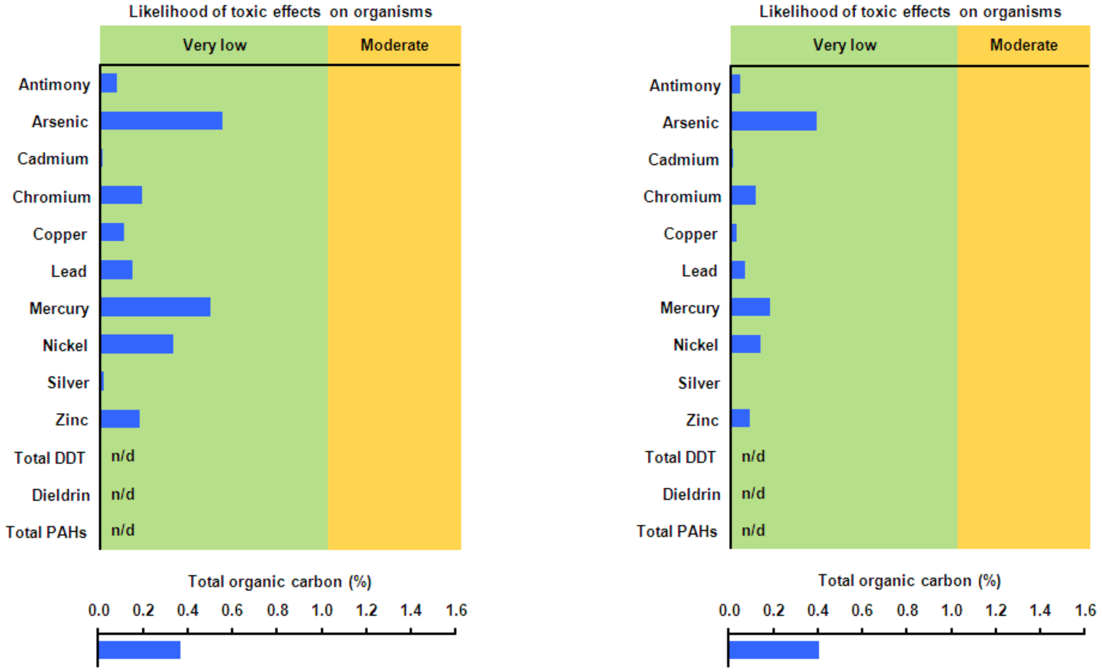


Appendix 6 – Trace elements and organic compounds

Figure A6.1: Likelihood of toxic effects of trace elements and organic compounds on aquatic organisms. Site locations are shown in Figure 2. n/d = not detected (below detection limit), n/s = not sampled.


Site 1

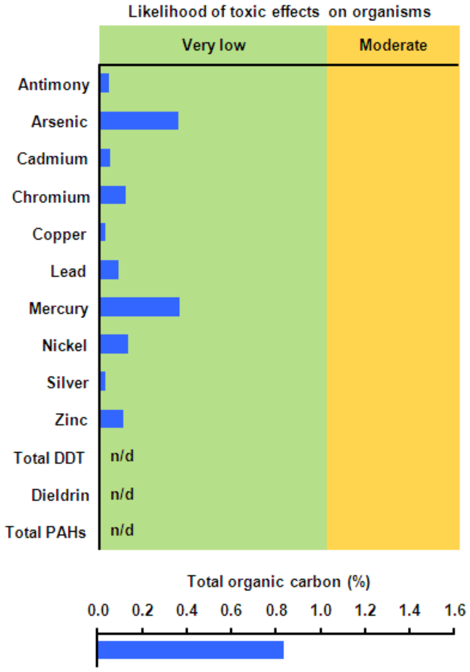
Site 2


Site 3

Site 4

Figure A6.1 continued

Site 5



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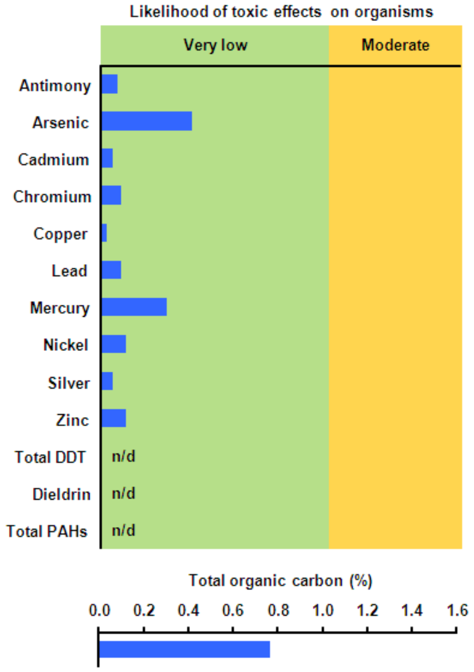

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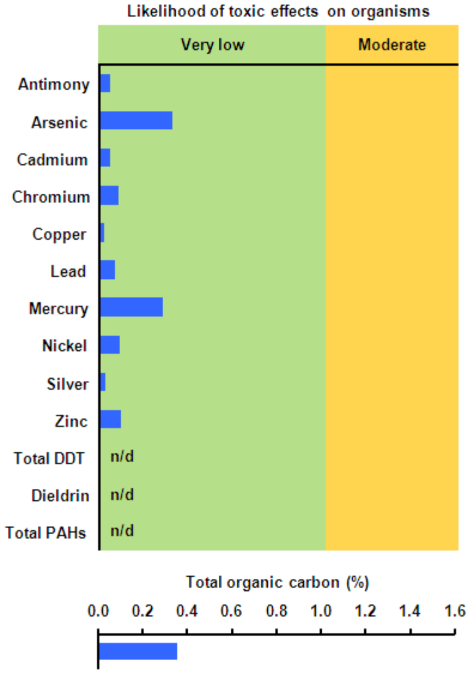

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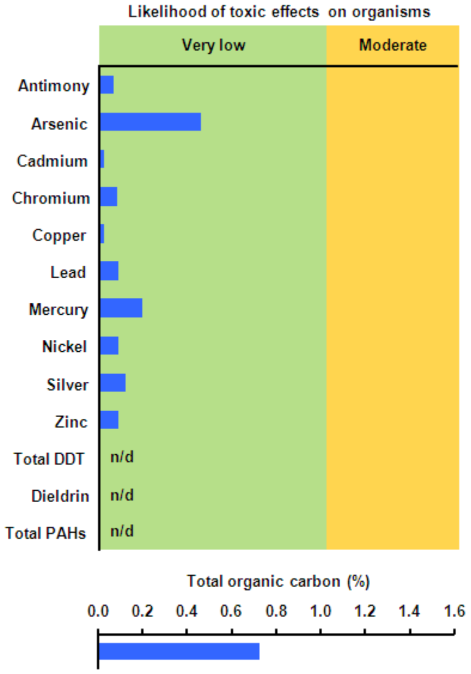

Figure A6.1 continued

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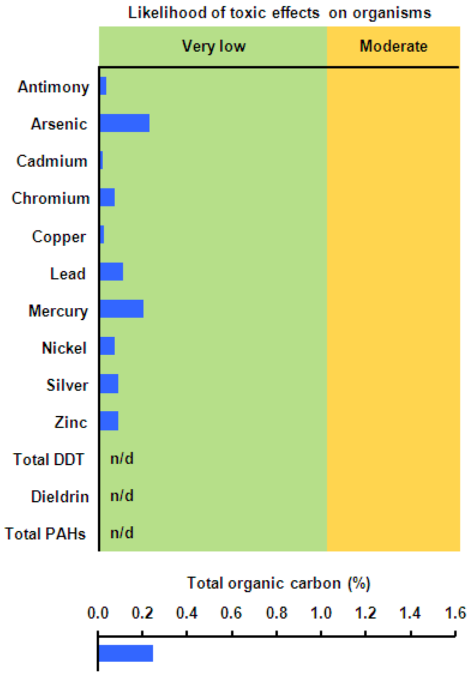

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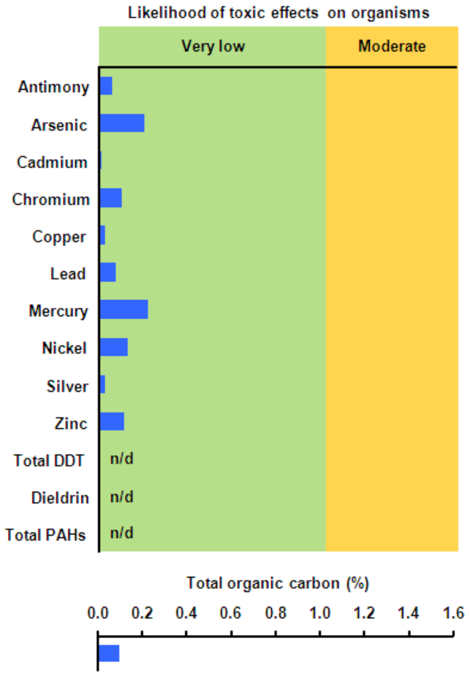

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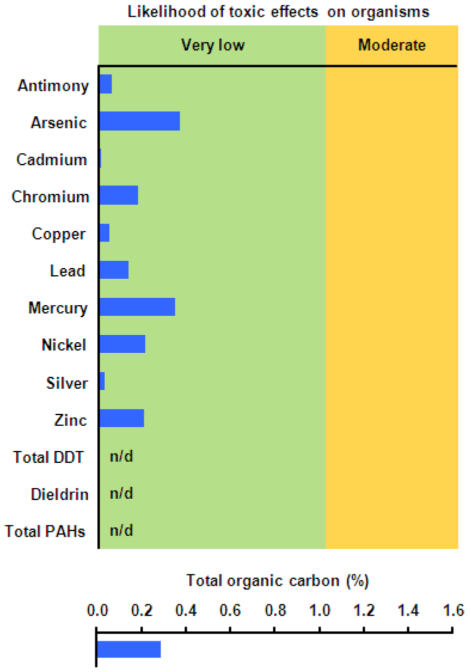

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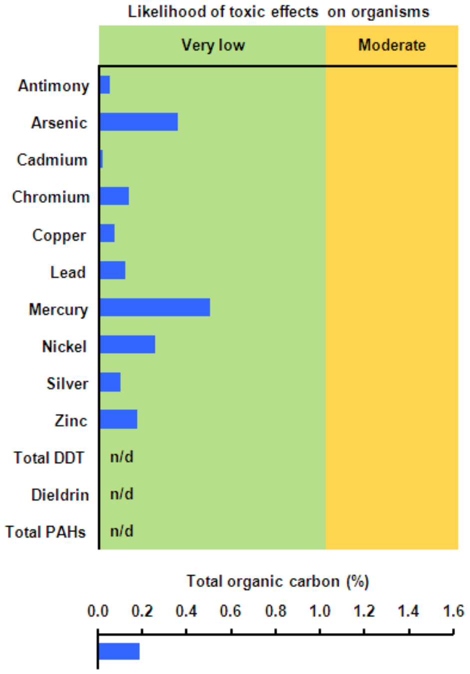

Figure A6.1 continued

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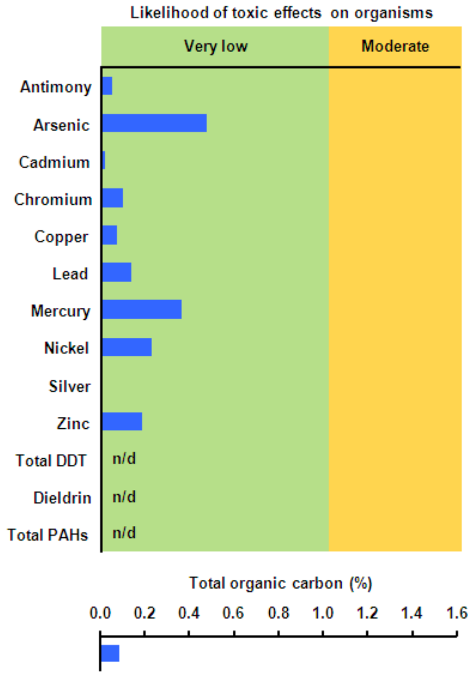

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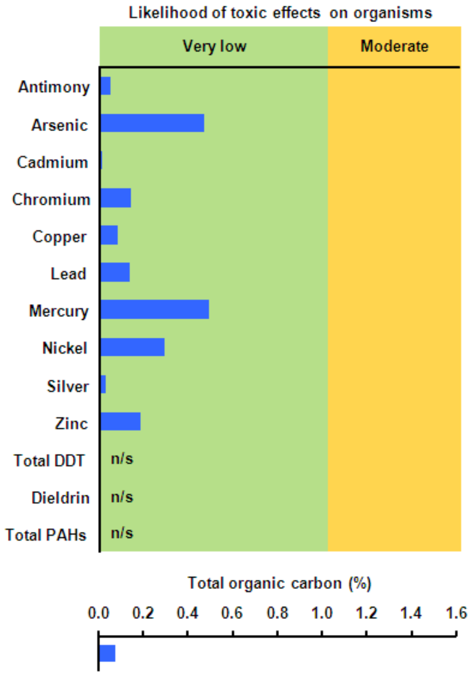

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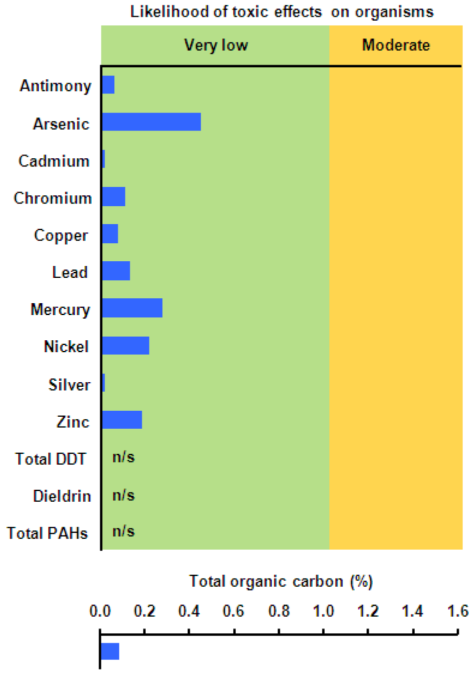

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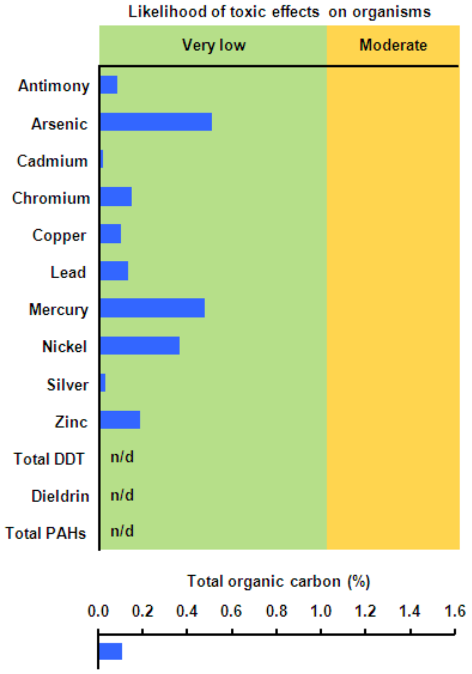

Figure A6.1 continued

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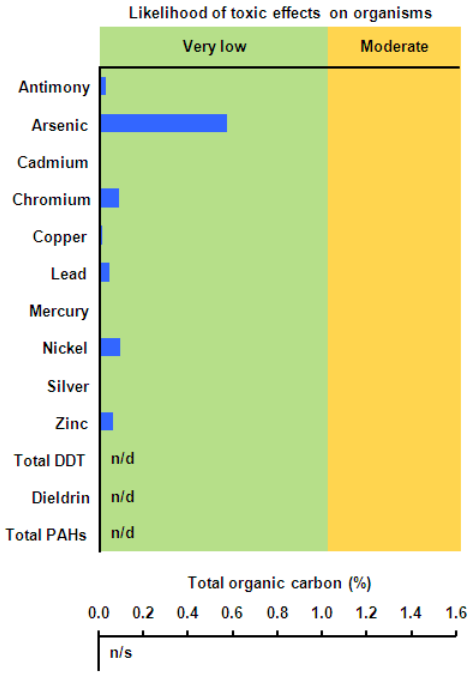

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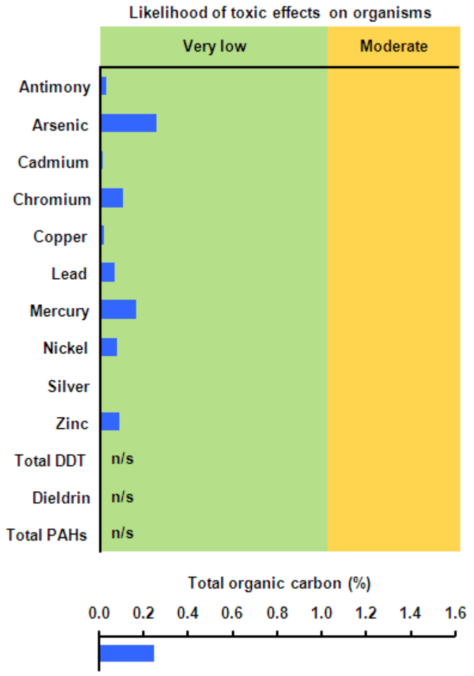

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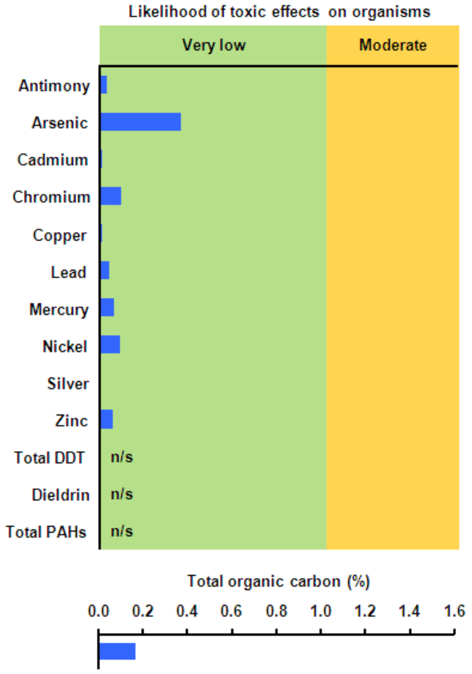

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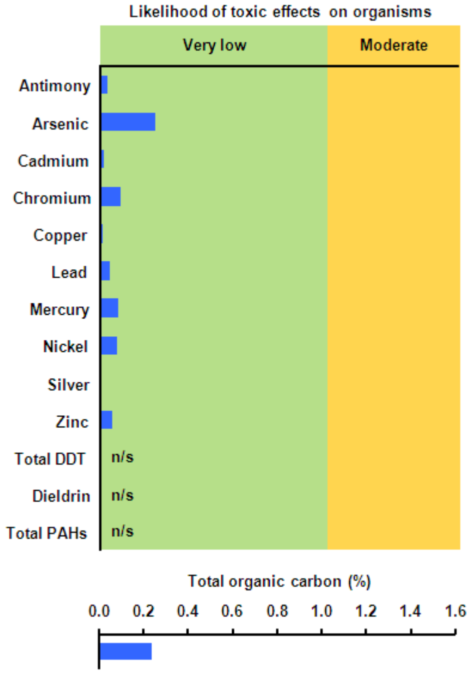

Figure A6.1 continued

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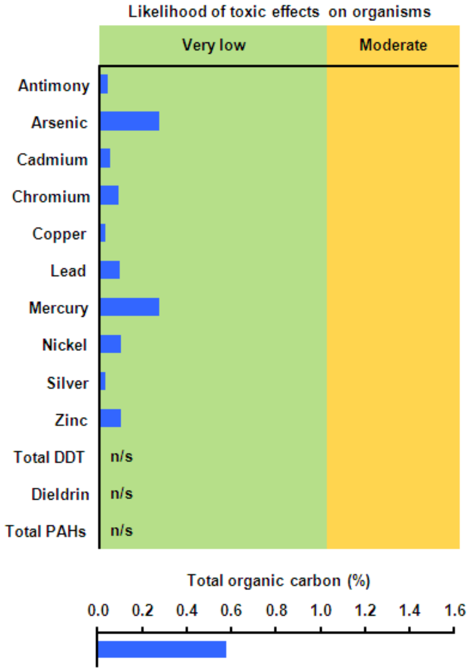

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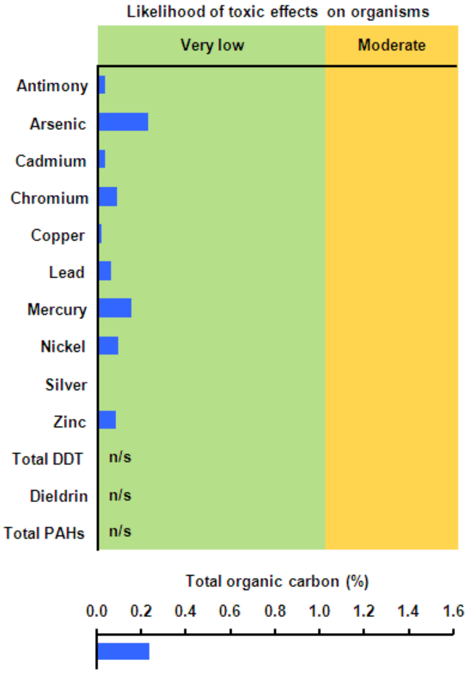

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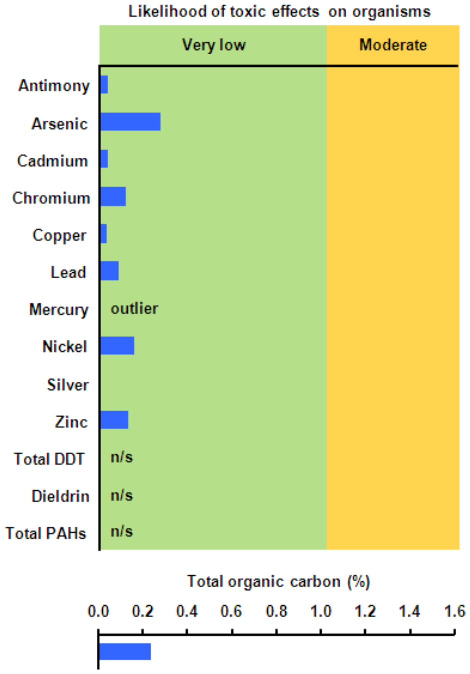

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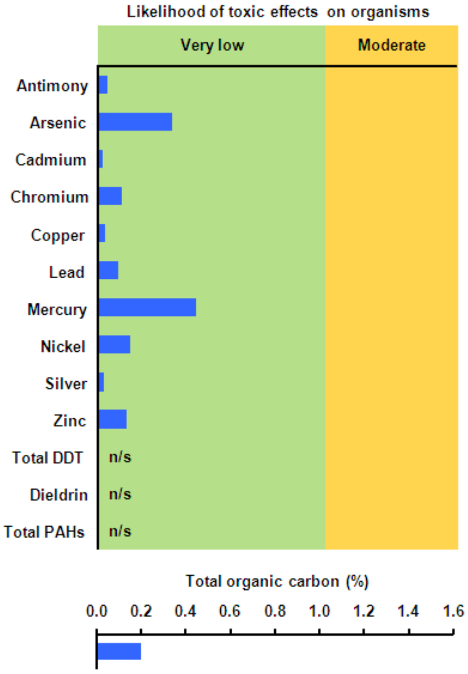

Figure A6.1 continued

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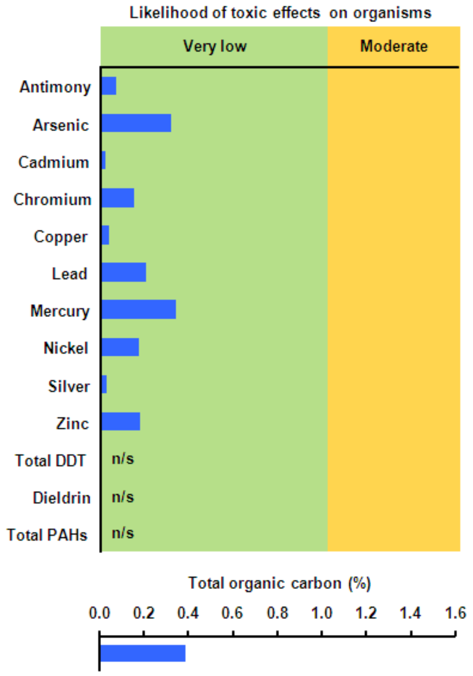

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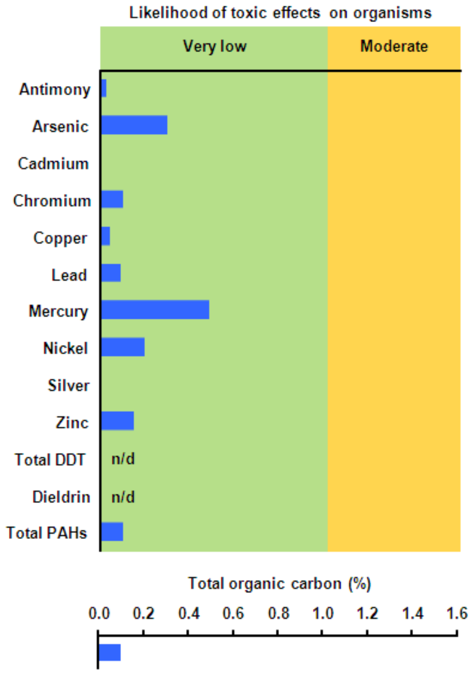

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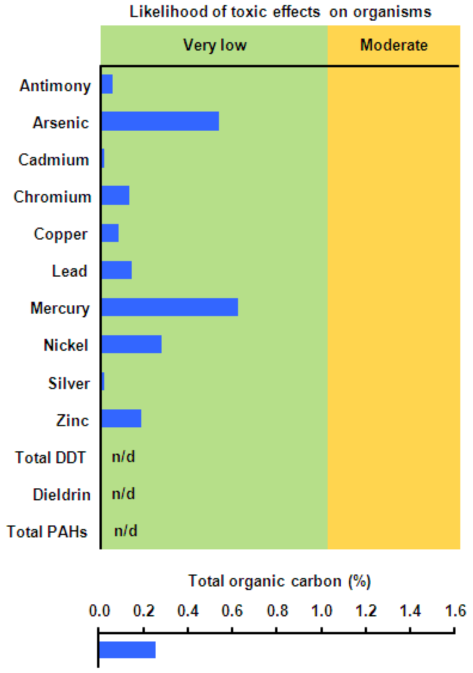

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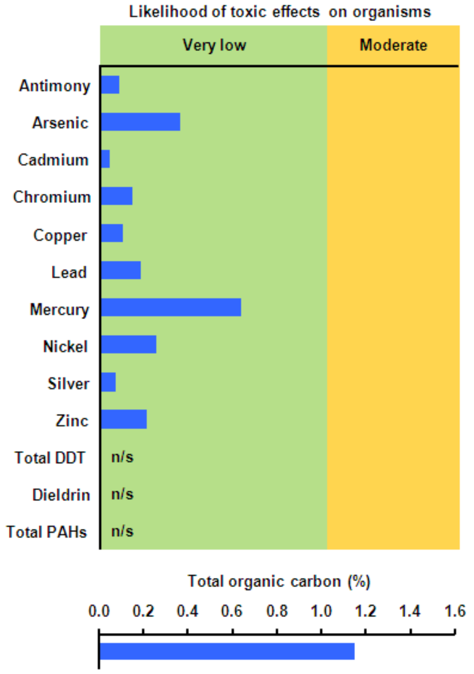

Figure A6.1 continued

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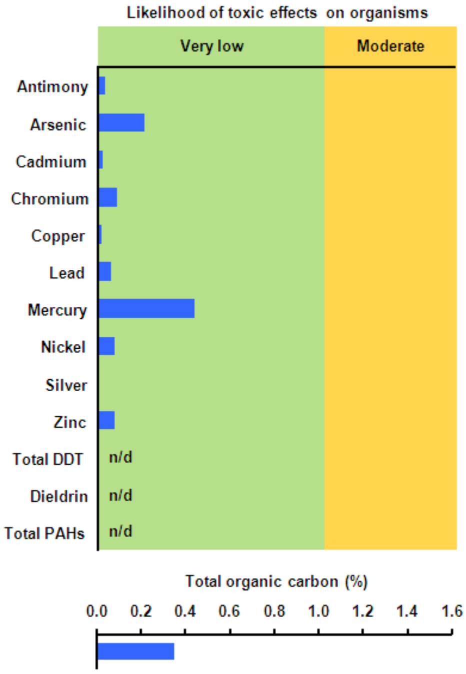

Table A6.1. Results of trace element and organic compound analyses. Site locations are shown in Figure 2. ND = not detected (below detection limit), blank cells = not sampled. No ISQG values exist for beryllium, selenium and thallium.

				Sampling site									
	Unit	**ISQG-Low**	**ISQG-High**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Organochlorine Pesticides													
Total DDT	mg/kg dry wt	0.0016	0.046	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Dieldrin	mg/kg dry wt	0.00002	0.008	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Polycyclic Aromatic Hydrocarbons													
Total PAHs	mg/kg dry wt	4	45	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Trace Elements													
Antimony	mg/kg dry wt	2	25	0.08	0.14	0.16	0.1	0.09	0.16	0.1	0.13	0.07	0.12
Arsenic	mg/kg dry wt	20	70	5.1	6.6	11	7.8	7.1	8.2	6.6	9.1	4.5	4.1
Beryllium	mg/kg dry wt			0.22	0.25	0.44	0.27	0.3	0.37	0.27	0.33	0.35	0.33
Cadmium	mg/kg dry wt	1.5	10	0.026	0.021	0.023	0.022	0.08	0.085	0.077	0.037	0.025	0.016
Chromium	mg/kg dry wt	80	370	6.1	8.8	15.4	9.3	9.8	7.7	6.8	6.4	5.7	8.5
Copper	mg/kg dry wt	65	270	0.9	1.8	7.1	2.2	2.1	2.1	1.5	1.6	1.7	1.9
Lead	mg/kg dry wt	50	220	2.8	5.6	7.4	3.5	4.5	4.7	3.5	4.3	5.4	3.8
Mercury	mg/kg dry wt	0.15	1	0.018	0.019	0.074	0.027	0.054	0.045	0.043	0.029	0.03	0.033
Nickel	mg/kg dry wt	21	52	1.3	1.9	6.9	2.9	2.8	2.4	1.9	1.8	1.5	2.7
Selenium	mg/kg dry wt			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Silver	mg/kg dry wt	1	3.7	0.05	ND	0.02	ND	0.03	0.06	0.03	0.12	0.09	0.03
Thallium	mg/kg dry wt			0.13	0.04	0.04	0.07	0.13	0.23	0.21	0.07	0.09	0.05
Zinc	mg/kg dry wt	200	410	12.3	23	36	18.4	22	23	19.7	17.5	17.8	23

Table A6.1. continued

				Sampling site									
	Unit	**ISQG-Low**	**ISQG-High**	**11**	**12**	**13**	**14**	**16**	**17**	**18**	**19**	**20**	**21**
Organochlorine Pesticides													
Total DDT	mg/kg dry wt	0.0016	0.046	ND	ND	ND			ND	ND			
Dieldrin	mg/kg dry wt	0.00002	0.008	ND	ND	ND			ND	ND			
Polycyclic Aromatic Hydrocarbons													
Total PAHs	mg/kg dry wt	4	45	ND	ND	ND			ND	ND			
Trace Elements													
Antimony	mg/kg dry wt	2	25	0.13	0.1	0.1	0.1	0.12	0.16	0.06	0.06	0.07	0.07
Arsenic	mg/kg dry wt	20	70	7.4	7.1	9.4	9.3	8.9	10.1	11.4	5.1	7.3	5
Beryllium	mg/kg dry wt			0.44	0.52	0.56	0.49	0.46	0.53	0.2	0.31	0.25	0.19
Cadmium	mg/kg dry wt	1.5	10	0.025	0.026	0.031	0.023	0.027	0.03	0.015	0.023	0.017	0.031
Chromium	mg/kg dry wt	80	370	14.3	11	7.9	11.1	8.6	11.9	6.8	8.2	8	7.5
Copper	mg/kg dry wt	65	270	3.3	4.6	4.7	5.4	5.1	6.3	0.7	1.1	0.7	0.7
Lead	mg/kg dry wt	50	220	6.8	6.1	6.8	6.8	6.5	6.4	2.3	3.4	2.2	2.3
Mercury	mg/kg dry wt	0.15	1	0.052	0.075	0.054	0.073	0.041	0.071	ND	0.024	0.01	0.012
Nickel	mg/kg dry wt	21	52	4.5	5.3	4.8	6.1	4.5	7.5	2	1.6	2	1.6
Selenium	mg/kg dry wt			ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Silver	mg/kg dry wt	1	3.7	0.03	0.1	ND	0.03	0.02	0.03	ND	ND	ND	ND
Thallium	mg/kg dry wt			0.04	0.04	0.04	0.04	0.06	0.07	0.02	0.09	0.07	0.09
Zinc	mg/kg dry wt	200	410	41	35	37	37	37	37	11.8	17.6	12.2	11.2

Table A6.1. continued

				Sampling site								
	Unit	ISQG-Low	ISQG-High	22	23	24	25	26	27	28	29	30
Organochlorine Pesticides												
Total DDT	mg/kg dry wt	0.0016	0.046						ND	ND		ND
Dieldrin	mg/kg dry wt	0.00002	0.008						ND	ND		ND
Polycyclic Aromatic Hydrocarbons												
Total PAHs	mg/kg dry wt	4	45						0.41	ND		ND
Trace Elements												
Antimony	mg/kg dry wt	2	25	0.08	0.07	0.08	0.09	0.14	0.06	0.12	0.17	0.07
Arsenic	mg/kg dry wt	20	70	5.4	4.5	5.5	6.7	6.3	6	10.7	7.2	4.2
Beryllium	mg/kg dry wt			0.28	0.24	0.39	0.37	0.47	0.45	0.56	0.59	0.19
Cadmium	mg/kg dry wt	1.5	10	0.077	0.05	0.056	0.033	0.033	0.017	0.031	0.071	0.039
Chromium	mg/kg dry wt	80	370	7.3	7	9.4	8.9	12.3	8.6	10.7	11.9	6.9
Copper	mg/kg dry wt	65	270	2	1.2	2.1	2.1	2.7	3	5.5	6.7	1.1
Lead	mg/kg dry wt	50	220	4.8	3	4.3	4.6	10.2	4.8	7.1	9.2	3
Mercury	mg/kg dry wt	0.15	1	0.041	0.023	outlier	0.066	0.051	0.073	0.093	0.095	0.065
Nickel	mg/kg dry wt	21	52	2.1	2	3.3	3.1	3.6	4.2	5.8	5.3	1.6
Selenium	mg/kg dry wt			ND	ND	ND	ND	ND	ND	ND	ND	ND
Silver	mg/kg dry wt	1	3.7	0.03	ND	ND	0.03	0.03	ND	0.02	0.07	ND
Thallium	mg/kg dry wt			0.18	0.15	0.12	0.08	0.06	0.03	0.05	0.16	0.18
Zinc	mg/kg dry wt	200	410	20	16.1	26	26	36	31	37	42	15