Ecological Survey of Tauranga Harbour

Manaaki Taha Moana

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ECOLOGICAL SURVEY OF TAURANGA HARBOUR

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MIHI

Korihi te manu
Takiri mai te ata
Ka ao, ka ao, ka awatea
Tihei mauri ora!

Ka mihi ake ka tangi ake
Ratau te hunga kua moe nga whatu
E moe mai ra i te wahangutanga o te po

Tatau e pikau nei i ngā ahuatanga o te ao turoa
tatau e kawe nei i ngā wawata o ratau ma
kei te mihi

Ki ngā maunga, ki ngā awa, heoi ki ngā iwi e noho taiamio nei i te moana o Te Awanui, kei te mihi
Ki ngā tini, ki ngā mano o Ngāti Ranginui, Ngāi te Rangi me Ngāti Pūkenga
Tena koutou katoa

Ka huri ngā mihi ki te Te Taiwhakapiri o Te Awanui, heoi ano ki a Chris Battershill no te Whare Wananga o Waikato, kia Bruce Gardner no te Bay of Plenty Regional Council tena korua ngā pouwhakarae, ngā pouwhakapiriri.
heoi ano ki ngā kaituao maha e hapai ana i ngā kaupapa o te rangahau nei, ma te hoe tahi kua whakakuku te waka ki uta, kua ea ngā wawata.
Na reira tena koutou, tena koutou, tena koutou katoa

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Revision history

1	K-means partitioning was used to group the ecological health categories rather than simply dividing them equally into 5 groups (Section 2.5.2). This is a more statistically defensible way of partitioning the groups and resulted in eight groups for sedimentation, six groups for nutrients and five groups for contamination. The results (Section 3.3 including Figures 15-20 and Tables 3-6) have been updated accordingly.	31 May 2017
2	Species response models were updated using new criteria to identify taxa suitable for modelling and maximum abundances instead of 95th percentiles (Section 2.5.2 including Figures 4-5). Some of the taxa modelled in the earlier version of the report were not suitable for modelling because they were not well represented by the 1 mm size fraction or not present in sufficient abundances across the study area. Additionally, maximum abundance rather than 95th percentile data was found to produce better models. The executive summary, results (Section 3.4 including Figures 21-23 and Table 7) and discussion (Section 4.2) have been updated accordingly.	31 May 2017
3	Deleted existing Appendix 3 because the groupings were not determined using k-means partitioning and instead put the details of the species response models as a new Appendix 3	31 May 2017

Disclaimer

EXECUTIVE SUMMARY

This report summarises the results of biological and physical data collected from a broad scale intertidal survey of Tauranga Harbour conducted between December 2011 and February 2012. The survey was designed to understand more fully the role of various anthropogenic stressors on the ecology of the harbour. The research was conducted as part of the Manaaki Taha Moana (MTM) programme. The wider research project aims to restore and enhance coastal ecosystems and their services of importance to iwi/hapū, by working with iwi to improve knowledge of these ecosystems and the degradation processes that affect them.

In this report we assess the health of macrofaunal benthic communities (bottom-dwelling animals) as well as trends in sediments, nutrients and contaminants. The results indicate that the sites identified as most impacted were generally located in the upper reaches of estuaries in some of the locations least exposed to wind, waves and currents. In addition, the biological community composition characterising sites with different sediment textures, nutrient and contaminant loadings were found to vary. Sediments within Tauranga Harbour were predominantly sandy with the percentage of mud within a similar range as measured for other New Zealand estuaries. The exceptions included Te Puna Estuary and Apata Estuary, which experience higher rates of sedimentation.

Heavy metal contamination in sediments is often highly correlated with the percentage of mud content due to the adherence of chemicals to fine sediments and/or organic content. It is, therefore, not surprising that heavy metal concentrations were also highest in the depositional inner areas of the harbour, such as Te Puna Estuary. The heavy metal contaminant levels within Tauranga were well below relevant guideline thresholds and lower than concentrations measured in many other estuaries in New Zealand and overseas. Although the three metals recorded were found to be highly correlated, zinc levels tended to be closer to guideline thresholds for possible biological effects.

Sediment nutrient concentrations in the harbour tended to decline with distance from the inner harbour and associated rivers. Te Puna Estuary showed comparatively high nitrogen and phosphorus loadings. Comparison of sediment nutrient concentrations with other New Zealand estuaries indicates that the Tauranga Harbour sits within a range typical for slightly to moderately enriched estuaries. Although total phosphorus was low compared with other estuaries, total N:P ratios suggest Tauranga Harbour is still limited by nitrogen.

We developed a BHM using statistical ordination techniques to identify key stressors affecting the ‘health’ of macrofaunal communities. Sediments, nutrients and heavy metals were identified as key ‘stressors’, *i.e.* variables affecting the ecology of the harbour. Therefore, three multivariate models were developed based on the variability in community composition using canonical analysis of principal coordinates (CAP). The ecological

assemblages generally reflected gradients of stress or pollution very well. However, the CAP models for sedimentation and contamination performed best.
In general, the multivariate models were found to be more sensitive to changing ecological health than simple univariate measures (abundance, species diversity, evenness and Shannon-Wiener diversity). This finding has also been reported in the literature where univariate measures based on abundance and diversity were only able to detect significant differences between the most and least disturbed sites, but were not able to differentiate between smaller relative changes in ecological health. Hence univariate measures were less sensitive to smaller degradative changes in community composition. For Tauranga Harbour, ordination models based on community composition appear to be a more sensitive measure of 'health' along an ecological gradient and should enable long term degradative change from multiple disturbances to be assessed. This BHM approach can be used as a management or monitoring tool where sites are repeatedly sampled over time and tracked to determine whether the communities are moving towards a more healthy or unhealthy state.

The key species at 'healthy' and 'impacted' sites as determined from the CAP models were also identified. Species at 'impacted' sites can be considered to be tolerant to the stressor (*i.e.* sediment, nutrients or contaminants), while species with high abundances at only 'healthy' sites are sensitive to increasing stressors. We developed species response models for 20 taxa. Although the type of response differed by taxa and stressor, variation in the abundance of most of the taxa modelled was most likely to be better predicted by sedimentation. Unimodal responses were almost always observed in response to nutrients, while declines or skewed unimodal responses were most often observed in response to sedimentation and metals.

The results from this study are consistent with models of macrofaunal species occurrence with respect to sediment mud content developed across a range of New Zealand estuaries by Thrush *et al.* (2003). Within this report we extend this analysis by also developing models of macrofaunal species occurrence with respect to nutrient and contaminants loadings. Ultimately such statistical models provide a tool to forecast the distribution and abundance of species associated with habitat changes in sediments, nutrients and metals.

In conclusion, Tauranga Harbour is a predominantly sandy harbour with slight to moderate enrichment and low levels of heavy metal contaminants. Sites identified as most impacted by elevated sediments, heavy metal contaminants and nutrients were generally located in the upper reaches of estuaries in some of the least exposed locations. To some extent, this reflects the natural progression of an estuary from land to sea; however, the rates of accumulation of sediments and nutrients have been accelerated as a result of anthropogenic land-based activities. Sediments and contaminants were found to explain the largest variance in benthic communities. Species response models suggest that taxa were either sensitive to elevated sediments, nutrients loading or contamination at all levels, or sensitive to these stressors beyond a critical point.

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GLOSSARY

Abbreviation	Definition
AFDW	Ash-free dry weight
ANZECC	Australia and New Zealand Environment and Conservation Council
A priori	Independent of experience, therefore, assumptions that may or may not be true are made
ARC	Auckland Regional Council
BHM	Benthic Health Model
CA	Correspondence analysis
CAP	Canonical Analysis of Principal coordinates
Chl-α	Chlorophyll-α
Cu	Copper
DistLM	Distance based Linear Modelling
Epifauna	Animals that live on the surface of the sediment
H	Shannon-Wiener diversity index ($\log_e$ base). A diversity index that describes, in a single number, the different types and amounts of animals present in a collection.
Infauna	Animals that live within the sediment
ISQG	Interim Sediment Quality Guideline, can be high or low
J	Pielou’s evenness, a measure of equitability, or how evenly the individuals are distributed amongst the different species/taxa
Macroalgae	Seaweeds large enough to be seen with the naked eye
Macrofauna	Animals large enough to be seen with the naked eye
nMDS	Nonmetric multidimensional scaling
Pb	Lead
PCA	Principal component analysis
PCO	Principal coordinate analysis
TN	Total nitrogen
TP	Total phosphorus
NIWA	National Institute of Water and Atmospheric Research
Zn	Zinc

1. INTRODUCTION

The ecological health of Tauranga Harbour — traditionally known to local iwi as Te Awanui — was recently summarised in order to inform the Tauranga community, iwi and stakeholders of the 'state of the harbour' and to identify information gaps and priorities for field research (Sinner *et al.* 2011). The report was based on a literature review of published scientific papers and technical reports and did not extend to new field work or new analysis and interpretation of data. To summarise, while studies have been conducted on a wide range of topics, studies that assess biodiversity of flora and fauna at the scale of the estuary have not been conducted since 1994. The spatial scale over which information has been collected also varies greatly from one study to the next, reflecting the diverse purposes for which specific studies were undertaken. In order to understand more fully the role of various anthropogenic stressors on biodiversity, a broad scale survey of Tauranga Harbour was recommended (Sinner *et al.* 2011).

This report summarises the results of biological and physical data collected from a broad scale intertidal survey of Tauranga Harbour conducted between December 2011 and February 2012. As well as providing general information on spatial trends of macrofaunal species distributions, sediment types, nutrients and heavy metal contaminant concentrations across the whole harbour, the report also develops a community based model of ecosystem health called a 'Benthic Health Model' (BHM). The BHM was originally developed by Auckland University and the National Institute of Water and Atmospheric Research (NIWA) for the Auckland Regional Council (ARC). The model was developed as a tool to classify intertidal sites within the region according to categories of relative ecosystem health, based on its community composition and predicted responses to stormwater contamination (Anderson *et al.* 2006).

In reviewing existing methods of defining and measuring ecological 'health' it was noted that many of the existing biological diversity indices do not differentiate amongst different types of taxa and are strongly affected by sample size (Gappa *et al.* 1990; Dunn 1994). This limits their ability to detect changes in composition across different communities and habitats. Furthermore, it is not immediately apparent what differences or similarities in these indices actually mean to ecological functioning, as a similar diversity value can be obtained from communities with very different species (Clarke 1993; Dufrene & Legendre 1997). Many of the existing metrics only detect one kind of impact (*e.g.* eutrophication or a specific contaminant). As a viable alternative, models that focus on community composition were recommended and developed (see Anderson *et al.* 2002, 2006; Anderson 2008; Hewitt & Ellis 2010).

Community composition comprises both the number and type of taxa (or animals) that make up a biological community at a site, together with their relative abundances.

Defining community composition requires the same information needed to generate many biological diversity indices; however, by preserving all the information on the abundance of specific taxa, a more sensitive, and more ecologically meaningful, response could be expected (Anderson *et al.* 2002). The community composition found in areas largely unaffected by anthropogenic disturbances versus that found in more ‘impacted’ areas can be used as a benchmark against which to assess the relative health of community composition found at specific sites. Thus, relative ‘health’ can be defined in terms of the range of communities present in comparable locations that are not considered to be affected by anthropogenically-derived inputs and should serve to identify both acute effects and broader-scale degradation. Community composition is generally determined using multivariate techniques including ordination. Multivariate techniques have been applied successfully to indicate the effects of pollution (Warwick *et al.* 1990; Olsgard & Gray 1995; Ellis *et al.* 2000) and subsequent studies have now shown that multivariate methods are better at determining differences between communities with different degrees of anthropogenic disturbance than univariate measures of communities (Hewitt *et al.* 2005). In the present study, a BHM was applied to Tauranga Harbour to rank the health of intertidal sites based on predicted responses to sedimentation, nutrients and contamination.

2. MATERIALS AND METHODS

2.1. Study site

Tauranga Harbour is a large estuary (approximately 200 km^2) located on the western edge of the Bay of Plenty on New Zealand's North Island (37 °40'S, 176 °10'E; Figure 1). The harbour is protected from the Pacific Ocean by a barrier island (Matakana Island) and two barrier tombolos, Bowentown at the northern entrance and Mount Maunganui to the south. Two harbour basins are separated by large intertidal flats in the central area of the harbour. Although the two basins are connected there is little water exchange between the two (Barnett 1985; de Lange 1988). The harbour is predominantly shallow (< 10 m deep), with intertidal flats comprising approximately 66% of the total area (Inglis *et al.* 2008).

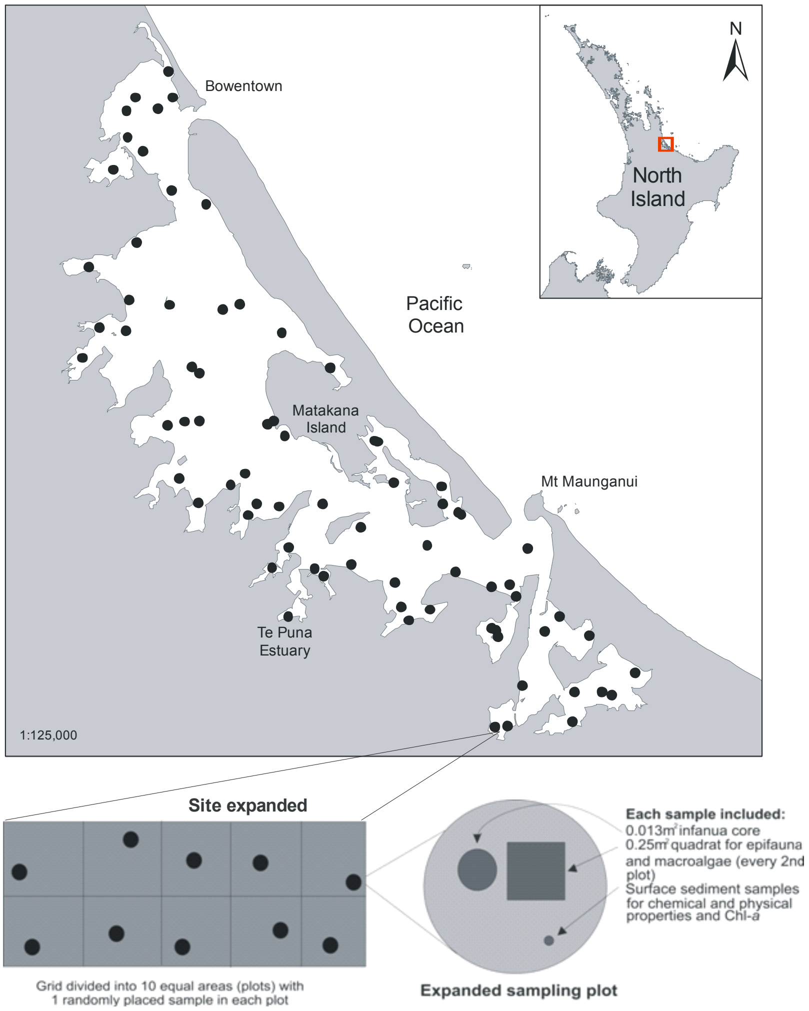

Figure 1. Map of Tauranga Harbour showing locations of the study sites and the sampling strategy.

Sampling was carried out over the December 2011 to February 2012 time period. The sampling design and methodologies were chosen to provide results generally comparable to those generated by the standardised Estuary Monitoring Protocol (Robertson *et al.* 2002a), which has been implemented in a range of New Zealand estuaries. A total of 75 sites across the harbour were sampled for benthic macrofauna and associated sediment characteristics (Figure 1; refer Appendix 1 for site location details). Sites were chosen to reflect a range of habitats including intertidal sand flats, shellfish beds, seagrass meadows and areas likely to be impacted by pesticides. At each site, a 2 x 5 grid of ten plots (10 m x 10 m) was marked out, and replicates were collected from each plot, yielding 750 samples overall (Figure 2, bottom left).

Figure 2. Photographs of sampling procedure. Clockwise from top left: taking infauna core; transporting samples; sampling for surface sediments with quadrat for photographs nearby; measuring out grid.

2.2. Physico-chemical variables

At each site, one 20 mm diameter core extending 20 mm deep into the sediment was collected from each of the 10 plots in the grid yielding 10 replicates for each site (Figure 2, bottom right). Only the top 2 cm was sampled as the majority of macrofauna present either live or feed no deeper than this, and this area is frequently mixed by both bioturbation and wave action. The replicates were composited into a single sample and the sediment was analysed for a variety of sediment characteristics (refer Table 1 for details); grain size, organic matter (as ash-free dry weight, AFDW), nutrients (total nitrogen, TN; total phosphorus, TP), heavy metals (lead [Pb], zinc [Zn], copper [Cu]) and chlorophyll-*α* (chl-*α*). At selected sites (sites 7, 10, 14, 29, 38, 47, 48, 50, 73) sediment samples were also analysed for various pesticides, however, these results are not presented in this report.

Table 1. Analytical methods and detection limits.

Parameter	Method	Detection limit
Grain size	Wet sieving and calculation of dry weight percentage fractions	-
Ash-free dry weight	Dry sediment weight loss after combustion at 550 ℃ (APHA 21st Edn, modified 2540 D+ E)	-
Total nitrogen	APHA 21st Edn 4500N C	0.1 mg/kg
Total phosphorus	USEPA 200.2 Digestion/ICP-MS	20 mg/kg
Lead	USEPA 200.2 Digestion/ICP-MS	< 2.0 mg/kg
Zinc	USEPA 200.2 Digestion/ICP-MS	< 10 mg/kg
Copper	USEPA 200.2 Digestion/ICP-MS	< 0.5 mg/kg
Chlorophyll-*α*	NIWA Periphyton Monitoring Manual	-

2.3. Infauna

To quantify benthic community structure at each site, samples of the macrofauna living within the sediment (infauna, *e.g.* worms, shellfish) were collected. One 130 mm diameter core extending 150 mm into the sediment was taken from each of the 10 plots in the grid yielding 10 replicates for each site (Figure 2, top left). The macrofaunal samples were separated using stacked sieves with mesh sizes of 1 mm and 500 µm. Macrofauna retained on the sieves were preserved with ethanol (diluted to ~70% with seawater). All 10 replicates from the 1 mm mesh size were sorted and identified to the lowest taxonomic resolution. However, due to budgetary constraints, only three replicates from the 500 µm fraction were processed.

Two versions of each model were constructed; one using only the 1 mm infauna data (means based on 10 replicates per site) and one using both the 1 mm and the 500 µm data (means based on three replicates from the 1 mm and the 500 μm fraction per site). Anderson *et al.* (2002) found that increasing sample size improved the models, most particularly by increasing classification accuracy and precision. However, although the models using means based on taking three cores at each site (rather than ten) were less precise, they were not biased in any way (Anderson *et al.* 2002).

Length frequency data for cockles (*Austrovenus stutchburyi*) and pipi (*Paphies australis*) were collected to provide an indication of the distribution of culturally important species within the harbour. Shell length (along the longest axis) was recorded for all cockles and pipi found within the infauna core samples. It is acknowledged that core samples are not the most appropriate sampling methodology for organisms of this size and a more detailed study of shellfish in Tauranga Harbour, using quadrat sampling, is in progress.

2.4. Epifauna and macroalgae

To quantify epifauna (animals living on the surface of the sediment, *e.g.* anemones, crabs, sea stars) community structure and macroalgal (seaweeds) cover at each site, one photograph was taken from every second plot in the grid yielding five replicates for each site. This data has been stored so that epifauna and macroalgae can be identified from the photographs and the abundance of percentage cover of each species determined if required.

2.5. Statistical analyses

2.5.1. General background to multivariate analysis

Multivariate analysis is the analysis of the simultaneous response of several variables. As such, it is often used to compare community composition within and between sites, *i.e.*, the types of organisms found and their relative abundances. Ordination is the ordering of observations (in this study, the ordering of sites) relative to one another on the basis of the information contained in the variables (in our case, taxa). The primary purpose of ordination is to reduce the multivariate dimensionality down to one, two or three dimensions in order to view patterns.

In the case of the present investigation, we consider that each taxon found at a site is a variable, and our interest lies in discovering whether the all taxa are responding to the ‘pollution’ or ecological gradients in a way that can be characterised. The abundance of each taxon at a site gives it a position along each of these dimensions and, therefore, places it in the multivariate space (Anderson *et al.* 2002). Large differences in either the relative abundance or the identities of the taxa between sites will cause the sites to be relatively distant from each other in terms of their position in multivariate space.

There are a number of different (unconstrained) ordination methods that are used to reduce dimensionality and position each sample for interpretation relative to others in a diagram. The most common of these are: principal component analysis (PCA), correspondence analysis (CA), principal coordinate analysis or metric multidimensional scaling (PCO), and nonmetric multidimensional scaling (nMDS). A good description of these methods is given in Legendre and Legendre (1998). For the current study, PCA was used to derive the ecological gradients for nutrients and contaminants because these stressors were characterised by more than one variable.

The ordination techniques described above allow us to graphically investigate similarities between the variable of interest (*e.g.* communities or ecological gradient) at different sites. However, in order to determine whether there is a significant relationship between the soft sediment faunal communities of the Tauranga region and the anthropogenic stressors, we go one step further into constrained ordination. A constrained ordination is one that uses a particular *a priori* model or hypothesis to draw an ordination diagram, rather than drawing the relative positions of samples based simply on the relative dissimilarities (see Anderson & Willis 2003). In the present investigation, we use Canonical Analysis of Principal coordinates, or CAP (Anderson & Robinson 2003; Anderson & Willis 2003), which allows a constrained ordination to be done on the basis of any dissimilarity or distance measure of choice (such as the Bray-Curtis measure; Bray & Curtis 1957). All CAP analyses were performed using specialised software by M. J. Anderson, written in FORTRAN and available as an executable file (CAP.exe) or in Primer 6 (version 6.1.13) and PERMANOVA (version 1.0.3).

2.5.2. Statistical model

An outline of the statistical methods used in this research is provided in Figure 3. Data from Site 48 (Te Puna Estuary) were excluded from the analyses because the measured parameters were outside the range of variation observed at other sites. Preliminary analysis of the Tauranga data using Distance based Linear Modelling (DistLM Primer E; Clark & Gorley 2006) with a backward selection procedure (AIC selection criteria) was performed to determine the key anthropogenic stressors. This analysis indicated that sedimentation (% mud content), nutrients (TP), chl-*α* (a measure of food that tends to increase in response to elevated nutrient loadings) and contamination (Cu, Pb) were important in explaining the variation in the harbour. Therefore three models, hereafter referred to as the sedimentation model, nutrient model and contamination model were developed. For each of the three models there are a number of steps involved in the statistical analyses, which are detailed below.

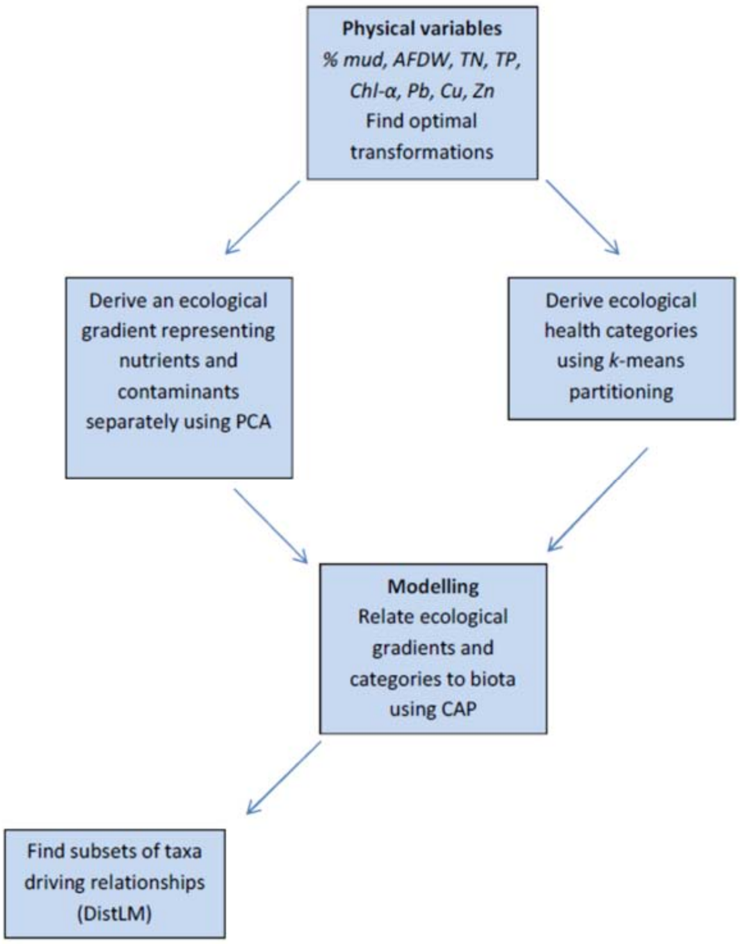

Figure 3. Flow chart showing an outline of the logical flow of statistical analyses for the modelling used in this investigation (modified from Anderson *et al.* 2006). AFDW = ash-free dry weight, TN = total nitrogen, TP = total phosphorus, chl-*α* = chlorophyll-*α*, Pb =lead, Cu = copper, Zn = zinc, PCA = principal component analysis; CAP = Canonical Analysis of Principal coordinates; DistLM = Distance based Linear Modelling.

Before developing the ordination models we were interested in assessing the relative contribution of each stressor in driving ecological variation. DistLM was used with variables grouped into three categories: sediment (% mud content), nutrient indicators (TN, TP, chl-*α*) and contaminants (Cu, Pb, Zn). DistLM was run seven times to obtain the percentage explained (R^2) by each group alone, then each pairwise combination and finally all three groups. The relative percentages explained by the different components were then determined by adapting variance partition methods (Borcard *et al.* 1992; Anderson & Gribble 1998).

Step one:

First the raw data for sediments (% mud content), nutrients (TN, TP), chl-*α* and contaminants (Cu, Pb, Zn) were analysed and optimal transformations performed if necessary. For sedimentation, the percentage mud was a key variable in explaining the biological variation in the data and this was used directly as the ecological gradient for health modelling purposes. For nutrients and contamination, however, a range of variables were measured (*e.g.* contamination was measured using Cu, Pb and Zn) and variables were often correlated. As there were a range of correlated measures, it was logical to seek a single variable which would characterise an overall ecological gradient corresponding to increases in the concentrations of all nutrients or metals in the field. PCA can generate a single variable based on the first PC axis of the ordination.

DistLM identified that nutrient concentrations (specifically TP) were important in explaining the variance in the harbour. However, in developing an overall ecological gradient corresponding to increases in the concentrations of nutrients in the field, we used TP, TN and chl-*α* in the PCA. Similarly for contamination DistLM identified that Cu and Pb were important in explaining the variance, but in generating an overall ecological gradient corresponding to concentrations of contamination in the field we used Cu, Pb and Zn in the PCA. For nutrients and contamination, PCAs were performed on the basis of square root transformed nutrient concentrations and log transformed metal concentrations using the PRIMER v6 computer program (Clark & Gorley 2006). Square root transformed TN, TP and chl-*α* were used in a PCA where the PC1 axis explained 91% of the variance (PCnutrients). For heavy metals, log transformed Cu, Pb and Zn were used in a PCA where the PC1 axis explained 85.5% of the variance (PCcontamination).

Step two:

The next step was to determine whether there was a significant relationship between the biotic assemblages and the ecological gradients (as described in Step one). This was done using CAP analyses (Anderson & Willis 2003). If we consider the biotic data as a multivariate cloud of sample points, the CAP model tries to find the axis through this cloud that is most highly correlated with the ecological gradient.

The model output was then used to place sites along the ecological gradient (referred to as a rank pollution index in Anderson *et al.* 2006) from healthy to impacted sites. Following Anderson e*t al.* (2006), *k*-means partitioning (MacQueen 1967) was used to identify possible groupings for each ecological gradient (sedimentation, nutrients and contamination). This was done using a special-purpose FORTRAN program (courtesy of Pierre Legendre, University of Montreal). This method begins with all samples together in a single large group. For a given number of groups (*k*), it divides the samples into *k* groups so as to minimize the sum of squared distances of the samples to their group centroid (defined as the average of the variables within that group). The question then becomes: what value of *k* is optimal for a given dataset? The optimal number of groups was selected using the Calinski-Harabasz criterion (Calinski & Harabasz 1974). This criterion is defined for a given number of groups (*k*) as:

$$CH_k = \frac{\{R^2/(k\text{-}1)\}}{\{(1\text{-}R^2)/(N\text{-}k)\}}$$

Where R^2 is the explained sum of squares, N is the total number of samples and k is the number of groups. For a given set of groups, the explained sum of squares will simply increase with increases in the number of groups. The CH_k criterion is therefore standardised (essentially like an F-statistic), in order to take this into account. An appropriate number of groups (k) is chosen where this criterion is maximised. K-means partitioning solutions and associated CH_k values were calculated for each model (sedimentation, nutrient, contamination) on the basis of their ecological gradients (PC1). The optimal number of groups as determined using k-means partitioning was eight for sedimentation, six for nutrients and five for contamination.

Step three:

It was also of interest to determine which species might be driving any relationship between the biotic assemblages and the ecological gradients (PC1). Specifically, it is of biological interest to consider which taxa may be most sensitive to ecological health/pollution gradients. Therefore DistLM modelling was again used to determine key sensitive and pollution tolerant species that may be driving the assemblage differences and the ecological gradients for sedimentation, nutrients and contamination (Anderson *et al.* 2006).

Species responses to increasing sediment, nutrients and contaminants were also investigated for 20 taxa (Figure 4; Figure 5). Taxa were considered for modelling if they were present at more than 10 of the 75 sites and in numbers of at least two individuals per replicate (on average). We modelled the 1 mm macrofauna size fraction because this enabled the inclusion of more replicates in the models, however, to ensure the 1 mm size fraction was representative of total abundance the 1 mm size fraction was compared to the combined 1 mm and 500 µm size fraction. Taxa were only modelled if the correlation between the 1 mm and the combined 1 mm and 500 µm size fractions was at least 0.85 and the 1 mm size fraction included at least 75% of the total abundance. Maximum abundances across gradients of sedimentation, nutrients and contamination were modelled using the method proposed by Blackburn et al. (1992). For these models, each of the three variables representing ecological gradients (percentage mud, PCnutrients and PCcontamination) were divided into categories; 20 categories for sedimentation, 21 for nutrients and 30 for contaminants, with intervals of 4.0, 0.5 and 0.33 used, respectively. Each category included no more than 20 observations, and there were roughly equal numbers of observations in at least three categories. For each category, the maximum abundance was calculated for each taxon.

For all taxa, regressions were conducted using the number of observations in each category as a weighting. Generalised Linear Models (GLMs) were fitted to the data, using the maximum abundance in each category as the dependent variable, a log link function and a Poisson likelihood function. The independent variable offered to the GLM included up to two degree polynomials. However, the number of higher degree terms entered into the final model was based on the Akaike Information Criterion (AIC) and only higher degree terms that increased the proportion of deviance explained by more than 1% were included. Data transformation (either log or square root) was applied to the independent variable if it decreased the AIC or increased R^2. The final model used for each taxon was that function which explained the most variability. All analyses were conducted using the R software package (R Core Team 2014).

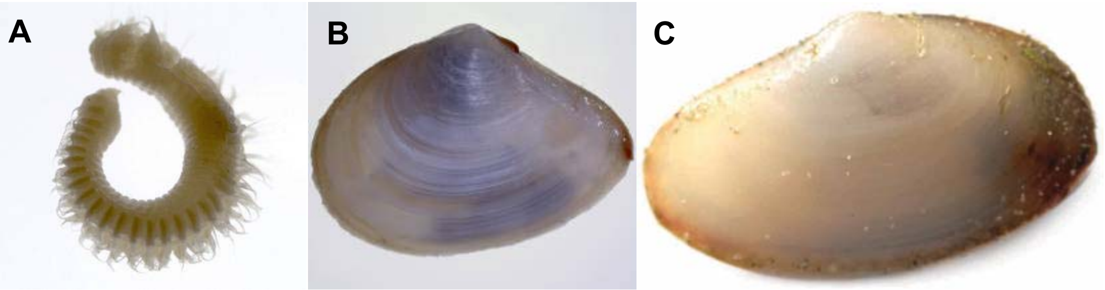

Figure 4. Examples of three species used in the species response modelling. A: marine worm (*Orbinia papillosa*), B: wedge shell (*Macomona liliana*), C: pipi (*Paphies australis*).

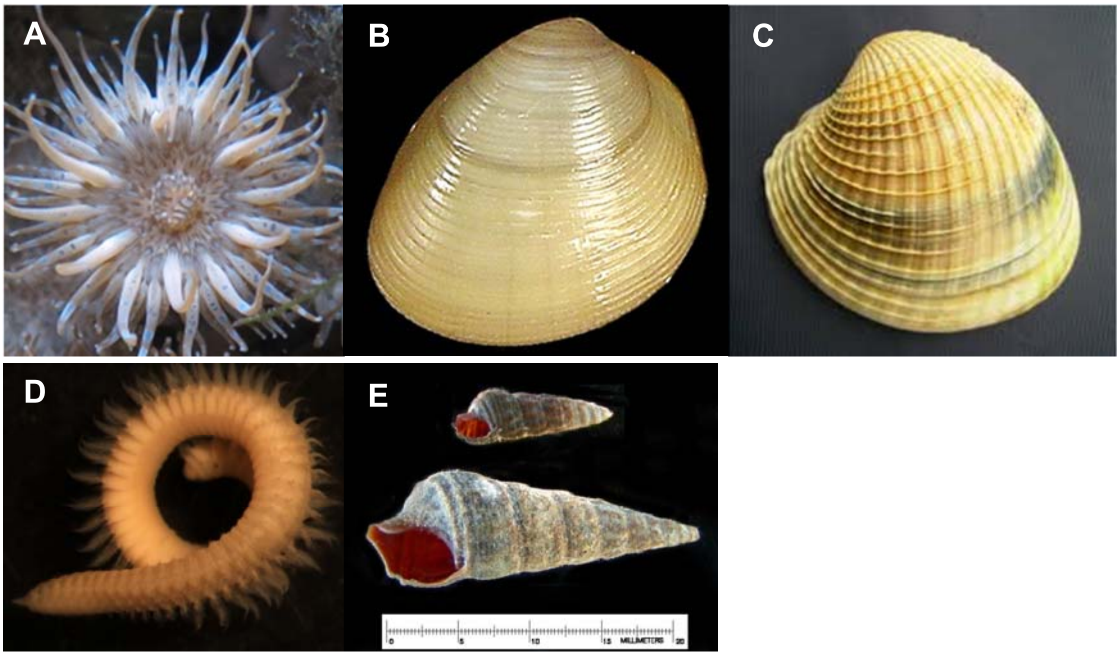

Figure 5. Examples of five species used in the species response modelling. A: brown anemone (*Anthopleura aureoradiata*), B: nut shell (*Linucula hartvigiana*), C: cockle (*Austrovenus stutchburyi*), D: marine worm (*Scoloplos cylindrifer*), E: horn shell (*Zeacumantus lutulentus*).

3. RESULTS

Site-specific details of physical variables and infauna descriptors can be found in Appendix 2.

3.1. Physico-chemical variables

3.1.1. Sediment grain size and organic content

Sediments within Tauranga Harbour were predominantly sandy (51-100% sand), with the exception of Site 48, in Te Puna Estuary, which was primarily mud (76% silt and clay; Figure 6). Sites near Apata (Sites 37 and 38), where the Wainui River flows into the harbour, also had relatively high levels of mud (48-49% silt and clay). In general, inner harbour areas contained more mud than outer harbour sites. The sandiest sites were Sites 20 and 18 in Blue Gum Bay (99-100% sand) and Site 60 in Otumoetai (99% sand).

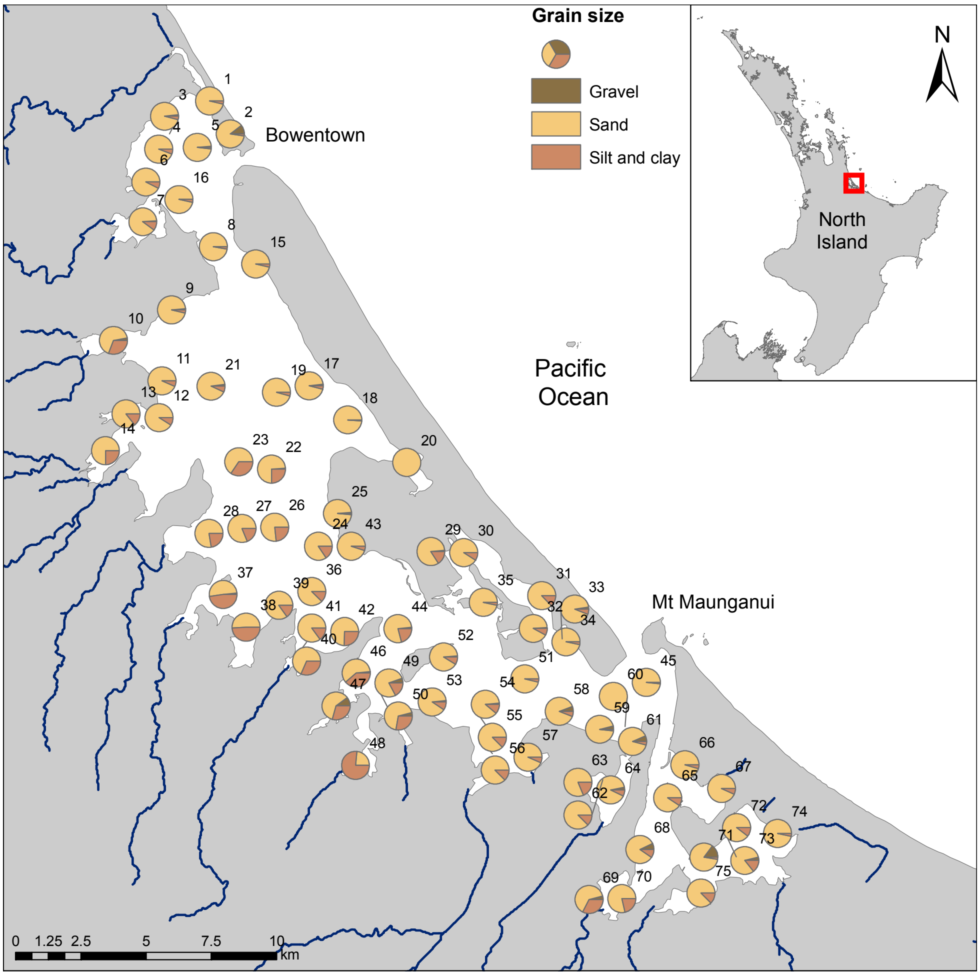

Figure 6. Grain-size (as a percentage of gravel, sand and silt/clay) for 75 sites sampled within Tauranga Harbour. Major rivers and streams entering the harbour are shown in blue.

Organic content of sediments in the harbour generally ranged from 0.9 to 4.5% AFDW (Figure 7). Inner areas of the harbour tended to have higher organic content than outer harbour sites. At 10% AFDW, the organic content of sediments from Site 48 in Te Puna Estuary, the muddiest site sampled, was much higher than measured in the rest of the harbour.

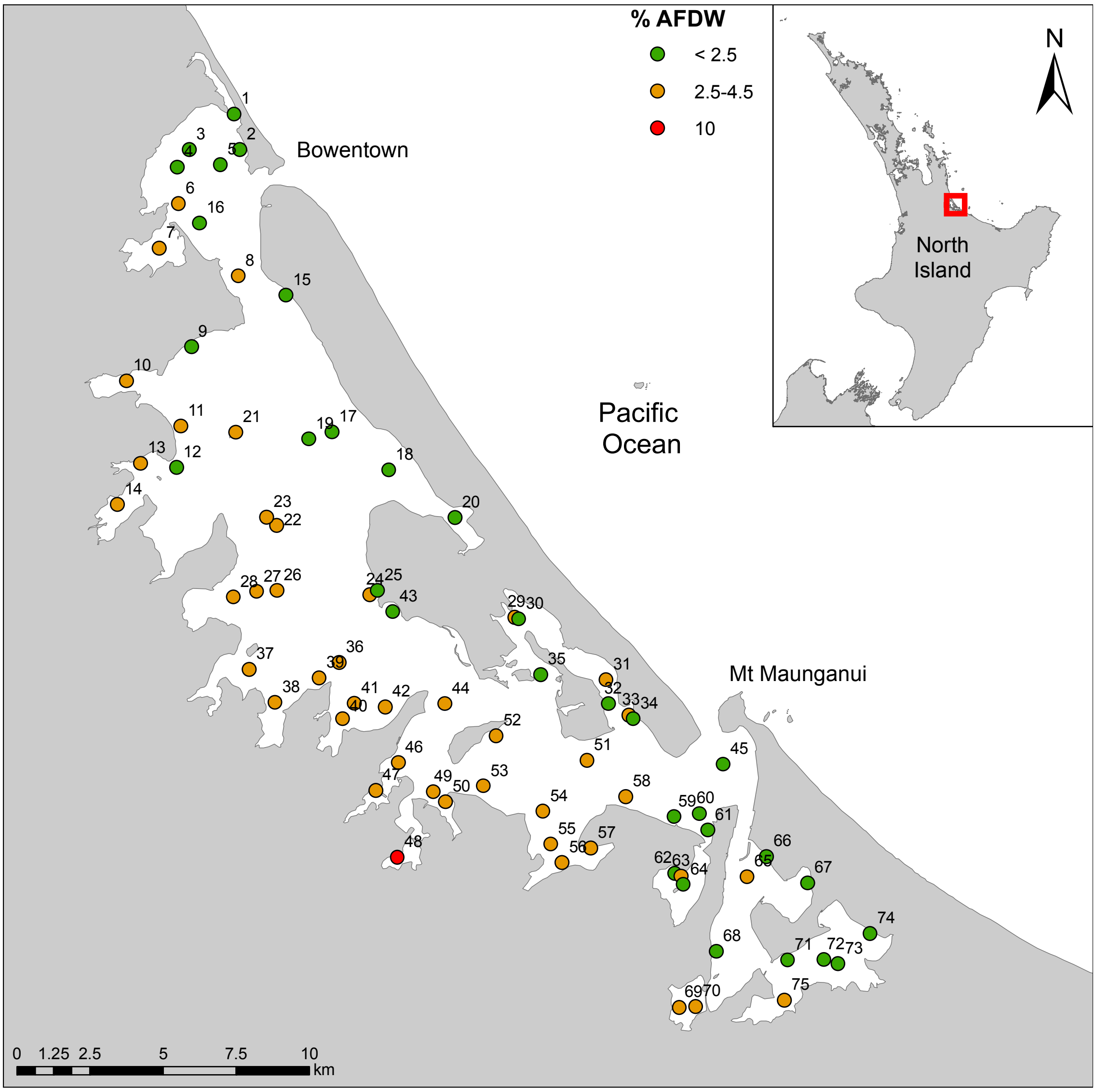

Figure 7. Sediment organic content (as % ash-free dry weight) for 75 sites sampled within Tauranga Harbour.

3.1.2. Nutrients

As with organic content, nutrient concentrations in the harbour tended to decline with distance from the inner harbour region and associated rivers (Figure 8; Figure 9). In general, total nitrogen in sediments ranged from 140 to 1000 mg/kg and total phosphorus from 51 to 340 mg/kg. Site 48, in Te Puna Estuary, showed comparatively high nutrient levels with nitrogen and phosphorus concentrations of 1900 and 580 mg/kg, respectively. Modeled nitrogen loadings (estimated from Freshwater Ecosystems of New Zealand (FENZ) using CLUES; Figure 8) predicts that the Te Puna Stream, which flows into Te Puna Estuary, would have relatively high levels of nitrogen, possibly explaining the high levels of nutrients in this area. Interestingly, the Kaitemako Stream, which flows into Welcome Bay, had the highest modeled nitrogen loadings in the area, however the sampling site in this area (Site 75) had relatively low nitrogen levels (280 mg/kg).

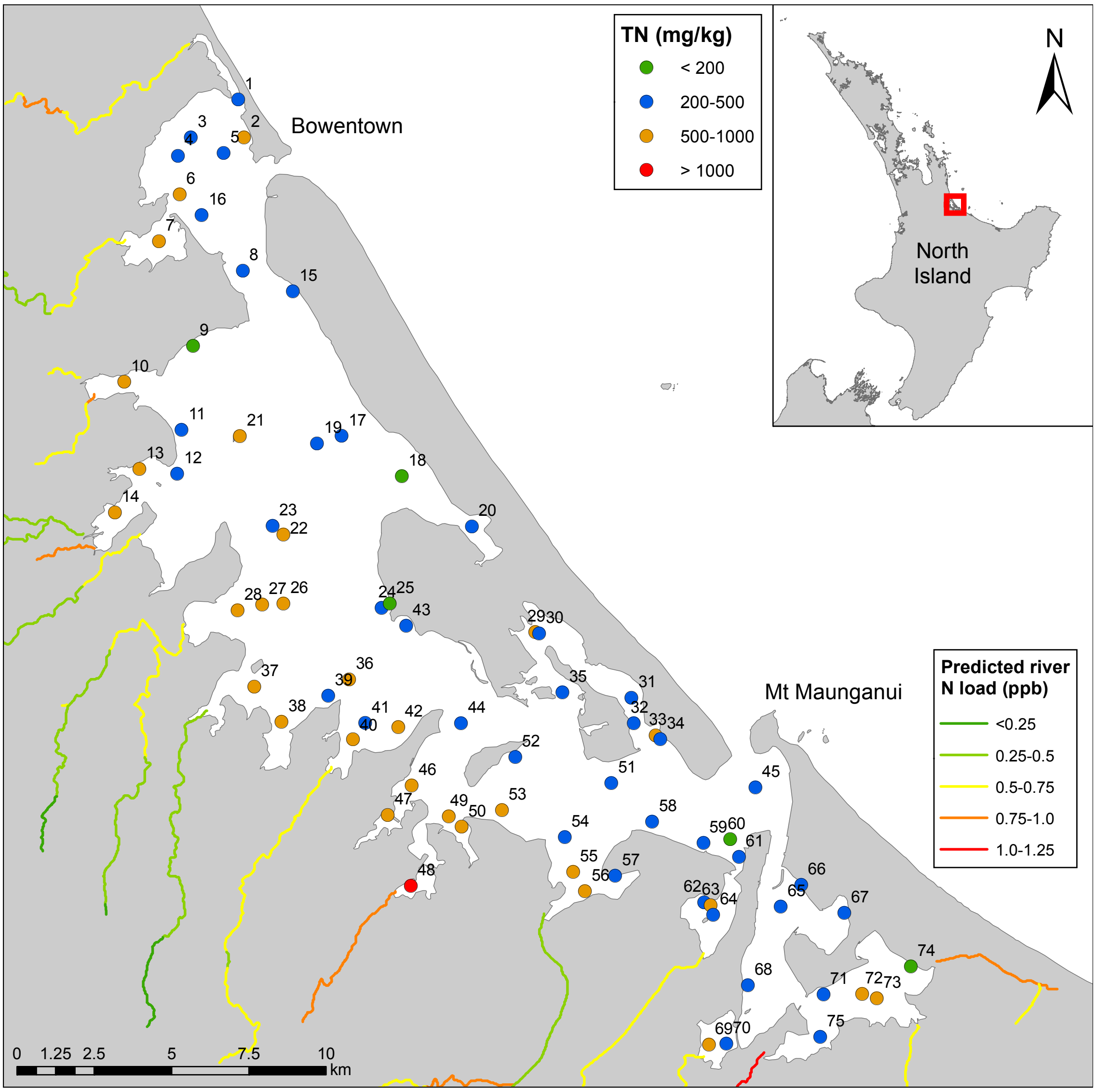

Figure 8. Total nitrogen (mg/kg) in sediments for 75 sites sampled within Tauranga Harbour. Major rivers and streams entering the harbour are shown with colours depicting modelled nitrogen loading (in ppb) for each segment (estimated from FENZ using CLUES; Woods *et al.* 2006; Leathwick *et al.* 2010).

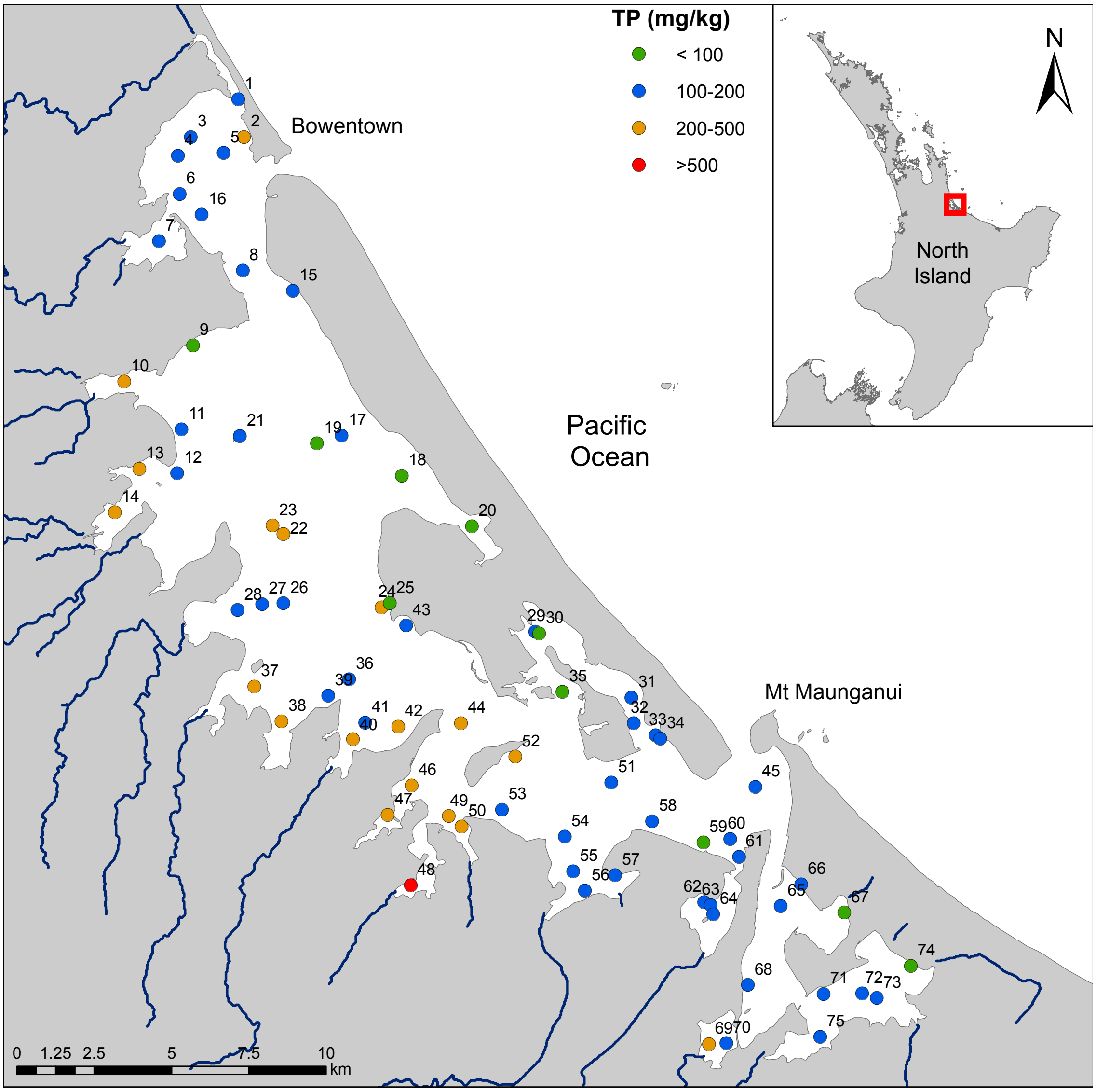

Figure 9. Total phosphorus (mg/kg) in sediments for 75 sites sampled within Tauranga Harbour. Major rivers and streams entering the harbour are shown in blue.

3.1.3. Chlorophyll-α

Sediment chl-*α* concentrations generally ranged from 1100 to 16000 µg/kg, with particularly low concentrations (210 µg/kg) at Site 18 in Blue Gum Bay (Figure 10). There was no obvious correlation between chl-*α* and nutrient concentrations. Highest chl-*α* concentrations were measured at Sites 55 and 56 (16000 and 15000 µg/kg, respectively), near the mouth of the Wairoa River, the largest river entering the Tauranga Harbour (~50% of freshwater input to harbour).

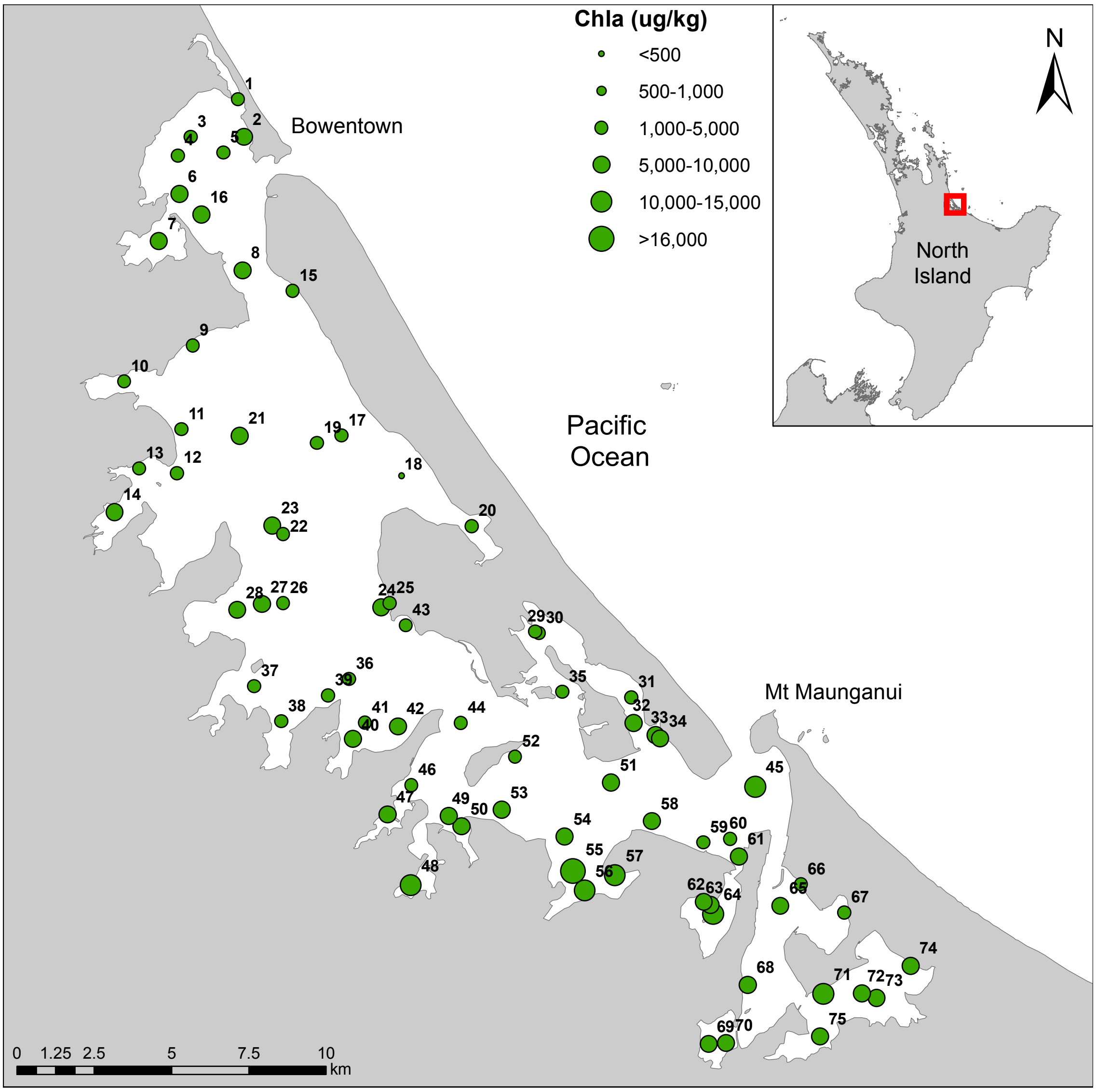

Figure 10. Sediment chlorophyll-*α* (µg/kg) concentrations for 75 sites sampled within Tauranga Harbour.

3.1.4. Heavy metals

Heavy metal concentrations in the harbour tended to be higher in inner areas compared with outer sites but all were well below Australian and New Zealand Environment and Conservation Council (ANZECC 2000) Interim Sediment Quality Guidelines, which provide thresholds for possible biological effects (ISQG-Low; Cu 65, Pb 50, Zn 200 mg/kg; Figure 11). Site 48, in Te Puna Estuary, had the highest copper and lead concentrations (6.1 and 13 mg/kg, respectively), and the second highest zinc concentration (46 mg/kg) after the nearby Site 49 (55 mg/kg). Site 10, in the Uretara Estuary, had the second highest copper (3 mg/kg) and lead concentrations (5.6 mg/kg).

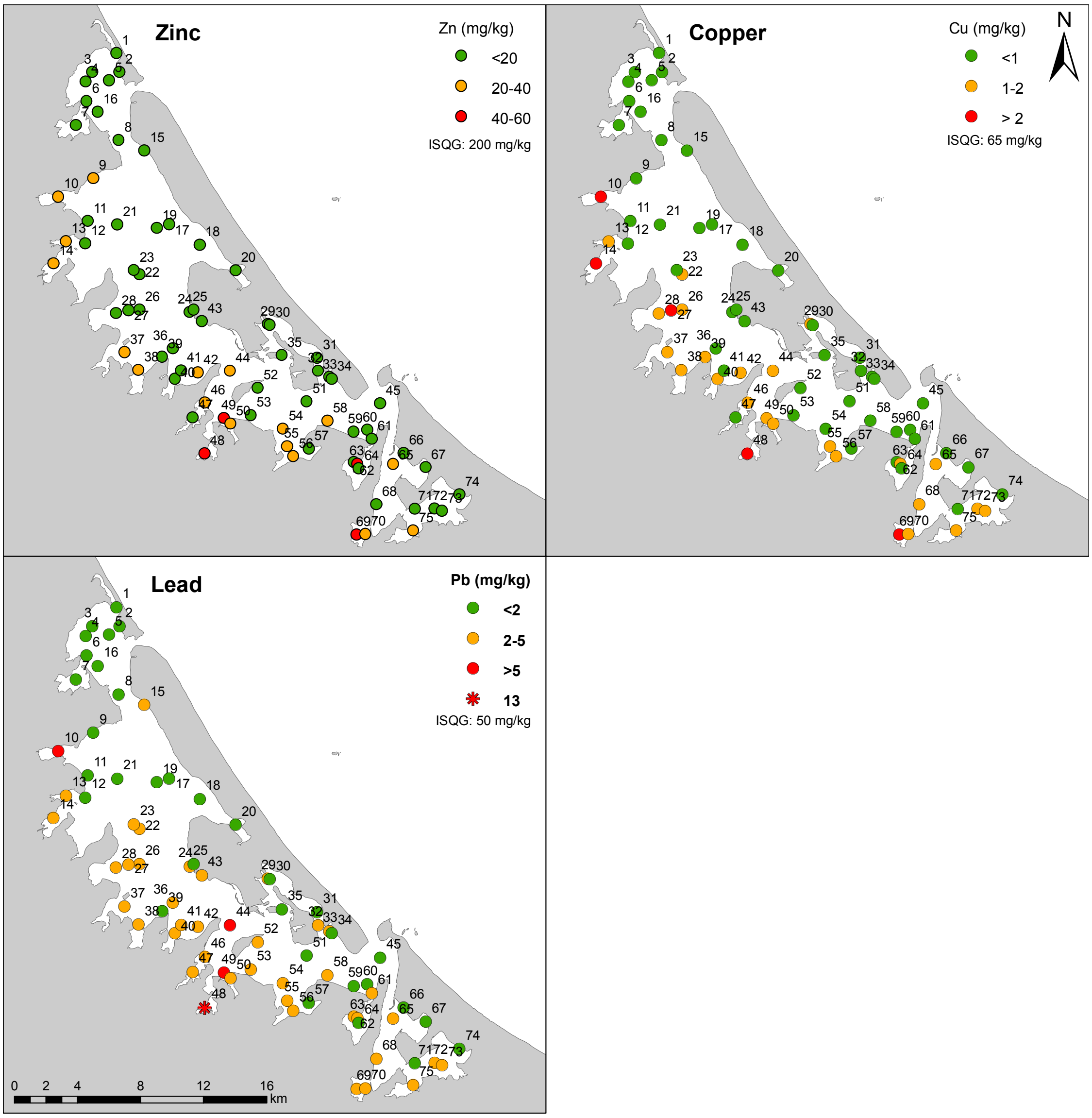

Figure 11. Heavy metal (zinc, copper and lead; mg/kg) concentrations for 75 sites sampled within Tauranga Harbour. ANZECC (2000) Low Interim Sediment Quality Guidelines (ISQG) for each metal are displayed in the legend.

3.1.5. Species distribution

No clear pattern of infaunal abundance or species diversity was seen with respect to location within the harbour (Figure 12). Total abundance (number of individual animals across all species) ranged from 29 to 333 per core and averaged 117. One hundred and thirty-one taxa were found within the harbour with the number of taxa per site ranging from 10 to 39 taxa (three cores). Site 28, in Aongatete, was dominated by Corophiidae amphipods, giving it the highest infaunal abundance (333 per core) in the harbour but the lowest number of taxa (10 taxa in the three cores). High numbers of Corophiidae amphipods were also partially responsible for the elevated total abundances at Sites 56 (Wairoa Estuary) and 53 (Te Puna). Site 48, the muddy area in Te Puna Estuary that was observed to have elevated levels of organic matter, nutrients and heavy metals, was found to have low species richness (11 taxa in the three cores from the site) but relatively high abundances (152 per core), suggestive of an enriched environment. Amphipods were primarily responsible for the high abundance at this site.

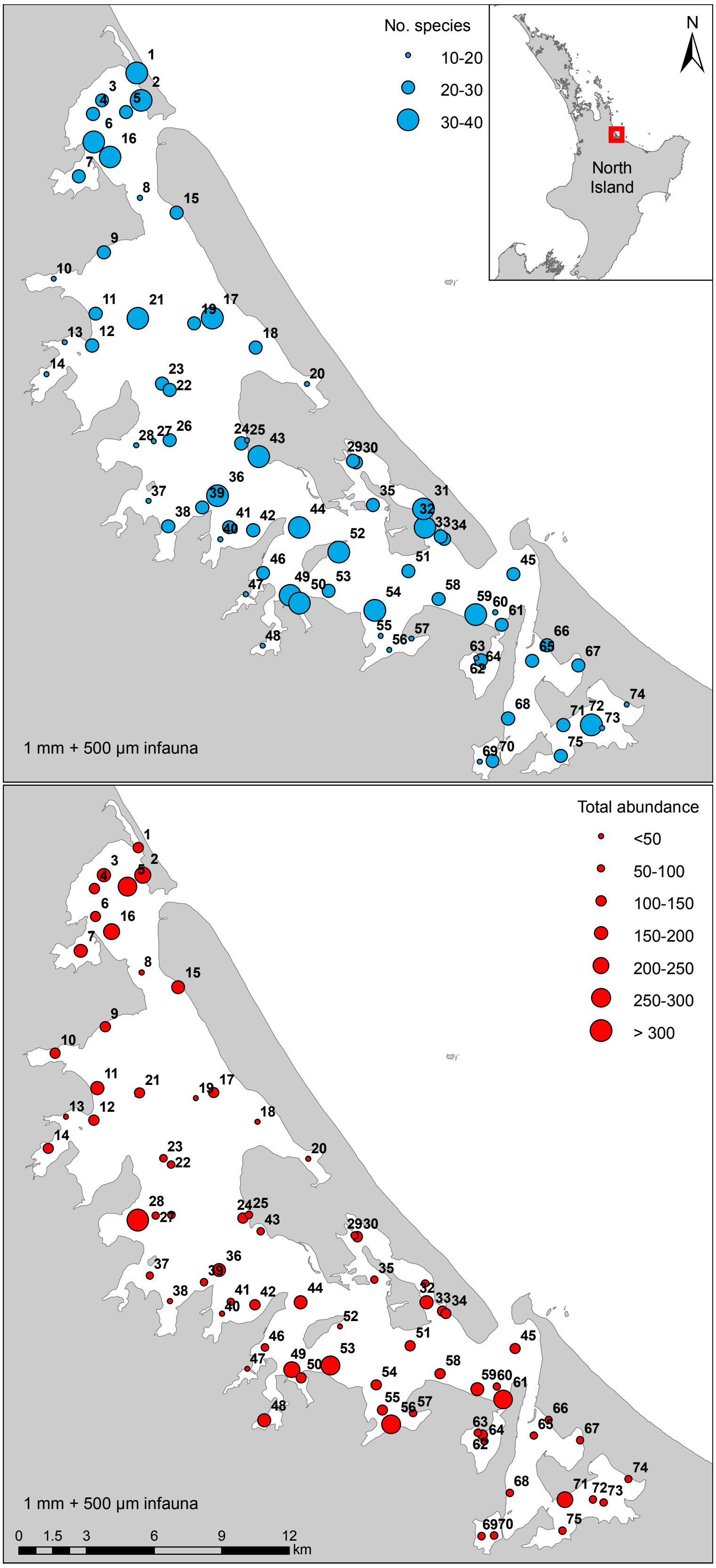

Figure 12. Number of taxa (per site) and average total abundance (per core) of infauna (1 mm and 500 µm size fractions) for 75 sites sampled within Tauranga Harbour.

Although cockles (*A. stutchburyi*) were fairly ubiquitous throughout the harbour (observed at 65 sites), the largest populations were observed in the northern basin, inshore of the Katikati entrance (Figure 13). Other large populations were observed in the upper north harbour (Site 17) and the Waikaraeo entrance (Site 61). Most sites contained a range of size classes with 5 to 20 mm sized cockles the most frequently observed size class. Large cockles (> 20 mm) were observed at 40% of sites, with the highest abundances seen at the Waikaraeo entrance (Site 61) and in the northern harbour (Sites 2 and 16). Small cockles (< 5 mm) were observed at 63% of sites and most common in the northern harbour (Sites 17, 16 and 6).

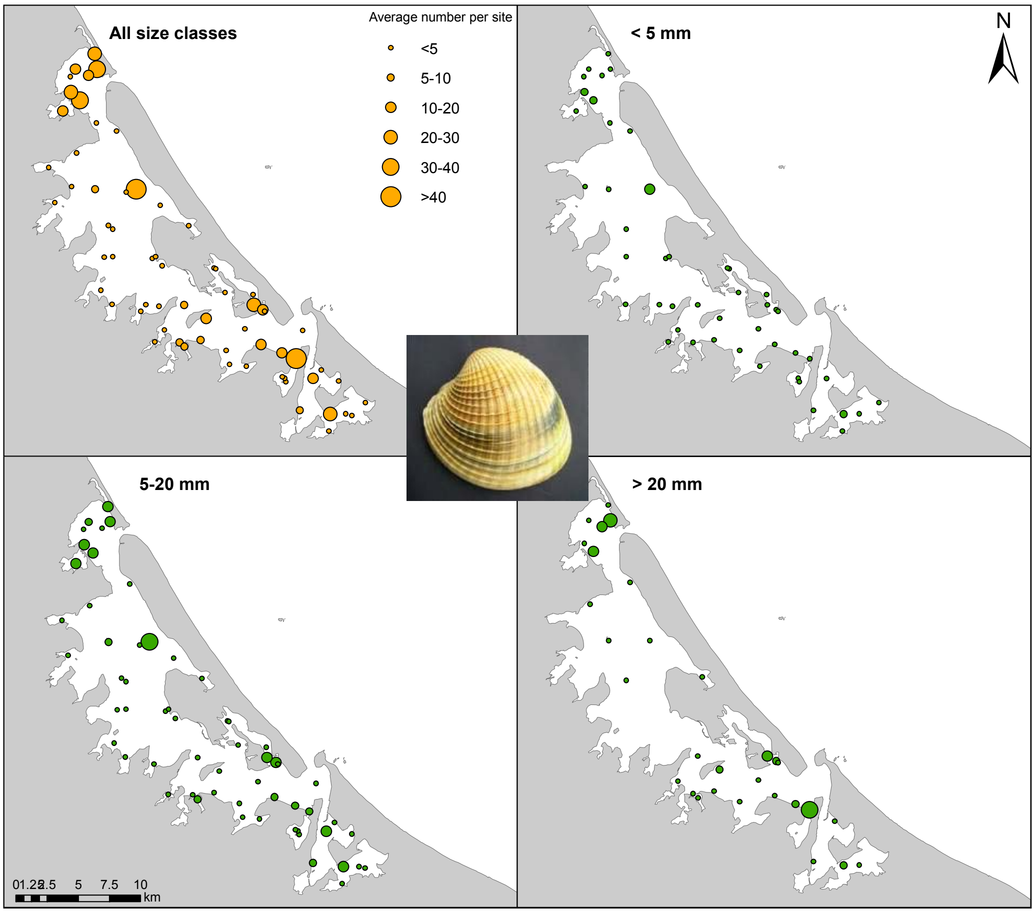

Figure 13. Size class distribution of cockles (*Austrovenus stutchburyi*) at 75 sites sampled within Tauranga Harbour. Numbers are average number per core at each site.

Pipi (*P. australis*) were only observed at 12 of the 75 sites sampled in the harbour and tended to be situated close to the subtidal channels (Figure 14). The largest population (178 pipi counted from 10 cores) was found on the Centre Bank (Site 45), near the Tauranga entrance to the harbour, and was primarily composed of large specimens (74% of pipi > 40 mm; largest 65 mm). Cole *et al.* (2000) also recorded the presence of substantial populations of pipi on Centre Bank. Pipi smaller than 5 mm were only observed at three sites (Sites 5, 53 and 51) and, even then, only in small numbers (1-2 per site). The largest pipi are usually found in the shallow subtidal (Park & Donald 1994), therefore, it is likely that our survey did not capture the full distribution of pipi in Tauranga Harbour. For example, Cole *et al.* (2000) recorded pipi with lengths of up to 82 mm in subtidal areas of Centre Bank. In their 1994 benthic macrofauna survey, Park and Donald found a trend of larger shellfish (cockles, pipi and wedge shells) near the harbour entrance and progressively smaller sizes in the upper harbour, and this pattern is typical of estuaries throughout New Zealand (pers. comm. P Gillespie, Cawthron Institute, March 2013). Park and Donald (1994) suggested that shellfish near the harbour entrances may have better feeding conditions due to food availability and better water quality.

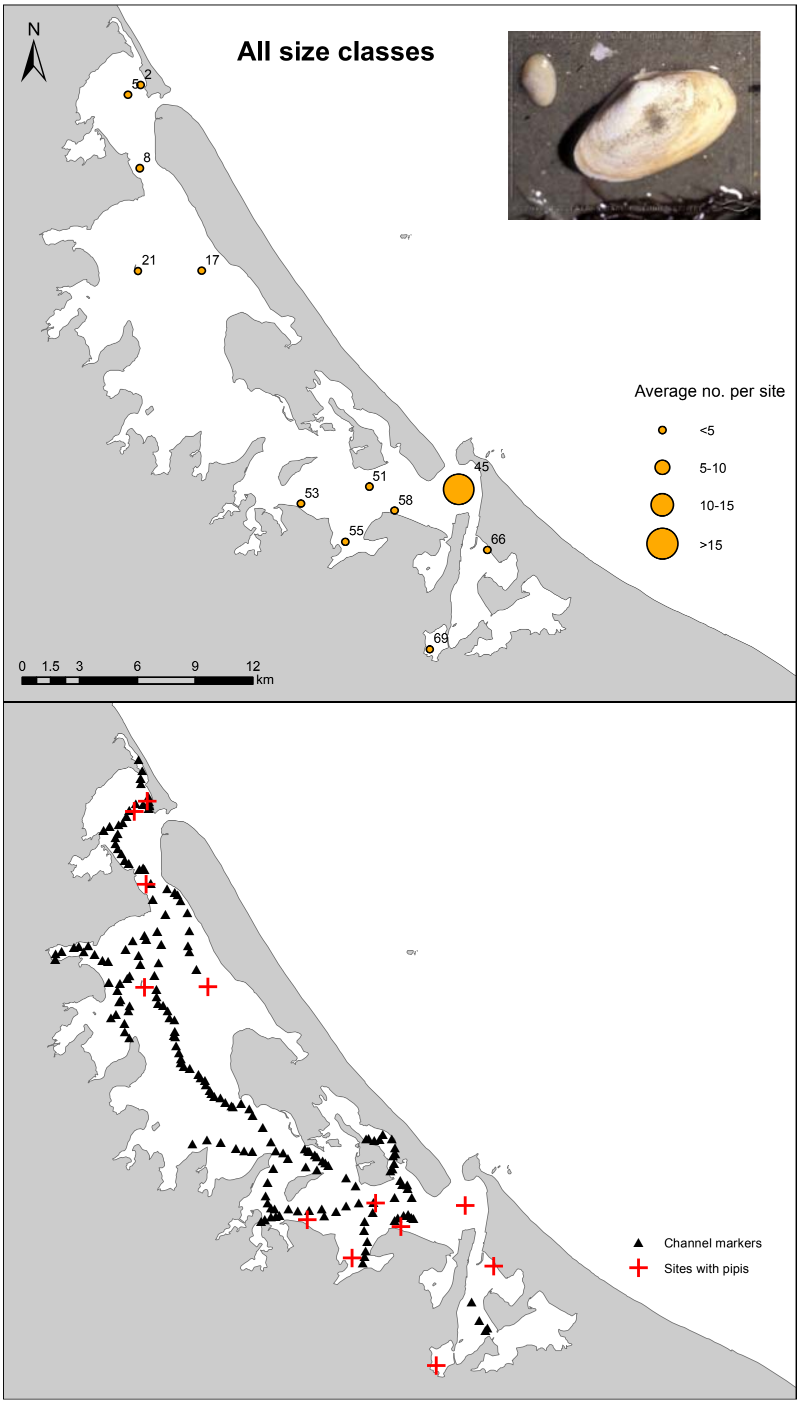

Figure 14. Distribution of pipi (*Paphies australis*) at 75 sites sampled within Tauranga Harbour (top) and location of sites in relation to channel markers (bottom). Numbers are average number per core at each site.

3.2. Key anthropogenic stressors

Adapting variance partitioning methods (Borcard *et al.* 1992; Anderson & Gribble 1998) showed that sedimentation and contamination alone explained most of the observed variation (4.9% and 7.5%, respectively). The intersection term of sedimentation and nutrients also explained a high percentage of the variance (6.1%). Therefore sedimentation and contamination together explained a higher percentage of the variance in the benthic community data than nutrients.

Table 2. Relative percentage variation explained by different anthropogenic stressors determined using adapting variance partitioning methods. Sedimentation (% mud), nutrients (total nitrogen, total phosphorus, chlorophyll-*α*), contamination (copper, lead, zinc).

Anthropogenic stressors	**Relative % variation explained**
Sedimentation	4.9
Nutrients	2.7
Contamination	7.5
Sedimentation*nutrients	6.1
Sedimentation*contamination	0.7
Nutrients*contamination	0.8
Sedimentation*nutrients*contamination	1.7

3.3. Canonical analysis of principal coordinates models

The CAP models are based on infauna data sampled down to the 500 µm fraction (including the 1 mm fraction). Site 48 was removed from both models because it was outside the range of variation observed at the other sites and was an outlier. Inclusion of Site 48 into the models would have resulted in a reduced sensitivity to detect changes across the sedimentation, nutrient and contamination gradients.

In general, results indicated that the sites identified as most impacted, for all three CAP models (sedimentation, nutrients and contamination), were located in the upper reaches of estuaries in some of the least exposed locations. In addition, the sensitivities of organisms characterising sites that have different sediment textures, as well as contaminant and nutrient loadings, were found to vary.

3.3.1. Sedimentation canonical analysis of principal coordinates model

A strong gradient of community change was observed in response to mud content of the sediment ($R^2 = 0.7683$) suggesting that this BHM can be used to determine potential effects of changes in sediment mud content. Over half (58%) of the sites were ranked in ecological health categories less than ‘5’, with most (23%) in ecological health category ‘2’, suggesting fairly healthy communities with regard to sedimentation (Figure 15; Figure 16). The sedimentation ecological health index, was based on the percentage mud content in the sediment, with the muddiest sites (48-49% mud) ranked as ‘8’ (impacted) and sandiest sites (<0.1-1.8% mud) as ‘1’ (healthy; Table 3). The organic content of the sediment increased with increasing ecological health category (mean 1.3% AFDW in category '1' increasing to 4.4% in category '8'), reflecting the tendency of organic material to accumulate in fine sediments. Sites in categories '7' and '8' (0.1% of sites), the most impacted ecological health category, were found in inner estuaries (Figure 16) where deposition of sediments would be expected to be highest. Conversely, sites in categories '1' and '2' (32% of sites) tended to be in outer areas of the harbour.

Interestingly, sites closest to the Wairoa sub-catchment (Sites 54, 55 and 56), the largest sub-catchment and therefore greatest contributor of sediment to the southern harbour (46% of total load; Elliott *et al.* 2010), did not show particularly high ecological health values for sedimentation (category '4-5'). However, sites in estuaries near smaller, but higher sediment yielding, sub-catchments (*e.g.* Apata, Wainui) did show correspondingly high ecological health values.

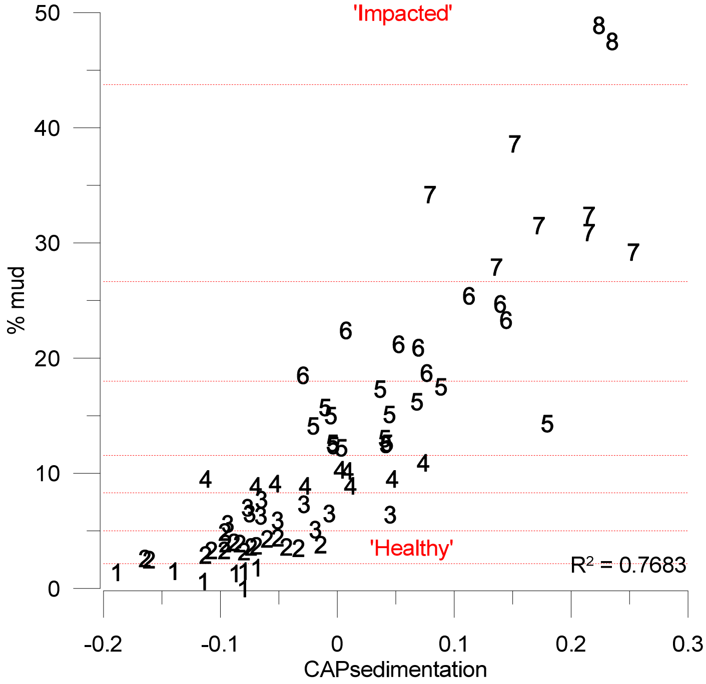

Figure 15. Canonical analysis of principal coordinates (CAP) for mud versus percentage silt and clay in sediment (mud) for 75 sites in Tauranga Harbour (1 mm + 500 µm model). Red dashed lines demarcate the eight sedimentation ecological health categories with '1' indicating a relatively 'healthy' community and '8' indicating a more 'impacted' community.

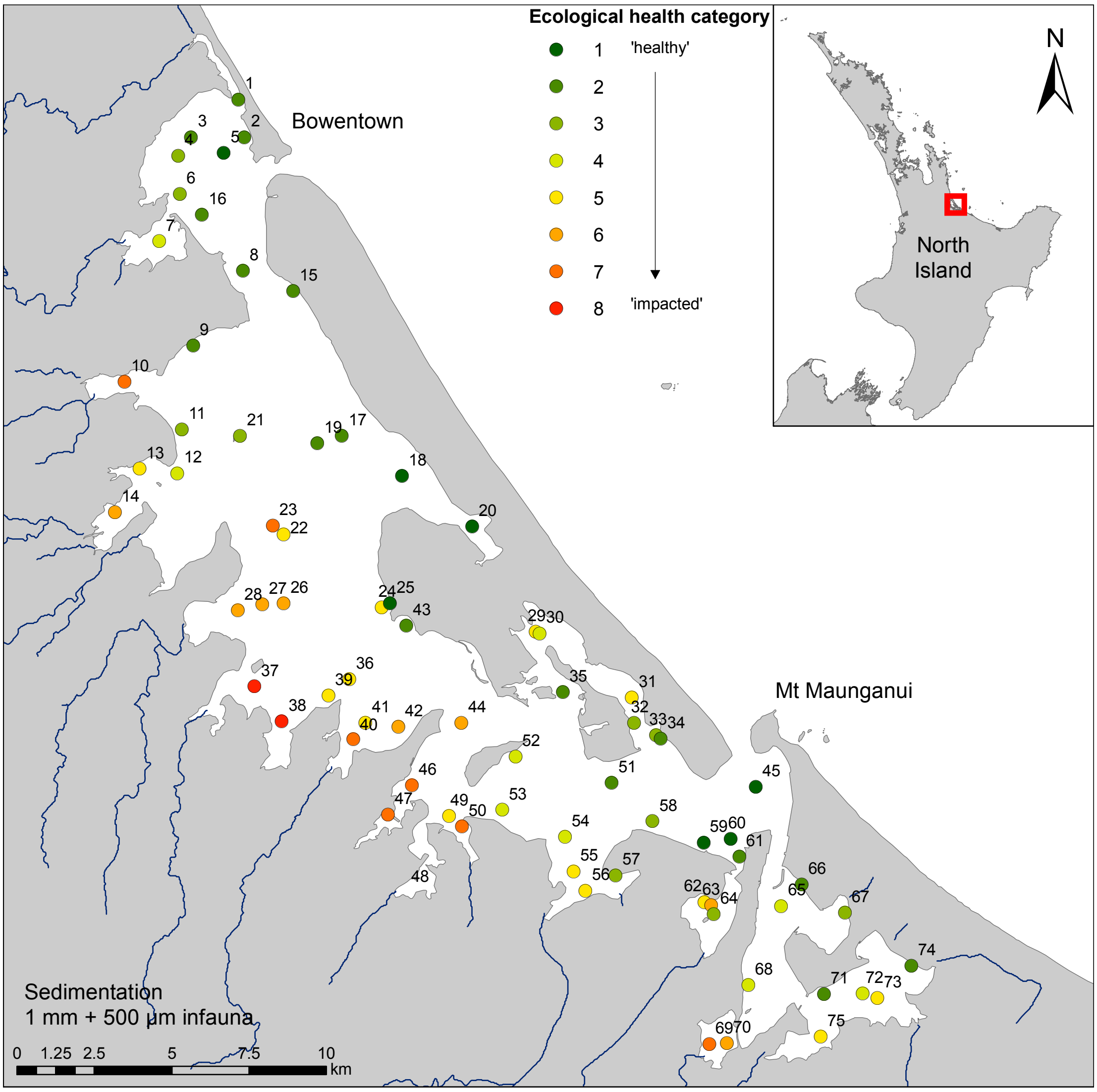

Figure 16. Canonical analysis of principal coordinates (CAP) for sedimentation (1 mm + 500 µm model) in Tauranga Harbour for 75 sites. Colours indicate the ecological health categories where a green (low) ranking indicates a low effect of sedimentation ('healthy') and a red (high) ranking indicates a high effect ('impacted'). Major rivers and streams entering the harbour are shown in blue.

Table 3. Sedimentation ecological health categories (1 mm + 500 µm model) for 75 sites in the Tauranga Harbour and corresponding ranges for key variables for each group. AFDW = ash-free dry weight, chl-*α* = chlorophyll-*α*, N = total abundance per core, S = total number of taxa per site, J = Pielou's evenness, H = Shannon-Wiener index.

	Category	Sites	% gravel	% sand	% silt/clay	% AFDW	Chl-*α* (µg/kg)	N	S	J	H
'Healthy'	1	5, 18, 20, 25, 45, 59, 60	< 0.1–4.0	94.2-100	<0.1-1.8	0.9–1.8	210-11000	42-257	17–39	0.6–0.8	1.9–2.7
	2	1, 2, 3, 8, 9, 15, 16, 17, 19, 34, 35, 43, 51, 61, 66, 71, 74	0.1–14.6	82.8-96.7	2.5-4.9	1.0–3.0	1200–11000	29–263	16–34	0.5–0.9	1.5–3.0
↓	3	4, 6, 11, 21, 32, 33, 57, 58, 64, 67	0.1–5.9	62.7–94	5.1–7.7	1.9–3.8	2600–11000	59–164	14–36	0.5–0.8	1.4–2.7
	4	7, 12, 30, 52, 53, 54, 65, 68, 72	0.1–7.1	83.4–91	8.9–10.9	1.8–3.4	1900–10000	68–267	23–37	0.6–0.8	1.8–2.9
	5	13, 22, 24, 29, 31, 36, 39, 41, 49, 55, 56, 62, 73, 75	0.1–5.6	51.6–87.5	12.2–17.5	2.5–4.2	2800–16000	39–268	14–35	0.4–0.8	1.2–2.8
'Impacted'	6	14, 26, 27, 28, 42, 44, 63, 70	< 0.1-1.6	73.9-81.3	18.5-25.4	3.1-4.5	3600-10000	61-333	10-39	0.08-0.8	0.2-2.7
	7	10, 23, 40, 46, 47, 50, 69	0.2-10.2	60-68.4	27.9-38.6	3.1-4.5	1100-9600	38-133	14-31	0.4-0.8	1.1-2.4
	8	37, 38	0.3-1.5	50.7-51	47.5-48.9	4.2-4.5	3300-4100	35-78	19-21	0.6-0.8	1.7-2.4

Note: Site 48 excluded from CAP analysis because it was an outlier (outside the range of variation observed at the other sites).

Infauna numbers were lowest at the most impacted category sites (ecological health categories ‘7’ and ‘8’, means of 85 and 56 per core, respectively) but no clear trend was observed amongst the other categories (means of 110-138 per core; Table 3). In general, species richness was slightly higher at healthier sites (means of 25-30 taxa per site) than more impacted sites (means of 20-24 taxa per site). The key species differences at healthy versus impacted sites along an increasing gradient of siltation are provided in Table 4. Key species associated with high silt and clay included the polychaete worms Nereididae, *Scolecolepides benhami* and *Heteromastus filiformis* and the deposit feeding bivalve *Arthritica bifurca*. Key benthic species associated with low silt and clay included the worms *Scoloplos cylindrifer* and *Scolelepis* sp., the gastropod *Halopyrgus pupoides* and Oligochaete worms.

Table 4. Key species identified along pollution gradients for sedimentation, nutrient and contamination models as determined using Distance based Linear Models (DistLM). Species that respond negatively to increasing nutrients/contaminants are sensitive to elevated nutrients/contaminants, while species that respond positively to increasing nutrients/contamination are more tolerant to that stressor and can be found at sites with high nutrient/contaminant loadings. Abbreviations for feeding mode D = deposit feeder, P = predator/scavenger, S = suspension feeder, G = grazer.

Model	Association	Species	Faunal group	Feeding mode
Sedimentation	Low mud	*Scoloplos cylindrifer*	Marine worm (Orbinid polychaete)	D (surface / subsurface)
		Scolelepis sp.	Marine worm (Spionid polychaete)	D
		Halopyrgus pupoides	Marine snail (Gastropod)	Microalgal and detrital grazer
		Oligochaeta	Marine worm (Oligochaete)	D
	High mud	*Scolecolepides benhami*	Marine worm (Spionid polychaete)	D (surface deposit)
		Heteromastus filiformis	Marine worm (Capitellid polychaete)	D (sub-surface deposit)
		Arthritica bifurca	Shellfish (Bivalve)	D
		Nereididae	Marine worm (Nereid polychaete)	P
Nutrients	Negative	*Scolelepis* sp.	Marine worm (Spionid polychaete)	D (surface)
	Positive	*Scolecolepides benhami*	Marine worm (Spionid polychaete)	D (surface deposit)
		Heteromastus filiformis	Marine worm (Capitellid polychaete)	D (sub-surface deposit)
		Amphipoda indeterminata	Amphipod	D, P, G
Contamination	Negative	*Orbinia papillosa*	Marine worm (Orbinid polychaete)	D
	Positive	*Scolecolepides benhami*	Marine worm (Spionid polychaete)	D (surface deposit)
		Heteromastus filiformis	Marine worm (Capitellid polychaete)	D (sub-surface deposit)
		Arthritica bifurca	Shellfish (Bivalve)	D
		Amphipoda indeterminata	Amphipod	D, P, G

3.3.2. Nutrient canonical analysis of principal coordinates model

The nutrient CAP model was based on a constrained ordination of benthic community taxa in relation to the ecological gradient (PCnutrients) generated from the concentrations of TN, TP and chl-*α* at each site. A gradient of community change was observed in response to nitrogen, phosphorus and chl-*α* concentrations in the sediment suggesting that the BHM can be used to determine potential effects of changes in nutrient concentrations. Most of the sites (26%) were ranked in ecological health category '2', with very few in the most healthy ('1') and impacted ('6') categories (9 and 7%, respectively; Figure 17; Figure 18). The level of impact from nutrients was closely related to concentrations of nitrogen and phosphorus in the sediment, with increasing TN and TP concentration as ecological health categories increased (*i.e.* became more impacted; Table 5). Organic content also increased along the nutrient gradient. Sites in categories '4' and '5', the most impacted categories, were generally found in estuaries along the inner coast of the harbour, whereas sites ranked lower tended to be situated in the outer harbour (Figure 18). While this CAP model was generated from a significant community response to a nutrient gradient, its correlation was the lowest (R^2 = 0.5135) compared to the CAP models for sedimentation and contamination.

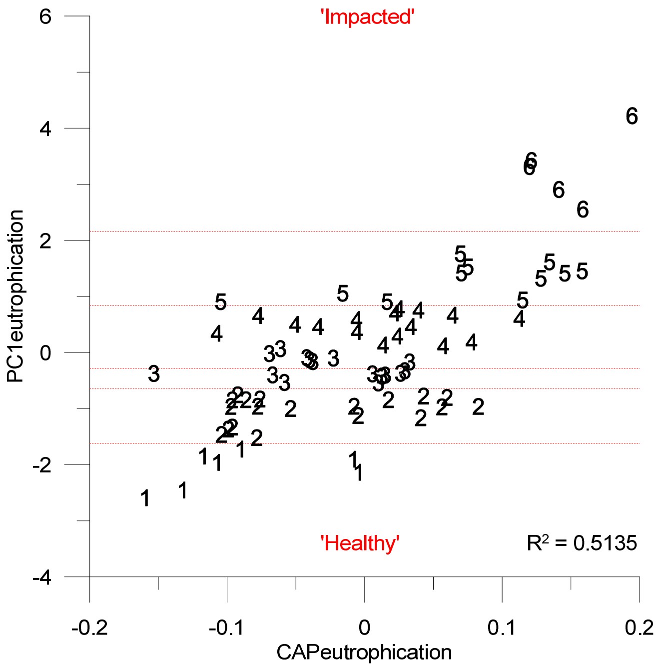

Figure 17. Canonical analysis of principal coordinates (CAP) for nutrients versus the PC1 axes derived from sediment nutrient data (TN, TP, chl-*α*) for 75 sites in Tauranga Harbour (1 mm + 500 µm model). Red dashed lines demarcate the six ecological health categories with '1' indicating a relatively 'healthy' community and '6' indicating a more 'impacted' community.

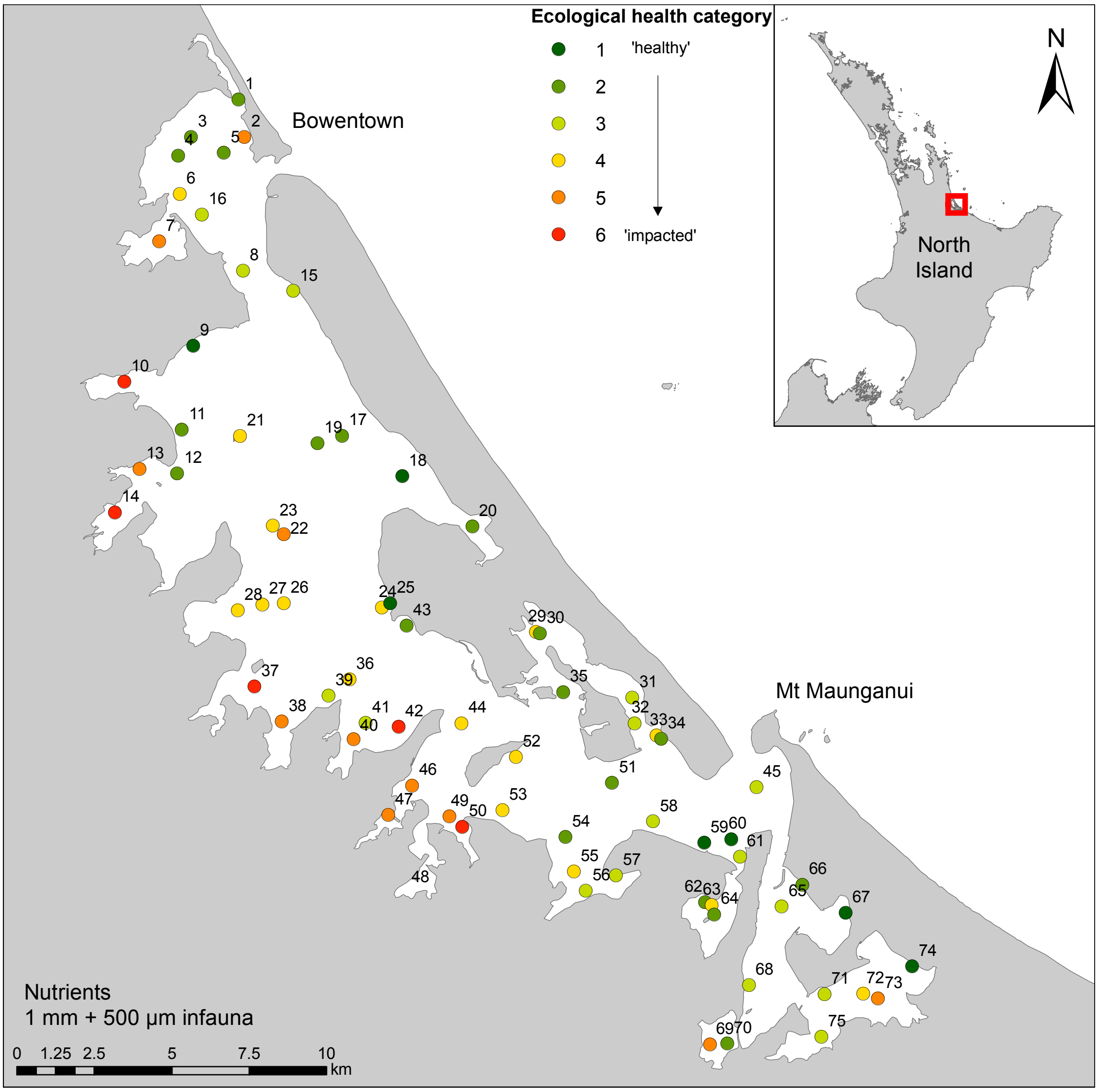

Figure 18. Canonical analysis of principal coordinates (CAP) for nutrients (1 mm + 500 µm model) in Tauranga Harbour for 75 sites. Colours indicate the ecological health categories where a green (low) ranking indicates a low effect of nutrients ('healthy') and a red (high) ranking indicates a high effect ('impacted').

Table 5. Nutrient ecological health categories (1 mm + 500 µm model) for 75 sites in the Tauranga Harbour and corresponding ranges for key variables for each group. TN = total nitrogen, TP = total phosphorus, AFDW = ash-free dry weight, chl-*α* = chlorophyll-*α*, N = total abundance per core, S = total number of taxa per site, J = Pielou’s evenness, H = Shannon-Wiener index.

‘Healthy’ → ‘Impacted’

Category	Sites	TN (mg/kg)	TP (mg/kg)	% AFDW	Chl-α (µg/kg)	N	S	J	H
1	9, 18, 25, 59, 60, 67, 74	140–220	51–110	0.9–1.9	210–4000	49–170	17–39	0.6–0.8	1.9–2.7
2	1, 3, 4, 5, 11, 12, 17, 19, 20, 30, 34, 35, 43, 51, 54, 62, 64, 66, 70	250–460	91–160	1.4–3.4	1200–11000	29–257	17–33	0.5–0.9	1.5–3.0
3	8, 15, 16, 31, 32, 39, 41, 45, 56, 57, 58, 61, 65, 68, 71, 75	280–520	120–180	1.2–3.5	1200–15000	46–268	14–33	0.5–0.8	1.4–2.7
4	6, 21, 23, 24, 26, 27, 28, 29, 33, 36, 44, 52, 53, 55, 63, 72	390–690	130–220	2.4–4.3	3600–16000	61–333	10–39	0.08–0.8	0.2–2.9
5	2, 7, 13, 22, 38, 40, 46, 47, 49, 69, 73	540–700	180–260	2.4–4.2	2800–10000	35–239	14–34	0.4–0.8	1.1–2.4
6	10, 14, 37, 42, 50	760-1000	280-340	4.0-4.5	1100-9600	78-133	13-31	0.4-0.7	1.1-2.4

Note: Site 48 excluded from CAP analysis because it was an outlier (outside the range of variation observed at the other sites).

No clear trend in abundances of organisms was apparent with infauna numbers highest at category '3' and '4' sites (means of 135 and 141 per core, respectively) and lowest at category '1' sites (mean 84 per core; Table 5). Species richness was similar in the first four categories (means of 24-27 taxa per site) but slightly lower at category '5' and '6' sites (means of 22 and 19 taxa per site, respectively). The univariate measures were, therefore, in general not as sensitive at detecting differences across the ecological health categories. The polychaete *Scolelepsis* sp. was associated with high nutrients while key species sensitive to elevated nutrient loadings included the polychaete worms *S. benhami* and *H. filiformis* and amphipods (Table 4).

3.3.3. Contamination canonical analysis of principal coordinates model

The contamination CAP model was based on a constrained ordination of benthic community taxa in relation to the ecological gradient (PCcontamination axis) generated from the concentration of heavy metals (Pb, Cu and Zn) at each site. A strong gradient of community change was observed in response to heavy metal concentrations in the sediment (R^2 = 0.7075) suggesting that the BHM can be used to determine potential effects of changes in metal concentrations. Most of the sites were ranked in ecological health categories '2' (24%), '3' (24%) and '4' (26%; Figure 19; Figure 20). All metal concentrations increased with increasing ecological health category (Table 6). The percentage mud of the sediment also tended to increase with increasing ecological health values, reflecting the tendency of metals to bind with fine sediments. As with the other CAP models, category '5' sites tended to be situated in inner harbour areas and category '1' and '2' sites further out.

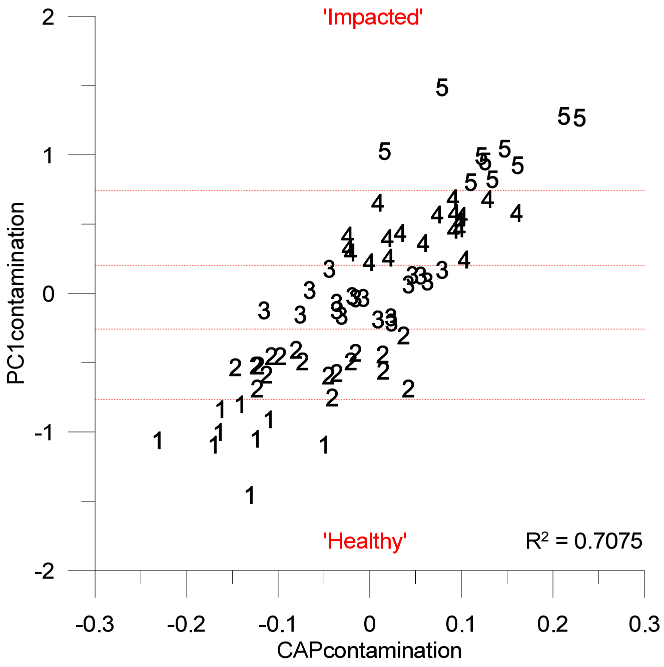

Figure 19. Canonical analysis of principal coordinates (CAP) for contamination versus the PC1 axes derived from heavy metal concentrations in sediments (Cu, Pb, Zn) for 75 sites in Tauranga Harbour (1 mm + 500 µm model). Red dashed lines demarcate the five ecological health categories with ‘1’ indicating a relatively ‘healthy’ community and ‘5’ indicating a more ‘impacted’ community.

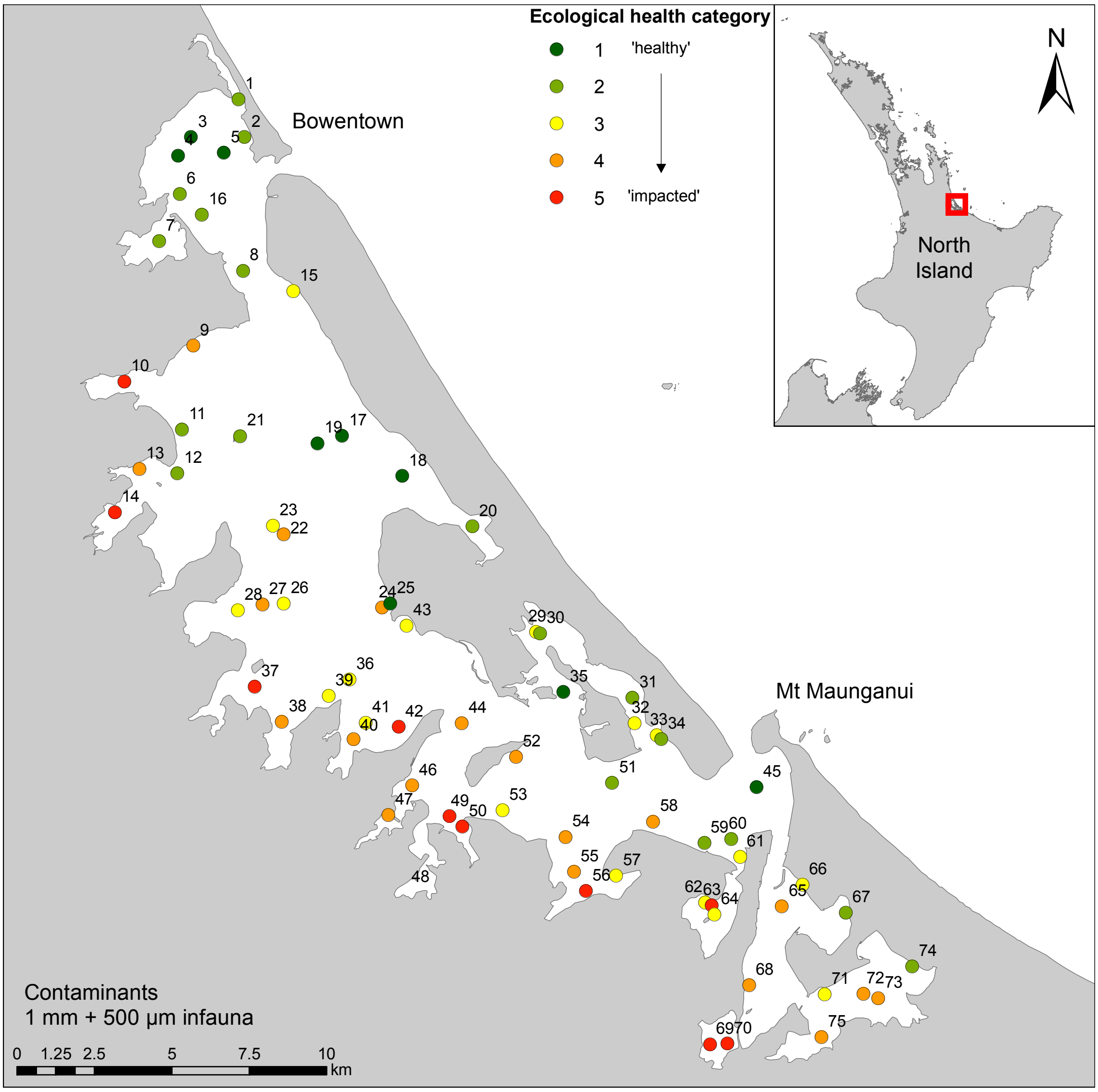

Figure 20. Canonical analysis of principal coordinates (CAP) for contamination (1 mm + 500 µm model) in Tauranga Harbour for 75 sites. Colours indicate the ecological health categories where a green (low) ranking indicates a low effect of contamination (‘healthy’) and a red (high) ranking indicates a high effect (‘impacted’).

Table 6. Contamination ecological health categories (1 mm + 500 µm model) for 75 sites in the Tauranga Harbour and corresponding ranges for key variables for each group. Pb = lead, Cu = copper, Zn = zinc, N = total abundance per core, S = total number of taxa per site, J = Pielou's evenness, H = Shannon-Wiener index.

	Category	Sites	Pb (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	% silt/clay	N	S	J	H
'Healthy'	1	3, 4, 5, 17, 18, 19, 25, 35, 45	< 1.0–1.4	< 1.0	< 5.1–8.0	1.3–5.6	29–257	17–32	0.6–0.8	1.9–2.6
	2	1, 2, 6, 7, 8, 11, 12, 16, 20, 21, 30, 31, 34, 51, 59, 60, 67, 74	< 1.0–1.9	< 1.0	7.5–12.0	< 0.1–13.0	42–241	16–39	0.5–0.8	1.5–2.7
↓	3	15, 23, 26, 28, 29, 32, 33, 36, 39, 41, 43, 53, 57, 61, 62, 64, 66, 71	1.2–3.1	< 1.0–1.6	12.0–20.0	2.6–34.2	56–333	10–35	0.08–0.9	0.2–3.0
'Impacted'	4	9, 13, 22, 24, 27, 38, 40, 44, 46, 47, 52, 54, 55, 58, 65, 68, 72, 73, 75	1.4–5.1	< 1.0–2.2	18.0–28.0	3.6–48.9	35–198	14–39	0.4–0.8	1.2–2.9
	5	10, 14, 37, 42, 49, 50, 55, 56, 63, 69, 70	3.0–5.6	1.3–3.0	26.0–55.0	12.5–47.5	67–268	13–34	0.4–0.7	1.1–2.4

Note: Site 48 excluded from CAP analysis because it was an outlier (outside the range of variation observed at the other sites).

Infauna numbers were lowest at category ‘4’ sites (mean 91 per core) and highest at category ‘3’ and ‘5’ sites (means of 136 and 134 per core; Table 6). Species richness did not greatly differ across the first four categories (means of 25-28 taxa per site) and was reduced slightly only at the most polluted sites (category ‘5’; mean 21 taxa per site). Again the univariate measures in general were not as sensitive as the multivariate ordinations at detecting differences across the ecological gradient. Key species associated with high contaminant loadings included the polychaete worm *Orbinia papillosa* while species sensitive to elevated contaminant loadings included the polychaete worms *S. benhami*, *H. filiformis*, amphipods and the deposit feeding bivalve *A. bifurca* (Table 4).

3.4. Species response models

None of the modelled taxa were found at the site with the highest sediment, nutrient and contaminant levels. All taxa displayed clear differences in abundance ($R^2 \geq 0.55$) as a function of at least one of the ecological gradients; sedimentation, nutrients or contamination (Table 7). Sedimentation (mud content) was generally the best predictor (explained the highest variability for 12 of the 20 taxa modelled), followed by nutrients (PC1 nutrients).

Table 7. Summary of generalised linear models predicting maximum density for 20 macroinvertebrate taxa in response to sedimentation, nutrients and contamination. Only significant ($p > 0.05$) models are displayed. Taxonomic groups are: A = Anthozoa, B = Bivalvia, D = Decapoda, G = Gastropoda, P = Polychaeta. Responses are: D = decline, SU = skewed unimodal, U = unimodal. Bold text indicates the stressor (sedimentation, nutrients or metal) that explained the highest variation in abundance (R^2) for a given taxon.

		Sedimentation		*Nutrients*		*Contamination*	
Taxa	*Group*	*R^2*	*Response*	*R^2*	*Response*	*R^2*	*Response*
Anthopleura aureoradiata	A	**0.88**	SU	0.56	U	0.37	D
Arcuatula senhousia	B	0.45	U	**0.75**	U	0.61	U
Austrovenus stutchburyi	B	0.77	SU	**0.92**	U	0.64	SU
Linucula hartvigiana	B	0.88	D	**0.91**	U	0.68	SU
Macomona liliana	B	0.45	SU	**0.55**	U	0.23	D
Paphies australis	B	0.90	D	0.95	U	**0.97**	D
Zemysia zelandica	B	0.63	U	**0.67**	U	0.54	U
Halicarcinus cookii	D	**0.82**	SU	0.43	U	0.63	SU
Diloma subrostratum	G	**0.75**	D	0.49	U	0.64	SU
Micrelenchus huttonii	G	0.49	SU	**0.64**	U	0.51	D
Notoacmea elongata	G	**0.93**	D	0.69	U	0.82	D
Zeacumantus lutulentus	G	**0.87**	D	0.18	U	0.55	U
Zeacumantus subcarinatus	G	**0.98**	D	0.63	U	0.87	U
Hyboscolex longiseta	P	**0.74**	U	0.54	U	0.41	U
Magelona dakini	P	0.98	D	**0.99**	U		
Maldanidae	P	**0.91**	SU	0.82	SU	0.37	SU
Orbinia papillosa	P	**0.77**	D	0.69	D	0.61	D
Owenia petersenae	P	**0.93**	D	0.70	U	0.64	U
Scoloplos cylindrifer	P	**0.79**	D	0.39	U	0.54	D
Terebellidae	P	**0.93**	U	0.23	U	0.68	U

The models revealed a variety of functional forms, indicating species-specific sensitivity to mud content, nutrients and/or contamination. We identified three types of responses; decline, unimodal and skewed unimodal. A decline response was defined as a relatively large increase in abundance followed by an equivalent decrease and a skewed unimodal response was defined as a relatively small increase in abundance at the lower end of the stressor range followed by a decrease. In most cases, skewed unimodal responses were more similar to decline responses than unimodal responses, however, in all cases an initial increase in abundance was observed at the lower end of the stressor range.

All taxa, except two, showed unimodal responses to nutrient loading, while all three types of responses were found for sedimentation and metals. No continuous increasing responses to the stressors were found for any of the taxa and only one model was non-significant. Appendix 3 details the models fitted to maximum abundance data (species response models) for sedimentation, nutrients and metals.

3.4.1. Sedimentation

For sedimentation, most models effectively explained variability in the distribution of maximum taxa abundance ($R^2 > 0.60$), except for three mollusc species (*Arcuatula senhousia, Macomona liliana* and *Micrelenchus huttonii*, $R^2 < 0.50$; Table 7). Most taxa (12) preferred sandier sediments and decreased in abundance in response to increasing mud (Figure 21). Responses of six taxa were classified as skewed unimodal with responses of the other four classified as unimodal. Most taxa were distributed over the majority of the modelled sedimentation range (0-50% mud) with *Zemysia zelandica, Paphies australis, Halicarcinus cookii* and *Magelona dakini* showing more restrained distributions (0-15% mud).

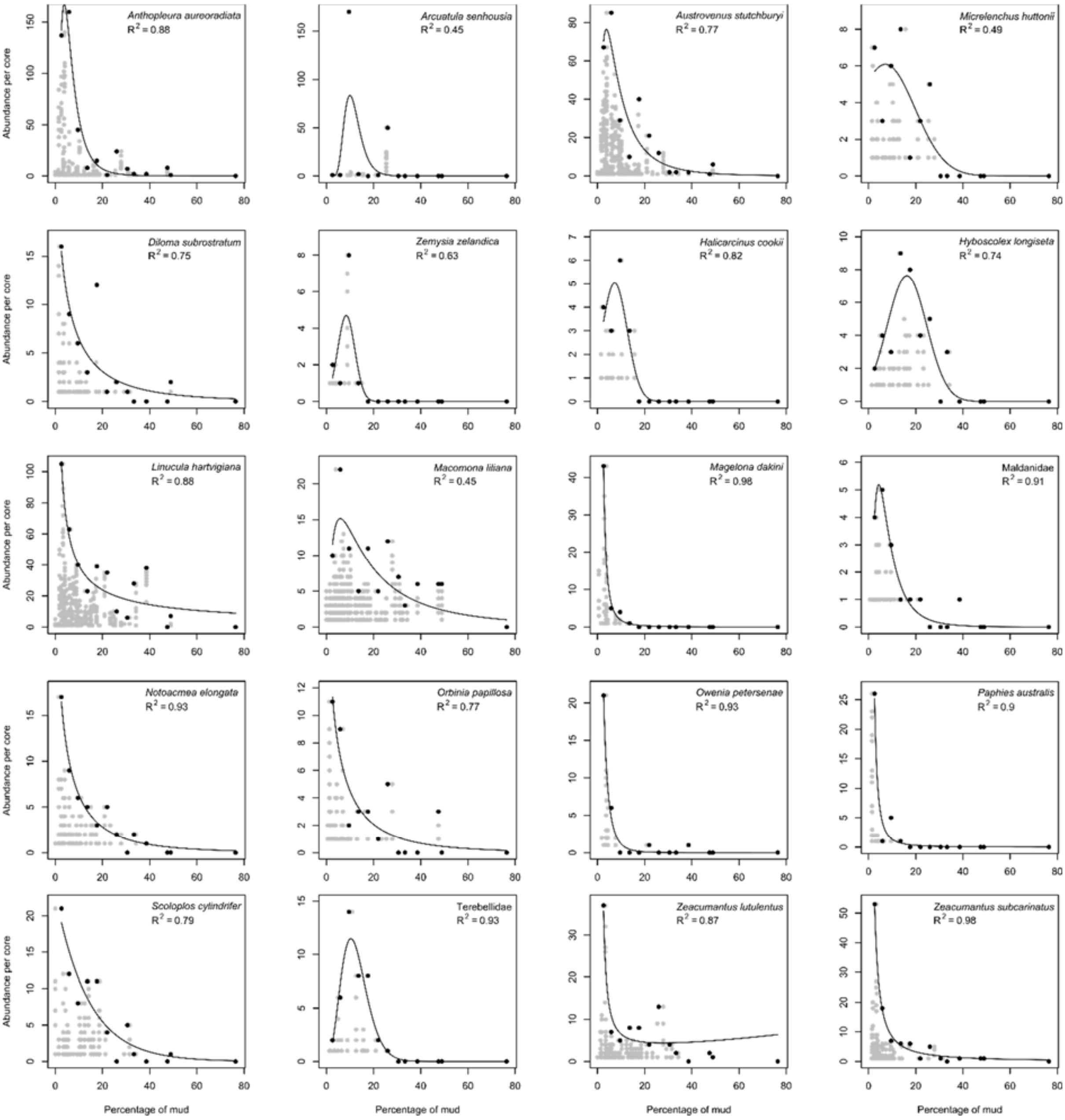

Figure 21. Plots of the relationship between individual taxa (as indicated) and percentage mud in the sediment. Each grey point is a single core, with 10 cores taken from each of 75 sites. Black points show the binned data. The generalised linear model for maximum abundance of the binned data is shown.

3.4.2. Nutrients

For nutrients, most models effectively explained variability in the distribution of maximum abundance ($R^2 > 0.50$), except for the crab (*Halicarcinus cookii*), two gastropods (*Diloma subrostratum* and *Zeacumantus lutulentus*) and two polychaetes (*Scoloplos cylindrifer* and Terebellidae), for which only 18 to 49% of the variability could be explained (Table 7). All taxa, except two, exhibited unimodal responses

(Figure 22). The polychaete *Orbinia papillosa* exhibited a decline with increased nutrient loading while the Maldanidae family of polychaetes showed a skewed unimodal response. Taxa distribution in response to nutrient loading was species specific. For example, some bivalves (*Paphies australis, Arcuatula senhousia* and *Zemysia zelandica*) exhibited small distributional ranges while others (*Macomona liliana, Linucula hartvigiana* and *Austrovenus stutchburyi*) were less restricted.

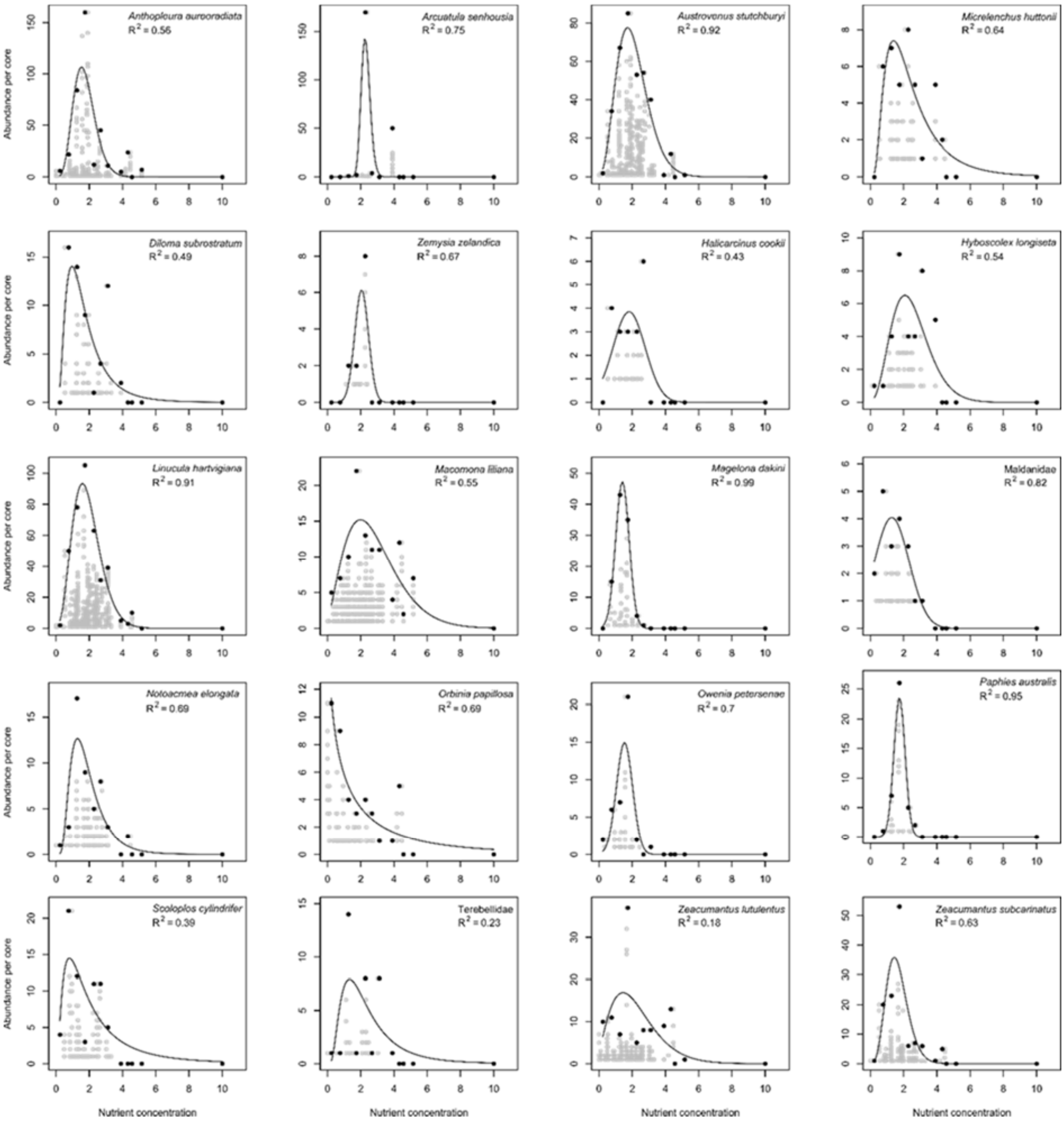

Figure 22. Plots of the relationship between individual taxa (as indicated) and nutrients (PC1 nutrients) in the sediment. Each grey point is a single core, with 10 cores taken from each of 75 sites. Black points show the binned data. The generalised linear model for maximum abundance of the binned data is shown.

3.4.3. Contamination

For metals, most models effectively explained variability in the distribution of maximum abundance ($R^2 > 0.50$), except *for Anthopleura radiata, Macomona liliana, Hyboscolex longiseta* and Terebellidae, for which only 21 to 41% of the variability could be explained (Table 7). No relationship between metal concentrations and abundance was found for the polychaete *Magelona dakini.* Many of the taxa were found across the majority of the modelled metal concentration range but, similar to sedimentation, *Zemysia zelandica, Paphies australis, Halicarcinus cookii* and *Magelona dakini* were restricted to less contaminated sites (Cu < 1.4, Pb < 3.6 mg/kg). Seven taxa declined in response to increasing sediment metal concentrations while another seven were classified as exhibiting a skewed unimodal response (Figure 23). The remaining seven taxa displayed unimodal responses. Many of the responses to metals were similar to those found for sedimentation, and even where the response changed from decline to unimodal, as for *Owenia petersenae, Zeacumatus lutulentus* and *Zeacumantus subcarinatus*, the maximum abundance for both stressors was still at the lower end of the range.

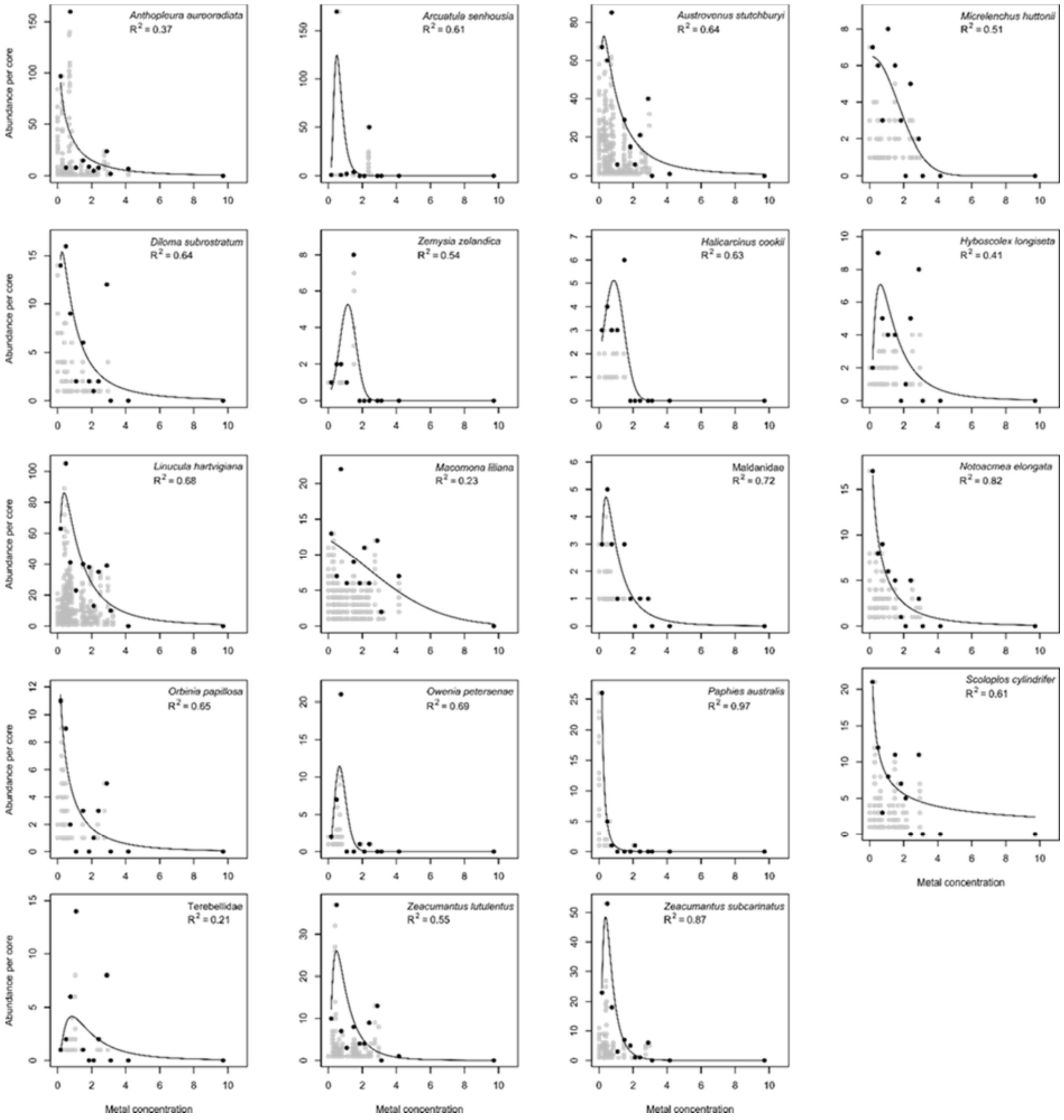

Figure 23. Plots of the relationship between individual taxa (as indicated) and metals (PC1 metals). Each grey point is a single core, with 10 cores taken from each of 75 sites. Black points show the binned data. The generalised linear model for maximum abundance of the binned data is shown. The plot for *Magelona dakini* is not shown because it was not significant.

4. DISCUSSION

In this report we summarise the results from a broad scale survey of the Tauranga Harbour that assessed both the health of macrofaunal benthic communities (bottom-dwelling animals) as well as trends in sediments, nutrients and contaminants. Sites identified as most impacted were generally located in the upper reaches of estuaries in some of the locations least exposed to wind, waves and currents. To some extent, this reflects the natural progression of an estuary from land to sea (for example, higher sedimentation close to the coast), however, the rates of accumulation of sediments and nutrients have been accelerated as a result of anthropogenic land-based activities.

In addition, the community composition and key species characterising sites with different sediment textures, nutrient and contaminant loadings were found to vary. Using community data we developed ordination models of ecological health for sedimentation, nutrients and contamination. Before discussing the results of these community-based models we first summarise general trends in sedimentation, nutrients and contamination that were recorded within Tauranga Harbour.

4.1. Physical patterns of elevated sediments, nutrients and heavy metal contamination

Sediments within Tauranga Harbour were found to be predominantly sandy with the percentage of mud within a similar range as measured for other New Zealand estuaries (Table 8). The exceptions included Te Puna and Apata Estuaries, which showed higher rates of sedimentation consistent with previous studies. The inner Te Puna Estuary was identified by Hume *et al.* (2010) as the most depositional sub-estuary in the southern harbour with net accumulation of 6.51 mm y^{-1}. Similarly, Park (2003) and Hancock *et al.* (2009) identified the Apata Estuary as one of the muddiest areas of the harbour. Modeling of sediment loads into the southern Tauranga Harbour identified both the Te Puna and Apata sub-catchments as having relatively high sediment yields, with the Apata sub-catchment yielding the most sediment of all the sub-catchments modeled due to the relatively high rainfall in conjunction with pasture land use and moderate slopes (Elliott *et al.* 2010).

Table 8. Comparison of average particle size and nutrient characteristics of sediments sampled during the present survey with previously reported values for some other New Zealand estuaries. Mean values are displayed with estuary ranges in brackets beneath. Mud-dominated sites are shaded.

Location	**Sand**	**Mud**	**AFDW**	**TN**	**TP**	**TN:TP**	**General estuary condition/health**
	%	**%**	**%**	**mg/kg**	**mg/kg**	**Molar**	
Tauranga Harbour (present study)							
Sand-dominated sites	85 (51-100)	13 (1–49)	2.8 (0.9–4.5)	462 (140–1000)	164 (51–340)	6.4	slightly to moderately enriched
Mud–dominated site (enriched) [a]	24	76	10	1900	580	7.3	enriched
Other NZ estuaries							
Kaipara (Otamatea Arm site C) [b]	50 (38–56)	33 (21–55)	4.5 (3.1–6.5)	1192 (800–1800)	572 (547–605)	4.6	moderately enriched
Ohiwa [c]	77 (53–92)	20 (7–44)	2.0 (0.7–3.7)	650 (250–1000)	278 (212–350)	5.1	slight to moderately enriched
Ruataniwha [d]	86 (67–94)	9 (6–18)	1.2 (0.5–1.7)	263 (250–700)	458 (330–580)	1.3	slightly enriched
Waimea [c]	74 (25–93)	24 (7–70)	1.4 (0.3–2.8)	506 (250–1000)	433 (243–562)	2.6	slight to moderately enriched
Havelock [e]	77 (68–85)	19 (13–26)	1.6 (0.7–2.3)	422 (70–900)	330 (241–433)	2.8	slight to moderately enriched
Avon–Heathcote [d]	94 (90–97)	5 (3–9)	1.0 (0.5–1.3)	301 (250–600)	327 (298–355)	2.0	moderately enriched
Kaikorai [f]	70 (61–78)	27 (20–33)	5.1 (3.9–6.9)	1650 (1500–2100)	799 (728–913)	4.6	moderately enriched but contaminant affected
New River [c]	98 (96–99)	2 (1–3)	0.6 (0.3–1.4)	250 (250–250)	280 (195–432)	2.0	non-enriched
Delaware (sites B, C) [g]	88 (79–98)	11 (2–20)	2.2 (1.9–2.3)	282 (230–310)	558 (540–580)	0.5	relatively undisturbed, naturally productive

Location	Sand	Mud	AFDW	TN	TP	TN:TP	General estuary condition/health
	%	%	%	mg/kg	mg/kg	Molar	
Nelson Haven [h]	87 (78–93)	12 (7–18)	1.4 (1.0–1.8)	276 (140–440)	339 (240–460)	1.8	very slightly enriched
Moutere [i]	88 (83–91)	12 (8–15)	1.6 (0.6–2.0)	339 (280–450)	530 (474–590)	1.4	slight to moderately enriched
Motupipi [j]	70 (54–86)	30 (13–47)	2.3 (1.8–2.8)	743 (570–990)	565 (520–600)	2.9	moderately enriched
Kaipara (Otamatea Arm sites A, B) [k]	27 (15–39)	68 (52–73)	6.3 (1.7–7.8)	1850 (1600–2400)	503 (443–619)	8.1	moderately enriched
Delaware (site A) [l]	26 (24–29)	73 (71–76)	3.4 (2.6–4.3)	823 (790–850)	587 (530–630)	3.1	relatively undisturbed, naturally productive
Orowaiti [m]	42 (32–47)	53 (42–60)	3.2 (1.6–5.1)	794 (590–1200)	938 (770–1040)	1.9	slightly to moderately enriched
Waimea [n] (highly enriched site—historical data)		82.5	9.1	4340	1063	8.9	highly enriched

a Highly enriched site (Te Puna)

b Subset of sand-dominated sites from an inter-estuary comparison, 2001 (Robertson *et al.* 2002b).

c Mean of four sand-dominated sites from an inter-estuary comparison, 2001 (Robertson *et al.* 2002b).

d Mean of three sand-dominated sites from an inter-estuary comparison, 2001 (Robertson *et al.* 2002b).

e Mean of two sand-dominated sites from an inter-estuary comparison, 2001 (Robertson *et al.* 2002b).

f Mean of one sand-dominated site from an inter-estuary comparison, 2001 (Robertson *et al.* 2002b).

g Subset of sand-dominated sites, 2009 (Gillespie *et al.* 2009).

h Mean of three sand-dominated sites, 2012, (Gillespie *et al.* 2012).

i Mean of two sand-dominated sites, 2006 (Gillespie & Clark 2006).

j Mean of two sand-dominated sites, 2008 (Robertson & Stevens 2008).

k Subset of mud-dominated sites from an inter-estuary comparison, 2001 (Robertson *et al.* 2002b).

l Subset of mud-dominated sites, 2009 (Gillespie *et al.* 2009).

m Mean of two mud-dominated estuaries, 2007 (Gillespie & Clark 2007).

n Mudflat affected by a freezing works effluent, 1981 (Gillespie & MacKenzie 1990)

Nutrient and organic matter concentrations in the harbour tended to decline with distance from the inner harbour region and associated rivers. Sediment nitrogen, phosphorus and organic content are indicators of organic nutrient enrichment that are often closely linked with sediment grain size. In general terms, higher nutrient and organic concentrations are usually associated with muddier substrata. This relationship may partially explain the comparatively high organic content and nutrient loadings at Te Puna Estuary. Comparison of sediment nutrient concentrations with other New Zealand estuaries (Table 8) indicates that the Tauranga Harbour sits within a range typical for slightly to moderately enriched estuarine conditions. Although sediment phosphorus concentrations were low in Tauranga Harbour compared with other estuaries, the total N:P ratios indicated that the estuary was still limited by nitrogen.

Recent studies have found that levels of nitrogen and phosphorus have changed little within Tauranga Harbour between the early 1990s and 2005 (see Sinner *et al.* 2011). Most major point source discharges of nitrogen and phosphorus (such as sewage outfalls) were removed from the harbour in the early to mid-1990s. Nutrient levels in many of the rivers and streams entering the harbour have declined due to improved rural practices and better control of surface runoff and land use changes. However, many of these rivers still have elevated nutrient levels, and some show increasing trends associated with agriculture and runoff from recently harvested forest (Scholes 2005; Sinner *et al.* 2011). The low residence times within Tauranga Harbour (see Heath 1976) result in rapid dilution of nutrients. The flushing rates largely mitigate seabed enrichment effects in the central and outer regions of the harbour, with localised seabed enrichment effects occurring near source streams.

Sediment contamination by heavy metals can also be highly correlated with the percentage of mud content due to the adherence of chemicals to fine sediments and/or organic content (see Green *et al.* 2001). It is, therefore, not surprising that heavy metal concentrations were highest in the depositional inner areas of the harbour, such as Te Puna Estuary. Acceptably low levels of copper, lead and zinc were found throughout Tauranga Harbour compared with ANZECC (2000) ISGQ trigger guidelines and the TELs (threshold effects level 18.7, 30.2 and 124 for copper, lead and zinc respectively) developed by MacDonald *et al.* (1996) and utilised by the Auckland Council. Although the three metals recorded were found to be highly correlated, zinc levels tended to be closer to guideline thresholds indicating possible biological effects. This trend was also reported for the Auckland region (Anderson *et al.* 2002). Comparison with other New Zealand and overseas estuaries showed Tauranga Harbour is performing well with respect to heavy metal contamination (Table 9).

Table 9. Concentrations of trace metals in sediments from Tauranga Harbour and a selection of New Zealand and overseas estuaries that have been contaminated to varying degrees. Some values drawn from other studies are approximate as they were estimated from figures.

Location		**Cu mg/kg**	**Pb mg/kg**	**Zn mg/kg**
ANZECC (2000a) ISQG-Low		*65*	*50*	*200*
ANZECC (2000a) ISQG-High		*270*	*220*	*410*
Tauranga (present study)	**All sites except 48**	1.5 (< 1–3)	2.6 (< 1–5.6)	17.2 (< 5–55)
	Site 48	6.1	13.0	46.0
EMP development study [a]	Kaipara (Otamatea Arm)	13.8	11.4	54.5
	Ohiwa	4.0	3.4	27.7
	Ruataniwha	7.1	4.7	37.5
	Waimea	9.6	7.4	41.8
	Havelock	10.7	5.6	43.0
	Avon–Heathcote	3.2	6.3	38.3
	Kaikorai	16.8	45.3	184.2
	New River	3.8	0.7	17.1
Other NZ sites	Delaware Inlet [b]	11.0	3.8	45.3
	Moutere Inlet [c]	6.1	4.2	25.9
	Nelson Haven [d]	5.5	3.8	24.3
	Motupipi Estuary [e]	7.7	5.1	35.7
	Orowaiti Estuary [f]	1.8	4.3	44.6
	Tamaki A (E1) [g]	27.8	132.1	136.1
	Tamaki B (E2) [g]	26.1	72.9	167
	Tamaki C (E3) [g]	29.4	69.7	173
	Tamaki D (E4) [g]	38.5	145.2	233
	Manukau (rural catch) [h]	20	9	114
	Manukau (industrial catch) [h]	90	58	285
	Waitemata Harbour [i]	60	65	161
	Lambton Harbour, Wellington [j]	68	183	249
	Porirua Harbour, Wellington [k]	48	93	259
	Aparima Estuary [l]	12	11	49
	Mataura Estuary [l]	6.6	6.2	27
Overseas sites	Delaware Bay, USA [m]	8.3	15	49.7
	Lower Chesapeake Bay, USA [m]	11.3	15.7	66.2
	San Diego Harbour, USA [m]	218.7	51	327.7
	Salem Harbour, USA [m]	95.1	186.3	238
	Rio Tinto Estuary, Spain [l]	1400	1600	3100
	Restronguet Estuary, UK [l]	4500	1620	3000
	Nervión Estuary, Spain [n]	50–350	50–400	200–2000
	Sorfjord, Norway [m]	12000	30500	118000

Sources: a (Robertson *et al.* 2002b), b (Gillespie *et al.* 2009), c (Gillespie & Clark 2006), d (Gillespie *et al.* 2012), e (Robertson & Stevens 2008), f (Gillespie & Clark 2007), g (Thompson 1987), h (Roper *et al.* 1988), i (Glasby *et al.* 1988), j (Stoffers *et al.* 1986), k (Glasby *et al.* 1990), l (Robertson 1995), m (Kennish 1997), n (Jezus-Belzunce *et al.* 2001).

4.2. Community-based models

We used ordination modelling approaches to identify key stressors affecting the ‘health’ of macrofaunal communities In Tauranga Harbour. Sediments, nutrients and heavy metals were identified as key ‘stressors’, *i.e.* variables affecting the ecology of the harbour. Therefore, three models were developed based on the variability in community composition using CAP analyses. The ecological assemblages generally reflected gradients of stress or pollution very well. However, the CAP models for sedimentation and contamination performed better than for nutrients.

The multivariate models were found to be more sensitive to changing ecological health than simple univariate measures (abundance, species diversity, Pielou’s evenness and Shannon-Wiener diversity). For sedimentation, univariate measures did detect changes in abundance and species richness between the most and least disturbed sites. However, for the nutrient and contamination models the univariate measures only observed differences in species richness at the least healthy sites. No clear patterns in the other univariate measures along the ecological gradient were observed. This trend has also been reported in the literature where univariate measures found significant differences between the most and least disturbed sites, but none of them were able to differentiate between smaller relative differences (Attayde & Bozelli 1998). It has, therefore, been recommended that utilising all of the information on the abundance of each taxon can increase the sensitivity and allow a more ecologically meaningful response to be observed (Attayde & Bozelli 1998, this study; Gray 2000; Pohle *et al.* 2001; Hewitt *et al.* 2005).

For Tauranga Harbour, constrained ordination models based on community composition appear to be a more sensitive measure than univariate measures of ‘health’ along an ecological gradient and should enable long term degradative change from multiple disturbances to be assessed. For all three analyses, a significant model relating changes in communities to changes in the environmental measures were able to be developed. This approach can be used as a management or monitoring tool where sites are repeatedly sampled over time and tracked to determine whether the communities are moving towards a more healthy or unhealthy state. New observations can also be placed into the model and community ‘health’ can be defined based on its position in the ordination space. Hence new sites can be placed into the canonical space in future (Anderson & Robinson 2003) and sites can be monitored over time to assess long term degradation or improvement in the ecology of an area.

Multivariate analysis based on all taxa also gives the ability to investigate which taxa are associated with changing ecological health (Hewitt *et al.* 2005). The key species at ‘healthy’ and ‘impacted’ sites as determined from the CAP models were identified. Species at ‘impacted’ sites can be considered to be tolerant to the stressor (*i.e.*

sedimentation, nutrients or contamination), while species with high abundances at ‘healthy’ sites only are sensitive to increasing stressors.

We also modelled the maximum abundances of populations in an effort to investigate limiting factors acting as constraints on organisms (Lancaster & Belyea 2006). Models were developed for 20 taxa. In ecology, a common phenomenon is for data points to be scattered beneath an upper (or above a lower) limit described as a ‘factor ceiling’ (Thomson *et al.* 1996). The ceiling to the data scatter implies a constraining factor, thus the form the ceiling takes allows us to derive maximum (or minimum) possible response curves to an environmental variable. This implies that over broad scales, while a number of factors (*e.g.* the potential for recruitment, historical conditions *etc.*) may affect the observed density, there is a limit (frequently an upper limit) that is controlled by the variable of interest.

Taxa were either sensitive to elevated sediments, nutrients loading or contamination at all levels, or sensitive to these stressors beyond a critical point. Although the type of response differed by taxa and stressor, variation in the abundance of most taxa modelled was most likely to be better predicted by sedimentation (12 or 20 taxa). Unimodal responses were almost always observed in response to nutrients, while declines or skewed unimodal responses were most often observed in response to sedimentation or contaminants. In most cases, responses to contamination were similar to those found for sedimentation, and even where the response changed from decline to unimodal, the maximum abundance for both stressors was still at the lower end of the range.

In terms of sedimentation, this study supports the general findings from previous research (Thrush *et al.* 2003; Anderson 2008) of strong changes in benthic macrofauna distribution in relation to percentage mud, with important implications for assessing long term responses of communities to habitat change. Increased sediment, either deposited on the seafloor via catastrophic events (Thrush *et al.* 2004) or chronic sediment suspended in the water column, can negatively impact organisms (*i.e.* via burial, scour, inhibiting settlement, decreasing filter feeding efficiency, decreasing light penetration) and lead to reductions in diversity, abundance and the loss of functionally important species (Ellis *et al.* 2004).

The present study extended current knowledge by examining the response of key macrofauna to two other important coastal stressors; nutrient and contaminant loading. Species responses to nutrients were generally unimodal threshold responses, with species abundance increasing to threshold nutrient levels and then decreasing beyond that point. Low levels of nutrient enrichment in estuarine and coastal environments can have a positive effect on the benthos due to improved primary productivity, and therefore food availability. Beyond a critical point, however, excessive nutrient discharges can lead to accelerated eutrophication of coastal environments and adverse symptoms of over enrichment (Cloern 2001; McGlathery *et* *al.* 2007). For metal contaminants, the majority of taxa exhibited negative relationships between maximum abundance and increasing contaminant levels. Although nutrient and contaminant levels in Tauranga Harbour were moderate to low, taxa showed distinct responses to these stressors, suggesting that benthic communities may be changing in response to these stressors at levels below recommended guidelines.

In general, model comparisons of the relative sensitivity of different taxa revealed wide variations in response to changes in environmental conditions. For example, *Hyboscolex longiseta* and Terebellidae showed unimodal responses to sedimentation whereas other polychaetes simply declined in abundance with increasing mud. Similarly, some bivalves had narrow distributions in response to nutrients while others were found across a wider range of concentrations. Other studies have also found species-specific differences in habitat preference (Thrush *et al.* 2003; Anderson 2008) and these differences have important implications for conclusions drawn from studies of low taxonomic resolutions, or aggregative indices of ecological change of ecosystem "health'. Species response models models can play a critical role in understanding of the likely effects of large-scale habitat change and enable ecologist and managers to forecast the response of macrofauna to future environmental changes.

4.3. Conclusion

Tauranga Harbour is a predominantly sandy harbour with slight to moderate enrichment and low levels of heavy metal contaminants. The community composition and key species characterising sites with different sediment textures, nutrient and contaminant loadings were found to vary. Te Puna Estuary (Site 48) was found to have high levels of mud, nutrients and heavy metals, outside the range of variation observed at other sites.

Sediments, nutrients and heavy metals were identified as key 'stressors' or variables affecting the ecology of the harbour. Sediments and contaminants were found to explain the largest variance in benthic communities. Sites classified as most impacted were generally located in the upper reaches of estuaries in some of the least exposed locations. In general, the multivariate models were found to be more sensitive to changing ecological health than simple univariate measures. Species response models showed that taxa were either sensitive to elevated sediments, nutrients loading or contamination at all levels, or sensitive to these stressors beyond a critical point. This BHM approach, initially developed by Auckland Regional Council (in conjunction with University of Auckland and NIWA), can be used as a management or monitoring tool where sites are repeatedly sampled over time and tracked to assess long term degradation or improvement in the ecology of an area.

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6. APPENDICES

Appendix 1. Tauranga Harbour sampling site location details.

Site	**Location**	**Habitat**	**A point**		**B point**		**Chart datum**	**Comments**
			NZTME	**NZTMN**	**NZTME**	**NZTMN**		
1	Athenree	BS	1862844	5850790	1862871	5850827	0.512	Small bivalves common
2	Athenree	BS/SF	1863039	5849578	1863034	5849604	0.682	Small bivalves common
3	Athenree	BS	1861313	5849572	1861344	5849525	0.702	Small bivalves common
4	Athenree	SG	1860899	5848974	1860854	5848952	1.132	
5	Bowentown flood delta	BS/SF	1862374	5849061	1862343	5849075	0.882	
6	Tanners Pt	SG	1860947	5847735	1860952	5847782	1.053	Small bivalves common, seagrass patchy
7	Tuapiro Est.	BS/P	1860284	5846213	1860303	5846242	0.836	Small bivalves common
8	Ongare Pt	BS	1862990	5845258	1863024	5845216	0.223	Bare sand
9	Kauri Pt	BS	1861385	5842837	1861360	5842796	0.384	Occasional *Ulva* and seagrass
10	Uretara Est.	BS/P	1859160	5841668	1859115	5841654	0.738	Small bivalves common, muddy
11	Katikati	SG	1861019	5840122	1861018	5840195	0.500	Lots of macroalgae (reds, *Ulva,* seagrass)
12	Katikati	BS	1860872	5838709	1860919	5838749	0.719	Occasional seagrass, small bivalves common
13	Katikati	BS	1859645	5838849	1859665	5838804	0.785	Small bivalves common
14	Rereatukahia Est.	BS/P	1858852	5837443	1858801	5837443	1.003	Bare sand, featureless
15	Matakana north	SG	1864615	5844595	1864572	5844619	0.203	
16	Bowentown flood delta	BS	1861876	5847073	1861837	5847105	0.715	Small bivalves common, *Ulva* present
17	Upper North Harbour	SG	1866194	5839926	1866229	5839901	0.575	
18	Blue Gum Bay	BS	1868133	5838623	1868083	5838619	1.158	Bare sand
19	Upper North Harbour	SG	1868953	5838230	1868932	5838276	0.955	
20	Blue Gum Bay	BS	1870400	5836995	1870439	5836962	0.919	Occasional small bivalve
21	Egg Island	SG	1862900	5839911	1862896	5839961	0.670	Seagrass thick in places, *Ulva* and reds present
22	Matahui Pt	BS/SG	1864304	5836733	1864267	5836765	0.691	Seagrass in a few quadrats
23	Matahui Pt	SG	1863958	5837013	1863973	5837060	0.838	
24	Matakana Pt	SG	1867485	5834361	1867456	5834322	0.378	Seagrass thick
25	Matakana Pt	BS	1867748	5834506	1867767	5834455	0.792	Thin patches of Seagrass in 3 quadrats
26	Aongatete	SG	1864309	5834506	1864292	5834551	0.891	
27	Aongatete	BS	1863615	5834467	1863588	5834510	0.598	Bare sand

Site	Location	Habitat	A point		B point		Chart datum	Comments
			NZTME	NZTMN	NZTME	NZTMN		
28	Aongatete	BS	1862821	5834277	1862779	5834317	0.966	Bare sand
29	Hunter's Creek	BS/P	1872451	5833584	1872463	5833633	0.433	Occasional small bivalve
30	Hunter's Creek	SG	1872580	5833532	1872613	5833566	0.505	Neptune’s necklace present
31	Hunter's Creek	SG	1875571	5831455	1875524	5831462	0.922	Dense Neptune’s necklace
32	Hunter's Creek	BS	1875642	5830632	1875624	5830681	0.497	Patches of reds, *Ulva* & small bivalves
33	Duck Bay	BS	1876347	5830239	1876299	5830230	0.179	Small bivalves common, *Ulva* present, thin patches of seagrass
34	Duck Bay	BS	1876500	5830117	1876537	5830148	0.298	Lots of *Ulva*, reds present, occasional small bivalve
35	Motungaio Island	BS	1873330	5831630	1873303	5831672	1.278	Occasional small bivalve
36	Ngakautuakina Pt	SG	1866358	5833025	1866386	5833067	0.299	
37	Wainui Est.	BS	1863363	5831812	1863333	5831852	0.875	Occasional small bivalve
38	Apata	BS/P	1864248	5830678	1864219	5830721	1.184	Bare sand
39	Ngakautuakina Pt	SG	1865756	5831517	1865777	5831564	0.713	Thick seagrass
40	Waipapa Est.	BS/SF	1866357	5830113	1866350	5830064	0.988	Bare sand
41	Omokoroa	SG	1866954	5830644	1866926	5830689	0.748	
42	Omokoroa	BS	1868018	5830518	1867981	5830554	0.191	
43	Matakana Pt	SG	1868270	5833779	1868316	5833756	0.180	
44	Omokoroa	SG	1870057	5830629	1870028	5830592	0.791	*Ulva* present
45	Center Bank	BS/SF	1879574	5828564	1879623	5828559	0.219	Pipi and *Ulva* present, covered with water
46	Omokoroa-Mangawhai Bay	BS	1868460	5828617	1868506	5828639	0.706	Small bivalves common
47	Mangawhai Est.	BS/P	1867687	5827666	1867647	5827634	1.150	Bare sand
48	Te Puna Est.**	BS/P	1868434	5825385	1868395	5825360	0.792	Bare mud
49	Te Puna	SG	1869659	5827627	1869609	5827599	0.866	Small bivalves common
50	Waikaraka Est.	BS/P	1870076	5827281	1870060	5827329	1.179	Small bivalves common
51	Rangiwaea Is.	BS/SF	1874915	5828700	1874907	5828649	0.062	
52	Motuhoa Island	SG	1871810	5829542	1871767	5829565	0.496	Small bivalves common
53	Te Puna	BS	1871371	5827820	1871364	5827839	0.461	
54	Te Puna	SG	1873409	5826958	1873449	5826941	0.998	
55	Wairoa Est.	BS	1873681	5825837	1873694	5825787	1.008	
56	Wairoa Est.	BS/SF	1874059	5825206	1874012	5825189	1.117	
57	Matua	BS	1875042	5825703	1875072	5825732	1.207	Bare sand

Site	Location	Habitat	A point		B point		Chart datum	Comments
			NZTME	NZTMN	NZTME	NZTMN		
58	Tilbey Pt	SG	1876239	5827455	1876283	5827431	0.683	Small bivalves common, *Ulva* present
59	Otumoetai	SG/SF	1877894	5826769	1877941	5826759	0.487	Occasional small bivalve
60	Otumoetai	BS	1878761	5826878	1878756	5826929	0.257	
61	Waikareao Entrance	BS/SF	1879047	5826309	1879032	5826360	0.689	Small bivalves common, *Ulva* present, seagrass in 1 quadrat
62	Waikareao Est.	BS	1877913	5824841	1877867	5824820	1.094	Occasional small bivale, *Ulva* present
63	Waikareao Est.	SG	1878131	5824740	1878083	5824737	1.019	
64	Waikareao Est.	BS	1878213	5824451	1878254	5824481	1.073	Occasional small bivalve
65	Waipu Bay	SG	1880395	5824712	1880349	5824721	1.110	Occasional small bivalve
66	Waipu Bay	BS	1881055	5825407	1881073	5825362	0.558	Occasional small bivalve, *Ulva* present
67	Waipu Bay	BS/SF	1882458	5824505	1882447	5824558	1.250	Occasional small bivalve
68	Waimapu Est.	BS	1879334	5822166	1879347	5822111	0.697	Small bivalves and *Ulva* common
69	Waimapu Est.	BS	1878074	5820248	1878124	5820262	0.912	Bare sand
70	Waimapu Est.	BS	1878638	5820282	1878603	5820238	0.798	Bare sand
71	Rangataua Bay	BS	1881779	5821870	1881778	5821840	0.112	Small bivalves common
72	Rangataua Bay	SG	1883024	5821883	1882986	5821900	0.523	Small bivalves common, *Ulva* present
73	Rangataua Bay	BS/P	1883502	5821744	1883489	5821782	0.573	Occasional small bivalve
74	Rangataua Bay	BS	1884604	5822782	1884578	5822833	1.095	Occasional small bivalve
75	Welcome Bay	BS	1881669	5820495	1881617	5820486	0.757	Small bivalves common

*BS = bare sand, SG = seagrass, SF = shellfish, P = pesticides

Appendix 2. Sediment characteristic data, infauna data and canonical analysis of principal coordinates (CAP) ecological health categories for the 1 mm + 500 µm infauna model. Ecological health categories range from 1 (‘healthy’) to 5 (‘impacted’). Sed = sedimentation, Nut = nutrients, Cont = contamination, AFDW = ash-free dry weight, S/C = silt/clay, TN = total nitrogen, TP = total phosphorus, Pb = lead, Cu = copper, Zn = zinc, chl-*α* = chlorophyll-*α*, N = total abundance per core, S = number of species per site, J = Pielou’s evenness, H = Shannon-Wiener index.

Site	Location	Habitat*	CAP category			Sediment properties										Infauna			
			Sed	Nut	Cont	AFDW	Gravel	Sand	S/C	TN	TP	Pb	Cu	Zn	Chl-*α*	N	S	J	H
						%				(mg/kg)					(ug/kg)	(per core)	(per site)		
1	Athenree	BS	2	3	3	1.6	0.4	96.0	3.6	380	110	1.1	<1	7.7	4600	116	32	0.7	2.4
2	Athenree	BS/SF	1	3	2	2.4	10.2	87.3	2.5	590	210	1.4	<1	8.8	6600	239	34	0.6	2.2
3	Athenree	BS	2	2	2	1.9	1.7	94.5	3.9	380	110	<1	<1	6.1	4600	154	30	0.7	2.3
4	Athenree	SG	2	1	1	2.5	0.4	94.0	5.6	350	120	<1	<1	6.1	3200	116	25	0.8	2.6
5	Bowentown flood delta	BS/SF	2	4	2	1.6	1.2	97.4	1.5	290	140	<1	<1	6.5	2400	257	30	0.5	1.9
6	Tanners Pt	SG	2	2	2	3.8	0.7	91.9	7.3	530	180	1.3	<1	11.0	8600	142	36	0.7	2.2
7	Tuapiro Est.	BS/P	3	3	3	3.0	1.1	88.7	10.2	640	180	<1	<1	11.0	10000	197	28	0.6	2.0
8	Ongare Pt	BS	1	1	2	3.0	0.3	96.7	2.9	380	160	1.3	<1	10.0	5300	46	16	0.5	1.4
9	Kauri Pt	BS	2	3	3	1.0	1.5	94.9	3.6	180	78	1.4	<1	27.0	2200	102	27	0.7	2.3
10	Uretara Est.	BS/P	5	5	5	4.4	2.9	66.2	30.9	1000	340	5.6	3.0	34.0	1100	109	18	0.8	2.2
11	Katikati	SG	3	4	3	2.8	0.9	92.5	6.5	390	120	1.1	<1	12.0	4400	157	27	0.4	1.3
12	Katikati	BS	3	3	3	2.0	0.1	91.0	8.9	300	120	1.9	<1	8.7	1900	125	23	0.7	2.2
13	Katikati	BS	5	5	4	3.1	0.6	85.1	14.3	540	250	3.4	1.5	22.0	2800	39	16	0.7	1.9
14	Rereatukahia Est.	BS/P	4	4	5	4.5	1.0	74.3	24.7	830	330	4.6	2.4	26.0	5600	126	13	0.7	1.6
15	Matakana north	SG	2	2	2	2.1	0.4	95.9	3.7	340	160	2.2	<1	13.0	1200	166	30	0.5	1.8
16	Bowentown flood delta	BS	2	3	2	1.8	0.7	96.1	3.3	310	180	1.5	<1	11.0	7000	241	32	0.6	2.0
17	Upper North Harbour	SG	2	2	2	2.1	2.0	94.1	3.9	370	110	<1	<1	8.0	4200	126	32	0.4	1.4
18	Blue Gum Bay	BS	2	1	2	0.9	0.2	98.5	1.3	140	53	1.1	<1	<5	210	49	22	0.7	2.0
19	Upper North Harbour	SG	2	1	1	2.1	0.1	95.6	4.3	310	91	1.2	<1	6.9	3000	29	23	0.8	2.5
20	Blue Gum Bay	BS	2	1	2	1.6	<0.1	100	<0.1	340	92	1.3	<1	10.0	1200	42	17	0.8	2.0
21	Egg Island	SG	2	2	2	3.8	20	91.3	6.5	540	180	1.3	<1	11.0	5100	134	35	0.7	2.3
22	Matahui Pt	BS/SG	4	5	4	4.2	0.9	51.6	17.5	700	220	3.5	1.7	18.0	3300	92	22	0.6	1.8
23	Matahui Pt	SG	4	3	4	3.1	0.8	64.9	34.2	430	200	3.1	1.0	14.0	7900	90	23	0.7	2.1
24	Matakana Pt	SG	3	3	3	2.6	0.8	83.5	15.7	390	200	3.1	<1	19.0	5600	111	25	0.9	3.0
25	Matakana Pt	BS	1	1	1	0.9	1.4	97.2	1.4	180	51	1.4	<1	6.1	3800	54	17	0.8	2.2
26	Aongatete	SG	4	4	3	4.0	0.1	76.5	23.3	590	130	2.7	1.3	13.0	3600	61	26	0.8	2.5
27	Aongatete	BS	4	4	4	4.2	<0.1	81.3	18.7	580	180	4.3	2.2	20.0	7300	82	14	0.7	1.6
28	Aongatete	BS	3	4	4	3.5	0.1	77.5	22.4	520	160	2.8	1.3	14.0	8600	333	10	0.3	0.7
29	Hunter's Creek	BS/P	3	3	4	2.7	1.2	82.6	16.2	690	150	2.5	1.2	16.0	3900	85	25	0.7	2.2
30	Hunter's Creek	SG	2	2	2	1.8	0.5	90.7	8.9	450	97	1.9	<1	8.7	4000	106	29	0.5	1.7
31	Hunter's Creek	SG	3	2	3	3.2	1.0	86.1	13	490	120	1.9	<1	9.5	4800	78	32	0.8	2.6
32	Hunter's Creek	BS	2	2	3	2.3	1.1	91.2	7.7	490	160	2.5	<1	12.0	8100	164	33	0.5	1.9
33	Duck Bay	BS	2	2	3	2.6	2.3	91.5	6.3	550	190	2.2	<1	12.0	7200	124	27	0.5	1.6
34	Duck Bay	BS	2	1	3	1.8	0.7	96.2	3.2	350	130	1.9	<1	7.5	5400	111	30	0.4	1.3
35	Motungaio Island	BS	2	2	1	1.4	0.7	96.0	3.3	290	93	1.2	<1	5.1	3300	80	23	0.7	2.2
36	Ngakautuakina Pt	SG	3	3	4	3.3	0.2	87.3	12.6	530	180	3.1	<1	15.0	4700	158	35	0.8	2.6
37	Wainui Est.	BS	5	5	4	4.5	1.5	51.0	47.5	760	310	4.5	1.4	26.0	3300	78	19	0.7	1.9

38	Apata	BS/P	5	4	4	4.2	0.3	50.7	48.9	620	260	4.1	1.1	21.0	4100	35	21	0.8	2.3
39	Ngakautuakina Pt	SG	3	3	3	2.6	0.8	84.2	15.0	460	130	2.0	1.6	12.0	4300	66	30	0.7	2.0
40	Waipapa Est.	BS/SF	5	5	4	3.8	0.2	68.4	31.5	650	220	4.0	1.4	19.0	6100	39	19	0.8	2.4
41	Omokoroa	SG	3	3	3	3.5	0.6	84.3	15.1	450	140	2.3	<1	15.0	5000	76	27	0.9	2.7
42	Omokoroa	BS	4	5	4	4.0	0.9	73.9	25.4	760	280	4.3	1.5	27.0	5900	126	24	0.6	1.9
43	Matakana Pt	SG	2	3	3	1.6	0.6	94.5	4.9	310	120	2.6	<1	14.0	5000	95	32	0.7	2.4
44	Omokoroa	SG	3	4	4	4.3	1.6	77.6	20.9	450	220	5.1	1.3	21.0	5000	198	39	0.6	2.1
45	Center Bank	BS/SF	1	3	1	1.2	1.0	97.5	1.5	320	180	<1	<1	6.4	11000	132	27	0.6	2.0
46	Omokoroa-Mangawhai Bay	BS	5	4	4	3.8	1.5	60.0	38.6	620	240	3.7	1.3	22.0	4900	95	25	0.5	1.3
47	Mangawhai Est.	BS/P	5	5	4	4.0	10.2	60.5	29.2	660	220	3.3	<1	18.0	8800	38	16	0.7	1.9
48	Te Puna Est.**	BS/P	-	-	-	10.0	<0.1	23.7	76.4	1900	580	13	6.1	46.0	11000	152	11	0.6	1.4
49	Te Puna	SG	3	4	4	3.0	5.6	77.2	17.3	680	210	5.4	1.7	55.0	5600	234	34	0.6	2.1
50	Waikaraka Est.	BS/P	4	4	5	4.5	3.9	68.2	27.9	920	290	4.2	2.0	34.0	9600	133	31	0.7	2.2
51	Rangiwaea Is.	BS/SF	3	3	3	2.7	0.4	95.7	3.8	380	120	1.7	<1	12.0	6700	116	30	0.6	2.1
52	Motuhoa Island	SG	2	3	3	2.7	1.4	89.7	8.9	450	200	4.3	<1	20.0	4500	144	37	0.6	2.2
53	Te Puna	BS	1	3	2	3.1	1.6	88.9	9.5	590	170	2.1	<1	17.0	7500	267	30	0.4	1.3
54	Te Puna	SG	4	4	4	3.4	1.5	87.6	10.9	350	120	3.4	<1	24.0	6000	133	33	0.9	2.9
55	Wairoa Est.	BS	3	3	5	3.0	0.3	87.0	12.6	590	180	4.3	1.1	21.0	16000	138	14	0.8	2.4
56	Wairoa Est.	BS/SF	3	2	4	3.3	0.1	87.5	12.5	520	130	4.3	1.3	35.0	15000	268	14	0.5	1.4
57	Matua	BS	3	3	3	3.2	0.1	93.5	6.4	460	150	2.0	<1	13.0	11000	98	14	0.6	1.3
58	Tilbey Pt	SG	2	2	3	3.5	5.9	88.1	5.9	410	180	2.6	<1	22.0	8700	111	29	0.7	2.4
59	Otumoetai	SG/SF	2	3	3	1.3	4.0	94.2	1.8	200	91	1.6	<1	8.4	4000	170	39	0.7	2.4
60	Otumoetai	BS	1	1	2	1.8	<0.1	99.3	0.6	190	110	<1	<1	11.0	3600	63	20	0.7	1.9
61	Waikareao Entrance	BS/SF	2	2	3	2.1	6.4	89.5	4.0	390	180	2.3	<1	20.0	8400	263	26	0.5	1.5
62	Waikareao Est.	BS	3	2	3	2.5	0.3	87.2	12.4	380	120	2.1	<1	16.0	6600	57	20	0.8	2.1
63	Waikareao Est.	SG	2	1	3	3.1	0.4	81.3	18.5	500	180	3.0	1.3	45.0	7500	108	25	0.8	2.5
64	Waikareao Est.	BS	2	1	3	2.5	2.1	62.7	5.1	460	100	1.8	<1	14.0	11000	68	20	0.8	2.4
65	Waipu Bay	SG	2	2	3	3.2	1.0	90.0	9.1	450	160	2.5	1.3	22.0	5400	68	29	0.7	2.4
66	Waipu Bay	BS	2	1	2	1.5	0.8	94.7	4.4	250	120	1.8	<1	15.0	4100	56	28	0.8	2.7
67	Waipu Bay	BS/SF	2	1	1	1.9	0.4	92.7	7.0	220	89	1.4	<1	9.5	2600	59	24	0.8	2.3
68	Waimapu Est.	BS	3	3	3	2.2	7.1	83.4	9.5	410	150	2.5	1.7	20.0	9000	86	27	0.8	2.3
69	Waimapu Est.	BS	5	4	5	4.0	4.2	63.4	32.4	560	210	4.4	2.2	44.0	8200	96	14	0.9	2.0
70	Waimapu Est.	BS	3	3	4	3.2	0.5	78.2	21.2	280	160	3.1	1.6	38.0	10000	67	21	0.9	2.5
71	Rangataua Bay	BS	1	2	3	2.0	14.6	82.8	2.6	470	150	1.2	<1	18.0	11000	214	25	0.5	1.8
72	Rangataua Bay	SG	3	3	4	2.4	0.9	88.8	10.3	580	190	2.7	1.2	20.0	9700	74	32	0.9	2.9
73	Rangataua Bay	BS/P	2	1	3	2.5	4.0	82.0	14.1	640	180	2.7	1.2	19.0	9800	67	18	0.7	2.1
74	Rangataua Bay	BS	2	1	3	1.8	0.3	96.3	3.5	180	93	1.2	<1	9.8	9100	93	19	0.8	2.4
75	Welcome Bay	BS	3	3	3	2.8	0.9	86.9	12.2	280	180	2.7	1.5	28.0	9100	79	28	0.8	2.5
Min						**0.9**	**<0.1**	**23.7**	**<0.1**	**140**	**51**	**<1**	**<1**	**<5**	**210**	**29**	**10**	**0.3**	**0.7**
Max						**10**	**14.6**	**100**	**76.4**	**1900**	**580**	**13**	**6.1**	**55**	**16000**	**333**	**39**	**0.9**	**3.0**
Average						**2.9**	**1.7**	**84.3**	**13.2**	**481**	**169**	**2.6**	**1.0**	**17.4**	**6144**	**119**	**25**	**0.7**	**2.1**

*BS = bare sand, SG = seagrass, SF = shellfish, P = pesticides and ** Site 48 excluded from CAP analysis because it was an outlier (outside the range of variation observed at the other sites).

Appendix 3. Summary of generalised linear models predicting maximum density for 20 macroinvertebrate taxa in response to sedimentation (% mud), nutrients (PCnutrients) and contamination (PCcontamination). Taxonomic groups are: A = Anthozoa, B = Bivalva, D = Decapoda, G = Gastropoda, P = Polychaeta. Responses are: D = decline, SU = skewed unimodal, U = unimodal. Distribution range indicates the stressor range where at least one individual occurs

Sedimentation

Taxa	*Group*	*Predictor transformation*	*Polynomial order*	*Null deviance*	R^2	*p value*	*Response*	*Distribution*
Anthopleura aureoradiata	A	Log	2	51792.75	0.88	<0.001	SU	<0.1-48.9
Arcuatula senhousia	B	Log	2	59362.92	0.45	<0.001	U	2.6-25.4
Austrovenus stutchburyi	B	Log	2	19035.70	0.77	<0.001	SU	<0.1-48.9
Linucula hartvigiana	B	Log	1	17984.46	0.88	<0.001	D	<0.1-48.9
Macomona liliana	B	Log	2	2339.94	0.45	<0.001	SU	<0.1-48.9
Paphies australis	B	Log	1	10982.79	0.90	<0.001	D	1.5-12.6
Zemysia zelandica	B	None	2	1886.33	0.63	<0.001	U	1.5-15.1
Halicarcinus cookii	D	None	2	1514.44	0.82	<0.001	SU	1.5-15.7
Diloma subrostratum	G	Square root	1	3582.62	0.75	<0.001	D	1.5-48.9
Micrelenchus huttonii	G	None	2	1621.65	0.49	<0.001	SU	1.5-27.9
Notoacmea elongata	G	Square root	1	3364.18	0.93	<0.001	D	<0.1-38.6
Zeacumantus lutulentus	G	Log	2	8896.73	0.87	<0.001	D	<0.1-48.9
Zeacumantus subcarinatus	G	Log	1	15535.34	0.98	<0.001	D	1.3-48.9
Hyboscolex longiseta	P	None	2	1497.78	0.74	<0.001	U	1.4-34.2
Magelona dakini	P	Log	1	17757.26	0.98	<0.001	D	0.6-12.6
Maldanidae	P	Log	2	1218.86	0.91	<0.001	SU	0.6-38.6
Orbinia papillosa	P	Square root	1	2697.50	0.77	<0.001	D	0.6-47.5
Owenia petersenae	P	Square root	1	9062.67	0.93	<0.001	D	1.8-38.6
Scoloplos cylindrifer	P	None	1	3635.93	0.79	<0.001	D	<0.1-48.9
Terebellidae	P	Square root	2	2831.26	0.93	<0.001	U	1.3-25.4

Nutrients

Taxa	*Group*	*Predictor transformation*	*Polynomial order*	*Null deviance*	R^2	*p value*	*Response*	*Distribution*
Anthopleura aureoradiata	A	Square root	2	40732.89	0.56	<0.001	U	0-5.2
Arcuatula senhousia	B	Log	2	75673.71	0.75	<0.001	U	1.1-3.9
Austrovenus stutchburyi	B	Square root	2	12221.16	0.92	<0.001	U	0-5.2
Linucula hartvigiana	B	Square root	2	16592.39	0.91	<0.001	U	0-4.6
Macomona liliana	B	Square root	2	1910.88	0.55	<0.001	U	0-5.2
Paphies australis	B	None	2	7680.36	0.95	<0.001	U	0.9-2.8
Zemysia zelandica	B	None	2	2662.60	0.67	<0.001	U	1.1-2.4
Halicarcinus cookii	D	None	2	1124.97	0.43	<0.001	U	0.5-2.6
Diloma subrostratum	G	Log	2	4236.58	0.49	<0.001	U	0.5-3.9
Micrelenchus huttonii	G	Log	2	1372.45	0.64	<0.001	U	0.5-4.5
Notoacmea elongata	G	Log	2	3036.31	0.69	<0.001	U	0-4.5
Zeacumantus lutulentus	G	Square root	2	6904.23	0.18	<0.001	U	0-5.2
Zeacumantus subcarinatus	G	Square root	2	12362.48	0.63	<0.001	U	0-4.5
Hyboscolex longiseta	P	Square root	2	1558.88	0.54	<0.001	U	0.1-3.9
Magelona dakini	P	None	2	15754.49	0.99	<0.001	U	0.5-2.8
Maldanidae	P	None	2	715.24	0.82	<0.001	SU	0.4-3.1
Orbinia papillosa	P	Square root	1	1179.14	0.69	<0.001	D	0-4.5
Owenia petersenae	P	None	2	5955.37	0.70	<0.001	U	0.4-3.1
Scoloplos cylindrifer	P	Log	2	3188.02	0.39	<0.001	U	0.5-3.3
Terebellidae	P	Log	2	4027.25	0.23	<0.001	U	0-3.9

Contamination

Taxa	*Group*	*Predictor transformation*	*Polynomial order*	*Null deviance*	*R^2*	*p value*	*Response*	*Distribution*
Anthopleura aureoradiata	A	Square root	1	42130.22	0.37	<0.001	D	0-4.2
Arcuatula senhousia	B	Log	2	76466.67	0.61	<0.001	U	0.3-2.5
Austrovenus stutchburyi	B	Log	2	15344.21	0.64	<0.001	SU	0-4.2
Linucula hartvigiana	B	Log	2	13934.47	0.68	<0.001	SU	0-3.2
Macomona liliana	B	None	2	1721.62	0.23	<0.001	D	0-4.2
Paphies australis	B	Square root	1	10523.95	0.97	<0.001	D	0-2.0
Zemysia zelandica	B	None	2	1880.24	0.54	<0.001	U	0-1.5
Halicarcinus cookii	D	None	2	1493.01	0.63	<0.001	SU	0-1.5
Diloma subrostratum	G	Log	2	3579.14	0.64	<0.001	SU	0-3.0
Micrelenchus huttonii	G	None	2	1323.47	0.51	<0.001	D	0-3.0
Notoacmea elongata	G	Square root	1	3702.77	0.82	<0.001	D	0-3.0
Zeacumantus lutulentus	G	Log	2	7636.53	0.55	<0.001	U	0-4.2
Zeacumantus subcarinatus	G	Log	2	13475.61	0.87	<0.001	U	0-3.0
Hyboscolex longiseta	P	Log	2	2021.35	0.41	<0.001	U	0-3.0
Magelona dakini	P	None	2	18031.19	1.00	>0.1	n/a	0-1.0
Maldanidae	P	Log	2	969.30	0.72	<0.001	SU	0-3.0
Orbinia papillosa	P	Square root	1	3232.45	0.65	<0.001	D	0-2.7
Owenia petersenae	P	Square root	2	5288.17	0.69	<0.001	U	0-2.5
Scoloplos cylindrifer	P	Log	1	3756.58	0.61	<0.001	D	0-3.0
Terebellidae	P	Log	2	2538.48	0.21	<0.001	U	0.2-3.0