Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

TECHNICAL REPORT Investigations and Monitoring Group

Sediments and invertebrate biota of the intertidal mudflats of upper Lyttelton Harbour/Whakaraupō

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Lesley Bolton-Ritchie

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PO Box 345
Christchurch 8140
Phone (03) 365 3828
Fax (03) 365 3194

75 Church Street
PO Box 550
Timaru 7940
Phone (03) 687 7800
Fax (03) 687 7808

Website: www.ecan.govt.nz
Customer Services Phone 0800 324 636

Executive summary

This is a study of the sediments and invertebrate biota of the intertidal mudflats in Governors Bay, Head of the Bay and Charteris Bay in upper Lyttelton Harbour/Whakaraupō. To my knowledge there is no historic information on the ecological state of these mudflats yet there is potential for impacts from human activities and there has been for some time. Concerns expressed by local residents about the health of the mudflats prompted this study.

To assess the state of the mudflats sediment and biota samples were collected from four sites in both Governors Bay and Charteris Bay and six sites from Head of the Bay. Sediment samples were analysed for sediment grain size, organic matter content and concentrations of total nitrogen, total recoverable phosphorus and the metals copper, lead and zinc. The biota collected on a 0.5 mm screen were identified and counted and all cockles present were measured.

The sediment at sampled sites ranged from very muddy, to muddy, to muddy sand, to muddy sand with shell/rock fragments. The organic matter content and TN results indicate the mudflat sediment is typically in good condition. However, the TRP values indicate the mudflat sediment is in a fair condition as there is phosphorus enrichment. The phosphorus source is likely to be the phosphorus-rich volcanic rock of Banks Peninsula. The sediment copper, lead and zinc concentrations are comparable to those in the loess topsoil in the harbour catchment and are not of ecological concern.

Fifty-four different animals were found to live on and in the sediment including two anemone, 13 snails and shellfish, 24 worm, 1 ribbon worm, 1 insect and 13 crustacea, taxa. The taxa recorded are typical of intertidal mudflats, with most also found in Okains Bay estuary and the mudflats of Akaroa Harbour. There was spatial variability in the number of individuals per square metre, i.e. between samples at a site, between sites within a bay and between bays.

Analysis of the data has revealed that sediment grain size does influence the presence and abundance of the animals living in the mudflats. The absence or low abundance of four animal taxa that are abundant in Akaroa Harbour, is likely explained by the sediment grain size distribution of mudflat sediment and possibly the influence of suspended sediment concentrations in the water. It is possible that these factors also influence the presence and abundance of at least two other mudflat animals. The abundance of seven of the eleven most abundant animal taxa of the Lyttelton Harbour/Whakaraupō mudflats is influenced by sediment grain size. The small limpet *Notoacmea helmsi,* the snail *Turbonilla* sp. and the louse Isopod sp are more abundant in the coarser grained gravel/sand sediment than the fine grained silt and clay sediment. The small bivalve *Arthritica bifurca,* the worm *Nicon aestuariensis* and the crab *Austrohelice crassa* are more abundant in the fine grained silt and clay sediment than the coarser grained gravel/sand sediment.

Cockles were present in the samples from all but one site, however there were a low number of individuals at the Governors Bay, Charteris Bay and inner Head of the Bay sites. Cockles were most abundant in Head of the Bay. Most of the cockles present were recruits and juveniles. The low number of individuals longer than 20 mm indicates low survival of the recruits. The results suggest the environment of the upper harbour is not conducive to the settlement and/or survival of cockle recruits and their growth to adult size.

I have made a number of recommendations for monitoring and investigations. These include sedimentation monitoring, sediments and biota monitoring, a hydrodynamics investigation, an investigation on factors influencing cockle survival and growth and an investigation on mollusc species and their abundance in the harbour. I also recommend that the stream catchments contributing the most sediment to the harbour need to be identified and prioritised for erosion control measures.

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1 Introduction

Lyttelton Harbour/Whakaraupō is the remnant crater of one of the two, large shield volcanos that formed Banks Peninsula. The harbour basin is 1.35-5.5 km wide and at high tide approximately 15 km long, covering an area of about 44 km^2 (Spigel, 1993). The water depth is greatest at the entrance and decreases up the harbour, progressing to extensive intertidal flats in Governors Bay, Head of the Bay and Charteris Bay. Most other parts of the harbour consist of shallow subtidal sediments.

One of the South Island's busiest ports is within the harbour. This port is the main transit point for goods shipped to and from the Canterbury Region. A dredged channel that has an average depth of 11.9 m is maintained for ship access to the port. Lyttelton township is the largest urbanised area of the harbour (population 3075 in 2006; Environment Canterbury, 2008). In 2006 there was a population of 1089 in Diamond Harbour and 870 in Governors Bay. Many of the bays accessible by road have smaller settlements including Corsair Bay, Cass Bay, Rapaki, Church Bay and Purau. These settlements are concentrated along the shores of the harbour. The scenic harbour environs and microclimates of the bays coupled with their accessibility from Christchurch City make the bays a popular location to live. Hence subdivision developments are now occurring on steeper slopes within the bays and on headlands. In early 2007 ten subdivision developments were underway (Environment Canterbury, 2008).

The hillsides around the harbour basin are generally steep and cover an area of about 9968 ha. The hillside soils are primarily basaltic mantle substrates beneath greywacke loess ($\leq$ 20 m) and loess colluviums (volcanic detritus) (Hart, 2004). Due to the high proportion of loess and steep slopes of the harbour margin, the soils are highly susceptible to erosion, particularly where there is no vegetation cover (Hart, 2004).

The forests that used to cover the hillsides have long-since gone as a result of historic deforestation by Māori and European settlers. The steep slopes of the harbour margin are now typically covered with pasture grasses. However, there are pockets of native and exotic forest and scrub, as well as bare vertical rock faces. Numerous historic and active erosion scars occur on the hillsides with soil runoff into the harbour a significant issue for the coastal environment (Environment Canterbury, 2008). Eroded hillside has in-filled the harbour basin over time with sediment up to a maximum depth of 47 m (Hart, 2004). Through thousands of years of soil erosion, extensive tidal flats have accreted at Governors Bay, Head of the Bay, and Charteris Bay. These flats cover a combined area of 11 km^2 at mean low water spring (MLWS) tide (Figure 1-1) (Hart, 2004). There is evidence of a number of periodic soil erosion events and accretion of sediment within the harbour over the period 1849 to the present day (Curtis, 1985, Goff, 2005).

Intertidal mudflats are ecologically important habitats. They support a high diversity and abundance of plants and invertebrate animals and are the feeding grounds for bird and fish species. The diversity and abundance of mudflat life is primarily influenced by the:

- grain size of the sediment, i.e. is the sediment sand or mud
- 'health' of the sediment, i.e. depth of oxygenation, concentrations of chemical contaminants, concentration of organic matter

Sedimentation is one of the key issues affecting the state of New Zealand estuaries/mudflats (Stevens and Robertson, 2008) and is a significant ecological issue for Lyttelton Harbour/Whakaraupō. Sedimentation has multiple impacts including changes to the grain size distribution of the seabed sediment. The result is muddier and more nutrient-enriched sediments. This may cause initial smothering of the biota followed by a shift in the biological community to one that is mud-tolerant. The grains of the present day Lyttelton Harbour/Whakaraupō mudflat sediment likely originate from sediment eroded from hillsides, stream banks and exposed land over time.

Figure 1-1: Topographical map showing the extent of the upper Lyttelton Harbour/Whakaraupō intertidal mudflats (as indicated by blue stippling)

Human activities and resulting contaminant inputs can alter the health of sediment. Such activities/inputs include:

- heavy metal and organic contaminants associated with port activities

- heavy metal and organic contaminants associated with roading and stormwater from urban areas
- nutrients (nitrogen and phosphorus) associated with agricultural activities, urban wastewater and stormwater, and eroded sediment.
- organic matter such as leaves/twigs and broken down herbage (e.g. the droppings of grazing herbivores).

To date there has been no assessment of the sediments and invertebrate (without a backbone) animals of the Lyttelton Harbour/Whakaraupō intertidal mudflats. The purpose of this study is to characterise the intertidal sediments and benthic[1] invertebrate animals[2] of the upper harbour mudflats. This provides an assessment of the state of the mudflats and also provides a baseline for future work. This study also provides information on the state of the cockles living in the mudflats. Cockles are an important seafood for tangata whenua (Te Hapū o Ngāti Wheke (Rāpaki rūnunga) of Ngāi Tahu) of the harbour area. For tangata whenua their cultural and traditional relationship with the harbour is based on their ability to harvest kaimoana (shellfish and fish) from the harbour.

2 Background information

2.1 Status of the mudflats

The Lyttelton Harbour/Whakaraupō mudflats are an area of Significant Natural Value (Environment Canterbury, 2005). The particular values identified for the mudflats are:

- Māori cultural values
- Protected areas
- Wetland, estuaries and coastal lagoons
- Marine mammals and birds
- Ecosystems, flora and fauna habitats
- Scenic sites
- Historic places.

Governors Bay is an area of value to Tangata Whenua (Environment Canterbury, 2005).

2.2 Mudflat bathymetry and sediments

The bathymetry and sediments of upper Lyttelton Harbour/Whakaraupō were mapped in 2008 (Hart *et al.*, 2008). The 2008 bathymetry and sediment results are presented in Figures 2-1 and 2-2. Information on the sites (GB1-4, HoB1-6, CB1-4) shown on these figures is provided in section 3 of this report.

2.2.1 Sediment sand content

Sand grains are 0.063-2.0 mm in size and are the coarser grains of sediment. The sand content of the intertidal mudflat sediment of the upper harbour differs within a bay and between bays. For example, the sediment along a stretch of the western side of Head of the Bay has a high sand content while that along all of the western side of Governors Bay has a low sand content (Figure 2-1).

[1] Benthic – the seabed
[2] Such as worms, anemones, shellfish such as cockles and pipis, snails, crabs and hoppers

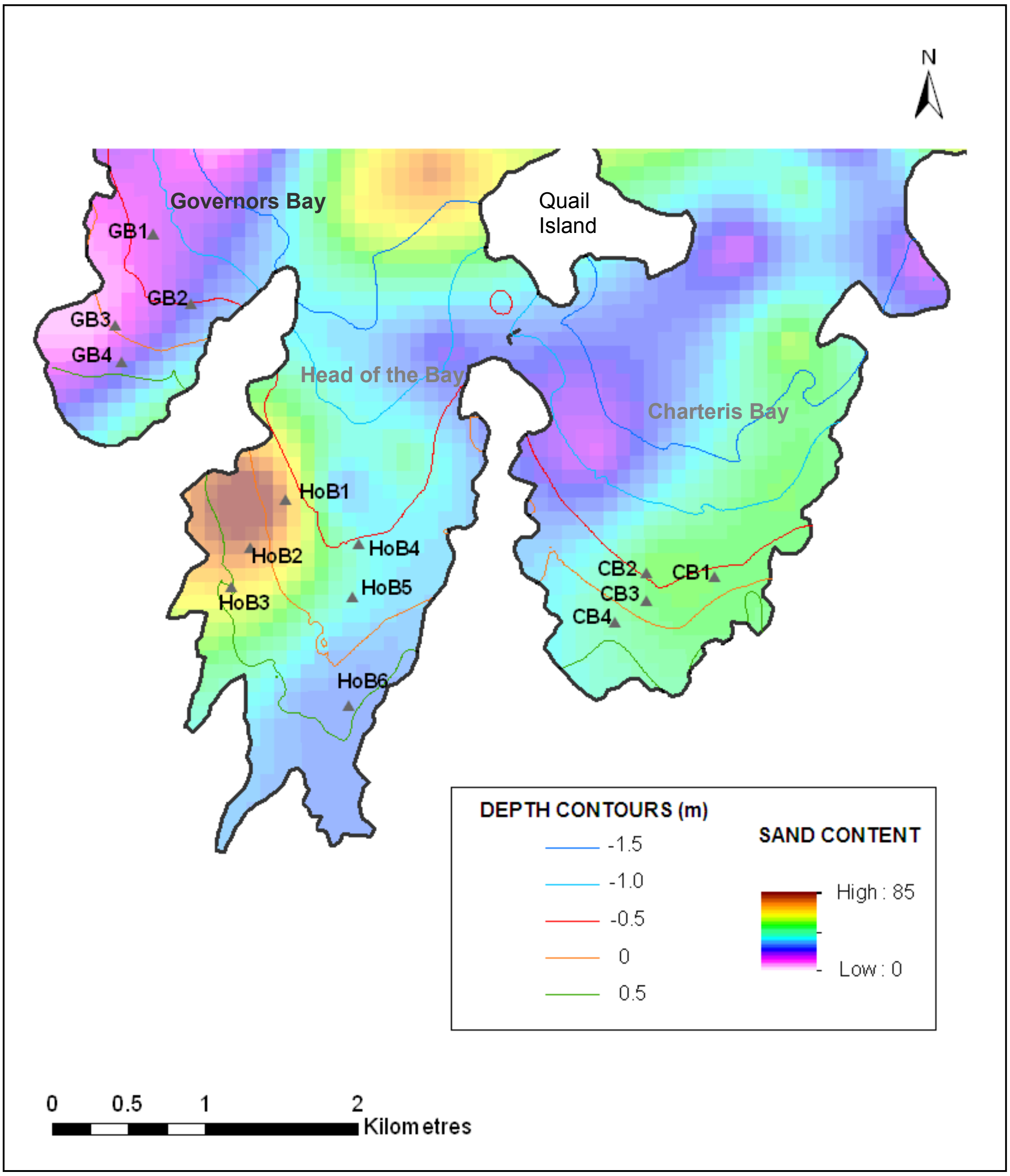


Figure 2-1: Bathymetry (depth contours) and sediment sand content

2.2.2 Sediment silt content

Silt grains are 0.004-0.063 mm in size and are the finer grains of the sediment. The silt content of the intertidal mudflat sediment of the upper harbour bays sediment differs within a bay and between bays. The sediments with high silt content have low sand content and vice versa. The sediment along a stretch of the western side of Head of the Bay has low silt content while that along all of the western side of Governors Bay has high silt content (Figure 2-2).

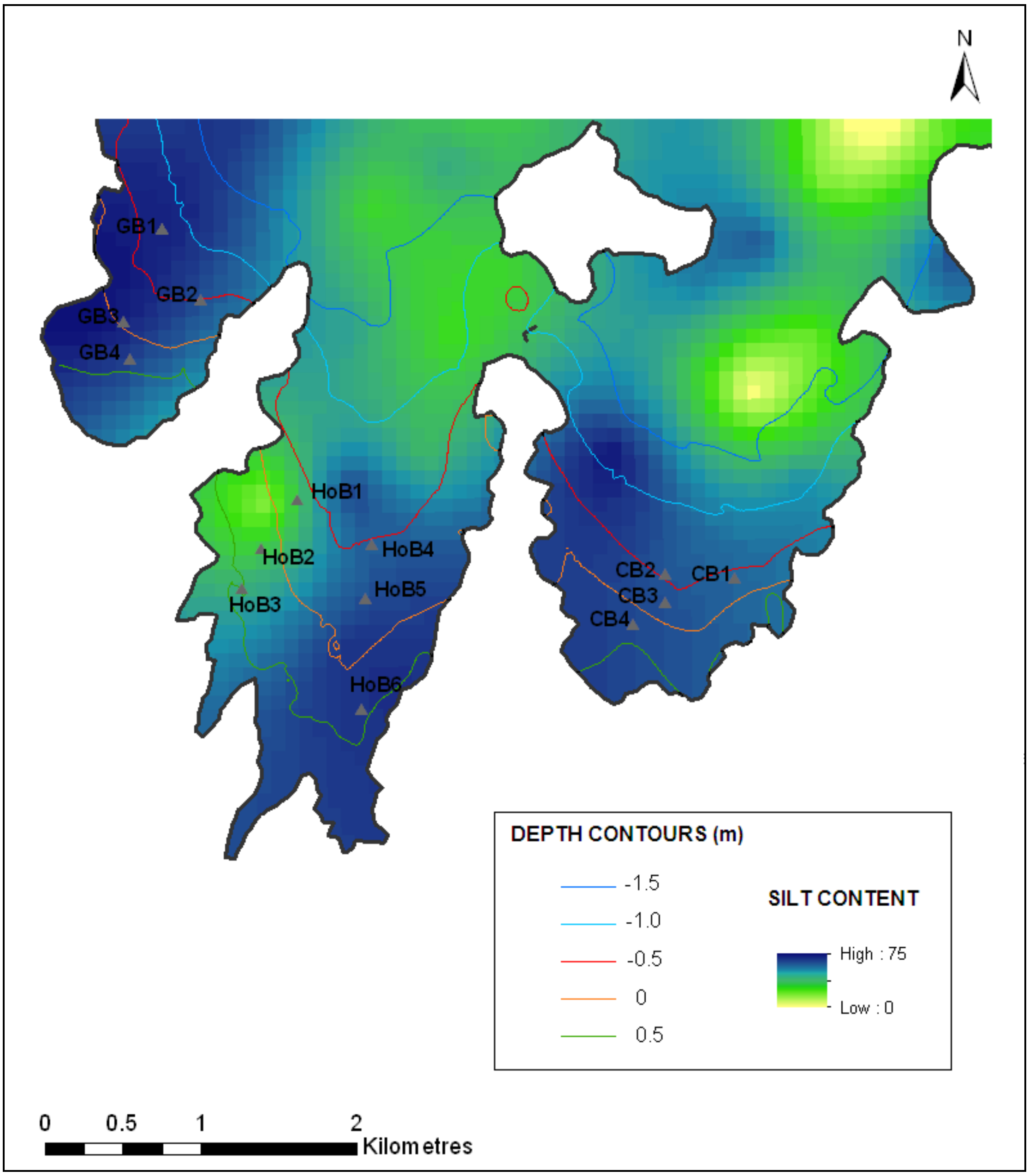


Figure 2-2: Bathymetry (depth contours) and sediment silt content

2.3 Study aims

This study of the Upper Lyttelton Harbour/Whakaraupō mudflats aims to:

1. document the condition of the sediments (grain size distribution, organic matter content, copper, lead and zinc concentrations and total nitrogen and total recoverable phosphorus concentrations)

2. list the benthic invertebrate animal species living in the mudflat sediment and provide information on species abundance

3. investigate the relationship between sediment grain size and the presence and abundance of the benthic invertebrate animals

4. assess the abundance and size distribution of cockles

5. identify issues affecting the health of the sediments and benthic invertebrate animals including cockles.

3 Methods

3.1 Sampling sites

We collected samples from four sites in both Governors Bay (GB) and Charteris Bay (CB) and six sites in Head of the Bay (HOB) (Figure 3-1). We walked to the sites in the Head of the Bay but kayaked to sites in Governors Bay and Charteris Bay. We used kayaks because the soft mud in these bays makes it difficult to walk to and from sites carrying sampling equipment and samples.

Sampling sites were at random selected locations. At each site a 50 m (along the shore) by 10 m (down the shore) area was marked out. A GPS reading was taken at one end of the 50 m line (Appendix 1). The 50 m by 10 m area was divided into five 10 m by 10 m areas. Randomly generated cartesian co-ordinates were used to position a sampling station in each 10 m by 10 m area.

3.2 Sample collection

We sampled Head of the Bay sites on 20-21 November, Charteris Bay sites on 4 December and Governors Bay sites on 5 December, 2007.

At each site we collected the following samples:

Benthic infauna[3]

a. five core (13 cm diameter (0.0133 m^2) by 15 cm deep) samples

Sediments

b. three surface (to a depth of 20 mm) samples for grain size analysis
c. three surface (to a depth of 20 mm) samples for chemical analyses

We collected sediment samples from three of the five sampling stations at a site. At the stations where we collected sediment, the biological and sediment samples were located close together.

[3] Infauna refers to the invertebrate animals living within the sediment

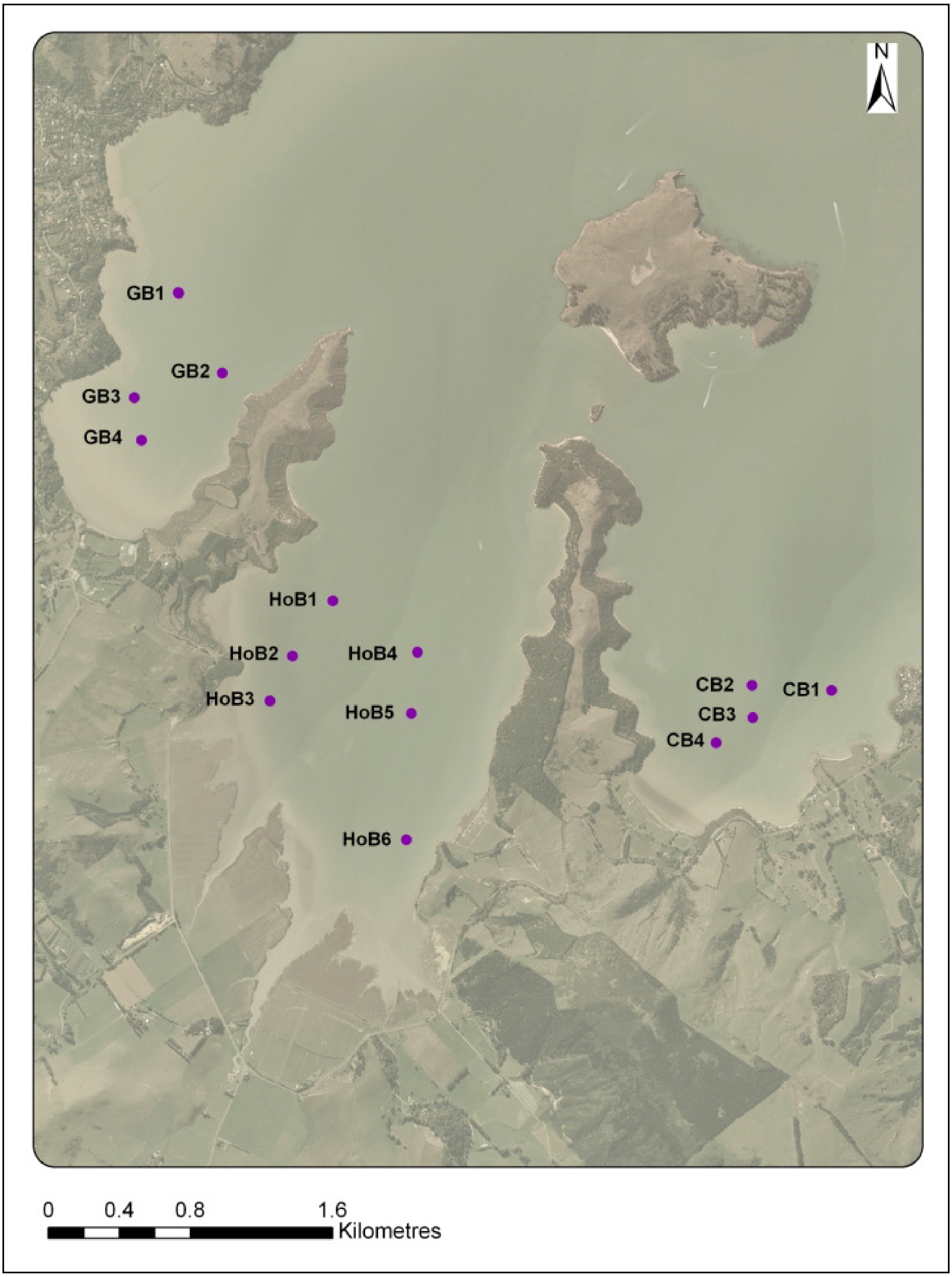


Figure 3-1: Sampling sites in Governors Bay (GB), Charteris Bay (CB) and Head of the Bay (HoB)

3.3 Sample processing

3.3.1 Sediments

Sediment samples were stored and transported chilled in chilly bins. Grain size analyses were carried out by staff of the Department of Geology, University of Canterbury. Chemical analyses (organic matter content, copper, lead, zinc, total nitrogen and total recoverable phosphorus concentrations) were undertaken at Hill Laboratories. Details of the analytical methods are given in Appendix 2.

3.3.2 Benthic infauna

We sieved each core sample through a 500 µm mesh. The material remaining on the sieve was preserved in 70% alcohol containing the fixative glyoxal. We sorted the animals present in each core sample from the debris. I identified the animals to species level where possible and counted them. I also measured the shell length of the cockles (*Austrovenus stutchburyi)* using vernier callipers or a microscope eyepiece micrometer.

3.4 Data analyses

For all data analyses and graphing I used Microsoft Excel 2003, STATISTICA (version 7) and PRIMER (version 6) (Clarke and Warwick, 2001).

To assess the quality of the sediment I compared the metal (copper, lead and zinc) concentrations to national sediment quality criteria (ANZECC 2000) and the nutrient concentrations and organic matter content values to sediment chemistry guidelines developed by Robertson and Stevens (2008). The ANZECC (2000) sediment quality criteria are Interim Sediment Quality Guideline-low (ISQG-low) and Interim Sediment Quality Guideline-high (ISQG-high). The ISQG-low value indicates a *possible* biological effect and is intended as a trigger value for further investigation, while the ISQG-high value indicates a *probable* biological effect. The sediment chemistry guidelines rate the sediment as either very good, low-moderate enrichment, enriched or very enriched. I have provided the details of the criteria for each of these ratings in Appendix 3.

Principal Components Analysis (PCA) is a useful tool for analyzing environmental data. The analysis finds which of the measured factors accounts for the maximum variance in the data and from the analysis a two-dimensional ordination of factors and sites is generated. I used a PCA to assess the sediment grain size data and limited the analysis to five principal components.

I examined the presence and abundance of infauna, producing a Multi-Dimensional Scaling (MDS) ordination to investigate similarities and differences between sites. I transformed the infauna data by $\log_{10}(x+1)$, then applied the Bray-Curtis similarity measure to the transformed data to get the similarity matrix. I then generated an MDS ordination from this similarity matrix. In this MDS ordination, sites are plotted in a spatial array using the presence and abundance data. Regarding these data, sites that are more similar will be plotted closer together. Each plot has a stress value. Stress (goodness-of-fit) is a measure of how well the 2-dimensional ordination of points on the plot represents the actual values in the similarity matrix (Clarke and Warwick, 2001). Low stress values indicate a good ordination and that the plot is not a misleading interpretation of the data.

I used regression analysis to investigate the relationship between sediment characteristics (% gravel, % sand, %silt and % clay) and the presence and abundance of taxa (the total number of taxa and individuals, the number of snails and shellfish taxa and individuals, the number of worm taxa and individuals and the number of crustacean taxa and individuals). I also used regression analysis to investigate the relationship between sediment characteristics (% gravel, % sand, %silt, % clay, % coarse sand, % very coarse sand, % fine sand, % very fine sand, % coarse silt, % medium silt, % fine silt and % very fine silt) and the abundance of 11 taxa.

4 Results

4.1 Sediments

4.1.1 Grain size

The per cent of eleven grain size categories (gravel, five sand categories, four silt categories and clay) in each sample is provided in Appendix 4. I used these data to calculate the per cent gravel, sand, silt and clay in each sample. From the results from each of the three samples at a site I calculated the mean percentage of gravel, sand, silt and clay per site; these results are shown in Figure 4-1. I also used the per cent of very fine sand, coarse silt, medium silt, fine silt, very fine silt and clay to compare the composition of finer grained sediment among sites (Figure 4-2).

Governors Bay

At GB1 and GB4 the sediment was 65-70% silt with 16-19% sand and 13-16% clay (Figures 4-1). At both sites there was more medium, fine and very fine, silt than coarse silt (Figure 4-2).The percentages of medium, fine and very fine, silt and clay at GB1 and GB4 were similar. The sediment at GB2 was 57% sand, 36% silt and 7% clay. Most of the sand was very fine sand and there was more coarse silt than medium, fine and very fine, silt (Figure 4-2). At GB3 there was 47% silt, 39% sand, 2% gravel and 9% clay. The GB3 sediment had less very fine sand but more medium, fine and very fine, silt than the sediment at GB2 (Figure 4-2).

Head of the Bay

The sediment at HoB1, HoB2, HoB3, HoB4 and HoB5 contained more sand than silt. At HoB6 the sediment had 6% more silt that sand (Figure 4-1). The sediment at HoB2 contained 75% sand, at HoB1, HoB3, HoB4 and HoB5 the sediment contained 54-57% sand and at HoB6 it contained 41% sand. At all sites there was more coarse silt than medium, fine and very fine silt (Figure 4-2). At the inshore sites of HoB3 and HoB6 the sediment contained <1% gravel; there was 4.5-9% gravel at the other sites with HoB1 having the most gravel. The mean percentage of clay was 8% at HoB6, 7% at HoB1, 6% at HoB3, 4% at HoB4 and HoB5 and 2% at HoB2.

Most of the coarser sediment (coarse sand, very coarse sand and gravel) at HoB1, HoB2 and HoB3 was shell fragments and whole shells (Figure 4-3). At sites HoB4, HoB5 and HoB6 the coarse sediment had variable amounts of rock, plant fragments and shell.

Charteris Bay

At CB2 and CB3 the sediment was 3-4% gravel, 48-49% sand, 39-41% silt and 6-8% clay. At CB1 and CB4 the sediment was 1-3% gravel, 43-44% sand, 45-46% silt and 8-9% clay (Figure 4-1). At CB1 there was more fine silt than at the other sites (Figure 4-2); at CB2 there was less coarse silt than the other sites; at CB3 there was less clay and very fine silt than the other sites (Figure 4-2) and at CB4 there was less gravel and more clay than the other sites.

Most of the coarser sediment (coarse sand, very coarse sand and gravel) at sites CB2, CB3 and CB4 was shell fragments and whole shells. At site CB1 the coarse sediment was both rock and shell.

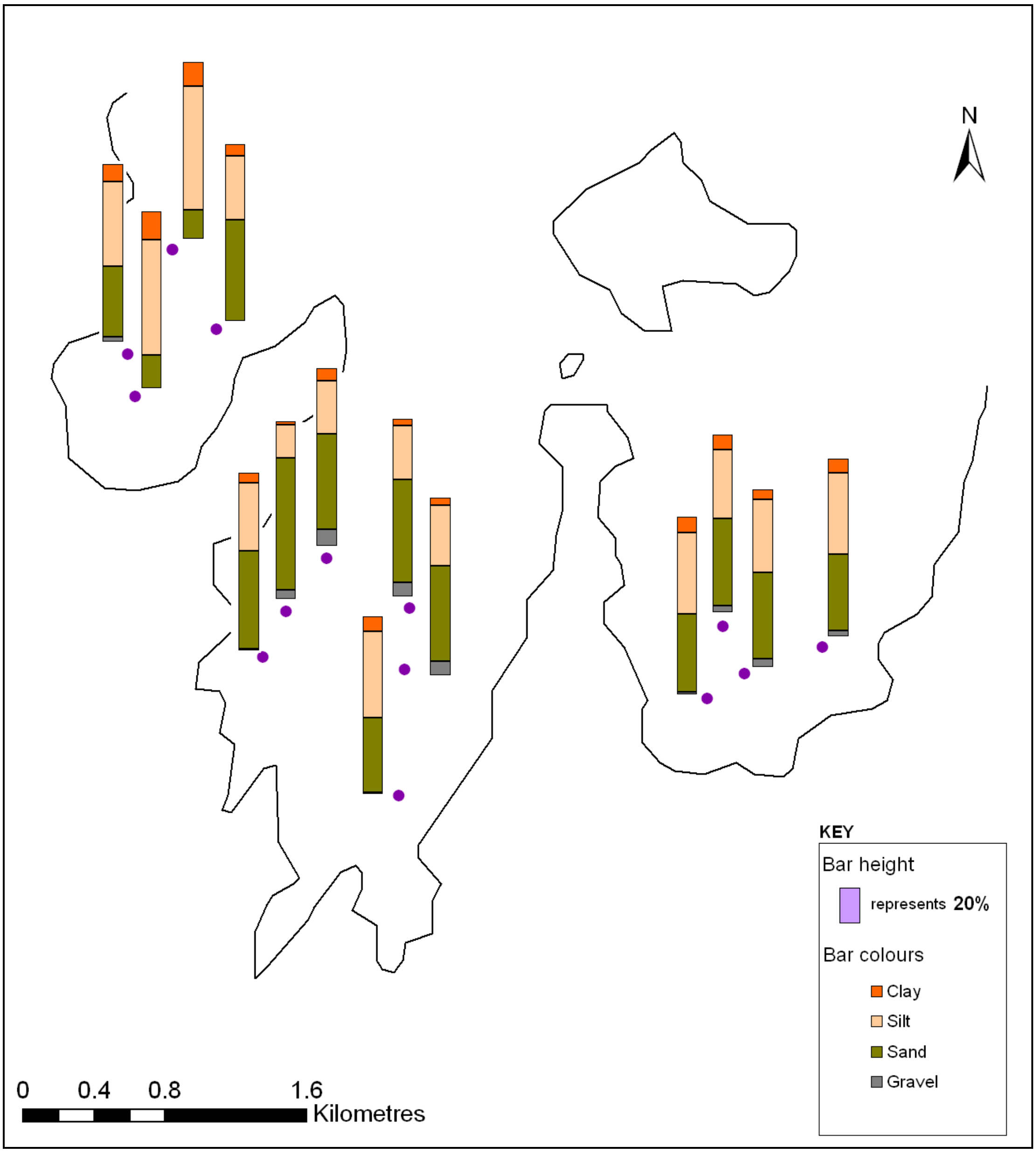


Figure 4-1: Percentage composition of the surface sediment at each site (mean from three samples at each site)

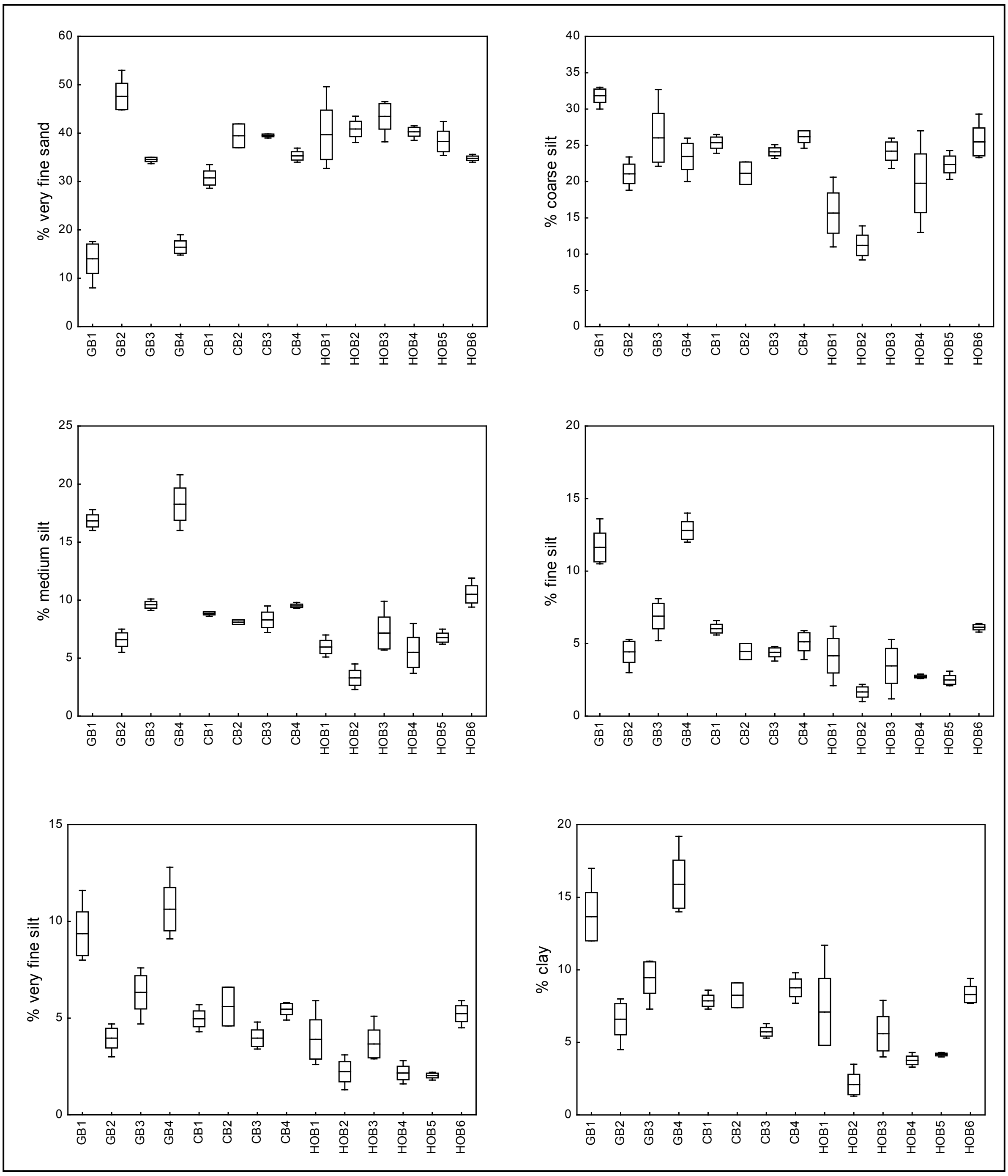


Figure 4-2: Percentage composition of the finer grained sediment (very fine sand, coarse silt, medium silt, fine silt, very fine silt and clay) at each site

Line = mean value, box = ±SE , whisker ends = minimum and maximum value

Figure 4-3: View of the sediment surface at a Head of the Bay site

4.1.2 PCA of sediment grain size distribution

I used a Principal Components Analysis (PCA) to examine the sediment grain size data. The PCA ordination is presented in Figure 4-4. A summary of the variation explained by each of five principal components is provided in Appendix 5. The combination of the grain size fractions making up each principal component is also provided in Appendix 5.

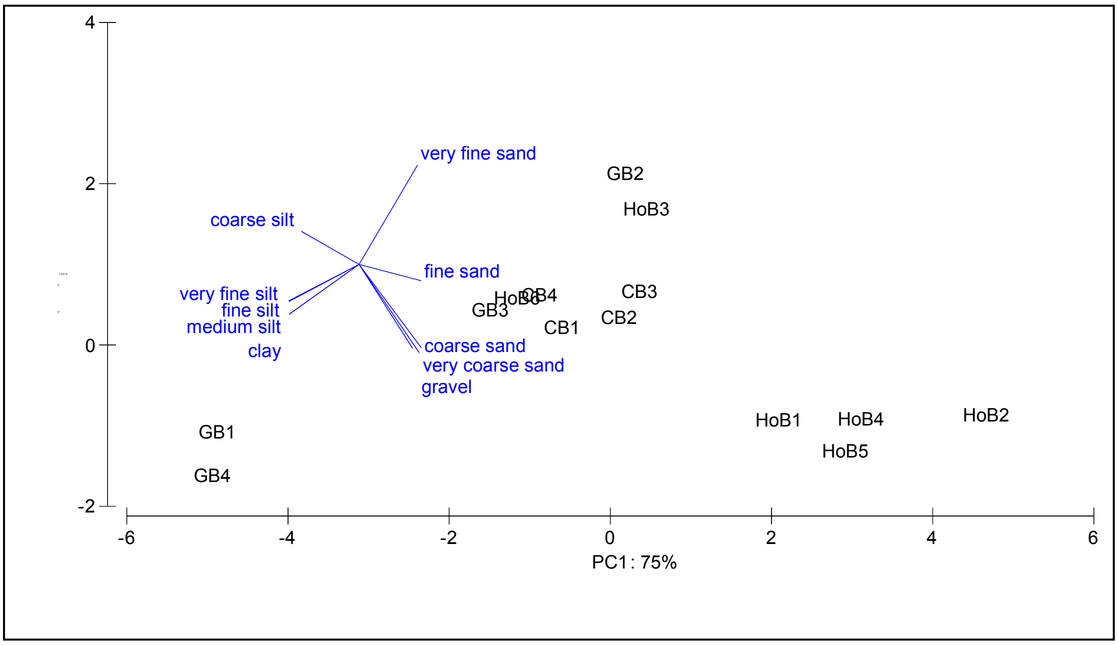


Figure 4-4: PCA ordination of sites based on sediment grain size

Principal component 1, along the horizontal axis in Figure 4-4, accounts for 75% of the variation between sites. Moving from left to right along this axis the sediment goes from fine grained (clay and medium to very fine silt) to coarser grained sediment (fine, coarse and very coarse sand and gravel). Along this axis the sites group into those dominated by fine grained sediment (GB1 and GB2), the sites that are about half and half sand and silt (all Charteris Bay sites, HoB 3, HoB6, GB2 and GB3) and the sites dominated by coarse grained sediment (Head of the Bay sites 1, 2, 4 and 5). The sediment grain size at HoB 2 is coarser than that at HoB1, 4, and 5.

Principal component 2 along the vertical axis in Figure 4-4, accounts for 12.9% of the variation between sites. Moving from top to bottom along this axis the sediment goes from very fine sand and coarse silt to the fine grained (clay and medium to very fine silt) sediment and fine sand to coarser grained sediment (coarse and very coarse sand and gravel). The group of sites in the middle of Figure 4-4 separate along this axis. GB2 and HoB3 have sediment containing more very fine sand and coarse silt than the sediment at all Charteris Bay sites, HoB6 and GB3.

4.1.3 Organic matter

The Organic matter (Loss on Ignition LOI) concentrations in the three sediment samples from each site are given in Appendix 6 and summarised in Figure 4-5. The organic matter content over all sites ranged from 0.9 to 2.6%. In Governors Bay the sandier sediment at GB2 and GB3 contained less organic matter than the muddier sediment at GB1 and GB4. In Charteris Bay and Head of the Bay I found no relationship between sediment grain size composition and organic matter content.

The mudflat sediment is typically in good condition with low to moderate organic matter enrichment (Robertson and Stevens, 2008: for information refer to Appendix 3).

4.1.4 Nutrient concentrations

The total nitrogen (TN) and total reactive phosphorus (TRP) concentrations in the three sediment samples from each site are given in Appendix 6 and summarised in Figures 4-6 and 4-7.

Total nitrogen

Total nitrogen (TN) concentration over all sites ranged from <500-990 mg/kg dry weight. Mean TN concentrations were not calculated because some values were less than the detection limit.

The highest TN concentrations occurred at Governors Bay sites with concentrations in Governors Bay higher than those in Head of the Bay. TN concentrations at CB1 and CB3 were higher than those at CB2 and CB4.

The mudflat sediment is typically in good condition with low to moderate nitrogen enrichment (Robertson and Stevens, 2008: for information refer to Appendix 3).

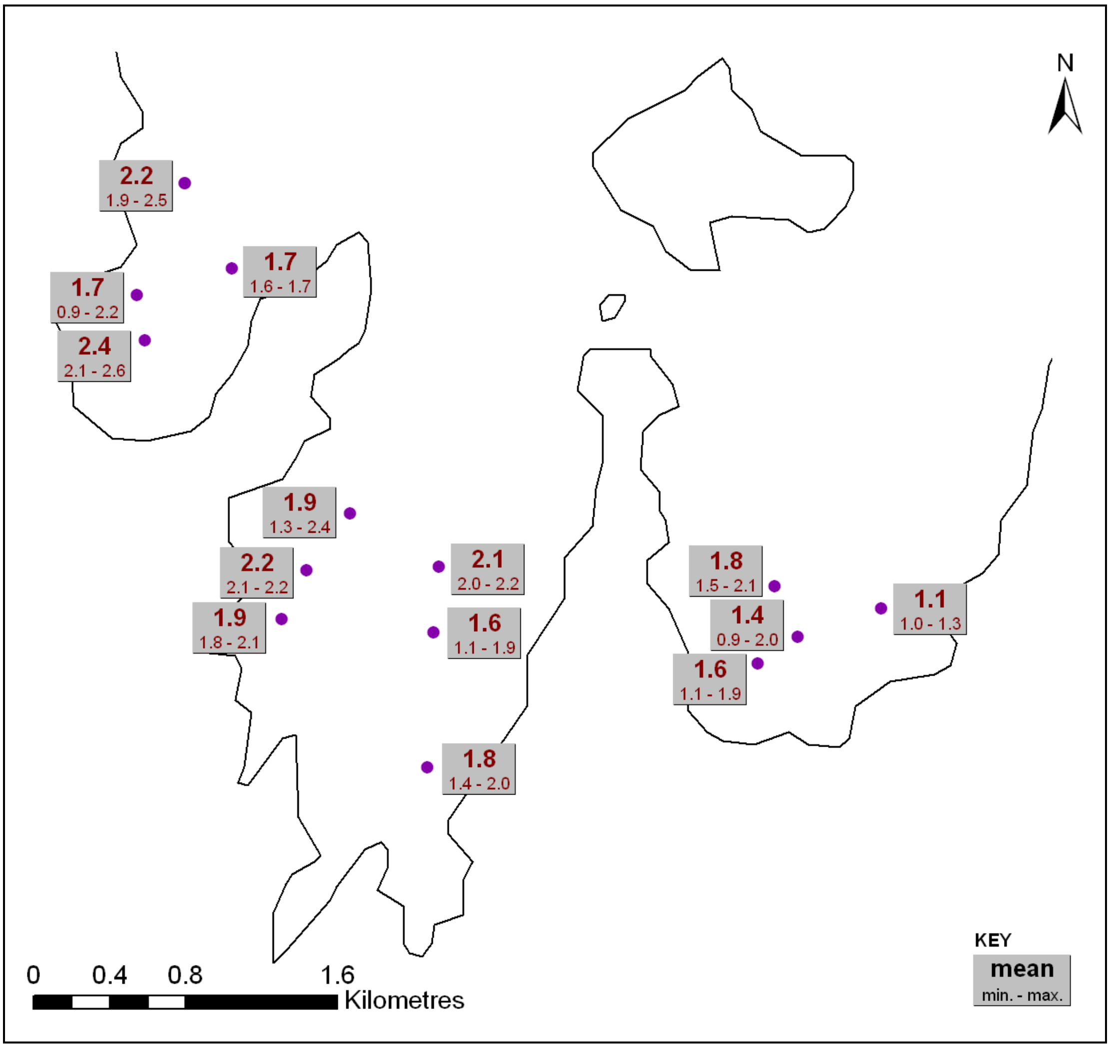


Figure 4-5: Mean and range in organic matter (%) at each site

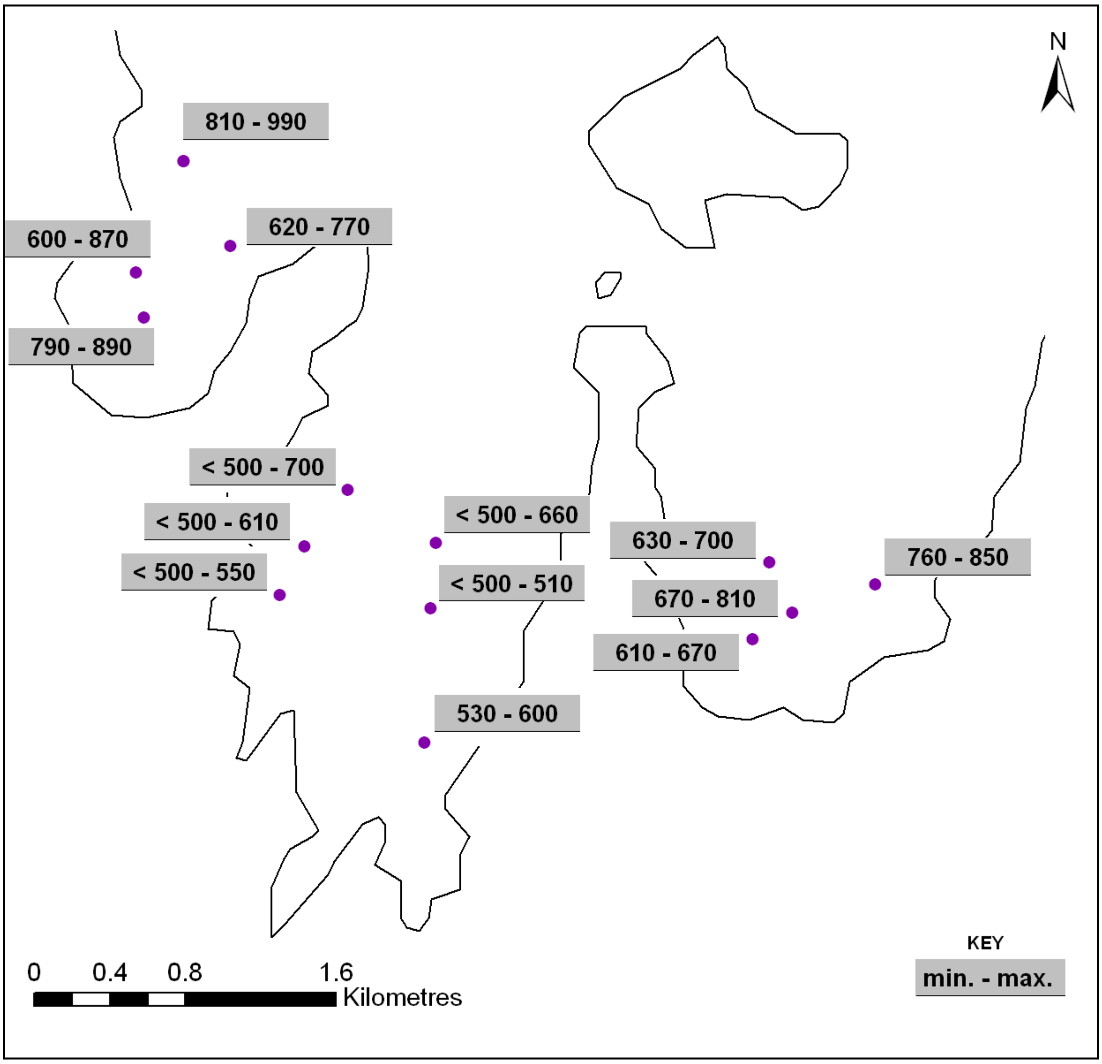


Figure 4-6: Range in total nitrogen concentration (mg/kg dry weight) at each site

Total recoverable phosphorus

Total recoverable phosphorus (TRP) concentrations over all sites ranged from 570-980 mg/kg dry weight. The mean and range in concentration typically varied between sites in a bay. In Governors Bay TRP concentrations were lower at GB2 than at the other sites; the highest concentrations were at GB1. In Head of the Bay the highest mean concentration was at HoB2 with the minimum concentration at this site higher than the maximum concentration at HoB1, HoB3 and HoB4. In Charteris Bay the highest concentration was at CB1 with the minimum concentration at this site higher than the maximum concentration at other sites in this bay. The lowest mean TRP concentrations in Head of the Bay and Charteris Bay were at sites furthest from the head of each bay.

The mudflat sediment is typically in fair condition, i.e. there is phosphorus enrichment (Robertson and Stevens, 2008: for information refer to Appendix 3). The phosphorus enriched mudflat sediment likely comes from the phosphorus-rich volcanic rock in the catchments (Lynn, 2005).

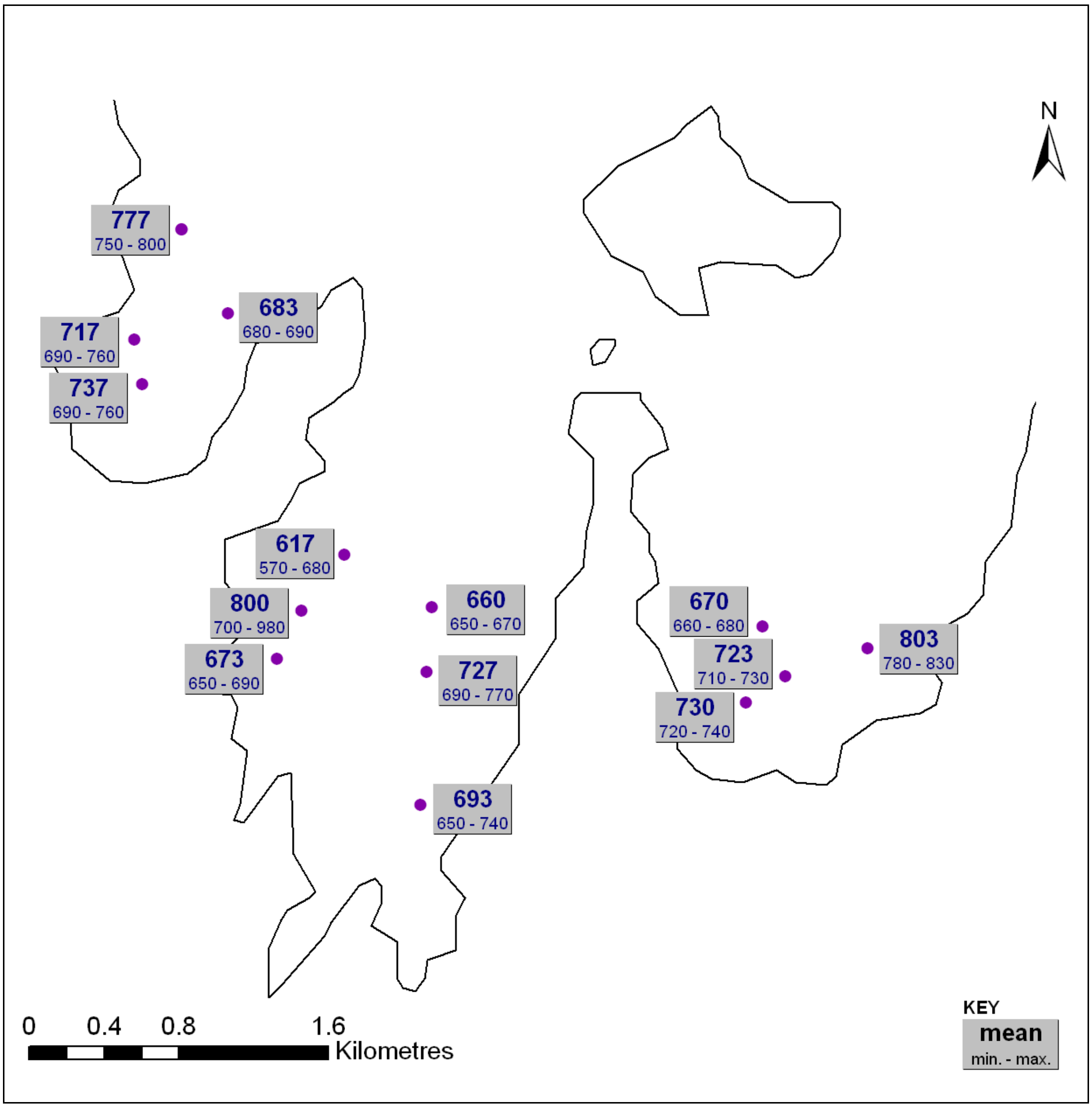


Figure 4-7: Mean and range in total reactive phosphorus concentrations (mg/kg dry weight) at each site

4.1.5 Metal concentrations

The copper (Cu), lead (Pb) and zinc (Zn) concentrations in the three sediment samples from each site are given in Appendix 6. These data are summarised in Figures 4-8 to 4-10.

Copper

The copper concentrations over all sites ranged from 4.5-14 mg/kg with all but one value less than 8 mg/kg. The mean Cu concentration varied slightly between sites in a bay. The range in concentrations at a site was typically small with the largest range being 8 mg/kg at HoB2.

All copper concentrations are below the ANZECC (2000) ISQG-low sediment quality guideline values of 65 mg/kg.

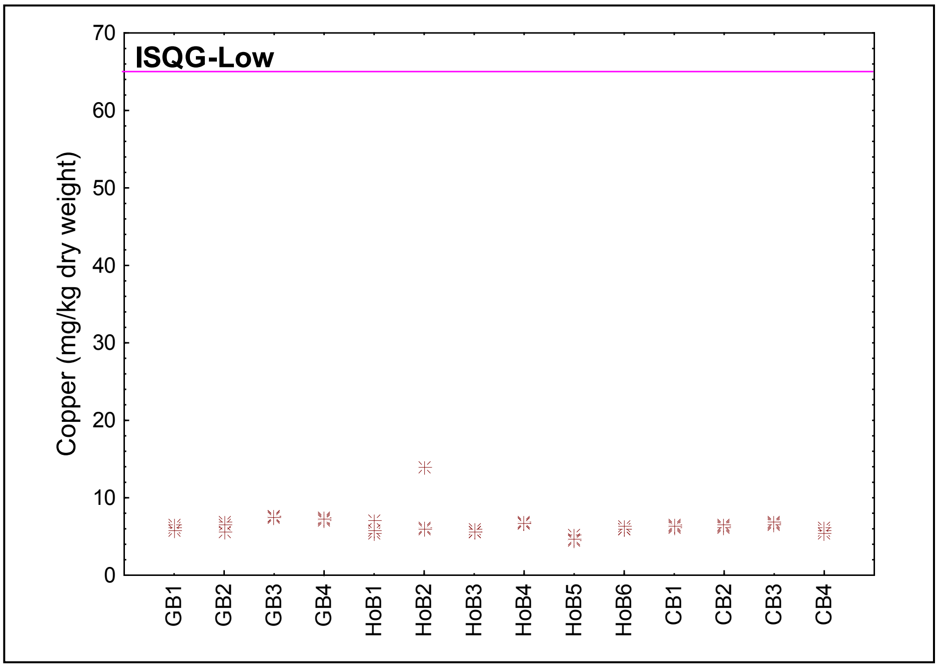


Figure 4-8: Copper concentrations (mg/kg dry weight) at each site

Lead

The lead concentration ranged from 2.1-20 mg/kg with 87% of values less than 5 mg/kg. The range in mean Pb concentration between sites in Head of the Bay and Charteris Bay was small with a larger range between sites in Governors Bay. The range in concentrations at a site was typically small with the largest range being 15.2 mg/kg at GB2.

All lead concentrations are below the ANZECC (2000) ISQG-low sediment quality guideline value of 50 mg/kg.

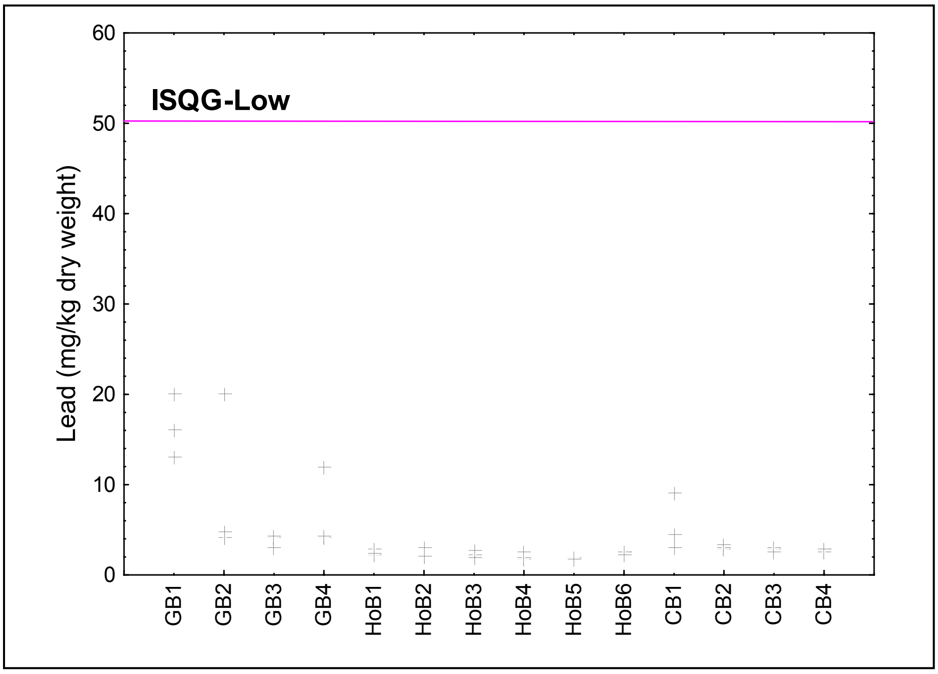


Figure 4-9: Lead concentrations (mg/kg dry weight) at each site

Zinc

The zinc concentration over all sites ranged from 34-62 mg/kg. Mean Zn concentration typically varied between sites in a bay with more variation between sites in Head of the Bay than in Governors Bay and Charteris Bay. The concentrations at HoB5 were lower than those at any other site. The range in concentrations at a site was typically small with the largest range being 14 mg/kg at HoB1.

All zinc concentrations were below the ANZECC (2000) ISQG-low sediment quality guideline values of 200 mg/kg.

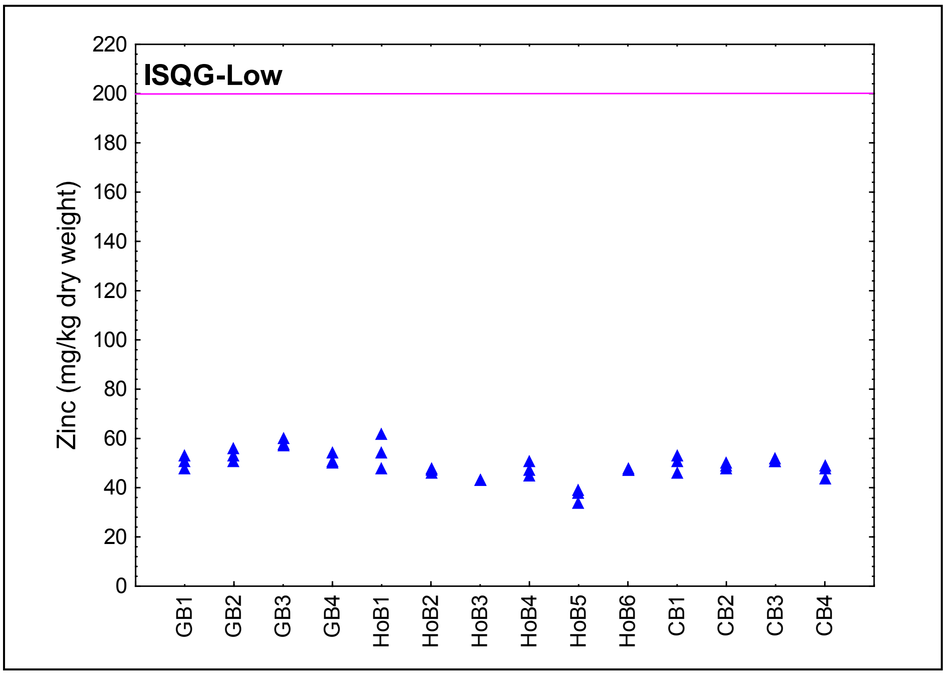


Figure 4-10: Zinc concentrations (mg/kg dry weight) at each site

4.2 Benthic infauna

4.2.1 Taxa present

I found fifty-four different animal taxa in the samples (Table 4-1). There were two anemone, 13 snails and shellfish, 24 worm, 1 ribbon worm, 1 insect and 13 crustacea, taxa.

4.2.2 Number of taxa at a site

I calculated the number of different taxa in all core samples from a site and grouped the taxa into snails and shellfish (molluscs), worms, crustacea and 'other' (nemertea = ribbon worm and anemones) (Figure 3-11). There were from 12 - 27 taxa at a site.

Table 4-1: Taxa found in the samples

Phylum		Scientific name	common name
Coelenterata (anemones)		*Edwardsia* sp.	sea anemone
		Unidentified sp.	anemone
Mollusca (snails and shellfish)	Bivalvia	*Arthritica bifurca*	
		Austrovenus stutchburyi	cockle
		Mactra ovata	soft-shelled shellfish
		Paphies donacina	tuatua
		Soletellina siliqua	
		Macomona liliana	wedge shell
	Gastropoda	*Amphibola crenata*	mudflat snail
		Cominella glandiformis	mudflat whelk
		Diloma subrostrata	mudflat top shell
		Micrelenchus tenebrosus	
		Notoacmea helmsi	small limpet
		Turbonilla sp.	
		Xymene plebeius	whelk
Annelida (worms)	Polychaeta	*Aonides* sp.	
		Aphelochaeta sp.	
		Asychis sp.	
		Boccardia (paraboccardia) syrtis	
		Caulleriella sp.	
		Capitella sp.	
		Glycera ovigera	
		Glycera lamelliformis	
		Glycinde dorsalis	
		Heteromastus filiformis	
		Magelona sp.	
		Nicon aestuariensis	
		Paradoneis sp.	
		Pectinaria australis	
		Perinereis ?brevicirris	
		Prionospio sp.	
		Scolecolepides benhami	
		Scolelepis sp.	
		Scoloplos cylindrifer	
		Streblosoma sp.	
		Syllidae (Exogoninae)	
		Syllid sp.A	
		Syllid sp.B	
		Terebellides sp.	
Nemertea		Unidentified sp.	ribbon wom
Arthropoda (crustacea and insects)	Insecta	Chironomid larva	
	Crustacea	Amphipod sp.A	hopper
		Amphipod sp.B	hopper
		Amphipod sp.C	hopper
		Amphipod sp. (phoxocephalid)	hopper
		Amphipod sp.G	hopper
		Amphipod. Sp.H	hopper
		Isopod sp.	louse
		Austrohelice crassa	mudflat crab
		Halicarcinus sp.	pill box crab
		Macrophthalmus hirtipes	stalk eyed mud crab
		Mysid sp.	shrimp
		Unidentified sp.	shrimp
		Elminius modestus	estuarine barnacle

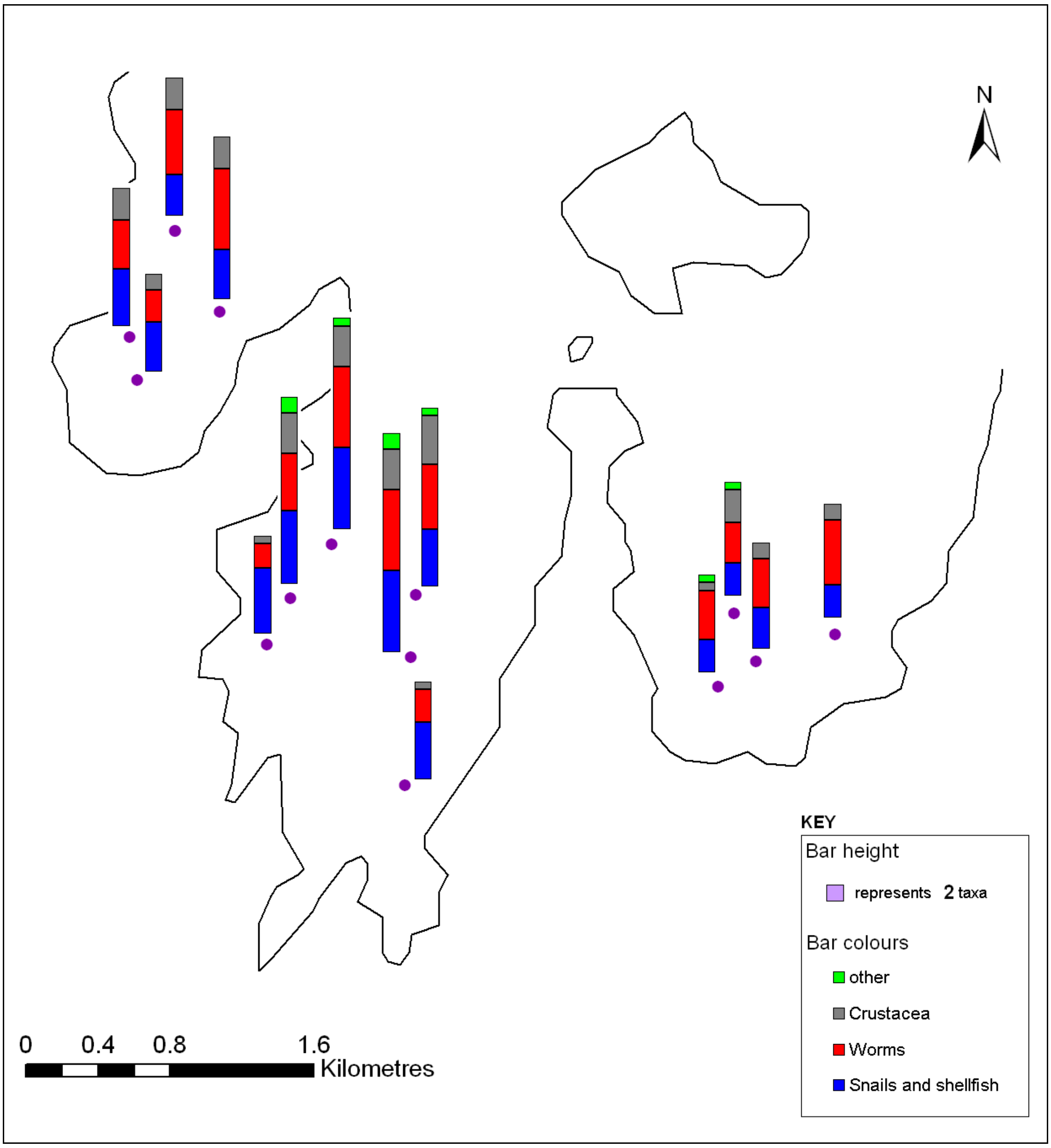


Figure 4-11: Total number of taxa and taxa composition of the infauna at each site

Governors Bay

Twenty taxa occurred at GB2, 17 taxa at both GB1 and GB3 and 12 taxa at GB4. At all sites there were snails and shellfish, worms and crustacea but no 'other' taxa. At GB1 and GB2 there were more worm taxa while at GB3 and GB4 there were more snails and shellfish taxa, than any other taxa groups.

Head of the Bay

Twenty-seven taxa occurred at HoB5, 26 at HoB1, 23 at HoB2, 22 at HoB4 and 12 at HoB3 and HoB6. At all sites there were snails and shellfish, worms and crustacea. Other taxa occurred at four sites but were not present at HoB3 and HoB6. At HoB1 and HoB5 the number of snails and shellfish and worm taxa was the same while at HoB2, HoB3 and HoB6 there were more snails and shellfish taxa than worm taxa and at HoB4 there were more worm taxa than snails and shellfish taxa.

Charteris Bay

Fourteen taxa occurred at CB2, 13 at CB3 and 12 at CB1 and CB4. Snails and shellfish, worms and crustacea were present at all sites. Other taxa occurred at CB2 and CB4 but were not present at CB1 and CB3. At all sites there were more worm taxa than any other taxa groups.

4.2.3 Number of taxa per core

The number of taxa per core ranged from four at HoB3 to nineteen at HoB5. In Governors Bay there were 5-12, in Charteris Bay 6-12 and in Head of the Bay 4-19, taxa per core.

4.2.4 Number of individuals

The number of individuals/m^2 ranged from 977 at HoB3 to 15038[4] at HoB5. There were 1730-9475 individuals/m^2 at sites in Governors Bay, 1429-8725 individuals/m^2 at sites in Charteris Bay and 977-15038 individuals/m^2 at sites in Head of the Bay. The mean number of individuals/m^2 per site and the taxonomic composition of individuals are shown in Figure 4-12.

At all sites except GB2 worms were the most numerous animals. At GB2 there were more snails and shellfish individuals than worm individuals.

Governors Bay

The mean number of individuals at GB1 was 3459/m^2, GB2 was 3068/m^2, GB3 was 7970/m^2 and GB4 was 6075/m^2.

Head of the Bay

The mean number of individuals at HoB1 was 7609/m^2, HoB2 was 5383/m^2, HoB3 was 1699/m^2, HoB4 was 6060/m^2, HoB5 was 10872/m^2 and HoB6 was 9278/m^2.

Charteris Bay

The mean number of individuals at CB1 was 6631/m^2, CB2 was 2752/m^2, CB3 was 6034/m^2 and CB4 was 5068/m^2.

[4] The number of individuals per core were used to calculate the number of individuals/m^2.

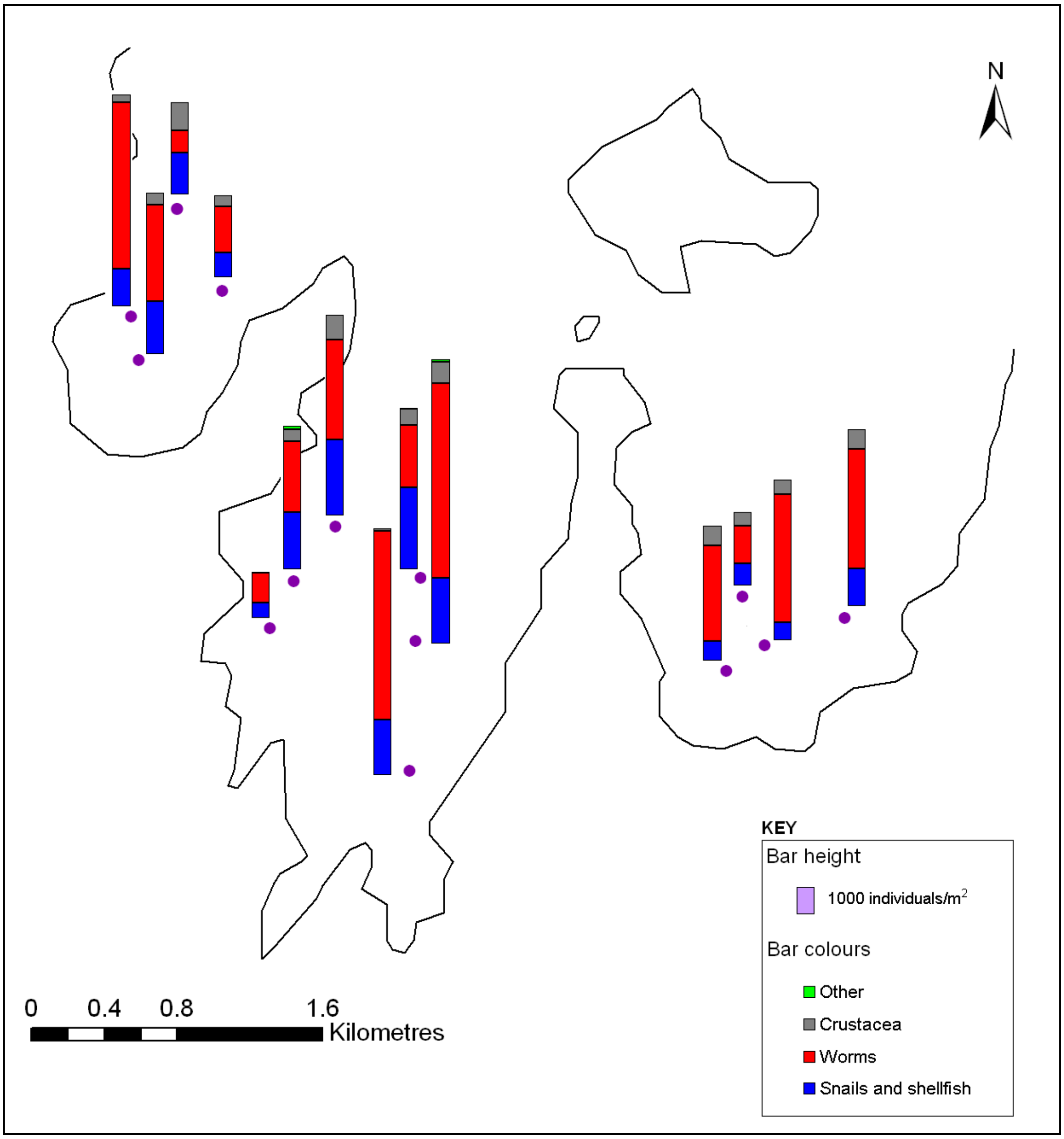


Figure 4-12: Mean number of individuals/m² and the taxonomic composition of the individuals

4.2.5 Composition of the infauna at each site

The proportion of individuals of each taxa present at each site is shown in Figures 4-13 to 4-15. The different groups of taxa are colour coded.
NOTE: At each site there were only a few individuals of a number of taxa. To graph the proportion of these low abundance taxa, I added the number of individuals of a taxa group (worm, snails and shellfish or crustacea) together and graphed the result.

Governors Bay
The GB1 infauna is notably different from that at the other sites in the bay (Figure 4-13). The most abundant animal at GB1 was the small bivalve *Arthritica bifurca* while at the other three sites the most abundant animal was the worm *Heteromastus filiformis.* However, the proportion of the individuals that were *Heteromastus filiformis* varied between these three sites. At GB1 the second most abundant animal was an isopod while at the other three sites it was *Arthritica bifurca.* The taxa composition of the remaining individuals at the sites was similar (Figure 4-13).

Head of the Bay

The most abundant animal at all sites was the worm *Heteromastus filiformis.* However, the proportion of the individuals that were *Heteromastus filiformis* varied between sites. The second most abundant taxa at HoB1, HoB2, HoB2 and HoB5 were cockles while at HoB3 and HoB6 it was the small bivalve *Arthritica bifurca.* The taxa composition of the remaining individuals varied between sites (Figure 4-14).

Charteris Bay

The most abundant animal at all sites was the worm *Heteromastus filiformis.* However, the proportion of the individuals that were *Heteromastus filiformis* varied between sites. The second and third most abundant taxa at sites were the small bivalve *Arthritica bifurca* and the mudflat crab *Austrohelice crassa.* The taxa composition of the remaining individuals at the sites was similar (Figure 4-15).

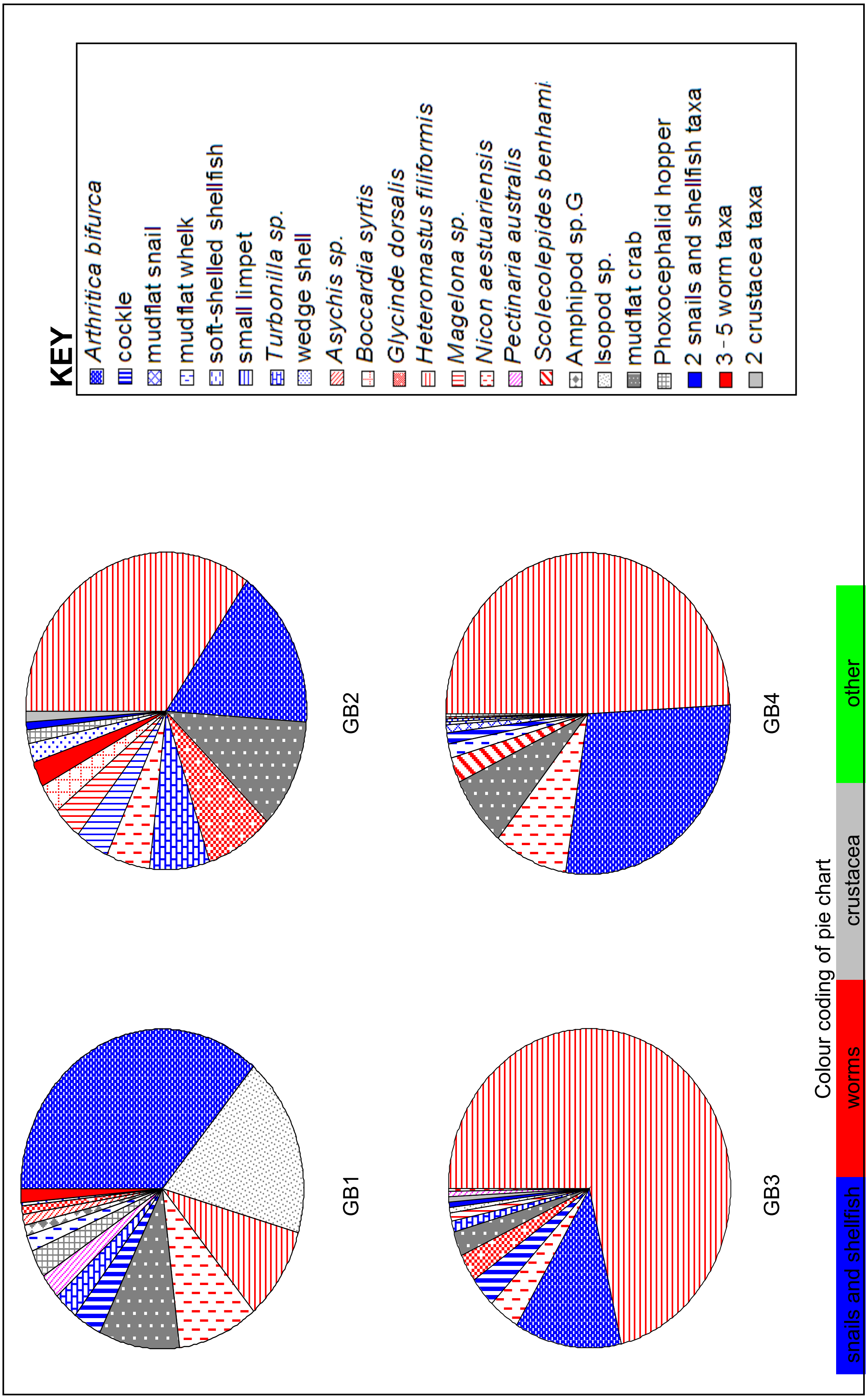


Figure 4-13: Proportion of individuals of each type of animal living in the mudflat at each site in Governors Bay

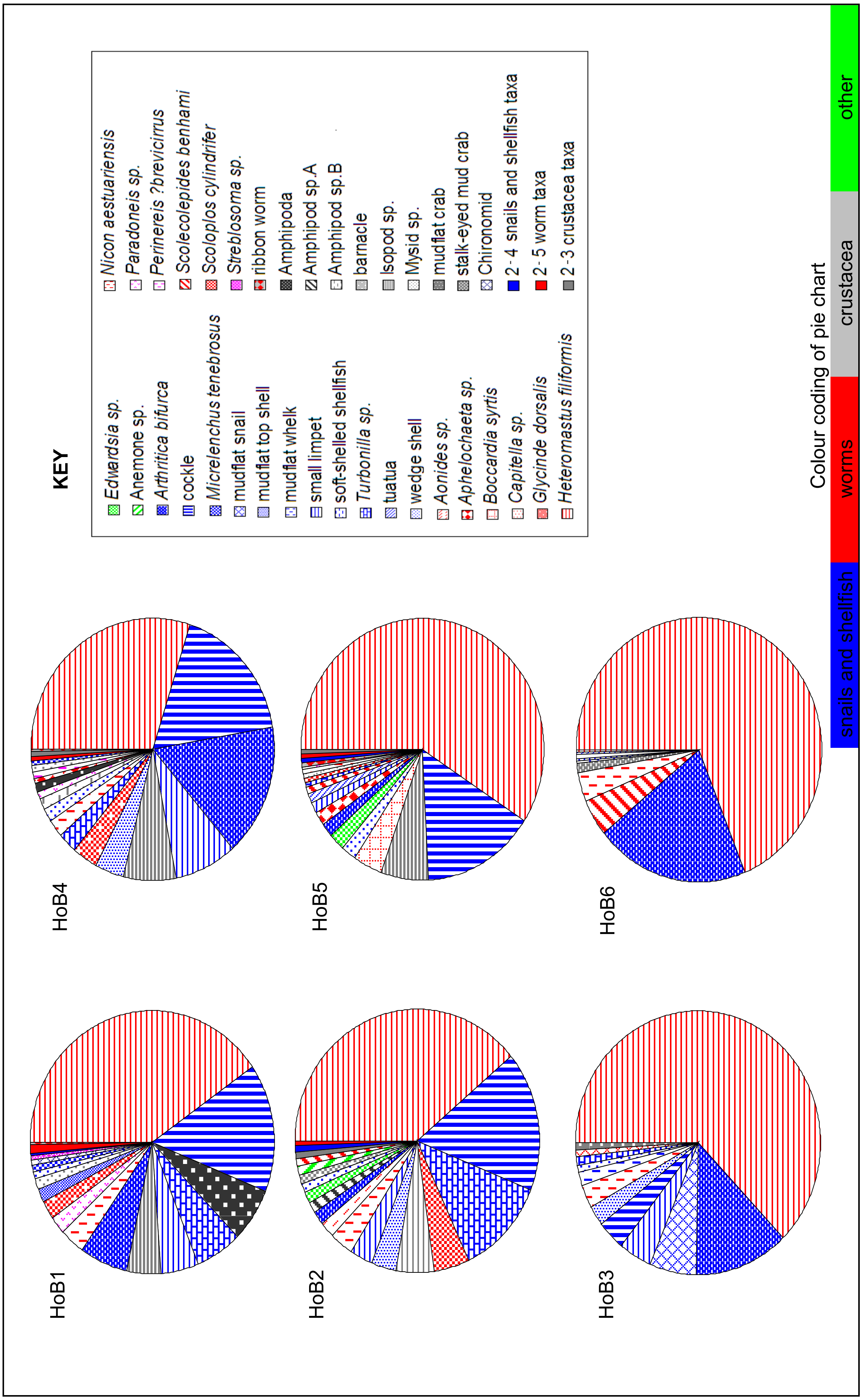


Figure 4-14: Proportion of individuals of each type of animal living in the mudflat at each site in Head of the Bay

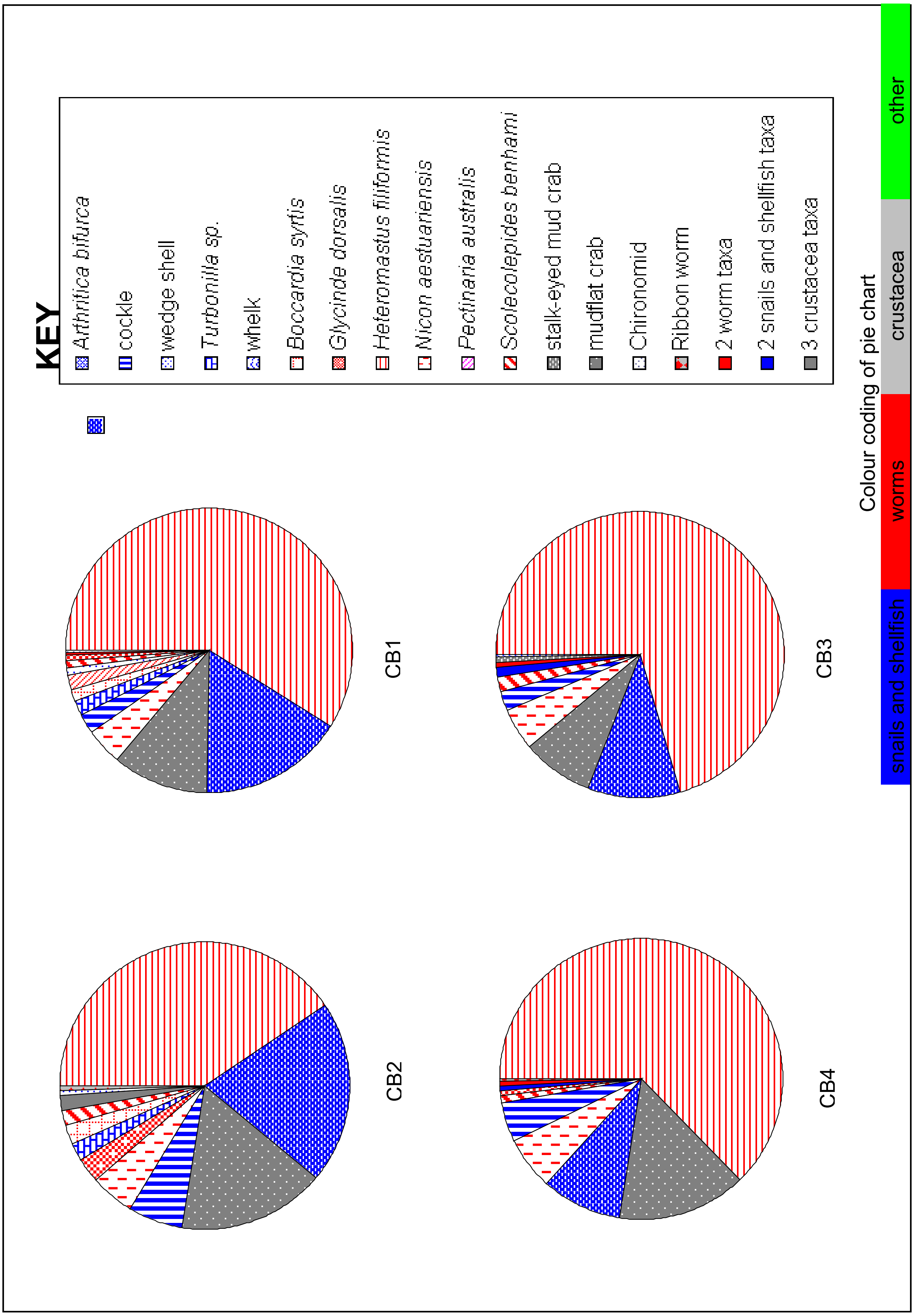


Figure 4-15: Proportion of individuals of each type of animal living in the mudflat in Charteris Bay

4.2.6 Similarity between sites based on the infauna

I used the taxa with a total of ten or more individuals over all core samples from all sites (26 taxa) to generate a multi-dimensional scaling (MDS) ordination of the sites (Figure 4-16). The stress level (0.1) indicates the plot is a good representation of the similarities between sites.

In Charteris Bay the infauna at the four sites is similar. In Governors Bay there are differences in the infauna between sites and in the Head of the Bay that are large differences in infauna between sites. The infauna at Governors Bay sites is more similar to that at Charteris Bay sites than Head of the Bay sites. In Head of the Bay the infauna at sites 3 and 6 is distinctly different from that at the other four sites. The infauna at Head of the Bay site 1 is most similar to that at Head of the Bay site 4.

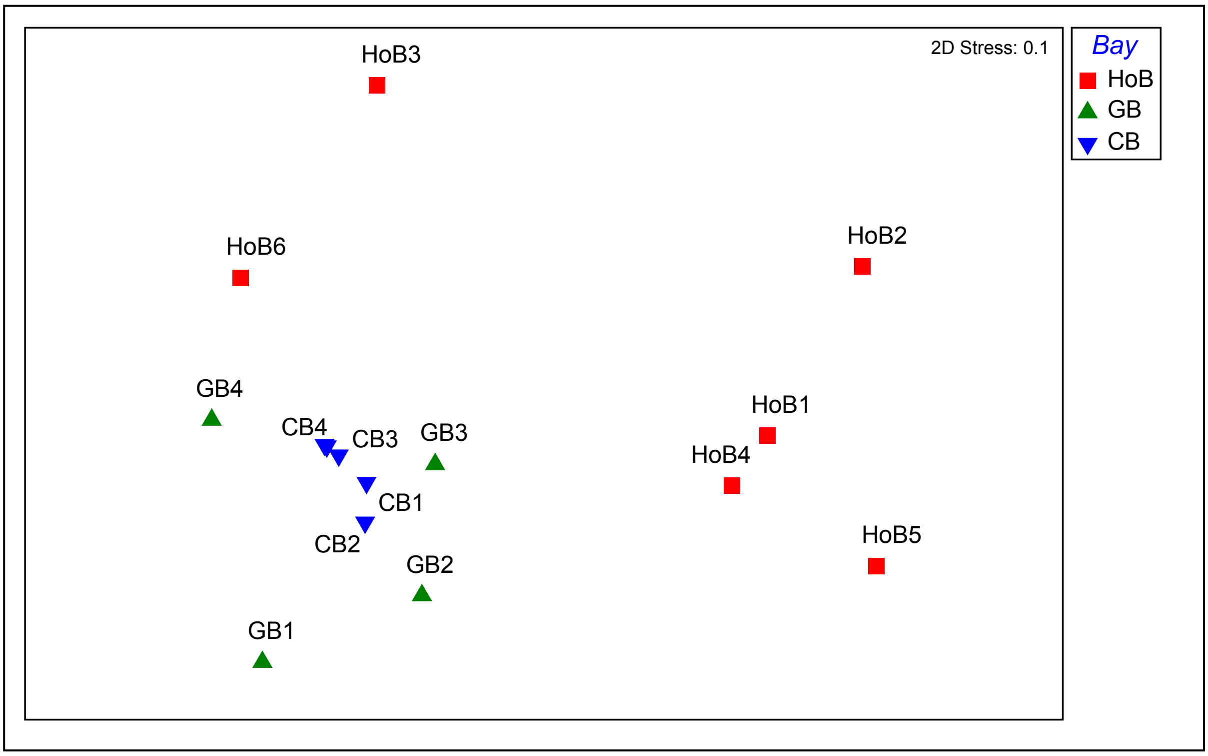


Figure 4-16: Multi-dimensional scaling ordination of sites based on the infauna

s = site

The grouping of sites based on the infauna (Figure 4-16) is similar to that for the grouping of sites based on sediment grain size (Figure 4-4). In both figures Head of the Bay sites 1, 2, 4 and 5 are together with HoB3 and HoB6 separated from this group. The Charteris Bay sites group together in both figures. Governors Bay sites 1 and 4 are separated from all other sites in both figures. However, there is a larger separation of sites GB1 and GB4 from all other sites in Figure 4-4 than on Figure 4-16.

4.2.7 Relationship of the similarity of sites based on infauna and sediment grain size

I have used bubble plots to investigate the relationship between the infauna at a site and each of ten grain size fractions. I have overlaid the MDS ordination based on the infauna with bubble plots of each of sediment grain size fraction (Figure 4-17). Bubble size increases as the quantity of the named grain size fraction increases.

The plots show there is a relationship between infauna and sediment grain size. At sites HoB1, HoB2, HoB4 and HoB5 on the right of the MDS ordination there is more coarse grained sediment (gravel, very coarse sand and coarse sand) and typically less fine grained sediment (clay, very fine silt, fine silt and medium silt) than at the sites on the left of the MDS ordination. GB4 and GB1 have more fine grained sediment (clay, very fine silt, fine silt and medium silt) than any other sites.

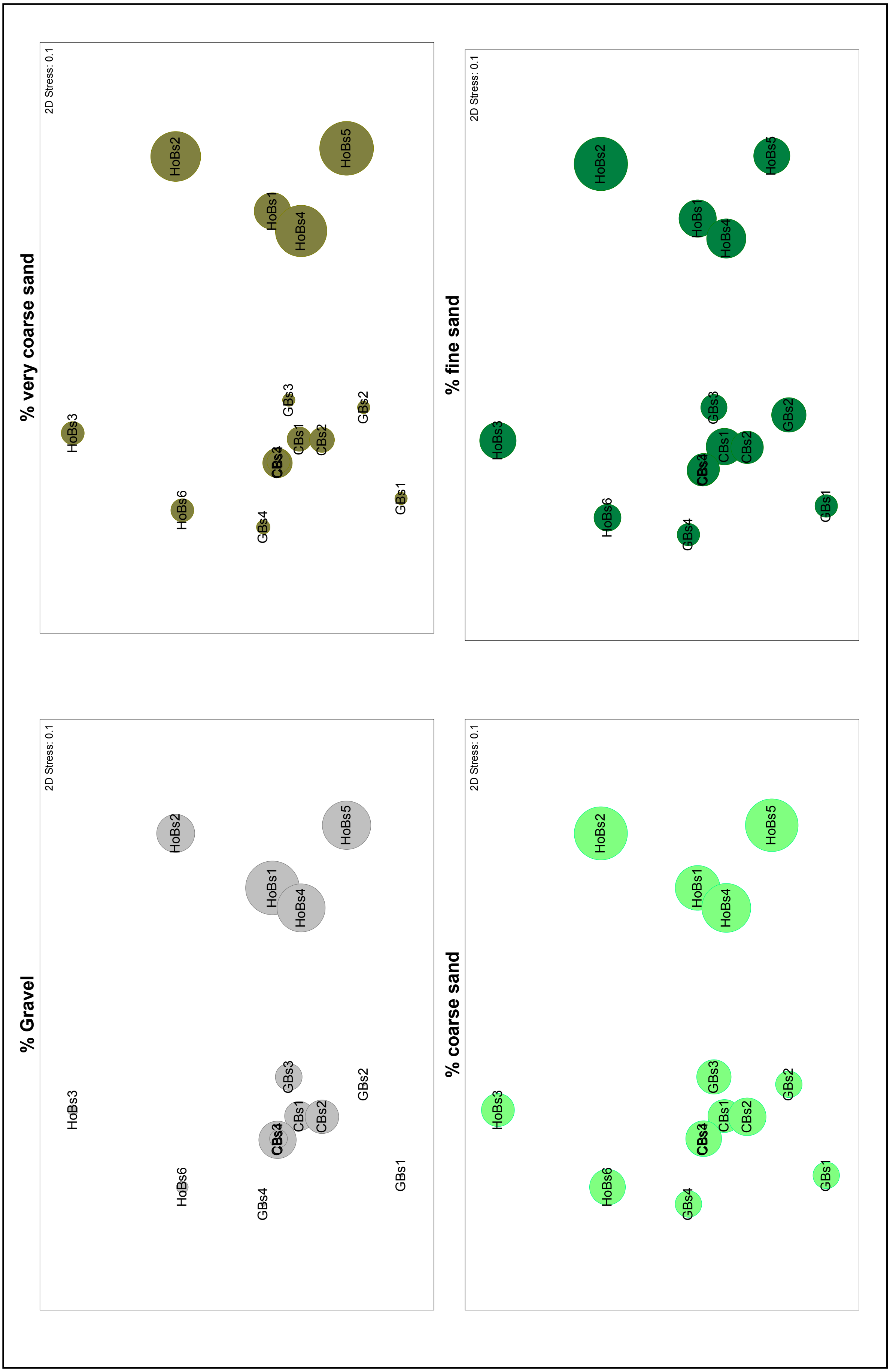
4.2.8 The influence of sediment grain size on taxa, individuals and named taxa

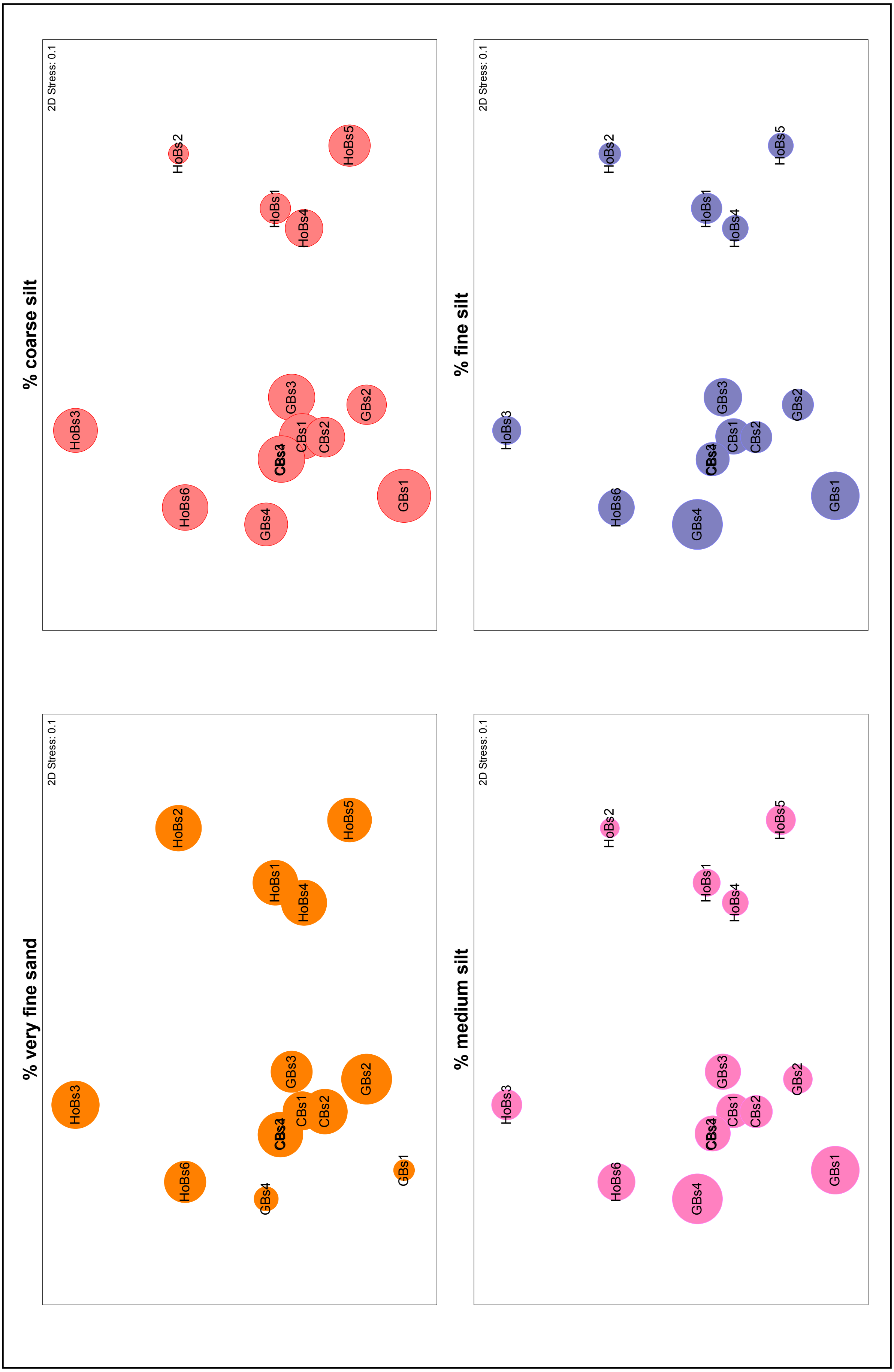
Taxa and individuals

I used regression analysis to investigate the influence of %gravel, %sand, %silt and %clay on the total number of taxa and number of snails and shellfish, worm and crustacean taxa as well as the total number of individuals and number of snails and shellfish, worm and crustacean individuals. I averaged the data by site before doing the analysis. The statistically significant results ($p<0.05$) are in Table 4-2. A positive r value means as the percentage of the given grain size fraction increases the listed biological value also increases. A negative r value means as the percentage of the given grain size fraction increases the listed biological value decreases. All of the statistically significant relationships have an r^2 value between 0.29 and 0.57. These r^2 values are not high. A perfect relationship has an r^2 value of 1. However, these results provide an indication of the influence of sediment grain size on the number of taxa and individuals present.

Table 4-2: Statistically significant relationships between sediment grain size and taxa and individuals

Relationship	r^2	r positive or negative	p
Total no of taxa:% Gravel	0.54	positive	0.003
No of snails and shellfish taxa:% Gravel	0.57	positive	0.002
No of snails and shellfish individuals:% Gravel	0.41	positive	0.014
No of snails and shellfish taxa:% Sand	0.35	positive	0.027
Total no of taxa:% Silt	0.29	negative	0.049
No of snails and shellfish taxa:% Silt	0.45	negative	0.008
No of snails and shellfish taxa:% Clay	0.36	negative	0.023


% very coarse sand
2D Stress: 0.1
HoBs2
HoBs5
HoBs1
HoBs4
HoBs3
GBs3
GBs2
CBs1
CBs2
CBs4
HoBs6
GBs1
GBs4
% fine sand
2D Stress: 0.1
% Gravel
2D Stress: 0.1
% coarse sand
2D Stress: 0.1


% coarse silt
% fine silt
% very fine sand
% medium silt
2D Stress: 0.1
HoBs1
HoBs2
HoBs3
HoBs4
HoBs5
HoBs6
GBs1
GBs2
GBs3
GBs4
CBs1
CBs2
CBs3
CBs4

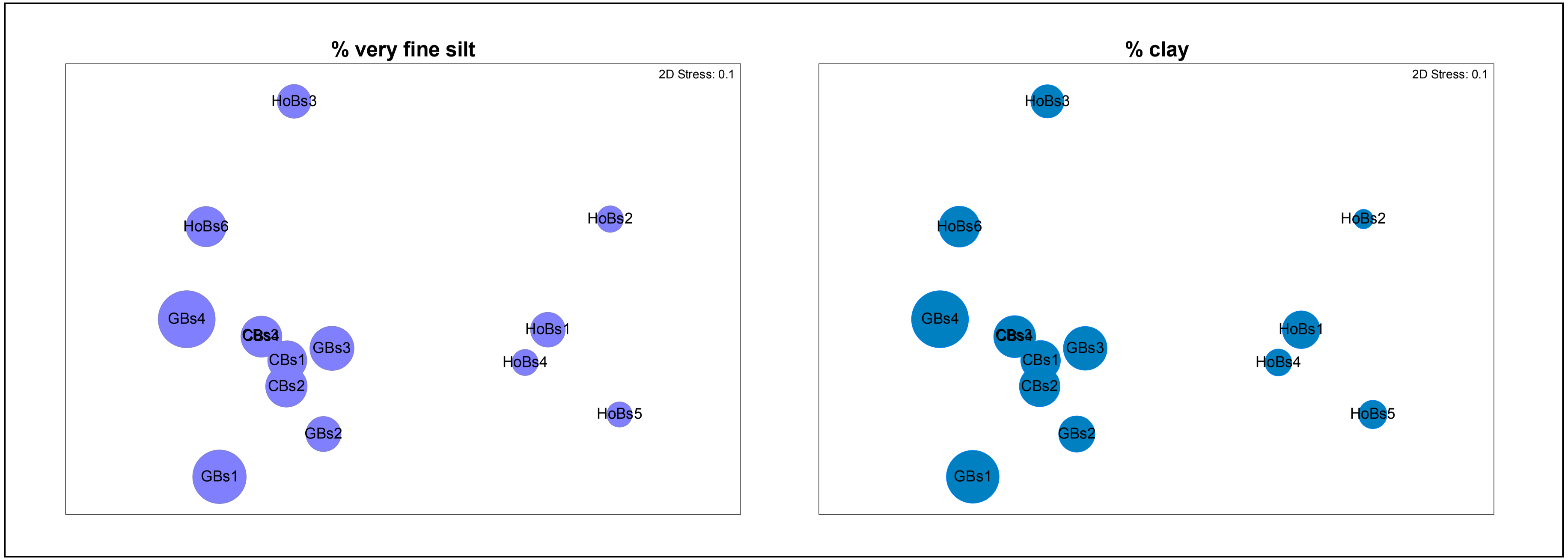


Figure 4-17: Multi-dimensional scaling ordination of sites based on the infauna overlaid with bubble plots of the relative quantity of each sediment grain size fraction

Bubble size: Bubble size increases as the quantity of the named grain size fraction increases. No bubble – grain size fraction not present.

As the %gravel increases so does the total number of taxa and the number of snails and shellfish taxa and individuals. As the %sand increases so does the number of snails and shellfish taxa. As the %silt increases the total number of taxa and the number of snails and shellfish taxa decreases. As the %clay increases the number of snails and shellfish taxa decreases.

Named taxa

I used regression analysis to investigate the influence of %gravel, %sand, %silt, %clay, %coarse sand, %very coarse sand, %fine sand, %very fine sand, %coarse silt, %medium silt, %fine silt and %very fine silt on the abundance of 11 taxa. These were the most abundant taxa and had more than 50 individuals over all samples. These taxa are the snails and shellfish *Arthritica bifurca,* cockles, *Notoacmea helmsi, Turbonilla* sp., the worms *Boccardia syrtis*, *Glycinde dorsalis, Heteromastus filiformis, Nicon aestuariensis* and *Scolecolepides benhami* and the crustacea *Austrohelice crassa* and Isopod sp. The statistically significant results ($p<0.05$) are in Table 4-3. Some of the r^2 values are not high. However, the results provide an indication of the influence of sediment grain size on the abundance of these taxa.

The abundance of the snails and shellfish Arthritica bifurca, cockles, Notoacmea helmsi, Turbonilla sp., the worm Nicon aestuariensis and the crustacea Austrohelice crassa and Isopod sp. is influenced by sediment grain size. The abundance of the worms Boccardia syrtis, Glycinde dorsalis, Heteromastus filiformis and Scolecolepides benhami is not influenced by sediment grain size.

Cockle abundance increased as the %gravel, %very coarse sand and %coarse sand increased and abundance decreased as the %silt, %clay, %coarse silt, %fine silt and %very fine silt increased. *Notoacmea helmsi* abundance increased as the %gravel, %very coarse sand and %coarse sand increased and abundance decreased as the %silt increased. *Turbonilla* sp. abundance increased as the %sand, %coarse sand and %fine sand increased and abundance decreased as the %silt, %coarse silt and %fine silt increased. Isopod sp. abundance increased as the %very coarse and %coarse sand increased. *Arthritica bifurca and Nicon aestuariensis* abundance increased as the %silt, %clay, %medium silt, %fine silt and %very fine silt increased and abundance decreased as the %sand and %very fine sand increased. For *Arthritica bifurca* abundance also decreased as the %fine sand increased. *Austrohelice crassa* abundance decreased as the %very coarse sand and %coarse sand increased.

Table 4-3: Statistically significant relationships between sediment grain size and named taxa

Relationship	r^2	r positive or negative	p
cockles:% gravel	0.75	positive	0.000
cockles:% silt	0.37	negative	0.021
cockles %:clay	0.31	negative	0.039
cockles:% very coarse sand	0.799	positive	0.000
cockles:% coarse sand	0.8	positive	0.000
cockles:% coarse silt	0.33	negative	0.031
cockles:% fine silt	0.28	negative	0.050
cockles: % very fine silt	0.36	negative	0.023
Arthritica bifurca: % sand	0.54	negative	0.003
Arthritica bifurca: % silt	0.46	positive	0.005
Arthritica bifurca: % clay	0.47	positive	0.007
Arthritica bifurca: % fine sand	0.41	negative	0.014
Arthritica bifurca: % very fine sand	0.44	negative	0.010
Arthritica bifurca: % medium silt	0.52	positive	0.004
Arthritica bifurca: % fine silt	0.54	positive	0.003
Arthritica bifurca: %very fine silt	0.45	positive	0.009
Notoacmea helmsi: % gravel	0.6	positive	0.001
Notoacmea helmsi: % silt	0.31	negative	0.039
Notoacmea helmsi: % very coarse sand	0.51	positive	0.004
Notoacmea helmsi: % coarse sand	0.46	positive	0.007
Turbonilla sp.:%sand	0.36	positive	0.023
Turbonilla sp.:%silt	0.41	negative	0.014
Turbonilla sp.:% coarse sand	0.32	positive	0.034
Turbonilla sp.:% fine sand	0.64	positive	0.001
Turbonilla sp.:% coarse silt	0.68	negative	0.000
Turbonilla sp.:% medium silt	0.29	negative	0.045
Nicon aestuariensis:% sand	0.52	negative	0.003
Nicon aestuariensis:% silt	0.47	positive	0.007
Nicon aestuariensis:% clay	0.59	positive	0.001
Nicon aestuariensis:% very fine sand	0.51	negative	0.004
Nicon aestuariensis:% medium silt	0.56	positive	0.002
Nicon aestuariensis:% fine silt	0.63	positive	0.001
Nicon aestuariensis:% very fine silt	0.598	positive	0.001
Austrohelice crassa:%very coarse sand	0.29	negative	0.046
Austrohelice crassa:% coarse sand	0.34	negative	0.030
Isopod sp.: %very coarse sand	0.38	positive	0.020
Isopod sp.: % coarse sand	0.3	positive	0.043

4.2.9 Size distribution of cockles

I found cockles at all sites. However a low number of cockles were present at the sites in Governors Bay and Charteris Bay. With few cockles at each site I combined the shell length (mm) data for each site in a bay to produce a size frequency graph for both bays (Figures 4-18 and 4-19).

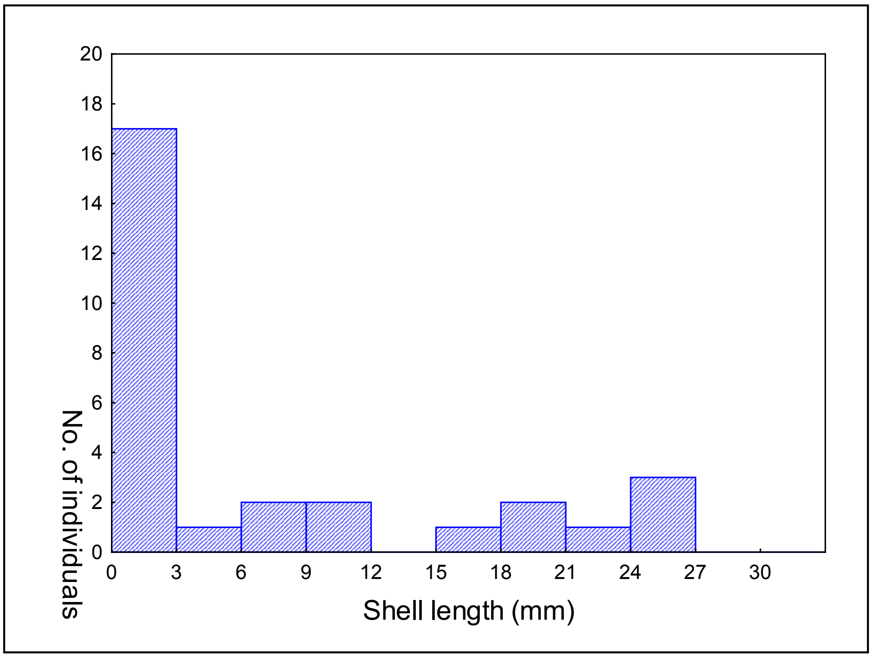


Figure 4-18: Distribution of cockle lengths from the sites in Governors Bay (29 individuals)

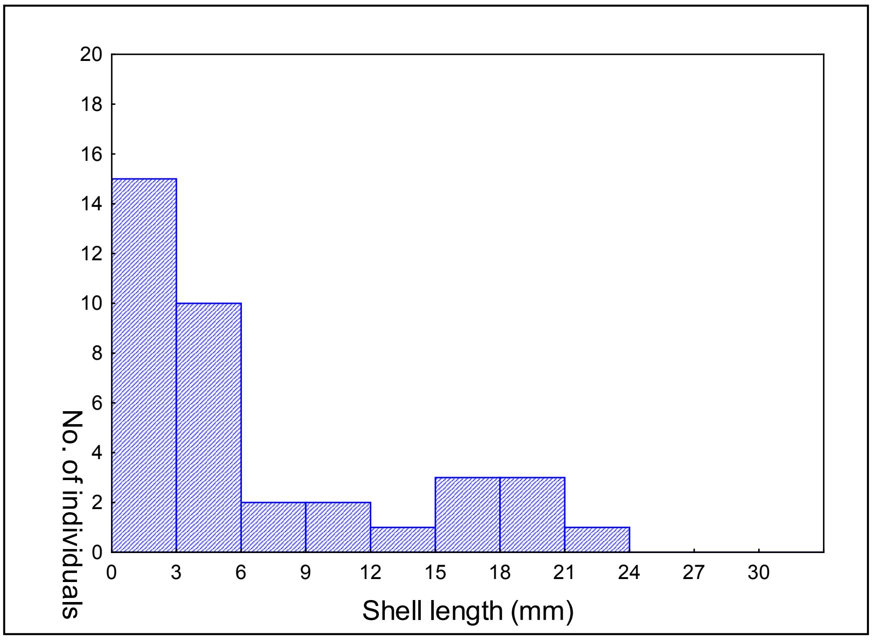


Figure 4-19: Distribution of cockle lengths from the sites in Charteris Bay (37 individuals)

Cockles were more abundant in Head of the Bay than in the other two bays. However in Head of the Bay there were a low number of cockles at sites 3 and 6 with the highest number (110) at site 5. I combined the Head of the Bay cockle shell length (mm) data for each site to produce one size frequency graph for this bay (Figure 4-20).

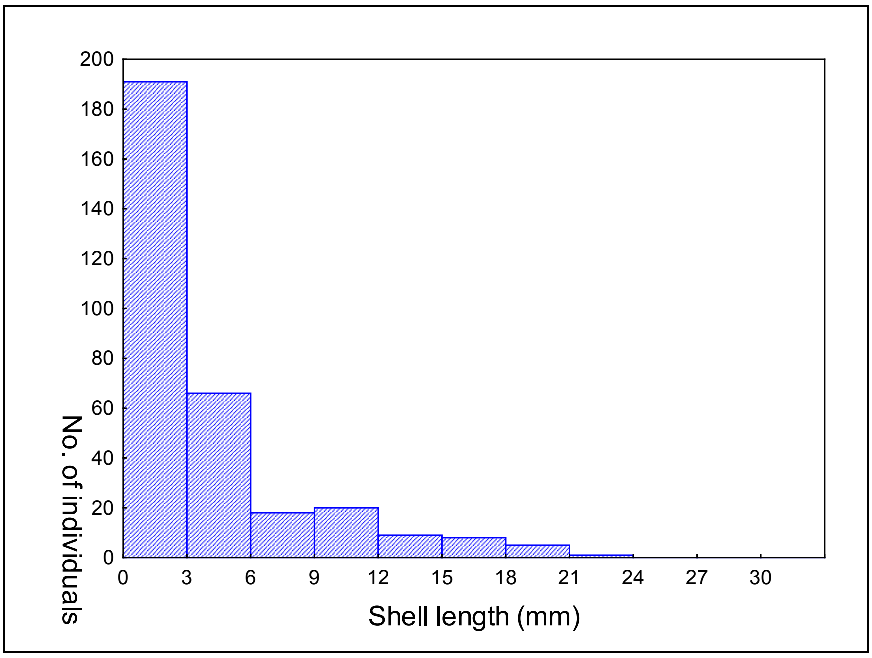


Figure 4-20: Distribution of cockle lengths from the sites in Head of the Bay (318 individuals)

Most of the cockles were smaller than 6 mm shell length. At this size they are recruits/juveniles. The low number of individuals larger than 20 mm suggests a low survival of the recruits that settle on these mudflats.

5 Discussion

In this discussion I evaluate the results from this study, compare the results to those from other studies in the upper harbour and the results from other sites on Banks Peninsula which includes bays of upper Akaroa Harbour (Bolton-Ritchie, 2005) and Okains Bay estuary (Bolton-Ritchie, 2008). I have included Okains Bay estuary in this comparison because the sediments and biota of upper bay or upper harbour mudflat sites elsewhere on Banks Peninsula or in Canterbury have not been assessed. The Lyttelton Harbour/Whakaraupō mudflats are not within an estuary. However, freshwater that flows into the upper harbour lowers the salinity at times with some estuarine invertebrate species living on the mudflats.

5.1 Sediment

5.1.1 Sediment grain size

The sediment grain size distribution varied between sites within a bay and between bays. The muddiest (highest quantity of silt and clay) sediment occurred at the innermost site in Governors Bay (80-90% mud) with a mud content of 80-82% at the outer western site in Governors Bay. The muddiest (51-59% mud) site in Head of the Bay was the innermost site. In Charteris Bay the western and eastern sites were muddier (52-55% mud) than those in the centre of the bay (44-48% mud). Conversely the coarsest (sand and gravel) sediment occurred at the middle site on the western side of Head of the Bay (72-80% coarse) with all but the innermost site in this bay having 47-74% coarse sediment. In Governors Bay there was more coarse sediment at the eastern-most site (53-65% coarse) than at other sites. In Charteris Bay there was more coarse sediment at the central sites (51-54% coarse) than at the other two sites.

The grain size results for sites 1 and 4 in Governors Bay and sites 1, 2, 3 and 6 in Head of the Bay are very similar to those found by Hart *et al.* (2008) and shown in Figures 2-2 and 2-3. At Governors Bay sites 2 and 3, Head of Bay sites 4 and 5 and all sites in Charteris Bay I found the sediment was sandier than that reported in Hart *et al.* (2008). Hart e*t .al.* (2008) extrapolated data from a limited number of intertidal sites a considerable distance apart to construct their figures. Therefore at locations some distance from a sampling site the 2008 results should be considered as an indication only of the sediment grain size distribution. For this reason I expected the results from this study to differ from those reported in 2008 because of differences between the actual location and number of sampling sites in each study.

The grain size distribution of the intertidal mudflats in this harbour is determined by the action of wind, waves and tidal currents on seabed sediment and sediment inputs to the harbour. Sediment enters the harbour via the streams, particularly with rainfall. The surface soil of the land surrounding the harbour is fine grained loess. Rainfall flowing down un-vegetated roadside escarpments, old and recent erosion scars and exposed soil entrains loess which ends up in the harbour. That is, the sediment that flows into the harbour is mostly fine grained. Wind, waves and currents influence where the sediment particles that flow into the harbour settle to the seabed. Fine grained sediment settles to the seabed in 'lower energy areas' than coarser sediment. The results suggest that the lowest energy bay is Governors Bay and the highest energy bay is Head of the Bay. Within Governors Bay the lowest energy sites are the outermost site and the innermost site on the western side of the bay. The results for Charteris Bay indicate the energy environment at all four sites is similar. Within Head of the Bay the results indicate differences in the energy environment with location in the bay; the lowest energy site being the innermost site on the eastern side. Differences in the energy environment between bays and within a bay occur because of the influence of headlands, islands/reefs and breakwaters on the speed and direction of tidal flows and wind and swell waves in the upper harbour.

In 2005 the sediments of the upper Akaroa Harbour intertidal mudflats were as follows: Duvauchelle 73-81 % sand, Robinsons Bay 89 - 96 % sand, Takamatua 71-78 % sand and Barrys Bay 92-96 % silt (Bolton-Ritchie, 2005). Hart *et al.* (2009) found the sediment in Barrys Bay was typically silt and clay with patches of silty-sand. They described Barrys Bay as a 'low energy environment' noting that southerly waves moving up the harbour get refracted and diffracted around the promontory between Wainui and French Farm Bay and then further refracted and diffracted by the Onawe Promontory before reaching Barrys Bay (Hart *et al.* 2009). The low energy environment of Barrys Bay likely accounts for the high silt content of the sediment in this bay. In Okains Bay estuary the sediment at two upper-mid estuary sites was 45-55 % silt and 38-54 % silt with sandier sediment at sites closer to the estuary mouth. The sediment of the Duvauchelle, Robinsons Bay and Takamatua intertidal mudflats is sandier, while that of Barrys Bay is siltier, than the sediment of the upper Lyttelton Harbour/Whakaraupō mudflats. The upper-mid Okains Bay sediment grain size distribution is similar to that in Charteris Bay.

5.1.2 Organic matter content

Organic matter originates from living things and typically consists of dead plant and animal matter. Organic matter occurs naturally in sediments with sandy sediments typically containing less organic matter than muddy sediments. However, inputs of effluent, stormwater and stream flows can add organic matter to the sediment. Elevated levels of organic matter can deplete the oxygen content in the sediment which affects the types and abundance of animals that can live there.

I found that the organic matter content did vary between samples at a site, for example at Charteris Bay site 2 it ranged from 0.9-2 %. This indicates that there is considerable natural variability in organic matter content. Organic matter content also varied between sites within a bay and between bays. My comparison of the results to sediment chemistry guideline values (Robertson and Stevens, 2008: refer to Appendix 3) indicates that the intertidal sediments can typically be considered low - moderately enriched with organic matter. However, at some sites values greater than 2 %, which indicate enriched sediment, did occur. The highest values occurred at sites in Governors Bay. The sediment at sites in Governors Bay had high mud content and it is known that muddier sediments contain more organic matter than sandier sediments. Therefore I do not consider that sediment in Governors Bay is unnaturally enriched with organic matter.

In 2005 the organic matter content of the upper Akaroa Harbour intertidal mudflats was as follows: Duvauchelle 0.5-1.5 %, Robinsons Bay 1.1-1.5 %, Takamatua 2.8-4 % and Barrys Bay 0.9-4.6 % (Bolton-Ritchie, 2005). In Okains Bay estuary the muddiest sediment had an organic matter content of 1.6-3.1 % and the sandiest sediment 0.5-1.8 % (Bolton-Ritchie, 2008). The organic matter content of upper Lyttelton Harbour/Whakaraupō intertidal mudflat sediment is within the range of that found at other intertidal sites in Banks Peninsula.

Nutrient concentrations

Nitrogen and phosphorus concentrations in intertidal mudflat sediment typically reflect background natural soil concentrations unless land in the surrounding catchments is urbanised, grazed or used for horticulture. These land uses can involve fertiliser use to improve land productivity with potential runoff of fertiliser with rainfall, nutrient enriched runoff from grazed land, urban stormwater inputs and seepage from septic tanks.

Total nitrogen (TN) and total recoverable phosphorus (TRP) concentrations varied between samples at a site, between sites within a bay and between bays. TN concentrations were lower at sites in Head of the Bay than sites in the other two bays. This suggests inputs or more inputs of TN into Charteris Bay and Governors Bay than Head of the Bay. Even so, the TN results indicate the mudflat sediments are typically in good condition with low to moderate nitrogen enrichment. The TRP results indicate the mudflat sediments are typically in a fair condition as there is phosphorus enrichment. The phosphorus-enriched mudflat sediment likely comes from the phosphorus-rich volcanic rock of the harbour catchments.

In 2005 the total nitrogen concentration of upper Akaroa Harbour intertidal mudflat sediments was as follows: Duvauchelle 800-1340 mg/kg, Robinsons Bay 1700-2600 mg/kg, Takamatua 1400 mg/kg and Barrys Bay 920-1600 mg/kg (Bolton-Ritchie, 2005). In Okains Bay estuary TN concentrations ranged from 730-1200 mg/kg (Bolton-Ritchie, 2008). The Akaroa and Okains Bay concentrations are higher than those from upper Lyttelton Harbour/Whakaraupō (<500-990 mg/kg). In 2005 I attributed the Akaroa Harbour mudflat TN concentrations to stream flows, nutrient inputs into the streams and the waterfowl populations. The seagrass beds on the Akaroa Harbour mudflats also contribute to the sediment TN concentration. The difference in TN concentrations between areas suggests less influence of stream flows, nutrient inputs into streams and water fowl in Lyttelton Harbour/Whakaraupō than Akaroa Harbour and there are no seagrass beds in Lyttelton Harbour/Whakaraupō.

In 2005 the total phosphorus (TP) concentration of upper Akaroa Harbour intertidal mudflat sediments was as follows: Duvauchelle 390-530 mg/kg, Robinsons Bay 520-830 mg/kg, Takamatua 540-570 mg/kg and Barrys Bay 510-650 mg/kg (Bolton-Ritchie, 2005). In Okains Bay estuary TP concentrations ranged from 670-880 mg/kg (Bolton-Ritchie, 2008). The TP concentrations from upper Akaroa sites are typically lower, while those from Okains Bay are similar to the TRP concentrations of 570-980 mg/kg from upper Lyttelton Harbour/Whakaraupō. As the phosphorus-enriched mudflat sediment likely comes from the phosphorus-rich volcanic rock of the harbour catchments the results suggest there is more soil runoff into Lyttelton Harbour/Whakaraupō than Akaroa Harbour.

5.1.3 Metal concentrations

I compared the copper (4.5-14 mg/kg), lead (2.1-20 mg/kg) and zinc (34-62 mg/kg) concentrations to those in Banks Peninsula soils (Tonkin and Taylor, 2007). Banks Peninsula loess soil contains 6.2-15.2 mg/kg copper, 8.25-27.5 mg/kg lead and 35.2-69.8 mg/kg zinc. Banks Peninsula basalts contain 10-27.3 mg/kg copper, 3.63-17.2 mg/kg lead and 50-116 mg/kg zinc. Metal concentrations in the intertidal mudflat sediment are comparable to those in Loess soils of the harbour catchments.

All recorded copper, lead and zinc concentrations were below the ANZECC (2000) ISGQ- low trigger values which indicates the concentrations are not of ecological concern.

5.2 Benthic infauna

I found fifty-four taxa in the core samples from the 12 sites sampled in Lyttelton Harbour/Whakaraupō. In Akaroa Harbour I found 104 taxa in samples from 12 sites (Bolton-Ritchie, 2005). Many of the sites in Akaroa Harbour were in seagrass beds; the diversity of taxa in seagrass beds is higher than in mudflats without seagrass. Seagrass provides both habitat and food for invertebrate taxa. At the three Akaroa sites where there was little to no seagrass I found 47 taxa. This is similar to the number of taxa I found in the Lyttelton Harbour/Whakaraupō mudflats. In the estuarine environment of Okains Bay I found thirty-six taxa in samples from four sites (Bolton-Ritchie, 2008). The taxa found in this study are typical of Banks Peninsula intertidal mudflats, with most also found in Okains Bay estuary and the mudflats of Akaroa Harbour.

There were between bay differences in the number of taxa present. More taxa occurred at Head of the Bay sites 1, 2, 4, and 5 than at the other two sites in this bay and in Charteris Bay and Governors Bay. The lowest number of taxa at a site was 12, with 12 taxa at the inner most sites of all three bays and the eastern-most site in Charteris Bay. The total number of taxa and the number of snails and shellfish taxa present at a site is influenced by sediment grain size. As the % gravel increased so did the total number of taxa while as the % silt increased the total number of taxa decreased. The number of snails and shellfish taxa increased as the % gravel and % sand increased, and the number decreased as the % silt and % clay increased.

In this study and the Okains Bay study I sieved the core samples through a 0.5 mm mesh. In the Akaroa Harbour study I sieved the samples through a 1 mm mesh. The difference in mesh size does not allow me to compare the number of animal individuals recorded in this study with those from the Akaroa Harbour mudflats. This is because a smaller mesh retains all animals 0.5-1 mm long, with many individuals being in this size range. The density of the infauna of the Lyttelton Harbour/Whakaraupō mudflats was 977-15,038 individuals/m^2. In 2007 the density of the infauna of Okains Bay was 0-23,998 individuals/m^2. The maximum infauna density found in this study is similar to that in Okains Bay estuary. I consider that the difference in the maximum number of individual animals found between localities reflects the natural spatial and temporal variability of populations.

I found differences in the number of individual animals per square metre between samples at a site, between sites within a bay and between bays. The lowest number of individuals per square metre occurred at a site in Head of the Bay while the highest number of individuals per square metre occurred at a different site in this bay. The number of snails and shellfish individuals at a site is influenced by the % gravel in the sediment. As the % gravel increased so did the number of snails and shellfish individuals.

The presence and abundance of the animals at the four sites in Charteris Bay is similar. There are differences in the presence and abundance of animals between sites in Governors Bay and notable differences between sites in Head of the Bay. The presence and abundance of animals at Head of the Bay sites is different from that in Governors Bay and Charteris Bay. The overlaying of the sediment grain size data over the MDS ordination based on the presence and abundance of the animals indicates sediment grain size does influence the presence and abundance of the animals.

The five most abundant taxa in the Lyttelton Harbour/Whakaraupō mudflats were the worm *Heteromastus filiformis,* the small bivalve *Arthritica bifurca,* cockles, the mudflat crab *Austrohelice crassa* and the worm *Nicon aestuariensis.* Cockles, *Heteromastus filiformis* and *Arthritica bifurca* were also amongst the most abundant taxa at sites with little or no seagrass in Akaroa Harbour. Cockles and *Arthritica bifurca* were amongst the most abundant taxa in Okains Bay estuary. However, taxa that were amongst the most abundant at the Akaroa sites with little or no seagrass, the worms *Boccardia* spp., *Magelona* sp and *Orbinia papillosa* and the wedge shell *Macomona liliana* were either not found or were in low abundance in Lyttelton Harbour/Whakaraupō. The other abundant taxa in Okains Bay estuary were estuarine and I did not expect them to be abundant in the upper harbour mudflats of Lyttelton Harbour/Whakaraupō.

Boccardia spp., *Orbinia papillosa* and the wedge shell *Macomona liliana* have specific sediment grain size requirements (Gibbs and Hewitt, 2004). The optimal sediment for *Boccardia syrtis* (one of the taxa identified as *Boccardia* spp.) is 10-15% mud, with this taxa present in sediment with 0-50% mud. The optimal sediment for *Orbinia papillosa* is 5-10% mud, with this taxa present in sediment with 0-40% mud. The optimal sediment for *Macomona liliana* is 0-5% mud, with this taxa present in sediment with 0-40% mud. There is no information on the sediment requirement for *Magelona* sp. However, the results for Akaroa Harbour indicate *Magelona* sp. prefers sandy over muddy sediment. It has also been found that suspended sediment has a negative impact on *Boccardia syrtis* and *Macomona liliana* (Nicholls *et al.,* 2009). For *Boccardia sytris* a suspended sediment concentration as low as 80 mg/L over an extended period of time had a negative effect on feeding rate (Nicholls *et al.,* 2009). For *Macomona liliana* a high suspended sediment concentration over an extended period of time resulted in the death of individuals. There has been no assessment of the impact of suspended sediment concentrations on other taxa (except cockles) present in the harbour. Re-suspension of seabed sediment in the shallow upper Lyttelton Harbour/Whakaraupō and inputs of soil with rainfall result in elevated total suspended sediment concentrations in upper harbour water (Bolton-Ritchie, 2011b). It is likely the absence or low abundance of these four named taxa in Lyttelton Harbour/Whakaraupō results from the sediment grain size distribution of the mudflats and possibly the influence of suspended sediment concentrations in the water.

I investigated the relationship between the abundance of each of 11 taxa and sediment grain size. The abundance of the snails and shellfish Arthritica bifurca, cockles, Notoacmea helmsi, Turbonilla sp., the worm Nicon aestuariensis and the crustacea Austrohelice crassa and Isopod sp. is influenced by sediment grain size. Notoacmea helmsi, cockles, Turbonilla sp. and Isopod sp are more abundant in the coarser grained gravel/sand sediment than the fine grained silt and clay sediment. Arthritica bifurca, Nicon aestuariensis and Austrohelice crassa are more abundant in the fine grained silt and clay sediment than the coarser grained gravel/sand sediment. The results for Notoacmea helmsi, Arthritica bifurca Nicon aestuariensis and Austrohelice crassa are supported by the results of Gibbs and Hewitt (2004). There is no information in Gibbs and Hewitt (2004) on the sediment requirements for Turbonilla sp. and Isopod sp. Gibbs and Hewitt (2004) found:

- the optimum sediment for Notoacmea helmsi is 0-5% mud with this taxa present in sediment with 0-10% mud.
- the optimum sediment for Nicon aestuariensis is 35-55% mud with this taxa present in sediment with 0-80% mud.
- the optimum sediment for Arthritica bifurca is 55-65% mud with this taxa present in sediment with 5-70% mud.
- the optimum sediment for Austrohelice crassa is 95-100% mud with this taxa present in sediment with 5-100% mud.

My analysis of Lyttelton Harbour/Whakaraupō data found that the abundance of the worms Boccardia syrtis, Glycinde dorsalis, Heteromastus filiformis and Scolecolepides benhami is not influenced by sediment grain size. Gibbs and Hewitt (2004) found:

- the optimum sediment for Heteromastus filiformis is 10-15% mud with this taxa present in sediment with 0-95% mud.
- the optimum sediment for Scolecolepides benhami is 20-30% mud with this taxa present in sediment with 0-85% mud.
- The optimal sediment for Boccardia syrtis is 10-15% mud, with this taxa present in sediment with 0-50% mud.

The capability of *Heteromastus filiformis* and *Scolecolepides benhami* to live in sediment with a wide ranging mud component probably explains why I did not find a relationship between sediment grain size and taxa abundance. It is likely that I did not find a relationship between *Boccardia syrtis* abundance and sediment grain size is this study because there were not enough individuals present in the samples. There is no information in Gibbs and Hewitt (2004) on the sediment requirement for *Glycinde dorsalis.*

The sediment grain size of the mudflats and/or the suspended sediment concentrations in the water could also influence the presence and abundance of other taxa. For example, the worm *Aonides* which does occur in Akaroa Harbour mudflats was not present in Lyttelton Harbour/Whakaraupō. This worm has a strong sand preference (Gibbs and Hewitt, 2004). Another example is the mudflat topshell *Diloma subrostrata.* This topshell was not found in Governors Bay and Charteris Bay but did occur at some sites in Head of the Bay. *Diloma subrostrata* has a strong sand preference (Gibbs and Hewitt, 2004).

Cockles

There were a low number of cockles present in the samples from Governors Bay and Charteris Bay. Cockles were most abundant in the Head of the Bay with a difference in abundance between sites. The abundance of cockles in the mudflats is influenced by sediment grain size. Cockle abundance increased as the % of gravel, very coarse sand and coarse sand increased and abundance decreased as the % silt, % clay, % coarse silt, % fine silt and % very fine silt increased. That is, they were more abundant in the sandy sediment than the muddy sediment. Cockles are known to occur in 0-65% mud but their optimal range is 5-10% mud (Gibbs and Hewitt, 2004).

Most of the cockles were smaller than 6 mm long. These individuals are recruits and juveniles. The number of recruits found depends on the time of year of sampling relative to the time of spawning. In Canterbury male cockles are reproductively active all year, while females tend to be reproductively active from December to February (Sue Adkins, PhD on cockles at UoC, pers, com). By comparison Wellington and Bay of Islands cockles typically spawn in October and March (http://www.seakeepers-nz.com/SHOREWEB/cockle.html). Following successful spawning, numerous small cockles recruit to the seabed. Recent recruitment will account for the small cockles present in the samples we collected in mid-November - early December. I found numerous recruits in samples collected from sites in Okains Bay in October (Bolton-Ritchie, 2008) and in samples collected from Akaroa Harbour in November-December (Bolton-Ritchie, 2005).

The low number of cockles longer than 20 mm indicates low survival of the recruits. Broadcast spawners such as cockles do produce numerous recruits with numbers reducing naturally over time through competition, predation and environmental influences to end up with the fittest individuals surviving to adulthood. However, the population size structure of Lyttelton Harbour/Whakaraupō cockles is different to that in Akaroa Harbour, Okains Bay estuary and the Avon-Heathcote Estuary/Ihutai (Bolton-Ritchie, 2011). In Akaroa Harbour 37% of cockles in Takamatua, 61% in Robinsons Bay, 73% in Duvauchelle and 88% in Barrys Bay were 20 mm or more long. In Okains Bay estuary 29% of cockles at one site and 13% at another site, and at the Plover Street site in the Avon-Heathcote Estuary/Ihutai in 2010 70%, were 20 mm or more long. In Lyttelton Harbour/Whakaraupō 14% of cockles in Governors Bay, 1 % in Head of the Bay and 5% in Charteris Bay were 20 mm or more long. While 14% of the Governors Bay cockles were 20 mm or more long there were only 29 individuals in the samples. This contrasts to Okains Bay where 812 individuals occurred in the samples at the site where 13% of the individuals were 20 mm or longer. My comparison of the size structure of the cockle populations from Lyttelton Harbour/Whakaraupō mudflats with those from the other locations suggests that environmental conditions of the upper harbour are not conducive to the survival and growth of cockles to adult size. Possible reasons are:

- the sediment grain size distribution of the mudflats.
- the fine seabed sediment re-suspended[5] by wind and wave action clogs cockle feeding structures and therefore their ability to feed and grow.
- physical damage of recruits including possible shell scouring through the re-suspension of fine seabed sediment.
- the re-suspension of seabed sediment by wind and wave action also re-suspends the juvenile cockles thereby increasing the chance of predation and/or transportation to areas unsuitable for them.
- not enough food in the water column because the suspended sediment limits light penetration and hence the growth and abundance of phytoplankton
- a low number of recruits to the mudflats because of either the low number of reproductive individuals within the harbour or water circulation patterns affecting spat from outside the harbour reaching the upper harbour.

[5] Re-suspension of seabed sediment in the shallow upper Lyttelton Harbour/Whakaraupō and inputs of soil with rainfall result in elevated total suspended sediment concentrations in upper harbour water (Bolton-Ritchie, 2011).

6 Summary and conclusions

I carried out this study to investigate the state of the sediments and benthic infauna of the intertidal mudflats in upper Lyttelton Harbour/Whakaraupō. We collected sediment and benthic infauna from four sites in both Governors Bay and Charteris Bay and six sites in Head of the Bay. The collected sediment was analysed to determine the sediment grain size, organic matter content and concentrations of total nitrogen, total recoverable phosphorus and the metals copper, lead and zinc. I identified and counted all the animals retained on a 0.5 mm screen and we measured the shell length of all the cockles.

The key findings are:

1. The sediment ranged from very muddy to muddy sand with shell/rock fragments.
2. The organic matter content and TN results indicate the mudflat sediment is typically in good condition.
3. The TRP values indicate the mudflat sediment is in a fair condition as there is phosphorus enrichment. The phosphorus source is likely the phosphorus-rich volcanic rock of the harbour catchment.
4. The sediment copper, lead and zinc concentrations are comparable to those in the loess topsoil in the harbour catchment, and the recorded concentrations are not of ecological concern.
5. Fifty-four different invertebrate animals live on and in the sediments with these animals typical of intertidal mudflats of Banks Peninsula.
6. There was spatial variability in the number of individuals per square metre, i.e. between samples at a site, between sites within a bay and between bays.
7. Sediment grain size does influence the presence and abundance of the animals living in the mudflats.
8. It is likely the absence or low abundance of four animal taxa that are abundant in Akaroa Harbour results from the sediment grain size distribution of mudflat sediment and possibly the influence of suspended sediment concentrations in the water. It is possible that these factors also influence the presence and abundance of at least two other mudflat animals.
9. The abundance of seven of the eleven most abundant animal taxa is influenced by sediment grain size. *Notoacmea helmsi,* cockles*, Turbonilla* sp. and Isopod sp are more abundant in the coarser grained gravel/sand sediment than the fine grained silt and clay sediment. *Arthritica bifurca, Nicon aestuariensis* and *Austrohelice crassa* are more abundant in the fine grained silt and clay sediment than the coarser grained gravel/sand sediment.
10. The environment of upper Lyttelton Harbour/Whakaraupō is not conducive to the settlement and/or survival of cockle recruits and their growth to adult size.

7 Recommendations for future work

I recommend the following scientific monitoring, scientific investigations and management approaches.

7.1 Monitoring sedimentation

Monitoring is the routine collection of data over time. The routine collection of data allows for the detection of changes or trends in the measured parameters over time. Such monitoring is used for a number of purposes including:

- to determine if a known parameter that has the potential to influence the functioning of an ecosystem is getting worse over time
- evaluation of the effectiveness of management actions

I recommend that a long term monitoring programme is developed on sediment deposition (sedimentation) on the upper harbour intertidal mudflats.

7.2 Monitoring of the sediments and biota

I recommend a long term monitoring programme is developed for the sediments and biota at one or more upper Lyttelton Harbour/Whakaraupō intertidal mudflat sites. This monitoring should be carried out at least annually. I recommend the following parameters are monitored:

- sediment grain size
- sediment organic matter content
- TN and TP concentrations
- presence and abundance of the biota including the abundance and size of shellfish

This monitoring will provide data on the nutrient status of the sediment, whether the grain size is changing, the state of the cockles and the general state of the biota.

7.3 Hydrodynamics investigation

Wind, wave and tidal energy influence where sediment particles settle to the seabed. Fine grained sediment settles to the seabed in lower energy areas than coarser grained sediment. Differences in the sediment grain size distribution between bays and sites within a bay indicate differences in energy between and within bays. It is possible that headlands, Quail Island and port structures affect the energy environment of the upper harbour. I recommend an investigation to evaluate the influence of these factors on tidal speed and direction, wind speed and direction and wave height and direction in the upper harbour.

7.4 Mollusc species and abundance investigation

Mollusc fragments and whole shells made up much of the coarse grained sediment particles of the upper harbour intertidal mudflats. This indicates that live molluscs are an important ecological component of the harbour ecosystem. I recommend that a detailed assessment of the presence, abundance and size distribution of intertidal and subtidal mollusc species is undertaken. Sampling must be statistically robust so that repeat sampling in the future can be used to assess changes in diversity and abundance over time.

7.5 Factors influencing cockle growth and survival

The cockle results indicate both a low number of cockles in some bays and a low survival of the recruits that settle on the mudflats. I recommend that a detailed investigation is undertaken to assess recruitment and survival of cockles in different intertidal areas within Lyttelton Harbour/Whakaraupō. Such an investigation would ideally be undertaken as a Master's thesis.

7.6 Sediment inputs

The input of soil is an ongoing and major ecological issue for this harbour. More widespread and effective on-land erosion control measures are required to reduce the quantities of soil being washed into the harbour with rainfall. The catchments that contribute the most soil to the harbour need to be identified and these catchments should be prioritised for erosion control measures.

8 Acknowledgements

Leigh Tait helped with sample collection, the sorting of biological samples and the measuring of cockles. The Geology Department of the University of Canterbury carried out the sediment grain size analyses. Hill Laboratories carried out the sediment chemistry analyses. Shane Kelly of Coastal and Catchment Limited peer reviewed this report and Michele Stevenson and Tim Davie from Environment Canterbury reviewed the report.

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Appendix 1: Site details

Bay	Site	Easting	Northing	Environment Canterbury Site ID
Governors Bay	1	2482300	5730890	SQ35323
	2	2482550	5730440	SQ35324
	3	2482050	5730300	SQ35325
	4	2482090	5730060	SQ35326
Head of the Bay	1	2483170	5729150	SQ35331
	2	2482940	5728850	SQ35332
	3	2482810	5738590	SQ35333
	4	2483640	5728870	SQ35334
	5	2483610	5728520	SQ35335
	6	2480580	5727810	SQ35336
Charteris Bay	1	2485970	5728650	SQ35327
	2	2485500	5729700	SQ35328
	3	2485530	5728500	SQ35329
	4	2485320	5728360	SQ35330

Appendix 2: Laboratory methods

Sediment grain size analysis

The following steps were involved in the grain size analysis of each sample.

1. Cone & Quarter
2. Wet Sieve and picking of fraction >0 phi. This fraction was then dried and weighed
3. The remains of the sample was treated with 5-20% of 34% H_2O_2 in distilled water
4. The sample was dried.
5. Cone & Quarter the dried sample
6. The sample was analysed using a Saturn 5200 DigiSizer

DigiSizer specifications are available at:
http://www.pss.aus.net/products/micromeritics/equip_particle_size/5200/5200.html#specs)

Sediment chemistry analysis

All analyses were carried out by Hill Laboratories Ltd.

Parameter	Analytical method	Detection limit
% Organic matter (LOI)	Ignition in muffle furnace 550°C, 6 hrs, gravimetric. APHA 2540 G 20th ed. 1998	0.04 g/100g dry weight
Total nitrogen	Catalytic Combustion, separation, Thermal Conductivity Detector [Elementary Analyser]	500 mg/kg dry weight
Total recoverable phosphorus	Nitric / hydrochloric acid digestion. ICP-MS (low level) USEPA 200.2	40 mg/kg dry weight
Copper (total recoverable)	Nitric / hydrochloric acid digestion. ICP-MS (low level) USEPA 200.2	0.2 mg/kg dry weight
Lead (total recoverable)	Nitric / hydrochloric acid digestion. ICP-MS (low level) USEPA 200.2	0.04 mg/kg dry weight
Zinc (total recoverable)	Nitric / hydrochloric acid digestion. ICP-MS (low level) USEPA 200.2	0.4 mg/kg dry weight

Appendix 3: Interpretation of sediment organic matter and nutrient concentrations

The Interpretation of sediment chemistry results is hindered by a lack of national guidelines. However, Robertson and Stevens (2008) have developed sediment chemistry guidelines to assess the state of New Zealand estuaries. Their guidelines for organic matter content, total nitrogen and total recoverable phosphorus concentrations in sediment are in the tables below. The ratings of Very Good, Low-moderate enrichment, Enriched and Very enriched refer to the state of the estuary sediment or in this report the state of harbour mudflat sediment.

Organic matter content

RATING	Values (g/100g) ≡ %
Very good	< 1
Low-mod enrichment	1 – 2
Enriched	2 – 5
Very enriched	> 5

Note Organic matter content is influenced by the grain size of the sediment. Fine grained mud dominated sediment has a higher organic matter content than coarse grained sand dominated sediment.

Total recoverable phosphorus

RATING	VALUES (mg/kg)
Very good	< 200
Low-mod enrichment	200 - 500
Enriched	500 - 1000
Very enriched	> 1000

Total nitrogen

RATING	VALUES (mg/kg)
Very good	< 500
Low-mod enrichment	500 - 2000
Enriched	2000 - 4000
Very enriched	> 4000

Appendix 4: Grain size distribution of each sediment sample

Site	gravel %	very coarse sand %	coarse sand %	medium sand %	fine sand %	very fine sand %	coarse silt %	medium silt %	fine silt %	very fine silt %	clay %
GBS1	0	0	0	0	2	8	30	17.8	13.6	11.6	17
GBS1	0	0	0	0	3.2	16.5	33	16	10.5	8.5	12
GBS1	0	0	0	0	2.4	17.6	32.5	16.7	10.8	8	12
GBS2	0	0	0	0	9	45	21	7.5	5.3	4.2	8
GBS2	0	0	0	0	8	44.8	23.4	6.8	5	4.7	7.3
GBS2	0	0	0	0	12.2	53	18.8	5.5	3	3	4.5
GBS3	3.06	0	0.5	0	3.6	35	23.3	9.6	7.4	6.7	10.6
GBS3	0	0	0	0	5	35	32.7	10.1	5.2	4.7	7.3
GBS3	3.6	0	0.5	0	4.7	33.7	22.1	9.1	8.1	7.6	10.5
GBS4	0.1	0.1	0	0	4	14.8	24.4	20.8	12.4	9.1	14.5
GBS4	0	0	0	0	2.5	15.5	20	16	14	12.8	19.2
GBS4	0	0	0	0	1	19	26	18	12	10	14
HoBS1	11.8	0.9	0.4	0	12.3	32.7	11	7	6.2	5.9	11.7
HoBS1	0.9	0.3	0.4	0	12.2	49.6	20.6	5.8	2.1	2.6	4.8
HoBS1	14.4	2.6	1.9	0	11.3	36.7	15.4	5.1	4.2	3.2	4.8
HoBS2	2.6	1.8	0.8	7.3	31.1	41	9.2	2.3	1	1.3	1.3
HoBS2	5.2	3.3	2.1	0	26.3	43.5	10.5	3.1	1.8	2.3	1.5
HoBS2	5.7	2.4	1.5	0	24.7	38.1	13.9	4.5	2.2	3.1	3.5
HoBS3	0.3	0.4	0.4	0	7.8	38.2	24.8	9.9	5.3	5.1	7.9
HoBS3	0.4	0.4	0	0	12	46.5	26	5.7	1.2	3	4
HoBS3	0.2	0.4	0.4	0	13.9	45.7	21.8	5.9	3.9	2.9	4.9
HoBS4	8.4	3	1.5	0	12	41.5	19.3	4.8	2.6	2.1	4.3
HoBS4	10	3.2	1.4	0	20.7	38.5	13	3.7	2.9	1.6	3.3
HoBS4	3.3	1.8	0.6	0	7.7	40.8	27	8	2.7	2.8	3.7
HoBS5	6.2	2.1	0.7	0	12.5	42.4	20.3	6.2	3.1	2.2	4
HoBS5	7.3	3.6	2.1	0	10.2	37	22.5	7.5	2.3	1.8	4.2
HoBS5	8.5	3.1	1.5	0	10.3	35.4	24.3	6.6	2.1	2.1	4.3
HoBS6	0.4	0.4	0.4	0	3.4	35.6	29.3	10.2	6.2	5.3	7.8
HoBS6	0.4	0.4	0.4	0.9	5.9	34.8	23.8	11.9	6.4	5.9	9.4
HoBS6	0.4	0.4	0.4	0	5.3	34	23.3	9.4	5.8	4.5	7.7
CBS1	0.6	0.3	0.1	0	11.7	33.5	26.5	9	5.6	4.3	7.3
CBS1	2	0.6	0.4	0	12.9	28.6	23.9	8.6	6.6	5.7	8.6
CBS1	5.4	0.5	0.3	0	9.3	30.1	25.7	9	5.9	4.9	7.7
CBS2	0.2	0.5	0.5	0	9.8	41.9	19.6	7.9	3.9	6.6	9.1
CBS2	6.8	0.5	0.5	0	6.8	37	22.7	8.3	5	4.6	7.4
CBS2	4.8	0.4	0.4	0	6.6	35.8	20.1	10.1	2.1	6.5	10.6
CBS3	4.6	1.4	0	0	6.8	39.8	23.2	8.2	3.8	3.7	5.3
CBS3	6.4	0.3	0.4	0	8.1	39	25.1	7.2	4.6	3.4	5.6
CBS3	2.1	0.6	0.4	0	7.7	39.8	24	9.5	4.8	4.8	6.3
CBS4	0.8	0.4	0.4	0	9.9	34	27	9.4	5.9	4.9	7.7
CBS4	0.7	0.4	0.4	0	7.8	35	27	9.8	3.9	5.8	8.8
CBS4	1.4	0.4	0.4	0	5.4	36.9	24.6	9.3	5.6	5.7	9.8

Appendix 5: Principal components analysis

Eigenvalues

PC	Eigenvalues	%Variation	Cumulative %Variation
1	7.5	75	75
2	1.3	13	87.9
3	0.629	6.3	94.2
4	0.38	3.8	98
5	0.113	1.1	99.1

Eigenvectors
Coefficients in the linear combinations of variables making up the principal components (PC's)

Variable	PC1	PC2	PC3	PC4	PC5
gravel	0.266	-0.415	-0.377	-0.596	0.457
very coarse sand	0.299	-0.437	-0.187	0.312	-0.308
coarse sand	0.31	-0.414	-0.079	0.188	-0.372
fine sand	0.309	-0.08	0.572	0.341	0.486
very fine sand	0.291	0.493	-0.055	-0.286	-0.39
coarse silt	-0.286	0.164	-0.636	0.468	0.302
medium silt	-0.347	-0.247	-0.004	0.1	-0.227
fine silt	-0.346	-0.246	0.14	-0.052	0.044
very fine silt	-0.348	-0.184	0.226	-0.138	-0.064
clay	-0.349	-0.181	0.105	-0.25	-0.143

Appendix 6: Sediment organic matter (%) and nutrient and metals concentrations (mg/kg dry weight)

Site	LOI	TN	TRP	Copper	Lead	Zinc
GB1	2.3	990	750	6.1	13	48
GB1	2.5	820	780	6.6	20	51
GB1	1.9	810	800	5.7	16	53
GB2	1.7	620	680	6.8	20	51
GB2	1.6	670	680	6.6	4.2	56
GB2	1.7	770	690	5.6	4.8	53
GB3	2.2	750	690	7.7	3.1	57
GB3	0.9	870	760	7.7	4.1	60
GB3	2	600	700	7.5	4.3	58
GB4	2.6	790	760	7.5	4.2	54
GB4	2.1	890	690	7	4.3	50
GB4	2.4	880	760	7.2	12	51
HoB1	1.3	<500	680	7	2.2	62
HoB1	1.9	610	570	5.3	2.9	54
HoB1	2.4	700	600	5.7	2.4	48
HoB2	2.2	<500	980	14	3	46
HoB2	2.2	580	700	6.1	2.1	48
HoB2	2.1	610	720	6	2.1	47
HoB3	1.8	<500	690	5.9	2.3	43
HoB3	1.8	<500	650	5.5	1.9	43
HoB3	2.1	550	680	5.5	2.7	43
HoB4	2.1	530	650	6.8	1.8	45
HoB4	2	660	660	6.7	2	47
HoB4	2.2	<500	670	6.7	2.6	51
HoB5	1.9	<500	720	5.2	1.9	38
HoB5	1.1	510	770	4.5	1.9	34
HoB5	1.7	<500	690	4.7	1.8	39
HoB6	2	600	740	5.9	2.5	48
HoB6	2	600	690	6	2.5	47
HoB6	1.4	530	650	6.3	2.3	47
CB1	1.3	850	800	6.2	3	46
CB1	1	760	780	6.5	4.5	51
CB1	1.1	790	830	6.3	9.1	53
CB2	1.5	630	680	6.3	2.8	49
CB2	2.1	700	660	6.1	3	50
CB2	1.7	660	670	6.5	3.4	48
CB3	1.3	670	730	6.7	2.9	52
CB3	2	790	730	6.5	3.1	51
CB3	0.9	810	710	6.8	2.5	51
CB4	1.9	670	730	5.7	2.6	48
CB4	1.8	610	740	6.2	2.8	44
CB4	1.1	650	720	5.4	2.8	49

Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

Everything is connected

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www.ecan.govt.nz

Environment Canterbury offices

Christchurch
58 Kilmore Street
PO Box 345
Christchurch 8013
P: 03 365 3828
F: 03 365 3194

Timaru
75 Church Street
PO Box 550
Timaru 7940
P: 03 687 7800
F: 03 687 7808