Wellington Harbour marine sediment quality investigation

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Executive summary

Contaminants in urban stormwater discharges have been identified as a potential medium to long-term risk to the health of the marine organisms living in our harbours, largely through the accumulation of these contaminants in the sediments. This report presents the results of an assessment of sediment quality and benthic community health at 17 subtidal sites in the Wellington Harbour receiving environment. These sites were sampled in October/November 2006.

Concentrations of lead, mercury, and to a lesser extent copper and zinc, are present above sediment quality guidelines in the subtidal sediments of various parts of Wellington Harbour, especially those adjacent to Wellington City. Tributyltin is only present above sediment quality guidelines at the entrance to the Lambton Basin and off Ngauranga, but its less toxic breakdown product dibutyltin is widespread. Fluorene, phenanthrene, benzo[a]anthracene, and total high molecular weight polycyclic aromatic hydrocarbons (Total HMW PAH) are above sediment quality guidelines in southern Evans Bay, and Total HMW PAH in northern Evans Bay and at the entrance to the Lambton Basin. Total DDT is present above sediment quality guidelines over much of the harbour. Concentrations of other heavy metals, organochlorine pesticides and PAHs are currently below guideline levels in the subtidal sediments of the harbour.

The benthic ecology data show that, although the concentrations of several contaminants are above sediment quality guidelines, there is no clear evidence any of the contaminants measured in the subtidal sediments have resulted in significant adverse effects on the benthic community structure of the sites as at November 2006. While the absence of effects is encouraging, the thresholds for such effects are still not known for this environment, indicating continued monitoring of both sediment quality and benthic ecology will be needed.

The chemical contaminant data collected to date are generally of good quality, with low variability for most analytes, which demonstrates the capacity of the methodology used to detect very small changes in contaminant concentrations over time. The main exceptions with respect to data quality are the organochlorine pesticides DDD, DDE and DDT.

The strong offshore gradients in contaminant concentrations and the chemical nature of some of the contaminants in the sediments of Wellington Harbour provide a clear indication of their land-based origin. A review of the available stormwater quality and stream monitoring data from the harbour's catchment indicates that urban stormwater is the principal agent in the transport of the majority of these contaminants to the harbour seabed, either directly or by way of urban streams.

Recommendations

1. A second sediment chemistry survey is undertaken in Wellington Harbour in 2011 at sites WH1–WH5, WH9, WH11, WH13, WH15, and possibly a new site off eastern Petone, in order to monitor trends in contaminant concentrations. Further surveys should be conducted every five or six years thereafter unless results and/or major changes in the catchment indicate a greater or lesser survey frequency is desirable.

2. A second benthic ecology survey is undertaken in Wellington Harbour at the sites listed in (1) above in order to monitor for changes in community structure with possible links to changes in contaminant concentrations. The survey should be carried out in late October 2011 to minimise seasonal influences, and coincide with the sediment chemistry survey if possible.

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1. Introduction

Wellington Harbour (Te Whanga nui a Tara) is regionally significant, offering a multitude of landscape, ecological, cultural, geological and recreational values. However, like other coastal environments surrounded by densely populated areas, the harbour receives significant urban stormwater inputs with the potential to adversely impact on the health of its ecosystems.

The most significant medium to long-term impact of urban stormwater discharges on the Wellington Harbour environment is likely to be the accumulation of stormwater-related contaminants in the sediments. This is because the contaminants can, over time, build up to concentrations that are toxic to sediment-dwelling organisms. Sediment-dwelling organisms are a major component of harbour and coastal ecosystems; they provide food for fish and other organisms, affect nutrient cycling and contribute significantly to marine productivity.

In 2000, the Greater Wellington Regional Council (Greater Wellington) commissioned the National Institute of Water and Atmospheric Research Limited (NIWA) to prepare a report synthesising existing information on the effects of urban stormwater discharges on aquatic receiving environments in the Wellington region (Williamson *et al*. 2001). For the marine environment, the report concluded that there was compelling evidence of stormwater impacts on the sediments of Wellington Harbour and Porirua Harbour, but that there was insufficient information to conclusively demonstrate adverse effects on marine animals from stormwater discharges.

In 2003, the Wellington City Council commissioned Montgomery Watson Harza New Zealand Limited (MWH) to document and assess current information relating to the environmental effects of Wellington's contaminated stormwater discharges[1] into Wellington Harbour and waters off the south coast (MWH 2003). In respect of effects on biological communities in Wellington Harbour, the key findings of this assessment were:

- heavy metal (and possibly polycyclic aromatic hydrocarbon (PAH)) accumulation in marine sediments is an issue in Wellington Harbour due to the history of urbanisation and industrialisation of its catchments and the semi-enclosed nature of its waters;
- there is some evidence that contaminant levels in *offshore* areas of Wellington Harbour peaked in the 1970s and have been declining since;
- the areas where metal contamination of sediments is greatest are the sheltered *inshore* depositional embayments of Lambton Harbour and Evans Bay; and
- the metal and organic content of sediment generally decreases away from stormwater outfalls, indicating that the outfalls are a primary source of the contamination.

[1] At the time, Wellington City Council held 12 coastal permits to discharge sewage-contaminated stormwater to the sea around Wellington City.

The management issues arising from the findings of Williamson *et al.* (2001) and MWH (2003) included the need for better monitoring of marine receiving environments, with a significant problem being the absence of time series information on trends in heavy metal and PAH contamination of marine sediments in the vicinity of stormwater outfalls and at more distant locations.

Following discussions with the Wellington City Council, Greater Wellington sought the advice of NIWA on the design and operation of a monitoring programme to detect long-term trends in the concentrations of chemicals generated by human activities in the bed sediments of harbours in the Wellington region. This advice (Ray *et al.* 2003) formed the basis of the sediment chemistry component of subtidal sediment quality investigations carried out in the Porirua Harbour in May 2004 and October 2005 (Williamson *et al.* 2005; Stephenson & Mills 2006), and in Wellington Harbour in October/November 2006.

This report presents the results of the Wellington Harbour sediment quality investigation, including the results of the biological component of the investigation reported by Stephenson (2007a). The biological component followed the same methods that were used to examine the benthos at the subtidal sediment quality monitoring sites in the Porirua Harbour (Stephenson 2005, 2006; Stephenson & Mills 2006).

1.1 Study objectives

The Wellington Harbour marine sediment quality investigation had the following objectives:

1. to make an assessment of the Wellington Harbour receiving environment in terms of sediment quality and benthic community health to provide a sound scientific basis for any management response in relation to urban stormwater discharges; and

2. to select the monitoring sites that might be used to detect changes in sediment quality and benthic community health over time, thereby allowing the ongoing evaluation of urban stormwater management actions directed at maintaining or enhancing the Wellington Harbour receiving environment.

1.2 Sampling sites

The sampling sites were selected based on advice from NIWA that, to be suitable for long-term monitoring, the sites must be:

1. representative of the area of concern;

2. likely to accumulate contaminants in a manner which reflects accumulation over the area; and

3. not likely to change markedly, particularly in their sediment texture, over time periods of decades.

In addition, the sediment at the sites should preferably have a relatively high proportion of mud because many contaminants tend to bind to fine sediment particles, and their low settling velocities mean that they are likely to be widely dispersed (i.e., represent far-field sources) (Ray *et al.* 2003).

Taking into account existing sediment contamination data, NIWA identified 17 locations in Wellington Harbour at which long-term sediment quality monitoring could be conducted. These locations were tested for their suitability for long-term monitoring by taking samples with an Ekman grab and assessing the textural homogeneity of the sediments and whether or not they contained at least 20% mud. At all 17 locations, the textures observed were indicative of stability over substantial periods of time and particle size analyses confirmed that well over 20% of the particles were in the mud fraction (Wellington Water Management Limited unpubl. data). As a result, these locations became the sampling sites for the Wellington Harbour marine sediment quality investigation (Figure 1.1, Table 1.1).

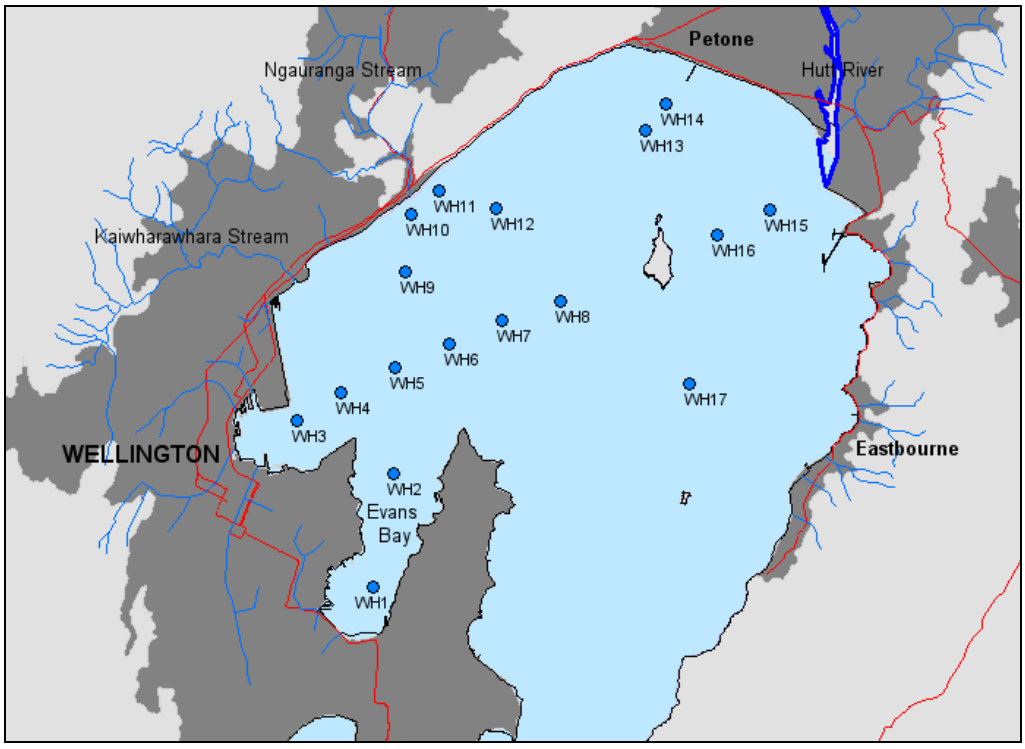

Figure 1.1: Map of Wellington Harbour showing the 17 subtidal locations sampled in 2006 for the Wellington Harbour marine sediment quality investigation.

The 17 sites selected for sampling provided good spatial coverage of Wellington Harbour, making this investigation the most comprehensive assessment of surface sediment quality in the harbour since that undertaken by Stoffers *et al*. (1986)[2]. Although selected to assess the impacts of stormwater discharges, the sites investigated only target *far-field* effects rather than effects in areas close to the discharge points, reflecting Greater Wellington's focus on the health of the wider harbour environment.

[2] Stoffers *et al.* (1986) collected 20 sediment cores and over 100 surface sediment samples across the harbour. Analysis of these samples was restricted to metals on the <20 µm fraction of the sediment, meaning that the results are not directly comparable with current sediment quality guidelines or the results of this investigation.

Table 1.1: Site position and collection details for the Wellington Harbour marine sediment quality investigation, October/November 2006.

Site	Location	Date	Position		Depth (m)
			Latitude	Longitude	
WH1	Southern Evans Bay	11/10/06	41°18'39.0"S	174°48'36.0"E	19
WH1B		13/11/06	41°18'39.5"S	174°48'34.4"E	
WH2	Northern Evans Bay	11/10/06	41°17'36.0"S	174°48'42.0"E	19
WH2B		13/11/06	41°17'36.5"S	174°48'43.5"E	
WH3	Lambton Basin entrance	03/11/06	41°17'03.0"S	174°47'30.0"E	18
WH3B		17/11/06	41°17'04.2"S	174°47'30.0"E	
WH4	≈ 0.7 km NW of Point	03/11/06	41°16'48.0"S	174°48'00.0"E	20
WH4B	Jerningham	17/11/06	41°16'48.9"S	174°48'00.5"E	
WH5	≈ 1.2 km NNE of Point	18/10/06	41°16'36.0"S	174°48'42.0"E	21
WH5B	Jerningham	17/11/06	41°16'37.1"S	174°48'41.8"E	
WH6	≈ 1.25 km NW of Point	18/10/06	41°16'21.0"S	174°49'21.0"E	22
WH6B	Halswell	17/11/06	41°16'21.7"S	174°49'20.2"E	
WH7	≈ 1.5 km N of Point	18/10/06	41°16'09.0"S	174°50'00.0"E	22
WH7B	Halswell	17/11/06	41°16'09.8"S	174°50'01.0"E	
WH8	≈ 1.5 km SW of	18/10/06	41°15'57.0"S	174°50'42.0"E	23
WH8B	Matiu/Somes Island	13/11/06	41°15'56.1"S	174°50'42.2"E	
WH9	≈ 1.5 km SSE of	03/11/06	41°15'45.0"S	174°48'48.0"E	20
WH9B	Ngauranga Stream mouth	08/11/06	41°15'43.7"S	174°48'50.3"E	
WH10	≈ 0.5 km SSE of	11/10/06	41°15'12.0"S	174°48'51.0"E	20
WH10B	Ngauranga Stream mouth	08/11/06	41°15'11.5"S	174°48'50.8"E	
WH11	≈ 0.5 km E of Ngauranga	03/11/06	41°15'00.0"S	174°49'12.0"E	20
WH11B	Stream mouth	08/11/06	41°14'59.5"S	174°49'13.4"E	
WH12	≈ 1.5km E of Ngauranga	03/11/06	41°15'09.0"S	174°49'54.0"E	21
WH12B	Stream mouth	08/11/06	41°15'08.4"S	174°49'55.5"E	
WH13	≈ 1.25 km S of Petone	11/10/06	41°14'24.0"S	174°51'42.0"E	16
WH13B	Wharf	08/11/06	41°14'23.8"S	174°51'43.6"E	
WH14	≈ 0.65 km S of Petone	11/10/06	41°14'09.0"S	174°51'57.0"E	12
WH14B	Wharf	08/11/06	41°14'09.7"S	174°51'58.7"E	
WH15	≈ 1.1 km SW of Seaview	11/10/06	41°15'06.0"S	174°53'15.0"E	16
WH15B	(Hutt River mouth)	13/11/06	41°15'06.9"S	174°53'15.7"E	
WH16	≈ 2.1 km SW of Seaview	18/10/06	41°15'21.0"S	174°52'36.0"E	19
WH16B	(Hutt River mouth)	13/11/06	41°15'21.1"S	174°52'31.1"E	
WH17	≈ 1.6 km NNW of	18/10/06	41°16'42.0"S	174°52'18.0"E	21
WH17B	Makaro/Ward Island	13/11/06	41°16'41.6"S	174°52'19.0"E	

B = Benthic ecology collection area

2. Methods

2.1 Sediment chemistry and particle size distribution

2.1.1 Sample collection

Sampling was conducted using a boat and divers equipped with SCUBA. At each site, the centre of the sediment chemistry collection area (a circle 20 metres in diameter) was located by a Global Positioning System (GPS) and marked with a buoy. On the seabed, the collection area was divided into quadrants on the cardinal points of the compass by laying out weighted ropes and six 50 mm diameter x 120 mm deep sediment cores were collected at random from each quadrant by the divers. A separate screw-top polyethylene bottle, with the bottom cut off and replaced with a plastic insert, was used for each core (Figure 2.1). A further sediment core was taken from near the centre of the collection area to give a total of 25 samples. The samples were kept upright in a specially designed crate until brought to the surface, and then placed in an insulated bin containing ice-packs for transport to the laboratory.

Figure 2.1: Example of a sediment core from Wellington Harbour. Only the top 30 mm of the sediment is used to analyse sediment particle size distribution and chemistry.

The sediment samples were stored upright in a refrigerator at 4°C for a minimum of 12 hours to allow the water content of the surface sediment to reduce. The 25 samples from a site were randomly assigned to five groups. These groups became the five replicate composite samples for that site. With each sample, the bottle was placed on a tray, the top cap removed, and any overlying water carefully siphoned off. The bottom plug was loosened and the core extruded until the top 30 mm remained unexposed. The core was cut at this level with a plastic ruler and the sediment beyond 30 mm depth was discarded. The top 30 mm of the sediment was collected in a polyethylene bag along with that from the four other samples in the group. The composite sample was then frozen.

2.1.2 Sample preparation

Sample preparation followed the steps shown in Figure 2.2. Each thawed composite sample was homogenised by mixing it in a shallow plastic tray. A sub-sample was removed from the composite and placed in a plastic container for the determination of particle size distribution. A second sub-sample of about 200 mL was removed from the composite, freeze-dried in a solvent-cleaned aluminium disposable dish, sieved on a 500 μm nylon screen, and the < 500 μm fraction retained in a solvent-cleaned glass jar with an aluminium foil-lined lid. A third sub-sample of about 50 mL was removed from the composite and wet sieved (nylon screen) to separate the < 63 μm fraction, which was then freeze-dried to recover the solids. The remainder of the composite sample was returned to frozen storage.

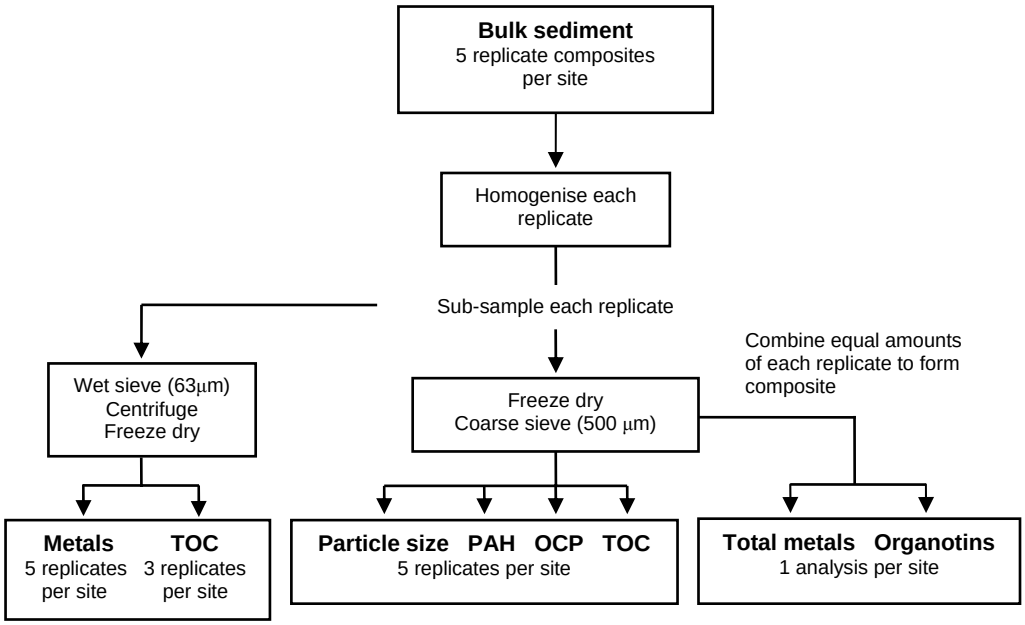

Figure 2.2: Sample preparation scheme (adapted from Williamson *et al.* 2005).

2.1.3 Sediment particle size distribution

Each sub-sample was freeze-dried and then dry-sieved through a 500 μm screen to remove coarse debris. Particle size analysis of the < 500 μm fraction was conducted using a Galai CIS-100 'time-of-transition' stream-scanning laser particle sizer, with the material ultrasonically dispersed for four minutes before, and also during, analysis. Traceable standards were used to ensure the reliability of particle size results. Particle volumes were calculated from the measured particle diameters, and used to produce a particle-size volume distribution for each sample.

2.1.4 Total metals

A composite was prepared from portions of the freeze-dried < 500 μm sub-samples of the five replicates for a site, digested using strong, hot hydrochloric and nitric acids, and the digest analysed by inductively coupled plasma-mass spectrometry (ICP-MS) for antimony, arsenic, cadmium, chromium, copper,

lead, mercury, nickel, silver and zinc. Use of a composite (rather than all replicates) is adequate for comparison with the sediment quality guidelines used in New Zealand because the precision of this comparison is of little interest.

2.1.5 Weak acid extractable metals

A portion of the < 63 μm fraction of each replicate at a site was extracted using weak (2M) cold hydrochloric acid and the extract analysed by ICP-MS for copper, lead and zinc. This technique minimises analytical variability, and therefore is better for trend analysis. In addition, the fine sediment fraction is the most ecologically relevant component of sediments in terms of contaminants, since it is more likely that benthic animals will ingest, or be in intimate contact with, fine rather than coarse materials. Hence the weak acid extractable fraction is a better measure of bio-available metals (ARC 2004).

2.1.6 Organotins

A composite was prepared from the freeze-dried < 500 μm sub-samples of the five replicates for each site and analysed for monobutyltin, dibutyltin, tributyltin and triphenyltin using a procedure involving methanol/acetic acid, sonication, ethylation and GC-MS. This analysis is solely for comparison with the sediment quality guidelines. Use of a composite (rather than all replicates) is adequate because the precision of this comparison is of little interest.

2.1.7 Total organic carbon

A portion of the freeze-dried < 500 μm fraction of each replicate at a site was analysed for total organic carbon using an Elementar Combustion Analyser, after acid pre-treatment to remove carbonates. Organic carbon can influence the bio-availability of toxic organic compounds. Comparison of toxic organic compound concentrations with the sediment quality guidelines used in New Zealand requires concentrations to be normalised to 1% organic carbon.

A portion of the < 63 μm fraction of three of the five replicates at a site was also analysed for total organic carbon. Organic carbon in sediment plays a central role as a binding phase for many trace metals, such as copper and zinc, and correlation of metal concentrations with organic carbon can allow detection of unusual contaminant depletion or enrichment patterns.

2.1.8 Polycyclic aromatic hydrocarbons

A portion of the freeze-dried < 500 μm fraction of each replicate was analysed for the 16 USEPA priority pollutant polycyclic aromatic hydrocarbons – naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-c,d)pyrene, dibenzo(a,h)anthracene and benzo(g,h,i)perylene – using a

procedure involving sonication solvent extraction and gas chromatography-mass spectrometry in selected ion mode (GC-MS-SIM)[3].

2.1.9 Organochlorine pesticides

A portion of the freeze-dried < 500 μm fraction of each replicate was analysed for the organochlorine pesticides alpha-BHC, beta-BHC, gamma-BHC (lindane), delta-BHC, hexachlorobenzene, aldrin, dieldrin, endrin, endrin aldehyde, heptachlor, heptachlor epoxide, endosulfan I, endosulfan II, endosulfan sulphate, cis-chlordane, trans-chlordane, 2,4′-DDE, 2,4′-DDD, 2,4′-DDT, 4,4′-DDE, 4,4′-DDD and 4,4′-DDT using a procedure involving sonication solvent extraction and GC-MS-SIM.

2.1.10 Quality assurance

Quality assurance for the sediment chemistry comprised duplicate analyses and analyses of archived samples or standard reference materials (SRM) as follows, with duplicates provided to the analysts under different identities to the original samples:

- Metals, strong hot acid technique: 2 duplicates, 1 archive.
- Metals, cold dilute acid technique: 5 duplicates, 3 archive.
- Total organic carbon (500 μm fraction): 5 duplicates, 2 archive.
- Total organic carbon (63 μm fraction): 4 duplicates.
- Polycyclic aromatic hydrocarbons: 5 duplicates, 3 archive.
- Organochlorine pesticides: 5 duplicates, 1 SRM.
- Organotins: 2 duplicates, 1 archive.

2.1.11 Long-term sediment sample storage

The remaining portions of all replicates have been stored in stable conditions to permit future analysis and quality control.

2.2 Benthic ecology

2.2.1 Sample collection and analysis

Sampling was conducted using a boat and divers equipped with SCUBA. At each site, the centre of the previously visited sediment chemistry collection area (a circle 20 metres in diameter) was relocated using a GPS. The boat then was moved 25 to 30 metres and the new position marked with a buoy. The co-ordinates of the new position were recorded, becoming the centre of the biology collection area, which was also a circle 20 metres in diameter.

[3] A range of alkylated PAHs, thiophene derivatives and biomarkers for source apportionment assessments were to be analysed in addition to the 16 USEPA priority pollutant PAHs. However, at the time of writing of this report, the data were not available due to prolonged problems with some essential equipment at the NIWA organics laboratory.

On the seabed, the collection area was divided into quadrants on the cardinal points of the compass by laying out weighted ropes and two 200 mm diameter x 250 mm deep sediment cores were collected at random from each quadrant by the divers to give a total of eight samples. Two 50 mm diameter x 120 mm deep sediment cores were taken from the central part of the biology collection area for particle size analysis.

The biology samples were transferred from the corers into labelled plastic bags for transport to the laboratory, where they were washed on a 500 μm screen. The material retained by the screen was placed in 400 mL polyethylene jars and fixed in a solution of 5% formalin in seawater. Animals were picked out under a binocular microscope, identified as far as practicable[4], counted, and preserved in 70% isopropyl alcohol. Prior to preservation, all individuals of each species which contributed significantly to the biomass of a sample were blotted dry and weighed to the nearest 0.001 g on an electronic balance. Body lengths of the heart urchin (*Echinocardium cordatum*) and shell lengths of selected species of bivalves were measured to the nearest 0.1 mm using an ocular micrometer (≤ 10 mm) or digital callipers (> 10 mm).

At the conclusion of the analysis of the fauna one or more specimens of each species was selected and labelled to become part of a reference collection.

Sediment samples were prepared and analysed for particle size in the same manner as the sediment chemistry samples. For each site, the sediment in the top 30 mm of the two cores was removed and combined to form a composite, which was then homogenised, freeze-dried, and sieved at 500 μm. Particle size analysis of the < 500 μm fraction was conducted using a Galai CIS-100 'time-of-transition' stream-scanning laser particle sizer, as described in Section 2.1.3.

2.2.2 Data analysis

Faunal data were analysed using SYSTAT (version 10). Multivariate analysis was used to examine the benthic community structure and relationships between any biotic patterns and physical and chemical variables, following the strategy proposed by Field *et al*. (1982).

(a) Benthic fauna

The number of species, mean number of species per sample, mean number of individuals per sample, and mean Shannon diversity index were determined for each site. One-way analysis of variance (ANOVA) and Tukey-Kramer HSD pairwise mean comparisons were used to identify any significant differences between sites for the latter three measures. Multiple comparison tests were conducted only after a significant ($p < 0.05$) ANOVA result was obtained.

Rank-abundance plots (Whitaker 1975) were used to examine the distribution of individuals amongst the species at each site, and numerical dominance hierarchy plots to examine between-site variations in the numbers of the most

[4] Where genus and species names could not be assigned with certainty due to damage to the specimens, small size, immaturity, or taxonomic difficulties, the species were designated "#1", "#2", "#3", etc., following the class, order, family or generic name as appropriate.

abundant species in the collection. Biomass dominance was assessed from wet weight measurements of animals made prior to their preservation in alcohol.

Species were assigned to one or more of five feeding modes: herbivores, predators + carrion feeders + scavengers, surface deposit feeders, subsurface deposit feeders, and suspension feeders. Species were assigned to feeding modes based on the literature. However, as the feeding biology of many of the species encountered has yet to be studied, it was often necessary to utilise data on their nearest taxonomic relatives and/or apparent ecological equivalents elsewhere to predict the most likely feeding mode for the species. Species whose feeding mode was uncertain or could not be predicted from the available data were placed in a separate class, giving six categories in all. For species which were assigned to more than one feeding mode, equal proportions of the individuals of that species were arbitrarily assigned to each mode; if the numbers would not divide equally the last individual was placed in what was known or considered to be the dominant feeding mode for the species in this environment. The percentage of individuals in each feeding mode at each site was calculated.

The mean abundances of species at each site were calculated and recorded in a species-by-site table. Community structure (composition and abundance) was compared by calculating a between-site pairwise similarity matrix using the Bray-Curtis similarity measure, before additive tree clustering and ordination by multi-dimensional scaling (MDS). The similarity matrix was calculated using "root-root" transformed[5] mean abundance values.

The size frequency distributions of the heart urchin and of selected species of bivalves were determined and summarised in diagrammatic form as dot displays.

(b) Linking the benthic community to physical and chemical variables

Relationships between the benthic communities at sites (or groups of sites) and the physical and chemical variables were explored by superimposing data for one variable at a time on the ordination derived from the MDS analysis of the similarity matrix based on mean species abundances.

[5] Species abundance data are typically skewed and symmetrical distribution about the mean is an underlying assumption of many statistical procedures. Transformation can make the distributions more symmetrical and also be used to reduce the influence of abundant species on the differentiation of sites.

3. Sediment quality guidelines

Determining the ecological effects of chemical contaminants in the receiving environment is a complex task, particularly when the chemicals are present at only low-to-moderate concentrations and in complex mixtures (e.g., urban stormwater-contaminated sediments). Ideally, evidence for adverse effects on aquatic life is obtained by assessing ecological health at the site(s) of interest, but unless contamination levels are very high (which is not common in New Zealand), impacts of contamination are difficult to distinguish from the effects of other environmental variables (e.g., salinity gradients and sediment textural variations in estuaries – Morrisey *et al.* 2003). Extensive studies in Auckland estuaries have demonstrated adverse effects on benthic community health related to sediment contamination, using a multivariate statistical model coupled with sediment chemistry and benthic ecology data from a number of sites spanning a pollution gradient (Anderson *et al*. 2006).

A "first-step" approach to assessing the potential impacts of contaminated sediments on benthic ecology is to compare contaminant concentrations with sediment quality guidelines. Guidelines provide indicative, rather than absolute, evidence for adverse effects. Any exceedance of the guidelines indicates that there is *potential* for an environmental impact, and that further investigations are required to determine with greater certainty whether or not effects are actually occurring at the affected site(s). Investigations could include ecological evaluations, toxicity testing, source identification, prediction of future sediment quality, and an evaluation of management options. Ongoing monitoring is then used to detect subsequent changes in environmental quality and evaluate the effectiveness of management actions.

The most widely used sediment quality guidelines are those originally developed by the US National Oceanic and Atmospheric Administration (NOAA) from an extensive North American database of sediment chemistry and toxicity studies (Long & Morgan 1990; Long *et al.* 1995). These were subsequently modified for application in Florida (MacDonald *et al.* 1996), and in Canada (Smith *et al.* 1996; CCME 2003). The Australian and New Zealand Environment and Conservation Council (ANZECC 2000) guidelines, which have been compiled for use in Australia and New Zealand, are essentially the Long & Morgan (1990) guidelines with some modifications[6].

ANZECC and international sediment quality guidelines provide low and high values:

1. The low values (e.g., ANZECC ISQG-Low, TEL[7] and ERL[7]) are nominally indicative of the contaminant concentrations where the onset of biological effects could possibly occur. These values provide an early warning, enabling management intervention to prevent or minimise adverse environmental effects.

[6] For example, changes introduced into the ANZECC guidelines include increases in the sediment quality guidelines for zinc and copper, and the use of organic carbon normalisation for organic contaminants.

[7] TEL is the Threshold Effects Level (MacDonald *et al.* 1996) and ERL is the Effects Range Low (Long & Morgan 1990 and Long *et al.* 1995).

2. The high values (ANZECC ISQG-High, PEL[8] and ERM[8]) are nominally indicative of the contaminant concentrations where significant biological effects are expected. Exceedance of these values – in particular the ANZECC ISQG-High values – therefore indicates that adverse environmental effects are probably already occurring, and management intervention may be required to remediate the problem.

The Auckland Regional Council (ARC) introduced "Environmental Response Criteria" (ERC)[9], derived from the Threshold Effect Levels (TEL) and Effects Range Low (ERL) values (with rounding) of MacDonald *et al.* 1994 and Long & Morgan (1990) respectively (Kelly 2007). These guidelines provide a conservative, yet practical[10] early warning of environmental degradation which allows time for investigations into the causes of contamination to be carried out and the options for limiting the extent of degradation to be developed (Kelly 2007, ARC 2004).

It should be noted that the ARC ERC, unlike the ANZECC guidelines, have single "amber/red" thresholds for the organochlorine pesticides. Any exceedance of these thresholds is considered to be of significant concern, warranting investigations to determine source(s), trends over time, and potential toxicity. Fortunately, few areas have been identified that exceed these levels, and those that do are generally the result of known historical causes (e.g., use in horticulture, spills around ports, and contaminated site discharges) rather than ongoing contamination from current activities.

Both the ANZECC (2000) and the ARC ERC (ARC 2004) sediment quality guidelines are being used to assess the potential ecological effects of contaminants in the Wellington Harbour marine sediment quality investigation (Table 3.1). These guidelines are generally considered to be reasonably robust, and conservative (i.e., they err on the side of environmental protection). They are not "pass or fail" numbers, and the developers of the guidelines emphasise that they are best used as one part of a "weight of evidence" approach to evaluating potential effects of contaminants on benthic biota.

[8] PEL is the Probable Effects Level (MacDonald *et al.* 1996) and ERM is the Effects Range Medium (Long & Morgan 1990 and Long *et al.* 1995).

[9] Note that these guidelines are currently under appeal.

[10] Some of the ANZECC guideline values are not practical. For example, the organochlorine pesticide dieldrin has an ANZECC ISQG-Low value of 0.02 µg/kg (parts per billion), which is below the analytical detection limits of almost all laboratories, and probably represents a level that would be present at most rural and urban estuaries in New Zealand. This value originated from the original guideline work by Long & Morgan (1990). The ARC ERC value for dieldrin is a more practical 0.72 µg/kg, and is based on a later derivation proposed for use in Florida (MacDonald *et al.* 1996) and adopted by Environment Canada (Smith *et al.* 1996; CCME 2003). Some other examples of differences between the ANZECC and ARC ERC guidelines are discussed in ARC (2004).

Table 3.1: Sediment quality guidelines used in the Wellington Harbour marine sediment quality investigation. Guideline values are taken from ANZECC (2000) and ARC (2004).

Analyte	ANZECC trigger values		ARC ERC thresholds	
	ISQG-Low	ISQG-High	amber	red
Metals (mg/kg dry wt):				
Antimony	2	25		
Arsenic[1]	20	70		
Cadmium	1.5	10		
Chromium	80	370		
Copper	65	270	19	34
Lead	50	220	30	50
Mercury	0.15	1		
Nickel	21	52		
Silver	1	3.7		
Zinc	200	410	124	150
Organotins (µg Sn/kg dry wt):				
Tributyltin	5	70		
Polycyclic Aromatic Hydrocarbons (µg/kg dry wt):[2]				
Naphthalene	160	2,100		
Acenaphthalene	44	640		
Acenaphthene	16	500		
Fluorene	19	540		
Phenanthrene	240	1500		
Anthracene	85	1,100		
Low Molecular Weight PAHs[3]	552	3,160		
Fluoranthene	600	5,100		
Pyrene	665	2,600		
Benzo[a]anthracene	261	1,600		
Chrysene	384	2,800		
Benzo[a]pyrene	430	1,600		
Dibenzo[a,h]anthracene	63	260		
High Molecular Weight PAHs[4]	1,700	9,600	660	1,700
Total PAHs	4,000	45,000		
Organochlorines (µg/kg dry wt):[2]				
Chlordane	0.5	6		
Dieldrin	0.02	8		0.72
Endrin	0.02	8		
Gamma-BHC (Lindane)	0.32	1		
4,4'-DDE	2.2	27		
2,4'-DDD + 4,4'-DDD	2	20		
Total DDT[5]	1.6	46		3.9

[1] Arsenic is, strictly speaking, a metalloid (ANZECC 2000).

[2] Normalised to 1% total organic carbon.

[3] Low Molecular Weight PAHs are the sum of the concentrations of naphthalene, 2-methyl-naphthalene, acenaphthalene, acenaphthene, fluorene, phenanthrene and anthracene.

[4] High Molecular Weight PAHs are the sum of the concentrations of fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[a]pyrene and dibenzo[a,h]anthracene.

[5] Total DDT is the sum of the concentrations of 2,4'-DDE, 2,4'-DDD, 2,4'-DDT, 4,4'-DDE, 4,4'-DDD and 4,4'-DDT.

4. Results

4.1 Sediment chemistry and particle size

The results of all the analyses from the Wellington Harbour marine sediment quality investigation are presented in Appendices 1 and 2, and their associated quality assurance results in Appendix 3. These results are summarised in this section.

4.1.1 Sediment particle size distribution

Mean particle size and the mean percentage of particles < 63 μm in the sediments of the 17 sites are shown in Table 4.1.

The mean percentage of particles < 63 μm in the sediments at the majority of the sites was between 66% and 95% (sandy mud or slightly sandy mud), with the higher mean percentages occurring at sites WH9–WH13 in the north-western portion of the harbour. The mean percentage of particles < 63 μm in the sediments at sites WH2 (northern Evans Bay) and WH3 (Lambton Basin entrance) was 58% (very sandy mud), while at sites WH1 (southern Evans Bay) and WH17 (≈ 1.6 km NNW of Makaro/Ward Island) it was only 26% and 38% respectively (muddy sand). Variability in the mean percentage of particles < 63 μm was low to moderate (coefficient of variation [c.v.] 1.2–26.3%), with a tendency to be higher at the sites with the sandier sediments.

4.1.2 Total metals

The total concentrations of copper, lead, mercury and zinc were generally higher in the sediments of sites adjacent to Wellington City (WH1, WH2, WH3, WH4, WH10, and WH11) than in those of sites elsewhere in Wellington Harbour (Figures 4.1, 4.2; Table 4.1). Total copper concentrations, which ranged from 11.9–31.6 mg/kg, exceeded the ARC ERC amber threshold at sites WH1 (southern Evans Bay), WH2 (northern Evans Bay), WH3 (Lambton Basin entrance) and WH4 (≈ 0.7 km NW of Pt Jerningham). Total zinc concentrations ranged from 83.9–132 mg/kg and exceeded the ARC ERC amber threshold at sites WH1 and WH3.

Total lead concentrations, which ranged from 24.9–67.1 mg/kg, exceeded both the ARC ERC red threshold and ANZECC ISQG-Low trigger value at five sites – WH1, WH2, WH3, WH4 and WH11 (≈ 0.5 km E of Ngauranga Stream mouth) – and the ARC ERC amber threshold at a further 10 sites. Total mercury concentrations ranged from 0.15–0.79 mg/kg and exceeded the ANZECC ISQG-Low trigger value at all sites except WH15 (≈ 1.1 km SW of Seaview).

Total antimony, arsenic, cadmium, chromium, nickel and silver concentrations were below their respective ANZECC ISQG-Low trigger values in the sediments of all sites (Figures 4.2, 4.3; Table 4.1). Total arsenic, cadmium, chromium and nickel concentrations showed no clear spatial pattern. Total

Table 4.1: Mean particle size, percentage of particles < 63 µm, and summary of concentrations and variability (coefficient of variation [c.v., %], n = 5) of metals, dibutyltin (DBT) and tributyltin (TBT) in sediments of 17 sites sampled in Wellington Harbour in 2006. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Regional Council Environmental Response Criteria (ARC ERC; ARC 2004). Values in amber exceed the ARC ERC amber threshold and values in red exceed the ARC ERC red threshold and/or ANZECC ISQG-Low.

Analyte	Fraction	ANZECC		ARC ERC		WH1		WH2		WH3		WH4		WH5	
	analysed	ISQG-Low	ISQG-High	amber	red	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.
Mean particle size (µm)	< 500 µm					94.02	3.5	60.31	18.7	59.31	21.3	43.25	20.2	35.27	15.3
% particles < 63 µm	< 500 µm					25.52	10.3	57.85	13.0	58.19	19.7	72.88	14.2	85.00	8.2
Metals (mg/kg, 2 M HCl):															
Copper	< 63 µm					20.8	7.9	14.2	5.9	25.0	6.3	14.4	6.2	9.8	8.5
Lead	< 63 µm					69.0	7.9	50.5	6.7	60.4	4.8	44.5	4.7	34.3	5.9
Zinc	< 63 µm					121.6	5.3	101.2	6.4	116.6	4.9	93.2	4.8	75.8	5.1
Metals (mg/kg, total digest):															
Silver	< 500 µm	1	3.7			0.7		0.5		0.6		0.4		<0.4	
Arsenic	< 500 µm	20	70			6.2		5.0		6.1		6.1		6.3	
Cadmium	< 500 µm	1.5	10			0.08		0.05		0.06		0.06		0.05	
Chromium	< 500 µm	80	370			23.7		24.5		25.6		24.9		24.4	
Copper	< 500 µm	65	270	19	34	25.7		19.2		31.6		20.2		16.9	
Mercury	< 500 µm	0.15	1			0.79		0.62		0.77		0.51		0.32	
Nickel	< 500 µm	21	52			16.6		17.6		18.2		17.3		18.4	
Lead	< 500 µm	50	220	30	50	67.1		51		62.5		50.5		37.9	
Antimony	< 500 µm					<0.4		<0.4		<0.4		<0.4		<0.4	
Zinc	< 500 µm	200	410	124	150	130		114		132		117		99.1	
Organotins (µg Sn/kg):															
Dibutyltin	< 500 µm					12		10		22		17		12	
Tributyltin	< 500 µm	5	70			< 5		< 3		9		6		< 3	

Table 4.1 *continued*: **Mean particle size, percentage of particles < 63 µm, and summary of concentrations and variability (coefficient of variation [c.v., %], n = 5) of metals, dibutyltin (DBT) and tributyltin (TBT) in sediments of 17 sites sampled in Wellington Harbour in 2006. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Regional Council Environmental Response Criteria (ARC ERC; ARC 2004). Values in amber exceed the ARC ERC amber threshold and values in red exceed the ARC ERC red threshold and/or ANZECC ISQG-Low.**

Analyte	Fraction	ANZECC		ARC ERC		WH6		WH7		WH8		WH9		WH10	
	analysed	ISQG-Low	ISQG-High	amber	red	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.
Mean particle size (µm)	< 500 µm					34.36	4.3	37.55	6.6	36.96	6.7	27.83	8.3	23.06	19.6
% particles < 63 µm	< 500 µm					87.53	2.3	85.13	3.5	84.90	3.6	93.18	3.9	95.17	6.7
Metals (mg/kg, 2 M HCl):															
Copper	< 63 µm					8.8	5.1	8.8	5.1	9.4	5.8	10.8	4.1	12.6	4.3
Lead	< 63 µm					32.4	5.0	32.0	4.8	33.9	5.3	40.1	2.5	45.8	2.1
Zinc	< 63 µm					70.8	4.2	73.0	5.2	76.2	3.9	85.4	2.7	92.8	2.1
Metals (mg/kg, total digest):															
Silver	< 500 µm	1	3.7			<0.4		<0.4		<0.4		<0.4		<0.4	
Arsenic	< 500 µm	20	70			6.7		6.0		6.8		6.3		6.9	
Cadmium	< 500 µm	1.5	10			0.05		0.04		0.04		0.05		0.05	
Chromium	< 500 µm	80	370			23.5		22.8		24.1		25.2		25.9	
Copper	< 500 µm	65	270	19	34	14.2		13.2		15.0		15.7		17.9	
Mercury	< 500 µm	0.15	1			0.25		0.21		0.19		0.29		0.36	
Nickel	< 500 µm	21	52			17.5		17.2		18.8		18.7		18.2	
Lead	< 500 µm	50	220	30	50	35.3		30.3		32.3		40.2		48.1	
Antimony	< 500 µm					<0.4		<0.4		<0.4		<0.4		<0.4	
Zinc	< 500 µm	200	410	124	150	96.3		88.3		93.6		103		113	
Organotins (µg Sn/kg):															
Dibutyltin	< 500 µm					12		11		14		16		12	
Tributyltin	< 500 µm	5	70			< 3		< 3		< 3		< 5		< 3	

Table 4.1 *continued*: **Mean particle size, percentage of particles < 63 µm, and summary of concentrations and variability (coefficient of variation [c.v., %], n = 5) of metals, dibutyltin (DBT) and tributyltin (TBT) in sediments of 17 sites sampled in Wellington Harbour in 2006. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Regional Council Environmental Response Criteria (ARC ERC; ARC 2004). Values in amber exceed the ARC ERC amber threshold and values in red exceed the ARC ERC red threshold and/or ANZECC ISQG-Low.**

Analyte	Fraction	ANZECC		ARC ERC		WH11		WH12		WH13		WH14		WH15	
	analysed	ISQG-Low	ISQG-High	amber	red	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.
Mean particle size (µm)	< 500 µm					24.75	32.0	27.99	18.0	27.57	6.1	34.00	4.0	50.06	6.7
% particles < 63 µm	< 500 µm					94.13	7.4	91.74	7.1	94.84	1.2	88.04	1.3	66.70	8.9
Metals (mg/kg, 2 M HCl):															
Copper	< 63 µm					13.2	3.4	11.2	4.0	13.6	6.6	15.6	3.5	13.4	4.1
Lead	< 63 µm					48.8	2.0	42.7	3.5	40.5	6.0	38.9	1.5	27.7	2.9
Zinc	< 63 µm					96.8	1.3	86.2	2.2	97.0	6.6	95.6	2.5	74.4	2.4
Metals (mg/kg, total digest):															
Silver	< 500 µm	1	3.7			<0.4		<0.4		<0.4		<0.4		<0.4	
Arsenic	< 500 µm	20	70			7.3		6.7		7.9		8.6		8.0	
Cadmium	< 500 µm	1.5	10			0.06		0.04		0.06		0.09		0.07	
Chromium	< 500 µm	80	370			26.1		25.4		25.7		21.7		18.3	
Copper	< 500 µm	65	270	19	34	18.6		16.0		18.4		18.3		15.4	
Mercury	< 500 µm	0.15	1			0.33		0.24		0.23		0.21		0.15	
Nickel	< 500 µm	21	52			18.5		18.3		19.7		16.1		15.1	
Lead	< 500 µm	50	220	30	50	50.5		40.1		40.2		38.2		24.9	
Antimony	< 500 µm					<0.4		<0.4		<0.4		<0.4		<0.4	
Zinc	< 500 µm	200	410	124	150	119		106		112		107		84.5	
Organotins (µg Sn/kg):															
Dibutyltin	< 500 µm					14		12		9		12		10	
Tributyltin	< 500 µm	5	70			< 5		12		< 3		< 5		< 3	

Table 4.1 *continued*: **Mean particle size, percentage of particles < 63 µm, and summary of concentrations and variability (coefficient of variation [c.v., %], n = 5) of metals, dibutyltin (DBT) and tributyltin (TBT) in sediments of 17 sites sampled in Wellington Harbour in 2006. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Regional Council Environmental Response Criteria (ARC ERC; ARC 2004). Values in amber exceed the ARC ERC amber threshold and values in red exceed the ARC ERC red threshold and/or ANZECC ISQG-Low.**

Analyte	Fraction	ANZECC		ARC ERC		WH16		WH17	
	analysed	ISQG-Low	ISQG-High	amber	red	mean	c.v.	mean	c.v.
Mean particle size (µm)	< 500 µm					41.88	15.1	74.17	12.3
% particles < 63 µm	< 500 µm					75.24	14.3	38.27	26.3
Metals (mg/kg, 2 M HCl):									
Copper	< 63 µm					11.2	7.5	9.8	4.6
Lead	< 63 µm					34.4	4.8	33.1	3.2
Zinc	< 63 µm					84.4	3.2	80.2	2.4
Metals (mg/kg, total digest):									
Silver	< 500 µm	1	3.7			<0.4		<0.4	
Arsenic	< 500 µm	20	70			7.0		6.2	
Cadmium	< 500 µm	1.5	10			0.05		0.03	
Chromium	< 500 µm	80	370			23.4		20.7	
Copper	< 500 µm	65	270	19	34	15.0		11.9	
Mercury	< 500 µm	0.15	1			0.19		0.16	
Nickel	< 500 µm	21	52			18.3		15.8	
Lead	< 500 µm	50	220	30	50	34.1		30	
Antimony	< 500 µm					<0.4		0.5	
Zinc	< 500 µm	200	410	124	150	97.7		83.9	
Organotins (µg Sn/kg):									
Dibutyltin	< 500 µm					23		9	
Tributyltin	< 500 µm	5	70			< 3		< 3	

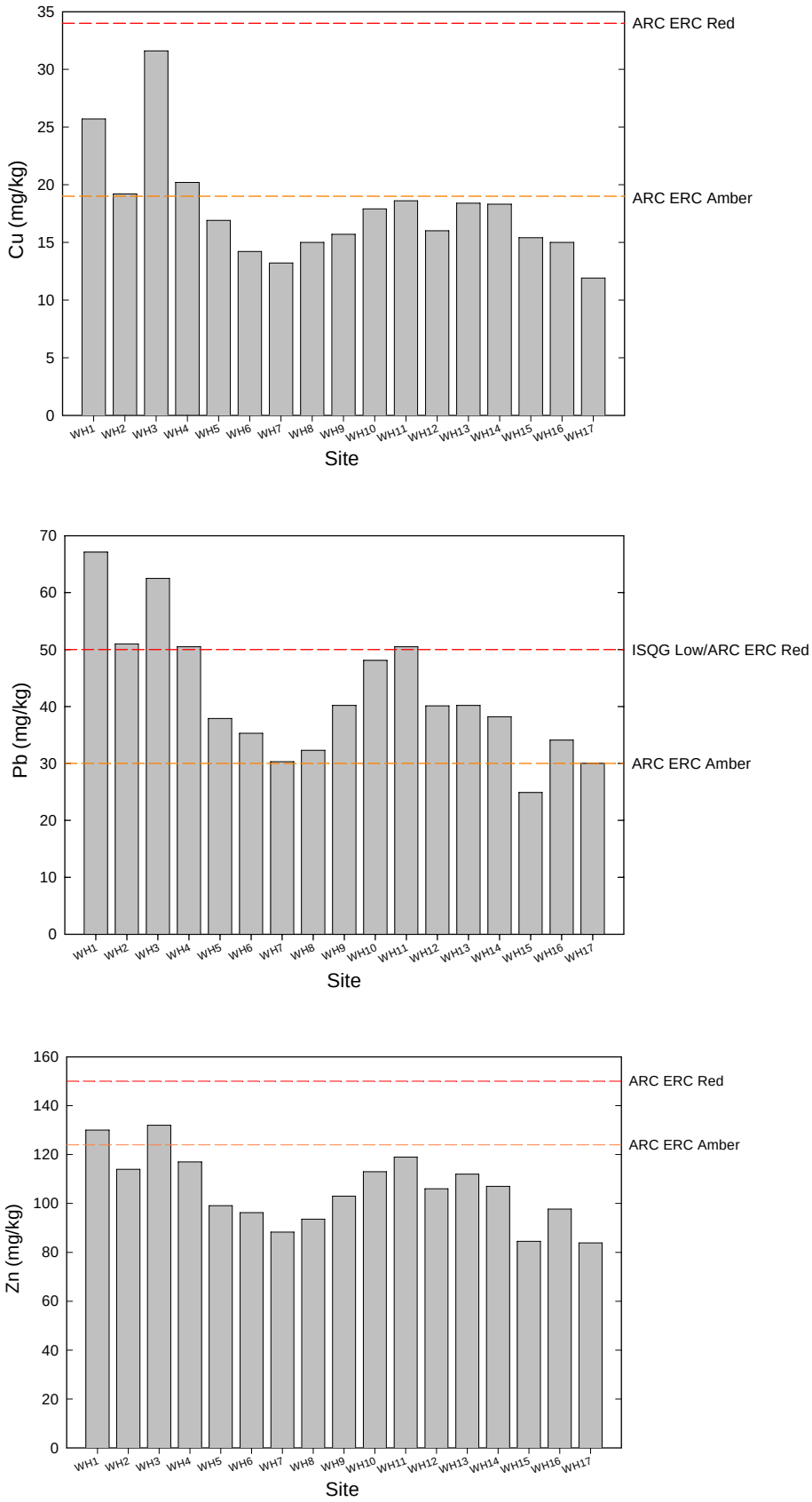

Figure 4.1: Concentrations of total copper (Cu), lead (Pb), and zinc (Zn) in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of a single composite sample from each site.

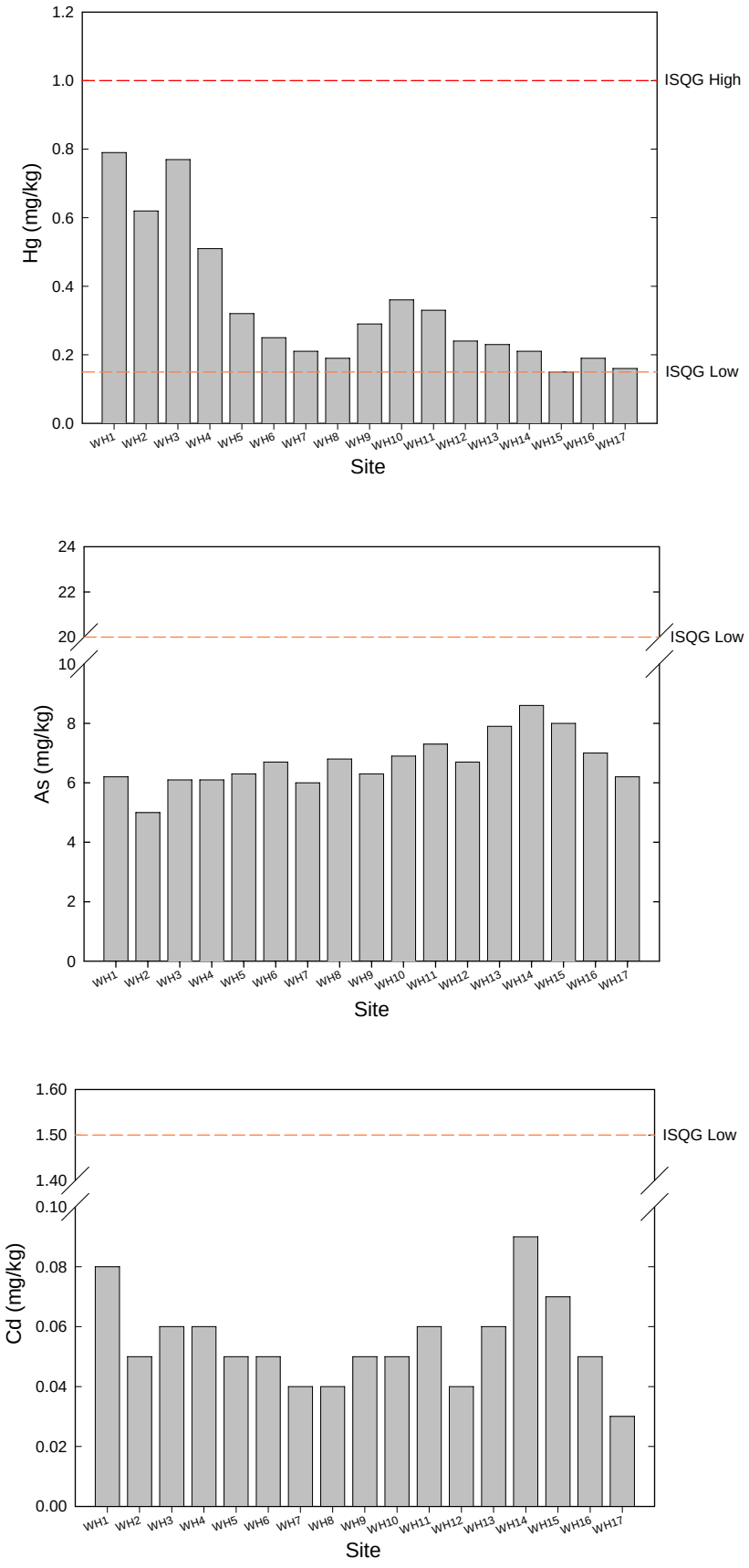

Figure 4.2: Concentrations of total mercury (Hg), arsenic (As) and cadmium (Cd) in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of a single composite sample from each site.

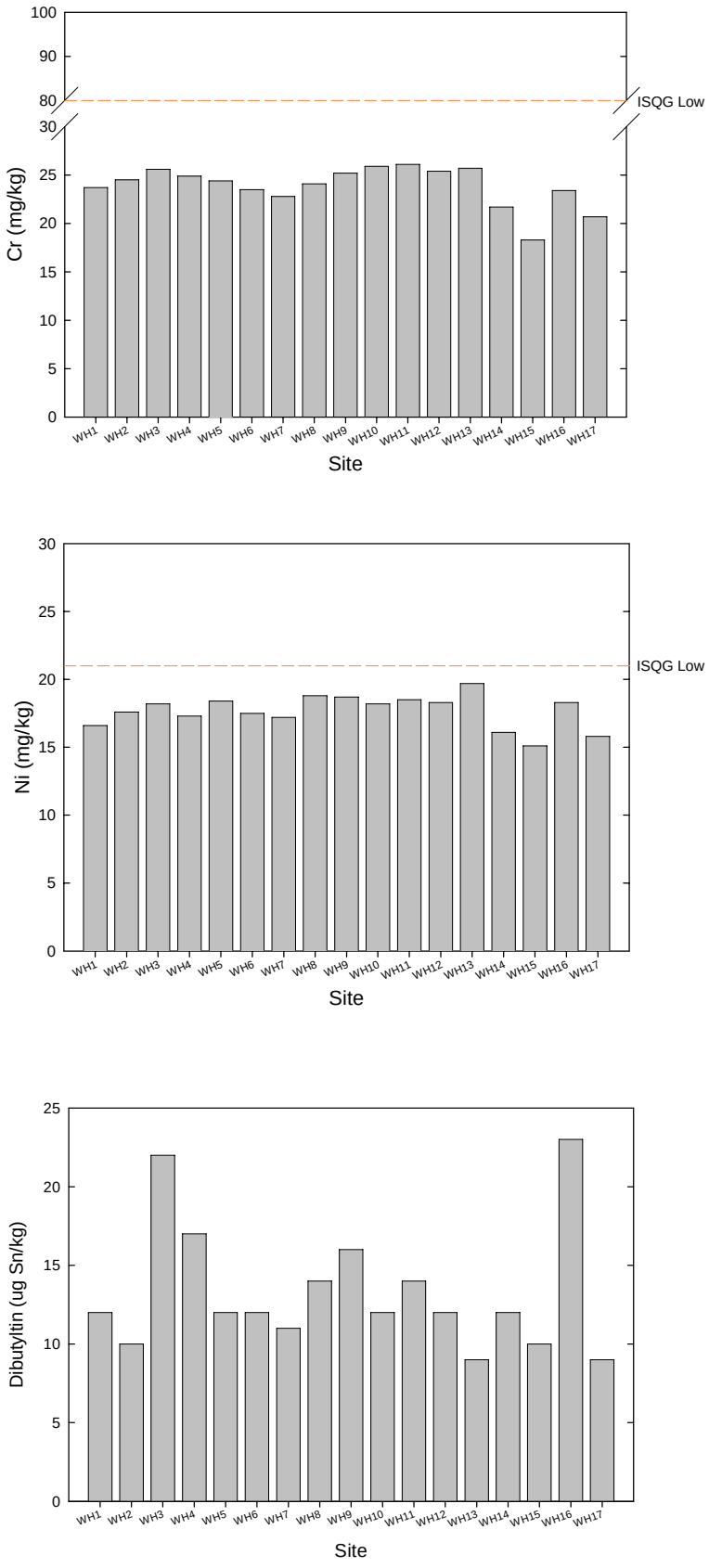

Figure 4.3: Concentrations of total chromium (Cr), nickel (Ni), and dibutyltin (DBT) in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of a single composite sample from each site. There is no ANZECC guideline for DBT.

silver and total antimony concentrations were only above their detection limits in the sediments of two sites (WH1 and WH4) and one site (WH17) respectively.

The concentrations of total copper, lead, mercury and zinc in the sediments were all strongly correlated (Pearson r = 0.843–0.963), as was the total concentration of chromium with that of nickel (r = 0.858). Only the total concentrations of arsenic and cadmium had significant correlations with the levels of organic carbon in the 500 μm fraction of the sediments.

4.1.3 Weak acid extractable metals

The mean concentrations of weak acid extractable copper, lead and zinc in the < 63 μm fraction of the sediments followed similar spatial patterns to their total metal concentrations, being higher in the sediments of sites adjacent to Wellington City than in those of sites elsewhere in Wellington Harbour (Figure 4.4; Table 4.1). The < 63 μm-fraction metals data showed low variability (c.v. 1.3–8.5%), which indicates that it should be possible to detect relatively small changes in concentrations over time. The mean concentrations of copper and zinc were weakly correlated (r = 0.546 and 0.403) with the levels of organic carbon in the 63 μm fraction of the sediments, while the mean concentration of lead showed no correlation at all.

4.1.4 Organotins

Monobutyltin concentrations were below the detection limits (4–5 μg Sn/kg) in the sediments of all 17 sites. In contrast, dibutyltin (DBT) concentrations were above the detection limits at all sites, the concentrations ranging from 9–23 μg Sn/kg (Figure 4.3; Table 4.1). There are no recommended trigger values for DBT in the ANZECC (2000) sediment quality guidelines.

Tributyltin (TBT) concentrations were below the ANZECC ISQG-Low trigger value of 5 μg Sn/kg in the sediments of 14 of the sites, although it should be noted that the analytical detection limits for these samples (3–5 μg Sn/kg) are close to the guideline. The remaining three sites – WH3 (Lambton Basin entrance), WH4 (≈ 0.7 km NW of Pt Jerningham) and WH12 (≈ 1.5 km E of Ngauranga Stream mouth) – had TBT concentrations of 9, 6 and 12 μg Sn/kg respectively.

Triphenyltin (TPhT) concentrations were below the detection limit (2 μg Sn/kg) in the sediments of all sites except WH4, which had a TPhT concentration of 6 μg Sn/kg. There are no recommended trigger values for TPhT in the ANZECC (2000) sediment quality guidelines.

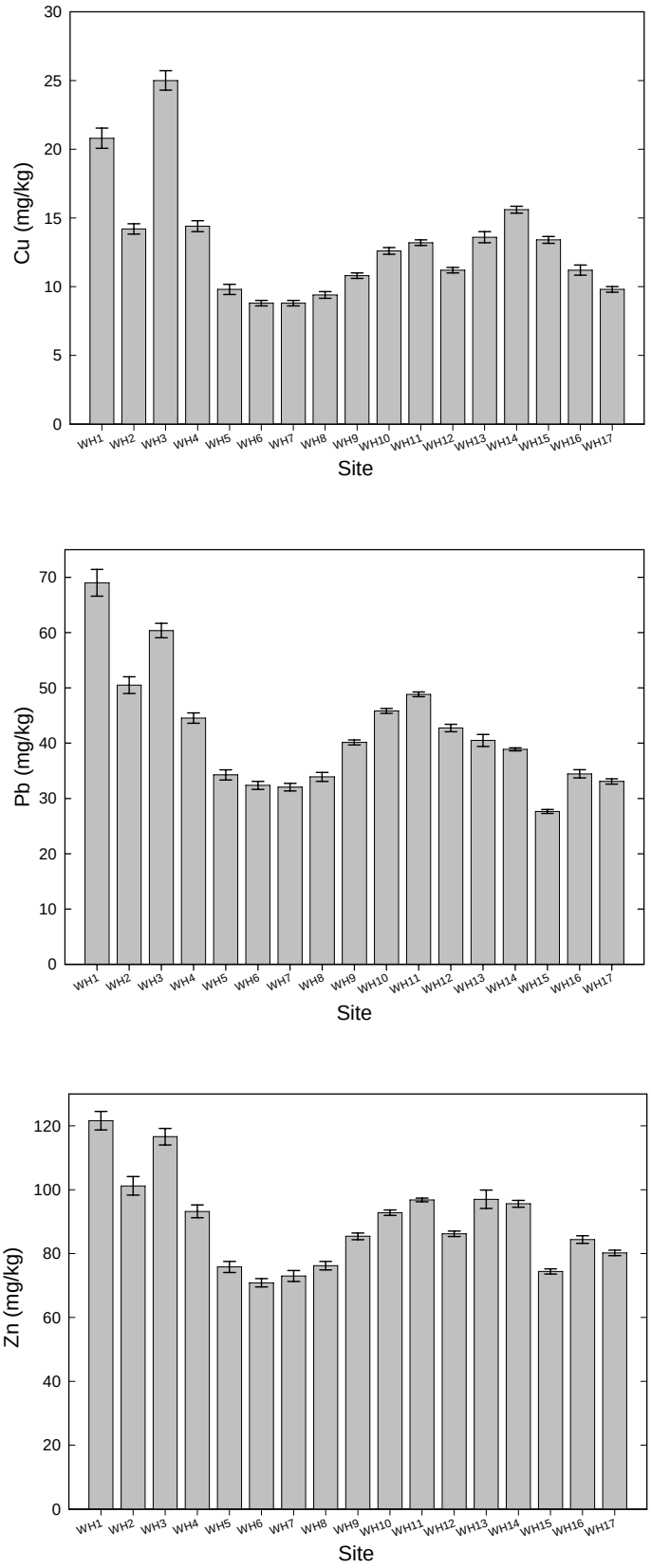

Figure 4.4: Mean concentrations of weak acid extractable copper (Cu), lead (Pb) and zinc (Zn) in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 63 µm fraction of five composite samples from each site. Error bars are ± 1 standard error of mean.

4.1.5 Total organic carbon

The mean total organic carbon (TOC) contents in the < 500 µm fraction of the sediments of the 17 sites are listed in Table 4.2, along with the mean concentrations and variability of selected organic contaminants.

The mean TOC contents in the < 500 µm fraction of the sediments ranged from 1.21–2.17%, with the highest mean TOC content recorded at sites WH14 (≈ 0.65 km S of Petone Wharf) and WH15 (≈ 1.1 km SW of Seaview) (Figure 4.5). Variability in the mean TOC content of the < 500 µm fraction was low for all sites (c.v. 0.5–2.8%).

Based on the three replicate samples for which both 500 µm and 63 µm TOC measurements were available, the mean TOC content in the < 63 µm fraction of the sediments was equal to or lower than that of the < 500 µm fraction at 13 sites, and higher at four sites. Sediments of sites WH14 (≈ 0.65 km S of Petone Wharf, – 16.3%) and WH17 (≈ 1.6 km NNW of Makaro/Ward Island, + 20.8%) had the greatest differences in mean TOC content between the two fractions.

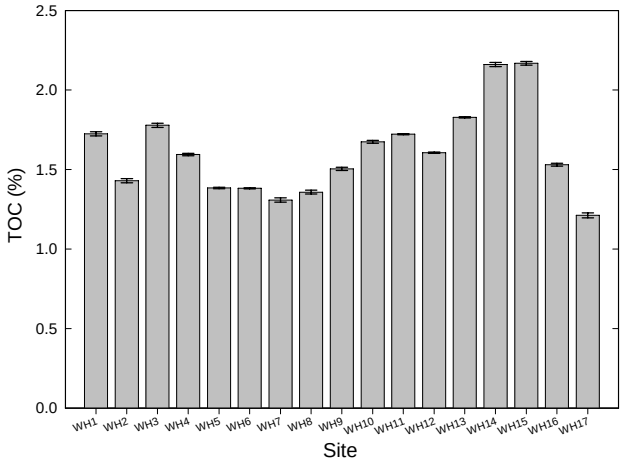

Figure 4.5: Mean total organic carbon (TOC) contents in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of five composite samples from each site. Error bars are ± 1 standard error of mean.

4.1.6 Polycyclic aromatic hydrocarbons

The mean Total PAH and mean Total High Molecular Weight PAH (Total HMW PAH)[11] concentrations were generally higher in the sediments of sites adjacent to Wellington City that in those of sites elsewhere in Wellington Harbour, although the differences in concentrations between sites WH1 (southern Evans Bay) and WH3 (Lambton Basin entrance) and the remaining sites were much more pronounced than for the metals (Figures 4.6, 4.7; Table 4.2).

Variability in Total PAH and Total HMW PAH concentrations was low (c.v. 0.4–12.4%).

[11] For an explanation of the terms "Total PAH" and "Total High Molecular Weight PAH", refer to the notes under Table 4.2.

Table 4.2: Summary of concentrations and variability (coefficient of variation [cv, %], n = 5) of total organic carbon (TOC) and selected organic contaminants in sediments of 17 sites sampled in Wellington Harbour in 2006. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Regional Council Environmental Response Criteria (ARC ERC; ARC 2004). Values in amber exceed the ANZECC ISQG-Low or ARC ERC amber threshold and values in red exceed the ANZECC ISQG-Low and ARC ERC red threshold.

Analyte	Fraction	ANZECC		ARC ERC		WH1		WH2		WH3		WH4		WH5	
	analysed	ISQG-Low	ISQG-High	amber	red	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.
TOC (%)	< 500 µm					1.72	1.7	1.43	2.0	1.78	1.6	1.59	1.0	1.38	0.6
Organics (µg/kg):															
Fluorene	< 500 µm					42.8	9.3	14.4	7.9	27.6	7.1	13.6	6.6	6.9	6.8
Phenanthrene	< 500 µm					428	11.0	160	6.3	348	4.7	158	8.3	71	6.1
Benzo(a)anthracene	< 500 µm					538	7.2	190	3.7	348	4.3	170	4.2	78.2	8.7
Total PAH[1,2]	< 500 µm					6,414	6.1	2,452	2.5	4,588	3.0	2,302	4.6	1,097	4.6
Total HMW PAH[1,2]	< 500 µm					3,585	6.5	1,368	2.3	2,601	3.4	1,279	5.2	593	5.7
Hexachlorobenzene	< 500 µm					< 0.2		< 0.2		0.6	52.0	< 0.2		< 0.2	
Total DDT[2,3]	< 500 µm					12.7	18.3	4.9	23.9	14.2	35.4	5.6	12.7	3.5	40.5
Fluorene	at 1% TOC[4]	19	540			25	8.3	10	9.0	16	7.1	9	7.2	5	6.5
Phenanthrene	at 1% TOC	240	1500			248	10.0	112	6.6	196	5.8	99	8.8	51.3	5.7
Benzo(a)anthracene	at 1% TOC	261	1600			312	7.9	133	3.8	196	3.8	107	5.1	56.5	8.3
Total PAH	at 1% TOC	4000	45000			3,722	6.5	1,715	3.5	2,580	3.1	1,445	5.3	793	4.2
Total HMW PAH	at 1% TOC	1700	9600	660	1700	2,081	7.0	957	3.4	1,463	3.3	803	5.9	429	5.3
Hexachlorobenzene	at 1% TOC					< 0.2		< 0.2		0.4	39.5	< 0.2		< 0.2	
Total DDT	at 1% TOC	1.6	46		3.9	7.4	18.6	3.4	22.5	8.0	35.1	3.5	11.7	2.5	40.8

[1] Polycyclic aromatic hydrocarbons have been summarised as "Total PAH" (all the PAH compounds analysed), and as "Total High Molecular Weight PAH", which is the sum of the concentrations of chrysene, fluoranthene, pyrene, benzo[a]anthracene, benzo[a]pyrene, and dibenzo[a,h]anthracene. This is the total used for the ANZECC (2000) sediment quality guidelines and ARC ERC (ARC 2004). All the PAH compounds analysed are listed in Appendix 2.

[2] For the purpose of calculating Total PAH, Total HMW PAH, and Total DDT, the concentration of any individual compound reported at "less than detection limit" has been replaced by a value one half of the detection limit.

[3] DDT and related compounds have been summarised as "Total DDT", which is the sum of the concentrations of 2,4'-DDE, 2,4'-DDD, 2,4'-DDT, 4,4'-DDE, 4,4'-DDD, and 4,4'-DDT.

[4] This TOC "normalisation" is used in the ANZECC sediment quality guidelines and ARC ERC for comparing sediments with different TOC content.

Table 4.2 *continued*: **Summary of concentrations and variability (coefficient of variation [cv, %], n = 5) of total organic carbon (TOC) and selected organic contaminants in sediments of 17 sites sampled in Wellington Harbour in 2006. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Regional Council Environmental Response Criteria (ARC ERC; ARC 2004). Values in amber exceed the ANZECC ISQG-Low or ARC ERC amber threshold and values in red exceed the ANZECC ISQG-Low and ARC ERC red threshold.**

Analyte	Fraction	ANZECC		ARC ERC		WH6		WH7		WH8		WH9		WH10	
	analysed	ISQG-Low	ISQG-High	amber	red	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.
TOC (%)	< 500 µm					1.38	0.6	1.31	2.4	1.36	1.9	1.50	1.5	1.67	1.2
Organics (µg/kg):															
Fluorene	< 500 µm					5.5	3.4	4.8	4.9	4.72	6.6	6.92	8.8	8.64	6.6
Phenanthrene	< 500 µm					47.4	3.2	38.6	6.0	35.8	5.4	65.4	15.8	88.6	5.3
Benzo(a)anthracene	< 500 µm					48.6	4.7	37.6	4.0	36.4	4.6	65.6	9.6	99.2	8.6
Total PAH[1,2]	< 500 µm					736	3.8	585	2.8	567	4.4	993	9.2	1354	2.4
Total HMW PAH[1,2]	< 500 µm					384	4.5	301	9.6	289	4.5	526	10.7	729	2.7
Hexachlorobenzene	< 500 µm					< 0.2		< 0.2		< 0.2		< 0.2		< 0.2	
Total DDT[2,3]	< 500 µm					3.2	19.1	2.9	12.8	2.4	15.8	3.0	8.0	3.6	9.4
Fluorene	at 1% TOC[4]	19	540			4	3.4	4	6.2	3	6.7	5	8.0	5	6.3
Phenanthrene	at 1% TOC	240	1,500			34	3.0	30	7.2	26	5.0	43	15.2	53	5.6
Benzo(a)anthracene	at 1% TOC	261	1,600			35	5.1	29	5.1	27	4.1	44	8.7	59	9.1
Total PAH	at 1% TOC	4,000	45,000			533	4.0	448	4.7	417	4.6	660	8.4	809	3.4
Total HMW PAH	at 1% TOC	1,700	9,600	660	1,700	278	4.7	230	5.1	213	4.4	350	9.8	435	3.5
Hexachlorobenzene	at 1% TOC					< 0.2		< 0.2		< 0.2		< 0.2		< 0.2	
Total DDT	at 1% TOC	1.6	46		3.9	2.3	19.1	2.2	12.6	1.8	14.9	2.0	7.5	2.1	9.4

[1] Polycyclic aromatic hydrocarbons have been summarised as "Total PAH" (all the PAH compounds analysed), and as "Total High Molecular Weight PAH", which is the sum of the concentrations of chrysene, fluoranthene, pyrene, benzo[a]anthracene, benzo[a]pyrene, and dibenzo[a,h]anthracene. This is the total used for the ANZECC (2000) sediment quality guidelines and ARC ERC (ARC 2004). All the PAH compounds analysed are listed in Appendix 2.

[2] For the purpose of calculating Total PAH, Total HMW PAH, and Total DDT, the concentration of any individual compound reported at "less than detection limit" has been replaced by a value one half of the detection limit.

[3] DDT and related compounds have been summarised as "Total DDT", which is the sum of the concentrations of 2,4'-DDE, 2,4'-DDD, 2,4'-DDT, 4,4'-DDE, 4,4'-DDD, and 4,4'-DDT.

[4] This TOC "normalisation" is used in the ANZECC sediment quality guidelines and ARC ERC for comparing sediments with different TOC content.

Table 4.2 *continued*: **Summary of concentrations and variability (coefficient of variation [cv, %], n = 5) of total organic carbon (TOC) and selected organic contaminants in sediments of 17 sites sampled in Wellington Harbour in 2006. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Regional Council Environmental Response Criteria (ARC ERC; ARC 2004). Values in amber exceed the ANZECC ISQG-Low or ARC ERC amber threshold and values in red exceed the ANZECC ISQG-Low and ARC ERC red threshold.**

Analyte	Fraction	ANZECC		ARC ERC		WH11		WH12		WH13		WH14		WH15	
	analysed	ISQG-Low	ISQG-High	amber	red	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.	mean	c.v.
TOC (%)	< 500 µm					1.72	0.5	1.61	0.6	1.83	0.5	2.16	1.3	2.17	1.2
Organics (µg/kg):															
Fluorene	< 500 µm					8.68	5.4	5.6	3.6	5.92	3.2	6.74	6.7	5.14	5.6
Phenanthrene	< 500 µm					90	7.2	54	2.9	51.2	2.9	56.8	7.0	34.6	3.3
Benzo(a)anthracene	< 500 µm					104.4	7.8	61	2.8	55	8.7	49.8	3.9	23.4	11.1
Total PAH[1,2]	< 500 µm					1,338	3.7	787	0.4	712	3.9	655	3.6	364	5.0
Total HMW PAH[1,2]	< 500 µm					726	5.6	421	1.0	381	4.0	358	3.8	186	7.1
Hexachlorobenzene	< 500 µm					< 0.2		< 0.2		< 0.2		< 0.2		< 0.2	
Total DDT[2,3]	< 500 µm					4.0	11.5	2.8	17.3	3.3	4.3	5.1	18.5	3.8	9.1
Fluorene	at 1% TOC[4]	19	540			5	5.4	3	3.2	3	3.3	3	7.8	2	6.1
Phenanthrene	at 1% TOC	240	1,500			52	7.3	34	3.0	28	2.7	26	8.1	16	3.2
Benzo(a)anthracene	at 1% TOC	261	1,600			61	7.6	38	2.3	30	8.6	23	5.2	11	11.0
Total PAH	at 1% TOC	4,000	45,000			777	3.5	490	0.7	389	3.8	303	4.9	168	4.8
Total HMW PAH	at 1% TOC	1,700	9,600	660	1,700	421	5.4	262	1.2	208	3.9	166	5.1	86	7.0
Hexachlorobenzene	at 1% TOC					< 0.2		< 0.2		< 0.2		< 0.2		< 0.2	
Total DDT	at 1% TOC	1.6	46		3.9	2.3	11.5	1.7	17.5	1.8	4.3	2.4	19.6	1.8	9.6

[1] Polycyclic aromatic hydrocarbons have been summarised as "Total PAH" (all the PAH compounds analysed), and as "Total High Molecular Weight PAH", which is the sum of the concentrations of chrysene, fluoranthene, pyrene, benzo[a]anthracene, benzo[a]pyrene, and dibenzo[a,h]anthracene. This is the total used for the ANZECC (2000) sediment quality guidelines and ARC ERC (ARC 2004). All the PAH compounds analysed are listed in Appendix 2.

[2] For the purpose of calculating Total PAH, Total HMW PAH, and Total DDT, the concentration of any individual compound reported at "less than detection limit" has been replaced by a value one half of the detection limit.

[3] DDT and related compounds have been summarised as "Total DDT", which is the sum of the concentrations of 2,4'-DDE, 2,4'-DDD, 2,4'-DDT, 4,4'-DDE, 4,4'-DDD, and 4,4'-DDT.

[4] This TOC "normalisation" is used in the ANZECC sediment quality guidelines and ARC ERC for comparing sediments with different TOC content.

Table 4.2 *continued*: **Summary of concentrations and variability (coefficient of variation [cv, %], n = 5) of total organic carbon (TOC) and selected organic contaminants in sediments of 17 sites sampled in Wellington Harbour in 2006. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Regional Council Environmental Response Criteria (ARC ERC; ARC 2004). Values in amber exceed the ANZECC ISQG-Low or ARC ERC amber threshold and values in red exceed the ANZECC ISQG-Low and ARC ERC red threshold.**

Analyte	Fraction	ANZECC		ARC ERC		WH16		WH17	
	analysed	ISQG-Low	ISQG-High	amber	red	mean	c.v.	mean	c.v.
TOC (%)	< 500 µm					1.53	1.3	1.21	2.8
Organics (µg/kg):									
Fluorene	< 500 µm					5.32	3.1	3.58	3.1
Phenanthrene	< 500 µm					38.8	3.8	30.8	4.2
Benzo(a)anthracene	< 500 µm					37.8	24.1	30.2	2.8
Total PAH[1,2]	< 500 µm					534	9.5	442	3.0
Total HMW PAH[1,2]	< 500 µm					278	12.4	230	3.1
Hexachlorobenzene	< 500 µm					< 0.2		< 0.2	
Total DDT[2,3]	< 500 µm					2.3	3.1	1.8	2.5
Fluorene	at 1% TOC[4]	19	540			3	4.0	3	5.2
Phenanthrene	at 1% TOC	240	1,500			25	2.9	25	5.4
Benzo(a)anthracene	at 1% TOC	261	1,600			25	24.5	25	5.5
Total PAH	at 1% TOC	4,000	45,000			349	9.8	365	5.5
Total HMW PAH	at 1% TOC	1,700	9,600	660	1,700	181	12.7	190	5.6
Hexachlorobenzene	at 1% TOC					< 0.2		< 0.2	
Total DDT	at 1% TOC	1.6	46		3.9	1.5	3.6	1.5	4.9

[1] Polycyclic aromatic hydrocarbons have been summarised as "Total PAH" (all the PAH compounds analysed), and as "Total High Molecular Weight PAH", which is the sum of the concentrations of chrysene, fluoranthene, pyrene, benzo[a]anthracene, benzo[a]pyrene, and dibenzo[a,h]anthracene. This is the total used for the ANZECC (2000) sediment quality guidelines and ARC ERC (ARC 2004). All the PAH compounds analysed are listed in Appendix 2.

[2] For the purpose of calculating Total PAH, Total HMW PAH, and Total DDT, the concentration of any individual compound reported at "less than detection limit" has been replaced by a value one half of the detection limit.

[3] DDT and related compounds have been summarised as "Total DDT", which is the sum of the concentrations of 2,4'-DDE, 2,4'-DDD, 2,4'-DDT, 4,4'-DDE, 4,4'-DDD, and 4,4'-DDT.

[4] This TOC "normalisation" is used in the ANZECC sediment quality guidelines and ARC ERC for comparing sediments with different TOC content.

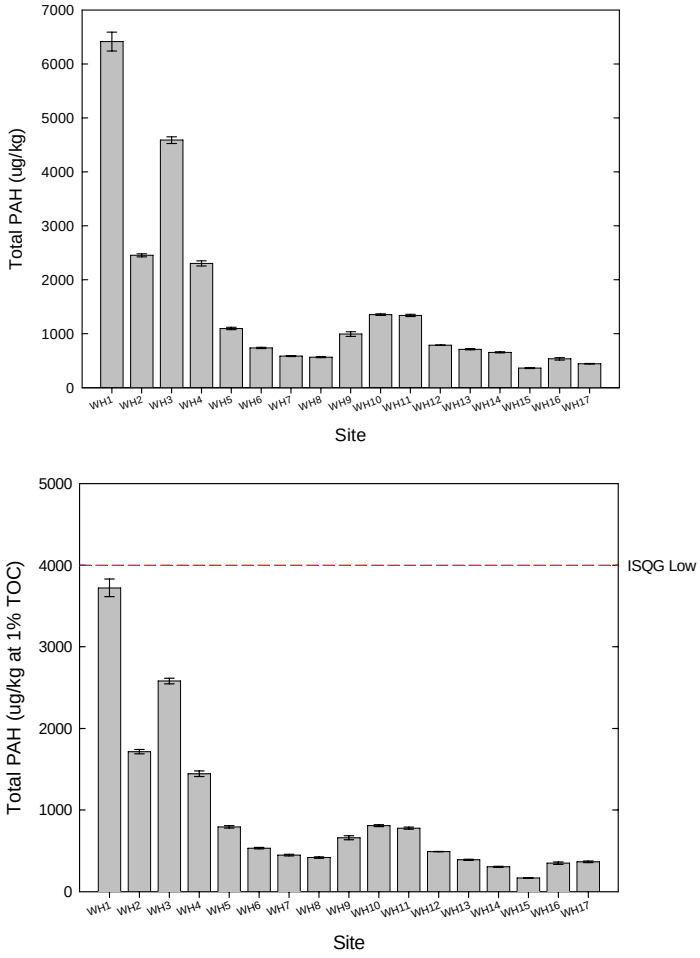

Figure 4.6: Mean concentrations of Total PAH and TOC-normalised Total PAH in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of five composite samples from each site. The concentrations include "less than detection limit" values as a value one half of the detection limit. Error bars are ± 1 standard error of mean.

TOC-normalised[12] mean Total PAH concentrations, which ranged from 168–3,722 µg/kg, were below the sediment quality guidelines in the sediments of all sites. TOC-normalised mean Total HMW PAH concentrations (Figure 4.7), however, exceeded both the ARC ERC amber threshold and the ANZECC ISQG-Low trigger value in the sediments of site WH1, and the ARC ERC amber threshold in the sediments of sites WH2 (northern Evans Bay), WH3 and WH4 (≈ 0.7 km NW of Pt Jerningham).

TOC-normalised mean concentrations for three individual PAH compounds – fluorene, phenanthrene, and benzo[a]anthracene – exceeded their respective ANZECC ISQG-Low trigger values in the sediments of site WH1. The other 13 PAH compounds tested were below sediment quality guidelines at all sites.

[12] TOC-normalisation gives a concentration equivalent to that which would be present in a sediment of 1% TOC content, assuming the concentration of the organic contaminant is correlated with TOC content. This approach has been adopted in the ANZECC sediment quality guidelines (ANZECC 2000) and ARC Environmental Response Criteria (ARC 2004) to allow better comparisons of potential toxicity between sites with different sediment TOC content, which for sites in the 2006 Wellington Harbour survey ranges between 1.2 and 2.2%.

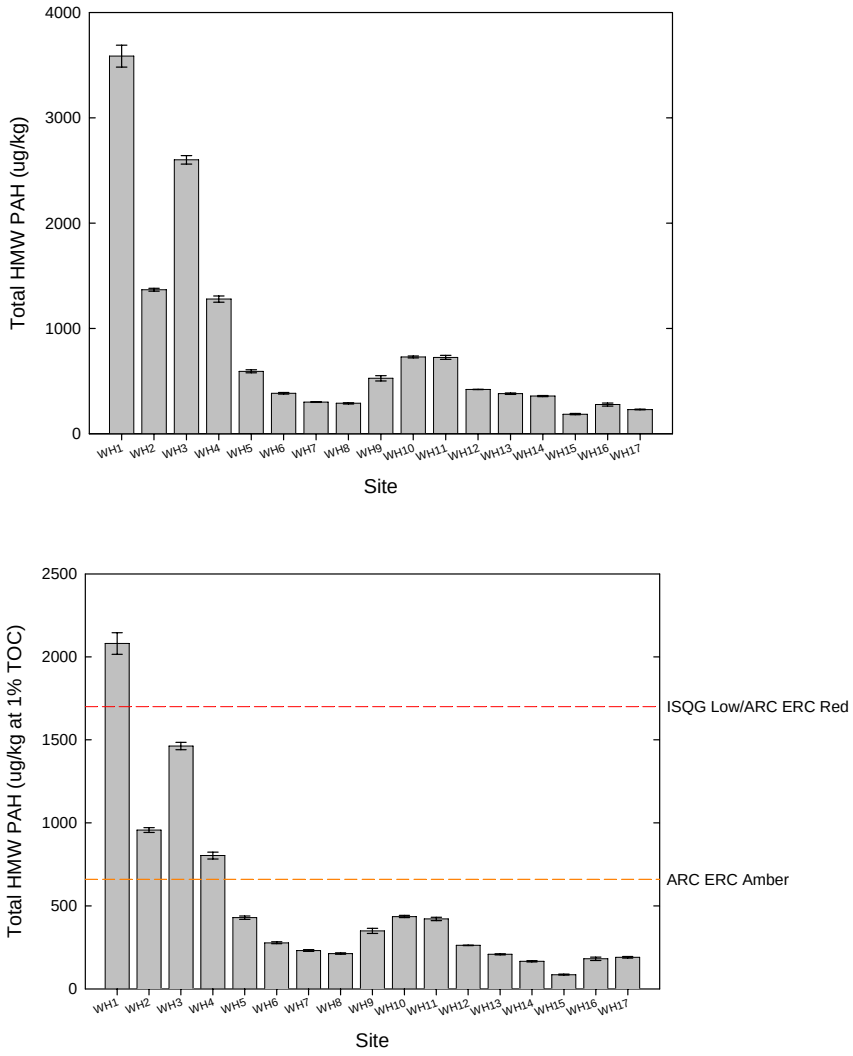

Figure 4.7: Mean concentrations of Total High Molecular Weight PAH and TOC-normalised Total HMW PAH in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of five composite samples from each site. The concentrations include "less than detection limit" values as a value one half of the detection limit. Error bars are ± 1 standard error of mean.

4.1.7 Organochlorine pesticides

Of the 22 organochlorine pesticides analysed, only DDT, DDE, and DDD were consistently found above detection limits in the sediments of all sites. Mean Total DDT[13] concentrations had a range of 1.8–14.2 µg/kg (including concentrations below detection limit at a value one half of the D.L.) (Figure 4.8; Table 4.2). TOC-normalised mean Total DDT concentrations were above the ARC ERC red threshold in the sediments of sites WH1 (southern Evans Bay) and WH3 (Lambton Basin entrance), and above the ISQG-Low trigger value at all sites except WH16 and WH17.

[13] For an explanation of the term "Total DDT" refer to the notes under Table 4.2.

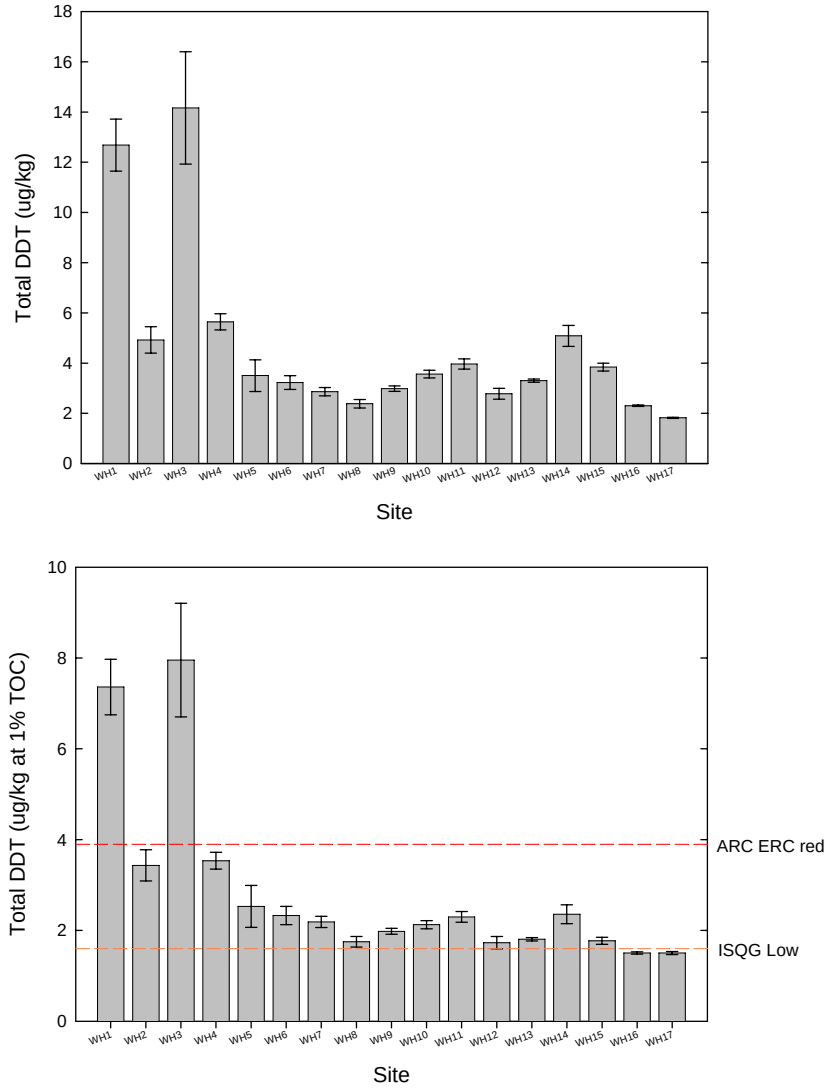

Figure 4.8: Mean concentrations of Total DDT and TOC-normalised Total DDT in sediments of 17 sites sampled in Wellington Harbour in 2006, based on < 500 µm fraction of five composite samples from each site. The concentrations include "less than detection limit" values as a value one half of the detection limit. Error bars are ± 1 standard error of mean.

Variability in Total DDT concentrations was low at nine sites (c.v. 2.5–12.8%) and moderate or moderately high at eight sites (c.v. 15.8–40.5%).

DDT was usually the dominant constituent at sites adjacent to Wellington City (Figure 4.9), with the proportion of DDT decreasing progressively away from the city to be scarcely higher than the other constituents at site WH14 (≈ 0.65 km SW of Petone Wharf), and replaced as the dominant constituent by DDE at sites WH13, WH15, WH16 and WH17, the latter three located on the eastern side of the harbour.

Hexachlorobenzene (HCB) was present in the sediments of site WH3 at a mean concentration of 0.6 µg/kg, but was below the detection limit (0.2 µg/kg) at other sites. There are no recommended trigger values for HCB in the ANZECC (2000) sediment quality guidelines.

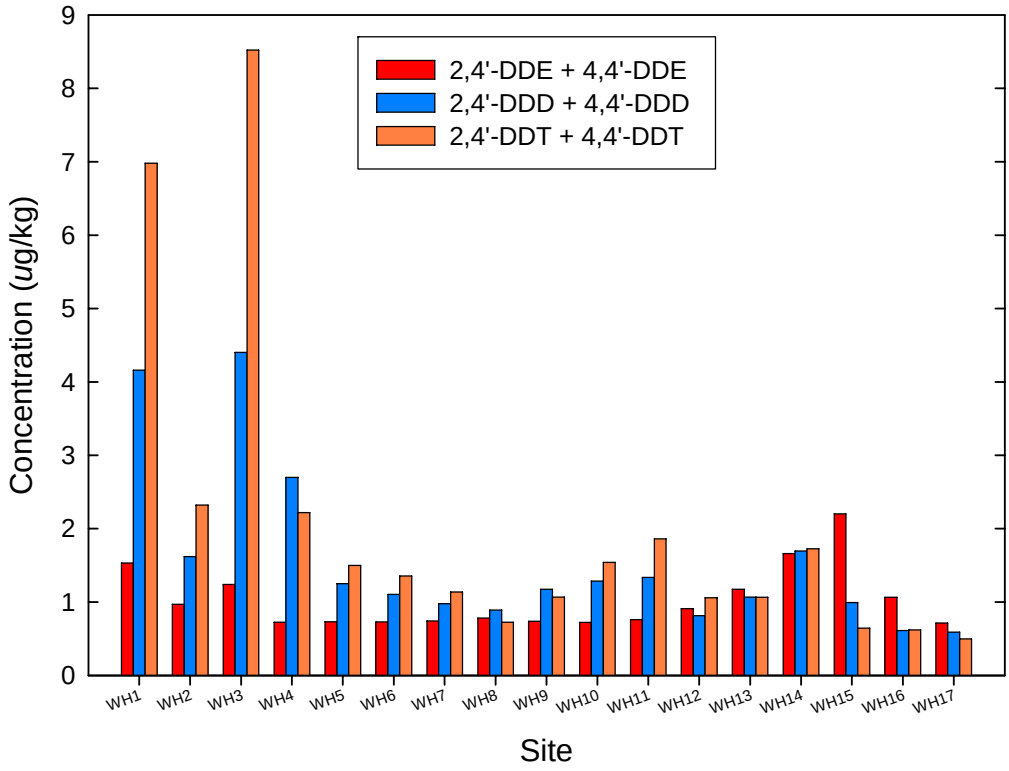

Figure 4.9: Total DDT composition in sediments of 17 sites sampled in Wellington Harbour in 2006. Values are means from each site (n = 5) and include "less than detection limit" values as a value one half of the detection limit.

4.2 Benthic ecology

4.2.1 Sediment particle size distribution

A summary of the particle size results from the benthic ecology collection areas of the 17 sites sampled in Wellington Harbour is presented in Table 4.3. The < 500 µm fraction of the near-surface sediment at the majority of the sites was either sandy mud, slightly sandy mud, or mud (< 63 µm fraction 70–100%). However, at site WH1 (southern Evans Bay) the < 500 µm fraction of the near-surface sediment was muddy sand (< 63 µm fraction 34%), and at site WH17 (≈ 1.6 km NNW of Makaro/Ward Island) it was very sandy mud (< 63 µm fraction 54%). At all sites the near-surface sediment also contained a minor gravel component made up primarily of shell fragments. Sediment textural characteristics appeared to be quite uniform to at least the depth sampled by the cores (*see* Appendix 4).

At nine of the sites the values for some of the sediment particle size classes in the single (composite) sample from the benthic ecology collection area were outside the range of variation recorded in the five (composite) samples from the adjoining sediment chemistry collection area. Most of the deviations were small (1–7%), but at site WH1 there was a deviation of 12% for very fine sand.

Table 4.3: Summary of particle size results from the benthic ecology collection areas of 17 sites sampled in Wellington Harbour in 2006, based on a single composite sample from each site.

Site	Median (µm)	Mean (µm)	< 63 µm (%)	63 – 125 µm (%)	125 –250 µm (%)	250 –500 µm (%)	Description of < 500 µm fraction
WH1	94	97	34	32	34	0	Muddy sand
WH2	39	41	76	24	0	0	Sandy mud
WH3	38	45	70	30	0	0	Sandy mud
WH4	23	31	89	11	0	0	Sandy mud
WH5	32	35	86	14	0	0	Sandy mud
WH6	25	30	94	6	0	0	Slightly sandy mud
WH7	34	35	89	11	0	0	Sandy mud
WH8	28	33	90	10	0	0	Sandy mud
WH9	22	27	98	2	0	0	Slightly sandy mud
WH10	21	27	96	4	0	0	Slightly sandy mud
WH11	15	18	100	0	0	0	Mud
WH12	17	22	98	2	0	0	Slightly sandy mud
WH13	23	28	96	4	0	0	Slightly sandy mud
WH14	29	32	92	8	0	0	Slightly sandy mud
WH15	43	45	73	27	0	0	Sandy mud
WH16	32	35	87	13	0	0	Sandy mud
WH17	59	61	54	43	3	0	Very sandy mud

4.2.2 Number of species

A total of 101 species were identified in the samples collected during the survey in Wellington Harbour in November 2006, the fauna being composed predominantly of species of polychaetes, crustaceans, bivalve molluscs, and nemerteans (Appendix 5). The number of species recorded at the individual sites ranged from 37 at site WH6 to 57 at site WH3, with the remaining sites all having between 42 and 51 species (Figure 4.10; Table 4.3). Seven of the eight sites with > 46 species (the median) were located either in Evans Bay or along the western and northern edges of the central basin; eight of the nine sites with ≤ 46 species were located in the more "offshore" portions of the central basin.

The mean number of species per sample showed relatively little variation between the sites, with the majority having a mean in the range of 21–25 species per sample (Figure 4.10). The exceptions were sites WH10 (≈ 0.5 km SSE of Ngauranga stream mouth) and WH15 (≈ 1.1 km SW of Seaview), which had means of 27 and 19 species per sample respectively.

One-way ANOVA to examine the effect of location on the mean number of species per sample gave a statistically significant result (p = 0.019, with n = 134 as two outliers were removed). The Tukey-Kramer HSD pairwise mean comparisons indicated this result was solely due to the difference in the mean number of species per sample between sites WH10 and WH15 (p = 0.005).

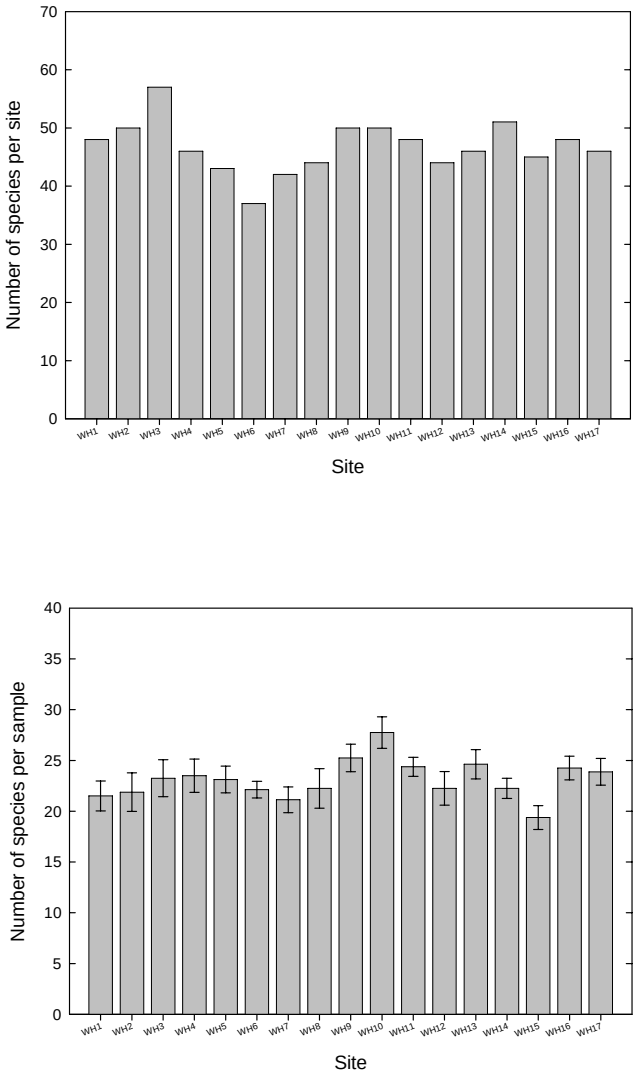

Figure 4.10: Number of species per site and mean number of species per sample at 17 sites in Wellington Harbour in November 2006. Error bars are ± 1 standard error of the mean (n = 8).

4.2.3 Number of individuals

A total of 14,562 individuals were counted in the Wellington Harbour samples. Polychaetes were the most abundant group (38.9% of all individuals), followed by sipunculids (21.5%), bivalve molluscs (14.5%) and tanaidaceans (8.3%). The most abundant polychaetes were *Cossura consimilis* (18.7% of all polychaetes), then Paraonidae sp.#1 (15.8%), *Labiosthenolepis laevis* (12.2%) and Cirratulidae sp.#1 (9.8 %). Sipunculida sp.#1 accounted for 99.8% of all sipunculids and Sipunculida sp.#2 for just 0.2%. The most abundant bivalve was *Theora lubrica* (50.8% of all bivalves), then *Arthritica* sp.#1 (24.1%) and *Nucula nitidula* (14.5%). Tanaidacea sp.#1 was the only tanaidacean recorded.

The mean number of individuals per sample showed some variation between the sites, although the majority had a mean in the range of 73–115 individuals per sample (Figure 4.11). The exceptions were sites WH3 (Lambton Basin entrance), WH10 (≈ 0.5 km SSE of Ngauranga stream mouth) and WH13

(≈ 1.25 km S of Petone Wharf), which had means of 133, 177, and 163 individuals per sample respectively.

One-way ANOVA to examine the effect of location on the mean number of individuals per sample gave a highly significant result (p = < 0.0005, with double square root transformation and n = 133 as three outliers were removed). The Tukey-Kramer HSD pairwise mean comparisons indicated this result was due both to differences in the mean number of individuals per sample between site WH10 and 11 other sites (p = < 0.0005–0.042) and to differences in the mean number of individuals per sample between site WH13 and sites WH2, WH8 and WH17 (p = 0.001–0.027).

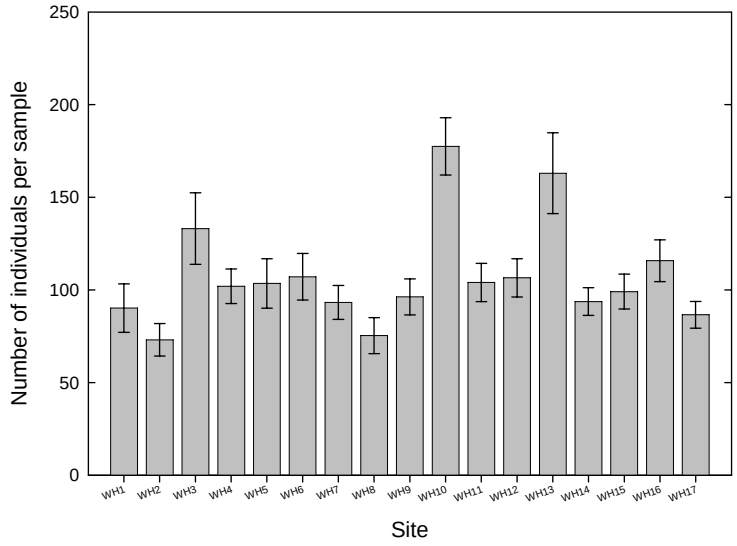

Figure 4.11: Mean number of individuals per sample at 17 sites in Wellington Harbour in November 2006. Error bars are ± 1 standard error of the mean (n = 8).

4.2.4 Shannon diversity index

The Shannon diversity index utilises information on the number of species and the number of individuals at a site to produce a single measure of "diversity". High values of the index nominally indicate a community made up of many species with relatively few individuals in each, while low values indicate a community made up of few species each with many individuals. Communities in the first category are regarded as being indicative of more stable environmental conditions than those in the second category.

The mean Shannon diversity index showed little variation between the sites, with the majority having a mean in the range of 2.5–2.8 (Figure 4.12). The exceptions were sites WH3 (Lambton Basin entrance) and WH15 (≈ 1.1 km SW of Seaview), which had means of 2.3 and 2.2 respectively. Mean values of the index ranged from 73–88% of their theoretical maximum (H'_{max} = ln[no. of species]).

One-way ANOVA to examine the effect of location on the mean Shannon diversity index gave a highly significant result (p = < 0.0005, with n =134 as two outliers were removed). The Tukey-Kramer HSD pairwise mean comparisons indicated this result was due both to differences in the mean Shannon diversity index between site WH3 and sites WH8, WH11 and WH17 (p = 0.003–0.027), and differences in the mean Shannon diversity index between site WH15 and sites WH6, WH8, WH9, WH11, WH12, WH14 and WH17 (p = 0.001–0.031).

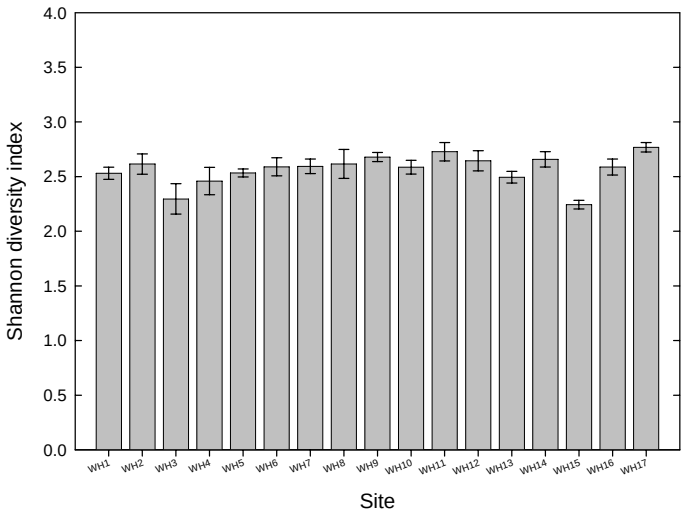

Figure 4.12: Mean Shannon diversity index at 17 sites in Wellington Harbour in November 2006. Error bars are ± 1 standard error of the mean (n = 8).

4.2.5 Numerical dominance hierarchy plots

Most of the individuals (77.28%) belonged to one of 12 species: Sipunculida sp.#1 (21.42%), Tanaidacea sp.#1 (8.33%), *Theora lubrica* (7.38%), *Cossura consimilis* (7.28%), Paraonidae sp.#1 (6.13%), Phoxocephalidae sp.#1 (5.73%), *Labiosthenolepis laevis* (4.75%), Cirratulidae sp.#1 (3.81%), *Arthritica* sp.#1 (3.50%), *Maldane theodori* (3.32%), *Aglaophamus macroura* (3.25%) and *Amphiura rosea* (2.38%). Although the 12 species were found at every site, their relative abundance varied considerably (Figure 4.13). Sipunculida sp.#1 was the most abundant species at all sites except WH1, WH12 and WH15, where it ranked second to *Theora lubrica*, Tanaidacea sp.#1 and *Cossura consimilis* respectively. Sipunculida sp.#1, *Cossura consimilis* and *Labiosthenolepis laevis* were the only species represented in the ten most abundant species at every site.

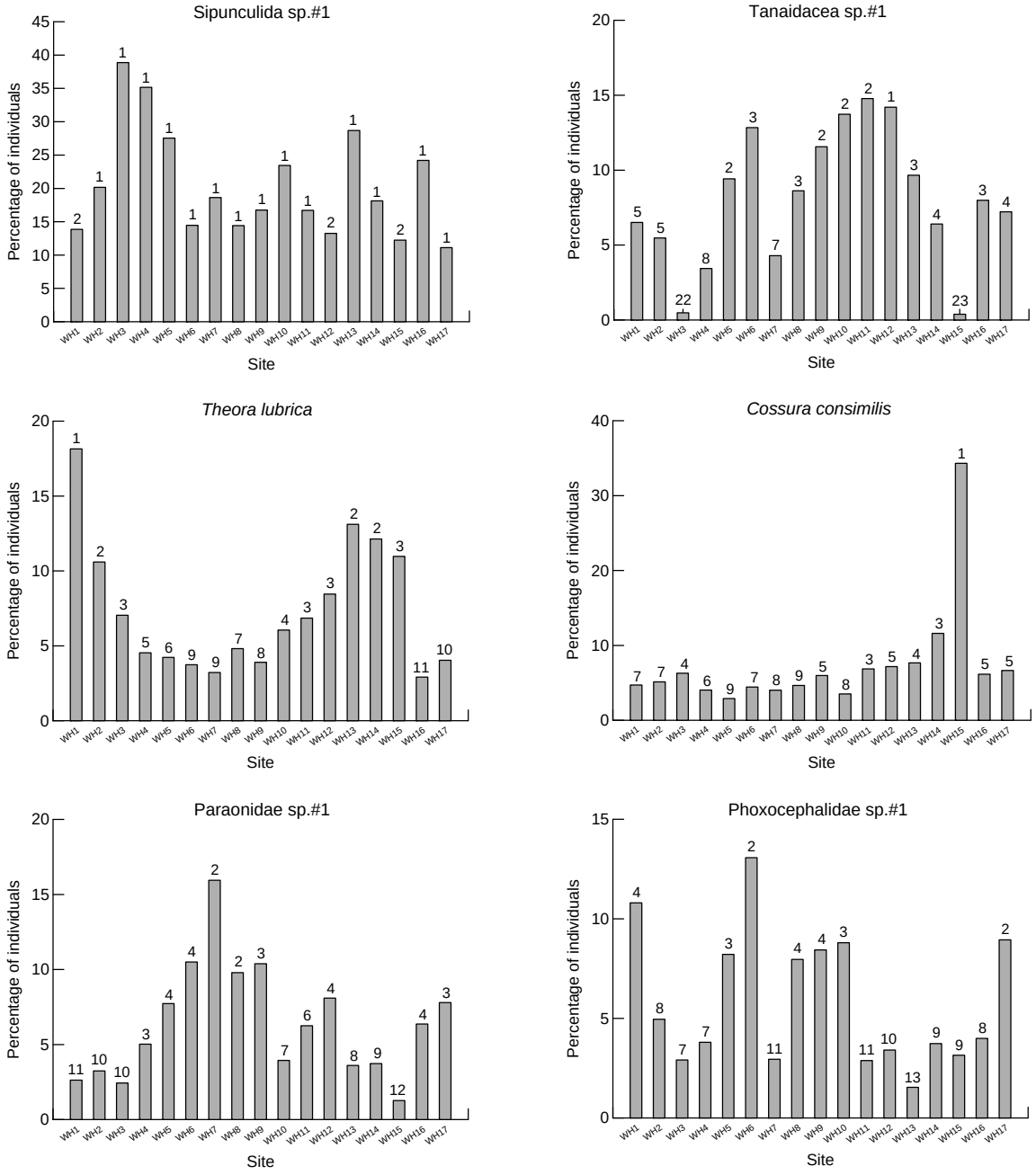

Figure 4.13: Numerical dominance hierarchy plots for the 12 most abundant species collected at 17 sites in Wellington Harbour in 2006. The abundance rank for each species at each site is indicated above the histogram block.

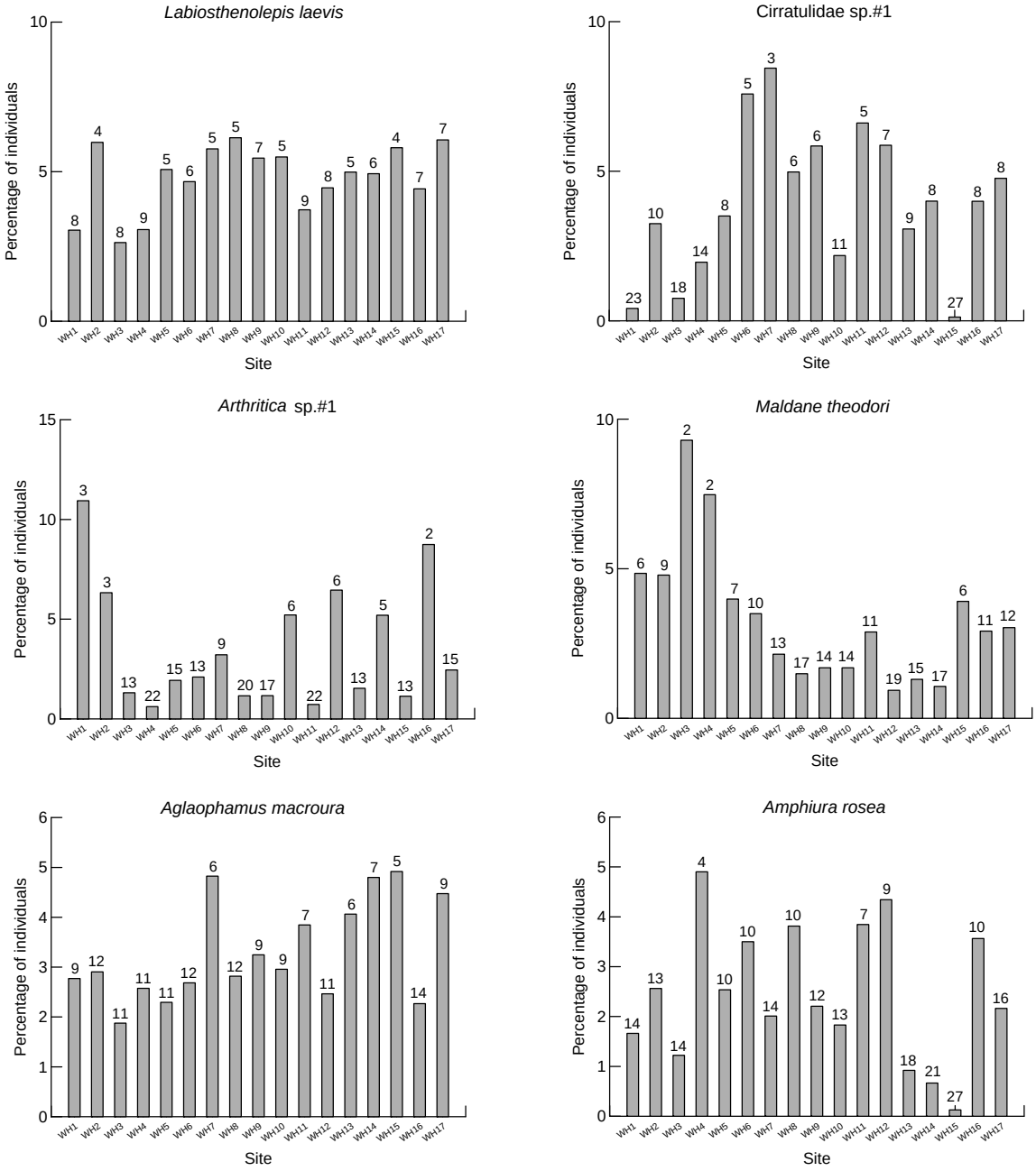

Figure 4.13 *continued*: **Numerical dominance hierarchy plots for the 12 most abundant species collected at 17 sites in Wellington Harbour in 2006. The abundance rank for each species at each site is indicated above the histogram block.**

4.2.6 Rank abundance plots

The rank abundance plots show that the more inequitable distributions of individuals amongst the species occurred at sites WH3, WH4 and WH15, where Sipunculida sp.#1 (WH3, WH4) or *Cossura consimilis* (WH15) accounted for 38.9%, 35.2% and 34.3% of the total number of individuals respectively (Figure 4.14). In contrast, the benthic communities at sites WH8 and WH17 demonstrated more equitable distributions of individuals amongst species, reflecting what appears to be a general trend of increasing equitability with distance from the shore. No site showed a truncation of the rank abundance curve indicating the absence of rare species. The apparent truncation of the curve at site WH15 is the result of few moderately abundant species being present (thereby increasing the slope of the curve) rather than a lack of rare species. The site recorded a total of 45 species (one less than the median for all sites), but 20 of them are represented by only one individual each.

4.2.7 Biomass

The biomass of most of the sites was dominated either by the heart urchin *Echinocardium cordatum*, the bivalve *Dosina zelandica*, the rag-worm *Onuphis aucklandensis*, the bamboo worm *Asychis trifilosa,* or a combination of these species (Table 4.4). The bivalve *Diplodonta globus* was also a major contributor to the biomass at several sites.

4.2.8 Trophic structure

All feeding modes except herbivores were represented in the benthic fauna of the sites. Deposit feeders dominated the benthic community at all 17 sites, but sites WH3 (Lambton Basin entrance), WH4 (≈ 0.7 km NW of Pt Jerningham), WH7 (≈ 1.5 km N of Pt Halswell) and WH15 (≈ 1.1 km SW of Seaview) had higher numbers of individuals in this feeding mode than the majority of the sites (Figure 4.15; Table 4.4). Subsurface deposit feeders were generally more numerous than surface deposit feeders, especially at sites WH3, WH4, and WH15, while at sites WH6, WH7, WH8, WH12, and WH17 surface deposit feeders slightly outnumbered subsurface deposit feeders.

Predators and scavengers accounted for 24–38% of individuals at most sites, but at sites WH3, WH4 and WH15 the proportion in this feeding mode was below 20%. Suspension feeders accounted for 23% of individuals at site WH1 (southern Evans Bay). Elsewhere, suspension feeders comprised 5–15% of individuals at a site.

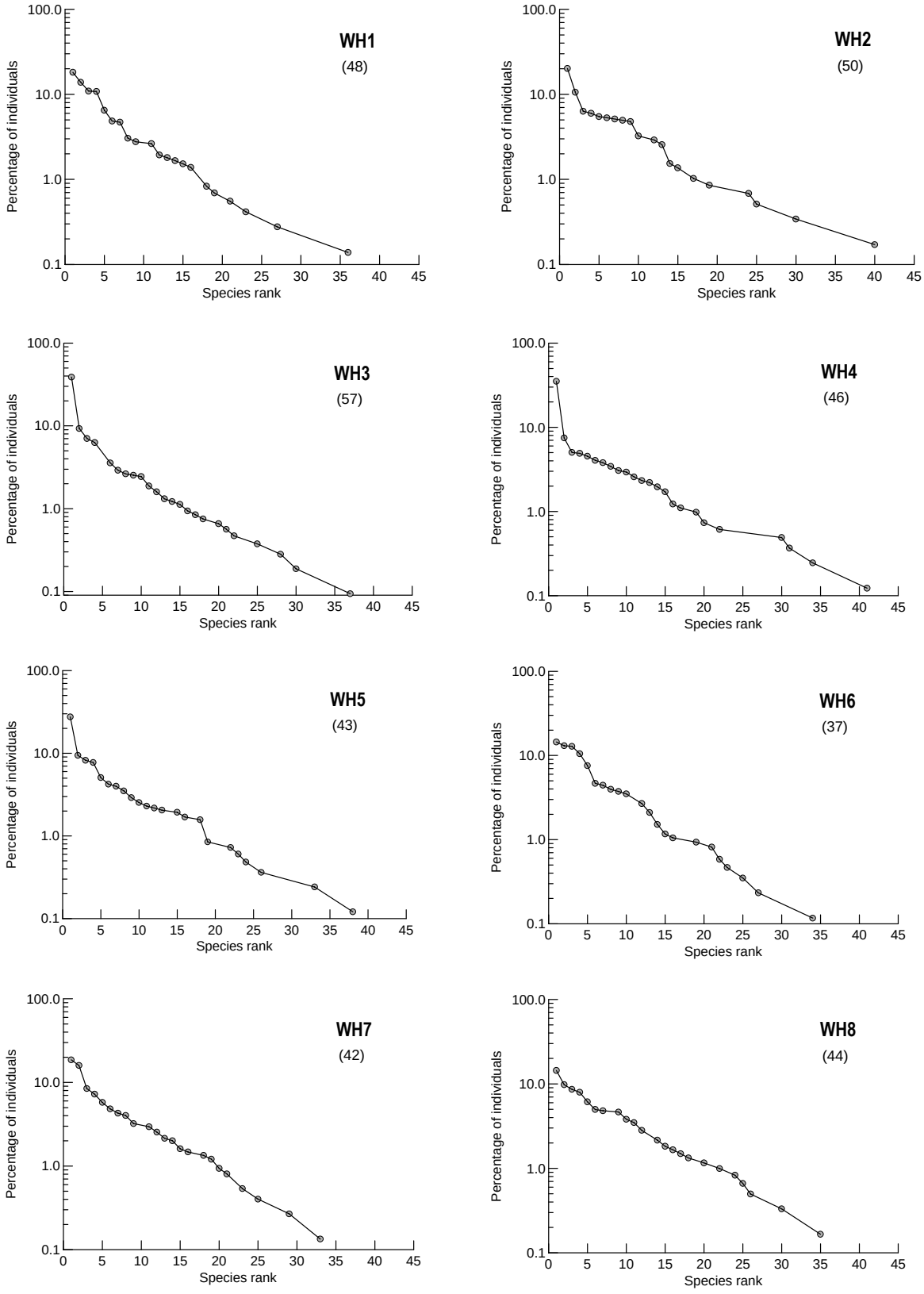

Figure 4.14: Rank abundance plots showing the distribution of individuals amongst species at selected sites in Wellington Harbour in 2006. Where species share ranks only one point is represented on the curve. Numbers in brackets are the total number of species at the site. Note the logarithmic scale on the y-axis.

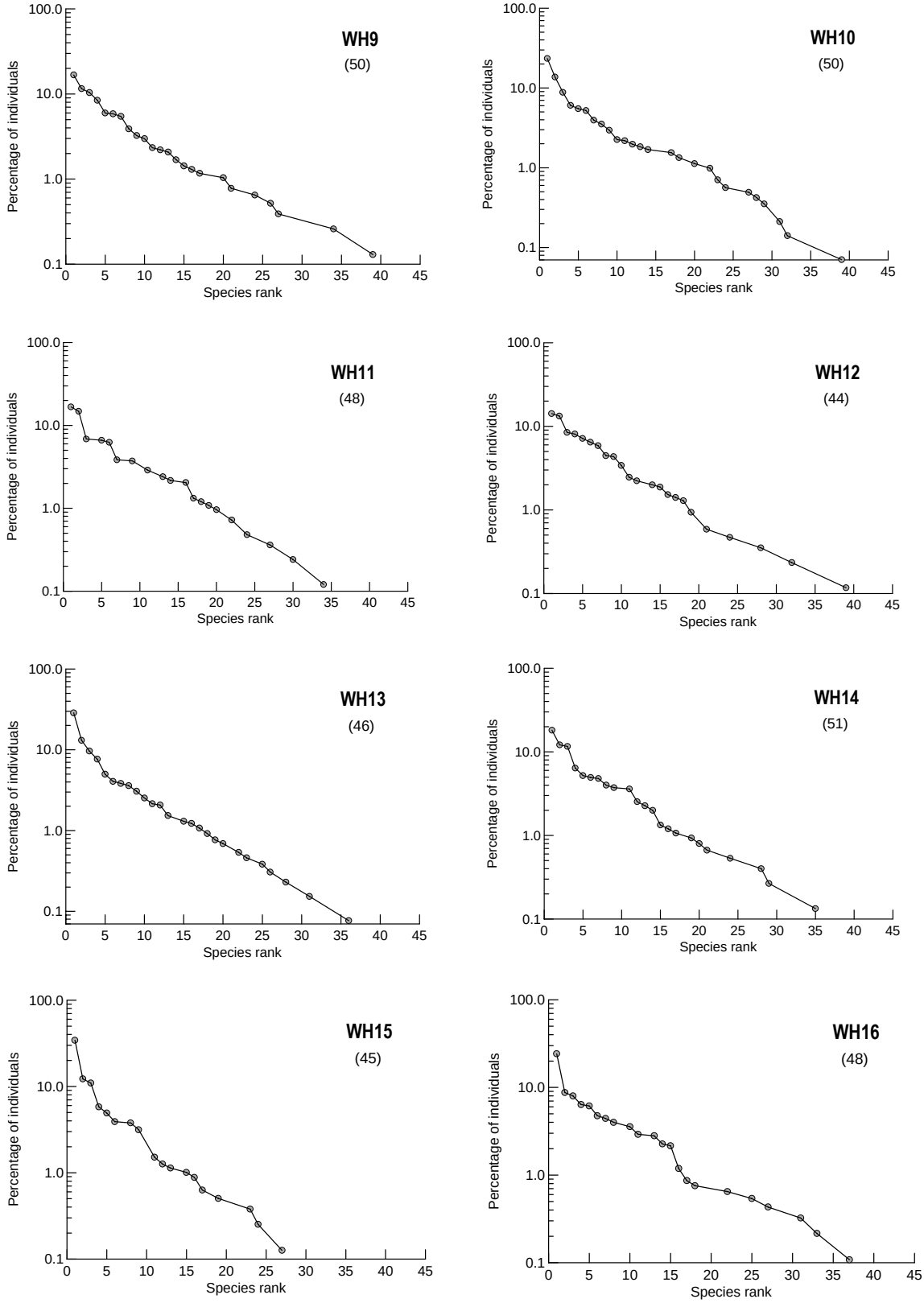

Figure 4.14 *continued*: **Rank abundance plots showing the distribution of individuals amongst species at selected sites in Wellington Harbour in 2006 (the plot for site WH17 has been omitted). Where species share ranks only one point is represented on the curve. Numbers in brackets are the total number of species at the site. Note the logarithmic scale on the y-axis.**

Table 4.4: Summary of features of the subtidal benthos at 17 sites in Wellington Harbour in 2006. For dominant species: Phoxo = Phoxocephalidae, 1 = sp.#1.

Feature	Site						
	WH1	**WH2**	**WH3**	**WH4**	**WH5**	**WH6**	**WH7**
Number of species	48	50	57	46	43	37	42
Estimated total individuals per m^2 [1]	2,888	2,340	4,260	3,264	3,312	3,428	2,984
Dominant species by numbers [2]	*Theora*	Sipunculida 1	Sipunculida 1	Sipunculida 1	Sipunculida 1	Sipunculida 1	Sipunculida 1
	Sipunculida 1	*Theora*	*Maldane*	*Maldane*	Tanaidacea 1	Phoxo 1	Paraonidae 1
	Arthritica	*Arthritica*	*Theora*	Paraonidae 1	Phoxo 1	Tanaidacea 1	Cirratulidae 1
	Phoxo 1	*Labiosthenolepis*		*Amphiura*	Paraonidae 1	Paraonidae 1	*Nucula nitidula*
		Tanaidacea 1					
		Onuphis					
Dominant species by biomass [3]	*Maoricolpus*	*Echinocardium*	*Onuphis*	*Diplodonta*	*Dosina*	*Echinocardium*	*Dosina*
	Echinocardium	*Onuphis*	*Maldane*	*Maldane*	*Diplodonta*	*Thracia*	*Echinocardium*
	Rynkatorpa	*Maldane*	*Asychis trifilosa*	*Asychis trifilosa*	*Echinocardium*	*Amphiura*	*Asychis trifilosa*
Trophic structure: [4]							
Predators/scavengers (%)	28.53	27.86	14.55	19.24	28.62	38.16	23.73
Surface deposit feeders (%)	19.11	21.20	12.21	20.71	21.98	30.11	39.01
Subsurface deposit feeders (%)	27.84	34.36	65.16	53.06	37.80	25.20	29.49
Suspension feeders (%)	23.13	15.04	7.23	5.76	10.51	6.07	7.10
Unknown (%)	1.39	1.54	0.85	1.23	1.09	0.47	0.67

[1] Estimate based on a sample area of 0.03 m^2 and a conversion factor of "mean number of individuals per sample multiplied by 32" (n = 8).

[2] Species are listed in descending order of mean number of individuals per sample, with the sum of the individuals of these species comprising 50–60% of the individuals recorded at the site.

[3] Species are listed in descending order of mean biomass per sample.

[4] For allocation of each species to a feeding mode (or modes) see Appendix 5.

Table 4.4 *continued*: **Summary of features of the subtidal benthos at 17 sites in Wellington Harbour in 2006. For dominant species: Phoxo = Phoxocephalidae, 1 = sp.#1.**

Feature	Site						
	WH8	**WH9**	**WH10**	**WH11**	**WH12**	**WH13**	**WH14**
Number of species	44	50	50	48	44	46	51
Estimated total individuals per m^2 [1]	2,412	3,080	5,680	3,328	3,408	5,216	3,000
Dominant species by numbers [2]	Sipunculida 1	Sipunculida 1	Sipunculida 1	Sipunculida 1	Tanaidacea 1	Sipunculida 1	Sipunculida 1
	Paraonidae 1	Tanaidacea 1	Tanaidacea 1	Tanaidacea 1	Sipunculida 1	*Theora*	*Theora*
	Tanaidacea 1	Paraonidae 1	Phoxo 1	*Cossura*	*Theora*	Tanaidacea 1	*Cossura*
	Phoxo 1	Phoxo 1	*Theora*	*Theora*	Paraonidae 1		Tanaidacea 1
	Labiosthenolepis	*Cossura*		Cirratulidae 1	*Cossura*		*Arthritica*
	Cirratulidae 1						
Dominant species by biomass [3]	*Echinocardium*	*Aphrodita*	*Onuphis*	*Onuphis*	*Echinocardium*	*Pentadactyla*	*Dosina*
	Diplodonta	*Zenatia*	*Asychis trifilosa*	*Dosina*	*Diplodonta*	*Asychis trifilosa*	Stomatopoda 1
	Asychis trifilosa	*Diplodonta*	*Echinocardium*	*Asychis trifilosa*	*Asychis trifilosa*	*Echinocardium*	*Rynkatorpa*
Trophic structure: [4]							
Predators/scavengers (%)	33.67	37.14	36.69	31.01	31.10	25.31	25.33
Surface deposit feeders (%)	29.52	26.75	16.41	28.73	29.34	20.02	22.40
Subsurface deposit feeders (%)	26.04	29.35	33.17	32.57	25.12	42.64	36.13
Suspension feeders (%)	9.95	5.32	10.92	6.25	13.26	11.58	15.20
Unknown (%)	0.83	1.43	2.82	1.44	1.17	0.46	0.93

[1] Estimate based on a sample area of 0.03 m^2 and a conversion factor of "mean number of individuals per sample multiplied by 32" (n = 8).

[2] Species are listed in descending order of mean number of individuals per sample, with the sum of the individuals of these species comprising 50–60% of the individuals recorded at the site.

[3] Species are listed in descending order of mean biomass per sample.

[4] For allocation of each species to a feeding mode (or modes) see Appendix 5.

Table 4.4 *continued*: **Summary of features of the subtidal benthos at 17 sites in Wellington Harbour in 2006. For dominant species: Phoxo = Phoxocephalidae, 1 = sp.#1.**

Feature	Site		
	WH15	**WH16**	**WH17**
Number of species	45	48	46
Estimated total individuals per m^2 [1]	3,172	3,704	2,772
Dominant species by numbers [2]	*Cossura* Sipunculida 1 *Theora*	Sipunculida 1 *Arthritica* Tanaidacea 1 Paraonidae 1 *Cossura*	Sipunculida 1 Phoxo 1 Paraonidae 1 Tanaidacea 1 *Cossura* *Nucula nitidula* *Labiosthenolepis*
Dominant species by biomass [3]	*Dosina* *Echinocardium* *Pentadactyla*	*Echinocardium* *Asychis trifilosa* *Amphiura*	*Asychis trifilosa* *Dosina* *Nucula nitidula*
Trophic structure: [4]			
Predators/scavengers (%)	19.17	27.54	33.04
Surface deposit feeders (%)	14.50	18.79	30.01
Subsurface deposit feeders (%)	54.73	40.28	27.99
Suspension feeders (%)	10.84	12.31	7.94
Unknown (%)	0.76	1.08	1.01

[1] Estimate based on a sample area of 0.03 m^2 and a conversion factor of "mean number of individuals per sample multiplied by 32" (n = 8).

[2] Species are listed in descending order of mean number of individuals per sample, with the sum of the individuals of these species comprising 50–60% of the individuals recorded at the site.

[3] Species are listed in descending order of mean biomass per sample.

[4] For allocation of each species to a feeding mode (or modes) see Appendix 5.

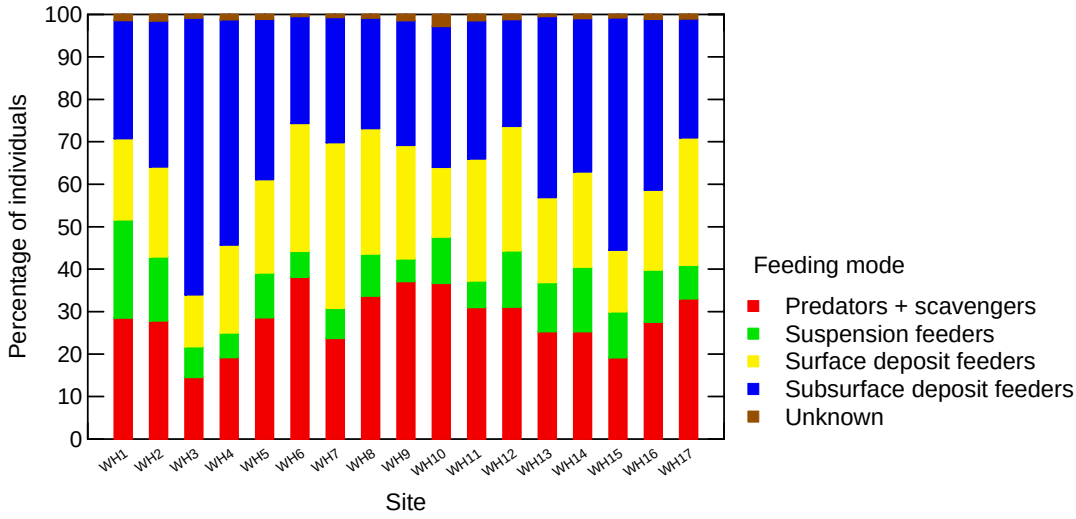

Figure 4.15: Percentage of individuals in each feeding mode at 17 sites in Wellington Harbour in November 2006.

4.2.9 Cluster and MDS analysis of community structure

Both the classification and the ordination of the similarity matrix derived from mean species abundances at each of the 17 sites give essentially the same results: one group of sites and five outliers (Figure 4.16). The group comprises 12 sites – WH2, WH4, WH5, WH6, WH7, WH8, WH9, WH10, WH11,

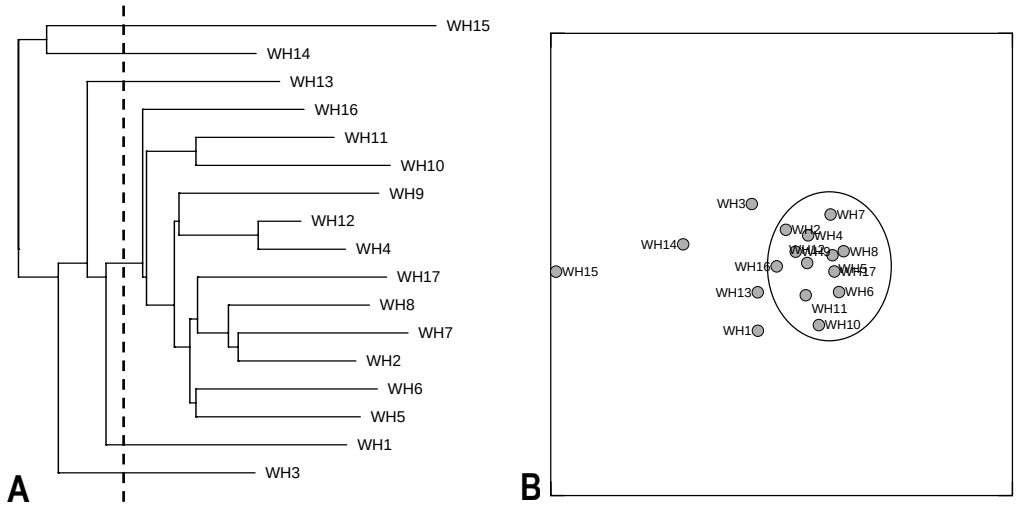

Figure 4.16: (A) Dendrogram showing the classification of 17 sites in Wellington Harbour based on a similarity matrix derived from mean species abundances. Abundances were root-root transformed to normalise the data before comparing the sites using the Bray-Curtis similarity measure, and the dendrogram formed by using additive tree with the minvar option. One group and five outliers are distinguished at an arbitrary distance from the root. (B) Ordination produced by MDS of the same similarity matrix that was used for the dendrogram. Stress = 0.144. The group distinguished on the dendrogram is superimposed by encircling the sites included in it. Axis scales are arbitrary and therefore not shown.

WH12, WH16 and WH17 – most of which are located at least 1.25 km from the shore and in water depths ≥ 19 m. Sites WH10 and WH11, however, are located just 0.5 km from the shore off Ngauranga, but at depths of 20 m, and there is some indication in the analysis that these may represent a sub-group. Sites in the group have sediments of sandy mud or slightly sandy mud except for site WH17, which has very sandy mud. The five outlying sites – WH1, WH3, WH13, WH14 and WH15 – are all located no more than 1.25 km from the shore in water depths up to 19 m. The sediments at these sites are muddy sand (WH1), sandy mud (WH3 and WH15) or slightly sandy mud (WH13 and WH14).

4.2.10 Heart urchin and bivalve populations

The body lengths of the heart urchin and the shell lengths of five species of bivalves were measured to try and establish their population structure at each of the sites. Measurements for each species from individual samples are detailed in Stephenson (2007a).

Echinocardium cordatum (heart urchin)

Echinocardium cordatum was recorded at all 17 sites, with estimated densities ranging from 4 per m^2 at sites WH1, WH3, WH14 and WH17 to 28 per m^2 at site WH16. The majority of individuals had body lengths between 10 and 30 mm, and individuals < 10 mm were found at only three sites (Figure 4.17).

Diplodonta globus

Diplodonta globus was recorded at a total of 9 sites (10 if the record from the sediment chemistry collection area at site WH1 is included), with estimated densities ranging from 4–16 per m^2. The species appeared to be absent in the northernmost portions of the harbour (sites WH13–WH16). All but two individuals had shell lengths > 15 mm (Figure 4.17).

Dosina zelandica

Dosina zelandica was recorded at a total of 11 sites, with estimated densities ranging from 4–16 per m^2 except at site WH15 (≈ 1.1 km SW of Seaview), where the estimated density was 36 per m^2. The majority of individuals had shell lengths > 10 mm (Figure 4.17).

Nucula hartvigiana (nut shell)

Nucula hartvigiana was recorded at all sites except WH14 and WH15, with estimated densities ranging from 4 per m^2 at sites WH1 and WH3 to 56 per m^2 at site WH17. In contrast to the other sites at which *N. hartvigiana* occurred, the populations at sites WH1 and WH3 not only had low densities, but also lacked any individuals with shell lengths < 4 mm (Figure 4.18).

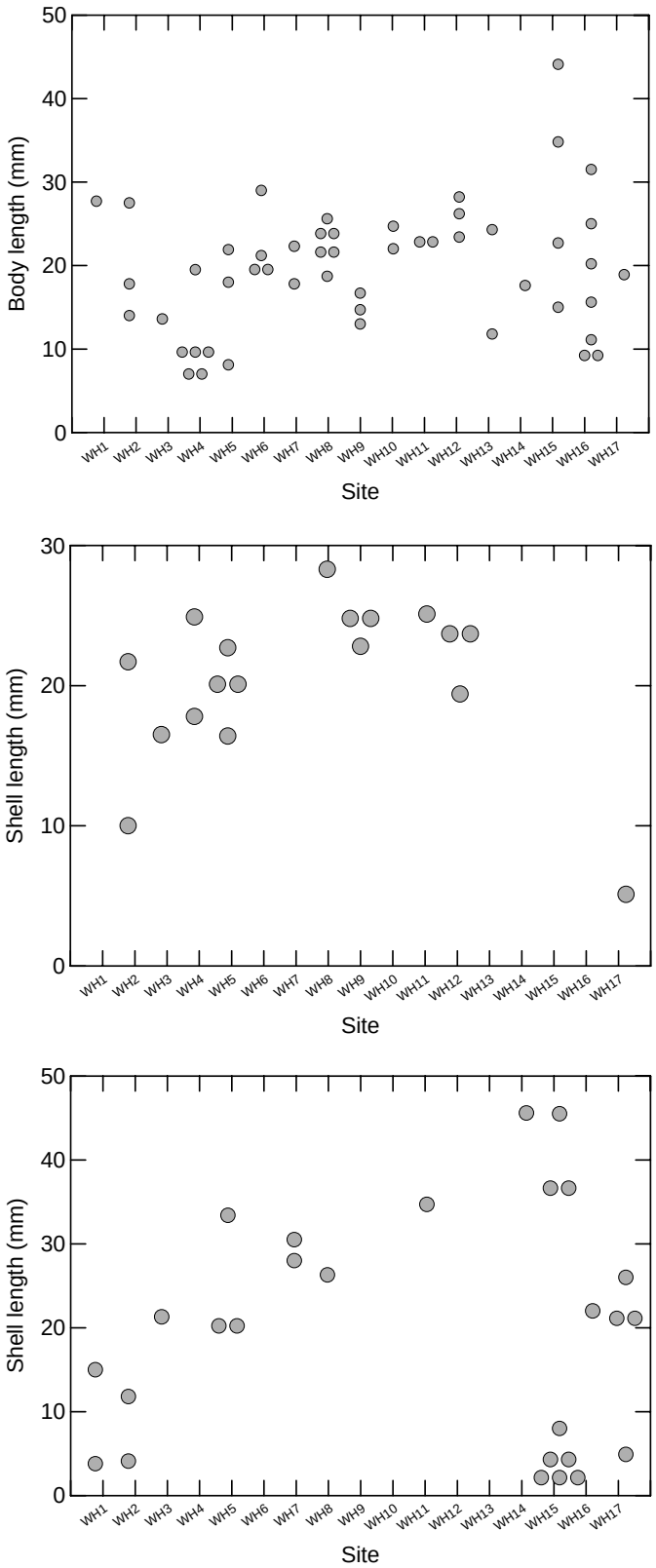

Figure 4.17: Size distribution of (top) *Echinocardium cordatum*, **(middle)** *Diplodonta globus* **and (bottom)** *Dosina zelandica* **at each of the 17 Wellington Harbour sites in November 2006.**

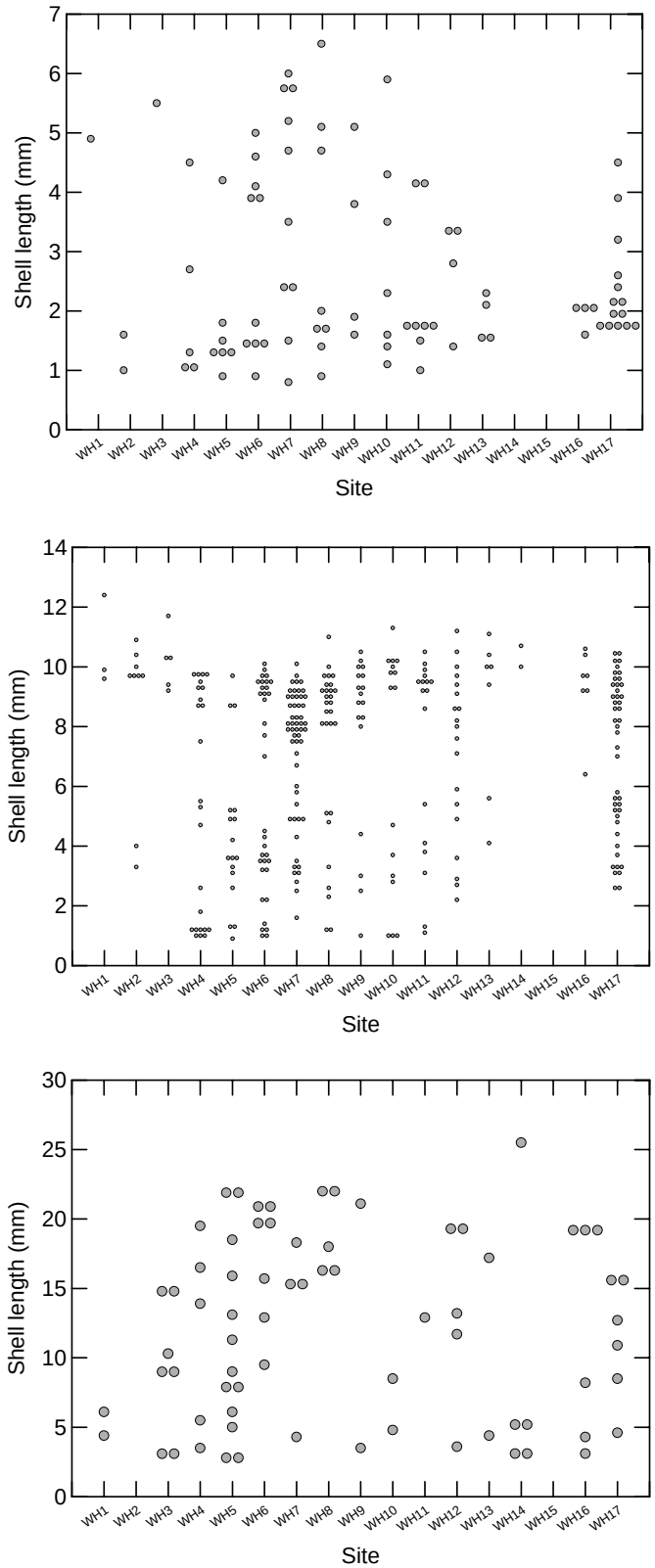

Figure 4.18: Size distribution of (top) *Nucula hartvigiana*, **(middle)** *Nucula nitidula* **and (bottom)** *Thracia vitrea* **at each of the 17 Wellington Harbour sites in November 2006.**

Nucula nitidula

N. nitidula was recorded at all sites except WH15, with estimated densities ranging from 8 per m^2 at site WH14 to 216 per m^2 at site WH7. In contrast to the other sites at which *N. nitidula* occurred, the populations at sites WH1, WH3, WH14 and WH16 not only had low densities, but also lacked any individuals with shell lengths < 6 mm (Figure 4.18).

Thracia vitrea

Thracia vitrea was recorded at all sites except WH2 and WH15, with estimated densities ranging from 4 per m^2 at site WH11 to 52 per m^2 at site WH5. The species appeared to be less common in Evans Bay (sites WH1 and WH2) and in the north-western portion of the harbour (sites WH9–WH13) than elsewhere. Populations at a few of the sites where *T. vitrea* was present lacked either smaller (WH8) or larger (WH1 and WH10) sized individuals (Figure 4.18).

4.3 Linking the benthic community to physical and chemical variables

The percentage of sediment particles < 63 μm, the percentage of TOC, and the concentrations of selected contaminants, were superimposed one variable at a time on the ordination derived from MDS analysis of benthic community structure. In the resulting plots (Figure 4.19) sites WH1 (southern Evans Bay) and WH3 (Lambton Basin entrance) are clearly identified as having significantly higher concentrations of copper, lead, mercury, Total HMW PAH and Total DDT, and slightly higher concentrations of zinc, than the remaining sites (both inside and outside of the group). Site WH1 is also distinguished by its much lower percentage of sediment particles < 63 μm. Sites WH13 (≈ 1.25 km S of Petone Wharf) and WH14 (≈ 0.65 km S of Petone Wharf) are distinguished by having a higher percentage of sediment particles < 63 μm than all of the other sites, while sites WH14 and WH15 (≈ 1.1 km SW of Seaview) have slightly higher percentages of TOC. In addition, sites WH13, WH14 and WH15 generally have similar or lower concentrations of contaminants to sites in the group.

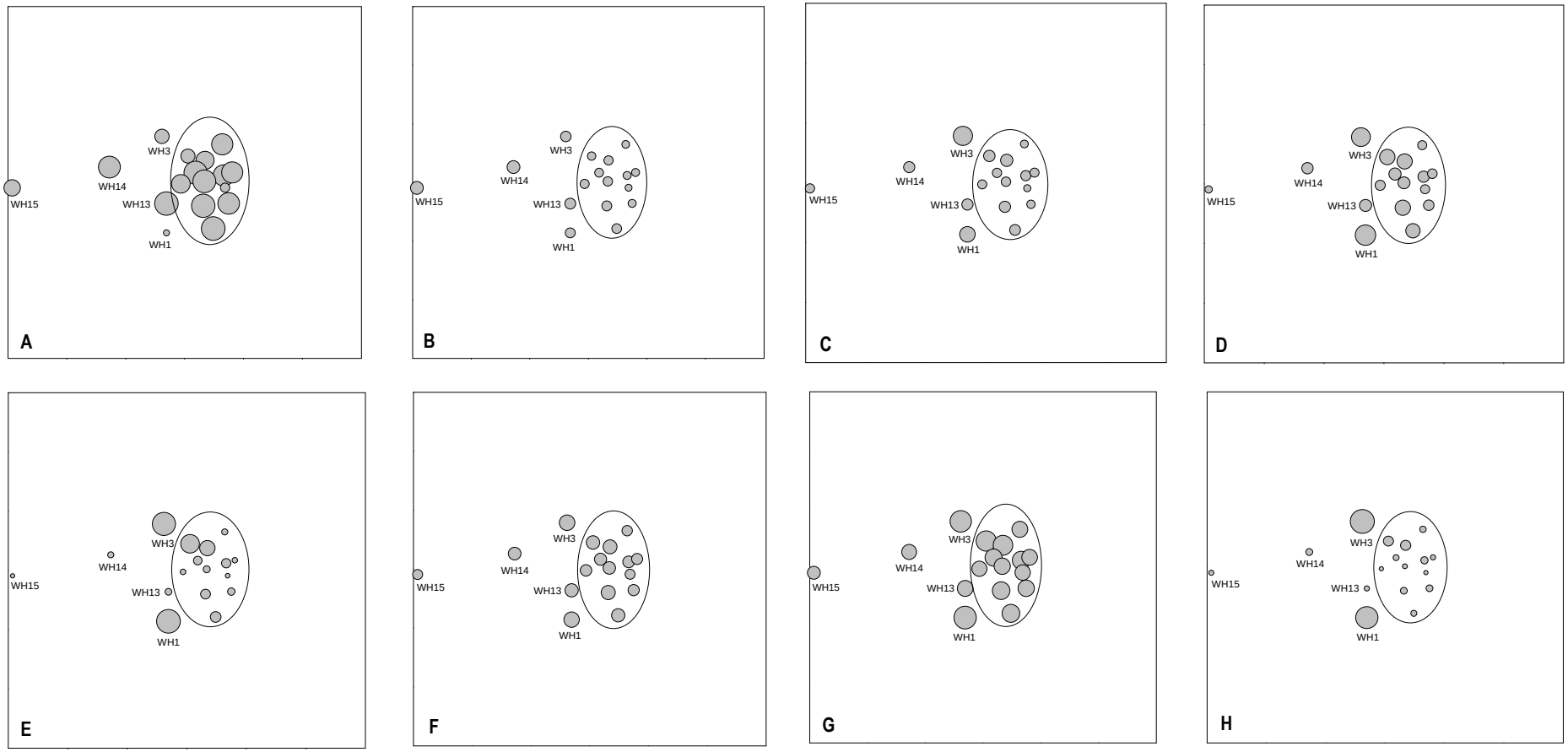

Figure 4.19: Relation of site group and outliers based on MDS analysis of benthic community structure to selected physical and chemical variables associated with the < 500 µm fraction of the sediment. A: Percentage of sediment particles < 63 um. B: Percentage of TOC. C: Total copper concentration. D: Total lead concentration. E: Total mercury concentration. F: Total zinc concentration. G: Total HMW PAH concentration. H: Total DDT concentration. Circle diameters proportional to the percentage or concentration at each site on a linear scale except plot G, which is on a logarithmic scale.

5. Discussion

This section examines some of the key sediment chemistry results and provides a brief commentary on the likely sources of sediment contamination. The benthic ecology results are also discussed, focussing primarily on any links between benthic community structure and the physical and chemical variables examined.

5.1 Sediment chemistry

In interpreting the sediment chemistry results, it is useful to first consider the Wellington Harbour receiving environment (Figure 5.1). The harbour is a roughly elliptical basin connected to the sea by an 8.5 km-long entrance channel. Evans Bay forms a narrow southward extension to the basin, parallel to the entrance channel and separated from the latter by the Miramar Peninsula. The maximum depth of the harbour is 32 m, SE and SW of Matiu/Somes Island, while the average depth is about 14 m (Heath 1977). Generally, the central harbour floor has gentle slopes (< 2°). The tides are semi-diurnal and of small amplitude (0.7–1.3 m), flowing clockwise around the harbour during the flood phase, and anticlockwise during the ebb phase. Tidal currents on the eastern side of the inner harbour can reach 0.26 m/s, while those on the western side rarely exceed 0.13 m/s. The estimated wave base is 8 m (Dunbar *et al.* 1997). The residence time is at least 10 days (Heath 1976) and this relatively slow turnover means that changes in water quality may persist for some time.

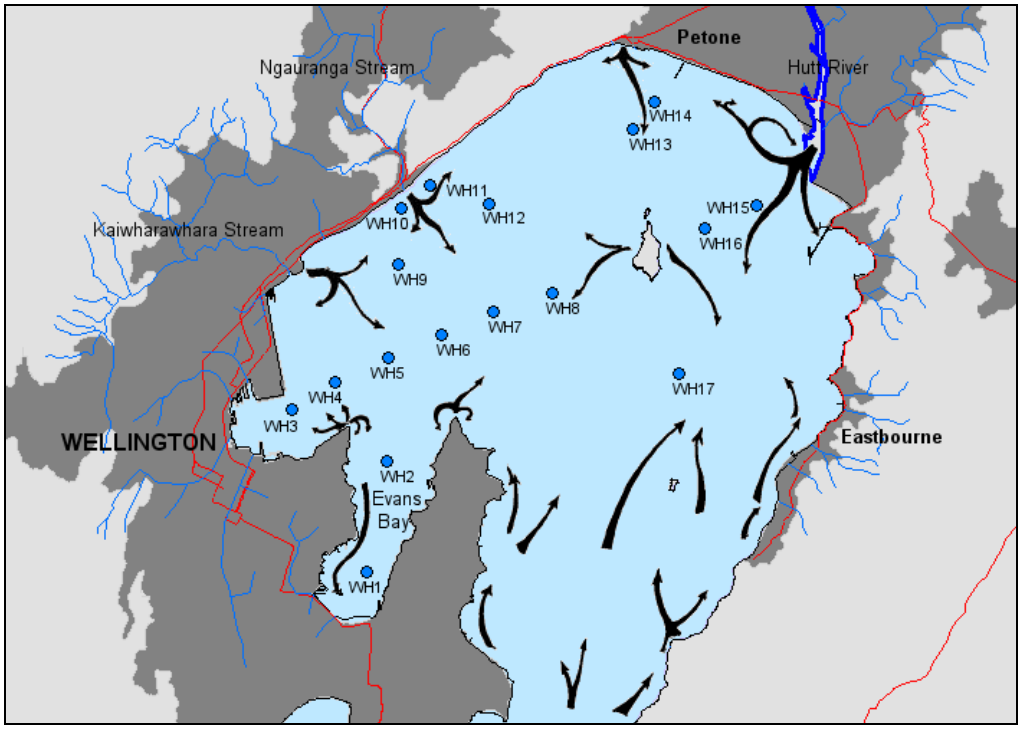

Figure 5.1: Supply and transport directions of sediment in Wellington Harbour.
(After van der Linden 1967)

The largest freshwater inflow to the harbour is from the Hutt River, an average of 24 m^3/s, with a mean annual peak flow during rainfall events of 925 m^3/s (Greater Wellington unpublished data). Depending on the combinations of

wind and tide, suspended particulate matter from the Hutt River may be carried either south towards Eastbourne or west across the face of the Hutt delta (*see* Brodie 1958; van der Linden 1967) (Figure 5.1). The input of this relatively uncontaminated sediment from rural and forested areas contributes to lower concentrations of contaminants in the northern and eastern parts of the harbour. This is superimposed over the general trend of decreasing contaminant concentrations in an offshore direction.

The Ngauranga, Kaiwharawhara, Korokoro and Horikiwi streams also flow into the harbour and in wet weather carry significant volumes of urban stormwater. Many smaller waterways within the Wellington and Hutt metropolitan areas have been channelled into the stormwater system over the last 160 or so years. As a result, there are a large number of outfalls discharging urban stormwater directly into Wellington Harbour. These stormwater discharges, together with wet weather flows in the streams, carry a range of contaminants in both the dissolved and particulate fractions.

5.1.1 Total metals

Four metals – copper, lead, mercury and zinc – show enrichment and are present at concentrations above sediment quality guidelines in the subtidal sediments of various parts of Wellington Harbour, especially those adjacent to Wellington City (Figures 5.2–5.3). Copper and zinc concentrations exceed the ARC ERC-amber threshold at several sites in this latter area. Lead concentrations exceed the ARC ERC-amber threshold, and sometimes the ARC ERC-red threshold and ANZECC ISQG-Low trigger value, at 16 sites, while mercury concentrations exceed the ISQG-Low trigger value at all 17 sites examined. Of the remaining six metals tested, arsenic, cadmium, chromium and nickel do not appear to be elevated relative to background concentrations, and do not exceed their ISQG-Low trigger values. Concentrations of antimony and silver are rarely above detection limits and their status relative to background concentrations cannot be assessed.

Source

As part of a larger investigation to characterise stormwater quality in the Wellington region, Greater Wellington measured a range of metal concentrations in the dissolved and particulate fractions of stormwater at four sites in the Wellington Harbour catchment in 2003/04. The dissolved concentrations of several metals (notably copper and zinc) were elevated and there was also significant enrichment of the particulates by copper, lead and zinc (KML 2005) – (Table 5.1). Similarly enriched sediments were reported at storm drain outlets in Evans Bay and Lambton Harbour by Pilotto (1996).

Work undertaken in Auckland and overseas has identified the primary sources of copper and zinc in urban stormwater as coming from vehicle brake pad wear and unpainted galvanized roofs respectively. Architectural uses (e.g., copper spouting) and vehicle tyre wear are key secondary sources (Timperley[14], pers. comm. 2008). In the case of mercury and lead, both of which were found to be

[14] Dr Mike Timperley, Timperley Associates (former Stormwater Action Team Leader, Auckland Regional Council).

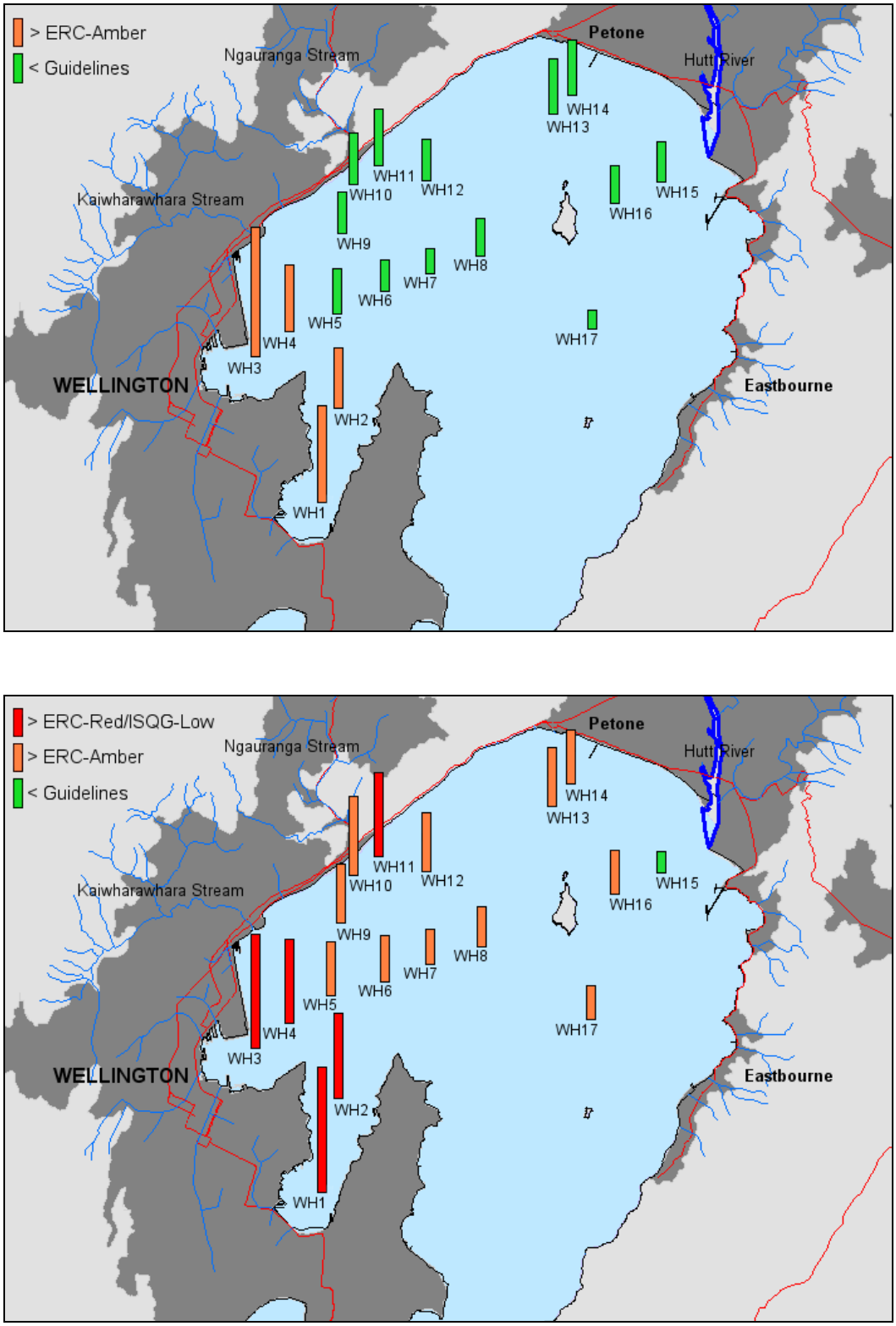

Figure 5.2: Relative concentrations of (top) total copper, and (bottom) total lead in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of a single composite sample from each site. Note that the scale used for the bars is unique to each map.

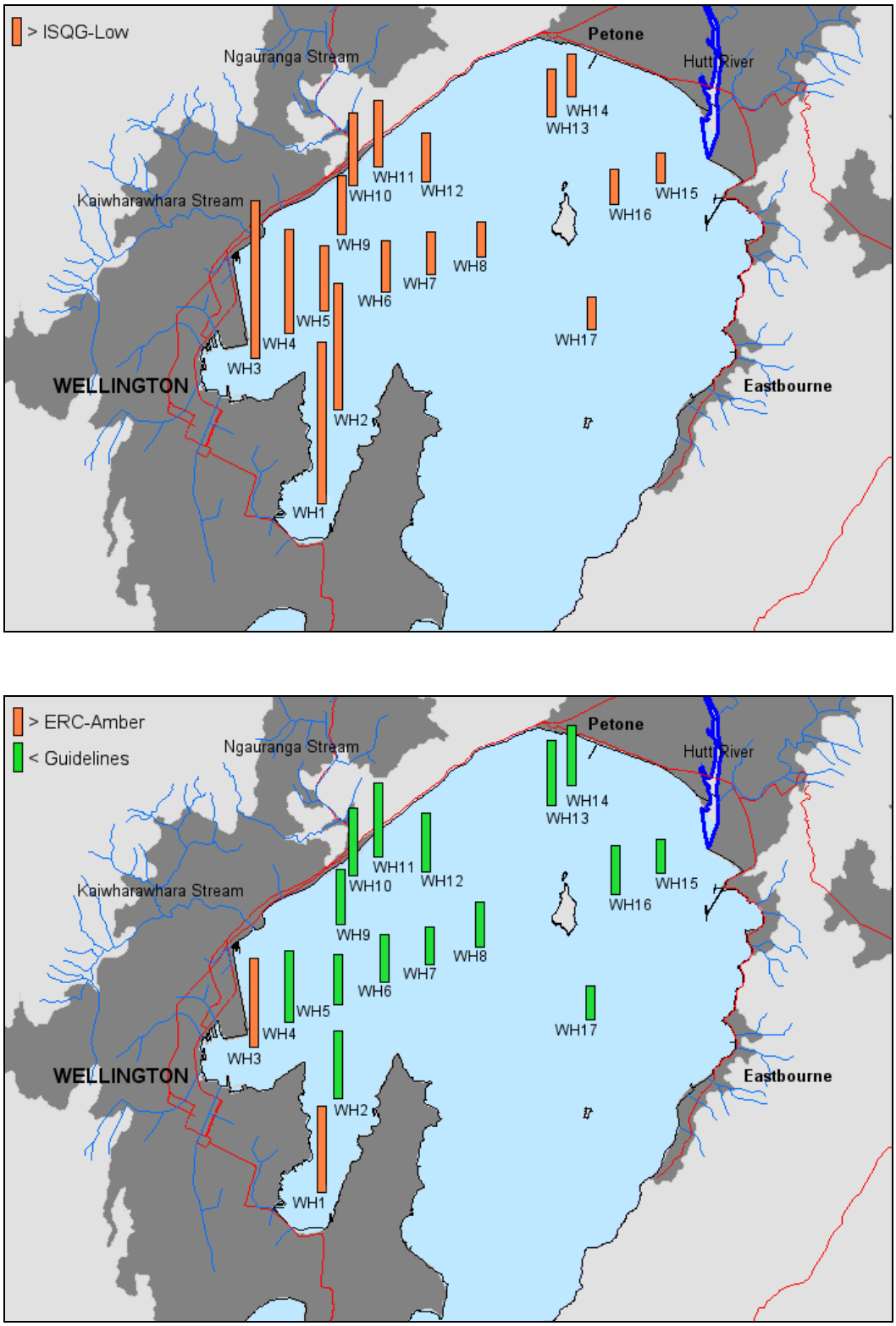

Figure 5.3: Relative concentrations of (top) total mercury, and (bottom) total zinc in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of a single composite sample from each site. Note that the scale used for the bars is unique to each map.

Table 5.1: Total copper, lead, mercury and zinc concentrations in stormwater sampled at four sites in the Wellington Harbour catchment in 2003/04. Concentrations are in mg/m³ for the dissolved fraction and mg/kg for the particulate fractions.

Analyte	Fraction	Site				Indicative background concentration
		McLeod Park, Upper Hutt	Hutt Park Rd, Lower Hutt	WaringTaylor St, Wellington	Parkside Rd, Lower Hutt	
Copper	Dissolved	10	9	22.5	8.1	0.2
Lead	Dissolved	3.5	2.8	2.5	11.5	< 0.07
Mercury	Dissolved	< 0.08	< 0.08	< 0.08	< 0.08	< 0.01
Zinc	Dissolved	108	247	108	589	0.5
Copper	0.4-59 µm	405	227	381	21,682	10
Lead	0.4-59 µm	1,076	896	298	844	10, silts and clays up to 25
Mercury	0.4-59 µm	< 50	< 50	90	157	≈ 0.1
Zinc	0.4-59 µm	8,896	2,263	1,117	3,532	50, may be higher in fine sediments
Copper	60-249 µm	296	255	374	428	
Lead	60-249 µm	685	864	405	3,391	
Mercury	60-249 µm	< 50	< 50	< 50	< 50	
Zinc	60-249 µm	5,546	1,639	1,032	5,591	

Source: KML 2005

elevated in the sediments of many of the sites sampled in Wellington Harbour in late 2006, it is likely that the sources are primarily historic. Although lead was removed from petrol in New Zealand in 1996, recent stormwater source investigations in Auckland have demonstrated that roadside soils remain contaminated with lead, with the contamination extending >100 m from road verges (Kennedy[15], pers. comm. 2008). Soils in some residential areas are also known to be contaminated with lead-based paint residues. Like lead, mercury has had many applications that are likely to result in it entering the stormwater system, including its use in herbicides, fungicides and antifouling agents (Timperley, pers. comm. 2008). Kennedy (2003) reported median values for road surface samples collected in the Wellington area ranging from 0.067–1.0 mg/kg dry weight (35 samples from six locations). Corresponding samples of material contained in three roadside catchpits had mercury concentrations ranging from 0.5–40 mg/kg.

With soil probably the largest reservoir of mobilised copper, lead, zinc and other metals in the urban environment (Kennedy, pers. comm. 2008), it is not surprising that elevated metal concentrations have been found in the bed sediments of seven urban streams in the Wellington Harbour catchment. For example, the Institute of Environmental Health and Forensic Sciences Limited sampled surface sediments of the Waiwhetu Stream (Lower Hutt) at 18 sites along its length (Deely *et al.* 1992). Between Naenae and the stream mouth concentrations of copper, lead and zinc on the <60 µm fraction ranged from

[15] Paul Kennedy, Principal Environmental Scientist, Golder Associates (Auckland).

12–103, 126–2,000 and 88–1,314 mg/kg respectively, with the highest concentrations recorded in the lower reaches of the stream. The corresponding concentrations on the 60–2,000 μm fraction were 4.81–42, 39–931 and 67–709 mg/kg.

Greater Wellington sampled surface sediments at three sites on the Kaiwharawhara Stream (Wellington City), and at one site each on the Ngauranga Stream (Wellington City), Opahu Stream (Lower Hutt), Stokes Valley Stream (Lower Hutt), Hulls Creek (Upper Hutt) and Mawaihakona Stream (Upper Hutt) in 2005. For the < 2 mm fraction, metal concentration ranges were 8.9–38.2 mg/kg for copper, 18.1–53.9 mg/kg for lead, 0.04–0.72 mg/kg for mercury, and 89.6–352 mg/kg for zinc (Milne & Watts 2008). Sediments in these streams therefore generally exhibit enrichment with copper, lead and zinc, which is derived from the surrounding urban areas through discharge of stormwater into the streams. In the steep gradient streams around Wellington City there is very little fine sediment present in the streambeds, indicating that most of the metals – whether they be in the dissolved or particulate fractions – will reach the harbour very quickly. Detention times will tend to be longer in the low gradient streams on the floor of the Hutt Valley, where rainfall intensity is more important in determining the quantities of particulates discharged.

Based upon available data, it is evident that urban stormwater is contributing to metal contamination of the harbour sediments. The contamination is arising through both dissolved elements[16] that are taken out of solution through sorption and removal processes when stormwater enters saline water, and the deposition of suspended particulates in stormwater.

5.1.2 Organotins

Tributyltin (TBT) is present above the ISQG-Low trigger value at three of the sites examined, while triphenyltin is present at one site. Organotins have a long persistence time in sediments. The half-life of TBT in aerobic sediments has been estimated to be 2.5–3 years (de Mora *et al.* 1995), but may be tens of years in anaerobic sediments (Dowson *et al.* 1996). The main degradation pathway for TBT in Wellington Harbour sediments appears to be to dibutyltin, and this compound is present at all sites. DBT is less toxic than TBT.

Source

The organotins in the sediments of Wellington Harbour are likely to be derived mainly from marine antifouling paints. Minor amounts are possibly derived from exposed timber, since TBT is a registered timber treatment for hazard class H3 (i.e., fencing grade).

In New Zealand, organotins have been completely banned from antifouling paints since 1993, so new inputs of TBT are now largely confined to leaching from overseas commercial vessels. Even this source is likely to be declining as the International Maritime Organisation some time ago proposed to phase out

[16] Some of the metals can be present at biologically significant concentrations in both piped stormwater and wet weather stream flows – *see* KML (2005) and Milne and Watts (2008).

the presence of TBT on ship's hulls by 2008. The decline in sources, coupled with the low concentrations of organotins recorded (close to detection limits in most cases) mean there is little value in continuing to monitor these compounds. Instead, consideration should be given to testing, in any future surveys, for the organic booster biocides (such as Diuron, Irgarol 1051 and Chlorothalonil) which are now being used in conjunction with copper compounds in marine antifouling formulations[17].

5.1.3 Polycyclic aromatic hydrocarbons[18]

The individual PAHs fluorene, phenanthrene and benzo[a]anthracene, as well as Total HMW PAH, are above sediment quality guidelines in southern Evans Bay, while Total HMW PAH also exceeds the guidelines in northern Evans Bay and at the entrance to the Lambton Basin (Figure 5.4).

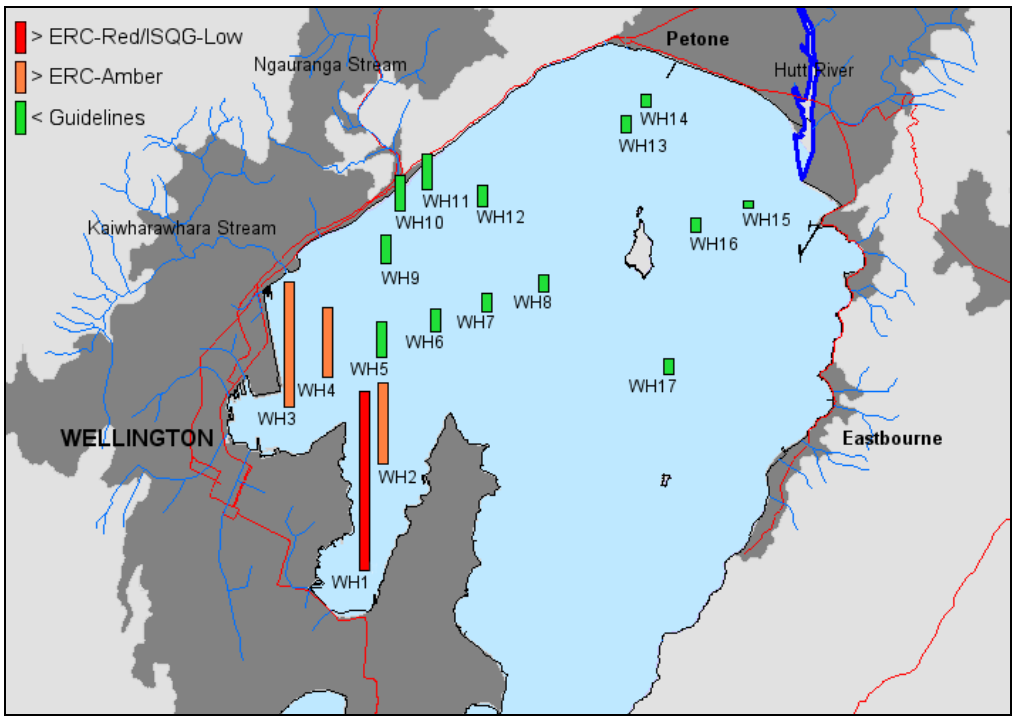

Figure 5.4: Mean concentrations of Total HMW PAH in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of five composite samples from each site. Note that the scale used for the bars is unique to this map.

The sediments of the sites show moderate levels of PAH contamination, and a spatial trend of decreasing concentrations away from the shore suggests land-derived input of the PAHs, presumably via runoff and direct deposition. Analysis of the relative abundance of the 16 individual PAHs measured shows that high molecular weight compounds dominate the "PAH signature" at all sites, with fluoranthene, pyrene and benzo(b)fluoranthene+benzo(j)fluoran-

[17] One-off testing of seawater samples collected at four locations within Wellington Harbour in 2006 (as part of a larger nationwide study) returned measurable concentrations of diuron; the concentration recorded at Seaview marina (250 ng/L) was amongst the highest concentrations found in the 30 seawater samples collected nationally (Stewart 2006).

[18] This section summarises the results of a report by NIWA which was commissioned by Greater Wellington. The reader is referred to this report (Ahrens & Olsen 2008) for details of the analysis and an explanation of the terminology.

thene (combined) the most prominent. The low molecular weight PAH phenanthrene contributes 6–10% of the Total PAH content, whereas other low molecular weight PAHs (such as naphthalene and fluorene) each contribute less than 2%.

The prominence of the high molecular weight PAHs is characteristic of an urban/industrial PAH signature dominated by "pyrogenic" inputs such as combustion processes (e.g., soot from transport emissions, or industrial and domestic heating), while the relatively low abundances of the low molecular weight PAHs indicate that the sediments are not significantly contaminated by fresh petroleum inputs. Nevertheless, slightly higher percentages of acenaphthylene at site WH1 (southern Evans Bay) and of phenanthrene at sites WH14 (≈ 0.65 km S of Petone Wharf) and WH15 (≈ 1.1 km SW of Seaview) compared with sites elsewhere in the harbour could indicate a small contribution of petrogenic PAHs at these locations.

The PAH Pyrogenic Index (PAHPY) for the sites ranges from 0.09–0.25 and correlates with total PAH concentrations in a strongly logarithmic fashion; sites with higher total PAH concentrations tend to have a higher PAHPY. Hence pyrogenicity decreases with distance from shore in step with total PAH concentrations except for Site WH15, which has a low PAHPY consistent with the slightly increased percentages of low molecular weight PAHs noted above. The observed trends suggest that pyrogenic PAHs originate on land and tend to become mixed with less pyrogenic PAHs further from shore. However, combustion-derived and other pyrogenic sources of PAHs predominate throughout the harbour.

Comparing the PAH isomer ratios of the sites with literature values (Yunker *et al.* 2002; Ahrens and Depree 2006) shows that overall the sediments fall within the range of pyrogenic sources, even though the individual isomer ratios are often less than the maximum ratios observed for single source combustion residues (such as coal soot, diesel soot and coal tar). This suggests the PAHs are not derived from a single source, but from a combination of several pyrogenic sources. Some materials with a similar PAHPY include various types of soot – such as those formed during combustion of lignite and bituminous coal, wood, kerosene, diesel and oil – as well as "urban air particulates".

Source

Greater Wellington measured PAHs in stormwater at four sites in the Wellington Harbour catchment in 2003/04. Total HMW PAH concentrations in the dissolved fraction ranged from 62.7–1,310 µg/m^3, on the 0.7–59 µm particulate fraction from 5,880–12,610 µg/kg (421–5168 µg/kg at 1% TOC) and on the 60–500 µm particulate fraction from 7,560–34,640 µg/kg (541–6,067 µg/kg at 1% TOC) (KML 2005). At McLeod Park (Upper Hutt) the PAH signature of the particulate fraction was dominated by pyrene and fluoranthene, at Waring Taylor Street (Wellington City) and Parkside Road (Lower Hutt) by pyrene, and at Hutt Park Road (Lower Hutt) by chrysene, benzo(b)fluoranthene and benzo(k)fluoranthene.

Sheppard (2001) reported Total HMW PAH concentrations of 4,250–19,500 µg/kg from the top 20 cm of cores taken in the bed of the Waiwhetu Stream at Hutt Park Bridge, with the PAH signature dominated by fluoranthene and pyrene. Bed sediments of a further six urban streams in the catchment have also been tested by Greater Wellington for PAHs, with Total HMW PAH concentrations on the < 2 mm fraction of 19–10,499 µg/kg (80–13,460 µg/kg at 1% TOC) being found (Milne & Watts 2008). At all of the sites except the Ngauranga Stream (Wellington City), the PAH signature was dominated by pyrene, fluoranthene and benzo(b)fluoranthene.

The PAHPY for the Greater Wellington stormwater sites ranged from 0.05–0.34, and for the stream sites from 0.07–0.43 (i.e., they generally had levels of pyrogenicity similar to those of the harbour sediments). Confirming the observed trends and assessment of PAH sources will be easier once additional PAH data, including alkylated PAH homologues, are available (refer Section 2.1.8).

5.1.4 Organochlorine pesticides

Total DDT (i.e., DDT + DDD + DDE) is above the sediment quality guidelines at all but two of the sites examined, being above the ISQG-Low trigger value and, in two instances, also above the ARC ERC-red threshold (Figure 5.5). DDT is the parent substance, previously used as a pesticide; DDD and DDE are the products of the environmental degradation of DDT.

A definite spatial pattern is apparent in the relative proportions of the three compounds (Figure 5.6). DDT is usually the dominant constituent at sites adjacent to Wellington City, which is consistent with inputs from less weathered sources (such as urban stormwater). The accompanying high proportions of DDD at these sites are indicative of in-situ anaerobic transformation of DDT to DDD in harbour sediments. The proportion of DDT decreases progressively towards the northern and eastern parts of the harbour, being scarcely higher than the other constituents at site WH14 (≈ 0.65 km SW of Petone Wharf), and replaced as the dominant constituent by DDE at sites WH13, WH15, WH16 and WH17. This pattern possibly reflects greater inputs from aerobically weathered DDT sources (such as agricultural soils) to these parts of the harbour by way of the Hutt River in particular.

The quality assurance results for some isomers of DDT and its breakdown products are not particularly satisfactory, with the failure to get good agreement with the SRM of particular concern. This problem of anomalous DDT results is not new (*see* Stephenson & Mills 2006). Nonetheless, monitoring of these compounds should continue as the significant concentrations of Total DDT present in some streambeds in the harbour's catchment (Milne & Watts 2008, Sheppard 2001) and in present-day stormwater discharges (KML 2005), together with further releases by any major earthworks or harbour dredging, all create a potential for increases in Total DDT concentrations in subtidal sediments over time.

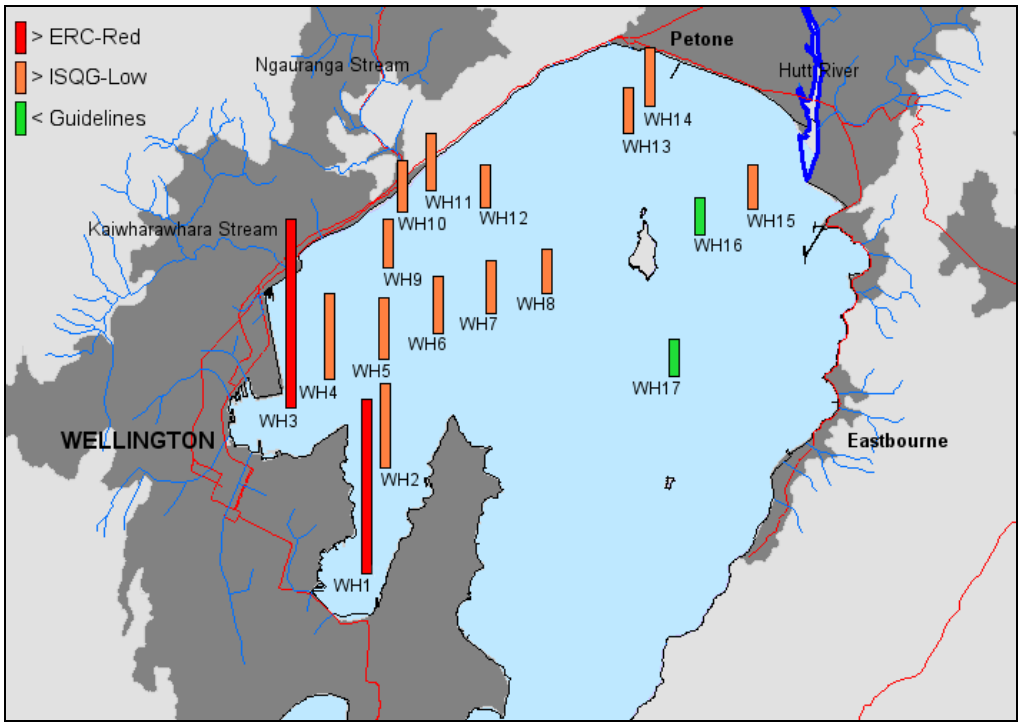

Figure 5.5: Mean concentrations of Total DDT in sediments of 17 sites sampled in Wellington Harbour in 2006, based on the < 500 µm fraction of five composite samples from each site. Note that the scale used for the bars is unique to this map.

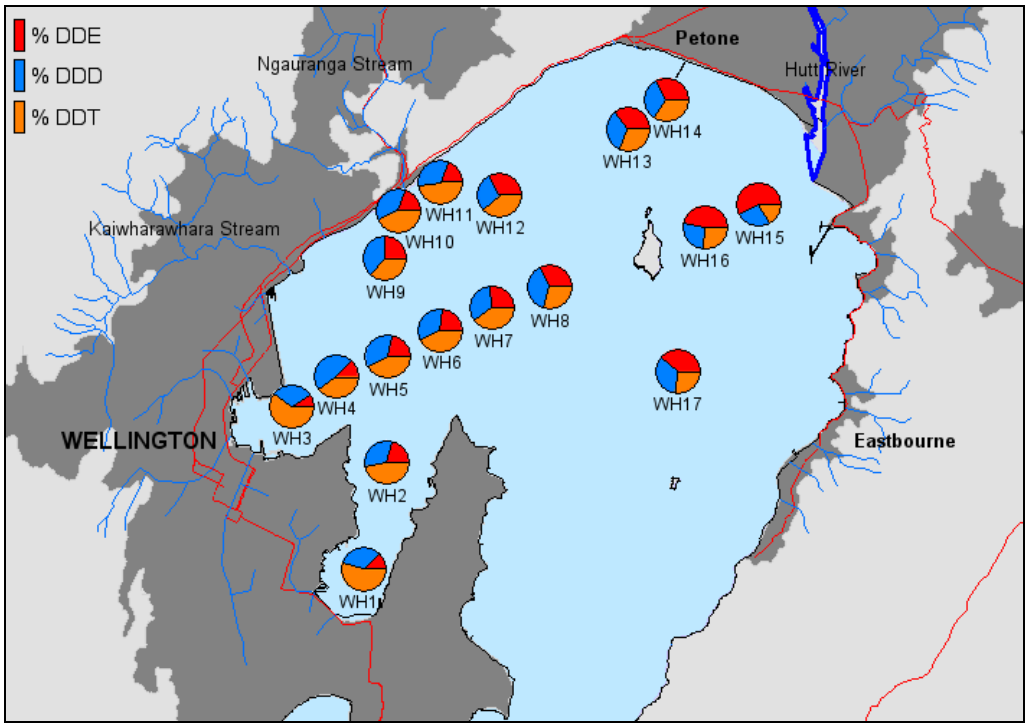

Figure 5.6: Total DDT composition in sediments of 17 sites sampled in Wellington Harbour in 2006. Values are means from each site (n = 5) and include "less than detection limit" values as a value one half of the detection limit.

Source

Greater Wellington measured organochlorine pesticide concentrations in stormwater at four sites in the Wellington Harbour catchment in 2003/04. Pesticides were detected in all of the samples, in both the dissolved and particulate fractions (KML 2005). Total DDT concentrations in the dissolved fraction ranged from 0.93–17.9 µg/m^3, on the 0.7–59 µm particulate fraction from 2.09–315 µg/kg (0.15–55 µg/kg at 1% TOC) and on the 60–500 µm particulate fraction from 30.9–1,170 µg/kg (2.2–205 µg/kg at 1% TOC). At McLeod Park (Upper Hutt), Waring Taylor Street (Wellington City) and Parkside Road (Lower Hutt) the dominant constituent was DDT, but at Hutt Park Road (Lower Hutt) it was DDD. This last observation is consistent with results obtained by Sheppard (2001) from the top 20 cm of cores taken in the bed of the Waiwhetu Stream at Hutt Park Bridge, which had DDD-dominated Total DDT concentrations of 1,950–5,700 µg/kg.

Bed sediments of a further six urban streams in the catchment have also been tested by Greater Wellington for organochlorine pesticides, with Total DDT concentrations of 4.0–38.5 µg/kg (5.6–38.1 µg/kg at 1% TOC) found on the < 2 mm fraction (Milne & Watts 2008). At all sites except for one on the Mawaihakona Stream (Upper Hutt), DDT was the dominant constituent. These results indicate that although the use of DDT in agriculture effectively ceased in the 1970s, and its use in urban areas was banned in the late 1980s, substantial sources remain in the environment. In the case of the breakdown product DDE, the bulk of this compound reaching the harbour is coming from the rural parts of the Hutt sub-catchment.

5.2 Benthic ecology

The small deviations in the values of some of the sediment particle size classes between the chemistry and biology collection areas at some sites are not thought to have resulted in the sampling of different benthic faunas. Examination of the animals present in the discarded portions of the cores taken for sediment chemistry in seven cases produced only species recorded in the adjoining benthic ecology collection area, and in 10 cases these plus between one and four additional species. Most of the latter were species recorded at other sites during the investigation.

Species richness tended to be higher at sites in Evans Bay and along the western and northern margins of the harbour, and lower at sites further offshore (Figure 5.7). However, the mean number of species per sample showed relatively little variation between sites, with only the means from the two sites at the extremes of the observed range being significantly different. All of the sites recorded a substantially lower number of species than the overall total of 101 species recorded in this investigation.

The highest densities were recorded at three sites (WH3, WH10 and WH13) along the western margin of the harbour. The mean number of individuals per sample showed some variation between sites, but only sites WH10 and WH13 had means significantly different from those of some of the other sites.

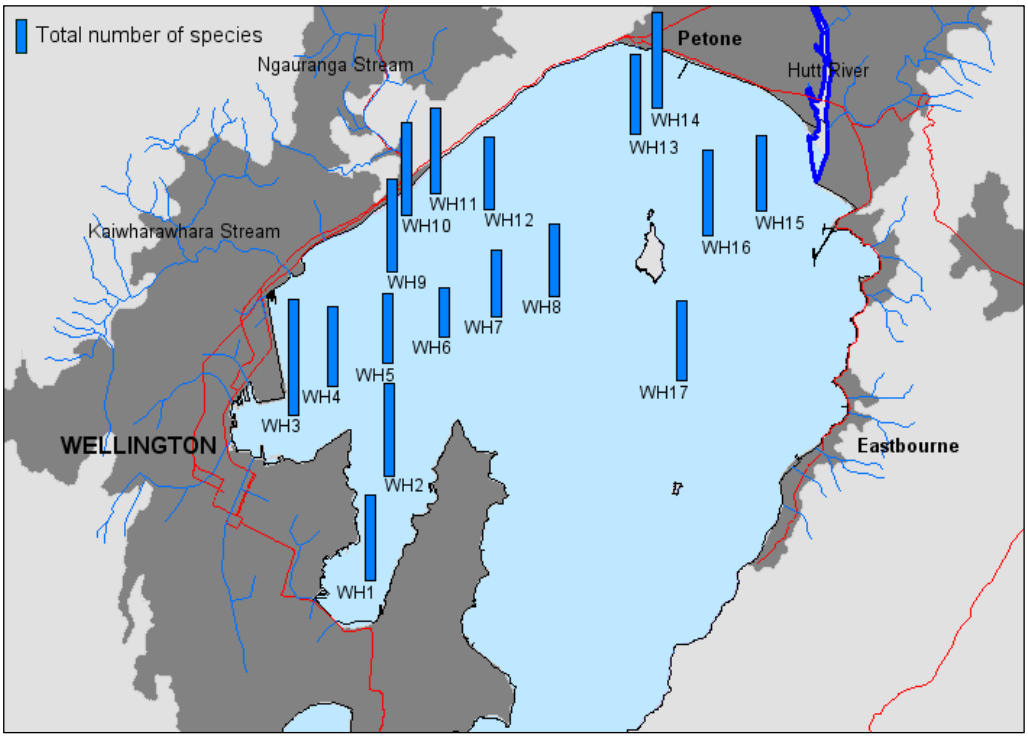

Figure 5.7: Number of species at each of the 17 sites sampled in Wellington Harbour in November 2006. Note that the scale used for the bars is unique to this map.

Rank abundance plots showed that equitability tended to be lowest at sites nearest to the shore. As a result, diversity as measured by the Shannon diversity index was lower at some of these sites than at sites elsewhere in the harbour (Figure 5.8). Only sites WH3 and WH15 had means significantly different from those of some of the other sites. However, with recorded values of the index > 2.0, diversity is considered to be high at all 17 sites sampled in Wellington Harbour in 2006.

None of the rank abundance plots were truncated, a feature which if present would have indicated the absence of rare species. The rank abundance plot for site WH15 was not consistent with those of the other sites owing to a disproportionate dominance by *Cossura consimilis*, very few species of moderate abundance, and a large proportion of the species each represented by only one individual. The results suggest that the benthic community at this site is in a recovery phase following disturbance. This disturbance may be linked to the proximity of the site to the Hutt River mouth.

The 12 most abundant species collected in this investigation exhibited considerable between-site variation in both numbers and relative abundance around the harbour, but were present at all sites. These variations partly explain the separation of the outlying sites in the MDS ordination from those in the group, while the presence of species of rare occurrence at the outlying sites also contributes. Site WH1 was the only site with the suspension feeding gastropod *Maoricolpus roseus*, while the sabellid polychaete *Megalomma* sp.#1, was found only here and at site WH17. These distributions are probably related to sediment particle size, as the sites had the coarsest sediments examined.

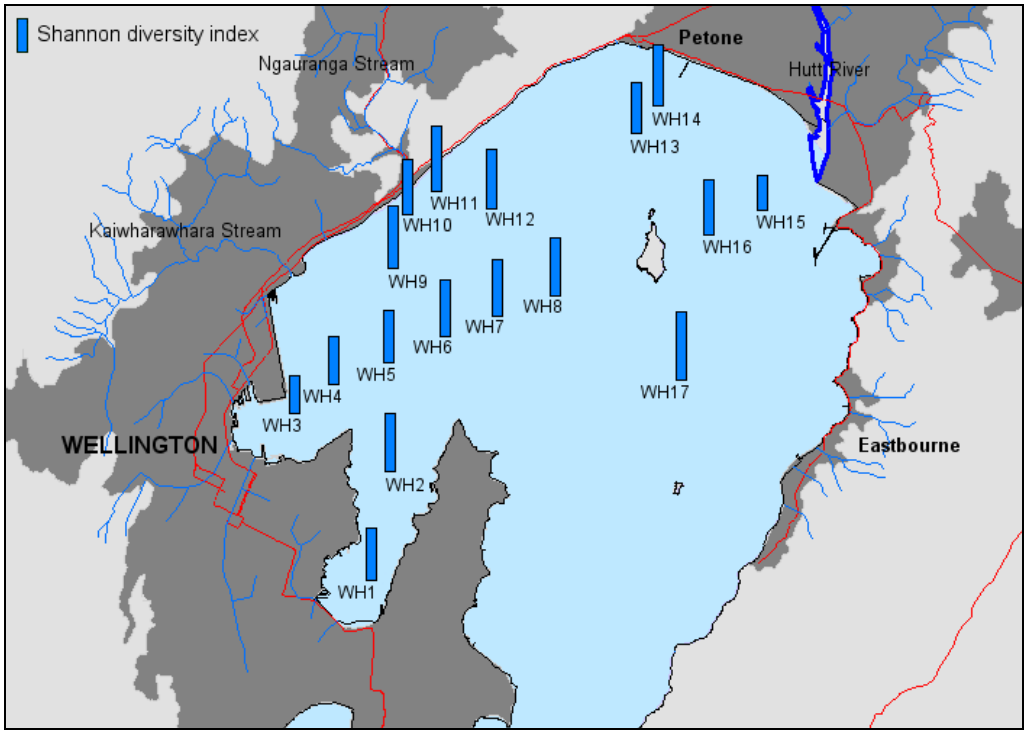

Figure 5.8: Mean Shannon diversity index at 17 sites in Wellington Harbour in November 2006. Note that the scale used for the bars is unique to this map.

Nemertea sp.#5 and Decapoda sp.#2 were found only at site WH3, Nemertea sp.#11 only at site WH13, and Ostracoda sp.#9 only at site WH15. Other species with just two or three records included Nemertea sp.#10 (at sites WH13 and WH15), Maldanidae sp. #1 (at sites WH3 and WH14), and the holothurian *Pentadactyla longidentis* (at sites WH3, WH13 and WH15).

The predominance of deposit feeders at all sites is consistent with the very fine and easily disturbed nature of the surface sediments and the frequent occurrence of a variety of large motile surface-dwelling or shallow-burrowing species such as the heart urchin *Echinocardium cordatum*, the tunnelling mud crab *Macrophthalmus hirtipes* and the brittle star *Amphiura rosea*. A high proportion of deposit feeders, mainly subsurface (such as at sites WH3, WH4 and WH15), can be associated with organic enrichment, but this seems an unlikely explanation in this instance as sediment TOC at these sites is similar to that at nearby sites with lower proportions of deposit feeders. The slightly higher proportion of suspension feeders at site WH1 is likely to be a response to the larger median particle size of the sediment at this site, a trend which has been documented elsewhere (e.g., Grange 1977).

Overall, the evidence suggests that the benthic faunas of both the group of sites and the outliers identified by cluster and MDS analysis of the similarity matrix derived from mean species abundances can be considered as being variants of an inner harbour "fine sediment community occurring below about 10 m depth". Localised differences in environmental conditions, species interactions and/or spatio-temporal variation in patterns of recruitment influence both the dominant and less common species. The principal species in this community were Sipunculida sp.#1, Tanaidacea sp.#1, *Theora lubrica*, *Labiosthenolepis*

laevis, *Cossura consimilis*, Paraonidae sp.#1, Phoxocephalidae sp.#1, Cirratulidae sp.#1, *Arthritica* sp.#1, *Maldane theodori*, *Aglaophamus macroura*, and *Amphiura rosea*. The heart urchin *Echinocardium cordatum*, the bivalve *Dosina zelandica*, the rag-worm *Onuphis aucklandensis*, the bamboo worm *Asychis trifilosa,* or a combination of these species, most often dominated the biomass.

5.3 Linking the benthic community to physical and chemical variables

Superimposing sediment physical and chemical variables on the ordination produced by MDS analysis of benthic community structure has shown quite clearly that variation in this structure across the 17 sites is not strongly correlated with the concentrations of the chemical contaminants that exceed sediment quality guidelines. Possible exceptions are the communities at sites WH1 (southern Evans Bay) and WH3 (Lambton Basin entrance). Concentrations of lead and Total DDT are above both the ARC ERC-red threshold and ANZECC ISQG-Low trigger levels at these sites, mercury is above ISQG-Low trigger level, and copper, zinc and HMW PAH are above ARC ERC amber thresholds.

If chemical contamination is a significant factor at sites WH1 and WH3, one or more of the following changes to the benthic community might be expected:

1. Reduction and/or loss of large-sized species.
2. Loss of rare species, and/or
3. Appearance or (if already present) increase in the numbers of pollution-tolerant species.

There is little evidence of any of these changes at sites WH1 and WH3. Species which grow to a large size when mature are still present at both sites, and although in low densities there were, in all cases, other sites with lower contaminant concentrations which recorded similar densities. Neither site shows a truncation of the rank abundance curve that would indicate the absence of rare species. Pollution-tolerant taxa such as the polychaete *Capitella capitata* and oligochaetes are either absent or no more numerous than at the other sites.

The disparity in the concentrations of some contaminants between sites WH1 and WH3 and all the other sites means that, despite the above observations, it is possible that there have been sub-lethal (or possibly even lethal) effects at the individual species level, and that these effects could have resulted directly or indirectly in a change in community structure at the sites. This possibility arises because similar population variations may have occurred elsewhere in the harbour but caused by factors other than chemical contaminants, making it difficult in this instance to recognise cause and effect. In addition, if the onset of obvious effects of one or more of the contaminants on any species is relatively abrupt, and the threshold for these effects is reached in the concentration range between that observed at sites WH1 and WH3 and the other sites, then this impact would be restricted to sites WH1 and/or WH3 and there would be no trends to detect. The low densities of *Echinocardium*

cordatum and the absence of juveniles of both species of *Nucula* at sites WH1 and WH3 are possible examples. *Echinocardium cordatum* plays a significant role in bioturbation[19] and hence can influence community structure. It is listed in the MarLIN[20] database as having a high intolerance to synthetic compounds (such as TBT and DDT) and hydrocarbons and an intermediate intolerance to heavy metal contamination. The *Nucula* species are subsurface deposit feeding bivalves and therefore vulnerable to contaminants attached to fine particles ingested whilst feeding. Possible explanations for the lack of juveniles might include the inhibition of settlement or greater juvenile sensitivity to chemical contaminants. No specific information is available for either *Nucula* species but such responses to chemical contaminants have been observed in other species of bivalves (e.g., Ahrens *et al*. 2002, Davis & Hidu 1969, Pelletier *et al*. 1997, Roper *et al*. 1995, Ruiz *et al*. 1995a, 1995b).

Based on the results of this investigation it is therefore not possible to conclude that there are no biological effects from chemical contaminants at all of the sites examined, only that there is *no clear evidence of significant adverse effects on the benthic fauna at the community level of organisation*.

5.4 Synthesis

The concentrations of some contaminants – including several heavy metals, HMW PAHs and Total DDT – are above sediment quality guidelines in the subtidal sediments of various parts of Wellington Harbour, especially those adjacent to Wellington City. The strong offshore gradients in contaminant concentrations (refer Figures 5.2–5.4) in the harbour sediments and the chemical nature of some of the contaminants provide a clear indication of their land-based origin. A review of the available stormwater quality and stream monitoring data from the harbour's catchment clearly suggests that urban stormwater is the principal agent in the transport of the majority of contaminants to the harbour seabed, either directly or by way of urban streams.

Although several contaminants are present at concentrations above sediment quality guidelines, based on an examination of the benthic fauna present at each site, there is no clear evidence of the elevated contaminants measured in the sediments having resulted in significant adverse effects on benthic community structure as at November 2006. However, this may not be the case at some sites (e.g., WH1 and WH3) in the future if contaminants continue to accumulate. This may also not be the case closer to shore. The number of far-field sites at which sediment quality guidelines were exceeded in this investigation, and the offshore gradients exhibited by the contaminants involved[21], clearly indicates that concentrations of these contaminants will be higher as their onshore sources are approached, with a parallel increase in the likelihood of effects on the benthic ecology.

In a study investigating the impact of stormwater discharges on the nearshore benthic environment in the inner harbour, Bolton-Ritchie (2003) identified

[19] Bioturbation is defined as the stirring or mixing of sediment by organisms, especially by burrowing or boring.

[20] The Marine Life Information Network for Britain and Ireland. www.marlin.ac.uk

[21] This was also demonstrated by Stoffers *et al* (1986) with respect to sediment metal concentrations.

significantly elevated metal concentrations (frequently above ANZECC (2000) ISQG-High trigger levels[22]) and levels of organic matter in close vicinity to stormwater outfalls that in some cases coincided with infauna community changes[23]. However, the areas studied were limited to within 50 m of selected outfalls in Evans Bay, Lambton Basin and along Aotea Quay. Similarly, Pilotto's (1996) investigation of metal concentrations in subtidal sediments was also undertaken adjacent to stormwater outlets. Investigations of possible ecological effects in the nearshore area beyond the immediate influence of stormwater outfalls have not been undertaken to date, although the Miramar Wharf stormwater outfall investigation commissioned by Wellington City Council in 2007 did examine a larger (200-m radius) area. Two or more of the four sites sampled and analysed by the same methods used in this investigation had antimony, arsenic, cadmium, copper, lead, silver, zinc, Total PAH and Total HMW PAH concentrations higher than at site WH1 (which is located about 400 m from the Miramar Wharf outfall), in some cases by a factor of three or more (Ahrens & Olsen 2007, WCC unpublished data). However, biological effects appeared to be limited to within a radius of little more than 30 m, which Stephenson (2007b) concluded was possibly due to the location of the outfall adjacent to relatively deep water and on a shoreline fully exposed to the prevailing north-westerly wind.

In addition to a case for investigating possible ecological effects in the nearshore areas beyond the immediate influence of stormwater outfalls – particularly within the wider Lambton Basin area, off the Kaiwharawhara Stream, and along the Petone foreshore – there is also a case for adding a further far-field site to any future sediment surveys. This site should be located on the 16 m depth contour approximately mid-way between sites WH13 and WH15 where it would improve detection of contaminants deposited in the area immediately to the west of the Hutt River mouth. It should initially be sampled in tandem with site WH15, but may prove more suitable in the longer term for this type of monitoring programme because it is less likely to be affected by short-term changes which may result from site WH15's proximity to the Hutt river mouth.

[22] This guideline comparison is indicative only because the method of analysis (X-Ray fluorescence) and fraction of sediment analysed (<63 micron) differ from those recommended in the ANZECC (2000) guidelines.

[23] For example, opportunistic and pollution-tolerant capitellid polychaetes were shown to increase proximally to the outfalls while the pollution-sensitive polychaete *Owenia fusiformis* decreased.

6. Summary and recommendations

Concentrations of lead, mercury, and to a lesser extent copper and zinc, are present above sediment quality guidelines in the subtidal sediments of various parts of Wellington Harbour, especially those adjacent to Wellington City. Tributyltin is only present above sediment quality guidelines at the entrance to the Lambton Basin and off Ngauranga, but its less toxic breakdown product dibutyltin is widespread. Fluorene, phenanthrene, benzo[a]anthracene, and total high molecular weight polycyclic aromatic hydrocarbons (Total HMW PAH) are above sediment quality guidelines in southern Evans Bay, and Total HMW PAH in northern Evans Bay and at the entrance to the Lambton Basin. Total DDT is present above sediment quality guidelines over much of the harbour. Concentrations of other heavy metals, organochlorine pesticides and PAHs are currently below guideline levels in the subtidal sediments of the harbour.

The chemical contaminant data collected to date are generally of good quality, with low variability for most analytes, which demonstrates the capacity of the methodology used to detect very small changes in contaminant concentrations over time. The main exceptions with respect to data quality are the organochlorine pesticides DDD, DDE and DDT. Nonetheless, monitoring of these compounds should continue – along with metals and PAHs – as the significant levels of Total DDT present in some streams in the harbour's catchment and in present-day stormwater discharges, together with further releases by any major earthworks or harbour dredging, all create a potential for increases in Total DDT concentrations in subtidal sediments over time.

The benthic faunas present at the marine sediment quality investigation sites in Wellington Harbour in 2006 can be considered as being variants of an inner harbour subtidal fine sediment community occurring in water depths > 10 m. The principal species in this community were Sipunculida sp.#1, Tanaidacea sp.#1, *Theora lubrica*, *Labiosthenolepis laevis*, *Cossura consimilis*, Paraonidae sp.#1, Phoxocephalidae sp.#1, Cirratulidae sp.#1, *Arthritica* sp.#1, *Maldane theodori*, *Aglaophamus macroura* and *Amphiura rosea*. The heart urchin *Echinocardium cordatum*, the bivalve *Dosina zelandica*, the rag-worm *Onuphis aucklandensis*, the bamboo worm *Asychis trifilosa,* or a combination of these species, most often dominated the biomass.

The benthic ecology data collected to date provide a good baseline for further studies. They also show that, although the concentrations of several contaminants are above sediment quality guidelines, there is no clear evidence any of the contaminants measured in the subtidal sediments have resulted in significant adverse effects on the benthic community structure of the sites as at November 2006. While the absence of effects is encouraging, the thresholds for such effects are still not known for this environment, indicating continued monitoring of both sediment quality and benthic ecology will be needed.

The strong offshore gradients in contaminant concentrations and the chemical nature of some of the contaminants in the sediments of Wellington Harbour provide a clear indication of their land-based origin. A review of the available stormwater quality and stream monitoring data from the harbour's catchment

indicates that urban stormwater is the principal agent in the transport of the majority of these contaminants to the harbour seabed, either directly or by way of urban streams.

6.1 Recommendations

It is recommended that:

1. A second sediment chemistry survey is undertaken in Wellington Harbour in 2011 at sites WH1–WH5, WH9, WH11, WH13, WH15, and possibly a new site off eastern Petone, in order to monitor trends in contaminant concentrations. Further surveys should be conducted every five or six years thereafter unless results and/or major changes in the catchment indicate a greater or lesser survey frequency is desirable. Future surveys should:

    - Follow the same sampling methods, sample preparation, and replication procedures used in this first baseline survey. While the low variability in the metals and TOC data indicate that fewer replicates (say 3) from each site could be analysed, organic contaminant concentrations, particularly PAHs, are inherently more variable than the metals, so continued analysis of five replicates per site may be required to obtain a reliable measure of mean values at each site.

    - Continue to include analysis of organochlorine pesticides with QA checks that include re-analysis of 2006 samples as blind replicates, and results from the concurrent analysis of an appropriate marine sediment standard reference material (SRM) to check consistency with previous results.

    - Exclude analysis of organotins. With organotin concentrations below the current analytical detection limits at most of the sites, and more sensitive analytical methods not available in New Zealand, there is little point in continuing to monitor these compounds, particularly as they are unlikely to increase in concentration as a result of future changes in the catchment.

    - Report SRM and between-batch QA sample results for PAHs, to check consistency and to ensure that if a change of laboratory occurs in the future the results will be comparable.

2. A second benthic ecology survey is undertaken in Wellington Harbour at the sites listed in (1) above in order to monitor for changes in community structure with possible links to changes in contaminant concentrations. The survey should be carried out in late October 2011 to minimise seasonal influences, and coincide with the sediment chemistry survey if possible. Future surveys should:

    - Follow the same sampling methods used in this first baseline survey, with the fauna identified to at least the same taxonomic levels.

- Ensure that the reference collection established during the 2006 survey continues to be maintained and representative specimen(s) of any additional species encountered, either at the existing sites or elsewhere, added to the collection.

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