Wellington Harbour subtidal sediment quality monitoring

Results from the 2011 survey

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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 a second survey of sediment quality and benthic community health at 16 subtidal sites in Wellington Harbour; ten of these sites were previously sampled in 2006 and six sites were new. The survey was jointly funded by Greater Wellington Regional Council and Wellington City Council and carried out in late 2011.

Consistent with the 2006 survey, the 2011 survey found that concentrations of total copper, lead, zinc and mercury exceed nationally recognised 'early warning' (ie, ARC ERC[1]-amber or ANZECC ISQG[2]-Low) sediment quality guidelines at several sites throughout Wellington Harbour and are indicative of contaminant concentrations where the onset of adverse biological effects could occur. There is evidence of a contaminant gradient extending offshore with some of the highest concentrations of copper, lead, zinc and mercury found at the inner harbour sites adjacent to Wellington city. Concentrations of high molecular weight polycyclic aromatic hydrocarbons (HMW PAHs) exceed ARC ERC-red and ANZECC ISQG-Low sediment quality guidelines at all of the inner harbour and Evans Bay sampling sites, although PAH source analysis indicates that much of this contamination is historic. The insecticide DDT remains a ubiquitous legacy contaminant throughout the harbour with total DDT concentrations being highest at the inner harbour sites where they exceed the ARC ERC-red threshold. Throughout the rest of the harbour total DDT concentrations are much lower but still exceed the ANZECC ISQG-Low threshold at all sites, with the exception of the outer most harbour site. Concentrations of other heavy metals are currently below sediment quality guidelines in the subtidal sediments of the harbour.

Although some statistically significant changes in contaminant concentrations were detected between the two surveys, for the metal concentrations the magnitude of change across sites was small (typically ±8% for weak acid-extractable copper, lead and zinc) and within analytical variability (1–14%). The magnitude of change was considerably higher for HMW PAHs and total DDT, however, high analytical variability explains most of this change and has been an issue for the analyses of organic contaminants, particularly total DDT. As this is only the second survey, it is still too early to assess trends or determine whether these changes are environmentally meaningful and if they will continue into the future; three to five surveys are required before trends can be detected.

A total of 124 invertebrate taxa were identified in the 2011 survey. The most abundant species within the community were polychaete worms, crustaceans, sipunculids and bivalves. The heart urchin, *Echinocardium cordatum,* was a dominant member of the biomass, along with the bivalve *Dosina zelandica,* and the brittle star *Amphiura rosea.* The offshore sediment contaminant gradient appears to be influencing the distribution of some species, such as polychaete worms and the invasive Asian bivalve, that display varying preferences for sediments with high contaminant concentrations.

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[1] Auckland Regional Council (ARC) Environmental Response Criteria (ERC)

[2] Australian and New Zealand Environment and Conservation Council (ANZECC) Interim Sediment Quality Guidelines (ISQG)

Although invertebrate community composition was broadly similar across the 2006 and 2011 surveys, there were some significant differences in the relative abundance of the most dominant species (eg, Sipunculida sp, Tanaidacea sp, *Maldane theodori*) at some sites. The reasons for this are unknown and cannot be attributed to changes in the physical or chemical sediment characteristics recorded at these sites. Furthermore, the contamination present in the harbour is a combination of significant historic inputs and modern sources and the benthic invertebrates found there likely represent an opportunistic community with a degree of pollution tolerance.

Overall, the offshore gradients in sediment contaminant concentrations confirm a land-based, stormwater-borne origin. This is supported by stormwater catchpit sampling which found significant concentrations of copper, lead and zinc in catchpit sediments, likely sourced from amongst other things, vehicle brake and tyre wear, galvanised roofs and historical inputs of road dust and soils contaminated by leaded petrol and lead based paints. Urban stormwater runoff, therefore, appears to be a source of ongoing heavy metal contamination for the harbour.

Contents

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. As contaminants build-up over time they can become toxic to the sediment-dwelling animals. 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 2006, in partnership with Wellington City Council (WCC) and Hutt City Council (HCC), Greater Wellington Regional Council (GWRC) carried out a baseline subtidal sediment survey of 17 sites in Wellington Harbour to assess sediment quality and benthic invertebrate health, with a view to undertaking a second survey within five years. In the intervening period, WCC was granted a global consent to discharge stormwater and occasionally untreated wastewater, directly to Wellington Harbour. A condition of this consent was to monitor harbour sediment quality and invertebrate community health at five-yearly intervals. Thus, the second survey of Wellington Harbour sediments was a joint GWRC/WCC survey designed to reassess sediment quality at sites previously sampled in 2006, and to assess sediment quality at eleven near-shore sites as stipulated in the WCC stormwater consent conditions.

This report presents the results of the second Wellington Harbour subtidal sediment quality investigation carried out from October to December 2011. Although there were some changes to sampling sites for this second survey, the core suite of contaminants and methods of collection and analysis were identical to those of the 2006 survey (Stephenson et al. 2008). In addition, sediments were collected from roadside stormwater catchpits at the bottom of five Wellington city catchments to reconcile information about hydrocarbon sources obtained from harbour sediments (recent *vs* historic). This sampling followed a recommendation by Depree (2010) after an assessment of the 2006 polycyclic aromatic hydrocarbon (PAH) survey data.

1.1 Monitoring objectives

The Wellington Harbour marine sediment quality monitoring programme has two primary objectives:

1. To assess temporal changes in the quality of subtidal sediments and benthic community health at selected sites in Wellington Harbour, likely to be influenced by urban stormwater discharges; and

2. To provide robust scientific information on the health of Wellington Harbour to inform management responses in relation to urban stormwater discharges.

2. Sites and methods

This section outlines the sites selected for sampling, sample collection methods and analytical and statistical techniques. The information presented is largely taken from Stephenson et al. (2008) and apart from some changes to site locations, is identical in methodology to the 2006 survey.

2.1 Sampling sites

2.1.1 Wellington Harbour sediments

Sixteen subtidal sites were sampled in 2011; ten of these sites were previously sampled in 2006 and six sites were new (Figure 2.1, Table 2.1). NIWA originally identified 17 locations in Wellington Harbour at which long-term sediment quality monitoring could be conducted. As a result, these locations became the sampling sites for the 2006 baseline investigation of Wellington Harbour marine sediment quality (Stephenson et al. 2008, Figure 2.1). Following the baseline investigation and a supplementary report on the baseline survey compiled by Milne (2010), the sampling sites were revised for the 2011 survey:

- Sites WH6–WH8, WH10, WH12, WH14 and WH16 were dropped;

- A new 'far-afield' site (WH18) was added at the eastern end of the Petone foreshore to improve detection of contaminants deposited to the west of the Hutt River mouth; and

- Five new 'near-shore' sites (one site in Evans Bay, two sites in Lambton Basin, and two sites east of Aotea Quay) were added, consistent with the requirements of WCC's global stormwater consent conditions to monitor sediment quality and benthic fauna community health.[3]

2.1.2 Stormwater catchpit sediments

Following recommendations by Depree (2010), stormwater catchpit sediment sampling was undertaken primarily to determine the proportion of harbour sediment polycyclic aromatic hydrocarbons (PAH) derived from historic versus recent sources. Four heavy metals were also examined (see Section 2.4.3).

Three catchpits in the lower reaches of each of five stormwater catchments in Wellington city were sampled on 23 September 2011 (Figure 2.2, Appendix 1). The stormwater catchments were selected to coincide with those nearshore harbour sites found to have the highest concentrations of stormwater contaminants in the 2006 survey. Stormwater catchpit sediments were sampled under the assumption that they represent the contaminants present in urban stormwater runoff.

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[3] Results of the 2006 survey indicated that sediment contamination was greatest in Evans Bay, Lambton Basin and the Kaiwharawhara/Aotea Quay area and therefore it was deemed appropriate during the consenting process that WCC monitor some additional 'stormwater impact' sites nearer to shore in these areas.

Figure 2.1: Map of Wellington Harbour showing the subtidal locations sampled in 2006 and 2011. Sample collection and analyses at sites EB1, WH1–5, LB1–2, AQ1–2 and WH10 were funded by Wellington City Council

Table 2.1: Locations and depths for the Wellington Harbour subtidal sediment quality sites sampled between October and December 2011

Site	Location	Depth (m)
WH1	Southern Evans Bay	19
WH2	Northern Evans Bay	19
WH3	Lambton Basin entrance	18
WH4	~ 0.7 km NW of Point Jerningham	20
WH5	~ 1.2 km NNE of Point Jerningham	21
WH9	~ 1.5 km SSE of Ngauranga Stream mouth	20
WH10	~ 0.5 km SSE of Ngauranga Stream mouth	20
WH13	~ 1.25 km S of Petone Wharf	16
WH15	~ 1.1 km SW of Seaview (Hutt River mouth)	16
WH17	~ 1.6 km NNW of Makaro/Ward Island	21
WH18	~1.75 km WSW of Seaview (Hutt River mouth)	16
EB	SW Evans Bay ~250 m from shore (Cobham Drive)	7
LB1	Lambton Harbour ~ 250 m from shore (Frank Kitts Park)	10
LB2	Lambton Harbour ~ 500 m from shore (Frank Kitts Park)	14
AQ1	~ 0.5 km ENE of Aotea Quay east	20
AQ2	~ 0.5 km ENE of Aotea Quay west	16

Further detailed information about site co-ordinates and sampling dates can be found in Appendix 1.

Figure 2.2: Map of Wellington city showing the stormwater catchments (coloured areas) and location of roadside catchpit samples (yellow circles) collected on 23 September 2013

2.2   Sediment quality

2.2.1   Sample collection

Sampling was conducted using a boat and divers equipped with SCUBA. At each site, the centre of the sediment quality collection area (a circle 20 m 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 2.3). 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 2.3: Example of a sediment core from Wellington Harbour. Only the top 30 mm of the core is used to analyse sediment particle size distribution and chemistry (Source: Gary Stephenson)

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.

2.2.2 Sample preparation

Sample preparation followed the steps shown in Figure 2.4 and is consistent with methods used in the 2006 baseline survey. Frozen sediment samples were thawed at room temperature and then transferred to a solvent-rinsed aluminium tray and thoroughly homogenised. A sub-sample of the homogenised sediment was transferred to a glass container for total petroleum hydrocarbon (TPH) analysis. For sites with large amounts of shell or debris (LB1, AQ2, EB1) the whole wet sediment was wet sieved at 1 mm to provide a suitable subsample for TPH analysis. Another subsample (~50 mL) of the homogenised sediment was removed and then carefully wet-sieved through a nylon mesh to obtain a representative <63 μm fraction (or mud fraction). The <63 μm material was freeze-dried prior to sub-sampling for analysis of weak acid extractable metals and long term storage.

The remainder of the whole sample was freeze-dried in preparation for chemical analyses of total metals, total organic carbon (TOC), organochlorine pesticides (OCPs) and polycyclic aromatic hydrocarbons (PAHs) and for particle size distribution. The freeze-dried sample was sieved though a 500 μm sieve to remove any large particles. For sites LB1, AQ2 and EB1 with large

amounts of shell or other debris, the mass of each particle size fraction >500 μm was also determined.
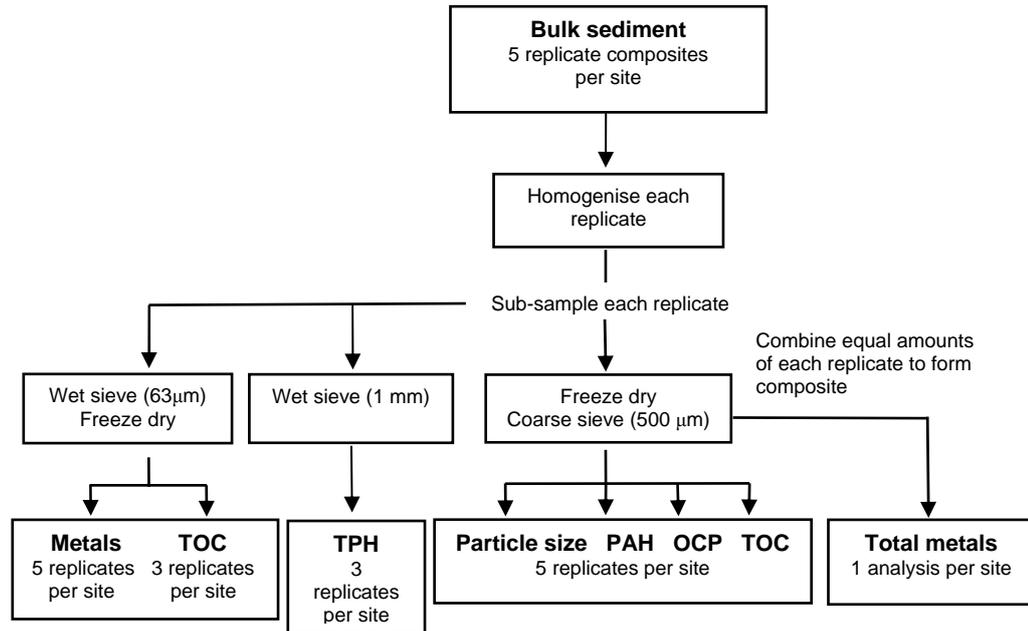
**Figure 2.4: Harbour sediment sample preparation scheme (adapted from Williamson et al. 2005)**

2.2.3   Sediment particle size distribution

Particle size analysis of the <500 μm fraction was conducted using an Eyetech particle size analyser. Initially, the samples were analysed using the A-lens of the Eyetech analyser consistent with the analyses of Porirua Harbour subtidal sediments in 2008 and 2010 (Milne et al. 2009; Oliver et al. in prep). However, inconsistencies between the 2011 sediment particle size results and those from the 2006 Wellington Harbour survey analysed on another machine, the Galai CIS-100 laser sizer, prompted reanalyses of all sediment particle size samples from both the 2006 and 2011 surveys. These reanalyses were all carried out in mid-2013 using the B-lens of the Eyetech particle sizer, following experimental trials at NIWA which found that this lens was better suited to mud samples that also contain a very small amount of sand particles. The B-lens has a larger measurement volume (10–500 μm compared with 0.1–300 μm using the A-lens) and provided a higher level of repeatability (Olsen et al. 2013).

Each sediment sub-sample was freeze-dried and then dry-sieved through a 500 μm screen to remove coarse debris. The material was ultrasonically dispersed for four minutes before analysis. Typically, 10^5–10^6 particles are counted per sample. 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.

2.2.4 Total organic carbon (TOC)

A portion of the freeze-dried <500 μm fraction of each replicate at a site was analysed for TOC using an Elementar Combustion Analyser, after acid pre-treatment to remove carbonates.

A portion of the <63 μm fraction of three of the five replicates at a site was also analysed for TOC.

2.2.5 Total metals

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

2.2.6 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.

2.2.7 Organochlorine pesticides (OCPs)

A portion of the freeze-dried <500 μm fraction of each replicate was analysed for a suite of OCPs – gamma-BHC (lindane), hexachlorobenzene, aldrin, dieldrin, endrin, heptachlor, heptachlor epoxide, cis-chlordane, trans-chlordane, cis-nonachlor, trans-nonachlor, 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 gas chromatography-mass spectrometry in selected ion mode GC-MS-SIM.

2.2.8 Polycyclic aromatic hydrocarbons (PAHs)

A portion of the freeze-dried <500 μm fraction of each replicate was analysed for the 16 USEPA priority pollutant PAHs – 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, dibenz(a,h)-anthracene and benzo(g,h,i)perylene – using a procedure involving sonication solvent extraction and GC/MS-SIM.

In addition, selected PAH chemical marker compounds (methylfluorenes, dimethylphenanthrenes, trimethylphenanthrenes and dimethyldibenzothiphenes) and hopanes (hopane, norhopane, and homohopane) were analysed using the same methods as above, to provide information about the sources of PAHs. Hopane analyses were carried out on a composite sample, prepared by combining equal quantities of the freeze-dried <500 μm sediments from the five replicates for each site.

2.2.9 Total petroleum hydrocarbons (TPHs)

A portion of the homogenised whole wet sediment (or 1 mm wet sieved sediment for sites with larger particles) for three replicates at each site was

analysed for TPHs, using the gas chromatography-flame ionization detection (GC-FID) method, USEPA 8015/NZ.

2.2.10 Quality assurance

Quality assurance for the sediment particle size and chemistry analyses 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:

- Particle size analysis: 15 duplicates
- TOC (500 µm fraction): 5 duplicates, 3 archive
- TOC (63 µm fraction): 3 duplicates, 3 archive
- Metals, strong hot acid technique: 2 duplicates, 1 archive
- Metals, cold dilute acid technique: 5 duplicates, 3 archive
- PAHs: 5 duplicates, 4 archive, 1 SRM
- TPHs (<1 mm fraction): 5 duplicates
- OCPs: 5 duplicates, 4 archive, 1 SRM

2.2.11 Long-term sediment sample storage

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

2.3 Benthic ecology

2.3.1 Sample collection

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

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. Five 50 mm diameter x 120 mm deep sediment cores were collected for particle size analysis, one from each quadrant and one from near the centre of the collection area.

2.3.2 Sample preparation and analysis

The benthic ecology 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

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[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, family or generic name as appropriate.

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 ($\leq$ 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 quality samples. For each site, the sediment in the top 30 mm of the five 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 the B-lens of the Eyetech laser particle size analyser, as described in Section 2.2.3.

2.4 Stormwater catchpit sediments

2.4.1 Sample collection

The catchpit lid was lifted and the samples taken manually using a plastic hand trowel. Generally there was little material in the catchpits but roughly one scoop of material was collected from each of three catchpits. Sediment was composited by catchment into plastic ziplock bags, labelled and frozen.

2.4.2 Sample preparation

Sample preparation followed the steps shown in Figure 2.5 and used the same methods as those provided in Section 2.2.2.
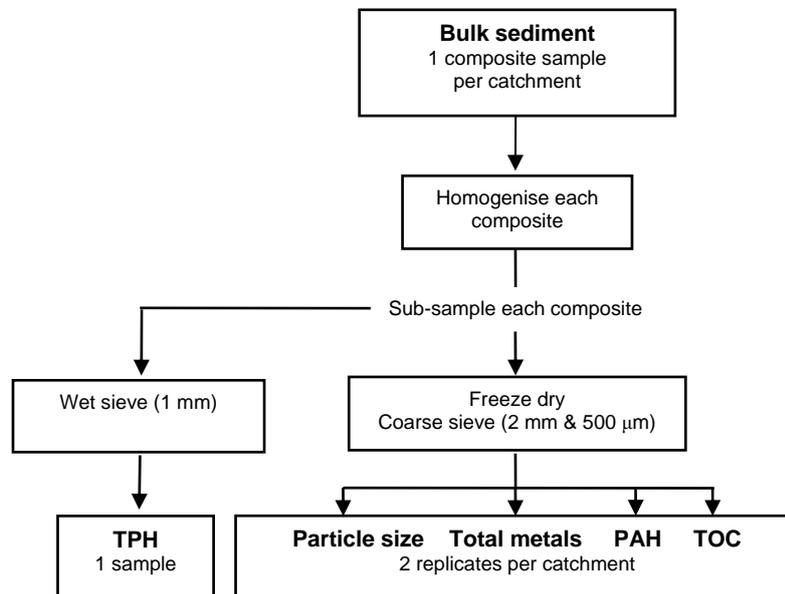

Figure 2.5: Stormwater catchpit sample preparation scheme (adapted from Williamson et al. 2005)

2.4.3 Sample analyses

All sample analyses for sediment particle size distribution, total metals, TOC, PAHs and TPH followed the same methods as those outlined in Section 2.2. Analyses of total metals, however, were restricted to lead, copper, zinc and

mercury as these are key stormwater contaminants and were present above sediment quality guidelines at inner harbour sites in the 2006 survey. QA included blanks, replicates, analyses of archived harbour sediments from 2006 and a SRM, and were carried out in conjunction with the QA performed on the harbour subtidal sediments (see Section 2.2.10).

2.5   Data analysis

2.5.1   Sediment quality guidelines

Consistent with the 2006 survey, both the ANZECC (2000)[5] and the ARC Environmental Response Criteria (ERC) (ARC 2004) sediment quality guidelines are used in this report to assess the potential ecological effects of contaminants identified in the 2011 Wellington Harbour subtidal sediment quality survey (Table 2.2). These guidelines are generally considered to be reasonably robust, and conservative (ie, 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.

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

1.   the 'low' values (ANZECC ISQG-Low, TEL[6] and ERL[2]) 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.

2.   the 'high' values (ANZECC ISQG-High, PEL[7] and ERM[3]) 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), derived from the Threshold Effect Levels (TEL) and Effects Range Low (ERL) values (with rounding) of MacDonald et al. (1994) and Long and Morgan (1990), respectively (Kelly 2007). These guidelines provide a conservative, yet practical 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).

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[5] Note that the ANZECC sediment quality guidelines are currently under review and some guideline values are likely to change.

[6] 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).

[7] 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).

Table 2.2: Sediment quality guidelines used in the Wellington Harbour subtidal 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):				
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
Polycyclic Aromatic Hydrocarbons (µg/kg dry wt):[2]				
Naphthalene	160	2,100		
Acenaphthalene	44	640		
Acenaphthene	16	500		
Fluorene	19	540		
Phenanthrene	240	1,500		
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.

It should be noted that the ARC ERC, unlike the ANZECC guidelines, have single "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 (eg, use in horticulture, spills around ports, and contaminated site discharges) rather than ongoing contamination from current activities.

It should also be noted that the use of sediment quality guidelines is a 'first-step' approach to assessing the potential impacts of contaminated sediments on benthic ecology. 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 (eg, such as the PAH source analyses contained in this report), prediction of future sediment quality, and an evaluation of management options.

2.5.2 Statistical analyses

(a) Sediment quality

Differences in the concentrations of weak acid extractable copper, lead and zinc, and the proportion of TOC and mud (<63 μm), were plotted using means and 95% confidence intervals (CI) so that differences among sites could be visualised. Changes through time (ie, between 2006 and 2011) were depicted with scatter plots of contaminant concentrations. The Mann Whitney Rank Sum Test was used to test for significant differences in TOC, %<63 μm (mud) sediment fraction, weak acid extractable metals, DDT and PAH between surveys. In Tables 3.1 and 3.2, the mean values are listed along with the coefficient of variation (c.v.), a normalised measure of dispersion.

Principal coordinates analysis (PCA) was used to explore the relationships between the physical and chemical sediment quality variables. Metal concentrations were log transformed and all sediment quality variables normalised prior to analyses.

(b) Benthic ecology

The number of species, wet weight of each species (biomass), mean number of species per sample and mean number of individuals per sample were determined for each site. The size frequency distributions of the echinoderm, *Echinocardium cordatum* and selected species of bivalves were determined and summarised in diagrammatic form as dot plots.

Spatial and temporal variation in the composition of benthic communities was examined using diversity indices and multivariate analyses. Non-metric multi-dimensional scaling (MDS) and cluster analysis were used to identify patterns in ecological data, based on the similarity (or dissimilarity) of species assemblages. Square root transformed[8] count data, using Bray Curtis similarity, were used to examine spatial differences and temporal changes in the composition of the benthic communities. Identification of the key species involved in producing the observed patterns was made by looking at similarity percentages (using Primer's SIMPER routine). All analyses were carried out using Primer-E (v6), and readers are referred to Clarke and Gorley (2006) and Clarke and Warwick (2001) for further details on most of the analyses used.

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[8] This transformation was chosen because it provided a better representation of the benthic fauna amongst sites, as indicated by lower stress values.

Species were also assigned to one or more of five feeding modes (predators/ scavengers, surface deposit feeders, subsurface deposit feeders, suspension feeders and unknown) (Stephenson & Mills 2006). 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 five 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.

3. Results

The results of the 2011 survey of Wellington Harbour subtidal sediments are summarised in this section, along with the results of the 2011 stormwater catchpit sediment sampling. Comparisons are also made with the 2006 subtidal survey results. The complete list of sediment particle size and chemistry results are presented in Appendices 2 and 3, respectively, and the quality assurance results are presented in Appendix 4. Sediment profiles for the six new sites sampled in 2011 are presented in Appendix 5 and lists of species recorded, their abundance, feeding modes and selected shell/body sizes are presented in Appendix 6.

3.1 Sediment quality

3.1.1 Sediment particle size distribution

Mean particle size and mean percentage of particles <63 μm for the 16 monitoring sites are given in Table 3.1 and shown in Figure 3.1. The key findings were:

- Just over half of the 16 sites had sediments with a mud content of between 63 and 90% and were deemed to be sandy mud or very sandy mud;
- Site EB1 had the lowest mud content (<63 μm fraction 1.8%);
- The inner harbour sites WH1, LB1, LB2 and AQ2 and the outer harbour site WH17 were dominated by sediments with a mud content ranging between 17–45%. These sites were characterised as muddy sands; and
- Three near-shore sites, LB1, AQ2 and EB1, had large amounts of shell fragments, gravel and/or seaweed. The proportion of sample represented by this larger material ranged from 1.7 to 17% (Appendix 2).

3.1.2 Total organic carbon (TOC)

The mean TOC contents in the <63 μm and <500 μm fractions of the sediments of the 16 monitoring sites are given in Table 3.1 and shown in Figure 3.2. The key findings were:

- The mean TOC contents ranged from 0.4 to 1.9% and varied widely throughout the harbour;
- The highest TOC contents were at sites WH13, WH15 and WH18, offshore from Petone Beach (1.8–1.9%);
- The TOC content was also high (>1.6%) at the inner harbour sites WH1, WH3, WH4, LB2 and AQ2, and at site WH10 near the mouth of the Ngauranga Stream; and
- Variability in the mean TOC content was higher in the near-shore inner harbour sites (c.v.=1.4–5.6%) than at outer harbour sites (c.v.=0.5–1.4%).

3.1.3 Total metals

The total concentrations of metals for the 16 monitoring sites are shown in Table 3.1 and presented graphically in Figures 3.3 to 3.5. The key findings were:

- The concentrations of most metals (Cu, Pb, Zn, Hg, Cd, Ag) were generally higher at the inner harbour sites (WH1–WH4, LB1–2, AQ1–2),

than the outer harbour sites (WH5, WH9 –WH10, WH13, WH15, WH17–WH18), with the exception of site EB1 where metal concentrations were often much lower than at all other harbour sites;

- Concentrations of chromium and nickel showed little spatial variation, whereas arsenic concentrations were higher at the outer harbour sites (WH13, WH15, and WH17);

- Copper concentrations exceeded the ARC ERC red threshold at the two Lambton Basin sites (LB1 and LB2) and the ARC ERC amber threshold at sites WH1 and WH3. Copper concentrations at sites WH4 and AQ1 were at the ARC ERC amber threshold;

- Lead concentrations exceeded the ARC ERC red threshold and the ANZECC ISQG-Low trigger value at the inner harbour sites WH1, WH2, WH3, LB1, LB2 and AQ2. Lead concentrations exceeded the ARC ERC amber threshold at all other sites in the harbour with the exception of site EB1 and the outer-most harbour site, WH17;

- Zinc concentrations were below guideline values at all sites, with the exception of site LB2, which exceeded the ARC ERC amber threshold. Zinc concentrations at site WH1 and WH3 were very close to the amber threshold; and

- Concentrations of arsenic, cadmium, chromium, nickel and silver, were all below their respective ANZECC ISQG-Low trigger values in the sediments of all sites. However, mercury concentrations exceeded the ANZECC ISQG-Low trigger value at all but one harbour site (WH17).

3.1.4 Weak acid-extractable metals

Mean concentrations and variability of weak acid-extractable metals (<63 μm fraction) for the 16 monitoring sites are shown in Table 3.1 and presented graphically in Figure 3.6. The key findings were:

- Copper, lead and zinc concentrations were all higher at the inner harbour and Evans Bay sites than at sites elsewhere;

- Both sites in Lambton Basin (LB1 and LB2) and in Evans Bay (EB1 and WH1) had consistently higher concentrations of copper, lead and zinc than other sites;

- Copper, lead and zinc were also high at site WH3, at the entrance to Lambton Basin;

- The concentrations of copper, lead and zinc were very weakly correlated with organic carbon content (r=0.49, 0.48 and 0.51, respectively, based on data from all sites);

- Copper, lead and zinc concentrations were strongly correlated with each other (r=0.84, 0.88 and 0.98 for mean copper/lead, copper/zinc, lead/zinc, respectively); and

- The data show reasonably low variability (c.v.=0–5.3%) across all sites, indicating that it should be possible to detect relatively small changes in metal concentrations through time.

Table 3.1: Mean particle size, percentage of particles <63 μm, and summary of concentrations and variability (co-efficient of variation [c.v.,%], _n_=5*) of metals in sediments of 16 sites sampled in Wellington Harbour in 2011. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Council Environmental Response Criteria (ARC ERC; ARC 2004). Cells highlighted 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 analysed	ANZECC		ARC ERC		Site							
		ISQG-Low	ISQG-High	amber	red	EB1	WH1	WH2	LB1	LB2	WH3	WH4	AQ1
Mean particle size (μm)	< 500 μm	-	-	-	-	167 (2)	93 (7)	57 (14)	147 (9)	98 (18)	53 (3)	58 (11)	67 (14)
% particles < 63 μm	< 500 μm	-	-	-	-	2 (9)	35 (6)	64 (10)	17 (16)	37 (15)	68 (3)	65 (8)	58 (14)
Total organic carbon (%)	< 63 μm	-	-	-	-	1.8 (1.0)	1.5 (1.3)	1.3 (1.2)	1.6 (2.1)	1.7 (1.2)	1.5 (0.8)	1.5 (0.7)	1.4 (2.2)
Total organic carbon (%)	< 500 μm	-	-	-	-	0.4 (4.9)	1.7 (1.6)	1.4 (1.4)	1.3 (2.0)	1.6 (2.2)	1.7 (1.4)	1.6 (2.4)	1.6 (1.6)
Weak acid-extractable metals (mg/kg):													
Copper (Cu)	< 63 μm	-	-	-	-	20.6 (5.3)	21.6 (2.5)	13.8 (4.2)	49.0 (2.0)	39.2 (1.1)	23.8 (3.5)	16.1 (1.8)	16.3 (4.4)
Lead (Pb)	< 63 μm	-	-	-	-	74.8 (3.5)	70.8 (0.6)	48.8 (2.2)	80.0 (2.7)	74.8 (3.7)	61.0 (1.6)	47.8 (3.4)	48.8 (1.7)
Zinc (Zn)	< 63 μm	-	-	-	-	122 (3.2)	119 (2.4)	96.6 (0.9)	135 (2.9)	133 (1.0)	115 (2.3)	99.2 (1.9)	100 (2.4)
Total metals (mg/kg):													
Silver (Ag)	< 500 μm	1	3.7	-	-	0.11	0.65	0.37	0.57	0.63	0.52	0.34	0.32
Arsenic (As)	< 500 μm	20	70	-	-	4.9	6.2	5.7	5.8	6.2	6.2	6.5	6.1
Cadmium (Cd)	< 500 μm	1.5	10	-	-	0.017	0.075	0.058	0.063	0.065	0.061	0.046	0.062
Chromium (Cr)	< 500 μm	80	370	-	-	12	24	24	21	26	26	26	24
Copper (Cu)	< 500 μm	65	270	19	34	4.9	22	16	39	38	26	19	19
Mercury (Hg)	< 500 μm	0.15	1	-	-	0.21	0.69	0.60	0.56	0.63	0.63	0.45	0.50
Nickel (Ni)	< 500 μm	21	52	-	-	5.3	15.2	15.4	12.5	15.3	15.7	16.9	16.2
Lead (Pb)	< 500 μm	50	220	30	50	27	68	51	62	67	60	49	47
Zinc (Zn)	< 500 μm	200	410	124	150	47	121	104	114	133	122	111	105

*For particle size and weak acid-extractable metals only

Table 3.1 *continued*: **Mean particle size, percentage of particles <63 μm, and summary of concentrations and variability (co-efficient of variation [c.v.,%], *n*=5*) of metals in sediments of 16 sites sampled in Wellington Harbour in 2011. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Council Environmental Response Criteria (ARC ERC; ARC 2004). Cells highlighted 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 analysed	ANZECC		ARC ERC		Site							
		ISQG-Low	ISQG-High	amber	red	AQ2	WH5	WH9	WH10	WH13	WH18	WH15	WH17
Mean particle size (μm)	< 500 μm	-	-	-	-	136 (3)	45 (5)	37 (15)	35 (7)	43 (10)	43 (7)	59 (4)	77 (5)
% particles < 63 μm	< 500 μm	-	-	-	-	25 (5)	78 (4)	89 (9)	90 (4)	82 (5)	81 (5)	62 (5)	45 (5)
Total organic carbon (%)	< 63 μm	-	-	-	-	1.4 (2.2)	1.3 (2.3)	1.4 (1.1)	1.5 (0.4)	1.6 (0.4)	1.6 (1.0)	1.7 (1.8)	1.2 (1.3)
Total organic carbon (%)	< 500 μm	-	-	-	-	1.4 (5.6)	1.3 (0.8)	1.5 (1.3)	1.6 (0.8)	1.8 (0.5)	1.8 (0.9)	1.9 (0.7)	1.2 (1.4)
Weak acid-extractable metals (mg/kg):													
Copper (Cu)	< 63 μm	-	-	-	-	16.7 (3.5)	10.7 (1.7)	9.6 (3.1)	12.3 (1.9)	12.9 (2.2)	12.0 (4.4)	12.7 (3.7)	9.6 (1.7)
Lead (Pb)	< 63 μm	-	-	-	-	53.8 (2.4)	35.0 (2.0)	36.6 (3.1)	42.8 (1.0)	37.6 (1.5)	33.8 (1.3)	29.0 (0)	29.2 (1.5)
Zinc (Zn)	< 63 μm	-	-	-	-	104 (2.6)	80.4 (2.1)	83.2 (1.8)	93.6 (3.0)	89.4 (1.3)	82.4 (1.1)	77.2 (1.9)	75.0 (0.9)
Total metals (mg/kg):													
Silver (Ag)	< 500 μm	1	3.7	-	-	0.25	0.23	0.25	0.30	0.28	0.25	0.20	0.20
Arsenic (As)	< 500 μm	20	70	-	-	6.5	6.4	6.4	6.7	7.9	8.1	8.3	6.0
Cadmium (Cd)	< 500 μm	1.5	10	-	-	0.076	0.042	0.047	0.055	0.054	0.056	0.057	0.038
Chromium (Cr)	< 500 μm	80	370	-	-	22	23	25	26	24	23	21	21
Copper (Cu)	< 500 μm	65	270	19	34	17.4	12.9	13.5	16.2	15.2	14.7	14.7	11.0
Mercury (Hg)	< 500 μm	0.15	1	-	-	0.44	0.29	0.24	0.27	0.20	0.16	0.16	0.12
Nickel (Ni)	< 500 μm	21	52	-	-	14.1	15.6	17.4	18.1	17.3	16.3	15.6	15.6
Lead (Pb)	< 500 μm	50	220	30	50	65	37	36	45	39	35	31	29
Zinc (Zn)	< 500 μm	200	410	124	150	104	90	96	109	102	95	90	80

*For particle size and weak acid-extractable metals only
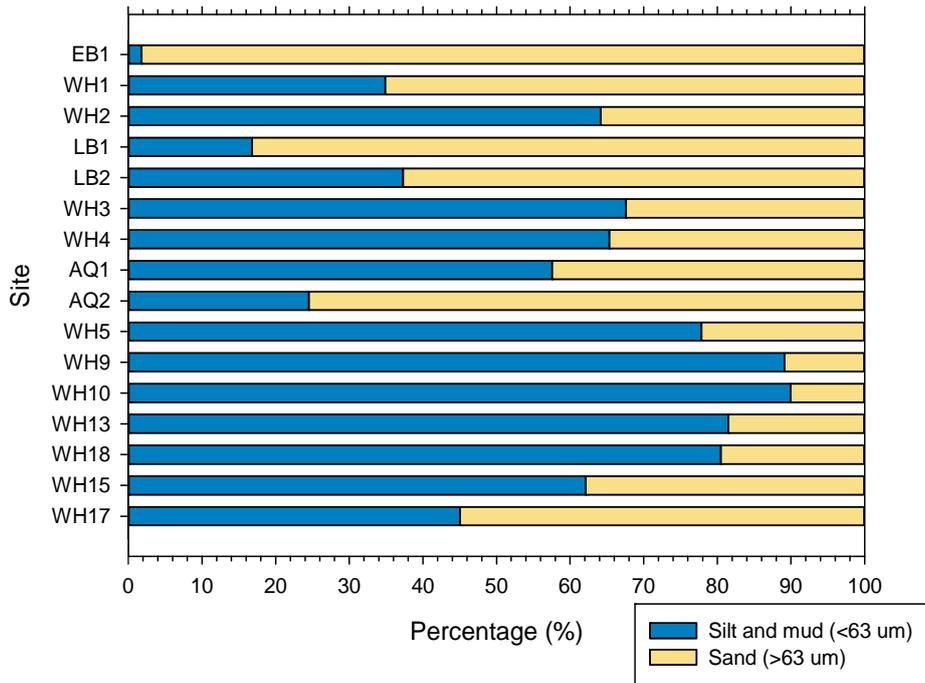
Figure 3.1: Mean proportion of mud (<63 μm) and sand fractions (>63 μm) in sediment of 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction of five composite samples from each site
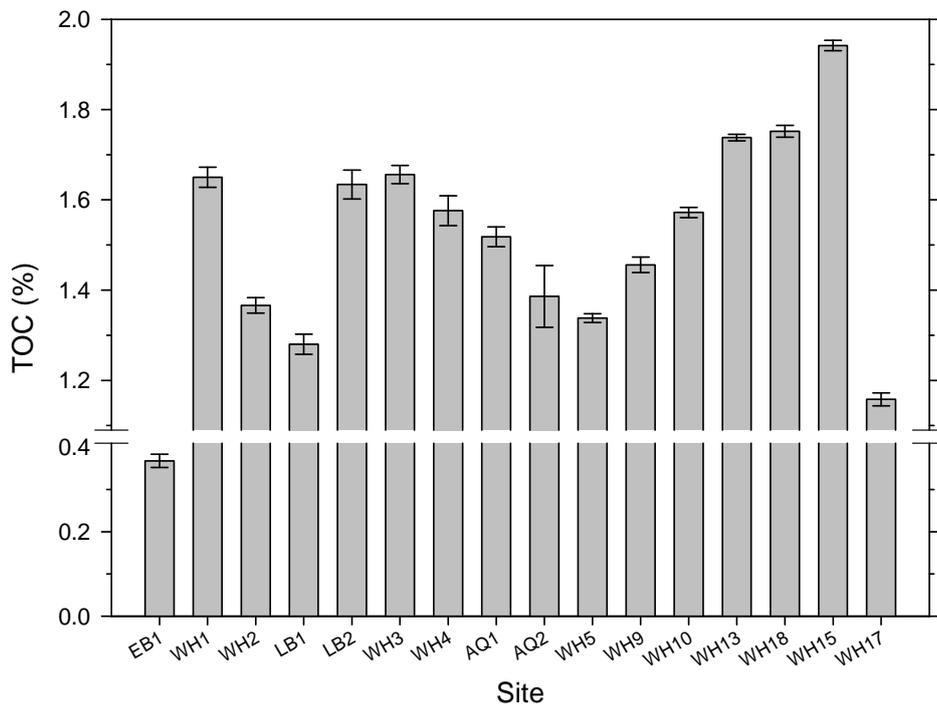
Figure 3.2: Mean (± 95% CI) total organic carbon (TOC) in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction of five composite samples from each site. Note the scale break on the *y*-axis
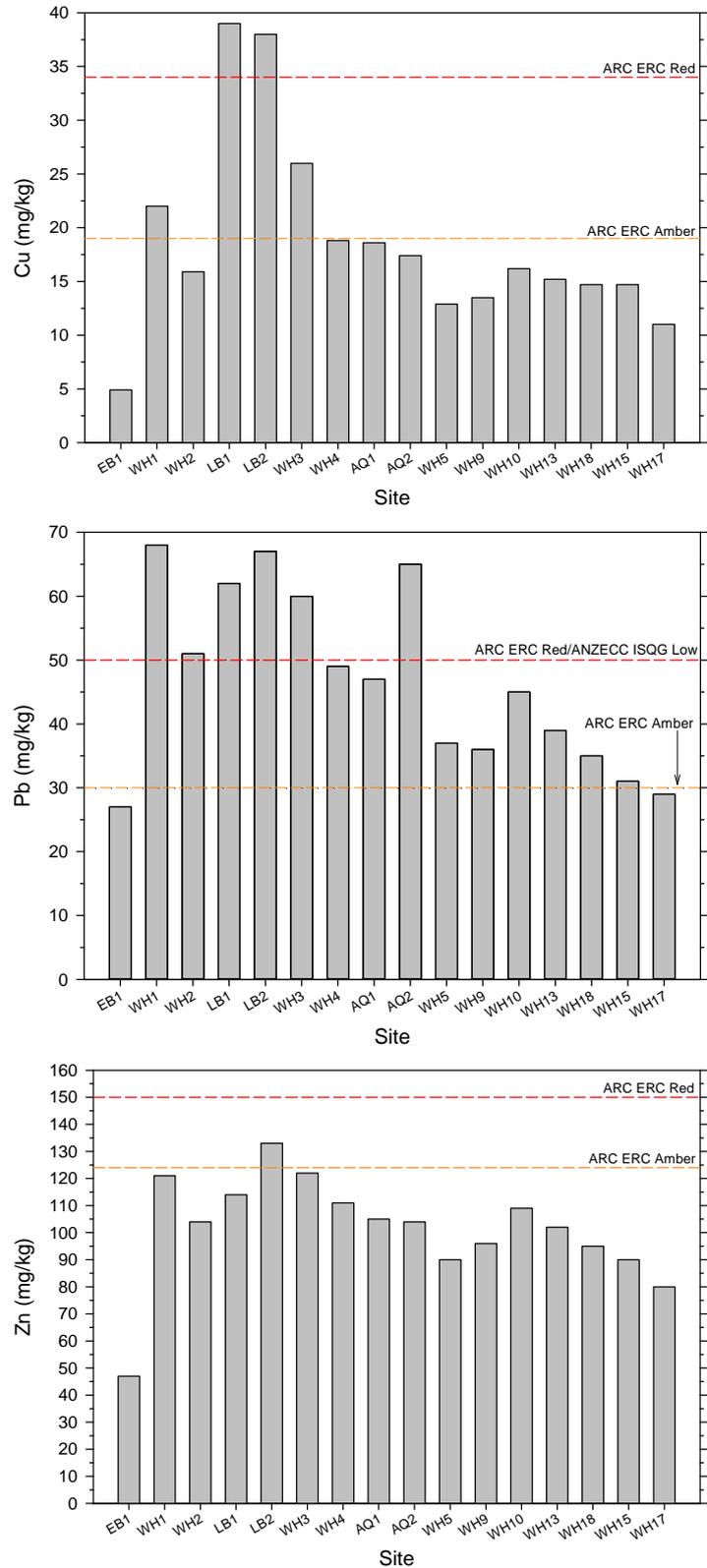
Figure 3.3: Concentrations of total copper (Cu), lead (Pb) and zinc (Zn) in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction of a single composite sample from each site
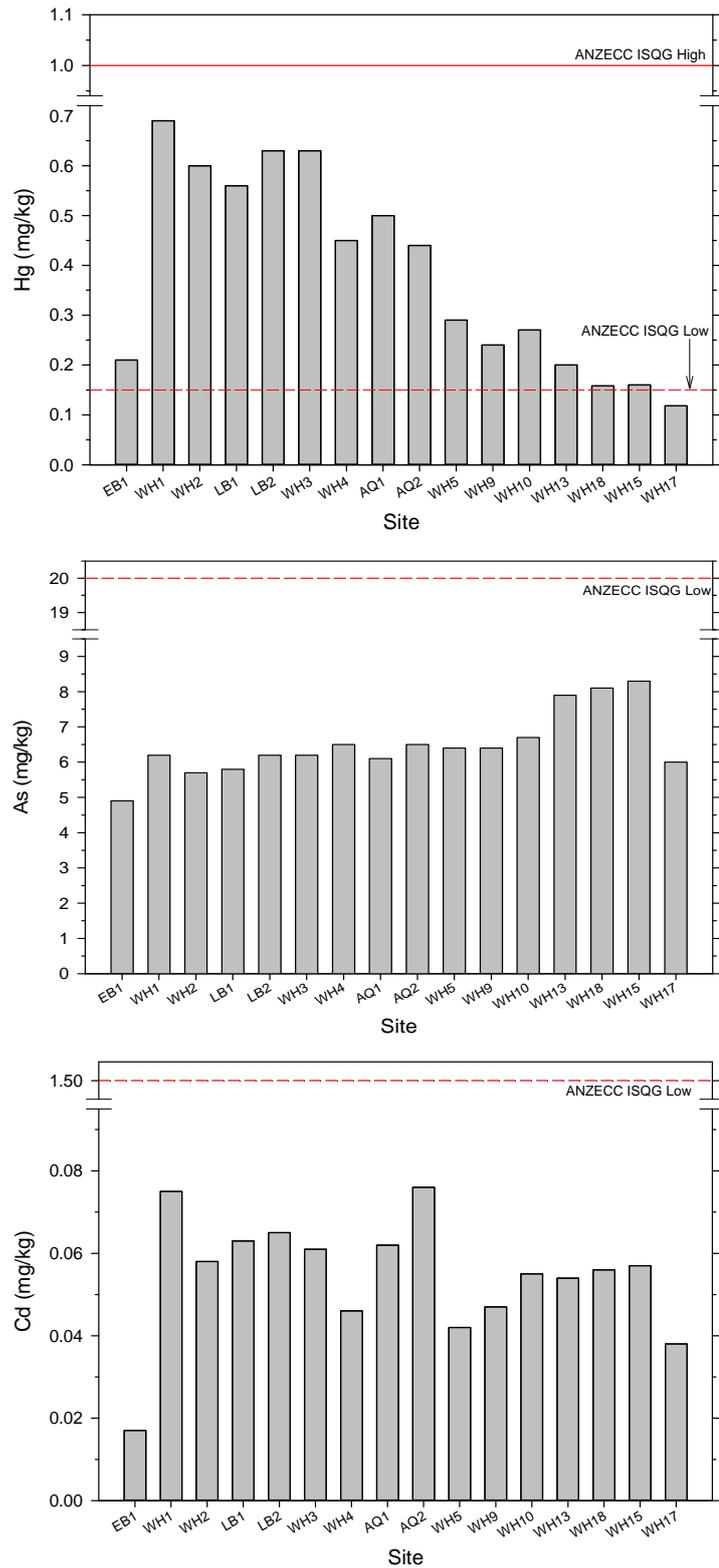
Figure 3.4: Concentrations of total mercury (Hg), arsenic (As), and cadmium (Cd) in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 µm fraction of a single composite sample from each site. Note the scale break on the *y*-axis of each graph
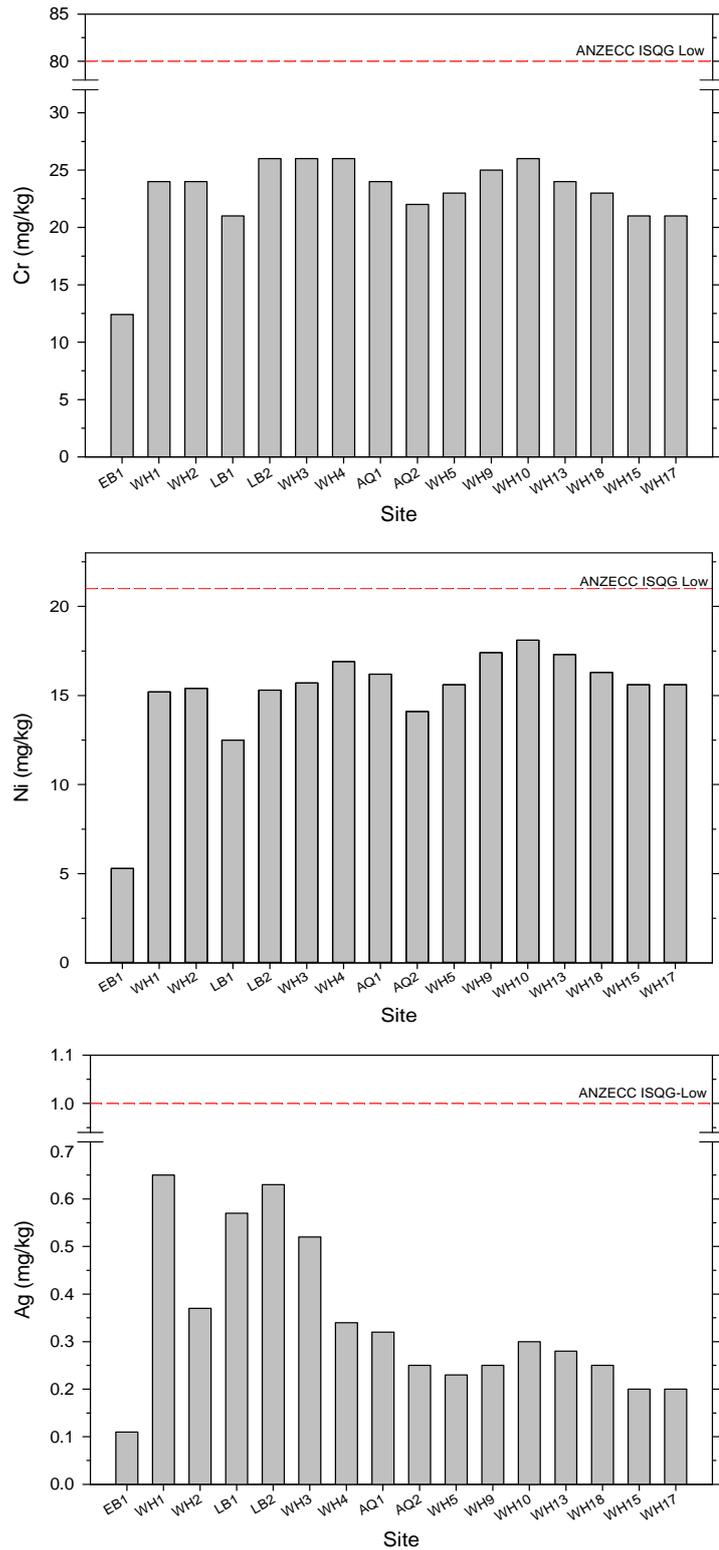
Figure 3.5: Concentrations of total chromium (Cr), nickel (Ni) and silver (Ag) in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction of a single composite sample from each site. Note the scale break on the *y*-axis of the Cr and Ag graphs
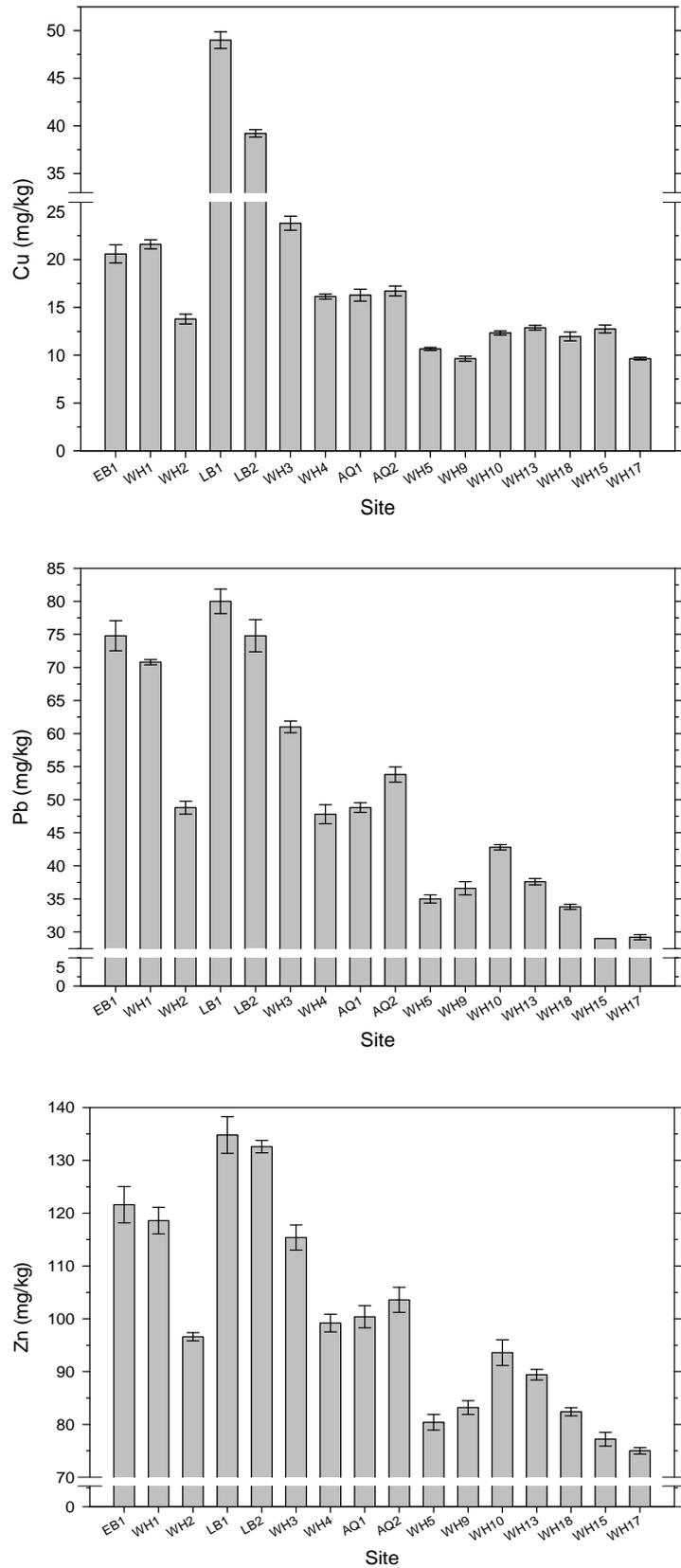
Figure 3.6: Mean (± 95% CI) concentrations of weak acid extractable copper (Cu), lead (Pb) and zinc (Zn) in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <63 μm fraction of five composite samples from each site. Note the scale break on the _y_-axis of each graph

3.1.5 Organochlorine pesticides (OCPs)

The mean concentrations of selected OCPs are shown in Table 3.2 and Figures 3.7 and 3.8. The key findings were:

- Of the 17 organochlorine pesticides that were analysed, only DDT, DDE, and DDD were consistently found above detection limits in the sediments of all sites;

- Total DDT concentrations were highest at site WH3, with replicate sample concentrations ranging between 10.7 and 61 µg/kg; variability between replicates was very high (mean total DDT concentration = 28 µg/kg; c.v.=82.2). Additional replicate analyses of sediments at site WH3, undertaken for quality assurance purposes, confirmed that DDT concentrations were high at this site;

- At all other sites, mean total DDT concentrations ranged between 0.9 and 19 µg/kg, with the higher concentrations recorded at the inner harbour sites of LB1 and LB2;

- TOC-normalised mean total DDT concentrations exceeded the ARC ERC red threshold at the inner harbour sites of WH1–WH4, LB1–2 and AQ1–2, and were above ANZECC ISQG-Low trigger values at all sites, with the exception of site WH17 (Figure 3.7);

- With the exception of site EB1, DDT was the dominant constituent of total DDT at inner harbour sites, with the proportion of DDT decreasing progressively with distance from the city. DDE was the dominant constituent at sites on the eastern side of the harbour (WH13, WH15, WH17–18) (Figure 3.8); and

- Hexachlorobenzene was present in the sediment of sites LB1, LB2 and WH3 at mean concentrations of 0.1–0.9 µg/kg, but was not detected at any other sites. There are no recommended trigger values for hexachlorobenzene in the ANZECC (2000) sediment quality guidelines.

3.1.6 Polycyclic aromatic hydrocarbons (PAHs)

The mean total PAH, mean total High Molecular Weight PAH (total HMW PAH) and selected PAH concentrations are shown in Table 3.2 and Figure 3.9. The key findings were:

- TOC-normalised total HMW PAH concentrations exceeded the ANZECC ISQG-Low trigger value at sites WH1 and LB1, and the ARC ERC amber threshold at the seven remaining inner harbour sites (EB1, WH2–4, LB2, AQ1-2);

- TOC-normalised total PAH concentrations did not exceed ANZECC (2000) sediment quality guidelines at any sites;

- TOC-normalised fluorene concentrations exceeded the ANZECC ISQG-Low trigger value at sites WH1, WH3, LB1 and LB2; and

- There was low variability between replicates at all sites (c.v.=1–8.6%) with the exception of site WH13 which showed high variability (c.v.=20.5 and 17.9% for HMW PAH and Total PAH, respectively).

Table 3.2: Summary of mean concentrations and variability (coefficient of variation [c.v., %], n=5) of total organic carbon (TOC) and selected organic contaminants in sediments of 16 sites sampled in Wellington Harbour in 2011. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Council Environmental Response Criteria (ARC ERC; ARC 2004). Cells highlighted 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 analysed | ANZECC trigger values | | ARC ERC thresholds | | Site | | | | | | | |
		ISQG-Low	ISQG-High	amber	red	EB1	WH1	WH2	LB1	LB2	WH3	WH4	AQ1
TOC (%)	< 500 µm					0.4 (4.9)	1.7 (1.6)	1.4 (1.4)	1.3 (2)	1.6 (2.2)	1.7 (1.4)	1.6 (2.4)	1.6 (1.6)
Organics (µg/kg dry wt):													
Hexachlorobenzene	< 500 µm					<0.1 (0)	<0.1 (0)	<0.1 (0)	0.1 (34)	0.6 (86)	0.9 (29)	<0.1 (0)	<0.1 (0)
Total DDT [2,3]	< 500 µm					0.9 (10)	10.6 (5.2)	4.9 (4.7)	19 (15)	12.9 (9.2)	28 (82)	6.2 (4.2)	9.8 (6.9)
Hexachlorobenzene [4]	at 1% TOC					0.1 (4.9)	<0.1 (0)	<0.1 (0)	0.1 (34)	0.4 (85)	0.5 (28)	<0.1 (0)	<0.1 (0)
Total DDT [2,3,4]	at 1% TOC	1.6	46		3.9	2.6 (10)	6.4 (4.6)	3.6 (3.8)	14.9 (16)	7.9 (9.9)	16.9 (82)	3.9 (5.6)	6.5 (6.3)
Naphthalene	< 500 µm					10.2 (12)	89.3 (9.6)	33.6 (1.8)	60.9 (3.9)	64.1 (2.4)	66.7 (4.7)	31.3 (5.5)	42.3 (8.3)
Fluorene	< 500 µm					4.7 (11)	49.8 (6.9)	19 (3.4)	40.7 (11)	35.6 (3.0)	32.9 (4.7)	16.9 (2.6)	22.8 (3.6)
Total HMW PAHs [1,2,4]	< 500 µm					299 (8.6)	3,285 (3.2)	1,439 (1.3)	2,506 (5.1)	2,724 (3.4)	2,478 (3.7)	1,227 (1.0)	1,489 (5.0)
Total PAH [1,2]	< 500 µm					553 (7.3)	5,787 (2.7)	2,585 (1.1)	4,440 (4.2)	4,820 (3.8)	4,387 (3.3)	2,237 (1.1)	2,700 (4.2)
Naphthalene [4]	at 1% TOC	160	2,100			27.7 (10)	54.2 (10)	24.6 (2.0)	47.6 (4.9)	39.2 (3.5)	40.3 (3.7)	19.9 (6.1)	27.9 (9.5)
Fluorene [4]	at 1% TOC	19	540			12.8 (8.1)	30.2 (6.9)	13.9 (3.6)	31.8 (10)	21.8 (5.1)	19.8 (3.5)	10.7 (4.1)	15 (4.2)
Total HMW PAH [1,2,4]	at 1% TOC	1,700	9,600	660	1,700	812 (8.5)	1,992 (3.9)	1,053 (1.2)	1,959 (6.1)	1,668 (5.3)	1,496 (2.6)	779 (3.2)	981 (5.9)
Total PAH [1,2,4]	at 1% TOC	4,000	45,000			1,503 (7.2)	3,508 (3.3)	1,892 (0.8)	3,471 (5.4)	2,952 (5.6)	2,649 (2.3)	1,420 (2.9)	1,780 (5.3)

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

[2]Total PAH, Total HMW PAH, and Total DDT values have been calculated using 'less than detection' limit values as '0.5 times the detection limit'.

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

[4]Total PAH, Total HMW PAH, fluorine, acenapthalene, naphthalene, hexachlorobenzene and Total DDT concentrations expressed for a sediment containing 1%TOC. TOC normalisation is used in the ANZECC (2000) sediment quality guidelines and ARC Environmental Response Criteria for comparing sediments with different TOC content.

Table 3.2 *continued*: **Summary of mean concentrations and variability (coefficient of variation [c.v., %], *n*=5) of total organic carbon (TOC) and selected organic contaminants in sediments of 16 sites sampled in Wellington Harbour in 2011. Sediment quality guidelines for comparison are ANZECC (2000) and Auckland Council Environmental Response Criteria (ARC ERC; ARC 2004). Cells highlighted 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 analysed	ANZECC trigger values		ARC ERC thresholds		Site							
		ISQG-Low	ISQG-High	amber	red	AQ2	WH5	WH9	WH10	WH13	WH18	WH15	WH17
TOC (%)	< 500 µm					1.4 (5.6)	1.3 (0.8)	1.5 (1.3)	1.6 (0.8)	1.8 (0.5)	1.8 (0.9)	1.9 (0.7)	1.2 (1.4)
Organics (µg/kg dry wt):													
Hexachlorobenzene	< 500 µm					<0.1 (0)	<0.1 (0)	<0.1 (0)	<0.1 (0)	<0.1 (0)	<0.1 (0)	<0.1 (0)	<0.1 (0)
Total DDT [2,3]	< 500 µm					8.1 (10)	3.4 (5.3)	2.8 (5.8)	4.7 (5.6)	3 .0 (4.4)	3.4 (6.0)	3.4 (3.0)	1.6 (5.6)
Hexachlorobenzene [4]	at 1% TOC					<0.1 (0)	<0.1 (0.8)	<0.1 (0)	<0.1 (0)	<0.1 (0)	<0.1 (0)	<0.1 (0)	<0.1 (0)
Total DDT [2,3,4]	at 1% TOC	1.6	46		3.9	5.9 (9.7)	2.6 (5.8)	1.9 (6.7)	3.0 (6.1)	1.7 (4.4)	1.9 (5.8)	1.7 (2.7)	1.4 (5.5)
Naphthalene	< 500 µm					43.1 (6.6)	17.6 (9.9)	13.9 (5.8)	17.9 (3.0)	12.6 (12.6)	8.3 (6.0)	7.7 (8.4)	9.9 (3.5)
Fluorene	< 500 µm					24.3 (6.3)	10.5 (7.9)	9.8 (13)	10.7 (3.5)	10.4 (4.2)	7.9 (8.4)	10.4 (11)	7.9 (8.1)
Total HMW PAHs [1,2,4]	< 500 µm					1,429 (2.6)	618 (2.4)	487 (2.1)	718 (3.4)	447 (20.5)	315 (2.5)	269 (6.1)	280 (3.9)
Total PAH [1,2]	< 500 µm					2,542 (2.4)	1,182 (1.8)	958 (2.4)	1,353 (2.8)	880 (17.9)	631 (2.2)	529 (5.6)	558 (3.1)
Naphthalene [4]	at 1% TOC	160	2,100			31.1 (5.9)	13.2 (10.3)	9.6 (6.5)	11.4 (3.8)	7.2 (12.5)	4.7 (6.5)	3.9 (8.5)	8.6 (4.0)
Fluorene [4]	at 1% TOC	19	540			17.6 (10.5)	7.9 (7.6)	6.7 (13.2)	6.8 (3.7)	6 .0(3.8)	4.5 (8.5)	5.3 (10.6)	6.8 (7.9)
Total HMW PAH [1,2,4]	at 1% TOC	1,700	9,600	660	1,700	1,034 (6.1)	462 (2.7)	334 (2.5)	457 (3.6)	257 (20.3)	180 (3.0)	139 (6.1)	242 (3.4)
Total PAH [1,2,4]	at 1% TOC	4,000	45,000			1,839 (6.2)	884 (2.1)	658 (2.8)	861 (3.0)	506 (17.7)	361 (2.7)	272 (5.5)	482 (2.5)

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

[2]Total PAH, Total HMWPAH, and Total DDT values have been calculated using 'less than detection' limit values as '0.5 times the detection limit'.

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

[4]Total PAH, Total HMW PAH, hexachlorobenzene and Total DDT concentrations expressed for a sediment containing 1%TOC. TOC normalisation is used in the ANZECC (2000) sediment quality guidelines and ARC Environmental Response Criteria for comparing sediments with different TOC content.

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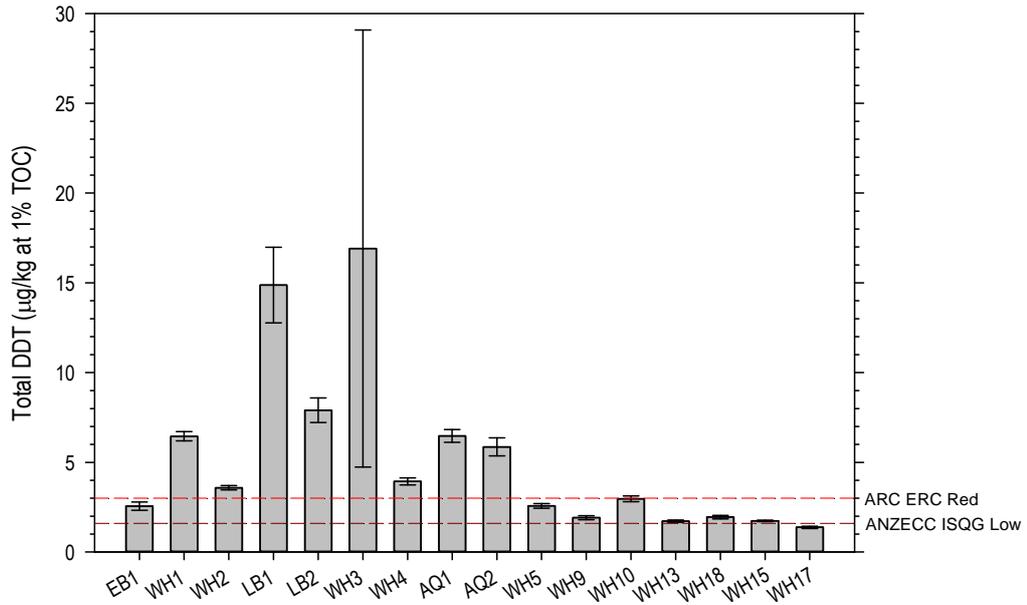
Figure 3.7: Mean (±95% CI) concentrations of TOC-normalised DDT in sediment of 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction of five composite samples from each site
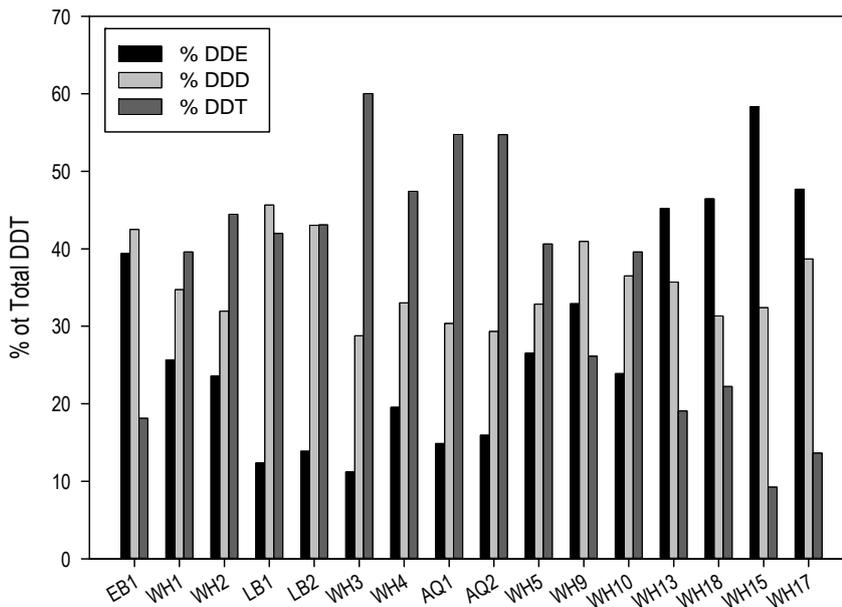
Figure 3.8: Mean proportion of DDT constituents in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction of five composite samples from each site
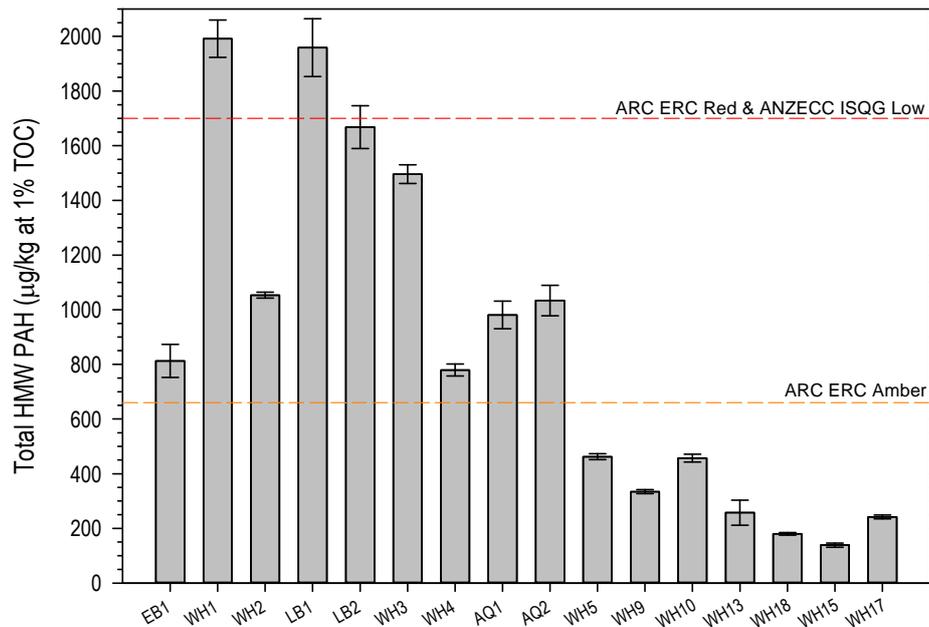
Figure 3.9: Mean (±95% CI) concentrations of TOC-normalised HMW PAH in sediments at 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction of five composite samples from each site

3.1.7 Total petroleum hydrocarbons (TPHs)

All samples analysed for TPH (including the five QA samples) were below the detection limit (60 mg/kg dry weight for C7–C44 fractions).

3.1.8 Quality assurance

The quality assurance results for particle size distribution showed good agreement. All 15 duplicate analyses were within ±10 μm of the mean particle size and within ±5% for the <63 μm fraction.

Overall, the quality assurance results for TOC, total metals and weak acid-extractable metals showed good 'within-sample'[9] and 'between-sample'[10] agreement (all duplicates and archived samples were within 9% of each other) (Appendix 4). The exception was weak acid-extractable copper for which variability between archived replicates was as high as 14%.

There was very good agreement (<6%) for four of the five 'within-sample' comparisons for total DDT. The exception was site WH3 which had very high replicate variability of 31.1%. There was variable agreement for the 'between-sample' comparisons for total DDT (differences between archived duplicates were between 4 and 28%) (Appendix 3). This variability is consistent with that noted before for DDT analyses (Stephenson et al. 2008, Milne 2010) and is attributable to matrix interference which makes it difficult to achieve accurate and repeatable quantitation of organochlorine compounds, particularly DDD and DDT (Olsen et al. 2013).

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[9] Within replicates from the same site sampled in 2011. This is distinct from normal sample replication as these QA samples may be analysed on different days and the site names changed for blind analysis.

[10] Between replicates from the same site analysed first in 2006 and then reanalysed in 2011.

There was good agreement (1.1 and 7.1%) for the 'within-sample' comparisons of HMW PAH. However, 'between-sample' variability was high; sites WH2, WH3, WH10 and WH15 all had higher concentrations of HMW PAHs when reanalysed in 2011 compared to 2006 (differences between duplicates were 15.5%, 20.3%, 12.9% and 2.2%, respectively). Care should be taken with any temporal trend assessment for these sites because of the variability observed.

3.1.9   Comparison with the 2006 survey

Ten sites were common to both the 2006 and 2011 surveys and a comparison of those sediment particle size and chemistry data is presented in this section. Note:

- Sediment particle size results are from the revised data set for both the 2006 and 2011 surveys following reanalysis in 2013 (Olsen et al. 2013) and not from Stephenson et al. (2008); and

- The organic contaminant values for 2006 have been taken from Milne (2010), not Stephenson et al. (2008)[11].

Overall, there was generally good agreement between the sediment particle size results for both surveys. There was a general tendency for the mud fraction (<63 μm) to be higher in 2011 than in 2006 and the results of the Mann-Whitney rank sum test confirmed that for sites WH3, WH9, WH10 and WH15, mud content was significantly higher in 2011 (Figure 3.10, Table 3.3).
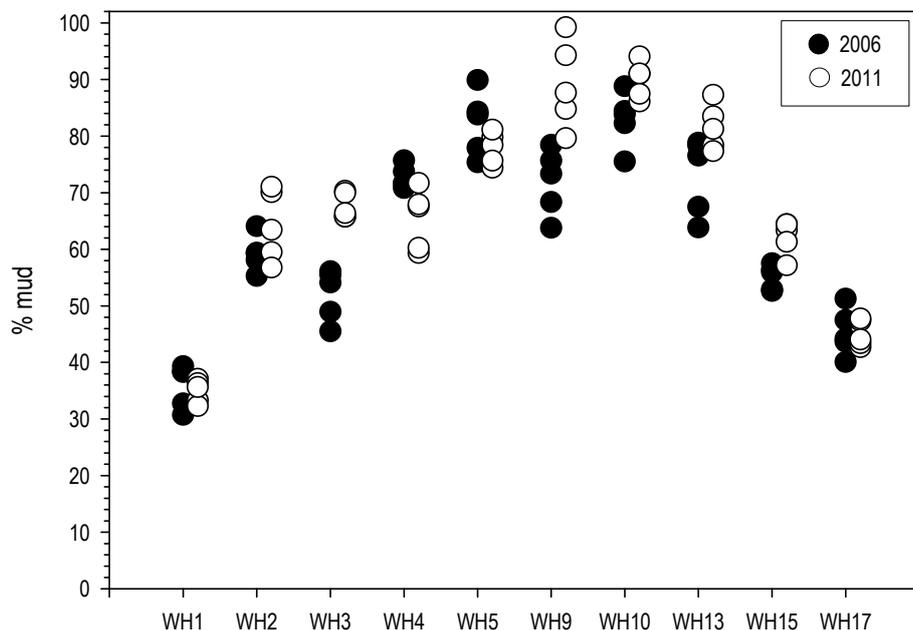
Figure 3.10: Percent mud in sediment of 10 sites sampled in Wellington Harbour in 2006 and 2011, based on five composites samples from each site

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[11] Due to equipment problems at NIWA Hamilton, initial analyses following the 2006 survey were carried out by RJ Hill Laboratories, Hamilton. In 2008 NIWA completed analyses of the PAH data at all 17 Wellington Harbour sites and OCPs at four inner harbour sites (see Milne 2010).

Table 3.3: Probability values from Mann-Whitney Rank Sum tests of the change in % <63 μm fraction and weak acid-extractable copper, lead and zinc concentrations (<63 μm sediment fraction) in sediments of ten sites sampled in Wellington Harbour in 2006 and 2011. Concentrations that have changed significantly (ie, p<0.05) between surveys are highlighted in red and the direction of change is indicated as + (increase) or – (decrease)

Site	% <63 μm	Copper	Lead	Zinc
WH1	0.55	0.42	0.15	0.55
WH2	0.22	0.31	0.22	0.15
WH3	<0.01 (+)	0.22	0.69	0.69
WH4	0.06	<0.01 (+)	0.056	<0.05 (+)
WH5	0.31	0.15	0.55	0.09
WH9	<0.01 (+)	<0.01 (-)	<0.01 (-)	0.15
WH10	<0.05 (+)	0.55	<0.01 (-)	0.42
WH13	0.06	0.10	<0.01 (-)	<0.01 (-)
WH15	<0.05 (+)	0.22	<0.01 (+)	0.03
WH17	0.84	0.15	<0.01 (-)	<0.01 (-)

The mean TOC content was lower (by 1 to 11%) at all sites in 2011 compared with 2006. However, this decrease may be largely explained by analytical variability as QA results showed that archived results were all lower in 2011 compared to 2006 (-2.0 to -8.5%).

Generally, the concentrations of weak acid-extractable metals (<63 μm fraction) were the same or lower (typically within 8%) in 2011 than in 2006 (Figure 3.11). Lead concentrations were significantly lower at sites WH9, WH10, WH13 and WH17 (Table 3.3) but slightly higher at site WH15 in 2011. The concentrations of zinc were significantly higher at the inner harbour site of WH4 but significantly lower at two outer harbour sites, WH13 and WH17. Copper concentrations were significantly higher at site WH4 and lower at site WH9 in 2011 compared to 2006 (Table 3.3). However, the variability between samples collected and analysed in 2006 and then reanalysed in 2011 was up to 9% for lead and zinc, and as high as 14% for copper (Appendix 3); this indicates that the statistically significant changes recorded are due, at least in part, to analytical variability.

The sum of the 4,4'-isomers of DDE, DDD and DDT (termed total DDT) normalised to 1% TOC was chosen to compare concentrations between the two surveys because these three compounds were the only ones consistently above analytical detection limits. The concentrations of total DDT at 1% TOC were significantly higher at three of the four inner harbour sites (WH1, WH2 and WH4) in 2011 when compared with results obtained by NIWA in 2008 (Table 3.4, Figure 3.12). Total DDT (at 1% TOC) concentrations at site WH3 did not differ significantly between surveys and high replicate variability was common to both surveys at this site.

Table 3.4: Probability values from Mann-Whitney Rank Sum tests of the change in Total DDT, Total DDT at 1% TOC, Total HMW PAH and Total HMW PAH at 1% TOC in sediments of ten sites sampled in Wellington Harbour in 2006 and 2011. Concentrations that have changed significantly (ie, $p<0.05$) between surveys are highlighted in red and the direction of change is indicated as + (increase) or – (decrease)

Site	Total DDT	Total DDT @ 1% TOC	HMW PAH	HMW PAH @ 1% TOC
WH1	<0.05 (+)	<0.05 (+)	<0.01 (+)	<0.01 (+)
WH2	<0.05 (+)	<0.05 (+)	0.06	<0.01 (+)
WH3	0.31	0.22	<0.01 (+)	<0.01 (+)
WH4	<0.05 (+)	<0.05 (+)	0.55	0.55
WH5			<0.01 (+)	<0.01 (+)
WH9			0.15	1.00
WH10			0.06	<0.01 (+)
WH13			<0.01 (+)	<0.01 (+)
WH15			<0.01 (+)	<0.01 (+)
WH17			<0.01 (+)	<0.01 (+)

Consistent with the findings of the 2006 survey, there is a spatial pattern present in the relative proportions of the three compounds that constitute DDT. DDT, the parent substance, is higher at sites adjacent to Wellington city, which is consistent with urban sources, whereas DDE predominates at sites further from the city and closer to the Hutt River mouth where weathered rural sources, such as those from agricultural soils, enter the harbour.

In terms of sediment PAH concentrations, only the HMW PAHs[12] at 1% TOC were chosen to compare concentrations between the two surveys because these compounds accumulate in sediments and are not susceptible to losses during sample handling and analyses, which makes them more reliable for monitoring purposes (Stephenson & Mills 2006). Mean total HMW PAH (at 1% TOC) concentrations were significantly higher at eight of the ten sites in 2011 compared with 2006 (Table 3.4, Figure 3.13), the exceptions being sites WH4 and WH9. At sites WH1 and WH3 concentrations of mean total HMW PAH (at 1% TOC) were 22 and 29% higher, respectively. However, as mentioned in Section 3.1.8, care should be taken when assessing this data for trend purposes given that 'between-sample' variability was as high as 16 to 20%.

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[12] For a list of HMW PAH compounds refer to the notes under Table 3.2.
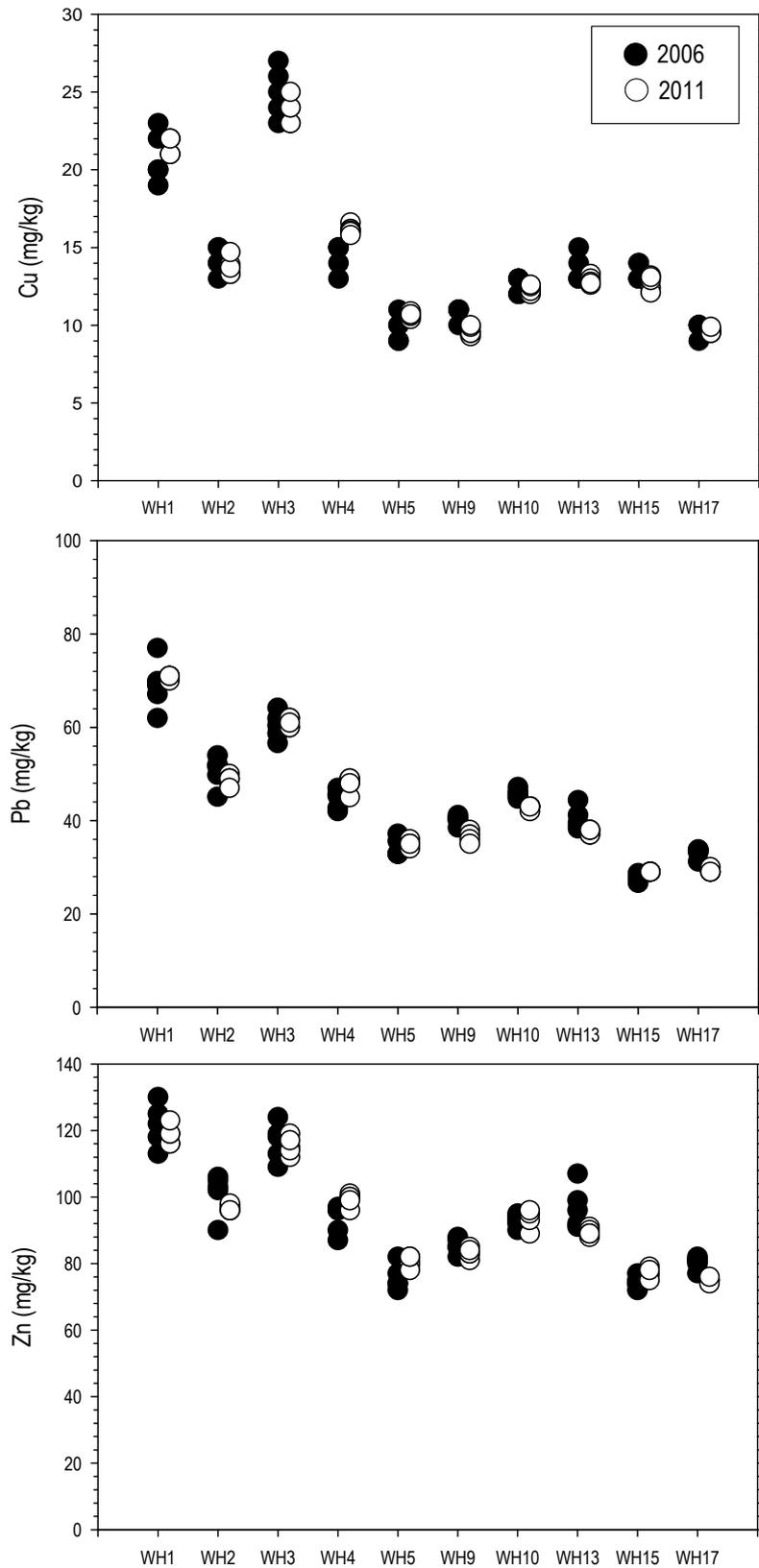
Figure 3.11: Concentrations of weak acid extractable copper (Cu), lead (Pb) and zinc (Zn) in sediments of 10 sites sampled in Wellington Harbour in 2006 and 2011, based on the <63 μm fraction of five composite samples from each site
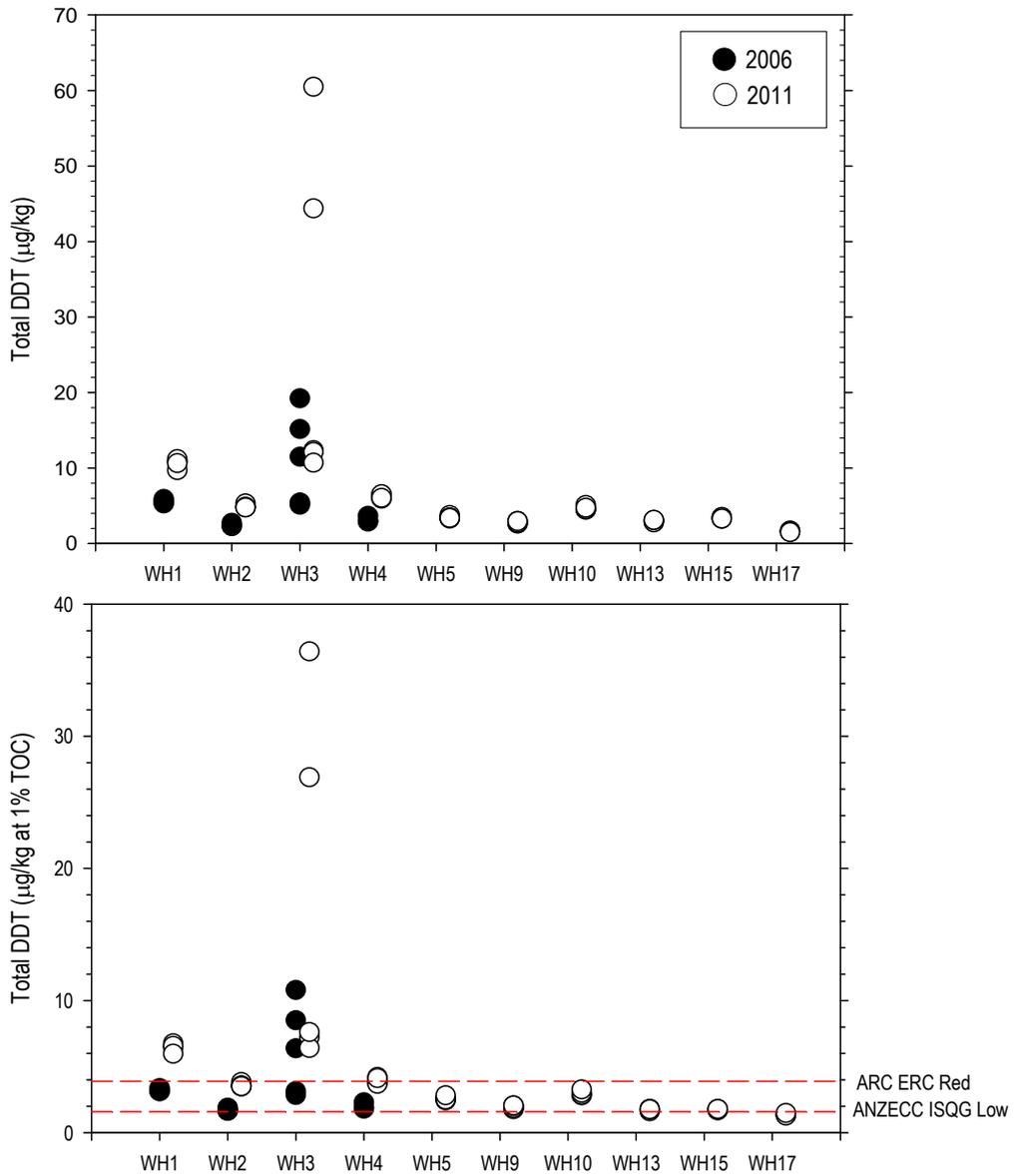
Figure 3.12: Concentrations of total DDT (top) and TOC-normalised total DDT in sediments at 10 sites sampled in Wellington Harbour in 2006 and 2011, based on the <500 μm fraction of five composite samples from each site
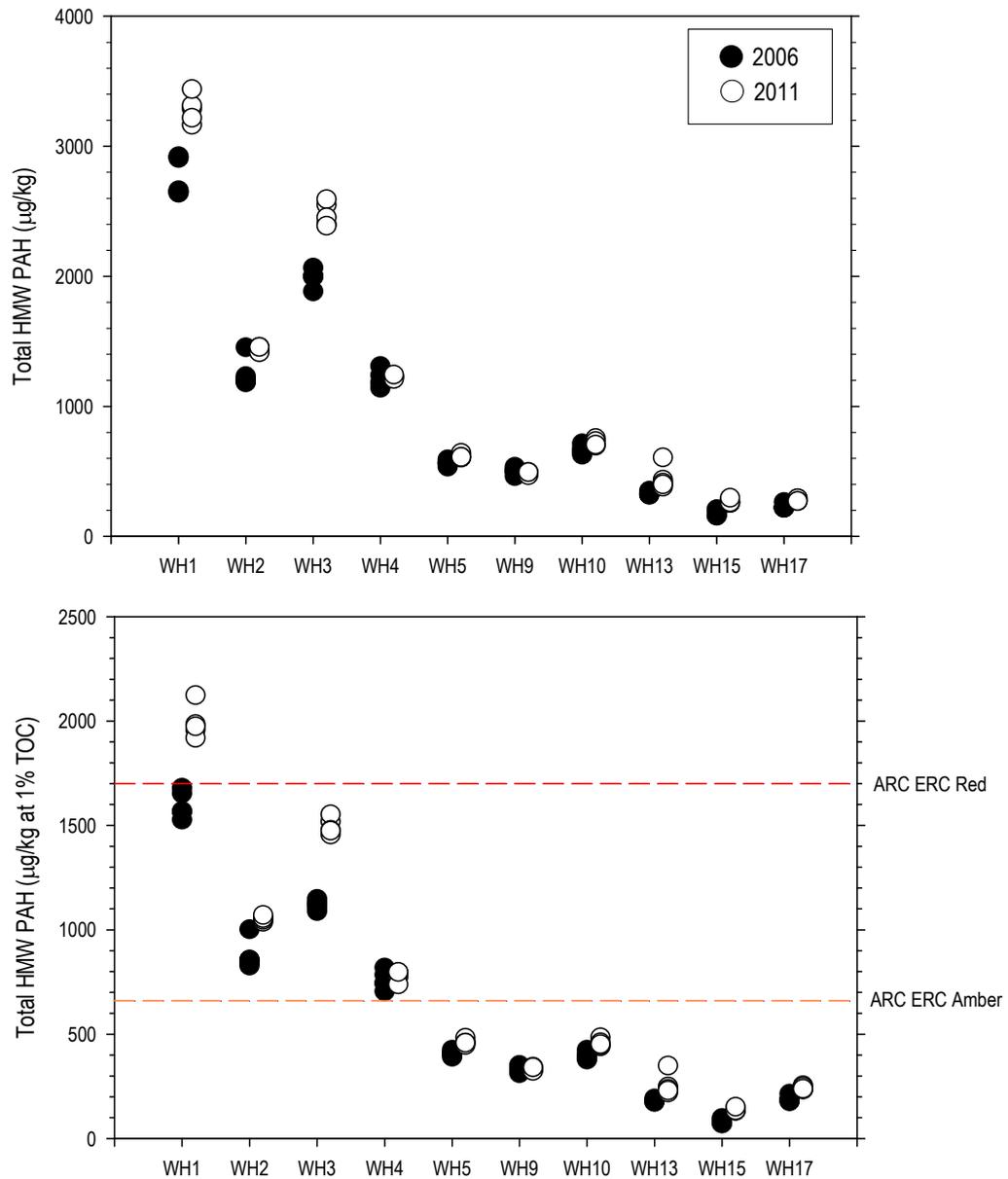
Figure 3.13: Concentrations of HMW PAH (top) and TOC-normalised HMW PAH in sediments at 10 sites sampled in Wellington Harbour in 2006 and 2011, based on the <500 μm fraction of five composite samples from each site

3.2 Benthic ecology

3.2.1 Sediment particle size distribution

A summary of the sediment particle size results from the benthic ecology collection areas of the 16 sites sampled in Wellington Harbour is presented in Table 3.5. The <500 μm fraction of the near-surface sediment at the majority of the sites was either sandy mud or very sandy mud (<63 μm fraction 63–100%). The inner harbour sites of WH1, LB1 and LB2 and the outermost site of WH17, were dominated by muddy sands (<63 μm fraction 17–49%). The southern Evans Bay site EB1 was characterised by sediment with less than 2% mud, the lowest mud content of all the sites.

The mud content (<63 μm fraction) in sediments from the benthic ecology collection areas was within 10% of the mean mud content in sediment from the corresponding sediment quality collection areas, with the exception of six sites. Sites WH1, AQ1, AQ2 and WH15 had differences[13] of 13–20% in mud content between the benthic ecology and sediment quality collection areas; these benthic ecology collection areas were typically muddier than the sediment quality collection areas. Sites LB1 and LB2 had differences in mud content of 31–76% between the benthic ecology and sediment quality collection areas; at site LB1 the benthic ecology collection area was muddier than the sediment quality collection area and the reverse was true for site LB2.

Table 3.5: Summary of the sediment particle size results for the 16 benthic ecology sites sampled in Wellington Harbour in 2011, based on a single composite sample from each site

Site	Mean (μm)	<63 μm (%)	63–125 μm (%)	125–250 μm (%)	Description of <500 μm fraction
EB1	168.7	1.82	21.9	76.3	Sand
WH1	78.7	41.9	39.0	19.1	Muddy sand
WH2	51.2	69.5	29.2	1.3	Sandy mud
LB1	129.1	23.0	27.5	49.5	Slightly muddy sand
LB2	159.0	16.8	20.3	62.9	Slightly muddy sand
WH3	56.8	63.8	31.5	4.6	Very sandy mud
WH4	52.4	68.3	27.2	4.5	Very sandy mud
AQ1	51.6	70.4	25.8	3.9	Sandy mud
AQ2	115.7	28.7	31.4	39.9	Muddy sand
WH5	46.9	77.5	22.5	0.0	Sandy mud
WH9	41.1	82.0	18.0	0.0	Sandy mud
WH10	39.5	82.5	16.2	1.3	Sandy mud
WH13	39.1	87.6	12.4	0.0	Sandy mud
WH18	43.2	80.1	18.6	1.3	Sandy mud
WH15	51.3	71.1	28.7	0.2	Sandy mud
WH17	71.7	49.0	37.0	13.9	Muddy sand

3.2.2 Number of species

A total of 124 taxa were identified in the samples collected during the 2011 Wellington Harbour survey (Stephenson 2012). The fauna was primarily composed of polychaete worms, crustaceans, bivalve molluscs and nemertean ribbon worms (Appendix 6). The number of species recorded at sites ranged from 38 at site WH9 to 52 at sites AQ2 and EB1 (Table 3.6).

The mean number of species per sample ranged from 18 to 25 and showed relatively little variation across the sites. The majority of sites had between 21 and 25 species per sample (Figure 3.14).

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[13] The difference has been calculated as (100 x (benthic ecology area result – sediment quality area result)/ mean of two results).

Table 3.6: Summary of features of the subtidal benthos at 16 sites in Wellington Harbour in 2011. For dominant species: *Asychis* **=** *Asychis trifilosa***, Phoxo 1 = Phoxocephalidae sp.#1**

Feature	Site						
	EB1	WH1	WH2	LB1	LB2	WH3	WH4
Number of species	52	50	42	51	48	48	40
Estimated total individuals per m^2 [1]	2,500	3,320	2,740	2,204	3,384	2,624	1,996
Dominant species by numbers [2]	*Heteromastus*	Sipunculida 1	Sipunculida 1	Sipunculida 1	Sipunculida 1	Sipunculida 1	Sipunculida 1
	Carazziella	*Theora*	Phoxo 1	*Labiosthenolepis*	*Theora*	*Cossura*	*Amphiura*
	Corbula	Tanaidacea 1	*Natatolana* 1	*Macrophthalmus*	*Cossura*	*Theora*	*Labiosthenolepis*
	Glycinde	Phoxo 1	*Theora*	*Theora*	Tanaidacea 1	*Labiosthenolepis*	Tanaidacea 1
		Labiosthenolepis	*Onuphis*	*Cossura*			
			Amphiura	Phoxo 1			
Dominant species by biomass [3]	*Maoricolpus*	*Echinocardium*	*Onuphis*	*Echinocardium*	*Dosina*	*Echinocardium*	*Dosina*
	Corbula	*Rynkatorpa*	*Amphiura*	*Diplodonta*	*Echinocardium*	*Diplodonta*	*Amphiura*
	Chirodota	*Paracaudina*	*Natatolana* 1	*Asychis*	*Amphiura*	*Amphiura*	*Echinocardium*
Shannon diversity (mean ±c.v.)	2.44 (15)	2.62 (8.5)	2.70 (5.6)	2.59 (11.2)	2.58 (10.8)	2.56 (5.9)	2.48 (11.1)
Pielou's Evenness (mean ±c.v.)	0.81 (8.5)	0.83 (9.9)	0.88 (3.7)	0.86 (7.6)	0.81 (8.9)	0.84 (4.0)	0.87 (5.3)
Trophic structure: [4]							
Predators/scavengers (%)	21.3	29.9	41.8	25.0	26.8	30.3	40.1
Surface deposit feeders (%)	17.9	13.9	24.8	21.4	15.1	10.5	24.9
Subsurface deposit feeders (%)	38.6	36.6	17.7	33.6	32.3	35.2	23.3
Suspension feeders (%)	18.6	19.3	15.2	18.7	24.5	23.3	10.6
Unknown (%)	3.7	0.4	0.6	1.3	1.3	0.6	1.2

[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 6.

Table 3.6 *continued*: **Summary of features of the subtidal benthos at 16 sites in Wellington Harbour in 2011. For dominant species:** *Asychis* = *Asychis trifilosa*, **Phoxo 1 = Phoxocephalidae sp.#1**

Feature	Site						
	AQ1	**AQ2**	**WH5**	**WH9**	**WH10**	**WH13**	**WH18**
Number of species	44	52	43	38	41	44	46
Estimated total individuals per m^2 [1]	3,120	2,360	2,336	3,332	1,956	2,472	2,976
Dominant species by numbers [2]	Tanaidacea 1	Sipunculida 1	Phoxo 1	Sipunculida 1	*Amphiura*	Sipunculida 1	Sipunculida 1
	Sipunculida 1	*Amphiura*	*Amphiura*	Tanaidacea 1	Sipunculida 1	*Cossura*	Tanaidacea 1
	Amphiura	*Labiosthenolepis*	Sipunculida 1	*Amphiura*	*Labiosthenolepis*	*Aglaophamus*	*Cossura*
	Labiosthenolepis	*Theora*	*Aglaophamus*		Phoxo 1	*Arthritica*	Phoxo 1
		Aglaophamus	*Nucula*		*Cossura*		
		Phoxo 1			*Theora*		
		Aphelochaeta					
Dominant species by biomass [3]	*Echinocardium*	*Pentadactyla*	*Dosina*	*Dosina*	*Echinocardium*	*Dosina*	*Echinocardium*
	Amphiura	*Amphiura*	*Echinocardium*	*Echinocardium*	*Amphiura*	*Echinocardium*	*Dosina*
	Asychis	*Glycera*	*Amphiura*	*Amphiura*	*Asychis*	*Asychis*	*Rynkatorpa*
Shannon diversity (mean ±c.v.)	2.53 (6.8)	2.89 (6.0)	2.57 (4.6)	2.29 (10)	2.61 (6.0)	2.25 (11)	2.48 (9.4)
Pielou's Evenness (mean ±c.v.)	0.82 (7.5)	0.91 (2.1)	0.85 (2.8)	0.78 (9.7)	0.89 (4.2)	0.77 (13)	0.82 (6.8)
Trophic structure: [4]							
Predators/scavengers (%)	52.4	35.9	37.8	42.3	32.7	22.0	34.5
Surface deposit feeders (%)	18.5	29.2	30.3	16.7	34.4	12.8	17.9
Subsurface deposit feeders (%)	16.5	18.5	20.6	31.6	21.3	48.7	36.8
Suspension feeders (%)	11.5	14.9	10.6	9.5	10.8	15.4	10.1
Unknown (%)	1.0	1.5	0.7	0.00	0.8	1.1	0.7

[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 6.

Table 3.6 *continued*: **Summary of features of the subtidal benthos at 16 sites in Wellington Harbour in 2011. For dominant species:** *Asychis = Asychis trifilosa*, **Phoxo 1 = Phoxocephalidae sp.#1**

Feature	Site	
	WH15	**WH17**
Number of species	51	42
Estimated total individuals per m² [1]	3,300	2,892
Dominant species by numbers [2]	Tanaidacea 1	Tanaidacea 1
	Cossura	Sipunculida 1
	Sipunculida 1	*Ennucula*
	Phoxo 1	*Theora*
	Aglaophamus	*Aglaophamus*
Dominant species by biomass [3]	*Dosina*	*Echinocardium*
	Echinocardium	*Asychis*
	Onuphis	*Zenatia*
Shannon diversity (mean ±c.v.)	2.52 (17)	2.53 (9.1)
Pielou's Evenness (mean ±c.v.)	0.79 (16)	0.84 (9.0)
Trophic structure: [4]		
Predators/scavengers (%)	48.1	44.0
Surface deposit feeders (%)	16.7	23.7
Subsurface deposit feeders (%)	21.9	21.3
Suspension feeders (%)	12.1	10.5
Unknown (%)	1.1	0.6

[1] Estimate based on a sample area of 0.03 m² 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 6.

Figure 3.14: Mean number of species per site, Shannon diversity index values and Pielou's evenness index values (±95% CI) at 16 sites in Wellington Harbour in 2011 (*n*=8)

3.2.3 Number of individuals

A total of 10,878 individuals were counted in the Wellington Harbour samples and the mean number of individuals per sample varied between 61 and 106, with most sites recording less than 90 individuals per sample. Polychaetes were the most abundant group (32% of all individuals), followed by crustaceans (26%), sipunculids (17%) and bivalve molluscs (15%). Of the polychaetes, *Labiosthenolepis laevis* was the most abundant (20% of all polychaetes), followed by *Cossura consimilis* (18%) and *Aglaophamus verrilli* (15%). The most abundant crustaceans were Tanaidacea sp.#1 (41% of all crustaceans) and Phoxocephalidae sp.#1 (24%). The three sipunculid, or peanut worm, species recorded were heavily dominated by a single species, Sipunculida sp.#1 (99.8% of all sipunculids). Amongst the bivalve molluscs recorded the invasive East Asian bivalve, *Theora lubrica*, was the most abundant (47% of all bivalves).

3.2.4 Diversity

The mean Shannon diversity index was very similar across all sites and ranged from 2.25 (±0.17, 95% CI) at site WH13 to 2.89 (±0.12, 95% CI) at site AQ2 (Table 3.6, Figure 3.14). Mean values of the index ranged from 51–97% of their theoretical maximum (H'_{max} − ln[no. of species]), based on the number of species being evenly distributed across each species present at the site.

Similarly, the mean values for Pielou's Evenness Index were the lowest at site WH13 (0.77 ± 0.07, 95% CI) and highest at site AQ2 (0.91 ± 0.01, 95% CI). Site AQ2, near Aotea Quay, was noticeable for having high diversity and evenness measures, significantly higher than the neighbouring site AQ1 (Table 3.6, Figure 3.14).

3.2.5 Biomass

The biomass of site EB1 was unique in being dominated by the suspension feeding gastropod *Maoricolpus roseus*, the clam *Corbula zelandica* and the sea cucumber *Chirodota nigra* (Table 3.6). The biomass of the remaining sites was mostly dominated by the heart urchin *Echinocardium cordatum,* the bivalve *Dosina zealandica* and the brittle star *Amphiura rosea* (Table 3.6). The bamboo worm, *Asychis trifilosa*, was also a dominant member of the biomass at many sites.

3.2.6 Trophic structure

All feeding modes except herbivores were represented in the benthic fauna of the sites. Deposit feeders dominated the benthic community at most sites, accounting for 35–61% of the individuals present. Of these, subsurface deposit feeders were more numerous than surface deposit feeders (Table 3.6, Figure 3.15).

Predators and scavengers accounted for 20–40% of individuals at most sites, but were more abundant at sites AQ1 and WH15, with 52 and 48%, of individuals in this group, respectively. Suspension feeders represented the smallest trophic group, ranging from 9–24% across all sites.
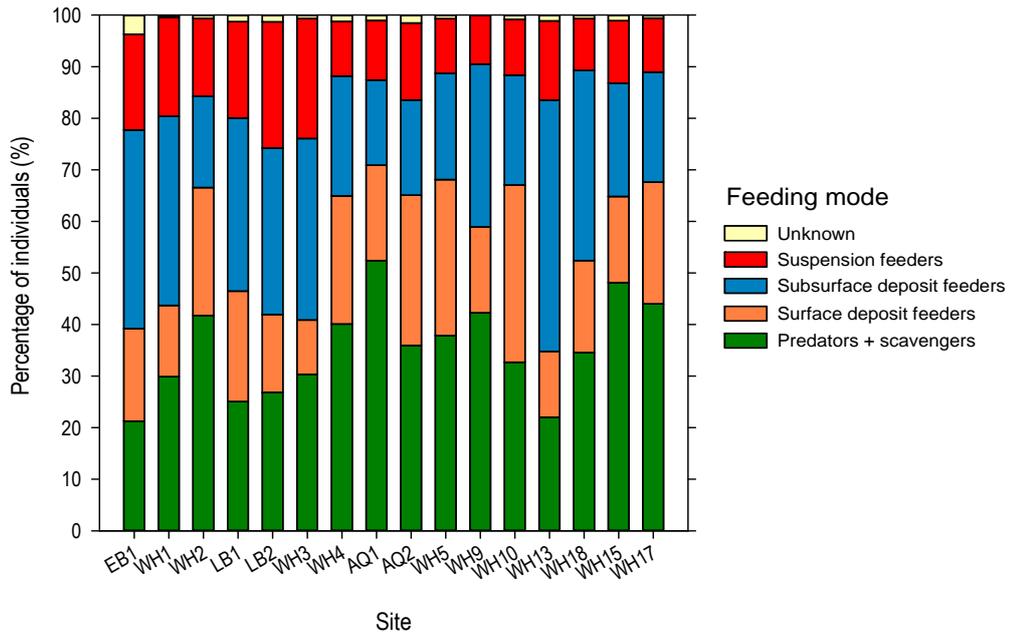
Figure 3.15: Percentage of individuals in each feeding mode at 16 sites in Wellington Harbour in 2011

3.2.7 Heart urchin and bivalve populations

The body lengths of the heart urchin and the shell lengths of eight species of bivalve were measured to try and establish their population structure at each of the sites. Measurements for each species from individual samples are detailed in Appendix 6. Figure 3.16 shows the range of species and their relative abundance across sites.
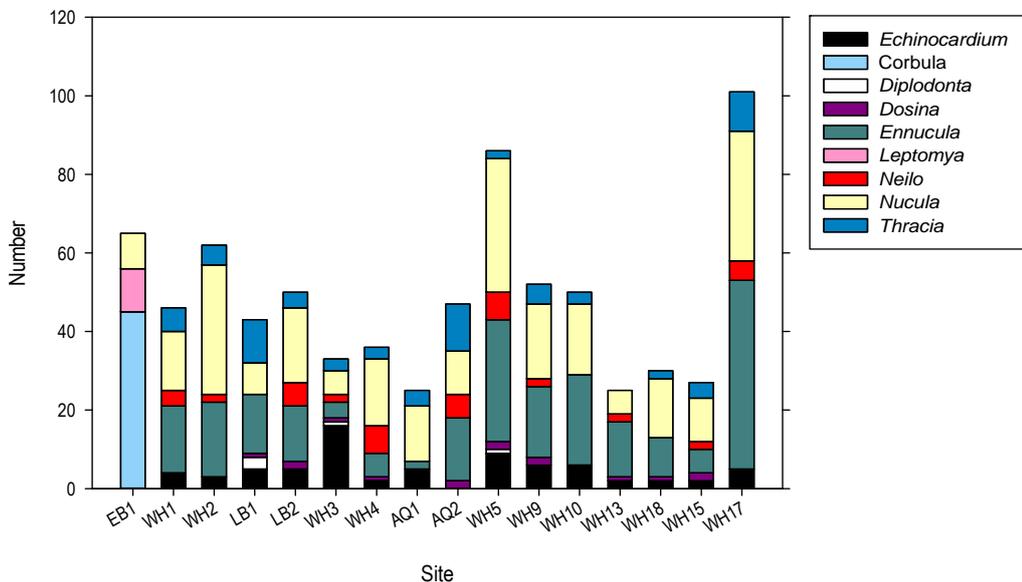
Figure 3.16: Abundance of heart urchin (*Echinocardium)* and selected bivalve species collected and measured at each of the 16 Wellington Harbour sites in 2011

Echinocardium cordatum (heart urchin)

The heart urchin was recorded at all sites with the exception of sites EB1 and AQ2. Estimated animal densities ranged between 8 per m^2 (at sites WH4, WH13, WH15 and WH18) and 68 per m^2 (at site WH3). Most individuals had body lengths between 10 and 30 mm (Figure 3.17).

Nucula hartvigiana (nut shell)

The nut shell was the most numerous bivalve recorded during the 2011 survey. Individuals were collected from all sites throughout the harbour and estimated densities ranged between 24 and 135 per m^2. Individual shell lengths were between 1 and 6 mm at all sites with the exception of site EB1; of the nine individuals measured at this site, eight were between 7 and 10 mm in shell length (Figure 3.17).

Ennucula strangei

The second most numerous bivalve was *Ennucula strangei* recorded from all sites except site EB1. The vast majority of sites had shell lengths between 1 and 12 mm and estimated densities ranged between 8 and 191 per m^2 (Figure 3.17).

Thracia vitrea

Thracia vitrea was recorded at all sites except site EB1. Densities were estimated to range between 4 and 48 per m^2 and shell lengths were typically between 2 and 17 mm (Figure 3.18).

Neilo australis

This bivalve species was recorded from 11 sites, at which densities were estimated to range between 8 and 28 per m^2. The size distribution of individuals was bimodal with the majority of the 45 animals having a shell length measuring between 1 to 7 mm and a second smaller group between 12 and 20 mm. There were three animals with larger shell lengths between 22 and 28 mm (Figure 3.18).

Corbula zelandica

The bivalve *Corbula zelandica* was recorded from site EB1 only, in the south-west corner of Evans Bay. The estimated density of individuals at this site was reasonably high at 179 per m^2 and all but three of the 45 animals measured were between 10 and 13 mm in shell length.

Diplodonta globus

Only five individuals of this bivalve species were recorded at sites WH3, WH5 and LB1. Estimated densities ranged between 4 and 12 animals per m^2 and body lengths ranged from 2.8 to 25 mm.
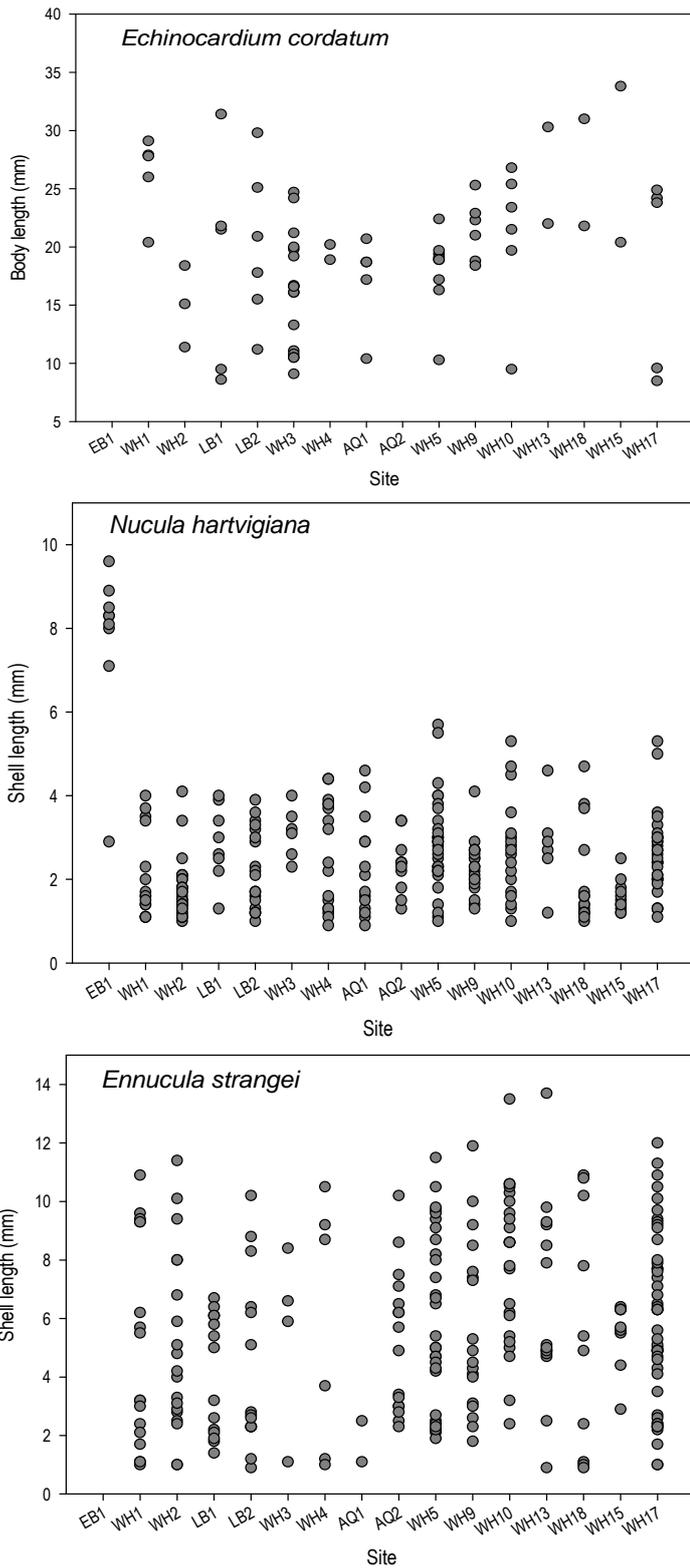
Figure 3.17: Size distribution of the heart urchin, *Echinocardium cordatum*, and two bivalve species at each of the 16 Wellington Harbour sites sampled in 2011
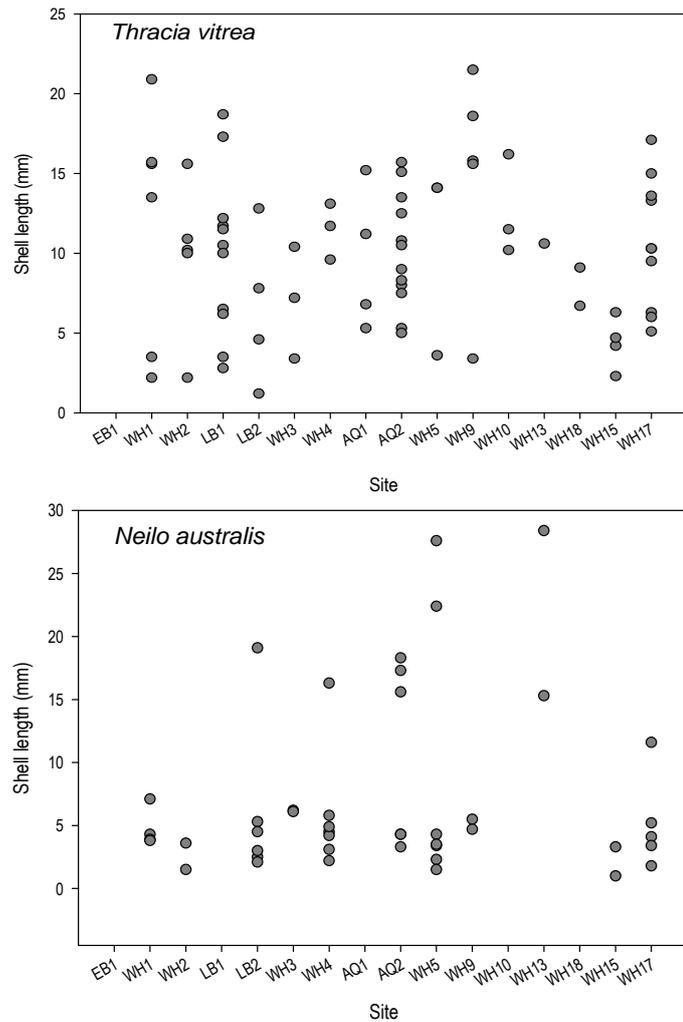
Figure 3.18: Size distribution of two bivalve species at each of the 16 Wellington Harbour sites sampled in 2011

Dosina zelandica

Fifteen individuals of *Dosina zelandica* were recorded from ten sites throughout the harbour and densities were estimated to be small at 4 to 8 specimens per m^2. Shell lengths for this species were amongst the largest of all the bivalves measured at 34 to 57 mm.

Leptomya retiaria

Twelve individuals of the species *Leptomya retiaria* were recorded from site EB1 only. Densities were estimated at 44 individuals per m^2 and shell lengths ranged from 6 to 15 mm.

3.2.8 Community structure

Hierarchical clustering and multidimensional scaling techniques were performed on square root transformed data averaged across sites.

Site EB1 in the south-west corner of Evans Bay was significantly different from all the other sites with respect to species composition (ANOSIM R-statistic=0.99; *p* <0.1%). The average dissimilarity percentage between site

EB1 and all other sites was 84.5% with 30% of this dissimilarity being explained by seven species; the polychaete *Heteromastus filiformis* and the bivalve *Corbula zelandica* were exclusive to this site, Sipunculida sp#1 occurred in low numbers relative to the other sites, and two species of polychaete (*Labiosthenolepis laevis* and *Cossura consimilis*), a brittle star (*Amphiura rosea*) and the shrimp-like tanaidaceans were completely absent from this site.

Cluster analysis of the similarity matrix derived from mean species abundances at each of the 15 sites differentiated one group of sites and two outliers (Figure 3.19). The two outliers were site LB1, the most inshore site in Lambton Basin, and site WH15, offshore from the mouth of the Hutt River. The differences were driven by a higher abundance of the stalk-eyed mud crab *Macrophthlamus hirtipes* and the absence of tanaidaceans and the brittle star *Amphiura rosea* at site LB1, and at site WH15 by slightly higher abundance of tanaidaceans, Ostracoda sp. #7 and several polychaete species. The other 13 sites were all contained within a group sharing greater than 70% similarity in benthic community composition. In addition, sites WH13 and WH18 shared more than 80% similarity in community composition; these two sites are located adjacent to each other on the 16 m contour offshore from Petone Beach.
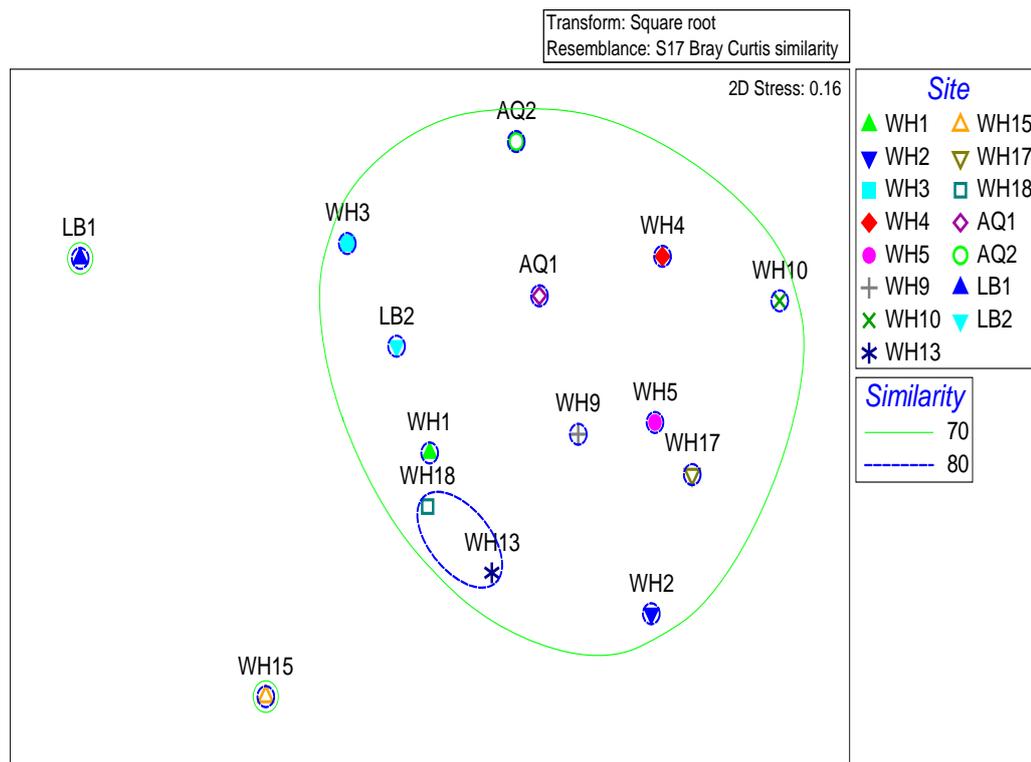

Figure 3.19: MDS plot of the similarity matrix derived from square-root transformed mean species abundances from 15 sites (excluding site EB1) in Wellington Harbour in 2011. Samples are grouped using the results of cluster analysis

Although most sites were found to be very similar in overall species composition and abundance, there were some differences as observed in the ordination (Figure 3.19). However, these differences are driven by lots of species with low abundance; more than 50% of the species recorded are represented by less than 10 individuals. Conversely, 25 species make up 88% of all individuals counted. So if we consider an ordination based on presence and absence of the 25 numerically dominant species and which ignores abundance, then species composition is the same amongst most sites, with the exception of sites LB1, AQ1, AQ2, WH5 and WH17 (Figure 3.20).
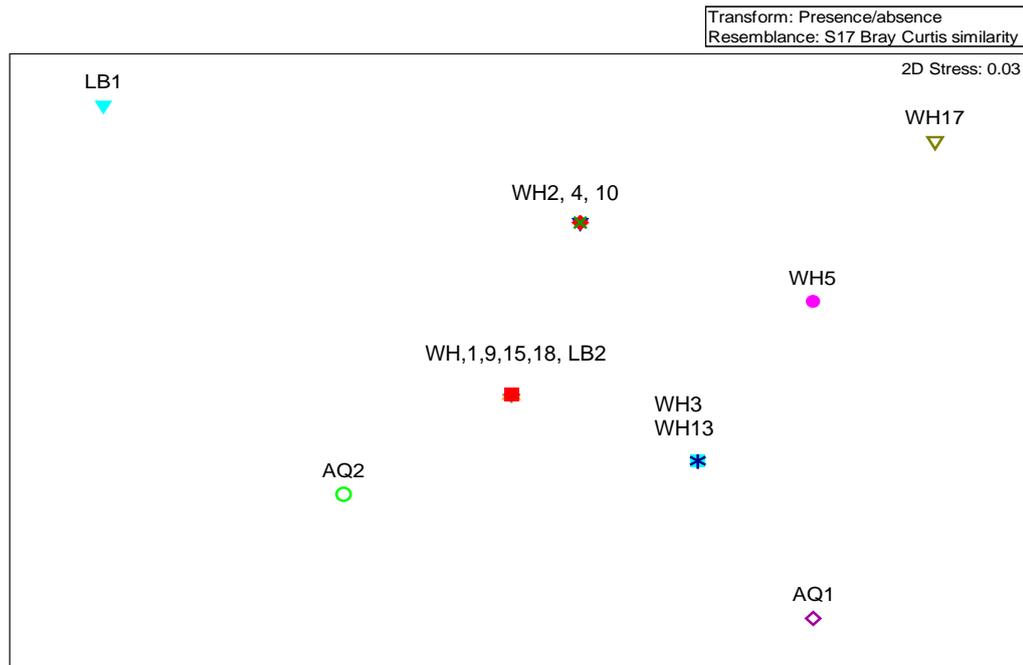
Figure 3.20: MDS plot of the similarity matrix derived from presence/absence species data for the most abundant 25 species at 15 sites (excluding site EB1) in Wellington Harbour

3.2.9 Comparison with the 2006 survey

Overall, the benthic invertebrates that reside in the subtidal sediments of Wellington Harbour represent variants of a soft-bottom harbour community. The species present were largely the same for both surveys though their relative abundance changed across sites. Across both surveys, the most abundant species within the community were polychaete worms, crustaceans, sipunculids and bivalves. The heart urchin, *Echinocardium cordatum*, was a dominant member of the biomass, along with the bivalve *Dosina zelandica*, and the brittle star *Amphiura rosea*.

The number of species per site was approximately the same for both surveys, as was the general composition of taxa across the sites (Figure 3.21), as measured by both numerical dominance and biomass. There were approximately 3,600 fewer individuals counted in 2011 compared with 2006.

The MDS plot (Figure 3.21) reveals a grouping of sites by survey year (left and right sides of the plot). The ANOSIM routine (a test for assemblage differences between groups) indicates that there are statistically significant differences in

community assemblage between the two surveys (R=0.577, *p*=0.001). The average dissimilarity percentage between years was 35.5%, with 50% of this dissimilarity being explained by 12 species. For example, the polychaete *Maldane theodori,* and Sipunculida sp#.1 were more abundant at certain sites in 2006 than in 2011. In contrast, Tanaidacea sp#.1 and the polychaete *Aricidea* sp. were less abundant in the 2011 survey; these four species explained 22% of the dissimilarity percentage.

Diversity indices and trophic structure showed little variation between surveys.
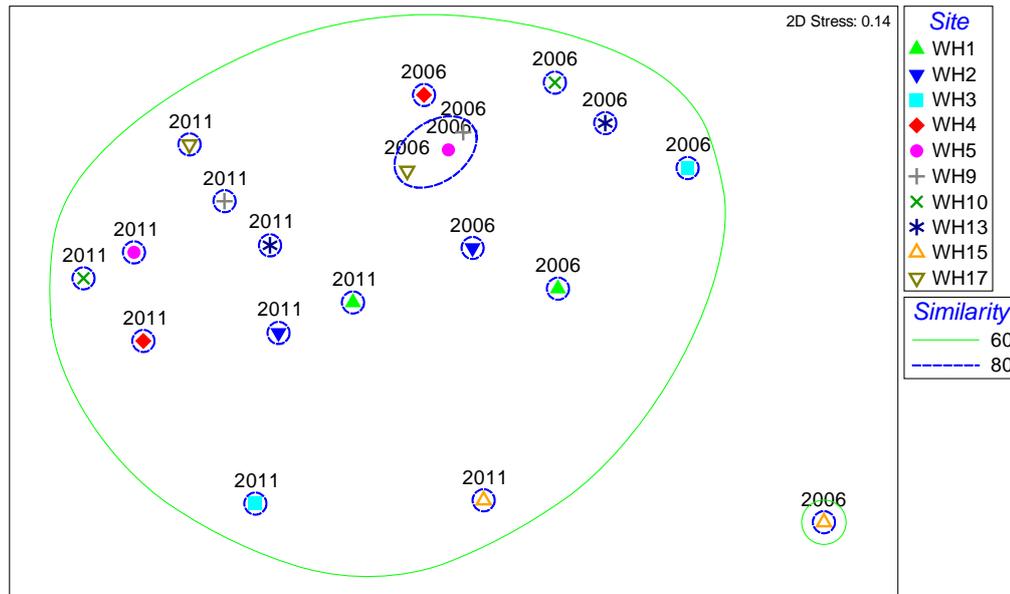
Figure 3.21: MDS plot of the similarity matrix derived from square-root transformed mean species abundances from 10 sites common to both the 2006 and 2011 Wellington Harbour sediment surveys. Samples are grouped using the results of cluster analysis

3.3 Relationship between benthic ecology and sediment quality

Principal components analysis (PCA) was used to examine the relationship between the chemical and physical (ie, sediment quality) characteristics of the sediment. The primary PCA axis for normalised mud content, TOC, metal (<63 μm and <500 μm fractions) and organics concentrations explained 80% of the variation in sediment quality variables, and therefore, provided a good proxy for overall environmental quality (Figure 3.22). Broadly speaking PC1 represents an axis of decreasing contaminant load and Figure 3.22 shows a pattern of environmental change moving from the more contaminated inner harbour sites in Lambton Basin and Evans Bay at the left of the plot, offshore to less contaminated sites further from the major contaminant sources at the right of the plot. PC1 is primarily driven by an inshore-offshore gradient in the concentrations of key urban contaminants (eg, zinc, copper, lead and PAHs), whereas PC2 is driven by relatively minor variation in sediment characteristics and secondary contaminants (eg, % mud, TOC, nickel and arsenic).
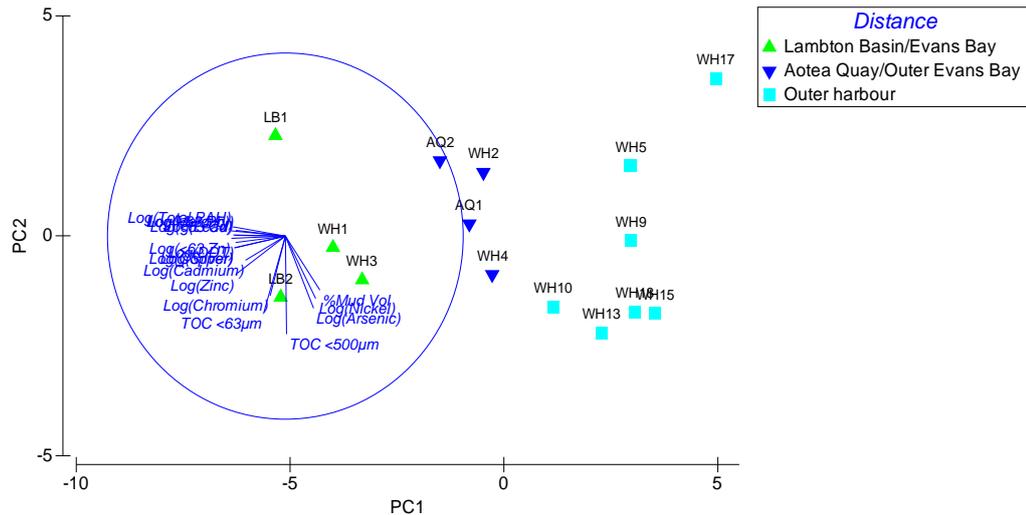
Figure 3.22: Two-dimensional PCA ordination of all sediment quality variables for the 15 sites (except EB1) sampled in Wellington Harbour in 2011. All variables are log-transformed and normalised

The RELATE[14] routine found there was some agreement in the multivariate patterns of benthic invertebrate distribution and sediment quality data (ρ=0.386, p=<0.01). However, the BEST[15] routine was unable to attribute the patterns in benthic invertebrate distribution to any specific sediment quality variable.

Prior to running the BEST routine, the transformed sediment quality variables were examined for evidence of collinearity using draftsman plots and the variables reduced to a subset of representatives. The BEST routine subsequently identified four variables that best grouped the sites in a manner consistent with the observed benthic invertebrate patterns (see Figure 3.19); <500 μm TOC, and concentrations of nickel, chromium and total DDT (ρ=0.63). With the exception of chromium, these variables are highly correlated with numerous other variables (eg, % mud, metals, total PAH) making it impossible to determine which specific aspects of environmental quality are driving the distribution of fauna.

Nonetheless, a similarity profile test (SIMPROF[16]) produces groupings based on those variables identified by the BEST routine, to identify sites sharing similar sediment quality. Overlaying these grouping on the ordination of benthic fauna indicates that sediment quality is influencing the composition and abundance of benthic communities at some sites (Figure 3.23). For example, sites WH13 and WH18 are similar in community composition and also share similar sediment quality. Sites LB1 and WH15 have community compositions quite different from each other and all other sites, and the sediment quality at these two sites is also significantly different (Figure 3.23).

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[14] The RELATE routine is a measure of how closely related two multivariate data sets are.

[15] BEST is a procedure to find the best subset of (in this case) environmental variables that match the ordination of biotic data.

[16] SIMPROF is a permutation test for multivariate structure in a specified set of samples and produces groups, or clusters, of sites that are significantly different from one another.
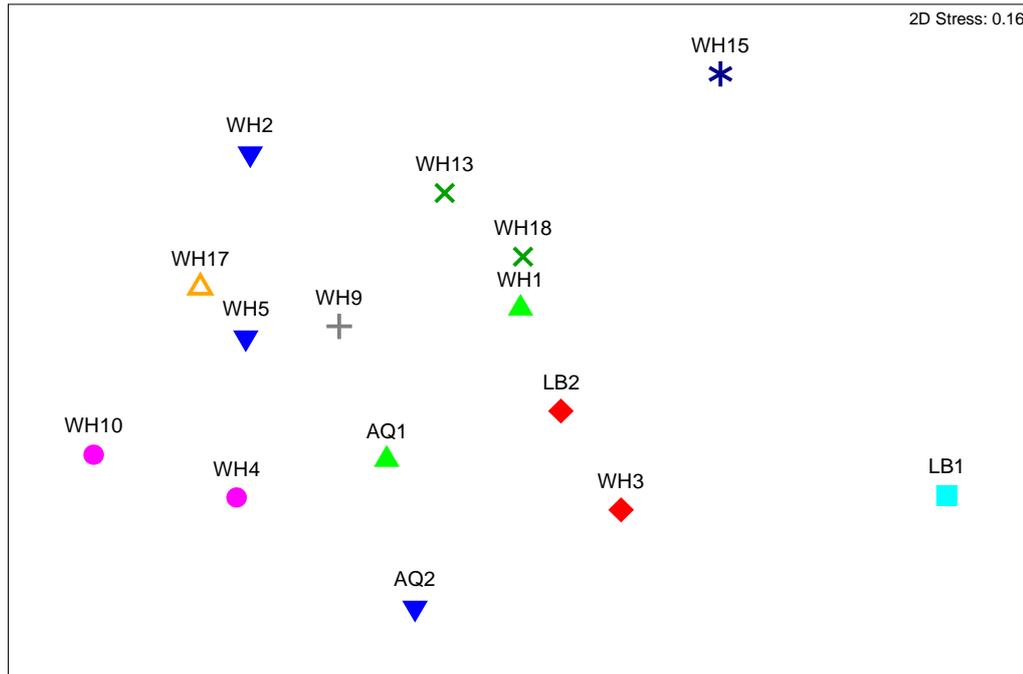
Figure 3.23: MDS plot of 2011 benthic fauna samples overlain with site groupings identified by cluster analysis of the four transformed and nomalised sediment quality variables identified by the BEST routine

Patterns of community diversity were examined using linear and non-linear regression techniques between the primary PCA axis, as a proxy for contamination gradient and distance from major contamination sources, and measures of community diversity (Figure 3.24). A visual assessment of the results indicated that Shannon diversity, Pielou's evenness and the number of species declined with increasing distance from major contaminant sources, but none of these trends were statistically significant (Figure 3.24).

Species differences between the sites were examined using the BEST routine to identify which of the 25 most abundant species best matched the observed sediment contaminant gradient. The analysis indicated that most of the variation in faunal patterns along the contaminant gradient was explained by five species: three polychaete species, *Aglaophamus verrilli*, *Labiosthenolepis laevis* and Polynoidae sp#1, the invasive East Asian bivalve *Theora lubrica* and a crustacean, Ostracoda sp#5. Three of the five species appeared to decrease in abundance with increasing distance from the CBD; Polynoidae sp#1 showed little response to the changing contaminant gradient and the sand-preferring burrowing polychaete, *A. verrilli*, increased in numbers with increasing distance from the CBD (Figure 3.25). However, only two of these relationships were statistically significant, *A. verrilli* (R^2=0.44, p <0.01) and *L. laevis* (R^2=0.56, p <0.01).
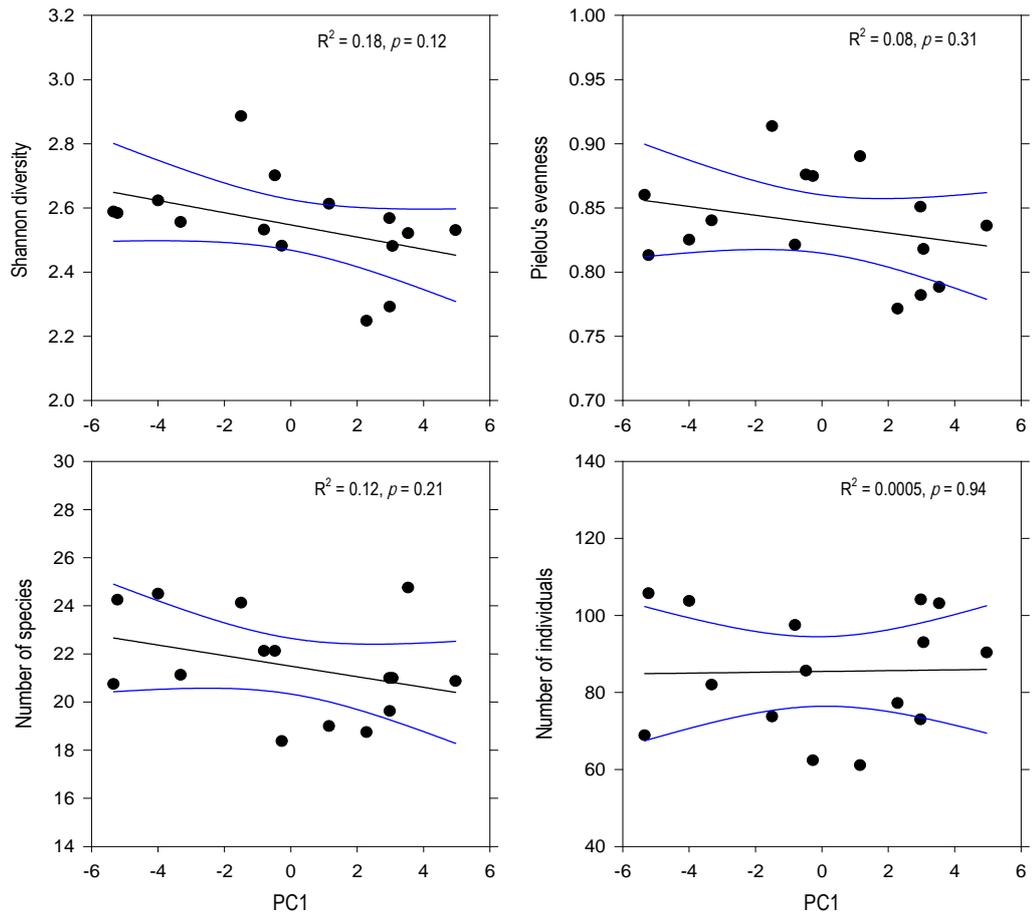
Figure 3.24: Relationship between primary PC axis and the diversity indices of Shannon diversity, Pielou's evenness, number of species and number of individuals ± 95% CI
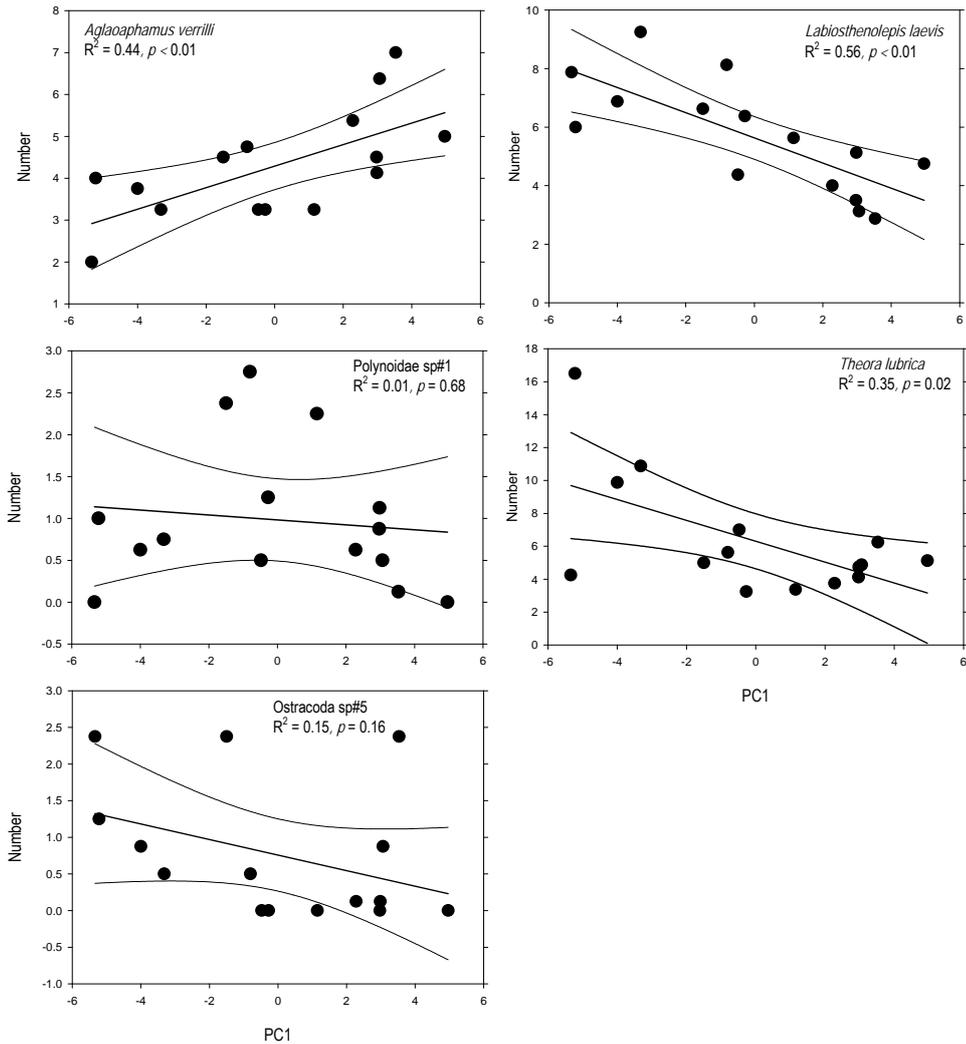
Figure 3.25: Relationship between the mean abundance (± 95% CI) of taxa selected by the BEST routine to match the environmental data and the primary PC axis

3.4   Stormwater catchpit sediments

A summary of the sediment chemistry results from the roadside catchpit samples of five Wellington city stormwater catchments is presented in Table 3.7 and Figure 3.26. Zinc concentrations were highest in the three inner city catchments of Thorndon, Waring Taylor and Newtown; copper was highest in the Newtown and Hataitai catchments; lead was noticeably high in Hataitai and mercury was highest in the Waring Taylor catchment (Figure 3.26). Total hydrocarbons and PAH concentrations were also highest in the Newtown catchpit sediments.

Table 3.7: Summary of mean concentrations of total organic carbon (TOC), total metals, total petroleum hydrocarbons (TPH) and total polycyclic aromatic hydrocarbons (PAHs) in catchpit sediments of 5 Wellington city stormwater catchments sampled in September 2011

| Analyte	Fraction analysed	n	Sites				
			Thorndon	Waring Taylor	Newtown	Hataitai	Miramar
TOC (%)	< 500 µm	2	3.0	4.1	7.3	9.1	5.4
Mean particle size	< 500 µm	1	172	83.3	153	172	167
% <63 µm	< 500 µm	1	3.5	32	8.0	7.4	6.7
Copper (mg/kg)	< 500 µm	2	129	189	335	285	250
Lead (mg/kg)	< 500 µm	2	144	255	196	420	215
Mercury (mg/kg)	< 500 µm	2	0.064	0.33	0.076	0.076	0.091
Zinc (mg/kg)	< 500 µm	2	870	895	885	715	810
Total TPH (mg/kg)	< 500 µm	1	1,940	1,220	2,300	460	940
Total PAH (µg/kg)	< 500 µm	2	4,300	8,241	9,411	3,794	2,796
Total PAH (µg/kg)	at 1% TOC	2	1,481	2,011	1,298	428	518

High variability was observed in the metal data with differences between replicates ranging between 0–48%. Mercury concentrations displayed the highest variability between replicates.

Concentrations of total copper, lead and zinc were generally five to ten times higher in the catchpit sediments compared with harbour sediments near major stormwater outfalls (Figure 3.26). In contrast, total mercury concentrations were approximately eight times lower in the catchpit sediments, with the exception of the Waring Taylor catchpit samples which were roughly half the concentration of nearby harbour sediment samples (Figure 3.26).

The concentrations of TPH ranged from 490–2,300 mg/kg in catchpit sediments but were all below the analytical detection limit (60 mg/kg[17]) in the harbour sediments at all sites. The mean concentrations of PAHs in catchpit sediments ranged from 2,796 µg/kg for Miramar to 9,411 µg/kg for Newtown. Total PAH concentrations were similar in the catchpit and harbour sediments, with the exceptions of the Waring Taylor and Newtown catchpit samples which were twice that of near shore harbour sediments (Figure 3.26). The PAH composition of catchpit sediments was similar to harbour sediments, though generally less pyrogenic. The dominant PAHs in both catchpit and harbour sediments were pyrene and fluoranthene (Appendix 3).

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[17] This is the laboratory detection limit for all Total TPH fractions (C7– C44).
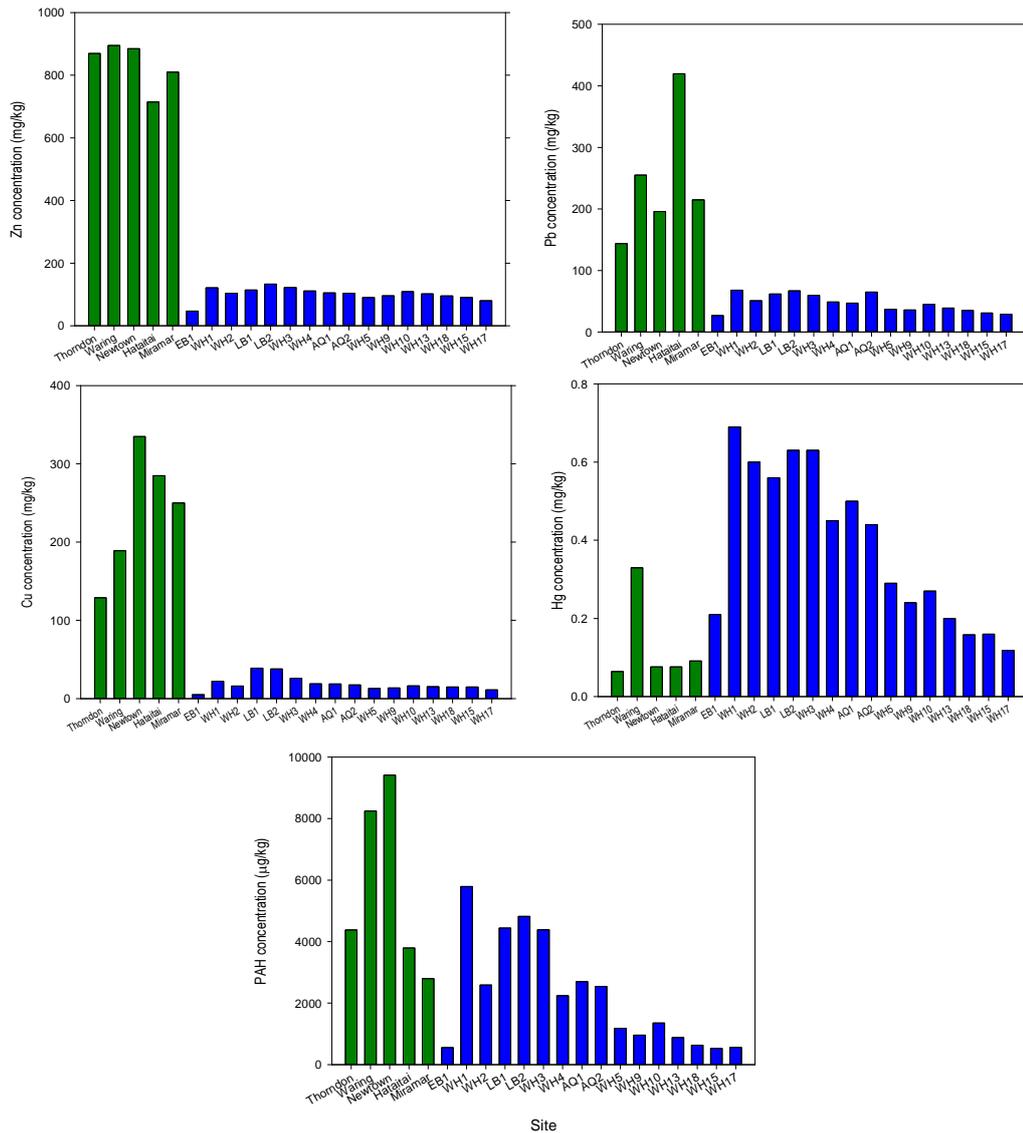
Figure 3.26: Concentrations of total zinc (Zn), lead (Pb), copper (Cu), mercury (Hg) and PAHs in catchpit sediments (mean of 2 samples) of five Wellington city stormwater catchments (green bars) and 16 harbour sites (blue bars) (n=1) sampled in 2011, based on the <500 μm fraction

4. Discussion

This section examines some of the key sediment quality and benthic ecology results. There is some discussion about possible sources of contamination and a comparison of results from both the 2006 and 2011 subtidal surveys. Also included in this section are the key findings from Depree (2013) with respect to the concentrations, distribution and sources of PAHs in Wellington Harbour.

4.1 Sediment quality

Site EB1 in the south-western corner of Evans Bay is somewhat anomalous compared to the other sites. This site was added to the sampling programme following recommendations by Milne (2010) to include more nearshore sites in the 2011 survey. However, this site was found to be significantly different from all of the other sites with respect to substrate (sand rather than mud), chemistry and benthos, and is not representative of the mud-dominated subtidal basin intended for monitoring.[18] Results for this site will be summarised but it is not recommended that this site be included in future surveys.

4.1.1 Sediment particle size

Sites sampled in 2011 were generally composed of sandy muds, whereby the mud and silt fraction makes up more than 50% of the total sediment volume. Sediment particle size structure appears to have changed little over the course of the two surveys, with the exception of sites WH3, WH9, WH10 and WH15 at which the mean percentage of mud has increased by 8 to 26% since 2006. The reason for these increases is unclear.

4.1.2 Metals

Concentrations of total copper, lead, zinc and mercury exceed 'early warning' (ie, ARC ERC amber or ANZECC ISQG-Low) sediment quality guidelines at several sites throughout Wellington Harbour and are indicative of contaminant concentrations where the onset of adverse biological effects could occur. Some of the highest concentrations of these four metals are found at the inner harbour sites adjacent to Wellington city (Figures 4.1 & 4.2), but concentrations further from the city are also elevated suggesting that metal contamination is more widespread. Concentrations of silver, arsenic, cadmium, chromium, and nickel are currently below sediment guidelines in the subtidal sediments of the harbour.

Weak acid-extractable metal concentrations remain highest at sites nearest to Wellington city. These metals tend to adsorb to fine grained particles (<63 μm fraction) where they are more readily available to benthic organisms. Sites in southern Evans Bay (EB1 and WH1) and Lambton Harbour (LB1, LB2 and WH3) had consistently higher concentrations of copper, lead and zinc. There were some changes in the concentrations of weak-acid extractable copper, lead and zinc between surveys (typically ±8, 7 and 8%, respectively) though the statistically significant changes observed at some sites were largely explained by analytical variability (1–14%).

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[18] To be suitable for long-term monitoring, sampling 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 they are likely to be widely dispersed (ie, represent far-field sources) (Ray et al. 2003).

Even with analytical variability taken into account, however, weak acid-extractable lead concentrations have decreased significantly at four sites since 2006; WH9 and WH10 offshore from the Ngauranga Stream, WH13 offshore from Petone Wharf and the most outer harbour site, WH17.
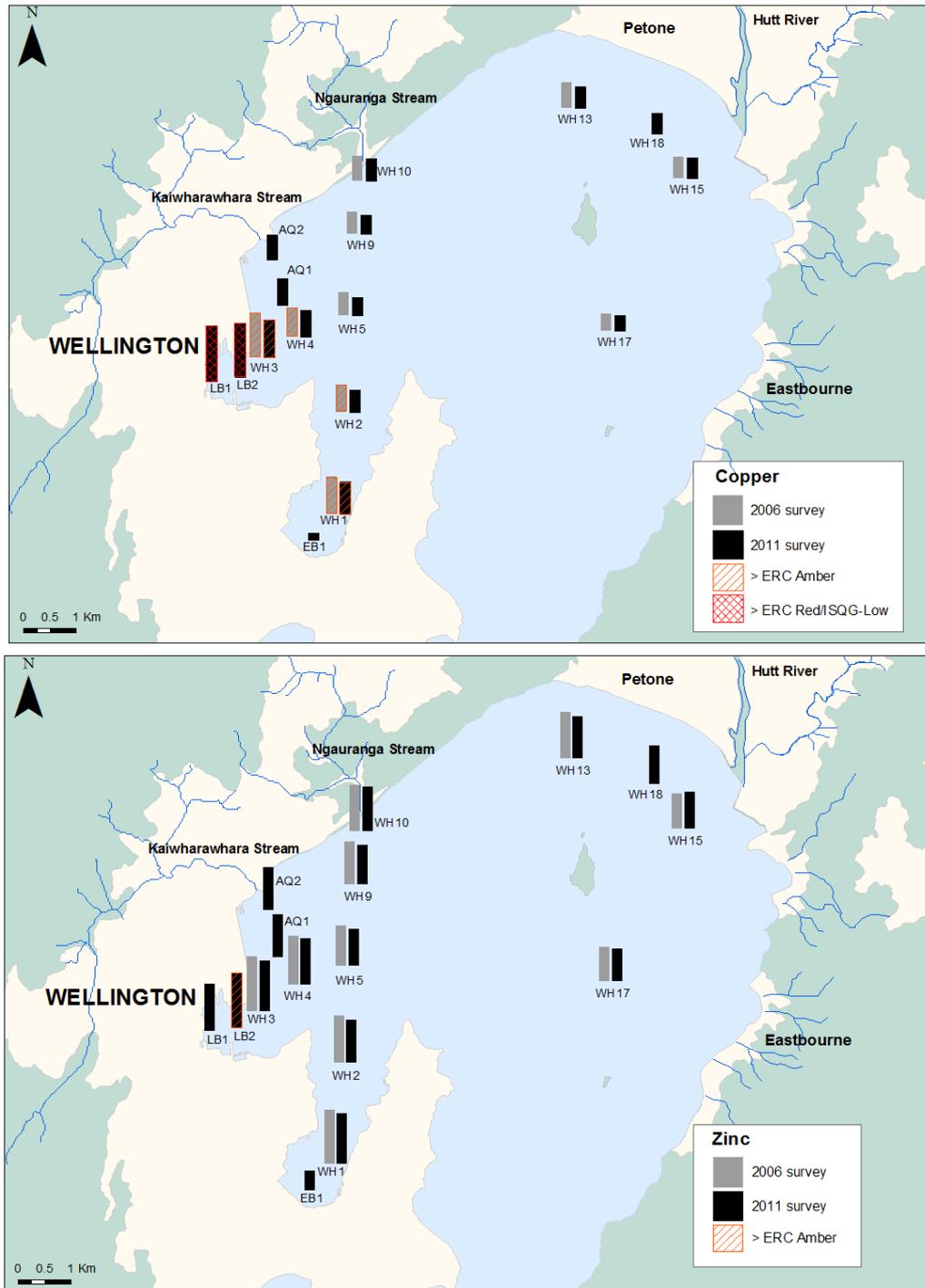

Figure 4.1: Relative concentrations of total copper (top) and zinc (bottom) in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 µm fraction of a single composite sample from each site. The 2006 survey results are also shown for comparison (10 sites). Note that the scale used for the bars is unique to each map
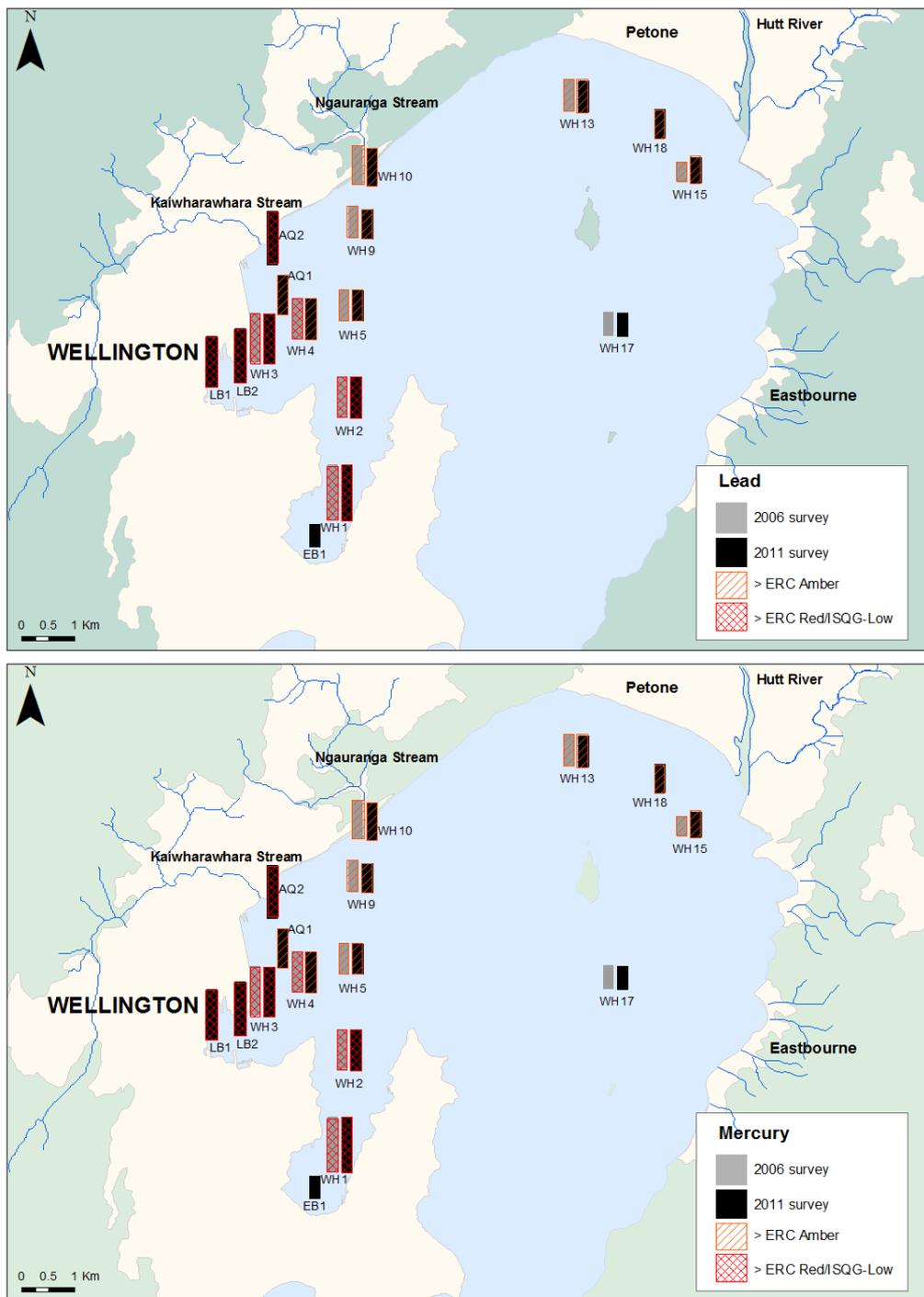
Figure 4.2: Relative concentrations of total lead (top) and mercury (bottom) in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction of a single composite sample from each site. The 2006 survey results are also shown for comparison (10 sites). Note that the scale used for the bars is unique to each map

Future surveys should consider performing replicate analyses on the total metals, as well at the <63 μm fraction metals. Historically the mud fraction (<63 μm) has been deemed the most important fraction in transporting trace elements and thus the most ecologically relevant component of the sediment. However, total metal concentrations are compared against sediment quality

guidelines and replicated analysis provides another method for checking trends over time and for assessing differences between sites (pers comm. Geoff Mills, Diffuse Sources Ltd).

Concentrations of total copper, zinc, lead and mercury were also recorded in the roadside catchpit sediments of five Wellington city stormwater catchments. Copper, zinc and lead concentrations were typically five to ten times higher than concentrations found in adjacent harbour sediments. This indicates that catchpit sediments contain significant concentrations of these metals, sourced from amongst other things, vehicle brake and tyre wear, galvanised roofs and historical inputs of road dust and soils contaminated by leaded petrol and lead based paints. Urban stormwater runoff, therefore, appears to be a source of ongoing contamination for the harbour. Additional sources of metal contamination within the harbour itself, such as copper leaching from anti-fouling paints applied to ship hulls, should be investigated.

Although there are no sediment quality guidelines with which to compare the catchpit sediment results, studies from elsewhere in New Zealand provide some context. Two studies of catchpit sediment contamination in Auckland city reported a similar range of copper concentrations and some higher lead and zinc concentrations (Table 4.1) (Moores et al. 2009b; Moores et al. 2009c). Consistent with Wellington catchpit sediment results, zinc concentrations were higher than the other two metals.

Table 4.1: Range of concentration of total metals, total petroleum hydrocarbons (TPH) and total polycyclic aromatic hydrocarbons (PAH) in <500 µm fraction of catchpit sediments of Wellington (this report) and Auckland cities (Moores et al. 2009a; 2009b; 2009c)

Analyte	Fraction analysed	Sites			
		n	Wellington	n	Auckland
TOC (%)	< 500 µm <1 mm[1]	2	2.95 – 9.1	36	0.7 – 7.1
Copper (mg/kg)	< 500 µm	2	129 – 335	36	88 – 880
Lead (mg/kg)	< 500 µm	2	144 – 420	36	76 – 1,320
Mercury (mg/kg)	< 500 µm	2	0.064 – 0.33	9	0.15 – 0.96
Zinc (mg/kg)	< 500 µm	2	715 – 895	36	279 – 1,810
Total TPH C7–C44 (mg/kg)	< 500 µm & <1 mm[2]	1	460 – 2,300	36	740 – 9,500
Total PAH (µg/kg)	< 500 µm	2	3,794 – 9,411	12	1,400 – 39,000

[1] Organic content was measured using Loss on Ignition (LOI) analyses of the <1 mm sediment fraction.

[2] The Auckland study measured TPH concentrations on the <1 mm fraction of the catchpit sediment.

In a third study, mercury concentrations were measured in industrial catchpits around Auckland, and also found to be comparable to the results recorded in Wellington city (Table 4.1) (Moores et al. 2009a). Mercury concentrations were approximately eight times lower in Wellington city catchpits compared to adjacent harbour sediments suggesting that urban stormwater runoff is not a significant source of mercury contamination. Mercury is deemed a persistent pollutant globally and the single greatest source of mercury pollution is from burning fossil fuels and subsequent atmospheric deposition onto land and water (Chen et al. 2012). Other sources of mercury are largely historical and include its use in herbicides, fungicides and antifouling agents. See Stephenson et al.

(2008) for further discussion on the anthropogenic sources of metal contamination.

4.1.3   Organochlorine pesticides

Consistent with the 2006 sediment survey, the insecticide DDT remains a ubiquitous contaminant in the harbour's surface sediments. TOC-normalised DDT concentrations are highest at the inner harbour sites where they exceed the ARC ERC-Red threshold. Throughout the rest of the harbour TOC-normalised DDT concentrations are much lower but still exceed the ANZECC ISQG-Low threshold at all sites, with the exception of site WH17 (Figure 4.3).

DDT concentrations remain particularly high at site WH3 with the associated problem of high analytical variability between sample replicates. Such variability is not a new issue, having been encountered in WH3 samples collected in 2006 (Milne 2010). Similar highly variable results have also been obtained with sediment samples from Porirua Harbour (Milne et al. 2009). The difficulty in achieving good repeatability is at least partly caused by matrix interference, when other components or analytes in the sample interfere with the test, reducing the ability to generate accurate results (Olsen et al. 2013).

The spatial distribution of DDT constituents observed in 2006 is still apparent throughout the harbour. The parent DDT substance is higher at sites near Wellington city, whereas the breakdown product DDE is higher at eastern harbour sites. This suggests that urban inputs of DDT to the harbour are ongoing and is consistent with previous studies of organochlorine pesticides in the Wellington Harbour catchment which showed that DDT was present in both the dissolved and particulate fractions of stormwater (KML 2005) and in the bed sediments of urban streams (Milne & Watts 2008). DDT was the dominant constituent in stormwater and sediments of predominantly urban catchments and DDE the dominant constituent of rural catchments. 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 (Stephenson et al. 2008).

Despite the high analytical variability, inherent to the analysis of organic contaminants, the results are still useful and ongoing monitoring of total DDT and its constituents should continue because of the widespread contamination throughout the harbour. However, the frequency with which the analyses are carried out could be reduced from five-yearly to ten-yearly. Samples collected during the next survey (proposed for 2016) could be stored in a stable, freeze-dried condition, as is standard practice and could be analysed for DDT at a later date, if needed.
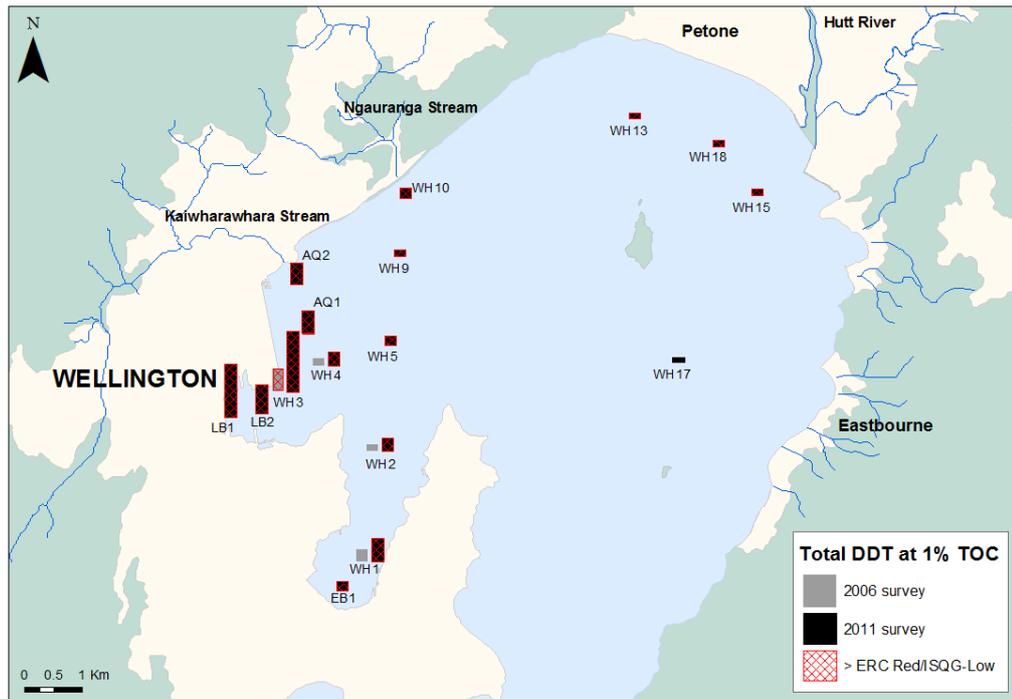
Figure 4.3: Mean concentrations of 1% TOC-normalised total DDT in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 μm fraction. The 2006 survey results are also shown for comparison (10 sites). Note that the scale used for the bars is unique to this map

4.1.4 Polycyclic aromatic hydrocarbons (PAHs)[19]

Concentrations of TOC-normalised HMW PAHs exceed ARC ERC-red and ANZECC ISQG-Low sediment quality guidelines at all of the inner harbour and Evans Bay sampling sites (Figure 4.4). It is worth noting that the HMW PAH (at 1% TOC) concentrations at site EB1 are low relative to all other sites because the sediments are very sandy, and that the low TOC concentrations (0.4%) contribute to the sediment guideline exceedance at this site. High concentrations at sites WH1, WH2, WH3 and WH4 are consistent with the 2006 survey results. TOC-normalised HMW PAH concentrations have increased significantly at eight of the ten sites in 2011 compared with 2006, although the variation (~20%) between archived samples collected in 2006 and then reanalysed in 2011 (as part of the QA/QC process) means that some of the observed differences are attributable to analytical variation. The increases were most notable at sites WH1 and WH3; TOC-normalised HMW PAH concentrations at these sites were 22% and 29% higher, respectively, than the mean concentrations in 2006.

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[19] This section summarises the results of a report prepared by NIWA and commissioned by GWRC. The reader is referred to this report (Depree 2013) for details of the analyses and an explanation of the terminology.
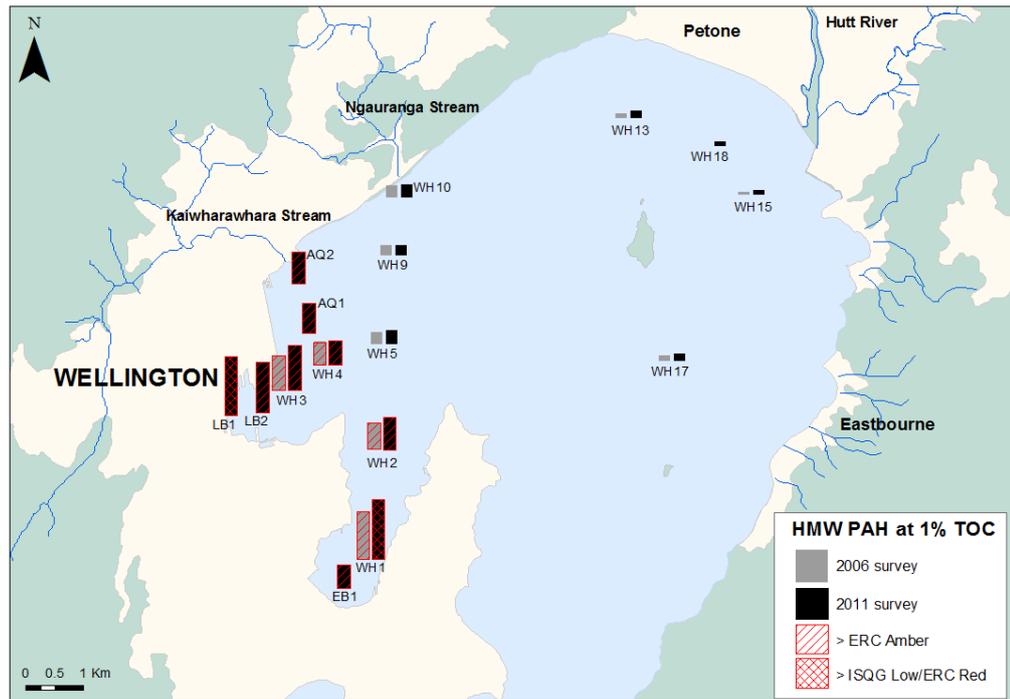
Figure 4.4: Mean concentrations of 1% TOC-normalised HMW PAH in sediments of 16 sites sampled in Wellington Harbour in 2011, based on the <500 µm fraction. The 2006 survey results are also shown for comparison (10 sites). Note that the scale used for the bars is unique to this map

With the exception of site WH1, the sites with the highest concentrations of TOC-normalised HMW PAHs are in close proximity to Wellington city indicating that stormwater discharges from the CBD have been a major source of PAH contamination in the harbour. In contrast, site WH1 recorded the highest TOC-normalised HMW PAH concentrations in both 2006 and 2011 (means = 1,598 and 1,991 µg/kg, respectively) though it appears less related to the nearby stormwater inputs; the TOC-normalised HMW PAH concentration at the nearby site EB1 was less than half the concentration of WH1 (mean = 812 µg/kg). The high TOC-normalised HMW PAH concentrations at site WH1 likely result from the historic Miramar gasworks discharging highly contaminated wastewater directly into Evans Bay during the early 1900s (Depree 2013).

Following the 2006 survey Depree (2010) used diagnostic ratios of various PAH compounds to characterise the PAHs present in Wellington Harbour sediments. These ratio plots indicated that, like Auckland estuarine sediments, Wellington Harbour sediments were pyrogenic (ie, derived from coal/wood soot or coal tar) in composition (Depree 2010).

Diagnostic ratios calculated using the 2011 harbour and catchpit data confirmed initial findings that harbour sediments were pyrogenic and revealed that catchpit sediments were more petrogenic (ie, derived from engine oil or bitumen) in composition. This suggests that the current PAH concentrations of Wellington Harbour sediments are mostly derived from historical sources, such as the Miramar Gasworks and the widespread use of coal tar in road

construction during the 1900s which would have resulted in higher PAH concentrations in catchment runoff.

To more accurately reconcile sources of PAH contamination in the harbour, roadside catchpit sediment samples were also analysed for two useful source markers: total petroleum hydrocarbons (TPH) and hopanes. The concentrations of these markers can be used to estimate the proportion of runoff particulates present in harbour sediments, and thus how much of the PAH contamination in harbour sediments is attributable to catchpit sources.

In reviewing the PAH and TPH data Depree (2013) concluded that, assuming the catchpits samples are representative of catchment runoff, the proportion of runoff particulates in harbour sediments is estimated to be between 4 and 8%. Therefore, modern day runoff may only account for a relatively small proportion of the PAH concentrations in the harbour sediments with historic inputs being a greater contributor at some sites. Depree (2013) proposed that the widespread use of coal tar in road construction up until the 1970s may have resulted in PAH-laden stormwater discharges to inner areas of Wellington Harbour. Furthermore, the concentrations of TPH were below detection limit in the harbour sediments indicating that there has been little recent contamination from petroleum-like substances at the sampling sites.

Depree (2013) also employed analysis of hopane to PAH ratios to more accurately assess the proportion of harbour sediment PAHs that could be accounted for by modern day runoff relative to historical sources. He determined that for sites close to the CBD where the highest PAH concentrations were recorded, modern day runoff accounted for a relatively low 10–35% of total PAH concentrations. At sites further from the CBD where PAH concentrations were lower, modern day runoff was estimated to account for 17 to 65% of the total PAH concentrations. These results suggest that historic inputs of PAHs to sites near the CBD were high and that PAHs have accumulated in the sediments at such concentrations that they are effectively 'diluting' the relative contribution of modern PAHs. In contrast, historic inputs were less evident at sites further from the CBD, and modern sources of PAHs comprise a larger proportion of total PAH concentrations at these sites.

It is worth noting, however, that although most of the PAH contamination may come from historic sources (ie, coal tar), it doesn't mean that inputs to the receiving environment are exclusively historic. Coal-tar may no longer be used in road building, but in low-trafficked residential suburbs where roads have not been fully replaced, it may be sealed beneath inert bitumen-based chipseals, and as such, large reservoirs of coal tar-derived PAHs can exist in road side shoulder and berm soils (Depree 2010) and are an ongoing source of contamination to the harbour.

As there was no evidence of obvious petrogenic PAH sources in harbour sediments, analyses of the large suite of petrogenic PAHs could be discontinued in the future. The most important PAH compounds for analysis are the 16 USEPA priority PAHs. TPH concentrations were below analytical detection limits at all harbour sites and these analyses could also be discontinued.

Depree (2013) recommends that a site near the middle of the harbour such as site WH7 or site WH8, last sampled in 2006, be included in the 2016 survey of Wellington Harbour to provide more adequate coverage of harbour sediments. Depree (2013) also recommends reducing the sediment depth of cores collected for analysis from 30 mm to 20 mm. He suggests that the current sampling depth of 30 mm may be integrating a longer time-scale (ie, 10 years, assuming a sedimentation rate of 3 mm/yr) and that reducing that depth to 20 mm may be more useful for monitoring PAH deposition trends. This requires further consideration; the current sampling depth reflects an earlier assessment by GWRC which estimated sedimentation rates outside of the central mud basins at approximately 6 mm/year, or 30 mm every five years (Stephenson, pers. comm. 2012). The current sampling depth is also consistent with that used in the four Porirua Harbour subtidal sediment surveys to date (Milne et al. 2009; Oliver et al. in prep). Further, regardless of surface sampling depth, physical and biological processes (eg, bioturbation) mean that the surface sediment may not just represent recent chemical contamination.

The other key recommendation made by Depree (2013) is for a more detailed survey of the runoff particulates from Wellington city catchments, to characterise the loads and composition of PAHs and other contaminants discharging to the harbour via the stormwater network.

4.2   Benthic ecology

The benthic invertebrates that reside in the subtidal sediments of Wellington Harbour are variants of soft-bottom inner harbour communities. The most abundant species within the community in 2011 were polychaete worms, crustaceans, sipunculids and bivalves. The heart urchin, *Echinocardium cordatum,* was a dominant member of the biomass, along with the bivalve *Dosina zelandica*, and the brittle star *Amphiura rosea*. Overall, invertebrate community composition was broadly similar across the 2006 and 2011 surveys, despite some significant differences in the relative abundance of the most dominant species (eg, Sipunculida sp, Tanaidacea sp, *Maldane theodori*) at some sites.

Multivariate analyses of a range of sediment quality variables and invertebrate abundance data showed that there was a similar pattern in the distribution of invertebrates and the sediment quality variables measured. The analyses, however, could not single out any specific sediment quality variable(s) that defined the relationship. Rather, the analysis identified several variables (many of which were correlated with other variables), namely TOC, mud, arsenic, copper, nickel, chromium and DDT which, in combination, explained some of the variation in community structure. This result is not surprising; the interrelationships between organisms, sediment particle size and chemistry are complex and unpredictable and benthic invertebrates vary widely in their relative accumulation and tolerance of contaminants (Macleod & Eriksen 2009). Furthermore, interactions between organisms may be driving some of the observed changes (eg, bioturbation, predation).

Of the most abundant species present within the harbour community, five species best matched the gradient of offshore sediment contamination; three species of polychaete, one invasive bivalve and an ostracod. There was a

significant relationship between distribution and contamination gradient for two species of polychaete and this may reflect their tolerance of polluted sediments. The invasive Asian bivalve, *Theora lubrica*, is highly tolerant of muddy, polluted sediments and thrives in marinas and harbours throughout New Zealand (Hayward 1997). This species was noticeably abundant at sites near the CBD.

5.   Conclusions

Consistent with the 2006 survey, the 2011 survey found that concentrations of total copper, lead, zinc and mercury exceed 'early warning' (ie, ARC ERC-amber or ANZECC ISQG-Low) sediment quality guidelines at several sites throughout Wellington Harbour and are indicative of contaminant concentrations where the onset of adverse biological effects could occur. There is evidence of a contaminant gradient extending offshore with some of the highest concentrations of copper, lead, zinc and mercury found at the inner harbour sites adjacent to Wellington city. Concentrations of TOC-normalised HMW PAHs exceed ARC ERC-red and ANZECC ISQG-Low sediment quality guidelines at all of the inner harbour and Evans Bay sampling sites, although PAH source analysis indicates that much of this contamination is historic. The insecticide DDT remains a ubiquitous legacy contaminant throughout the harbour with TOC-normalised total DDT concentrations being highest at the inner harbour sites where they exceed the ARC ERC-red threshold. Throughout the rest of the harbour TOC-normalised total DDT concentrations are much lower but still exceed the ANZECC ISQG-Low threshold at all sites, with the exception of the outer most harbour site. Concentrations of other heavy metals are currently below sediment quality guidelines in the subtidal sediments of the harbour.

Although some statistically significant changes in contaminant concentrations were detected between the two surveys, for the metal concentrations the magnitude of change across sites was small (typically ±8% for weak acid-extractable copper, lead and zinc) and within analytical variability (1–14%). The magnitude of change was considerably higher for TOC-normalised HMW PAHs and TOC-normalised total DDT, however, high analytical variability explains most of this change and has been an issue for the analyses of organic contaminants. As this is only the second survey, it is still too early to assess trends or determine whether these changes are environmentally meaningful and if they will continue into the future; three to five surveys are required before trends can be detected.

A total of 124 invertebrate taxa were identified in the 2011 Wellington Harbour survey. The most abundant species within the community were polychaete worms, crustaceans, sipunculids and bivalves. The heart urchin, *Echinocardium cordatum*, was a dominant member of the biomass, along with the bivalve *Dosina zelandica*, and the brittle star *Amphiura rosea*. The offshore sediment contaminant gradient appears to be influencing the distribution of some species, such as polychaete worms and the invasive Asian bivalve, that display varying preferences for sediments with high contaminant concentrations.

Although invertebrate community composition was broadly similar across the 2006 and 2011 surveys, there were some significant differences in the relative abundance of the most dominant species (eg, Sipunculida sp, Tanaidacea sp, *Maldane theodori*) at some sites. The reasons for this are unknown and cannot be attributed to changes in the physical or chemical sediment characteristics recorded at these sites. Furthermore, the contamination present in the harbour is a combination of significant historic inputs and modern sources and the

benthic invertebrates found there likely represent an opportunistic community with a degree of pollution tolerance.

Overall, the offshore gradients in sediment contaminant concentrations confirm a land-based, stormwater-borne origin. This is supported by stormwater catchpit sampling which found significant concentrations of copper, lead and zinc in catchpit sediments, likely sourced from amongst other things, vehicle brake and tyre wear, galvanised roofs and historical inputs of road dust and soils contaminated by leaded petrol and lead based paints. Urban stormwater runoff, therefore, appears to be a source of ongoing heavy metal contamination for the harbour.

5.1 Recommendations

For the third subtidal sediment quality survey of Wellington Harbour in late 2016 it is recommended that:

- Sediments are resampled for particle size, chemistry and benthos at the following sites: WH1–5, LB1–2, AQ1–2, WH9–10, WH13, WH15, WH17 and WH18;

- Site EB1 is replaced with another site in the subtidal mud basin at the south-western corner of Evans Bay and site WH7 or WH8 is reinstated;

- Field collection and preparation of samples for both sediment chemistry and benthic invertebrate identifications follow the same methodology as used in the first two surveys. However, consideration should be given to whether the depth of sediment core samples could be reduced from 30 mm to 20 mm;

- Replication (n=3) of total metals is included along with continued replication of TOC and the <63 μm sediment fraction metals as carried out to date;

- PAH analyses are limited to the 16 USEPA PAHs;

- Consideration is given to reducing the frequency of DDT analysis from five-yearly to ten-yearly;

- A review is undertaken of emerging contaminants (eg, personal care products) of potential relevance to Wellington Harbour and consideration given to their inclusion for monitoring; and

- The QA component of the monitoring programme is reviewed and a bulk reference sediment sample collected to improve assessment of within and between survey analytical variability.

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Acknowledgements

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