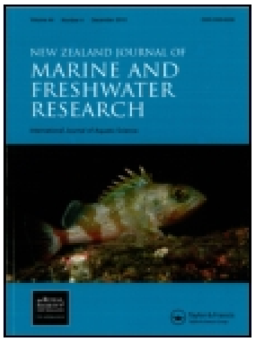

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Effect of storm drain discharge on the soft shore ecology of Porirua Inlet, New Zealand

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Abstract The effect of storm drain discharge on the ecology of the soft shore community near the Semple Street outfall in Porirua Inlet, New Zealand, was investigated from December 1998 to April 1999. Biological community structure, sedimentary properties, and heavy metal concentrations of surficial sediments were examined at increasing distance (5, 90, 140 m) from the storm drain at two (upper and lower) shore heights (total of six sites). Concentrations of copper (Cu), lead (Pb), and zinc (Zn) at nine sites from the storm drain to the mouth of the inlet were estimated in April 1999. Typically, mean numbers of individuals decreased, whereas mean numbers of taxa, and the Shannon-Wiener diversity index increased with increasing distance from the storm drain. Analysis of variance revealed that the 5, 90, and 140 m sites at both tidal heights exhibited small but significant differences in community structure which were attributable to differences in species abundance, rather than to differences in the suite of species which characterise these sites. It was not possible to identify temporal trends in the data set. Analysis of similarities revealed significant differences in species abundance among the three sites for the high shore, the low shore, and both tidal heights combined. Sites furthest apart (5 versus 140 m) exhibited the greatest, and sites closest together (90 versus 140 m) exhibited the least, difference in biological community structure, suggesting that storm drain outflow modifies benthic community composition immediately in front of the drain and up to <100 m away. Non-metric multidimensional scaling (MDS) ordination of taxon abundance showed community structure at the two 5 m sites to be dissimilar from that at the other four sites, where it was similar. Despite this, however, changes in taxon abundance with increasing distance from the storm drain were minimal, with the result that indicator taxa could not be identified which explained significant differences in community structure on the scale of this study. A survey of heavy metal concentrations along the length of the inlet indicated that Cu, Pb, and Zn concentrations decreased in a linear manner with distance away from the storm drain and that biological communities in at least the southern half of the inlet are exposed to elevated levels of Cu, Pb, and in particular, of Zn, which exceed internationally recognised threshold, and sometimes, probable effect levels.

Keywords Porirua Inlet; New Zealand; estuary; storm drain discharge; soft shore; indicator species; heavy metals; community ecology

INTRODUCTION

Urban stormwater is produced when rainfall flows over impervious surfaces picking up pollutants, before being channelled into stormwater drainage systems and discharging into receiving water bodies such as streams and estuaries. The exact origins of stormwater-borne pollutants are difficult to trace in any one catchment because of the diverse nature of non point-source pollution. There are, however, many contaminants characteristically associated with stormwater, including sediment, nutrients, organic matter, inorganic matter, heavy metals,

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polycyclic aromatic hydrocarbons, organochlorines, dioxins, and bacteria (Vincent & Thomas 1997). The quality and volume of urban stormwater discharge is known to differ according to catchment size, drain location, time of day, climate, and season (Pitt et al. 1993).

Estuaries, such as Porirua Inlet, are transitional zones between sea and freshwater environments, with unique biological, chemical, and physical attributes (Knox 1986). When fresh water enters an estuary from a stream or stormwater drain, all except the finest transported particles settle within a short distance, because of reductions in current velocity and differences in pH and ionic composition of sea water (Knox 1986). Deposited particles can be resuspended by the incoming tide, creating turbid conditions. At lower particle concentrations both photosynthetic primary production and suspension feeding can be reduced, whereas at higher particle concentrations photosynthetic primary production and suspension feeding can be precluded. Deposit feeders ingest sediment particles, removing the bio-organic surface film, and if inhabiting areas close to storm drain discharge, will also ingest contaminants adsorbed to the particles that they are feeding on (Williamson et al. 1999). Heavy metals are one category of pollutants that persist in the environment, and are capable of accumulating in organisms, culminating in sub-lethal or lethal effects. This, in turn, can affect species population levels and community structure, and can ultimately result in large-scale environmental impacts (Long et al. 1995).

Two studies of contamination levels in Porirua Harbour (i.e., Porirua Inlet and Pauatahanui Inlet) have been carried out. Glasby et al. (1990) investigated heavy metal levels in Porirua Harbour sediments. Copper (Cu), lead (Pb), and zinc (Zn) concentrations were higher in Porirua Inlet sediment samples than in Pauatahanui Inlet sediment samples, and sediment concentrations of Pb and Zn declined with increasing distance up Porirua Inlet from Porirua City. However, this study had no biological or temporal component with which to assess the ecological impact (if any) of the heavy metals, nor the change over time (if any) of the heavy metal concentrations. In a joint study by the Wellington Regional Council (WRC) and Porirua City Council (PCC) levels of sediment and shellfish contamination were investigated in Porirua Harbour (Berry et al. 1997). Flesh samples of the cockle *Austrovenus stutchburyi* from five sites were assayed for levels of heavy metal and microbial contamination. Sediment samples were analysed for concentrations of heavy metals, organochlorines, and polycyclic aromatic hydrocarbons (PAHs) at 11 sites. Concentrations of Cu, Pb, and Zn were highest in cockle samples from the southern end of Porirua Inlet. Of the sediment samples taken from 11 sites, concentrations of heavy metals and high molecular weight PAHs were highest (organochlorine levels were also high) at the southernmost end of Porirua Inlet, closest to the storm drain. The study did not investigate temporal changes in the distribution of contaminants or associated patterns in the distribution of infauna.

Within New Zealand there is increasing interest on the part of local government authorities to determine what might loosely be termed the "health" of the near-shore marine environment. With this in mind, and assisted by PCC and the WRC, we investigated the ecological impact of storm drain discharge on benthic infaunal estuarine communities near the Semple Street storm drain in Porirua Harbour. We conducted our research at this particular storm drain because PCC staff believed it to be the "worst drain" in the region, i.e., the ecological effects of the storm water discharge were expected to be pronounced. In contrast to the previous studies undertaken in Porirua Harbour, response to storm drain discharge was studied at the community level over time and related to a number of environmental variables. Biological community structure, heavy metal concentrations, and sedimentary properties were examined at increasing distance (5, 90, and 140 m) from the storm drain at two shore heights (upper and lower) at three time intervals (December 1998, February and April 1999). Our research focused on 12 environmental variables, including the concentrations of three heavy metals (Cu, Pb, and Zn) and nine sedimentary properties (% organic matter, skewness, kurtosis, % carbonate, % gravel, % sand, % silt, sorting, mean grain size). We recognise that many other variables (e.g., polyaromatic hydrocarbons, mercury, tributyltin (TBT), polychlorinated biphenols (PCBs), etc.) also influence community structure but we specifically chose to analyse these 12 variables in anticipation of identifying a subset of key variables which can be analysed quickly and cheaply to permit rapid indirect assessment of environmental community health. These variables are routinely examined in studies of this sort and several of them have previously been measured at this location. Specifically, we tested the following hypotheses: (1) that, in the vicinity (0–140 m range) of the storm drain, 12 environmental variables exhibit temporal and/or spatial variability which is associated with proximity to the drain, and

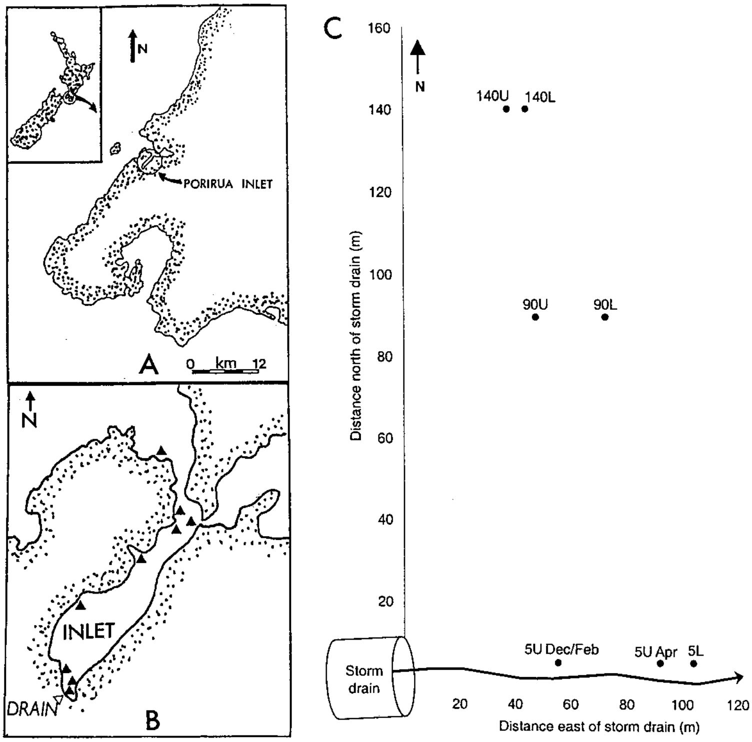

Fig. 1 **A**, Location of Porirua Inlet, New Zealand; **B**, nine sampling sites at the Semple Street storm drain, Porirua Inlet; and **C**, the locations from which surficial sediment samples were taken for background heavy metal analysis on 21 April 1999.

(2) that, in the vicinity of the storm drain, infaunal community structure exhibits temporal and/or spatial variability which is associated with proximity to the drain. These hypotheses are linked directly to a primary aim of this research which was to determine if a small number of variables (indicator species and/or geochemical properties and/or sedimentary properties) could be identified which can act as rapid, cheap, and accurate indicators of the health of the near-shore marine environment. This research complements similar ongoing research in Wellington Harbour (Bolton-Ritchie et al. 1999) and is part of a larger programme aimed at determining the ecological impact of storm drain discharge in New Zealand.

MATERIALS AND METHODS

Site description

Porirua Harbour is situated 21 km north of Wellington and is composed of two inlets (Fig. 1). Pauatahanui Inlet, to the east, has been called the "largest relatively unmodified estuarine area" in the southern North Island (Rosier 1993), whereas Porirua Inlet, to the west, which is 4 km long and up to 2 km wide, is extensively modified (Glasby et al. 1990). Porirua Stream, the main freshwater source for Porirua Inlet, enters at the southern end, and has a catchment of 5538 ha which consists of 38% pasture, 33% urban, and 29% forest and shrub land cover (WRC; information obtained from Land Information New Zealand, pers. comm.). The Semple Street storm drain discharges stormwater collected from the Porirua Stream catchment into the southern end of Porirua Inlet, c. 165 m from the Porirua Stream. At high tide the stormwater discharges directly into the sea, when the tide comes up to the drain outlet, whereas during low tide the stormwater runs over the estuary flats and into Porirua Stream.

Sampling locations

The study was conducted from December 1998 until April 1999. Sampling was carried out at six 4 × 4 m sites located at two tidal heights at distances of 5, 90, and 140 m from the storm drain (Fig. 1). Selection of the six sites was dictated by the slope and width of the shore. The lower tidal sites were c. 0.4 m above mean low water springs (MLWS) (0.6 m above chart datum, CD) and separated from the upper tidal sites by c. 15 cm vertical distance. Each site was marked with a plastic peg hammered into the substrate. At the beginning of each sampling period, the three upper tidal sites (5U, 90U, and 140U) and the three lower tidal sites (5L, 90L, and 140L) were resurveyed to ensure they still fell along the same, previously determined tide level, and if not, the marker pegs were adjusted accordingly (the 5U site in April was repositioned as a consequence of a change in the slope of the substrate in front of the storm drain).

Biological analysis

In December 1998, and February and April 1999, three cores each of 1250 cm^3 containing both epifaunal and infaunal species were taken at random at each of the six sites. The cores were gently washed through 2 and 0.5 mm sieves and both size fractions of retained material were preserved in 10% formol sea water for 24 h, before being transferred to 70% isopropyl alcohol for long term storage. Each size fraction was stained with rose bengal for 1 h, dyeing pink any recently living organic matter, to aid in sorting. Organisms were picked out, stored in 70% alcohol, and identified to lowest practical taxonomic level.

Sediment analysis

In December 1998, and February and April 1999, a 170 cm^3 sediment core was taken adjacent to the first core used for biological material at each site and analysed for nine sedimentary variables. Each sample was dried at 40°C and weighed at room temperature to 2 decimal places (d.p.), then 10% H_2O_2 was added until all organic matter was removed. Samples were rinsed 3 times with distilled water by centrifuging at 5000 rpm for 10 min, before being dried at 40°C and reweighed at room temperature (Barrett & Brooker 1989). Percent organic matter content (% OM) was calculated for each sample from weight loss after treatment with H_2O_2. A 10% HCl solution was then added to each sample until all carbonate was removed. Samples were rinsed 3 times with distilled water by centrifuging at 5000 rpm for 10 min, before being dried at 40°C and reweighed at room temperature (Barrett & Brooker 1989). Percent carbonate (% CO_3) content was calculated for each sample from weight loss after treatment with HCl. Samples were then put through a half-phi interval sieve series (–3.5 to 5 phi) on a Fritsch shaker for 6 min each on intermittent mode, micro mode, and intermittent mode again, and each size fraction weighed to 2 d.p. (Barrett & Brooker 1989). From these data we calculated mean grain size, sediment sorting coefficient, skewness, kurtosis, % gravel, % sand, and % silt.

Heavy metal analysis

In December 1998, and February and April 1999, a plastic scoop and dual plastic bags were used to remove one surficial sediment sample at each site. Each sediment sample was washed with glass-distilled water through a 63 μm plastic sieve into an ethanol rinsed glass beaker. The fine sediment (<63 μm) and distilled water were centrifuged at 5000 rpm for 10 min, the water decanted off, and the sediment dried at 40°C until all moisture was removed. The dried sediment was ground to a fine powder in an ethanol rinsed mortar and pestle, and stored in a plastic bag. Four grams of powdered sediment from each sample were pressed into a pellet, and pellets run through a Philips PW 1404 X-ray Fluorescence Spectrometer (calibrated against international reference standards—http://www.geo.vuw.ac.nz/analytical/xfr.htm) to analyse for Cu, Pb, and Zn concentrations. We focused on these three heavy metals because they show high levels of increase compared with background levels in the region (Dickinson et al. 1996), they have been previously measured at this location (Glasby et al. 1990), and they can be measured cheaply and quickly, but with accuracy. Other methods for heavy metal analysis such as ICP-MS or atomic absorption spectrophotometry (AAS) are substantially more expensive, and although they may be more accurate (depending on acid leach protocol) than XRF analysis at low metal concentrations, given the elevated concentrations of Cu, Pb, and Zn at Porirua Inlet, this accuracy differential is negligible. In April 1999, we conducted a survey of Cu, Pb, and Zn concentrations in sediment from nine locations throughout Porirua Inlet to ascertain background levels of these elements along the entire length of the inlet (Fig. 1).

Data analysis

Faunal abundance and environmental data were analysed using, and following recommendations of, the software package PRIMER (Plymouth Routines in Multivariate Ecological Research, Clarke & Warwick 1994). Other statistical tests were carried out using either SYSTAT (version 8.0) or STATISTICA (version 5.5) unless otherwise stated.

Biological analysis

The PRIMER routine DIVERSE was used to calculate a range of diversity indices. ANOVA was performed on the numbers of individuals, the numbers of taxa, and the Shannon-Wiener diversity index to test for differences between and among distance from the storm drain (fixed term), tidal height (fixed term), and time of sampling (random term). The full model was tested, with all possible 2-way and 3-way interactions, then non-significant terms dropped, until a best fit model was found. PRIMER routines CLUSTER and non-metric multi-dimensional scaling (MDS) were employed to examine the effects of shore heights, distance from the drain, and time periods on the species-by-site abundance data. The Bray-Curtis similarity coefficient was used in CLUSTER to calculate a between-sample pairwise similarity matrix, before hierarchical agglomerative clustering and ordination by MDS. The similarity matrix was calculated from square root transformed taxon abundance values. Using the average abundance of the three replicates per site (1 averaged sample of 3 replicates × 2 tidal heights × 3 distances × 3 time periods = 18 points) an MDS plot was used to investigate changes in taxon-specific abundance at each tidal height, as a function of distance from the storm drain and time of sampling. The PRIMER routine SIMPER was used to calculate the degree of community structure similarity (1) between pairs of sites at the same tidal height and (2) between pairs of sites at the same distance from the storm drain (Bray-Curtis similarity values were square root transformed for these analyses). SIMPER was also used to identify which taxa contributed most to differences between pairs of sites. One-way multiple analysis of variance (MANOVA) was used to test for differences in non-rare taxon abundances for upper and lower shore heights among sites located at different distances from the storm drain for each of the three time periods. Thus, all non-rare taxa were tested for differences in their abundance at each of the three distances from the storm drain at each time period (for brevity, only statistically significant results are displayed in the MANOVA table). Rare taxa removed from the data set were those with an average abundance of <3 individuals at all three distances from the storm drain, in any of the three time periods. The PRIMER routine ANOSIM (analysis of similarities: a randomisation procedure to generate significance levels to permit hypothesis testing of multivariate community data) was used to test for differences in biological community structure between pairs of sites (5, 90, and 140 m) in (1) the upper shore, (2) the lower shore, and (3) across the whole study area (i.e., upper and lower shore combined). For each ANOSIM analysis we ran 5000 permutations and for each of the three tests we pooled data from all three time periods to provide maximum statistical robustness during testing. ANOSIM testing of differences in community structure between/among sites for each of the three separate time periods was not possible because of low statistical power.

Sediment analysis

Mean grain size, sediment sorting coefficient, skewness, kurtosis, % gravel, % sand, and % silt were calculated for each sediment sample with the Grain Size 1-2 software program (School of Earth Sciences, Victoria University, Wellington) using indices developed by Folk & Ward (1957).

Environmental variable analysis

PRIMER routines CLUSTER and MDS were employed to test for differences among shore heights, distance from the drain, and time periods using the 12 environmental variables. Comparison was then made between the MDS plots of the biological variables and the corresponding environmental variables.

Linking biological and environmental variables

The PRIMER routine BIOENV was used to determine if we could identify a subset of the 12 environmental variables best explaining biological community structure by maximising a rank correlation between the two similarity matrices using the weighted Spearman correlation coefficient (ρ_w). This differs from the usual Spearman correlation coefficient, and as a consequence it is not possible to test the statistical significance of the correlation (Clarke & Ainsworth 1993). We standardised our data (environmental variables are measured on different scales and failure to standardise will not weight each variable equally) by using normalised Euclidean distances. Because there is no *a priori* knowledge of which environmental factor or combination of factors is most likely to explain maximum variation in the biological data set, all possible factor permutations (single factor, 2-factor, 3-factor, …., 12-factor) of the 12 environmental variables were tested against the biological data set. The underlying assumption is that a large data set composed of many environmental variables (in this case 12) can be reduced to a simple model involving relatively few environmental variables which explain most of the variation in the biological data set (Clarke & Warwick 1994). This analysis was carried out from three different perspectives. First, we

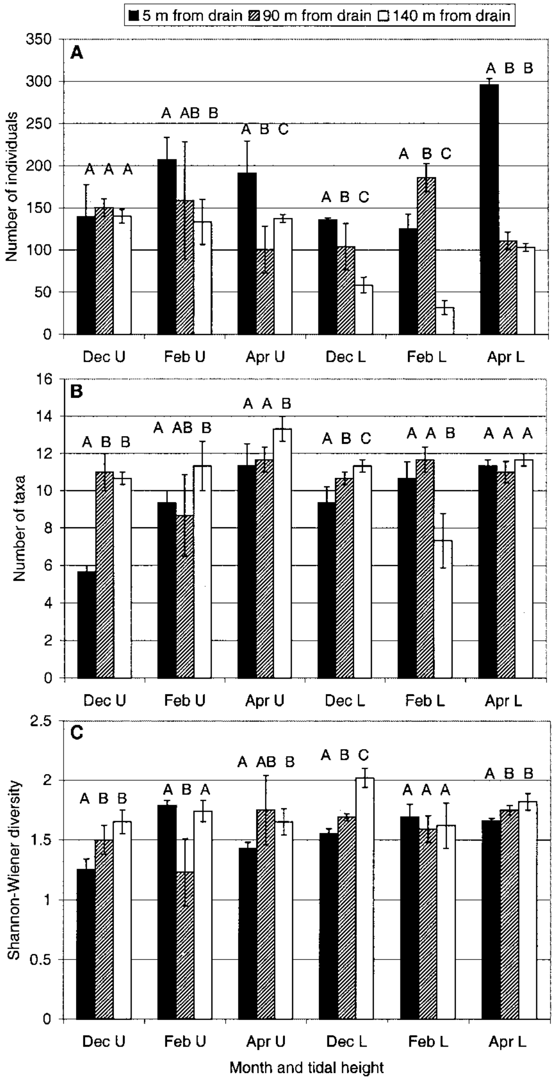

Fig. 2 Faunal diversity indices for sites sampled near the Semple Street storm drain, Porirua Inlet (U, upper shore; L, lower shore). Significant differences among samples are indicated by different letters above the appropriate bars.

investigated the effects of distance from the storm drain at both tidal heights (i.e., we conducted separate analyses within either tidal height location: 5U versus 90U versus 140U; 5L versus 90L versus 140L). Second, we investigated the effects of height on the shore at all distances from the storm drain (i.e., we conducted separate analyses for each distance from the storm drain: 5U versus 5L; 90U versus 90L; 140U versus 140L). Third, we investigated which environmental variables best explained variation in the biological data set encompassing the two tidal heights and the three distances from the storm drain (this is the "big picture" analysis).

Heavy metal analysis throughout Porirua Inlet

Cu, Pb, and Zn concentrations were plotted as a function of linear distance from the Semple Street storm drain. We used the software package S-Plus to test the following hypotheses, that the concentrations of the three heavy metals as a function of increasing distance from the storm drain can be represented best by: (1) three non-parallel lines; (2) three lines, all parallel; (3) three lines, with Cu and Pb being parallel, and Zn non-parallel; (4) two non-parallel lines (i.e., Cu and Pb as one line, Zn as the other); (5) two parallel lines (i.e., Cu and Pb as one line, Zn as the other); and (6) one single line representing all three metals.

RESULTS

Biological analysis

Diversity indices

A total of 7527 individuals was identified from all core samples. Polychaetes were the most abundant group (71% of all individuals), followed by bivalves (16%), amphipods (5%), and oligochaetes (5%). The most abundant polychaete was *Scolecolepides benhami* (43% of all polychaetes), then *Scolelepis* sp. (27%) and *Capitella* sp. (19%). The most abundant bivalve was *Arthritica bifurca* (84% of all bivalves), then *Austrovenus stutchburyi* (14%). *Amphibola crenata* accounted for 41% of the gastropods, and *Notoacmea helmsi* for 31%. A total of 31 taxa, composed of 11 polychaetes, 11 molluscs, 7 crustaceans, 1 nemertean, and 1 oligochaete, were identified for all sites at all time periods.

Plots of mean numbers of individuals (±SE), mean numbers of taxa (±SE), and mean Shannon-Wiener diversity (±SE) are presented in Fig. 2. For all three indices, standard errors were small compared with mean values, indicating that the three replicate samples have described with sufficient accuracy these indices. Typically, mean numbers of individuals decreased, whereas the mean numbers of taxa and the Shannon-Wiener index increased with increasing distance from the storm drain. Significant differences among samples are indicated by different letters above the appropriate bars.

ANOVA was carried out to test for the effects of tidal height, distance from the drain, month of sampling and their interactions upon (1) numbers of individuals, (2) numbers of taxa, and (3) the Shannon-Wiener diversity index (Table 1). All three models were significant (*P* 0.03), but all contained one or more significant (*P* 0.05) interaction terms, meaning that biological interpretation of the analyses is complex. The best fit model was obtained for number of taxa (r^2 = 0.598), then number of individuals (r^2 = 0.562), and then the Shannon-Wiener diversity index (r^2 = 0.388).

MDS analysis of faunal abundance

MDS ordinations of average faunal abundances for the two tidal heights and the three distances from the storm drain and the three time periods are presented in Fig. 3A (stress value = 0.13). The points for the 5 m sites occurred to the left of the plot, and the points for the 140 m sites occurred to the right of the plot. Thus, the single factor influencing biological community structure the most is distance from the storm drain, rather than tidal height or time of sampling.

Taxon similarity among sites

With increasing distance from the storm drain, corresponding sites in the upper and lower shore exhibited increasing similarity (56.74 versus 59.58 versus 61.24%), suggesting an effect of the storm drain upon community structure at the two tidal heights (Table 2). For the three pair-wise comparisons, seven of the 31 taxa (*Perinereis nuntia*, amphipods, *Scolelepis* sp., *Scolecolepides benhami*, *Arthritica bifurca*, *Capitella* spp., and oligochaete spp.) explained at least half of all of the similarity between sites (Table 2).

In the upper shore, the 5U versus 90U, and the 5U versus 140U samples showed approximately equal levels of similarity, whereas the 90U versus 140U samples exhibited the highest level of similarity (Table 3). In the low shore, the 5L versus 90L and the 90L versus 140L samples exhibited approximately equal levels of similarity, whereas the 5L versus 140L samples were the least similar (Table 3). For the six pair-wise comparisons, seven taxa (the same seven taxa as previously listed) explained at least half of all of the similarity between sites.

Differences among sites for non-rare taxa

Differences in taxon-specific abundance among the sites in the upper and lower shores for each separate time period are presented in Table 4 (only statistically significant results are shown). In December, significant differences in taxon abundance in the upper shore were observed for *Perinereis nuntia* (polychaete) and *Nicon aestuariensis* (polychaete) which were most abundant at 5U and at 90U respectively, and *Scolelepis* sp. (polychaete), *Axiothella*

Table 1 ANOVA for the effects of distance from drain, tidal height, and time of sampling on the numbers of individuals, numbers of species, and Shannon-Wiener diversity index.

Source	d.f.	*F*	*P*
Numbers of individuals			
Model			
Distance	2	12.181	<0.001
Distance × Tidal height	2	3.344	0.045
Distance × Time	4	4.335	0.005
Tidal height × Time	2	3.434	0.041
Number of species			
Model			
Time	2	8.315	0.001
Distance	2	3.582	0.037
Distance × Time	4	3.351	0.019
Distance × Tidal height	2	4.964	0.012
Distance × Tidal height × Time	4	2.723	0.043
Shannon-Wiener diversity index			
Model			
Distance	2	3.903	0.027
Tidal height	1	6.810	0.012
Distance × Time	4	3.651	0.012

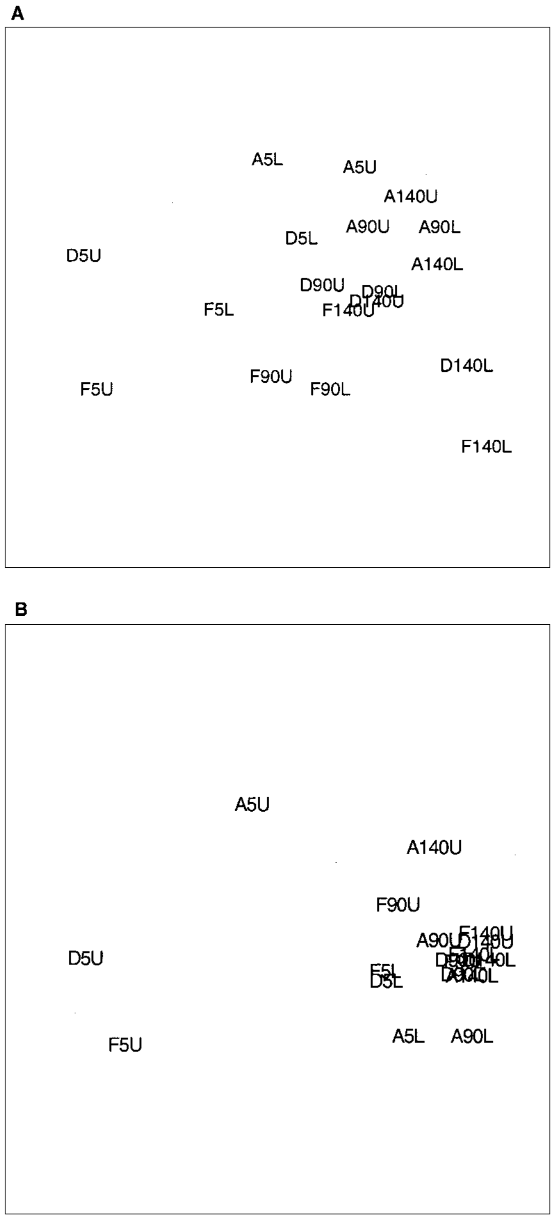

Fig. 3 Non-metric multidimensional scaling (MDS) ordination of: **A**, average faunal abundance; and **B**, 12 environmental variables for upper and lower shore sites at 5, 90, and 140 m from the Semple Street storm drain, Porirua Inlet, in December 1998 and February and April 1999 (A5U, April 5 m upper shore site; F140L, February 140 m lower shore site, etc.).

serrata (polychaete), and *Arthritica bifurca* (bivalve) which were most abundant at 140U. In the lower shore, *Scolecolepides benhami* (polychaete) was most abundant at 90L, whereas *Axiothella serrata*, *Austrovenus stutchburyi* (bivalve), and amphipod spp. were all most abundant at 140L. Significant differences in taxon abundance in February were observed in the upper shore for *Perinereis nuntia*, oligochaete spp., and isopod spp. (most abundant at 5U) and for *Nicon aestuariensis* and *Scolecolepides benhami* (most abundant at 140U), and in the lower shore for *Perinereis nuntia*, *Amphibola crenata* (gastropod), and *Arthritica bifurca* (bivalve) (most abundant at 5L), and for *Scolelepis* sp., *Capitella* sp. (polychaete), and *Austrovenus stutchburyi* (most abundant at 90L). In April there were no significant differences in taxon abundance in the upper shore, but *Perinereis nuntia*, *Capitella* sp., *Scolelepis* sp., *Scolecolepides benhami*, *Amphibola crenata*, and *Arthritica bifurca* were all most abundant at 5L.

Analysis of similarities (ANOSIM) across all three time periods gave $r = 0.246$ and $P < 0.001$ for the three upper shore sites, $r = 0.444$ and $P < 0.01$ for the three lower shore sites, and $r = 0.192$ and $P < 0.0001$ for all six sites combined. Thus, in all three cases, significant differences existed in biological community structure. Pairwise tests to identify the location of significant differences gave the following results for the upper shore, lower shore, and all sites combined: 5 m versus 90 m sites, $P = 0.025$, $P < 0.001$, $P < 0.001$ respectively; for 5 m versus 140 m sites, $P = 0.006$, $P < 0.001$, $P < 0.001$ respectively; and for 90 m versus 140 m sites, $P = 0.012$, $P = 0.023$, $P = 0.257$, respectively. Thus, with the exception of the 90 m versus 140 m contrast for the combined data set, all pairwise comparisons were statistically significant, indicating significant differences in the biological communities at these locations. The most pronounced differences were observed between sites furthest apart (5 m versus 140 m) and the least pronounced differences were observed between sites closest together (90 m versus 140 m), suggesting a significant effect of distance from the storm drain in the high shore, low shore, and when the two are combined.

Sediment analysis

There was a decrease in mean grain size from 5U to 90U, then a relatively small increase from 90U to 140U, at all sampling times (Table 5). There was an increase in mean grain size from 5L to 90L to 140L m at all sampling times. Mean grain size was reasonably constant with time in both the upper and lower shore at all sampling times, except for a pronounced decrease at 5U in February, compared with December and April. Mean grain size at 5U was

Table 2 Biological similarity between pairs of sites at the same distance from the storm drain and the five species contributing most to differences between pairs of sites across all time periods (only significant results are presented).

Pairwise comparison of sites	Mean % similarity between sites	Species contributing most to differences between sites	% contribution
5U and 5L	56.74	*Scolelepis* sp.	15.14
		Arthritica bifurca	12.77
		Perinereis nuntia	11.72
		Oligochaete spp.	9.54
		Capitella spp.	8.86
90U and 90L	59.58	*Scolelepis* sp.	17.30
		Scolecolepides benhami	11.15
		Amphipods	11.09
		Capitella spp.	10.65
		Arthritica bifurca	6.98
140U and 140L	61.24	*Scolelepis* sp.	16.17
		Capitella spp.	13.08
		Scolecolepides benhami	12.20
		Arthritica bifurca	8.00
		Amphipods	6.58

Table 3 Biological similarity between pairs of sites along the upper and lower shores and the five species contributing most to differences between pairs of sites across all time periods (only significant results are presented).

Pairwise comparison of sites	Mean % similarity between sites	Species contributing most to differences between sites	% contribution
5U and 90U	52.06	*Perinereis nuntia*	13.02
		Amphipods	10.58
		Scolecolepides benhami	10.32
		Oligochaete spp.	10.10
		Arthritica bifurca	9.77
5U and 140U	52.84	*Scolelepis* sp.	14.29
		Perinereis nuntia	13.42
		Oligochaete spp.	9.78
		Arthritica bifurca	9.06
		Scolecolepides benhami	7.54
90U and 140U	62.16	*Scolelepis* sp.	14.08
		Scolecolepides benhami	11.40
		Amphipods	11.04
		Capitella spp.	10.99
		Arthritica bifurca	6.50
5L and 90L	62.27	*Arthritica bifurca*	12.61
		Capitella spp.	12.53
		Scolelepis sp.	11.68
		Scolecolepides benhami	8.42
		Amphipods	7.39
5L and 140L	50.52	*Arthritica bifurca*	13.17
		Scolelepis sp.	12.81
		Capitella spp.	12.35
		Scolecolepides benhami	11.70
		Oligochaete spp.	5.49
90L and 140L	61.81	*Scolelepis* sp.	21.02
		Capitella spp.	10.22
		Arthritica bifurca	8.82
		Scolecolepides benhami	8.59
		Oligochaete spp.	7.69

larger than at 5L at all times, while mean grain size at 90U was smaller than mean grain size at 90L at all times (these differences were all very small). Mean grain size at 140U was larger than at 140L in December and February, but not in April. Both 5U and 5L were more poorly sorted than the four other sites at all sampling times (Table 5). There was, however, no clear pattern of sediment sorting evident at the six sites because sorting changed over time: 5U was very poorly sorted (>2.00) to poorly sorted (1.00–2.00), 90U and 140U fluctuated between being moderately well sorted (0.50–0.70) to poorly sorted, 5L fluctuated between being moderately (0.70–1.00) to poorly sorted, whereas 90L and 140L remained moderately well sorted all the time. Sediment percent organic content (% OM) was higher at 5U and 5L than at the four other sites, at all sampling times (Table 5). % OM increased at all sites at both upper and lower shore levels from December 1998 to February 1999, then decreased in April 1999 at all sites except 90L. % OM at 5U and 90U was greater than at 5L and 90L, respectively, in December and February, but less than in April. % OM at 140U was less than at 140L at all sampling times. Sediment percent CO_3 (% CO_3) content decreased with distance from the drain, along both the upper and lower shore, at all sampling times except for the lower shore sites in April (Table 5). There were no clear differences between upper and lower shore % CO_3 content.

MDS analysis of 12 environmental variables

MDS ordinations of the 12 environmental variables for the two tidal heights and the three distances from the storm drain and the three time periods are presented in Fig. 3B (stress value = 0.06). The points for the 5 m sites occurred to the left of the plot (5 m upper shore points to the far left, 5 m lower shore points to the left), whereas the points for the 90 and 140 m sites occurred to the right of the plot with some evidence of the 140 m points occurring to the far right of the plot. Thus, the single factor most influencing the environmental

Table 4 One-way multiple analysis of variance (MANOVA) and multiple comparison tests for the effect of distance from the drain on non-rare taxon abundance of the upper and lower shore for each time period.

Tidal height	Time of sampling	Taxon	*P*	Multiple comparison*
Upper	Dec	*Arthritica bifurca*	0.004	140 > 90 > 5
		Nicon aestuariensis	0.004	90 > 140 > 5
		Axiothella serrata	0.008	140 > 90 = 5
		Perinereis nuntia	0.011	5 > 90 > 140
		Scolelepis sp.	0.016	140 > 90 > 5
	Feb	*Perinereis nuntia*	0.004	5 > 90 > 140
		Oligochaete spp.	0.009	5 > 90 > 140
		Isopod spp.	0.011	5 > 140 > 90
		Scolelepis sp.	0.036	140 > 90 > 5
		Nicon aestuariensis	0.045	140 > 90 > 5
Lower	Dec	*Scolecolepides benhami*	0.001	90 > 5 > 140
		Axiothella serrata	0.007	140 > 90 > 5
		Austrovenus stutchburyi	0.025	140 > 90 > 5
		Amphipod spp.	0.028	140 > 90 > 5
	Feb	*Scolelepis* sp.	0.001	90 > 5 > 140
		Capitella sp.	0.001	90 > 5 > 140
		Perinereis nuntia	0.003	5 > 90 = 140
		Amphibola crenata	0.004	5 > 90 > 140
		Arthritica bifurca	0.004	5 > 90 > 140
		Austrovenus stutchburyi	0.009	90 > 140 > 5
	Apr	*Capitella* sp.	0.001	5 > 140 > 90
		Scolelepis sp.	0.002	5 > 90 > 140
		Perinereis nuntia	0.003	5 > 90 > 140
		Amphibola crenata	0.003	5 > 90 > 140
		Scolecolepides benhami	0.006	5 > 90 > 140
		Arthritica bifurca	0.019	5 > 90 > 140

*Multiple comparison indicates differences in abundance with respect to distance from storm drain (5, 90, and 140 m).

variables is distance from the storm drain, rather than tidal height or time of sampling.

Linking biological and environmental variables

In the upper shore (5U versus 90U versus 140U), the optimal combination of environmental variables "best explaining" community structure had a correlation of 0.724 and was comprised of four variables (Zn, Pb, % gravel, % OM of sediment). In the lower shore (5L versus 90L versus 140L), the optimal combination of variables best explaining community structure had a correlation of 0.521 and consisted of five variables (Zn, % sand, % silt, kurtosis, % CO_3 of sediment).

The optimal combination of environmental variables best explaining community structure at 5U and 5L had a correlation of 0.812 and was comprised of four variables (Zn, Cu, kurtosis, % OM of sediment). At 90U and 90L the maximum correlation was 0.768 for five variables (Zn, Pb, mean grain size, kurtosis, and % CO_3 of sediment). At 140U and 140L the maximum correlation was 0.701 for two variables (% silt, skewness).

The optimal combination of environmental variables best explaining community structure at all six locations had a correlation of 0.475 and was composed of three variables (Zn, % sand, and % OM of sediment).

Table 5 Sedimentary properties of samples from six sites at all time periods. (% OM = % organic matter in sediment; % CO_3 = % carbonate in sediment.)

Parameter	Site	Dec	Feb	Apr
Mean grain size ϕ	5U	1.97	2.16	1.93
	90U	2.82	2.81	2.78
	140U	2.57	2.56	2.61
	5L	2.85	2.83	2.92
	90L	2.72	2.76	2.70
	140L	2.62	2.61	2.51
Sorting	5U	2.07	1.81	1.98
	90U	0.56	1.14	0.79
	140U	0.53	0.55	1.20
	5L	0.99	1.02	0.91
	90L	0.59	0.59	0.59
	140L	0.58	0.67	0.63
% OM	5U	2.18	3.94	1.56
	90U	1.33	1.38	1.37
	140U	0.79	0.93	0.81
	5L	1.81	2.39	2.19
	90L	1.02	1.33	1.67
	140L	1.03	1.36	1.18
% CO_3	5U	10.89	7.78	8.28
	90U	5.64	5.18	4.73
	140U	3.37	3.05	2.82
	5L	9.21	7.34	7.05
	90L	8.00	5.03	12.59
	140L	3.50	3.82	7.91

Table 6 Marine sediment quality guidelines (developed by the Canadian Council of Ministers of the Environment (1994)) compared with minimum and maximum heavy metal concentrations of sediment near the Semple Street storm drain, Porirua Inlet (TEL, threshold effects level; PEL, probable effects level).

	TEL (ppm)	PEL (ppm)	Min. (ppm)	Max. (ppm)
Copper	18.7	108	47.2	96.3
Lead	30.2	112	81.4	122.8
Zinc	124.0	271	463.0	989.9

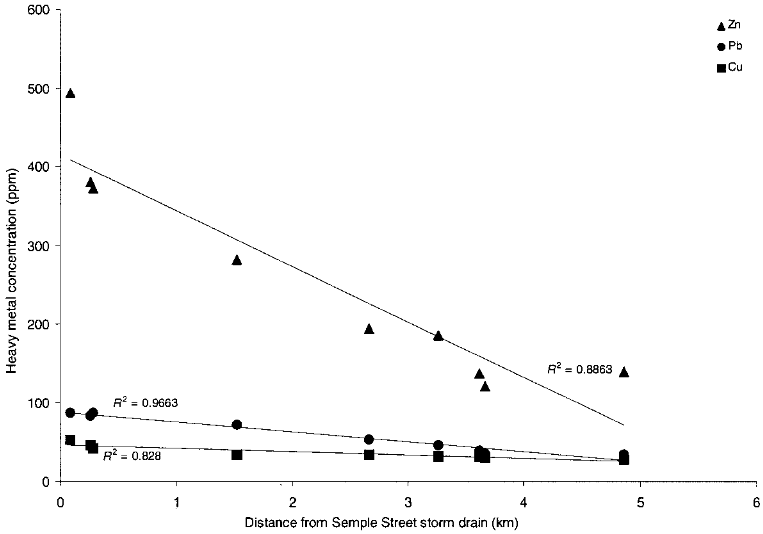

Fig. 4 Copper (Cu), lead (Pb), and zinc (Zn) concentrations of Porirua Inlet surficial sediment from the southern end to the entrance.

Heavy metal analysis throughout Porirua Inlet

There were statistically significant linear relationships between heavy metal concentrations and distance from the storm drain for Cu ($r^2 = 0.828$, d.f. = 7, $P < 0.001$), Pb ($r^2 = 0.966$, d.f. = 7, $P < 0.001$), and Zn ($r^2 = 0.886$, d.f. = 7, $P = < 0.001$) (Fig. 4). F-tests between models indicated that the slopes for the lines representing Cu and Pb were equal, that a difference did exist between the slopes for Cu and Pb versus Zn, that we could replace the three separate lines with two lines (Cu and Pb as one line, Zn as the other), and that these two separate lines were not parallel (i.e., we could not represent the three heavy metals with one line). Finally, a test of the two slopes model versus the two lines model (i.e., do Cu and Pb have different intercepts, even though their slopes are the same?) indicated that a single line can be used to represent both Cu and Pb. Thus, the best overall model representing the decrease in the three heavy metal concentrations with distance from the storm drain was composed of two non-parallel lines, one for Cu and Pb, the other for Zn.

DISCUSSION

Disturbance events such as point-source pollution discharge from storm drains are known to cause substantial changes to benthic community structure if the disturbance is of sufficient magnitude and/or of sufficient duration (Clarke & Ainsworth 1993). This change in community structure typically involves a shift from a community dominated by few large individuals of many species (the "climax" or K-selected community) to a community dominated by many small individuals of few species (the "opportunistic" or r-selected community). We observed that mean numbers of individuals decreased, and mean numbers of species and Shannon-Wiener index values increased with increasing distance from the storm drain. ANOVA of these three separate dependent variables identified single factors and combinations of factors (i.e., interaction terms) which explained significant variation in the biological data set. Although interpretation of these results is made difficult by the significant interaction terms (for example, we cannot identify a temporal trend in the data), it is clear that distance from the storm drain is an important factor in explaining biological community structure. These findings indicate that, on the scale of tens of metres and over a 15 cm vertical decrease in shore height, benthic community structure is different at locations 5, 90, and 140 m away from the Semple Street storm drain. This conclusion is reinforced by the ANOSIM analysis which revealed significant differences in community structure among the three sites within the high and low shore locations, and for two of three pairwise comparisons when all data were pooled (the 90 versus 140 m comparison was not significant). Again, a strong association exists between biological community structure and distance from the storm drain. These findings are consistent with outflow from the storm drain having a significant effect upon soft substrate biological community in the immediate vicinity of the storm drain, but with this effect diminishing in the range 90–140 m distant from the storm drain.

Storm drains can discharge large volumes of fresh water, and copious quantities of solids, including sediment, organic matter such as leaf debris, as well as a wide range of pollutants including dissolved and particulate material (Vincent & Thomas 1997). This outflow usually results in the long-term accumulation of material in front of, and grading away from, the storm drain. Typically, the greatest negative effect upon the biological community occurs closest to the storm drain, an effect which has been termed the storm drain's "sphere of influence" (Bolton-Ritchie et al. 1999). We observed that sediment at 5U and 5L was more poorly sorted, sediment % OM was higher, and Cu, Pb, and Zn concentrations were higher than at the four sites further away from the storm drain. MDS ordination of species abundance data showed community structure at the upper and lower 5 m sites to be more dissimilar from that at the upper and lower 90 and 140 m sites, where it was reasonably similar (the MDS results for the biological data mirrored the MDS results for the environmental data). Despite this however, changes in individual species abundance with increasing distance from the storm drain were not pronounced. For each pairwise comparison of sites a group of five taxa accounted for c. 50% of the similarity between sites. For all pairwise analyses seven different taxa (<25% of all taxa observed) explained c. 50% of the similarity between sites, meaning that indicator species which discriminated absolutely between sites nearest to and furthest from the storm drain could not be identified. The response of the biological community with increasing distance from the storm drain involved both a small decrease in the number of individuals and a small increase in the number of taxa, rather than a large-scale change in the suite of taxa present. This low-moderate level biological response is likely to be observed in the vicinity of many storm drains, and in many respects is the hardest response to quantify because it falls somewhere between the two extremes of grossly disturbed and completely undisturbed which are more easily quantifiable.

The MDS ordinations of average faunal abundance (Fig. 3A) and the 12 environmental variables (Fig. 3B) show considerable similarity in the placement of points and indicate a difference between all 5 m samples and all other samples. This effect is most pronounced in the upper shore (closest to the storm drain) across all three time periods for the biological and the environmental data. In both ordinations there is a shift from the 5 m sites (left of the plot), via the 90 m sites, to the 140 m sites (right of the plot), which reflects the underlying change in biological community structure with increasing distance away from the storm drain. By comparison, there is no evidence of a strong temporal or tidal height effect. These findings suggest that storm drain outflow has affected the nearby biological community regardless of tidal height and time of sampling. The theoretical expectation is that with increasing distance from the storm drain community structure will tend towards an unmodified or "natural" state, with the result that sites further away from the storm drain will be more similar in terms of biological community structure than are sites closer to the storm drain. Thus, the biological similarity of the 90 and 140 m sites, and their combined dissimilarity to the 5 m sites, indicates that the negative influence of the storm drain is substantially diminished in both the upper and lower shore regions by 90 m distance from the drain. Thus, the drain's sphere of greatest influence is of the order of tens of metres and does not, apparently, extend past a distance of c. 90–140 m.

Among the three upper shore sites, a combination of two heavy metals (Zn and Pb) and two sedimentary properties explained greatest variation in the biological data set, whereas among the three lower shore sites a combination of one heavy metal (Zn) and four sedimentary properties explained greatest variation in community structure. Thus, with a move from upper to lower shore there has been a change in the variables themselves as well as a change in the numbers of clearly identifiable pollutant variables (in this case, heavy metals) which best explain community structure. A similar response was observed with increasing distance from the storm drain, independent of tidal height. Maximum variation in biological community structure was explained at the 5 m sites by four variables (Zn, Cu, and two sedimentary variables), at the 90 m sites by five variables (Zn, Pb, and three sedimentary variables), and at the 140 m sites by two variables (both were sedimentary variables). Further, the correlations of each of the 12 environmental variables with biological community structure at the different distances from the drain showed a pronounced pattern for the diminishing ranking of Zn, Pb, and Cu: at the 5 m sites they ranked 1, 2, and 4; at the 90 m sites they ranked 1, 6, and 3; at the 140 m sites they ranked 11, 9, and 8. Thus, with increasing distance from the storm drain there is a diminishing effect of clearly identifiable pollutants (heavy metals) upon biological community structure. Across all sampling locations and all sampling periods, three environmental variables which best explained variation in the biological community could be identified, namely, Zn, % sand, and sediment % OM. In terms of routine monitoring of environmental variables which might represent the "health" of the storm drain environment, these three could be measured accurately, quickly, and reasonably cheaply. Elevated concentrations of Zn are representative of a suite of anthropogenic pollutants derived from industrial sources, and as such the identification of Zn as a single variable associated with (and potentially responsible for) biological community change is important. The two other variables, % sand and sediment % OM, are harder to classify, because variation in these variables (as it explains community structure) could represent a natural underlying difference in the vicinity of the storm drain, or could be representative of a suite of substances which are washed by rainfall from the surrounding catchment area into the storm drain. Thus, for example, elevated levels of sediment % OM could result from the influx of large quantities of material such as leaves, twigs, and even cigarette butts, and elevated levels of % sand could result from the influx of substantial quantities of "grit" washed off roads, etc., which ultimately empties out of the storm drain. We are presently unable to disentangle the possibility of natural variation in % sand and % OM in the vicinity of the storm drain from the possibility of enhanced levels of these variables which result from run-off.

Comparison can be made between the study of Glasby et al. (1990) in Porirua Inlet and the present work for maximum concentrations (ppm) of Zn (435 versus 990), Cu (93 versus 96.3), and Pb (170 versus 122.8). Williamson et al. (1999) predicted an acceleration in the build up of Zn and Cu concentrations in sediments of Pakuranga estuary, Auckland, New Zealand. Zn, Cu, and Pb concentrations began to accumulate above background levels in the late 1950s with the onset of urbanisation. The large increase in Zn and the small increase in Cu concentrations in Porirua Inlet from 1990 (Glasby et al. 1990) to 1999 (present study) are consistent with this hypothesis, while the decrease in Pb concentration, also predicted by Williamson et al. (1999), is consistent with the recent advent of lead-free fuels. Sampling of background heavy metal concentrations along the length of Porirua Inlet was carried out in April when heavy metal concentrations near the Semple Street storm drain were by far the lowest of the study. Even under this scenario, maximum Zn concentrations in Porirua Inlet were still much higher in 1999 than in 1990, suggesting the long-term cumulative effect of storm water outflow into the inlet.

Marine sediment quality guidelines for the protection of aquatic life have been developed by the Canadian Council of Ministers of the Environment (1994). Two assessment values have been calculated for a range of pollutants—the threshold effect level (TEL) and the probable effect level (PEL). The TEL is the concentration below which deleterious effects are expected to occur rarely and the PEL is the concentration above which deleterious effects are predicted to occur frequently (Table 6). These assessments are based on data compiled from 121 modelling, laboratory, and field studies (Long et al. 1995), but are not directly comparable to bioavailability data. The TELs and PELs therefore represent what can be thought of as mean indicator concentrations for threshold and probable effects which have been derived from many studies which differ in their bioavailability levels. As such, the TELs and PELs are valuable to managers and biologists alike because they can be applied, as in the present context, as indicators to the health of the environment. During the three sampling periods of December 1998, February and April 1999, concentrations of Cu, Pb, and Zn in Porirua Inlet exceeded TELs at all sites, and Pb and Zn concentrations exceeded PELs at certain times. Cu concentrations near the Semple Street storm drain fell about midway between the TEL and the PEL, while Pb concentrations were close to the PEL, and exceeded it on two occasions, both at the upper shore 5 m site closest to the storm drain. Zn concentrations substantially exceeded the PEL on every occasion at every site, and by 3.5 times in February at the upper shore 5 m site. Zn concentrations of 260 ppm in sediment affected benthic community composition in Puget Sound and concentrations of 205 ± 90 ppm were highly toxic to bivalve larvae in San Francisco Bay (Long & Morgan 1991). In the context of these international findings the elevated concentrations of Cu, Pb, and in particular, Zn, at the southern end of Porirua Inlet are likely to have had a detrimental effect on community composition at the Semple Street site. However, given the complex and highly variable nature of stormwater, we are not able to identify any cause and effect type patterns from our data.

The statistically significant linear decrease in Cu, Pb, and Zn concentrations with distance away from the storm drain towards the mouth of Porirua Inlet follows similar trends reported by Glasby et al. (1990). In our study, Cu and Pb showed a similar response in terms of decreasing concentration with distance from the storm drain, whereas Zn concentration was greater closer to the drain and decreased at a faster rate with distance away from the drain. Data from the sampling of nine sites along the length of the inlet carried out in April 1999, indicate that TELs for all three heavy metals were exceeded along the entire length of Porirua Inlet. At this time of sampling, PELs for Cu and Pb were not exceeded, but the PEL for Zn was exceeded from 0 to 1.8 km from the storm drain. These data suggest that the entire length of Porirua Inlet is contaminated above TELs with these three heavy metals.

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