supervising scientist report **115**

MOUNT LYELL REMEDIATION

Monitoring of benthic invertebrates in Macquarie Harbour, western Tasmania

Sonia Talman, Nicholas O'Connor, Brenton Zampatti & Frances Cannon

Mount Lyell Remediation Research and Demonstration Program

a Tasmanian and Commonwealth Government initiative

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Department *of* Environment and Land Management

supervising scientist

A joint program between the Supervising Scientist and the Department of Environment and Land Management, Tasmania.

This report describes research that is part of the Mt Lyell Remediation Research and Demonstration Program, a joint program between the Supervising Scientist and the Department of Environment and Land Management, Tasmania.

Sonia Talman, Nicholas O'Connor, Brenton Zampatti & Frances Cannon – Water Ecoscience

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Executive summary

Over the last century Macquarie Harbour and the Mount Lyell region to the north-east of the Harbour have been affected by mining activities at the Mount Lyell copper mine. In that time the mine has discharged large quantities of mine tailings into the Queen River. This material has been washed downstream, resulting in the deposition of over 100 million cubic metres of tailings, as well as slag and topsoil, in the King River and Macquarie Harbour.

In 1995 the Tasmanian and Federal Governments established a joint program, the Mount Lyell Remediation Research and Demonstration Program (MLRRDP), aimed at investigating remediation strategies for the impacted areas. As part of MLRRDP Project 13B, Water Ecoscience P/L have begun an ongoing biological monitoring program aimed at assessing the ecological health of Macquarie Harbour. In accordance with the first objective of this program, a survey of benthic invertebrates in Macquarie Harbour was conducted in order to establish the current status of this community.

The use of benthic invertebrate communities as a biomonitor in Macquarie Harbour follows recommendations based on a pilot biological survey conducted by Water Ecoscience P/L in 1995 (O'Connor et al 1996). Benthic invertebrate communities were found to fit the selection criteria more closely than other ecosystem components (eg macroalgae, seagrass, zooplankton, phytoplankton and fish).

In addition to recommending the use of benthic invertebrates to detect recovery of ecosystem health, O'Connor et al (1996) outlined the most suitable program design, including statistical analysis, dependent variable selection, site selection and environmental variable selection. This design was adopted for the biological monitoring program.

This report presents the findings of the initial benthic invertebrate survey in Macquarie Harbour for the biological monitoring program.

The results indicate an impoverishment of invertebrate species and individuals in Macquarie Harbour when compared with coastal embayments elsewhere in south-eastern Australia (eg Poore et al 1975, Poore 1982, Edgar 1991). In an estuary the size of Macquarie Harbour, around 100 to 200 species of benthic invertebrates might be expected to occur if the area were free of mining impacts. In the present study 45 species were collected which brings to 84 the total number of benthic invertebrate species recorded from Macquaire Harbour.

Copper contamination and sediment organic matter content appear to be the main determinants of the current population structure, as species richness, total abundance and species distribution all followed a pattern which corresponded to the pattern of sediment copper concentrations and the amount of sediment organic matter in the harbour. Other environmental factors such as sediment grain size, depth and temperature did not appear to affect the abundance and diversity of benthic invertebrates.

The copper concentration of waters entering Macquarie Harbour from the King River is expected to decline with remediation of the Mount Lyell mine site and the Queen and King Rivers. Any change to the benthic invertebrate community of Macquarie Harbour as a result of improving sediment and water quality is likely to be detected in future surveys with the present study providing valuable baseline data.

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Acknowledgments

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1 Introduction

Over the last century, Macquarie Harbour, and the Mount Lyell region to the north-east of the Harbour have been affected by mining activities at the Mount Lyell copper mine operated by the Mount Lyell Mining and Railway Company Limited at Queenstown. In that time the mine has discharged large quantities of mine tailings into the Queen River. Furthermore, local atmospheric pollution at Queenstown associated with the mining industry, together with woodcutting and burning, has deforested surrounding hill slopes. This has led to additional input of erosion-derived sediment into the Queen River. Tailings and sediment entering the Queen River have been washed downstream resulting in the deposition of over 100 million cubic metres of tailings, slag and topsoil in the King River and Macquarie Harbour. The material forms a 250 ha delta deposit at the mouth of the river in Macquarie Harbour (McQuade et al 1995). Tailings discharge to the river ceased in December 1994.

In 1995 the Tasmanian and Federal Governments established a joint program, the Mount Lyell Remediation Research and Demonstration Program (MLRRDP), aimed at investigating remediation strategies for the impacted areas. As part of MLRRDP Project 13B, Water Ecoscience P/L have begun an ongoing biological monitoring program aimed at assessing the ecological health of Macquarie Harbour. In accordance with the first objective of this program, a survey of benthic invertebrates in Macquarie Harbour was conducted in order to establish the current status of this community.

This report presents the findings of this initial survey. Information on species richness, total abundance and species distribution is provided. Environmental data are also presented and their importance in determining invertebrate community structure assessed. It is envisaged that this information will provide a valuable baseline against which to measure changes in benthic invertebrate communities following the implementation of remedial works on impacted sites.

2 Methods

2.1 Sample site selection

A survey of benthic invertebrates in Macquarie Harbour was conducted by Water Ecoscience over 2 days from 13 March 1996 to 14 March 1996. For the purposes of assessing the extent of impact from copper contamination in the harbour, O'Connor et al (1996) divided the harbour into four zones corresponding to sediment copper concentration categories (Koehnken 1996) (fig 1). These were as follows:

1 > 600 ppm copper

2 100–600 ppm copper south-eastern Macquarie Harbour

3 100–600 ppm copper in the north-western tidal exchange area

4 < 100 ppm copper

Zones 2 and 3 were distinguished on the basis of sediment characteristics with zone 3 sediments being coarser than those of zone 2. Zone 3 was excluded from the sampling program for two reasons. Firstly, there was an insufficient number of samples collected in the pilot study (O'Connor et al 1996) in zone 3 to determine the appropriate sample size for the detection of statistically significant differences between this zone and the other zones. Secondly, zones 2 and 3 had similar sediment copper concentrations so there may have been some redundancy in the additional data.

Thirteen sites were chosen at random within a depth range of 3 to 10 m in each of zones 1, 2 and 4. Sediments at this depth are exposed to the middle layer of a three-layered halocline which exists in most of Macquarie Harbour (Koehnken 1996). This middle layer consists of copper rich water produced when waters from the King and Gordon Rivers meet and mix at the mouth of the King River. As this water flows southward, it is overlain by unpolluted water from the Gordon River and underlain by unpolluted marine water originating from the Southern Ocean (Koehnken 1996).

Remediation measures at the Mount Lyell mine and in the Queen and King Rivers are likely to lead to a substantial decrease in the copper concentrations of water entering Macquarie Harbour from the King River (Dr L Koehnken, Department of Environment and Land Management, *personal communication*). Sampling benthic invertebrates at a depth where they are in contact with this water will mean that any changes to community structure resulting from improved water quality will be detected.

2.2 Sample collection

Sampling was conducted from the *Wilsons Pride*, a 25 m commercial fishing vessel hired from Mr Ron Morrison of Southern Ocean Trout Pty Ltd. Benthic samples were taken using a Smith-MacIntyre grab (sample area = 0.1 m^2, sample depth = 10 cm) operated by a winch and derrick from the *Wilsons Pride*. Samples were washed through 1 mm sieves on board, preserved in buffered formalin and returned to the laboratory for further washing, sorting and identification. Fauna were identified to the species level or as close to this level as possible.

Latitude and longitude were recorded for each sampling site using a Global Positioning System (GPS) on board the *Wilsons Pride*. The GPS was accurate to 30 metres. These co-ordinates were later used to plot sample sites on a map generated using the ARCINFO GIS software (fig 1). Depth and water temperature were recorded at each site and a sediment sample was collected from each grab sample prior to sieving. In the laboratory, sediment samples were dried at 90°C to determine dry weight. Organic matter content was determined by burning 10 g of dried sample in a muffle furnace for 60 minutes and reweighing. The particle size distribution of sediments was determined across three categories by sieving 10 g of dried sample through a series of Endecott sieves. The categories were gravel (material retained on a 2 mm sieve), sand (material retained on a 0.0625 mm sieve) and silt and clay (the remaining fraction).

2.3 Statistical methods

For benthic macroinvertebrate data, the community indices of species richness and total numbers of individuals were tabulated. Biological and environmental variables were evaluated for differences between zones by using a one-way ANOVA. These variables were: total number of invertebrates (log transformed), number of invertebrate species, amount of sediment organic matter (%) and sediment grain size (3 categories). Total abundance and species richness were also evaluated for differences according to sediment organic matter and sediment grain size by using one-way ANOVAs. If a significant difference was detected by the ANOVA, a Tukeys HSD multiple comparisons test was used to indicate where the difference occurred. The data were not considered sufficiently complex to warrant multivariate analysis.

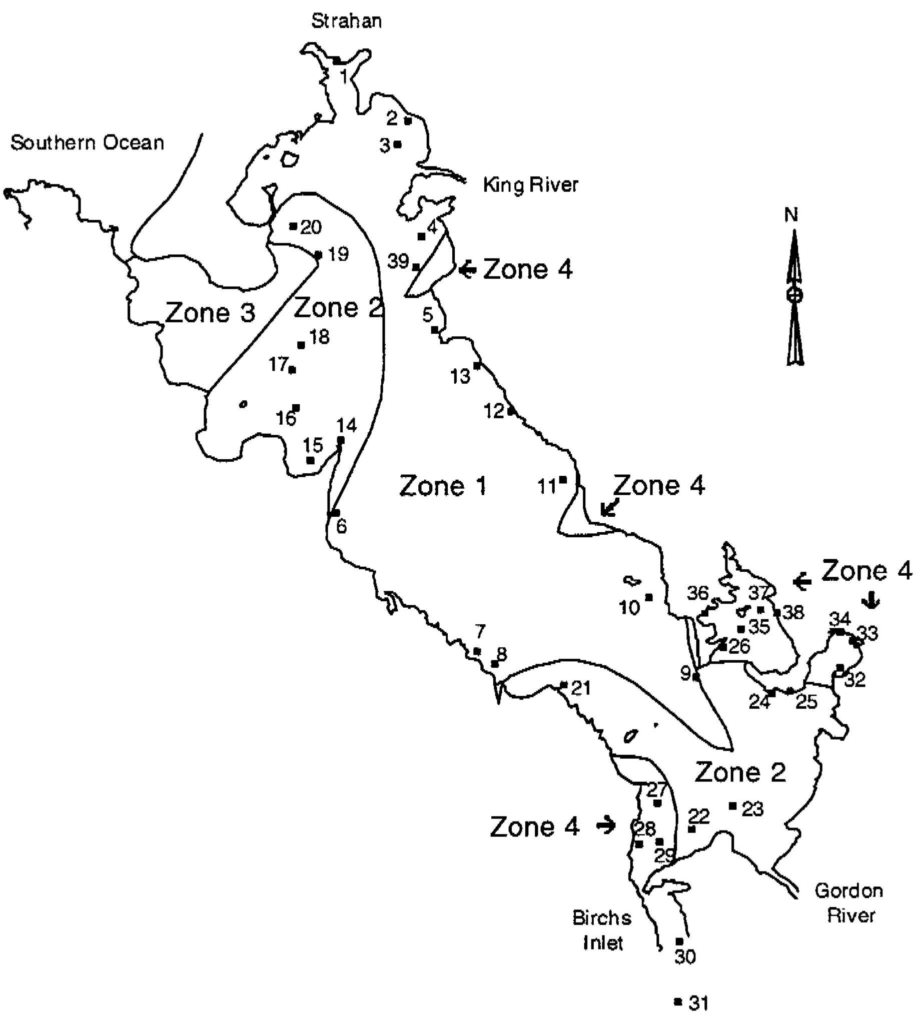

Figure 1 Sample sites within zones in Macquarie Harbour. Zones are based on the sediment copper concentrations recorded in 1993 by Koehnken (1996).

3 Results

The benthic invertebrate community in Macquarie Harbour is depauperate (table 1; appendix A) when compared with coastal embayments elsewhere in south-eastern Australia (eg Poore et al 1975, Poore 1982, Edgar 1991). The thirty-nine samples processed yielded a total of 1466 individuals in 41 taxa.

The dominant taxa (in approximate order of abundance) were two species of bivalve (*Arthritica semen* and *Xenostrobus securis*), a gastropod (*Tatea rufilabris*) and an amphipod species (*Paracorophium* sp. MoV voucher number 1784). Overall, molluscs accounted for 72% of recorded species (56% bivalves, 16% gastropods), crustaceans for 13% and polychaetes for 14%. Rare taxa included an opisthobranch gastropod, a leech, an ostracod, a nematode, hydroids, nemerteans and chironomid larvae. The chironomid larvae probably originated from a nearby freshwater source (Dr Richard Marchant, Museum of Victoria, *personal communication*).

Table 1 Invertebrate taxa recorded in Macquarie Harbour, 13–14 March 1996

Phylum	Class	Order	Family	Species
Annelida	**Polychaeta**		Orbiniidae	*Leitoscoloplos kerguelensis*
				Leitoscoloplos normalis
			Maldanidae	Maldanid sp. 2
			Phyllodocidae	*Phyllodoce* sp. 1
				Hypereteone otati
			Sabellidae	Sabellid sp. 2
				Sabellid sp. 3
			Terebellidae	*Amaena trilobata*
			Spionidae	*Prionospio tatura*
			Nephtyidae	*Nephtys gravieri*
			Cirratulidae	Cirratulid sp. 1
			Nereididae	*Neathes vaalii*
			Hesionidae	Hesionid sp. 1
			Capitellidae	Capitellid sp. 1
			Flabelligeridae	*Diplocirrus* sp. MoV 435
	Hirudinida		Glossiphoniidae	Glossiphoniid sp. 1
Arthropoda: Crustacea	**Maxillopoda**	Myodocopa	Cypridinidae	*Vargula* sp.
	Malacostraca	Mysida	Mysidae	*Gastrosaccus dakini*
				Tasmanomysis oculata
		Amphipoda	Caprellidae	*Paracaprella alata*
			Corophiidae	*Paracorophium* sp. MoV 1784
			Phoxocephalidae	*Limnoporeia yarrague*
				Brolgus tattersalli
			Exoedicerotidae	*Exoediceros fossor*
			Oedicerotidae	Oedicerotid sp. MoV 1785
			Lysianassidae	Lysianassid sp. MoV 1793
			Melphidippidae	Melphidippid sp. MoV 1974
		Decapoda	Hymensomatidae	*Amarinus laevis*
			Grapsidae	*Paragrapsus gaimardii*
Mollusca	**Bivalvia**		Lasaeidae	*Arthritica semen*
			Veneridae	*Irus carditoides*
			Mytilidae	*Xenostrobus securis*
	Gastropoda		Rissoidae	*Tatea rufilabris*
			Nassariidae	*Nassarius burchardi*
			Planorbidae	*Physastra gibbosa*
		Opisthobranchia		Opisthobranch sp. 1
Arthropoda: Uniramia	**Insecta**	Diptera	Chironomidae	*Polypedilum nubifer* *Procladius* sp.
Cnidaria	**Hydrozoa**	Hydroida		Hydroid sp. 1
Nemertea				Nemertean sp. 1
Nematoda				Nematode sp. 1

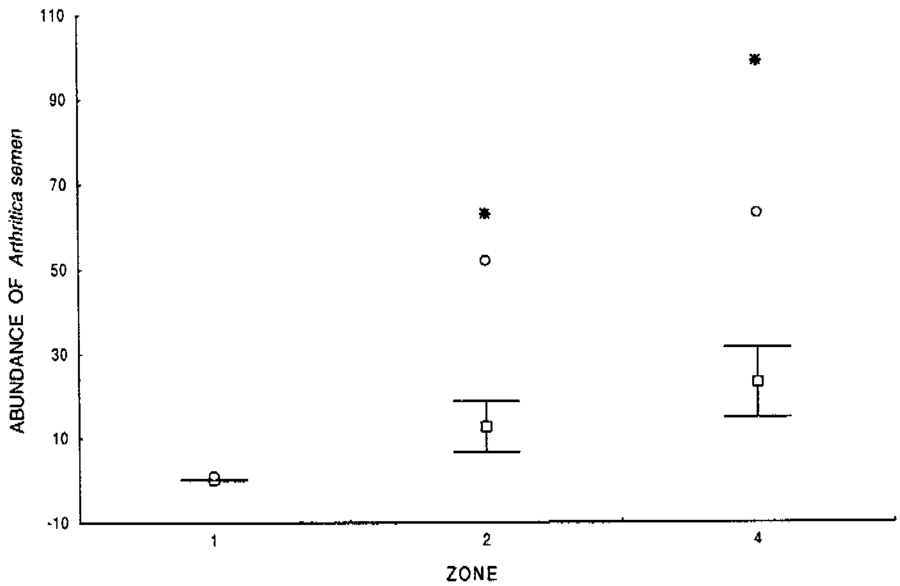

Figure 2 Distribution of the bivalve *Arthritica semen* in Macquarie Harbour (means ± standard errors)

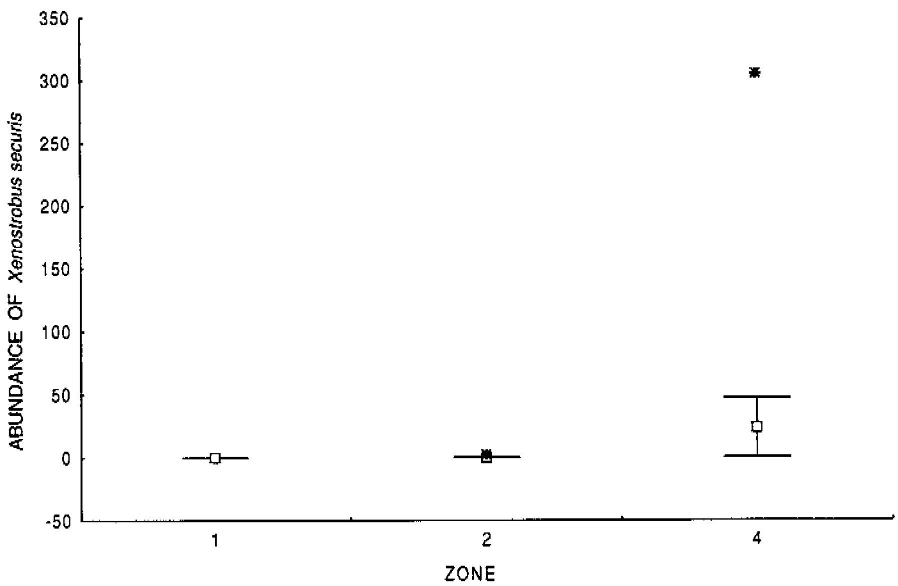

Figure 3 Distribution of the mussel *Xenostrobus securis* in Macquarie Harbour (means ± standard errors)

The four most abundant taxa, *Arthritica semen* (fig 2), *Xenostrobus securis* (fig 3), *Tatea rufilabris* (fig 4) and *Paracorophium* sp. MoV 1784 (fig 5) all showed the same pattern of abundance, being most abundant in zone 4, less abundant in zone 2, and rare in zone 1.

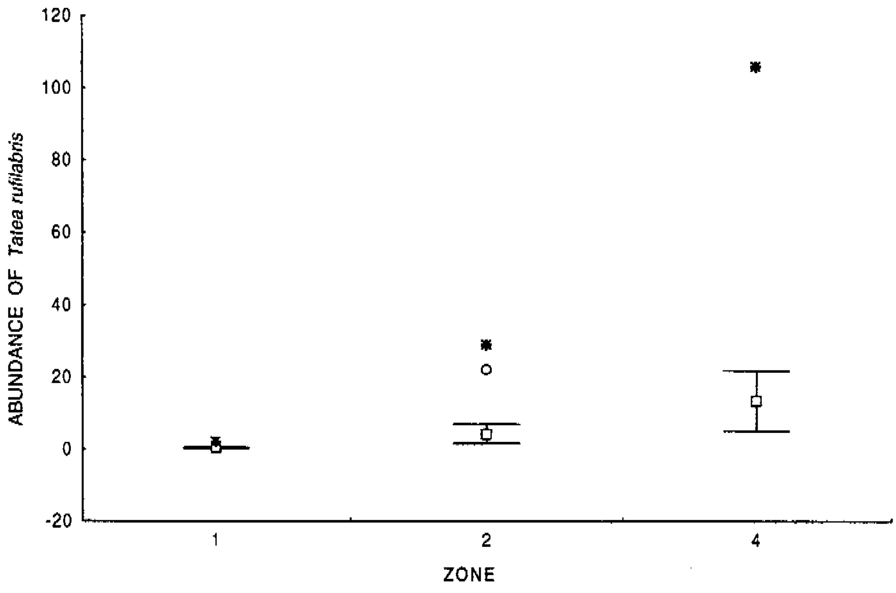

Figure 4 Distribution of the gastropod *Tatea rufilabris* in Macquarie Harbour (means ± standard errors)

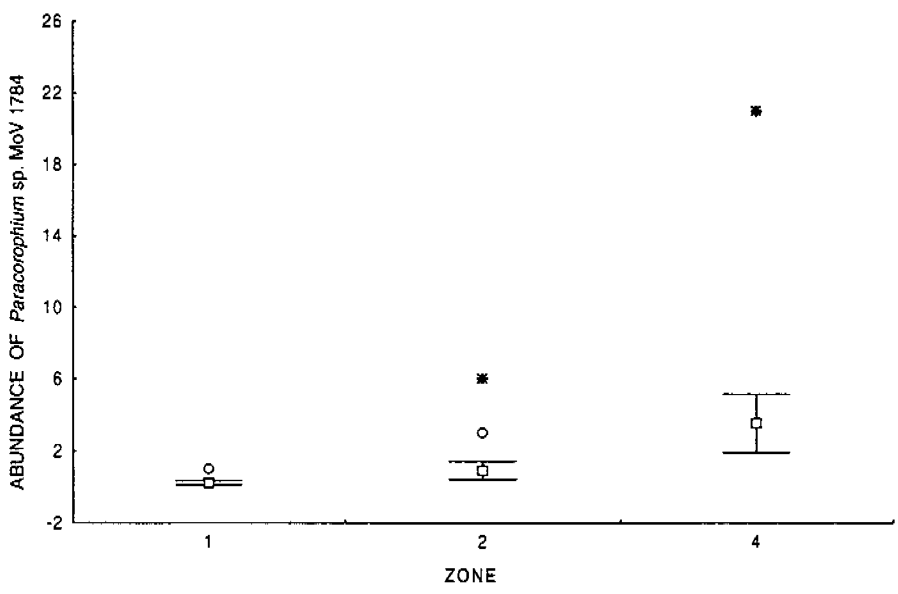

Figure 5 Distribution of the amphipod *Paracorophium* sp. MoV 1784 in Macquarie Harbour (means ± standard errors)

The total number of invertebrates (log transformed) and the number of invertebrate species differed significantly between zones (table 2). A Tukeys HSD test on the total abundance data revealed a significant difference between zone 1 and zones 2 and 4 with fewer individuals occurring in zone 1 (fig 6 and 7). The same test on the species richness data revealed a significant difference between zones 1 and 4 with fewer species occurring in zone 1 but no difference between zones 1 and 2 (fig 8), indicating the limited sensitivity of the species richness index (O'Connor et al 1996).

Table 2 Results of the one way ANOVAs (zone) for total number of invertebrates (log (x+1) transformed) and number of invertebrate species

Source	Degrees of freedom	Mean-square	F-ratio	Probability
Total numbers of macroinvertebrates				
Zone	2	2.784	10.084	0.000
Error	36	0.276		
Number of macroinvertebrate species				
Zone	2	32.410	4.697	0.016
Error	36	6.915		

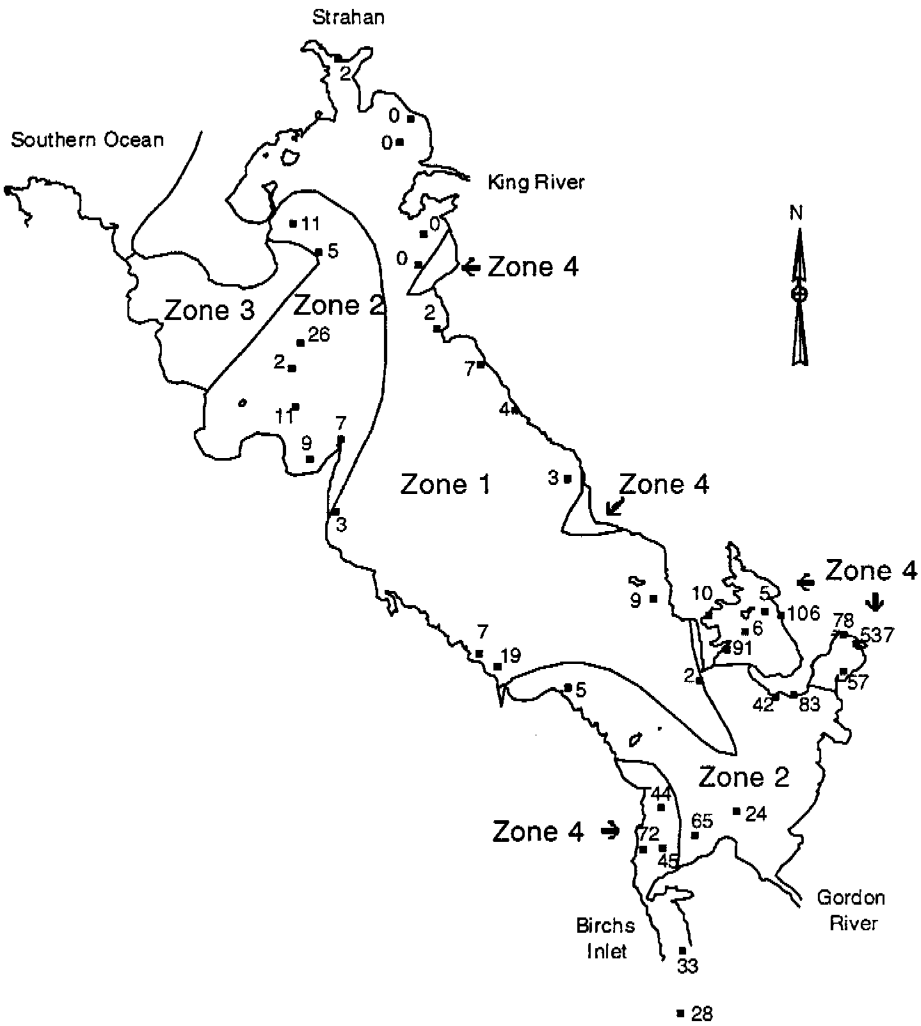

Figure 6 Total numbers of macroinvertebrates in Smith-McIntyre benthic grab samples collected in Macquarie Harbour

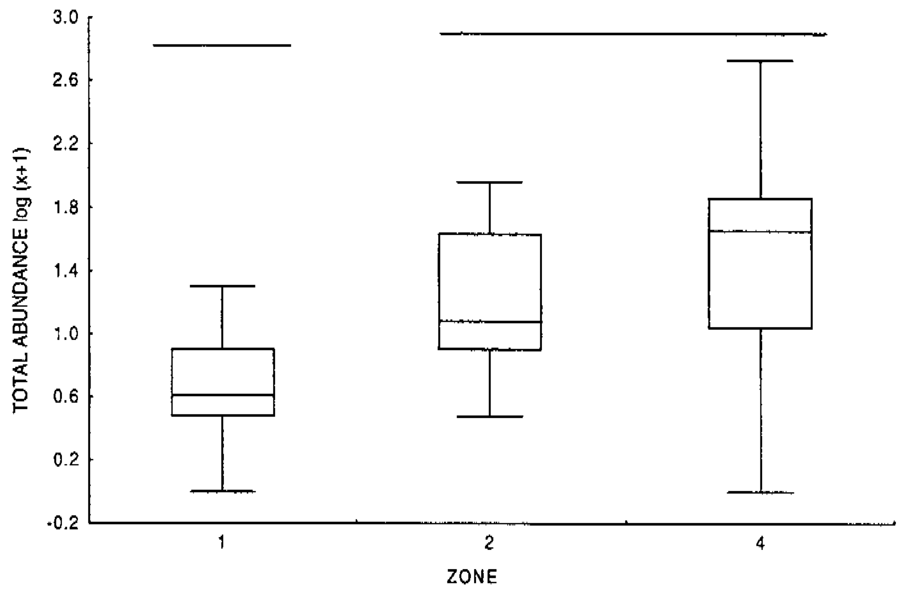

Figure 7 Boxplots of the total number of invertebrates (log (x+1) transformed) recorded from each zone in Macquarie Harbour. Zones connected by lines shown at the top of the graph were not significantly different from each other (p<0.05) as indicated by Tukeys HSD tests.

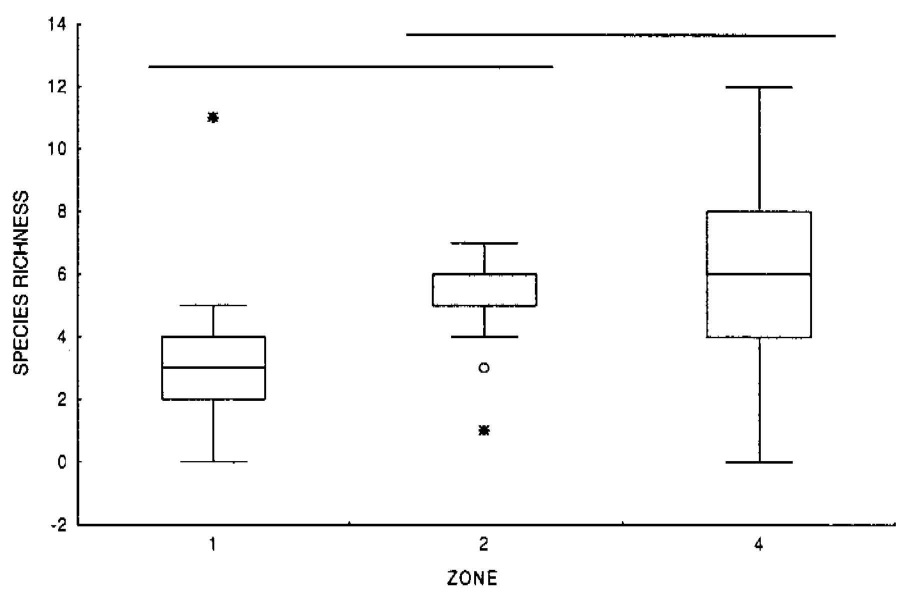

Figure 8 Boxplots of the number of invertebrate species recorded from each zone in Macquarie Harbour. Zones connected by lines shown at the top of the graph were not significantly different from each other (p<0.05) as indicated by Tukeys HSD tests.

The proportion of organic matter in sediments differed significantly between zones (table 3). A significantly greater amount of organic matter was found in sediment from zone 4 compared with that from zones 1 and 2 (fig 9). The dominant sediment grain size category also differed significantly between zones (table 4). Sediments from zone 4 were primarily silt and clay, sediments from zone 2 were primarily sand and zone 1 sediments were a mixture of both (appendix A).

Table 3 Results of the one way ANOVA (zone) for the amount of organic matter (%) recorded in sediments

Source	Degrees of freedom	Mean-square	F-ratio	Probability
Zone	2	1125.090	39.712	0.000
Error	36	28.331		

Table 4 Results of the one way ANOVA (zone) for sediment grain size categories. Categories were (1) silt & clay, (2) sand and (3) gravel.

Source	Degrees of freedom	Mean-square	F-ratio	Probability
Zone	2	1.564	8.927	0.001
Error	36	0.175		

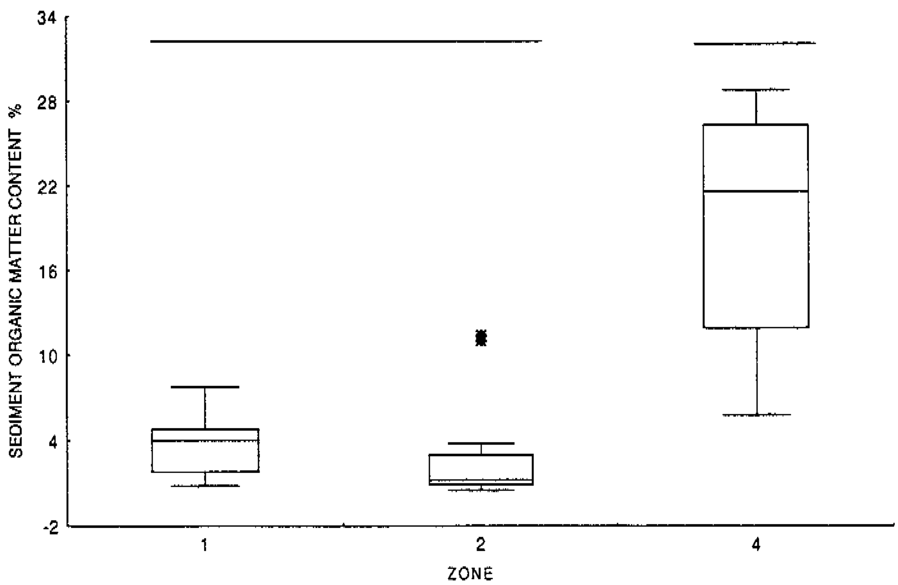

Figure 9 Boxplots of the amount of organic matter (%) in sediments from each zone in Macquarie Harbour. Zones connected by lines were not significantly different from each other ($p<0.05$) as indicated by Tukeys HSD tests.

Total abundance (log transformed) and species richness were significantly correlated with the proportion of organic matter in sediments ($r = 0.450$, $n = 39$, $p = 0.004$ and $r = 0.323$, $n = 39$, $p = 0.045$) but not with sediment grain size category (table 5). Depth and temperature were relatively constant throughout the study sites (appendix A).

Table 5 Results of the one way ANOVAs (sediment grain size category) for total number of invertebrates (log (x+1) transformed) and number of invertebrate species. Categories: (1) silt and clay and (2) sand.

Source	Degrees of freedom	Mean-square	F-ratio	Probability
Total numbers of macroinvertebrates				
Category	1	0.045	0.108	0.744
Error	37	0.418		
Number of macroinvertebrate species				
Category	1	2.787	0.332	0.568
Error	37	8.404		

4 Discussion

The results from the present study and previous survey (O'Connor et al 1996) indicate an impoverishment of benthic invertebrate species and low abundances in Macquarie Harbour when compared with other estuaries in south-eastern Australia (Poore 1982, Edgar 1991). As discussed by O'Connor et al (1996), truly estuarine environments have a lower benthic species diversity than predominantly marine habitats due to varying salinity levels. For example, in Victoria, Poore et al (1975) recorded 713 species from Port Phillip Bay, which is a marine habitat, compared with 90 species from the estuarine Gippsland Lakes (Poore 1982). Nevertheless, in an estuary the size of Macquarie Harbour and a sampling effort similar to that of the Port Phillip Bay and Gippsland lakes studies, around 100 to 200 species of benthic invertebrates could still be expected to occur if the harbour was unpolluted. To date, 84 species have been recorded from Macquarie Harbour. This includes 41 taxa from the present study, 49 taxa from the pilot study (O'Connor et al 1996) and 9 species previously recorded (Tasmanian Department of Environment 1975, de Blas 1994). The pilot survey and the present survey had 15 species in common. As these two surveys were conducted at different depths, the difference in the faunal component can be attributed to different habitats and hence environmental conditions.

4.1 Copper toxicity

Without prior studies, it is difficult to estimate whether the depauperate fauna of Macquarie Harbour is the result of previous mining conditions. Nevertheless, copper pollution appears to be a major determinant of current population structure as species richness, total abundance and species distribution all followed a pattern which corresponded to sediment copper concentrations in the harbour. Invertebrate abundance and diversity decreased significantly as copper concentrations increased. The four most abundant species also followed this pattern with declining abundances in zones of increasing sediment copper concentration.

The effect of copper in reducing the total abundance and species richness of benthic infauna has been demonstrated in a number of studies (eg Hall & Frid 1995, Ahn et al 1995, Somerfield et al 1994). Hall & Frid (1995) showed that the polychaetes *Capitella capitata* and *Malacoceros fuliginosus*, the oligochaete *Tubificoides* spp. and nematodes (predominantly *Pontonema* spp.) were all negatively affected by the presence of copper in microcosm experiments. Similarly, copper contamination of a mudflat in Korea led to a sharp decrease in species number and diversity in the resident community (Ahn et al 1995). Somerfield et al (1994) showed that nematode fauna from copper contaminated sites was less abundant, had a lower generic richness and a lower species diversity compared with that from less contaminated sites.

The toxicity of copper on benthic invertebrates, however, is not restricted to reducing diversity. Copper pollution may lead to the establishment of an invertebrate community which is quite different from the original community. If the copper concentration is sufficient to exert a selection pressure, the resultant change in community structure could include an increase in genetically inherited tolerance, physiological adaptation of individuals and/or the replacement of sensitive species by less sensitive species (Millward & Grant 1995). Millward and Grant (1995) provided evidence to support this theory with their investigation into estuarine nematode communities. Nematodes from a severely contaminated estuary were more resistant to copper than those from a less contaminated estuary. The authors suggest that this was a result of an increase in the abundance of copper resistant species, the evolution of enhanced copper tolerance in some species and the probable exclusion of more sensitive species. The benthic invertebrate community present in Macquarie Harbour today may be the result of such changes, however, this cannot be assessed without ecotoxicological experimentation.

Of the benthic invertebrates present in Macquarie Harbour, the most abundant are molluscs, crustaceans and polychaetes. It is possible that this assemblage represents a copper tolerant fauna, but without copper tolerance data for each species, it is difficult to assess. Nevertheless, there is some evidence that these taxa are able to develop metal tolerance. For example, some bivalve species are able to survive with high concentrations of heavy metals in their body tissues. Studies on the Pacific oyster, *Crassostera gigas,* in Macquarie Harbour have found copper concentrations of up to 837 µg/g wet weight (de Blas 1994) which is extreme considering the maximum background copper concentration in clean ocean water is 0.2 µg/l.

Some crustaceans may be able to tolerate high background levels of heavy metals through pre-existing physiological adaptations. For example, the shore crab *Carcinus maenus* is a euryhaline crustacean with physiological adaptation to salinities less than that of standard seawater. In addition to minimising ionic and osmotic fluxes, such an adaptation may also impair the uptake of dissolved heavy metals (Depledge 1990). Copper tolerance may also arise through physiological changes which make the crab more copper resistant. Depledge et al (1995) found that when a group of *C. maenus* were exposed to copper in the laboratory, the proportion of individuals with a copper resistant phenotype (P1 – low levels of haemolymph protein) increased as the proportion of individuals with the copper sensitive phenotype (P4 – high levels of haemolymph protein) decreased. This fall in the number of P4 individuals was partly due to a fall in haemolymph protein concentration resulting in the animals being reassigned to P1. In their experiment, crabs became more tolerant of copper via changes to their physiology.

The ability of polychaete worms to develop a tolerance to the toxic effects of copper is well demonstrated (Bryan & Hummerstone 1971, Grant et al 1989, Rygg 1985). Bryan and Hummerstone (1971) showed that lethal copper levels were higher for the polychaete *Nereis diversicolor* growing in high-copper sediment than those in low-copper sediment. Grant et al (1989) demonstrated that the elevated tolerance of *N. diversicolor* to copper was inheritable. Similarly, Rygg (1985) found *Capitella* spp. were tolerant of very high concentrations of sediment copper in contaminated Norwegian fjords.

4.2 Sediment particle size and organic matter content

In addition to sediment copper concentrations, the sediment organic matter content is important in determining species richness and abundance of invertebrates in Macquarie Harbour. There were more species and individuals in zone 4 where sediments were significantly more organic. The amount of sediment organic matter is important for benthic infauna as it is a potential food source (Ahn et al 1995). Although zones 1 and 2 did not differ in sediment organic matter content, they did differ in terms of invertebrate abundance. It is therefore possible that sediment copper concentrations are primarily determining biological differences between zones 1 and 2.

Sediment grain size did not significantly affect invertebrate diversity or abundance. Sandy sediments were expected to have a higher diversity of invertebrates than muddy sediments [based on a previous study of benthic fauna in Port Phillip Bay (Poore & Rainer 1979)]. Although zones could be distinguished on the basis of sediment grain size, this did not significantly correlate with patterns of diversity.

Sediment grain size and sediment organic matter may determine invertebrate abundance and diversity by affecting copper bioavailability in sediments (Athalye & Gokhale 1991, Pesch 1979). Finer sediments adsorb more copper than coarser sediments which may reduce the amount of copper available to benthic organisms. This may account for the higher mortality rate of the polychaete *Neanthes arenaceodentata* in sand compared with mud when exposed to the same copper levels in seawater (Pesch 1979). Similarly, the amount of sediment organic matter determines copper bioavailability as copper has a high affinity for organic matter. Thus, highly organic environments will have less bioavailable copper. Support for this comes from a study by Athalye and Gokhale (1991) who found that polychaete worms in sediment with a high organic content appear to be more tolerant of metal contamination than worms in sediment with low organic content.

Copper pollution in Macquarie Harbour is expected to decline with remediation of the Mount Lyell mine site and the Queen and King Rivers. Hunt and Smith (1982) found that sediment copper concentrations decrease rapidly when uncontaminated water is passed over the sediment, with flux rates ranging between 0.16 and 2.3 $\mu mol/m^2/day$. Similarly, Hall and Frid (1995) found considerable improvement of sediment quality occurred within days of cessation of contaminant input. However, faunal recolonisation and recovery takes much longer, with population densities not reaching those seen in uncontaminated sediments even after 1 year (Hall & Frid 1995).

Any change to the benthic invertebrate community of Macquarie Harbour as a result of improving sediment and water quality is likely to be detected in future surveys with the present study providing valuable baseline data.

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Appendix A Macroinvertebrate abundances and environmental data collected in Macquarie Harbour in March 1996

Zone	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2
Replicate	1	2	3	4	5	6	7	8	9	10	11	12	13	1	2	3	4	5	6	7
Sample site number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Taxon																				
Leitoscoloplos kerguelensis	0	0	0	0	0	0	0	2	0	0	0	0	3	0	0	4	0	0	0	1
Leitoscoloplos normalis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maldanid sp.2	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0
Phyllodoce sp.1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Hypereteone otati	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Sabellid sp.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
Sabellid sp.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amaena trilobata	0	0	0	0	0	0	1	1	0	0	1	0	0	7	0	0	1	0	0	1
Prionospio tatura	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nephtys gravieri	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Cirratulid sp.1	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	1
Neathes vaalii	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Hesionid sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Capitellid sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Diplocirrus sp. MoV 435	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Glossiphoniid sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vargula sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Gastrosaccus dakini	0	0	0	0	0	6	2	0	1	1	0	0	1	0	0	1	0	1	1	0
Tasmanomysis oculata	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Paracaprella alata	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	7
Paracorophium sp. MoV 1784	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	2	0	0
Limnoporeia yarrague	0	0	0	0	1	1	1	2	0	3	1	1	2	0	5	1	0	0	1	0
Brolgus tattersalli	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Exoediceros fossor	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oedicerotid sp. MoV 1785	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Lysianassid sp. MoV 1793	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Melphidippid sp. MoV 1974	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amarinus laevis	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Paragrapsus gaimardii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Arthritica semen	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0
Irus carditoides	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	17	1	0
Xenostrobus securis	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tatea rufilabris	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Nassarius burchardi	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Physastra gibbosa	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Opisthobranch sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polypedilum nubifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	1	0
Procladius sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hydroid sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nemertean sp.1	0	0	0	0	0	0	2	0	0	0	0	1	0	0	3	0	0	4	0	0
Nematode sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Biological indices																				
Total abundance	2	0	0	0	2	3	7	19	2	9	3	4	7	7	9	11	2	26	5	11
Species richness	2	0	0	0	2	3	5	11	2	5	3	3	4	1	3	7	6	6	5	5
Environmental variables																				
% Organic matter	5.1	4.8	7.8	4.5	4	0.8	1.8	3.2	1.4	4	3.4	1.2	6.9	1.2	1.1	0.9	0.7	0.9	0.5	1.7
Proportion silt	1	1	0.5	1	1	0	0.06	0	0	0	0	0	1	0	0	0	0	0	0	0
Proportion sand	0	0	0.5	0	0	1	0.8	1	1	1	1	1	0	1	1	1	1	1	1	1
Proportion gravel	0	0	0	0	0	0	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0

Zone	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4	4	4	4	4	4
Replicate	7	8	9	10	11	12	13	1	2	3	4	5	6	7	8	9	10	11	12	13
Sample site number	20	21	22	23	24	24	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Taxon																				
Leitoscoloplos kerguelensis	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0
Leitoscoloplos normalis	0	0	3	4	14	0	1	1	7	3	1	2	0	8	0	0	0	0	0	0
Maldanid sp.2	0	0	0	0	1	2	0	0	0	0	0	0	3	0	0	0	0	0	0	0
Phyllodoce sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0
Hypereteone otati	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sabellid sp.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sabellid sp.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Amaena trilobata	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Prionospio tatura	0	0	0	0	1	0	0	3	2	2	0	0	0	0	2	2	0	0	0	0
Nephtys gravieri	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cirratulid sp.1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
Neathes vaalii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hesionid sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0
Capitellid sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	86	0
Diplocirrus sp. MoV 435	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Glossiphoniid sp.1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Vargula sp.	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Gastrosaccus dakini	0	0	1	6	0	5	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Tasmanomysis oculata	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Paracaprella alata	7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paracorophium sp. MoV 1784	0	0	1	6	0	0	3	2	21	3	8	2	1	6	3	0	0	0	0	0
Limnoporeia yarrague	0	2	3	2	0	0	0	1	7	0	2	0	3	1	0	3	3	1	0	0
Brolgus tattersalli	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
Exoediceros fossor	0	0	0	2	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oedicerotid sp. MoV 1785	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lysianassid sp. MoV 1793	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Melphidippid sp. MoV 1974	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0
Amarinus laevis	0	0	0	1	1	1	0	0	2	0	0	0	2	6	1	0	0	0	0	0
Paragrapsus gaimardii	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Arthritica semen	0	0	52	3	20	27	63	35	24	36	18	20	2	99	63	0	3	0	0	0
Irus carditoides	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Xenostrobus securis	0	0	0	0	0	0	2	0	0	0	0	0	0	305	0	0	0	0	0	0
Tatea rufilabris	0	0	5	0	0	29	22	0	7	1	3	0	44	106	9	0	3	1	2	0
Nassarius burchardi	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Physastra gibbosa	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Opisthobranch sp.1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Polypedilum nubifer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Procladius sp.	0	1	0	0	0	0	0	1	1	0	1	1	0	0	0	0	0	0	4	0
Hydroid sp.1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Nemertean sp.1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0
Nematode sp.1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Biological indices																				
Total abundance	11	5	65	24	42	83	91	44	72	45	33	28	57	537	78	6	10	5	106	0
Species richness	5	4	6	7	6	7	5	7	9	5	6	7	8	9	5	4	4	4	12	0
Environmental variables																				
% Organic matter	1.7	3.8	11	0.7	3	2.2	11.4	11.9	27.6	26.3	25.9	28.8	10.6	18.2	21.6	22.7	27.6	7.3	19	5.8
Proportion silt	0	0	0	0	0	0	1	1	0	1	1	1	0.1	1	1	1	1	0	1	1
Proportion sand	1	1	1	1	1	1	0	0	1	0	0	0	0.89	0	0	0	0	1	0	0
Proportion gravel	0	0	0	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0

Appendix B Latitude and longitude of macroinvertebrate samples collected in Macquarie Harbour in March 1996

Zone	Site number	Latitude	Longitude
1	1	42.09.38	145.19.06
1	2	42.10.61	145.21.02
1	3	42.11.11	145.20.73
1	4	42.13.00	145.21.30
1	5	42.14.94	145.21.62
1	6	42.18.62	145.18.70
1	7	42.21.55	145.22.58
1	8	42.21.83	145.23.08
1	9	42.22.19	145.28.67
1	10	42.20.51	145.27.38
1	11	42.18.02	145.25.13
1	12	42.16.63	145.23.70
1	13	42.15.68	145.22.78
2	14	42.17.16	145.18.90
2	15	42.17.52	145.18.06
2	16	42.16.47	145.17.70
2	17	42.15.67	145.17.60
2	18	42.15.16	145.17.88
2	19	42.13.32	145.18.44
2	20	42.12.70	145.17.72
2	21	42.22.30	145.24.99
2	22	42.25.34	145.28.43
2	23	42.24.88	145.29.57
2	24	42.22.56	145.30.75
2	24	42.22.51	145.31.26
2	26	42.21.58	145.29.39
4	27	42.24.76	145.27.50
4	28	42.25.60	145.26.97
4	29	42.25.58	145.27.51
4	30	42.27.64	145.28.00
4	31	42.28.90	145.27.95
4	32	42.22.07	145.32.62
4	33	42.21.52	145.33.03
4	34	42.21.30	145.32.68
4	35	42.21.22	145.29.90
4	36	42.20.86	145.28.94
4	37	42.20.81	145.30.45
4	38	42.20.89	145.30.91
4	39	42.13.62	145.21.13