supervising scientist report

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MOUNT LYELL REMEDIATION

A pilot biological survey of Macquarie Harbour, western Tasmania

NA O'Connor, F Cannon, B Zampatti, P Cottingham & M Reid

Mount Lyell Remediation Research and Demonstration Program

a Tasmanian and Commonwealth Government initiative *supervising scientist report* **113**

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Department *of* Environment and Land Management

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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.

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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 13A, Water Ecoscience P/L have undertaken a pilot biological survey of Macquarie Harbour. The aims of the pilot study were to:

- describe the vertebrate, invertebrate and floristic communities of Macquarie Harbour;
- to report on the trace metal concentrations in tissue of edible fish species from Macquarie Harbour;
- recommend a community (eg benthic invertebrates, macroalgae, seagrass) best suited as a monitor of the ecological health of the harbour; and
- suggest a sampling regime to establish the present status of this community and to test for subsequent changes following the implementation of measures to reduce the level of pollutants entering the harbour from the King River.

This report presents the findings of the pilot survey. It also includes a detailed section on the recommended community for monitoring and an appropriate statistical design for an ongoing monitoring program.

A pilot biological survey of Macquarie Harbour was conducted by Water Ecoscience over 7 days from 30 August 1995 to 4 September 1995. Benthic invertebrate samples were collected from 28 sites throughout the harbour using a Smith-MacIntyre grab. Fish species were recorded from 7 sites which were seine netted and five sites which were gill netted and included samples set aside for trace metal analysis. Due to the time of year and poor water visibility, investigation of seagrass and macroalgae coverage was reduced to qualitative assessments of species present. Phytoplankton and zooplankton samples were collected from 14 sites throughout the harbour, while benthic diatoms were collected from 12 sites.

The benthic infauna recorded were less numerous and diverse than might have been expected in an estuary the size of Macquarie Harbour, although the recorded taxa were generally common to estuaries across southern and south-eastern Australia. As there had been no prior investigations of benthic fauna in Macquarie Harbour, it is difficult to asses the extent to which previous mining operations or natural conditions have affected population assemblages. However, based on the limited knowledge of the physical environment of Macquarie Harbour and comparisons with studies conducted on other south-east Australian estuaries, it is possible that 100 to 200 species of benthic invertebrates might be expected in the harbour, excluding potential mining impacts. In the present study only 49 benthic species were collected and this brings to 58 the total number of benthic invertebrate species recorded from Macquarie Harbour.

A total of thirteen fish species were collected by seine netting in Macquarie Harbour, with Tasmanian smelt *Retropinna tasmanica* the most widely distributed species. The highest abundances of this species were recorded in areas with low salinity. The silver fish *Leptatherina presbyteroides* was also common, especially in areas with high salinity. Other recorded species included the smallmouth hardyhead (*Atherinosoma microstoma*), shortsnout hardyhead (*Kestratherina breviostris*), common jollytail (*Galaxias maculatus*) and Tasmanian whitebait (*Lovettia sealii*).

Abundances and diversity of fish species captured by gill netting were relatively low. Most of the species captured were marine with the exception of brown trout (*Salmo trutta*) and Atlantic salmon (*Salmo salar*), both introduced salmonids. The greatest diversity of fish was caught at Neck Island (6 species) whilst the lowest diversity was caught at Double Cove (1 species). Red cod (*Pseudophycis bachus*) and greenback flounder (*Rhombosolea tapirina*) were the most abundant species, comprising 29% and 33% of the catch respectively. An undescribed species of skate in the Genus *Raja* was captured at Neck Island and Cosy Corner. This species of skate has only previously been captured in Bathurst Harbour, South-West Tasmania. Other species included juvenile blue grenadier (*Macruronus novaezelandiae),* and short-finned eels (*Anguilla australis*).

Seagrass and macrophyte assemblages were difficult to locate and sparse at the visited sites. This was most likely due to the survey occurring during the senescencing phase of the seagrass life cycle and low light penetration in the harbour waters. Senesced blades of the seagrass *Zostera muelleri* were found at Yellow Bluff and Swan Basin, the brown algae *Ectocarpus fasciculatus* was collected from the fish farm nets near Liberty Point, while the stonewort *Nitella* sp. was found at Farm Cove and Kelly Basin.

The phytoplankton in Macquarie Harbour were characterised by low species abundance and the presence of freshwater taxa in most samples, primarily reflecting the freshwater layer occupying the euphotic zone. Dinoflagellate species characterised the sites located in the southern area of the harbour, while diatoms characterised the sites influenced by marine inputs near the harbour mouth. This distribution pattern may be due to light availability in the water column (the environmental variable measured as significantly affecting phytoplankton distribution), and/or increased copper complexing capacity in fresher waters together with the greater copper tolerance of diatoms than other algal groups.

Zooplankton may be loosely placed into two groups within the harbour. The 'northern' group at the harbour mouth and the outlet of the King River had a lower species abundance and diversity, while having a majority of truly marine taxa. The 'southern' group occurred in areas receiving inflow from four rivers and contained the majority of freshwater taxa recorded in the survey.

Six species of fish were analysed for trace metal concentrations, including the short-finned eel (*Anguilla australis*), brown trout (*Salmo trutta*), Atlantic salmon (*Salmo salar*), red cod (*Pseudophycis bachus*), longsnout flounder (*Ammotretis rostratus*) and greenback flounder (*Rhombosolea tapirina*). Tissue metal concentrations for individual fish were generally below the maximum permitted concentrations of the Food Standards Code (FSC) of the National Food Authority and Tasmanian regulations. The exception was for selenium in fish collected from four of the five sampling sites (mainly greenback flounder and red cod), which in many instances was above the recommended levels of 1 mg/kg. In addition one of the two short-finned eels caught had a mercury concentration above the FSC recommended limits, although still within Tasmanian regulations. As the sample sizes for determination of metal concentrations was small, some further investigation is requred to evaluate whether selenium levels in fish pose a risk to public health with consumption.

For the purposes of developing a biological monitoring program, the Macquarie Harbour ecosystem can be divided into the following component communities (with some overlap):

- zooplankton;
- phytoplankton;
- fish;
- seagrass; and
- benthic macroinvertebrates.

Although all these components are important parts of the Macquarie Harbour ecosystem, logistic and financial constraints decree that only one such community can be sampled as part of a monitoring program. The community chosen needs to meet the following criteria:

- life histories of constituent taxa need to be in the order of several months to a few years so that they do not exhibit marked short term fluctuations in response to seasonal climatic changes;
- the taxa need to be reasonably persistent in a spatial sense (ie do not undergo great seasonal fluctuations in distribution and abundance due to factors such as migration);
- the taxa need to be relatively sedentary, rather than migratory, so that it is clear they can tolerate conditions at the sampling site;
- the taxa need to be in close association with potentially contaminated sediments on the bottom of the harbour rather than isolated from sediments, high in the water column;
- the costs of sampling the community and the identification of the constituent taxa need to be feasibly born by a monitoring agency and need to be competitive with other types of environmental monitoring; and
- the community chosen needs to be an important part of the Macquarie Harbour ecosystem with extensive links to other components so that observed changes will reflect changes in the health of the whole harbour.

Benthic macroinvertebrate communities fit these criteria more closely than the other ecosystem components listed above. As a result, *benthic macroinvertebrates are the most commonly used ecosystem components in most marine impact assessment and monitoring programs and are the recommended community for the Macquarie Harbour biological monitoring program.* The effectiveness of the monitoring program may be greatly increased if data on a range of physical and chemical variables is simultaneously collected along with each sample. Additional parameters recommended for sampling include:

- sediment copper concentration;
- depth of sample site;
- sediment particle size;
- sediment organic matter content;
- salinity at the sample site; and
- temperature.

As recovery of the harbour is expected to proceed over a number of decades, it is recommended that future monitoring occur on an annual basis as little additional information is likely to be gained with seasonal monitoring.

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Acknowledgments

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1 Pilot biological survey of Macquarie Harbour

1.1 Introduction

Over the last century, Macquarie Harbour and the Mount Lyell region to the north-east of the harbour (figure 1.1) have been affected by mining activities at the Mount Lyell copper mine. In that time the mine, operated by The Mount Lyell Mining and Railway Company Limited at Queenstown, 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 and 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 and this has resulted in the deposition of over 100 million cubic metres of tailings, slag and topsoil in the King River and Macquarie Harbour. A large proportion of this material is present in a 250 ha delta deposit at the mouth of the river in Macquarie Harbour (McQuade et al 1995).

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 13A, Water Ecoscience P/L have undertaken a pilot biological survey of Macquarie Harbour. The aims of the pilot study were to:

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- suggest a sampling regime to establish the present status of this community and to test for subsequent changes following the implementation of measures to reduce the level of pollutants entering the harbour from the King River.

It is envisaged that this information will provide a valuable baseline against which to measure changes following the implementation of remedial works on the lease site, and the tailings deposits in the rivers and Harbour. This report presents the findings of the pilot survey. It also includes a detailed section on the recommended community for monitoring and an appropriate statistical design for the monitoring program.

1.2 The Macquarie Harbour environment

Macquarie Harbour is a large (276 km^2), almost enclosed harbour situated on the west coast of Tasmania in a region of World Heritage significance (figure 1.1). The land surrounding the harbour consists mainly of National Park and conservation zones with the only significant nearby population centres being located at Strahan (population 600) and Queenstown (population 3500). The main activities in Macquarie Harbour are aquaculture (salmonid farming), tourist cruises, and recreational fishing (Locher & Koehnken 1993). The harbour

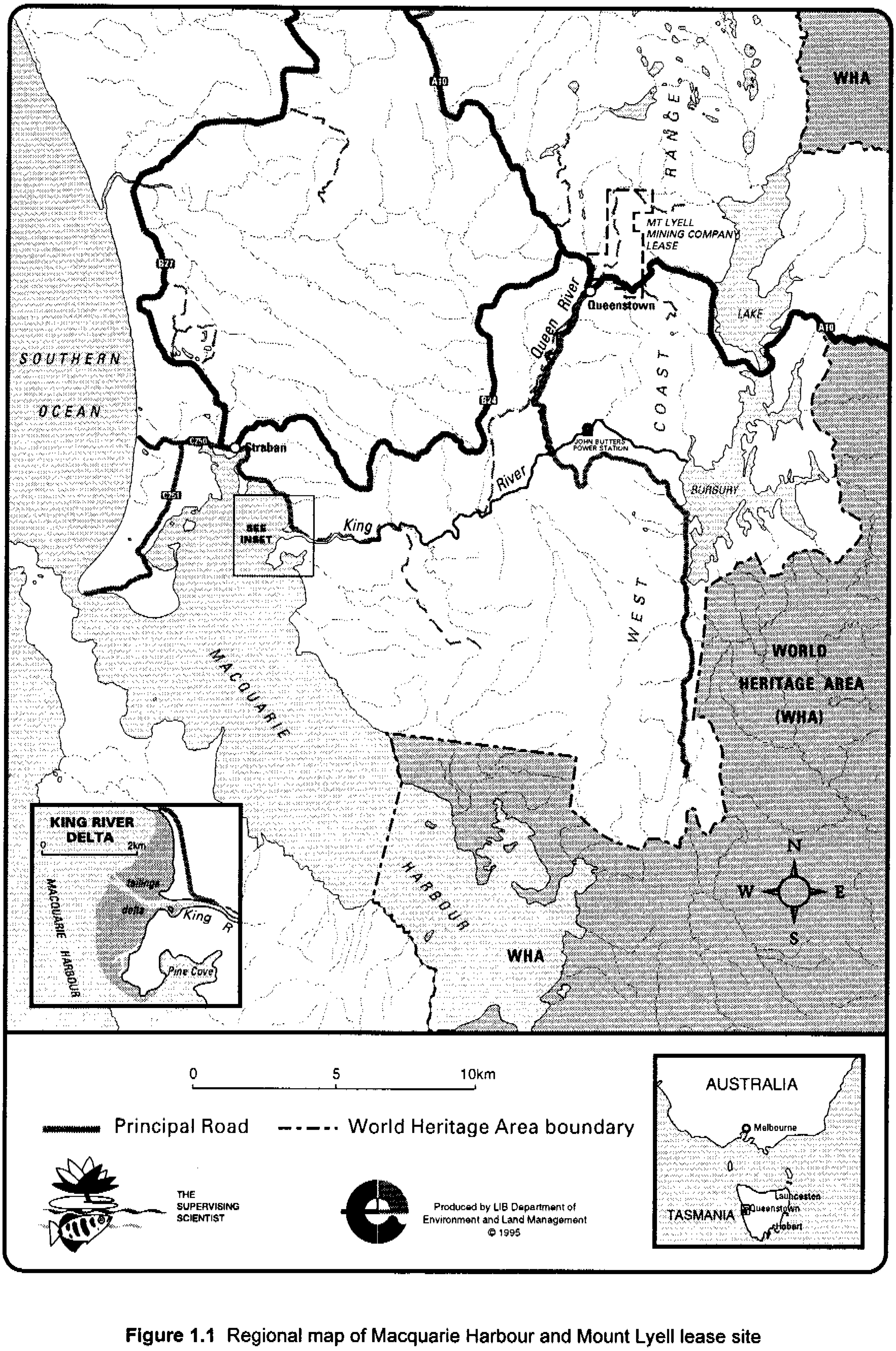

Figure 1.1 Regional map of Macquarie Harbour and Mount Lyell lease site

received tailings from the Mount Lyell mine which were discharged to the Queen River from 1892 until the closure of the mine in 1994. The new mine operator has built a tailings dam to avoid the need for tailings discharge. Presently, the harbour receives municipal waste water from the towns of Strahan and Queenstown (Locher & Koehnken 1993). There has also been some modification of freshwater inputs into Macquarie Harbour from the Gordon River as a result of hydroelectric operations at the Gordon Power Station and from the King River due to the John Bulters Power Station at Crotty Dam.

Oceanographic studies by Cresswell et al (1989) revealed the existence of a three-layered halocline in Macquarie Harbour:

1. A surface layer in the upper 10 m dominated by seasonal heating and cooling and river runoff. These waters have a 10 °C annual temperature variation. The runoff from the Gordon River and to a lesser extent the King River, brings waters low in salinity and high in oxygen and silicate into the harbour.
2. A middle layer with longer residence times at about 20 m depth. This layer has a small temperature range (0.8 °C), low levels of dissolved oxygen, and generally shows the highest nitrate concentration along the depth profile.
3. A deep marine layer where salinities exceed 31 ppt and the oxygen concentration increases with depth. This layer has an annual temperature variation of 1.5 °C, similar to that of the ocean. It is probably replenished by flood tides bringing in marine water which is subsequently modified by mixing across the harbour entrance before sinking to the deepest basins (Cresswell et al 1989).

According to Cresswell et al, a large part of the harbour floor may be covered by the middle layer with low dissolved oxygen levels and the chemistry and biota may reflect this.

In an earlier study conducted by the Department of the Environment, sediment samples were collected from 62 sites in the harbour, the substrate particle size noted (by allocation to one of several visual categories) and analysed for heavy metal concentrations (mercury, cadmium, copper, lead, zinc, chromium, manganese, iron, cobalt and nickel) (Department of the Environment 1975). Based on the sediment survey, the authors divided the harbour into five broad zones. These zones are described here in detail since they are likely to have some effect on benthic macroinvertebrates, notwithstanding possible toxic effects of heavy metal contaminated sediments. The zones are:

- sandy sediments near the harbour entrance. These are probably scoured by higher current velocities associated with tidal exchanges between the harbour and the Southern Ocean;
- a generally brown ooze ranging from south-east of Strahan to Farm Cove on the northern shore and to south of Sarah Island on the southern shore. This region also appears to correspond closely to the regions of highest copper contamination and the surface layers may contain high levels of mine tailing deposits;
- black to brown sandy and muddy sediments in the south-east region of the harbour;
- black, sulphide smelling ooze in Kelly Basin and Birch's Inlet. These strongly reducing sediments are probably due to decaying plant material either derived from seagrass beds or riparian plant litter deposited by river flows; and
- a generally brown sand and mud layer stemming from Swan Basin south-west of Strahan to south-east of Liberty Point. This sediment appears to be intermediate in shape and

form between zones 1 and 3; flood tides bringing in marine water which is subsequently modified by mixing across the harbour entrance before sinking to the deepest basins (Cresswell et al 1989).

These observations concur with our observations of sediments in grab samples taken from similar regions of Macquarie Harbour in August 1995.

1.3 Methods

A pilot biological survey of Macquarie Harbour was conducted by Water Ecoscience over 7 days from 30 August 1995 to 4 September 1995. Sampling was conducted from the *Wilsons Pride*, a 25 m fishing vessel hired from Mr Ron Morrison of Southern Ocean Trout Pty Ltd. Diving teams undertaking seagrass and macroalgal surveys operated from a 5 m aluminium dinghy with an outboard motor. The dinghy was also used to ferry crew from the *Wilsons Pride* to shore sampling sites (eg for fish seining work). Weather conditions during the survey were extremely rough and hampered sample collection at all sites. This accounts for a small number of sites where either benthic samples or accompanying water quality data was not collected.

1.3.1 Benthic macroinvertebrates

Benthic samples were taken from each of 28 sites on an approximately 3 km by 3 km grid throughout the harbour (figure 1.2) using a Smith-MacIntyre grab. Since this was an exploratory survey, single grabs of 0.1 m^2 were taken at each site to maximise spatial coverage of the harbour. The grab was operated by a winch and derrick from the *Wilsons Pride*. Samples were washed through 1.0 mm sieves on board, preserved in buffered formalin and returned to the laboratory for further washing, sorting and identification. Since it became apparent during sampling that benthic diversity was low and with improved weather conditions on the final day, an opportunity was taken to sample extra sites in the north-western section of the harbour near Strahan (sites 27–29, figure 1.2).

1.3.2 Fish communities

Seine netting

A total of 7 sites were seine netted in Macquarie Harbour from 30 August 1995 to 1 September 1995. Sites were selected to cover a range of habitats (fresh and salt water influences and substrate types) within the harbour. Strong north-westerly winds during the survey period resulted in the water level in the harbour being equivalent to a high tide. As a consequence there were few exposed beaches in the harbour and in many places vegetation extended to the waterline. This made hauling seine nets onto the shore for examination impossible at many sites that might otherwise have been sampled.

At each site, four 20 m hauls were conducted perpendicular to the shore with a 10 m by 2 m seine (6 mm mesh). If the net became snagged, the haul was repeated in an adjacent area. Fish were identified, weighed and measured on site or, if a large number of small fish were caught or which were difficult to identify in the field, the catch from each haul was preserved in 4% formalin and retained for identification in the laboratory. Identification of fish species was carried out using a range of references (eg Gomon et al 1994; McDowall 1980; McDowall & Frankenberg 1981; Last 1983; Last & Stevens 1994; Cadwallader & Backhouse 1983). A brief description of the conditions encountered at each site is given below.

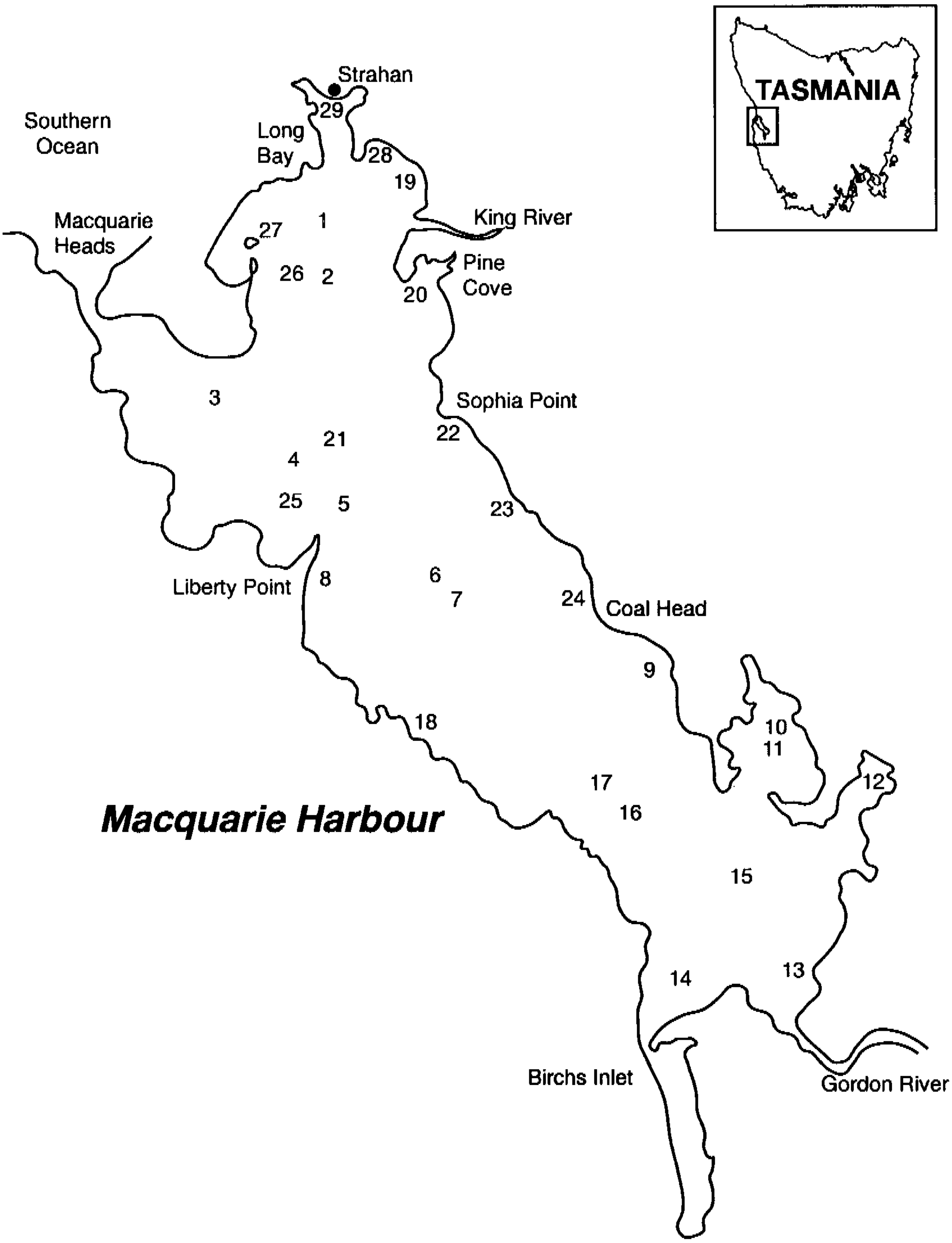

Figure 1.2 Sampling sites for benthic macroinvertebrates

Site S1, Yellow Bluff. This site was situated at the north-western end of Macquarie Harbour and is primarily marine influenced. The shore was comprised of small pebbles and gravel extending into the water for about 3 m before the bottom substrate changed to firm sand. Water depth 20 m from shore was approximately 1.4 m. Terrestrial vegetation extended to the waterline and comprised *Banksia, Acacia* and *Leptospermum* with a *Pinus radiata* plantation inland. A considerable amount of plastic debris was deposited along the shore. Habitat consisted of a small amount of submerged woody debris, sparse senescent seagrass and fine sand.

Site S2, Fish farm (Cosy Corner). This site was situated near an Atlantic salmon farm adjacent to Kelly Channel at the heads of Macquarie Harbour. The site consisted of a small sandy beach (15 m long and 2 m wide) surrounded by sparse native vegetation (*Leptospermum* and *Banksia*) burnt by bush fires a year earlier. A small tannin stained stream enters the harbour at the site. Water depth 20m from shore was 1.4 m. Habitat consisted mainly of submerged rocks (10–25 cm in diameter) interspersed with firm sand. There was a small amount of the macroalgae *Ulva* sp. growing on the rocks but no sea grass and little woody debris. There was also a small amount of green and red algae scattered throughout the site, probably deposited as drift from outside the harbour. A small amount of plastic debris was also visible along the shore.

Site S3, Double Cove. Double Cove is situated about half way up the southern side of Macquarie Harbour. The site is very open to north-westerly winds, which prevailed during the survey period. A small stream flows into the harbour in the middle of the cove and there was little plastic debris along the shore. The beach consists of a pebble substrate which extends about 10m into the water. Water depth 20 m from shore was approximately 2 m, with waves of 0.5–1 m due to prevailing winds. Terrestrial vegetation extended to the waterline and consisted of *Banksia, Acacia* and *Pomaderris*. Woody debris was the only habitat overlying the substrate in the area netted. Submerged, algae covered rocks, provided habitat in the western corner of cove, however no aquatic vegetation (ie seagrass) was evident elsewhere.

Site S4, Kelly Basin (St Leger Point). Kelly Basin is located at the south-eastern end of Macquarie Harbour. Seine net hauls were conducted on the inside of St Leger Point in Kelly Basin. The site was sheltered from prevailing winds and there was little wave action. Terrestrial vegetation extended down to the waterline and consisted predominantly of *Banksia, Acacia* and *Pomaderris*. A considerable amount of plastic was washed up on the shore. Substrate consisted of small lengths (2–6 m) of pebbly beach extending 5 m from shore after which the bottom became firm sediment, covered in areas by the submerged macrophytes *Nitella* sp. and *Ruppia* sp. Other habitat included a large amount of woody debris. Water depth 20 m from shore was approximately 1.8 m.

Site S5, Big Pebbly Beach. Big Pebbly Beach is a 200 m long expanse of pebbles situated at the south-eastern end of Macquarie Harbour, north of the Gordon River. Terrestrial vegetation is similar to that in Kelly Basin but ceases approximately 5–8 m above the waterline. The beach is subject to considerable wave action, with a near shore gutter (1.8 m deep) then a sandbar (depth 1.3 m) approximately 20 m offshore. The pebbles end just below the water line where the substrate changes to firm sediment with a large amount of submerged woody debris. There was no observable aquatic vegetation.

Site S6, Pine Cove. This site was situated in the first cove north-east of the King River. The beach was exposed and open to extensive wave up to 0.5 m action from the west and south-west. Vegetation ceased 5–10 m from the shore. The beach was littered with plastic debris (more so than any other site in Macquarie Harbour). Water at the site was noticeably turbid. A 1.6 m deep gutter ran next to the shore and water depth returned to 1.2 m approximately 15m from the shore. Habitat consisted of a firm mud substrate with a large amount of submerged woody debris and areas of smooth pebbles (10–30 cm in diameter). There was no observable aquatic vegetation.

Site S7, Neck Island (north and east). The beach on the east side of Neck Island is a steep sloping pebble bank. Dense vegetation grows down to the waters edge with only 1 m of bare pebbles separating the vegetation from the water. There was little wave action as site was sheltered from prevailing winds at the time of sampling the site. Water depth 20 m from shore was approximately 1.7 m. Habitat consisted almost entirely of bare pebbles. The beach on the northern end of Neck Island was wider (approximately 4 m) and comprised smaller pebbles than the eastern beach. This beach was also sheltered and shelved off quickly to about 2 m deep 10 m from the shore where the substrate consisted of firm sand.

Gill netting

In order to target larger fish species and to collect specimens for the tissue trace metal analysis study (see Section 2) gill nets were set at five sites in Macquarie Harbour from 2–3 September 1995. As for the seine netting, gill netting sites were selected to encompass a range of different habitats throughout the harbour. Eight nets (78–127 mm mesh, 30–60 m long) were set overnight at five sites in Macquarie Harbour: Neck Island (G1), Cosy Corner (G2), Table Head (G3), Double Cove (G4) and Kelly Basin (G5). Site descriptions for Neck Island, Cosy Corner, Double Cove and Kelly Basin are provided in section1.3.2, seine netting. Table Head is a rocky headland situated south-east of Cosy Corner. Water depth ranged from 2 m at the shore to approximately 5 m at the offshore end of the net. Visual observations suggested that substrate consisted of rocky outcrops inshore (no aquatic vegetation) and a mixture of firm sediment and scattered rocks offshore. Gill netting was conducted in deeper water than seine netting and, as a consequence of the tannin stained water, habitat type was difficult to ascertain.

1.3.3 Seagrass and macroalgal communities

Where possible, nearshore seagrass and macroalgal beds around the harbour were located on advice from local fishermen. Attempts were made by divers to survey the beds to record percentage cover along transects. However, this proved unfeasible due to the sparse coverage of seagrass and lack of clearly defined macroalgal beds. According to local residents seagrass beds go through a seasonal cycle of growth and senescence. Unfortunately the survey period coincided with the senescence phase of the growth cycle. To gain knowledge of what species of aquatic flora may grow in nearshore areas, divers conducted extensive searches of the nearshore harbour bed at several locations, collecting specimens for later laboratory identification.

Seagrass and macroalgae distribution in Macquarie Harbour is greatly affected by the highly coloured waters. These appear to be caused by leached tannins derived from the humic soils of the region. The influx of tidal seawater appears to have little effect on *in situ* light conditions as high rainfall in the region ensures a constant supply of tannins.

Due to the deep staining of the water, standard methods used to map and survey seagrass and macroalgae including aerial photography and non-destructive semi-quantitative algal assessment methods using SCUBA, cannot be used in Macquarie Harbour. Harvesting for biomass was ineffective as the seagrass and macroalgae, when present, was sparse and patchy. As a result, the approach adopted for this study was to determine seagrass and macroalgae presence based on habitat type within Macquarie Harbour. The following five locations were selected based on sediment type, fresh/seawater influence and available substrate:

- Yellow Bluff and Swan Basin;
- Kelly Channel;
- Farm Cove and Kelly Basin;
- Pine Cove; and
- Liberty Point fish farms.

In the shallow inlet areas of Yellow Bluff and Swan Basin, an observer was positioned on the bow of a slowly moving dinghy estimating seagrass cover over a known area. Spot dives and collections were made of species present. Divers investigated the extent of seagrass with increasing depth and reduced light conditions. In sites where it was not possible to observe benthic assemblages from the surface, spot dives for collections of species present were made over areas known to support seagrass and macroalgae. At Farm Cove, spot divers covering 50 m by 20 m were carried in the north-west corner of the cove, and similary at the west point of Soldier Island and on the south-east shoreline. In addition, divers collected specimens of algae attached to the netting of salmon farm cages for identification.

1.3.4 Phytoplankton

Phytoplankton was sampled from an aluminium dinghy at 14 sites within the harbour (figure 1.3) using a 0–5 m integrated polyethylene tube sampler. A 250 mL sample was collected and preserved immediately in Lugols solution. In the laboratory 100 mL of sample was poured into marked cylinders and stored in the dark for at least 24 hours to allow the cells to settle. The supernatant (90 mL) was siphoned off and cells resuspended in the remaining 10 mL subsample. Approximately 1 mL of the subsample was transferred to a Sedgewick-Rafter counting cell and using an inverted microscope, plankters in 500 of the etched square grid fields were identified and counted. Identification was carried out using a range of taxonomic references (Bourrrelly 1966; Foged 1978; Fritsch microfiche; Gasse 1986; Huber-Pestalozzi 1942; Hustedt 1930; Patrick & Reimer 1966 and 1975; Prescott 1978; Thomas 1983; von Stosch 1985; and Walne et al 1986).

1.3.5 Benthic diatoms

Surface sediment was sampled from an aluminium dinghy, using an extenable coer made from polycarbonate tubing, at 3 sites in each of the main harbour, Kelly Basin, fish farm and the King River delta. At each of the sites, four replicate surface material samples were taken from the uppermost 10 mm of sediment. Sub-surface sediment was sampled from a single replicate to a depth of 9 cm at Kelly Basin and 16 cm at the remaining sites.

Sediments were prepared for diatom analysis using the method outlined in Battarbee (1986). Cleaned samples were diluted and mounted in the mounting medium 'Naphrax'. Identification was carried out using a range of taxonomic references (John 1983; Foged 1978; Hustedt 1930–1966; Giffen 1963, 1967, 1970; Hendey 1970; Li 1978; Huang 1990; Navarro 1981a, 1981b, 1982a, 1982b, 1982c, 1983a, 1983b and Navarro et al. 1989) and at least 300 valves were counted in each sample. Tabulations of taxa were arranged according to salt tolerance, based on ecological information provided by John (1983), Foged (1978), Hustedt (1930–1966), Giffen (1963; 1967; 1970), Hendey (1970), Li (1978), Huang (1990), Navarro (1981a, 1981b, 1982a, 1982b, 1982c, 1983a and 1983b) and Navarro et al (1989).

1.3.6 Zooplankton

Daytime horizontal surface tows tor zooplankton were made at 14 sites (coinciding with phytoplankton sites) at a depth of 0.3 m using a 25 cm diameter, 25 μm mesh net towed slowly behind an aluminium dinghy for 120 s. A digital flow meter was attached to the net, allowing calculation of the volume of water passing through the net. Samples were preserved in 70% ethanol + 2% glycerol in the field. In the laboratory the samples were backwashed with water through a 60 μm mesh to a known volume, as there was too much sediment in most of the original samples to permit accurate counting. Zooplankton were counted on 10 mL subsamples using a Bogarov counting chamber under a dissecting microscope. The whole sample was then scanned and any additional taxa were recorded as present.

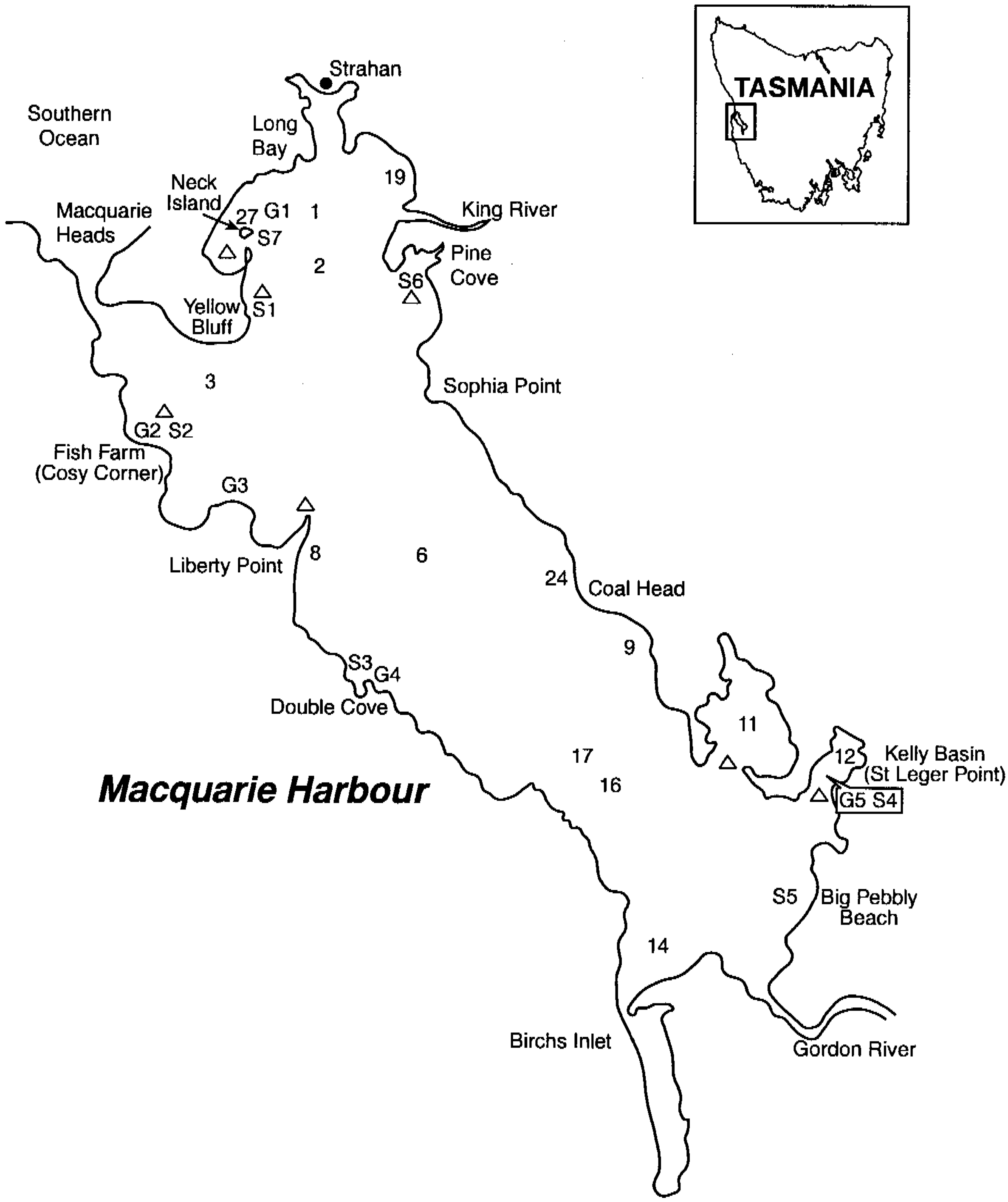

Figure 1.3 Sampling sites for phytoplankton and zooplankton, fish (seine (S) and gill (G) netting) and seagrass surveys (Δ)

1.3.7 Statistical methods

A statistical software package 'PATN' (Belbin 1995) was used to analyse phytoplankton and zooplankton data. Benthic macroinvertebrate and fish data was not considered sufficiently complex to warrant multivariate analysis. In the case of benthic macroinvertebrates total abundances were too low to use the dissimilarity indices which constitute one of the major steps in ordination analyses.

Prior to statistical analyses, phytoplankton and zooplankton abundance data were log10(x+1) transformed and standardised to range between 0 and 1 by dividing the abundance value for each species by the maximum value it obtained in any sample. These standardisations and transformations prevent abundant taxa from dominating the ordination outputs.

The data were then used to construct a Bray-Curtis dissimilarity coefficient matrix. This matrix was used as input for semi-strong-hybrid (SSH) multidimensional scaling. To determine if species were responding to the environmental variables measured, vectors of maximum correlation between environmental variables and sample site coordinates in the ordination space were calculated using the principal components coordination (PCC) module of PATN.

For benthic diatoms, incremental sum of squares cluster analyses were carried out on the data using the computer package 'Tilia' (Grimm 1991) to identify similarities in diatom taxa composition between samples and subsamples. Cluster analysis was favoured over ordination analysis in this case to present clearer classifications of the data.

1.4 Results

1.4.1 Benthic macroinvertebrates

Benthic macroinvertebrates were scarce at all sites (table 1.1) by comparison with inshore embayments elsewhere in south-eastern Australia (eg Port Phillip Bay (Poore et al 1975), Western Port (Coleman et al 1978), Gippsland Lakes (Morgan 1986)). The samples contained large amounts of terrestrial detritus (mostly leaf and wood fragments), and little evidence of organic matter of marine origin. A few sites contained faecal pellets or tube fragments but contained no animals.

Of the 49 species recorded, the dominant taxa (in approximate order of abundance) were:

- Orbiniidae (polychaete worms);
- the burrowing heart urchin *Echinocardium cordatum* (echinoid); and
- the burrowing shrimp *Axiopsis werribee* (Decapod crustacean).

Other animals present in lower numbers were amphipods, ostracods, bivalves, polychaetes (Lumbrineridae). Overall, polychaetes accounted for 58% of recorded species, gastropods and crustacea for 15% of species respectively, while bivalves and echinoderms accounted for 6% of recorded species respectively.

1.4.2 Fish communities

Seine netting

A total of thirteen fish species were collected by seine netting in Macquarie Harbour (table 1.2), with Tasmanian smelt *Retropinna tasmanica* the most widely distributed species. The highest abundances of this species being caught in Kelly Basin (S4) and at Big Pebbly Beach (S5), coinciding with the lowest surface water salinities recorded in the harbour (table 1.3). Low numbers of Tasmanian smelt were caught at all other sites

The second most widely distributed fish was silver fish *Leptatherina presbyteroides* which belongs to the family Atherinidae. This essentially marine fish was found predominantly in the north-western region of the harbour, coinciding with high salinities (table 1.3). Two other Atherinids were also captured, namely the smallmouth hardyhead *Atherinosoma microstoma* and shortsnout hardyhead *Kestratherina brevirostris*. Although relatively common in

Table 1.1 Macroinvertebrate taxa recorded at monitoring sites.

Invertebrate taxa	Class	Family	Species	Number of records (MQH sites)
Mollusca	Gastropoda	Nassariidae	*Nassarius nigellus*	2
		Rissoidae	*Tatea rufilabris*	4
		Hydrobiidae	*Ascorhis victoriae*	1
		Aglajidae	*Melanochlamys* sp.	3
	Bivalvia	Nuculidae	*Nucula pusilla*	4
		Mytilidea	*Brachiodontes erosus*	1
		Thyasiridae	*Thyasira* sp.	3
			Thyasira verconis	1
		Lasaeidae	*Arthritica semen*	2
Polychaeta		Ampharetidae:	Ampharetid sp.	1
		Arenicolidae:	Arenicolid sp.	1
		Cirratulidae:	Cirratulid sp. 1	2
		Cossuridae:	Cossurid sp.	1
		Glyceridae:	*Glycera* sp.	2
		Hesionidae	Hesionid sp. 1	4
		Lumbrineridae:	*Lumbrineris* sp.	1
		Maldanidae:	Maldanid sp. 1	1
		Nephtyidae:	Nephtyid sp. 1	1
		Orbiniidae:	*Leitoscoloplos bifurcatus*	1
			Leitoscoloplos kerguelensis	11
			Leitoscoloplos normalis	2
		Phyllodocidae:	*Phyllodoce* sp.	2
			Hypereteone otati	2
		Sabellidae:	Sabellid sp. 1	3
			Sabellid sp. 2	1
		Syllidae:	Syllid sp.	1
		Terebellidae:	*Pista* sp. 1	2
Crustacea		Mysidae	*Pseudomma australe* MoV 1792[1]	4
		Axiidae:	*Axiopsis werribee*	3
		Cylindroleberidae	*Archasterope* sp. MoV 1027[1]	1
		Cypridinidae:	*Vargula* sp. MoV 1646[1]	9
		Hymenosomatidae	*Amarinus laevis*	2
		Philomedidae:	*Euphilomedes* sp. MoV 1647[1]	4
		Ampelisicidae	*Byblis mildura*	1
		Carophiidae	*Paracorophium* sp. MoV 1784[1]	3
		Oedicerotidae	Oedicerotid sp. MoV 1785	8
		Phoxocephalidae	*Brolgus tattersalli*	6
		Liljeborgiidae	*Liljeborgia dubia*	1
		Lysianassidae	*Amaryllis macrophthalma*	1
			Parawaldeckia sp. MoV 290[1]	1
		Melphidippidae	*Homelia* sp. MoV 1783	1
		Nannastacidae	*Campylaspis thompsoni*	1
		Nebaliidae	*Nebalia* sp. MoV 1666	1
Echinodermata		Amphiuridae:	*Amphipholis squamata*	1
		Loveniidae:	*Echinocardium cordatum*	7
Cheliceriformes	Pycnogonida	Ammontheidae	*Achelia assimilis*	1
		Family indet.	Pycnogonida *cf.* sp. MoV 96[1]	1

1 MoV: Museum of Victoria voucher number

sheltered marine habitats in Tasmania, the shortsnout hardyhead was only caught at Yellow Bluff (S1). At the time of sampling, this site had the highest recorded surface water conductivity (31.8 mS/cm) in the harbour. The smallmouth hardyhead is common throughout south-eastern Australia in shallow bays, coastal lakes and estuaries. This species is euryhaline and was found in Macquarie Harbour at sites with conductivities ranging from 2.0–13.78 mS/cm.

The remaining species were found in relatively low numbers. The common jollytail *Galaxias maculatus* and Tasmanian whitebait *Lovettia sealii* are diadromous fish with the latter once forming a large whitebait fishery in Tasmania. The whitebait fishery, which peaked at 480 000 kg in 1947 (McDowall 1980), probably included a number of the small bodied fish captured in this survey. The size range of the common jollytails (Appendix A) suggests that these fish were the beginning of the spring migration of juvenile fish from the sea to freshwater habitats.

Congolli (also known as tupong or sandies, *Pseudaphritis urvilli*) are also diadromous and individual specimens were found at both the south-eastern (low salinity) and north-western (high salinity) ends of the harbour. Only one specimen of the big belly seahorse *Hippocampus abdominalis* was caught in the primarily marine influenced waters at the north-western end of the harbour. Low numbers of yellow-eye mullet *Aldrichetta forsteri*, longsnout flounder *Ammotretis rostratus* and greenback flounder *Rhombosolea tapirina* were also caught at sites with the greatest marine influence. The lagoon goby *Tasmanogobius lastii* was only found in the south-eastern end of the harbour at Big Pebbly Beach (S5).

Gill netting

A total of eight fish species were collected by gill netting in Macquarie Harbour (table 1.4). Total abundances were low, the most abundant species being red cod *Pseudophycis bachus* and greenback flounder *Rhombosolea tapirina*. Both species were found in approximately the same numbers in the north-western end of the harbour. The most widely distributed species in the Harbour was the blue grenadier *Macruronus novaezelandiae*. Individuals of this species were found in both the north-western and south-eastern ends of the harbour. The most diverse site was Neck Island (site G1) where six species of fish were caught.

Table 1.2 Abundances of fish species collected by seine netting

Species	Site						
	S1	S2	S3	S4	S5	S6	S7
Anguilla australis	1						
Retropinna tasmanica	2	13	6	68	26	2	2
Lovettia sealii					2		
Galaxias maculatus				1		1	
Atherinosoma microstoma			2	8	2		
Kestratherina brevirostris	110						
Leptatherina presbyteroides		440	2			2	2
Hippocampus abdominalis							1
Aldrichetta forsteri	2	2					
Pseudaphritis urvilli		1			1		
Tasmanogobius lasti					1		
Ammotretis rostratus	1						
Rhombosolea tapirina	2	1					

Table 1.3 Surface water physico-chemical measurements at each seine netting site

Site	EC[1] (mS/cm)	DO[2] (mg/L)	pH	Water Temp (°C)
S1	31.8	8.1	7.3	11.5
S2	18.4	8.5	7.0	11.0
S3	13.8	8.7	6.8	10.1
S4	6.7	9.4	7.2	9.5
S5	2.0 - 4.0	9.8	7.0	7.6
S6	15.9	8.6	7.3	9.8
S7	31.3	8.5	7.0	12.1

1 Conductivity
2 Dissolved Oxygen

Table 1.4 Abundances of fish species collected by gill netting

Species	Site				
	G1	G2	G3	G4	G5
Raja sp.	1	1			
Anguilla australis					2[1]
Salmo trutta			1		2
Salmo salar	1				
Pseudophycis bachus	1	4	1	3	
Macruronus novaezelandiae	1		1		1
Ammotretis rostratus	1				
Rhombosolea tapirina	4	1	5		

1 Captured by angling

Table 1.5 Summary of fish species captured by seine and gill netting

Specific name	Common name
Raja sp.	maugean skate
Anguilla australis	short-finned eel
Salmo trutta	brown trout
Salmo salar	Atlantic salmon
Retropinna tasmanica	Tasmanian smelt
Lovettia sealii	Tasmanian whitebait
Galaxias maculatus	common jollytail
Pseudophycis bachus	red cod
Macruronus novaezelandiae	blue grenadier
Atherinosoma microstoma	smallmouth hardyhead
Kestratherina brevirostris	shortsnout hardyhead
Leptatherina presbyteroides	silver fish
Hippocampus abdominalis	bigbelly seahorse
Aldrichetta forsteri	yellow-eye mullet
Pseudaphritis urvilli	congolli
Tasmanogobius lasti	lagoon goby
Ammotretis rostratus	longsnout flounder
Rhombosolea tapirina	greenback flounder

An undescribed species of skate *Raja* sp. was captured at both Neck Island (G1) and Cosy Corner (G2). This species of skate has previously only been caught in Bathurst Harbour, south-western Tasmania (Last & Stevens 1994). Of the other species captured in low numbers two were introduced salmonids, namely the brown trout *Salmo trutta* and Atlantic salmon *Salmo salar*.

1.4.3 Seagrass and macroalgal communities

A qualitative description of seagrass and macroalgal communities around Macquarie Harbour is given below.

Yellow Bluff

Yellow Bluff is protected from prevailing west and south-west winds. The sediment is sandy with no sharp drop-offs with distance from shore. In an area of 300 m by 50 m, sparse and patchy remnant seagrass stems from the previous growth season occupied a narrow 3 m band parallel to shore. Interspersed amongst the stems was a small number of emerging new blades of *Zostera mueleri.* The new growth and old senescing stems of *Z. mueleri* were not observed in water depths greater than 1.5 m. The extent of seagrass was probably dependent on the interrelated variables, depth and light availability. In total, seagrass covered less than 5% of the area investigated. No other seagrass or macroalgal species were found.

Swan Basin

Swan Basin (approximately 2000 m by 2000 m) is a protected inlet in the north-west of Macquarie Harbour. The basin is further protected from easterly winds by Neck Island. The substrate is sand and slopes gently to 4 m at the deepest point.

Swan Basin had a broad, but patchy fringe (20 m width) of old senescing stems of *Z. mueleri* interspersed with newly emerging *Z. mueleri* blades. The seagrass was observed in depths of 0.5–1.75 m covering the south and west shoreline of the basin. As with Yellow Bluff, seagrass distribution was probably dependant on depth and light. In total, seagrass covered 10–15% of the area investigated. No other seagrass or macroalgal species were found.

Kelly Channel

Kelly Channel, is the continuation of the shipping entrance through Hells Gates into Macquarie Harbour. The channel is exposed to the full brunt of westerly winds with shifting sand bars and depths varying from 3–10 m.

A short spot dive was carried out in the Channel at 5 meters depth covering 10 by 20 m. The visibility was zero on the floor of the channel and the substrate was fine sand. No macroalgae or seagrass was observed.

According to local information (Ron Morrison, pers comm) Fraser Flats in the north of Kelly Basin is exposed for some periods in the summer months and covered by seagrass.

Farm Cove

Farm Cove in the south-west of Macquarie Harbour is fringed by Huon pine *Lagarostrobos franklinii*, myrtle *Nothofagus cunninghamii*, celery top pine *Phyllocladus aspeniifolius*, leatherwood *Eucryphia lucida* and sassafras *Atherosperma moschatum*. The shoreline slopes steeply and the sediment type is black and organic.

The fresh water macrophyte *Nitella* sp. was found in dense patches in the north-west corner of Farm Cove with small patches of senescent stems of *Z. muelleri* towards the eastern section of the area investigated.

At the western end of Soldier Island small sparse patches of *Nitella* sp. were found. The steep slope and hence quickly decreasing light availability surrounding Soldier Island would have limited further macroalgal/macro-phyte growth.

The more exposed south-east shoreline of Farm Cove had sparse patches of *Nitella* sp. and an unidentified species of filamentous red alga.

Available substrate was limited to submerged trunks and branches of trees, leaf litter and the occasional pebbles. The fresh water species *Nitella* sp. was also abundant in undulation troughs in the sediment floor.

Kelly Basin

Kelly Basin is fringed with vegetation as for Farm Cove. Similarly, the shoreline quickly drops off to over 2 m in depth and the sediment is black and organic. *Nitella* sp. was the the only species present.

Pine Cove

In this study Pine Cove was the closest site to the mouth of the King River. The shoreline was notable for having the most litter, primarily plastics, washed up on the beach. A small amount of drift macroalgae *Macrocystis angustifolia* and terrestrial leaf litter made up the rest of the beach detritus.

The site investigated was 200 m by 5 m. The substrate was fine silty sand, gently sloping with a band of small to medium sized rocks. The rocks were covered with a fine silt and no macroalgal growth was observed.

Fish farm

Samples of macroalgae were collected from fish cages at a salmonid farm operated by Southern Ocean Trout Pty Ltd located in Cosy Corner. The circular cage nets were 60 m in diameter, 6 m deep, and contained approximately 4000 salmon. The first 10 cm of the nets submerged in water had a moderate covering of filamentous brown algae (*Ectocarpus fasciculatus*). Light penetrated to a depth of 1 m. The remainder of the net had very few attached filaments. According to the proprietor algal growth is so vigorous on the nets in the summer months that they are cleaned up to every 3 weeks (R Morrison, pers comm).

A summary of findings is presented in table 1.6

Table 1.6 Summary of seagrass survey site characteristics

Site name	Sediment	Fresh/seawater influence	Available substrate
Yellow Bluff and Swan Basin	fine silt, sand	seawater (~31.00 mS/cm)	occasional small pebbles, *Zostera* spp. blades from remnants of previous summer growth and emerging new growth, terrestrial leaf litter, fallen branches.
Kelly Channel	fine silt, sand	seawater - brackish (~18.00 mS/cm)	nil
Farm Cove and Kelly Basin	Black, organic	freshwater - brackish (~7.00 mS/cm)	Submerged branches, leaf litter, small pebbles
Pine Cove	coarse, pyritic	seawater - brackish (~16.00 mS/cm)	Small to medium rocks
Fish farm	fine silt, sand		Salmon farm nets

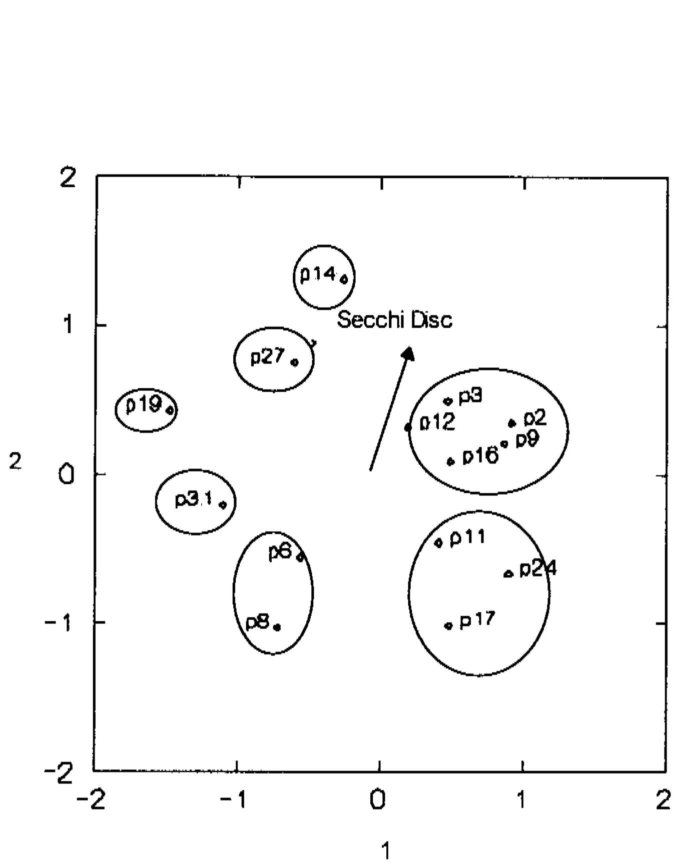

Figure 1.4 Macquarie Harbour phytoplankton sites ordination with environmental variable of maximum correlation (secchi disc). Data transformed and standardised using Log10(x+1) and divided by the maximum value. Seven groupings were identified by eye on the ordination plot: Group 1: sites 2, 3, 9, 12, 16; Group 2: sites 11, 17, 24; Group 3: sites 6, 8; Group 4: site 14; Group 5: site 27; Group 6: site 19; Group 7: site 3.1

Table 1.7 Monte-Carlo significance tests of environmental variables in ordination space.. Significant correlations are in bold type

Environmental variable	Correlation coefficient	Number of Monte Carlo randomizations with correlation coefficients less than the original data
Depth	0.1986	29
Air temperature	0.4457	65
Secchi disk	**0.5885**	**95**
Electrical conductivity	0.4171	71
Dissolved oxygen	0.2033	21
pH	0.1366	5
Water temperature	0.4682	77

1.4.4 Phytoplankton

Site ordination results (minimum stress value = 0.25) and the direction and best fit of the statistically significant environmental variable (secchi disc) have been presented together (Figure 1.4). A Monte-Carlo test identified that none of the remaining six environmental gradients were statistically significant (table 1.7). This indicates that one of the major influences on phytoplankton communities in Macquarie Harbour is light attenuation as measured by secchi disk (this includes effects of turbidity and colour). Other factors that may have affected phytoplankton community composition such as water nutrient levels were not measured.

The secchi disk vector gradient (figure 1.4) indicates more light penetrates into the water column at sites 14 (Birch's Inlet) and 27 (Swan Basin) whilst the least amount of light penetrates through the water column at sites 17 (Steadman Point), 11 (Kelly Basin) and site 24 (Coal Head).

Based on the ordination results the most similar sites were grouped together and listed with the percentage abundance of each taxa and a rank total species abundance for each site (table 1.8).

1.4.5 Phytoplankton community groupings

Group 1: Kelly Basin, Sarah Is, Phillip Is, East of Round Head, Yellow Bluff
The sites included in this grouping are near the entrance and southern end of the harbour. The almost exclusively marine and brackish euglenophycean genus *Eutreptiella* (*Eutreptiella* sp.?), is most abundant and common at each site, possibly due to its heterotrophic capabilities. The diatom *Surirella* sp. is known to tolerate low levels of light (Patrick & Reimer 1966) and was found in the darker waters of Kelly Basin.

Group 2: Swan Basin, Steadman Point, Coal Head
The waters of this site grouping have the lowest light penetration, the highest species abundance and are characterised by the Dinophyceae and nanoplankton The abundance of the nanoplankton at this site separates this group from group 1.

Group 3: south of Liberty Point and Double Cove
Both of these sites are close to the western shore of Macquarie Harbour and have an abundance of freshwater Chlorophyceae species. Interestingly, the diatoms and dinophyceae are not the dominant component of the flora in this site grouping, possibly a result of the proximity to shore.

Group 4: Birch's Inlet
This site has the highest light attenuation through the water column and is characterised by the lowest species diversity and abundance. It is not clear from the data available what has caused the depauperate flora.

Group 5: Swan Basin
Swan Basin has a diatom flora similar to the fish farm and King River delta sites, including the marine to brackish water species *Rhopalodia* sp., *Synedra* sp., *Achnanthes* sp. and *Melosira nummuloides*. The freshwater diatom *Aulocoseira granulata* was also found and is indicative of the sites proximity to shore. The family Desmomonadaceae, found throughout the harbour and the most abundant group of the Dinophyceae at this site, consists of motile unicells with the envelope surrounding the cell not developing any of the complex series of plates that is characteristic of the higher Dinophyceae. *Cladopyxis setifera* present at this site was also found at other sites near to shore which suggests it prefers lower salinity environments.

Group 6: King River delta
The King River is the passage by which heavy metals enter Macquarie Harbour with heavy metal concentrations of up to 1000 times the background sea-water concentrations (Carpenter et al 1991), it is therefore surprising to find as many species as at other sites in the Macquarie Harbour, although with relatively low abundances, at this site. The freshwater diatom *Tabellaria flocculosa* and *Tabellaria fenestrata* (found only at this site) are species common to acid waters (Patrick & Reimer 1966).

Table 1.8 Macquarie Harbour phytoplankton relative abundance and community groupings. Groups determined by site clusters in multidimensional scaling ordination. Where possible an indication of salt tolerance is given for the Bacillariophyceae based on ecological information provided by Fritsch microfische; Hustedt 1930; Lowe 1974; Patrick & Reimer 1966, 1975.

Phytoplankton community groups	1				2			3		4	5	6	7	
SPECIES	**P2**	**P3**	**P9**	**P16**	**P12**	**P11**	**P17**	**P24**	**P6**	**P8**	**P14**	**P27**	**P3**	**P19**	**salt tl**
BACILLARIOPHYCEAE															
Pinnularia sp.		2		2				2							F
Fragilaria sp.		2			2		1	1	1		2		1	2	F-M
Navicula sp.		2		2	2	1		1	1	2	2			2	F-M
Synedra sp.	1							1	1			2			F
Attheya sp.	1														F
Entromoneis robusta	1							2					2	2	*
Rhapalodia sp.												2			*
Achnanthes sp.												2			F-B
Surirella sp.					2										F-M
Meridion circulare					2								1		*
Nitzchia sp.			2		2	2			1				2	2	F-M
Amphora sp.						1						2	1		F-B
Cocconeis sp.	1														F-B
Tabellaria fenestrata														2	F
Tabellaria flocculosa	1		1	2					1				1	3	F
Unidentified pennates	2	3	3	2		2		2	2	2			4	2	*
Aulocoseira granulata	2	4				2		2	2		2	2	1		F
Aulocoseira varians									1				3		F
Melosira nummuloides	2	2	1									2	2		M
Unidentified centrics	2	3	2	2			2	2			2	2			*
DINOPHYCEAE															
Small Dinoflagellate		2		3											
Gymnodinium sp.		2					2								
Glenodinium sp.	1						2		1						
Cladopyxis setifera					2	1				2		3		2	
Desmomonadales	1	2		2	2	3	3	3			2	2	1		
Acanthodinium sp.								1							
CRYPTOPHYCEAE															
Cryptomonads		2		2	2	2	2		2	2		2	2		
Chroomonas					2	2									
EUGLENOPHYCEAE															
Eutreptiella sp.	4	4	4	4	4	4	3	4	2	2		2	2	2	
Trachelomonas													1		
CHRYSOPHYCEAE															
Chrysomonad	1		2			1			1				2		
CHLOROPHYCEAE															
Ankistrodesmus sp.		2	1	2	2	2	2	2	1	3	2	2	2	3	
Chlamydomonads		2	2			2	4	3	2						
Crucigenia sp.				2	3			1						3	
Coccoid greens		2							2			2	2		
Scenedesmus sp.														2	
Nanoplankton		2		2		4	4	4	2	4				2	
CYANOPHYCEAE															
Unidentified Filaments		2	2	2		2			1	2	2	2	2		
Chroococcus	1				2						2				
Rank Species abundance	11	2	10	7	6	4	3	1	13	5	14	12	8	9	

relative abundance: 1, present; 2, rare; 3, occasional; 4, common

salt tl: salt tolerance, F, freshwater; F-B, fresh-brackish; F-M, fresh-marine; *, unknown

Group 7: Fish farm

The fish farm exhibits the largest species diversity with a middle-order rank for species abundance. Both members of the Euglenophyceae identified from Macquarie Harbour are found at this site, however in low numbers. Even though there is a continual input of nutrients at this site due to large scale fish feeding operations as well as a high concentration of fish faeces, the phytoplankton flora does not appear to be indicative of a nutrient enriched environment.

1.4.6 Benthic diatoms

The sediments at the King River delta site were found to be devoid of diatom valves and were thus not included in further analysis. Surface and sub-surface samples at the remaining two sites were found to contain valves in sufficient concentrations and of adequate preservation for counting and identification (figure 1.5). Samples from Kelly Basin contained the highest concentration of valves.

While no physical analysis of the sediments was carried out, casual observation suggested lower sand content and higher organic content in Kelly Basin sediments, hence better preservation of frustules at this site. Sand content was high and preservation occasionally poor at the fish farm site.

The percentage abundances of the common taxa have been arranged according to salt tolerance (table 1.9). The incremental sum of squares cluster analysis carried out on this data utilised square root data transformation and is presented as a dendrograms (figure 1.6). Based on the results of these analyses, the samples were placed into four groups with the taxa that characterise each group (table 1.10).

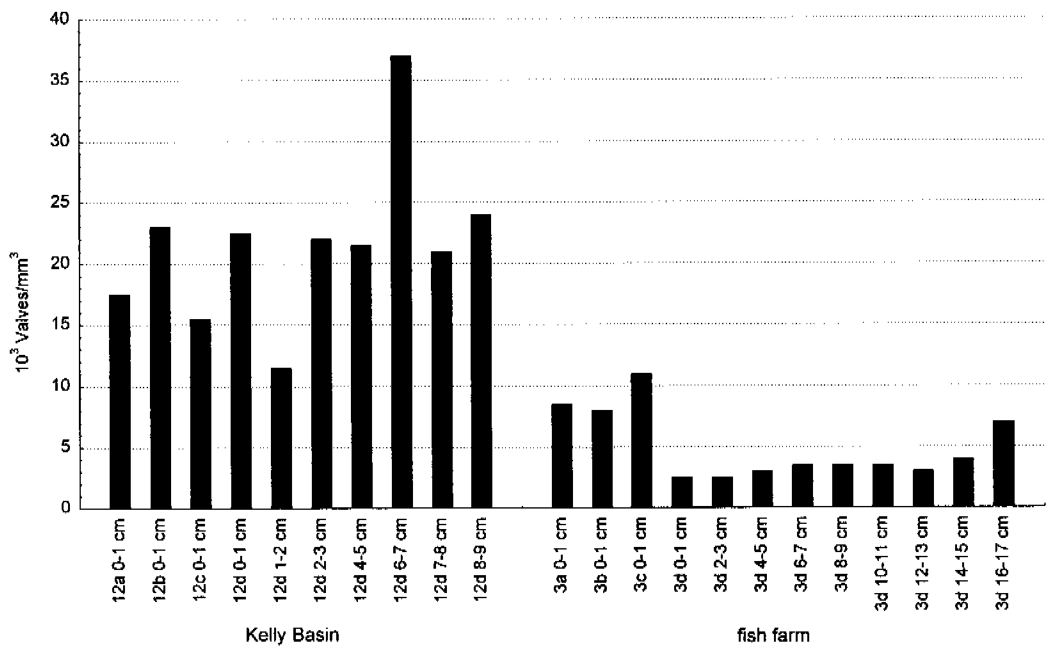

Figure 1.5 Diatom concentrations at Kelly Basin (site 12) and fish farm (site 3)

Table 1.9 Percentage abundances of common diatom taxa. Taxa are arranged according to salt tolerances

Species	Kelly Basin (site 12)										Fish Farm (site 3)											
	Surf-A	Surf-B	Surf-C	Surf-D core	1–2 cm	2–3 cm	4–5 cm	6–7 cm	8–9 cm	9–10 cm	Surf-A	Surf-B	Surf-C	Surf-D core	2–3 cm	4–5 cm	6–7 cm	8–9 cm	10–11 cm	12–13 cm	14–15 cm	16–17 cm
Fresh																						
Fragilaria spp.	-	-	-	1	1	-	-	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-
Eunotia spp.	-	-	-	-	-	-	-	-	-	-	-	1	-	1	-	-	-	-	-	-	-	-
Achnanthes spp.	1	1	2	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1
Cocconeis neodiminuta	1	-	-	-	-	-	-	-	-	-	1	1	1	-	-	-	1	1	1	-	-	1
Cocconeis cf. neothumensis	1	1	1	1	1	1	1	1	2	1	2	2	2	-	1	1	1	1	1	1	1	2
Cocconeis placentula	1	1	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1	1	-	1	1	1
Navicula spp. *(minisculae)*	-	-	1	-	-	-	-	-	-	-	1	1	1	-	-	-	-	-	-	-	-	1
Navicula cf. halophila (small form)	1	-	1	1	1	1	1	1	1	1	1	-	1	-	-	1	-	1	-	1	1	1
Diatomella balfouriana	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-
Nitzschia spp. *(lanceolatae)*	1	1	1	1	1	1	1	1	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Fresh - Brackish																						
Tabularia spp. *(Synedra tabulata)*	1	1	-	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	1	-
Achnanthes holsatica	-	1	1	1	1	1	-	-	1	-	1	1	1	1	-	1	1	1	1	1	1	1
Achnanthes delicatula	2	1	1	1	1	1	2	1	2	1	2	2	2	-	-	-	-	-	-	-	-	2
Achnanthes ploenensis v. gessneri	2	1	1	1	1	1	1	1	1	1	-	-	1	-	-	-	-	-	-	-	-	-
Navicula spp. *(lineolatae)*	-	-	-	1	-	1	-	1	1	-	1	1	1	-	-	-	-	-	-	-	-	1
Navicula perminuta	1	1	1	1	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	1	1
Nitzschia spp.	-	1	1	1	1	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-	1	1
Brackish - Marine																						
Melosira moniliformis	-	1	-	1	-	1	-	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-
Cyclotella hakanssoniae	3	3	2	3	2	3	3	2	2	2	1	1	1	-	-	1	1	-	-	-	1	1
Cyclotella hakanssoniae - fine	1	1	1	1	1	1	1	1	1	1	-	-	1	-	-	-	-	-	-	-	-	-
Actinocyclis ehrenbergii	1	1	1	-	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Opephora alsenii	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Achnanthes spp.	-	-	1	-	-	-	-	1	-	-	1	1	1	-	-	-	-	1	-	-	-	1
Achnanthes reversa	2	2	3	2	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	1	1

Table 1.9 (continued) Percentage abundances of common diatom taxa. Taxa are arranged according to salt tolerances

	KELLY BASIN (SITE 12)										FISH FARM (SITE 3)											
SPECIES	Surf-A	Surf-B	Surf-C	Surf-D core	1–2 cm	2–3 cm	4–5 cm	6–7 cm	8–9 cm	9–10 cm	Surf-A	Surf-B	Surf-C	Surf-D core	2–3 cm	4–5 cm	6–7 cm	8–9 cm	10–11 cm	12–13 cm	14–15 cm	16–17 cm
BRACKISH - MARINE (continued)																						
Cocconeis pediculus	1	1	1	1	1	1	2	1	1	2	-	-	-	-	-	-	-	-	-	-	-	-
Cocconeis grata	-	-	-	-	-	-	-	-	-	-	1	2	-	1	1	1	1	1	1	1	1	1
Cocconeis heteroidea	1	-	1	1	-	1	1	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Cocconeis pelta	1	-	-	1	1	-	1	1	1	1	3	3	3	4	4	3	4	4	4	4	3	3
Navicula florinae	-	-	-	-	-	-	-	-	-	-	1	1	1	1	1	1	1	1	1	1	1	1
Cocconeis peltoides	-	-	-	-	-	-	-	-	-	-	-	1	-	1	1	1	1	1	1	1	1	-
Cocconeis scutellum	-	-	-	1	1	1	-	1	1	1	-	1	1	1	1	1	1	1	1	1	1	-
Navicula halophila	-	-	1	1	1	-	1	1	-	1	1	1	1	-	-	-	-	1	-	1	1	1
Navicula regularis	-	-	-	-	-	-	-	-	-	-	1	1	1	5	4	5	4	4	4	4	2	2
Navicula oculiformis	-	-	-	-	-	-	-	-	-	-	-	-	-	1	1	-	1	-	1	1	1	-
Navicula ponticula	-	-	-	-	-	-	-	-	-	-	1	-	-	1	1	1	1	1	1	1	1	1
Navicula tenera	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	-	1	-	-	-	1	1
Diploneis spp.	1	1	1	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Cymbella pusilla	-	-	-	-	1	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Amphora spp.	1	1	1	1	1	1	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-
Gomphonema exiguum v.	-	1	1	-	1	1	1	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mastogloia spp.	-	-	1	1	1	1	1	1	1	1	-	-	1	-	-	1	-	1	1	1	-	-
Nitzschia spp.	1	1	1	1	-	-	1	1	-	-	-	1	-	-	-	-	-	-	-	-	-	-
Nitzschia valdestriata	-	1	-	1	-	1	-	-	1	1	1	1	1	-	-	-	-	1	1	-	1	1
UNKNOWN																						
Fragilaria spp.	-	-	1	-	-	-	-	-	-	--	-	-	-	-	-	-	-	-	-	-	-	-
Achnanthes cf. minutissima	-	-	-	-	-	-	-	-	1	-	-	1	1	-	1	1	1	1	1	1	1	1
Cocconeis spp.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-
Navicula spp.	-	1	1	-	1	1	1	-	-	-	1	1	1	-	-	-	-	1	-	-	1	1
Nitzschia spp.	-	-	-	-	-	-	-	-	-	1	-	-	1	-	-	-	-	-	-	-	-	-

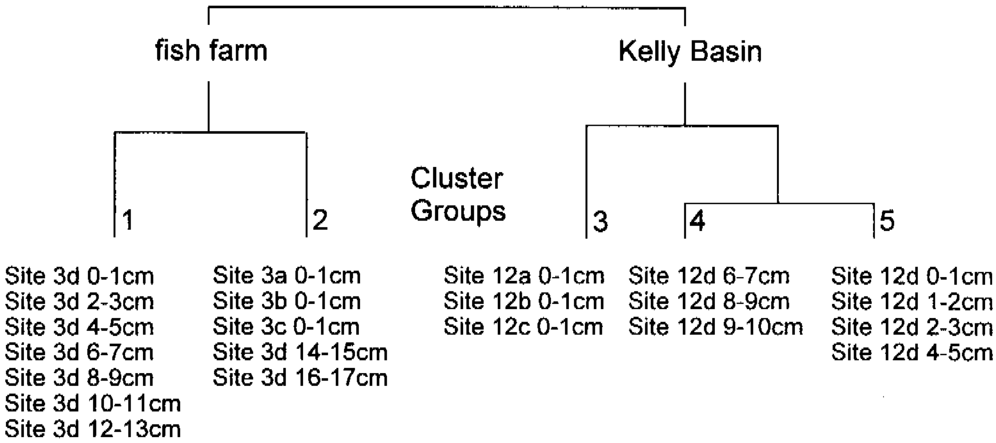

Figure 1.6 Incremental sum of squares cluster analysis dendrogram

Table 1.10 Sample groups based on incremental sum of squares cluster analysis. using a synthesis of square root and no data transformation, variables standardised to mean 0, standard deviation1 and sample vectors normalised to length 1

	Site	Common species
Group 1	fish farm core D: 0–1 cm	*Cocconeis pelta*
	fish farm core D: 2–3 cm	*Navicula florinae*
	fish farm core D: 4–5 cm	*Cocconeis peltoides*
	fish farm core D: 6–7 cm	*Cocconeis scutellum*
	fish farm core D: 8–9 cm	*Navicula regularis*
	fish farm core D: 10–11 cm	
	fish farm core D: 12–13 cm	
Group 2	fish farm surf B: 0–1 cm	*Cocconeis af. neothumensis*
	fish farm surf C: 0–1 cm	*Achnanthes delicatula*
	fish farm core D: 0–1 cm	*Cocconeis pelta*
	fish farm core: 14–15 cm	*Navicula regularis*
	fish farm core: 16–17 cm	
Group 3	Kelly Basin surf A: 0–1 cm	*Cocconeis placentula*
	Kelly Basin surf B: 0–1 cm	*Diatoma balfouriana*
	Kelly Basin surf C: 0–1 cm	*Achnanthes delicatula*
		Achnanthes ploenensis v.gessneri
		Cyclotella hakanssoniae
		Achnanthes reversa
Group 4	Kelly Basin core: 6–7 cm	*Cocconeis placentula*
	Kelly Basin core: 8–9 cm	*Cyclotella hakanssoniae*
	Kelly Basin core: 9–10 cm	*Achnanthes reversa*
Group 5	Kelly Basin surf D: 0–1 cm	*Cocconeis af. neothumensis*
	Kelly Basin core: 1–2 cm	*Cocconeis placentula*
	Kelly Basin core: 2–3 cm	*Achnanthes delicatula*
	Kelly Basin core: 4–5 cm	*Cyclotella hakanssoniae*
		Achnanthes reversa
		Cocconeis pediculus

1.4.7 Zooplankton

A list of the taxa recorded from the zooplankton survey of Macquarie Harbour is provided in table 1.11. Relatively low numbers of zooplankton were recorded at all sampled sites with the exception of copepod nauplii. The highest species diversity was recorded at sites throughout the harbour including sites 16 (Sarah Island), 9 (Phillip Island), 8 (Double Cove), 3 (fish farm) and 19 (King River delta). A number of common freshwater taxa were observed at site 16 (Sarah Island); these included *Bosmina meridionalis, Calamoecia ampulla* and rotifers.

Zooplankton site ordination results (figure 1.7) show some distinction between the 'northern' and 'southern' harbour sites, with the exception of site 14 (Birch's Inlet) which has a low total number and diversity of zooplankters, characteristic of the northern sites. In addition site 19 (King River delta) had a relatively large total number of zooplankters, predominantly nauplii, characteristic of the 'southern' sites. No nematodes were present from sites in the 'northern' part of the harbour including the King River delta.

Using the Monte-Carlo randomisation test it was determined that none of the measured environmental variables had a significant effect on zooplankton community structure (table 1.12).

As few representatives from most taxa were present, and even fewer species, for the following results and discussion the species have been placed under higher taxonomic groupings.

Copepoda
Copepod nauplii were present at all sites in the harbour and were the most abundant zooplankter in every sample. The greatest number of nauplii were observed in sites located in the southern half of the harbour where outlets from the Brandon, Bird, Gordon and Sobell Rivers are also located.

Calanoida
The calanoid *Sulcanus conflictus* was the second most abundant zooplankton, featuring at 11 of the 14 sites. This monotypic estuarine species was found at its highest levels in samples from sites 10 and 11, within Farm Cove. It was not recorded at sites 2, 3, 6 and 27, which were all in the northern part of the harbour in the vicinity of the harbour mouth. Calanoid copepodites were seen at several sites but were not identifiable to genus.

Harpacticoida
The third most abundant taxon, members of this order were observed at various sites throughout the harbour. They tended to co-occur with *S. conflictus* and were also most abundant at Farm Cove.

Cyclopoida
Most cyclopoids were distributed around the north-east of the harbour, but were recorded in low numbers.

Cladocera
Daphnia sp. was recorded at site 3 and observed, but not counted, in samples from site 8 (Double Cove) and 16 (Sarah Island). *Bosmina meridionalis* was recorded at Sarah Island, and also observed but not counted at site 6. Both are common freshwater taxa and were present in very low numbers.

Table 1.11 List of zooplankton taxa

Zooplankton Taxa	Zooplankton Taxa
ARTHROPODA	**SARCODINA**
CRUSTACEA	RHIZOPODEA
MAXILLOIDA	Lobosia
Copepoda	*Testacida*
Nauplii	*Arcella* sp.
Calanoida	*Centropyxis* sp.
Calamoecia ampulla	*Cyclopyxis* sp.
Calanoid copepodites indet.	*Difflugia* sp.
Sulcanus conflictus	**ROTIFERA**
Harpacticoida	MONOGONONTA
Euterpina sp.?	*Bdelloidea*
Harpacticoids indet.	*Bdelloid* sp.
Microsetella sp.	DIGONONTA
Cyclopoida	*Flosculariaceae*
Cyclopoids indet.	*Conochilus* sp.
Oithona sp.	*Filinia cf grandis*
BRANCHIOPODA	*Brachionus* sp.
Cladocera	*Epiphanes?* sp.
Anamopoda	*Keratella* sp.
Ctenopoda	**NEMATODA**
Bosmina meridionalis	Unidentified nematodes
Daphnia sp.	

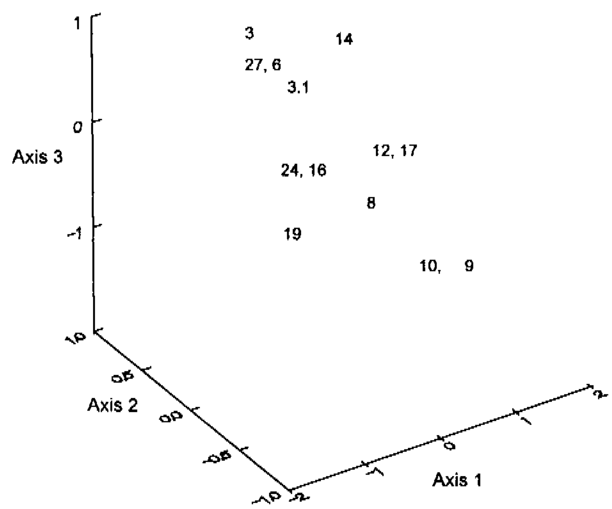

Figure 1.7 Macquarie Harbour zooplankton sites ordination. Data transformed and standardised using Log10(x+1) and division by the maximum value. Two groupings; 'northern' harbour sites 3, 27, 6 (except site 14); 'southern' harbour sites 24, 16, 17, 12, 8, 10 ,9 (except site 19)

Table 1.12 Monte-Carlo significance tests of zooplankton environmental variables in ordination space.. There were no significant correlations

Environmental variable	Correlation coefficient	Number of Monte Carlo randomizations with correlation coefficients less than the original data
Secchi disk	0.3411	35
Dissolved oxygen	0.5248	71
pH	0.5756	84
Water temperature	0.6149	92
Electrical conductivity	0.5931	88
Depth	0.4555	72
Air temperature	0.4310	56

Rotifera

Representatives of this phylum were restricted to five sites close to shores around the harbour. The greatest abundances occurred in the southern half of the harbour, but nowhere in the harbour were rotifers found in high numbers. Soft-bodied forms appear to be associated with freshwater inlets.

Testate amoebae

The distribution of the protists was similar to the rotifers with the exception of *Cyclopyxis* sp., which was observed at the fish farm site. Numbers recorded were very low.

Nematoda

Nematode were found at low abundances at six sites in the southern section of the harbour. No nematodes were found at Farm Cove.

1.5 Discussion

1.5.1 Benthic macroinvertebrates

The benthic infauna recorded in this survey were less numerous and diverse than might have been expected in an estuary the size of Macquarie Harbour. The taxa recorded (44 families, 46 genera and 49 species) were generally common to estuaries across southern and south-eastern Australia. The possible exception was the polychaete *Leitoscoloplos kerguelensis*, which is a sub-antarctic species. While records of this species on the Australian mainland exist, it is likely that these records are erroneous (R Wilson, pers comm).

As there had been no prior investigations of benthic fauna in Macquarie Harbour, it is difficult to asses the extent to which previous mining operations or natural conditions have affected population assemblages. However, based on the limited knowledge of the physical environment of Macquarie Harbour and comparisons with studies conducted on other south-east Australian estuaries, it is possible that 100 to 200 species of benthic invertebrates might be expected in the harbour, excluding potential mining impacts. This estimate is based on values recorded in the Gippsland Lakes in Victoria (Poore 1982), and in Bathurst Harbour, Tasmania (Edgar 1991a). Truly estuarine environments such as these have a lower benthic species diversity than predominantly marine habitats due to varying salinity levels. Poore (1982) recorded 90 species of benthic invertebrates from the Gippsland Lakes, whilst Edgar (1991a) recorded a total of 340 species on artificial substrates (rope fibres) from Bathurst Harbour but with most species being found at Port Davey where the freshwater influence is greatly diminished. As few as 29 species occurred at Dixon Island in Bathurst Harbour itself.

Edgar revealed discrete assemblages in the Bathurst Harbour and Port Davey system with an increase in species richness with increasing proximity to the ocean.

In comparison to estuarine habitats, the fauna of marine nearshore zones in south-eastern Australia is very diverse. For example, Poore et al (1975) recorded 713 species from 86 sites in Port Phillip Bay, Victoria; Morgan (1986) recorded 390 species from Corner Inlet, Victoria, and Coleman et al (1978) recorded 572 species from Western Port Bay, Victoria.

Bathurst Harbour shares many similarities with Macquarie Harbour, the most significant of which are a pronounced halocline and location on Tasmania's west coast. Unlike Macquarie Harbour, however, Bathurst Harbour is relatively unimpacted and may be considered as a reference site against which the environmental health of Macquarie Harbour can be compared.

Unfortunately, Edgar (1991a) chose not to sample the Bathurst Harbour benthos, arguing that it would be closely related to substratum type and therefore too variable to discern '*whether a particular species occurred in a sample because of habitat requirements or because of the hydrological environment*'. The artificial habitats he deployed selectively sample mobile epifauna and do not provide habitat for benthic infauna. In Port Phillip Bay, the most important species in terms of biomass and abundance are all burrowing infauna, eg the bivalves *Notospisula trigonella* and *Theora lubrica*, the sea urchin *Echinocardium cordatum*, and the decapod *Neocallichirus limosa* (Wilson et al 1993). Such species cannot be collected using Edgar's method.

Edgar (1991a) presents a list of the 73 most abundant taxa on rope fibre habitats in Bathurst Harbour. Several of these taxa (either species or genus) were also recorded by Morgan (1986) at Corner Inlet near Wilsons Promontory, Victoria. These were the amphipods *Paradexamine, Mallacoota diemenensis,* and *Aora*; the polychaetes *Platynereis dumerilli antipoda, Neanthes vaalii, Phyllodoce*, and *Pionsyllis*; the crab *Halicarcinus ovatus*; and the shrimp *Macrobrachium*. Although none of these taxa were collected in the present study, many of them might be expected to occur in Macquarie Harbour given its intermediate location between Bathurst Harbour and Corner Inlet.

Invertebrate species actually recorded from Macquarie Harbour include the Pacific oyster, *Crassostrea gigas*, which de Blas (1994) reported as relatively abundant around Macquarie Heads, and blue mussel *Mytilus edulis*, which was recorded from the outer channel entrance. De Blas also reported a personal communication from the former Warden of Strahan that encrusting mussels were common on wharves at Regatta Point in the 1940s and that crabs were common scavengers on fish nets. However mussels are now apparently absent and crabs uncommon (de Blas 1994). In their search for specimens for tissue heavy metal analysis, the authors of the 1975 Department of Environment report on Macquarie Harbour (Department of the Environment 1975) were only able to locate shellfish between the harbour mouth and Liberty Point with the exception of a few mussels (*Modiolus pulex*) near Sarah Island. The sandy sediments near the harbour mouth reportedly contained the cockles, *Venerupis diemenensis* and *Donacilla erycinaea*. Other taxa collected by the University of Tasmania (cited in Department of the Environment 1975) were all intertidal molluscs. These were the serpent-headed chiton *Sypharochiton pellis-serpentis*, gold-mouthed conniwink *Bembicium auratum*, common mud oyster *Ostrea angasi*, and smooth-mouthed triangle *Anapella cycladea*. None of these taxa were collected in the present study, although this region of the harbour was not surveyed. The total number of invertebrate species recorded for the above and current survey is therefore 41.

In a study of the Port Phillip Bay benthic fauna, Poore and Rainer (1979) identified several species groupings mainly related to sediment particle size. In particular, there was a diverse fauna associated with sandy sediments in the south-east region of the bay where tidal currents were strongest. This was the region of greatest exchange with Bass Strait waters and the fauna is thought to be similar to the Bass Strait fauna. In the central region of the bay, muddy sediments had a lower diversity (although still relatively high). A similar pattern of high diversity in sandy sediments and lower in central muddy areas is likely to occur in Macquarie Harbour (excluding possible impacts of mining sediment contamination). Anecdotal evidence from local divers supports this hypothesis (R Morrison, pers comm). The patterns of benthic diversity in Macquarie Harbour may also be affected by the strong vertical and longitudinal salinity gradients. In particular, the low oxygen concentration of the middle layer of halocline may affect benthic invertebrate communities where this layer comes into contact with the harbour bottom.

1.5.2 Fish populations

Two previous studies have been conducted on fish populations in Macquarie Harbour: de Blas (1994), which reported on trace metal levels in tissues of some commercial fish species, and a preliminary fisheries survey conducted jointly by the Inland Fisheries Commission and the Sea Fisheries Division of the Department of Primary Industries (Fulton & Schaap 1989).

De Blas (1994) collected 4 species of fin-fish; brown trout *Salmo trutta*, red cod *Pseudophycis bachus*, greenback flounder *Rhombosolea taparina*, and white-spotted dogfish *Squalus acanthias*. Sand flathead (probably *Platycephalus bassensis*) also occurred in Macquarie Harbour, but were too difficult to catch in sufficient numbers for analysis. Other species collected by de Blas were the skate *Raja* sp., and rock ling *Genypterus tigerinus*.

Fulton and Schaap (1989) recorded the following species in addition to those found by de Blas; rainbow trout *Oncorhynchus mykiss*, Atlantic salmon *Salmo salar*, morwong *Nemadactylus macropterus*, jack mackerel *Trachurus declivis* and yellow-eyed mullet *Aldrichetta forsteri*. It was reported that there appeared to be two populations of brown trout in Macquarie Harbour, a resident darker and broad-bodied morphotype and a silvery coloured (possibly sea-running) morphotype.

An additional 12 species of fish were captured in Macquarie Harbour in the present survey. The increase in the number of previously uncaptured species is most likely a result of a change in sampling gear. The aforementioned surveys utilised only gill nets whilst the present survey used both gill and seine nets. Most of the new species, with the exception of longsnout flounder, blue grenadier and short-finned eels, are small bodied fish that would elude capture in gill nets. A list of all fish species recorded in Macquarie Harbour is provided in Appendix B.

The distribution of fish in Macquarie Harbour appears to be affected by salinity levels. During the present survey inflows from the Gordon River created a surface water salinity gradient from the south-eastern to the north-western end of the harbour, a common occurrence during winter (Koehnken 1996). The fish fauna in the north-western end of the harbour was almost exclusively marine; the exceptions were euryhaline species such as the smallmouth hardyhead. The fish fauna in the south-western end of the harbour was dominated by the diadromous Tasmanian smelt. Although little is known about the biology of this species, mature adults are known to migrate from the sea to freshwater to breed during spring and summer (McDowall 1980). The abundance of Tasmanian smelt in the less saline part of the harbour may have been a consequence of this spawning migration.

The occurrence of juvenile blue grenadier in Macquarie Harbour is significant in that this species supports a major fishery in Australia and New Zealand (Gunn et al 1988). The main blue grenadier fishing grounds in Australia are located near the spawning area off western Tasmania (Kailola et al 1993). Gunn et al (1988) found spawning to occur in the vicinity of Cape Sorell and that it is likely that this is the only spawning area for the Australian population. Juvenile blue grenadier are found in sheltered bays and harbours in western and south-western Tasmania and may penetrate freshwater (Last et al 1983 and Gomon et al 1994). As such Macquarie Harbour is likely to be an important nursery ground for this species.

Macquarie Harbour may also be one of only two locations where the Maugean skate (*Raja* sp.) occurs. Previously only captured in Bathurst Harbour, this marine species has not been captured in trawl surveys off the coast of Tasmania unlike most other Australian skates that also occur in shallow water (Edgar 1991b). The capture and identification of this skate in Macquarie Harbour confirms previous reports of an undescribed species of skate that may previously have been misidentified as the thornback skate *Raja lemprieri* (Edgar 1991b).

The capture of low numbers of species such as Tasmanian whitebait and the common jollytail may not provide an accurate indication of the abundance of these species in Macquarie Harbour. The fact that only a very small proportion of the total area of Macquarie Harbour was sampled during the present survey and that sampling occurred at the end of August, possibly before the spring migrations of these diadromous species, means that catch rates may have been lower than expected. Juveniles of other diadromous galaxiids such as spotted mountain trout *Galaxias truttaceus* and climbing galaxias *Galaxias brevipinnis* may also be present in the harbour during spring.

Only two other Australian estuaries have a similar hydrological profile to Macquarie Harbour, these being Bathurst Harbour (south-western Tasmania) and the Huon River estuary (southern Tasmania). The species composition and distribution of fishes in Bathurst Harbour, a relatively unimpacted environment, was investigated by seine and gill netting in October 1988 and July 1989 (Edgar 1991b). A total of 90 fish species have been recorded in the Port Davey/Bathurst Harbour region (Edgar 1991b). To date only 24 fish species have been recorded in Macquarie Harbour, most of these species also being found in Bathurst Harbour. Edgar (1991b) suggested that compared to other large estuaries the fish fauna of the Pt Davey/Bathurst Harbour region was relatively depauperate, possibly as a consequence of its southern location. In comparison, Macquarie Harbour is even less diverse in fish species, though more intensive studies would be necessary to confirm this. Future studies of the fish fauna of Macquarie Harbour are necessary to survey the deep water areas in the middle of the harbour and near shore areas where seagrass may be present during the summer months.

As total copper concentrations in the harbour waters are greater than those recommended in the ANZECC Guidelines for the Protection of Aquatic Ecosystems (Koehnken 1996) it is possible that this metal is either directly or indirectly affecting the biology of the fish fauna.

1.5.3 Seagrass and macroalgal communities

Seagrasses were difficult to locate during the survey with only a few senesced leaf blades of *Zostera muelleri* found at Yellow Bluff and Swan Basin. According to local information seagrass is present on the sand flats in Kelly Channel for the summer months with peak abundances corresponding to maximum daylight hours. No *Heterozostera tasmanica* or *Z. muelleri sensu strictu* were observed in the harbour or washed up as drift as was described by Rees (1993).

No macroalgae was observed in Farm Cove and Kelly Basin, however large mats of the stonewort *Nitella* sp. were found up to 10 m from the shoreline. *Nitella* sp. generally thrives under mildly acidic conditions (Sainty & Jacobs 1981) and may be benefiting from acid drainage from past mining operations in the Farm Cove and Kelly Basin catchment.

Small tufts of filamentous brown algae *Ectocarpus fasciculatus* were collected from the fish farm nets near Liberty Point. The growth at this time of year was slow, although during the summer months the nets require regular cleaning (R Morrison, pers comm).

No aquatic plant life was observed at Pine Cove except for *Macrocystis augustifolia* washed up as drift along with large amounts of human litter.

No data on Macquarie Harbour benthic algal communities could be located prior to this study. The most relevant work on which to base a comparrison with results obtained fot Macquarie Harbour is that of Edgar (1991a) in Bathurst Harbour. According to Edgar (1991a) at Sarah Island in Bathurst Harbour which is under ocean influence '*a highly diverse sessile community of over 50 species of macroalgae, sponges, hydroids, and anthozoans occurs, whereas at Bathurst Channel* [which is under estuarine influence], *a maximum of four species of macroalgae, Ecklonia radiata,* *Ulva* sp., *Hormosira banksii, and Carpoglossum confluens and a few sessile animals are present*'. Other macroalgae that may be present in Macquarie Harbour include *Sargassum, Macrocystis,* and *Caulerpa.*

Hamdorf and Kirkman (1995), in an issues paper on the status of Australian seagrass communities state that *Heterozostera tasmanica* grows around Tasmania, whilst *Posidonia australis* occurs along the north coast and *Amphibolus antarctica* occurs along the east coast.

According to Poore (1982) seagrass communities in the Gippsland Lakes are confined to relatively saline areas and if this trend holds true for Macquarie Harbour, then little seagrass should occur near major freshwater inputs such as the Gordon River and King River.

1.5.4 Phytoplankton

The mixture of fresh to marine phytoplankton species found in Macquarie Harbour is indicative of its estuarine nature. The abundance of freshwater taxa in most samples reflects the primarily freshwater layer occupying the euphotic zone, particularly close to shore, and in the southern part of the harbour. The three-layer water system in Macquarie Harbour has been described in previous studies (Carpenter et al 1991; Creswell et al 1989; Koehnken 1996). Phytoplankton growth and productivity is influenced by a range of physico-chemical factors, predominant among which are light, temperature, and organic and inorganic nutrient levels. The low zooplankton species diversity and abundance suggests grazing has limited influence in determining the phytoplankton populations in Macquarie Harbour.

The waters of Macquarie Harbour are coloured an intense brown from the high concentration of humic substances entering the harbour via the Gordon River and runoff from the surrounding shore. Dinoflagellate species characterise the sites nearest the Gordon River, while diatoms characterise the sites closest to the mouth of the harbour. Similarly, in a study of plankton in Bathurst Harbour (Edgar and Creswell 1991), dinoflagellate numbers were found to decline in importance from Bathurst Harbour towards the more marine influenced Port Davey, while diatoms showed the opposite trend.

During the winter sampling event at Bathurst Harbour, Edgar and Creswell (1991) only recorded the diatom species *Nitzschia* sp. and *Cheatoceros*, while 38 phytoplankton species were recorded in the present study. This difference may have been related to counting methodology as no time limit was placed on identifying samples during this study. The diatom *Cheatoceros* sp. was not found as a component of the Macquarie Harbour flora which may be attributed to the higher salinities at the mouth of Bathhurst Harbour. Generally, coastal phytoplankton communities contain a high proportion of diatoms with dinoflagellates beginning to dominate the flora as nutrient levels fall with increasing distance from the land (Dring 1982; Hallegraeff 1981). In Macquarie and Bathurst Harbours, diatoms assemblages may be responding to the increased influence of marine waters, although as the colour of water in Macquarie Harbour is a significant factor in phytoplankton distribution, humic substances and their effect on water chemistry may also influence phytoplankton growth and productivity.

Temperature affects the rate of phytoplankton metabolic processes and often determines the rate at which species can grow, although in light limited systems temperature has been found to have little effect on photosynthesis and growth (Soeder & Stengel 1974). Seasonality of phytoplankton has been recorded in Bathurst Harbour, where the lowest species diversity and abundance is recorded in winter (Edgar & Creswell 1991). This may have been due to shorter day length in winter, lower light levels and/or reduced nutrient availability. In coastal waters there are distinct spring and autumn diatom maxima generally associated with oceanic currents, and the type of nutrient supply largely determines the kind and extent of diatom dominance (Patrick & Reimer 1966). To determine if the recorded winter Macquarie Harbour diatom flora represents the lower extreme of species diversity and abundance requires further investigation.

The macro-nutrients required for the growth of phytoplankton are inorganic carbon, inorganic phosphorus and inorganic nitrogen, whilst micro-nutrients include various metals (iron, manganese, copper, zinc and molybdenum), and bromine, iodine and a number of vitamins (Dring 1982). Diatoms also have an additional macro-nutrient requirement for silica. The absolute requirements for these compounds is extremely low and a number of the above metals, particularly zinc and copper, are toxic to phytoplankton at elevated levels (Fisher 1979). Elevated concentrations of heavy metals have been found in waters throughout Macquarie Harbour (Carpenter et al 1991), and although zinc was well within the ANZECC guidelines for marine and freshwaters, the total concentration of copper measured at some sites (up to 11 μg/L) exceeded ANZECC guidelines (2.0 to 5.0 for freshwater and 5.0 μg/L for marine waters) (ANZECC 1992). Copper levels that are usually toxic to most algae may be tolerated by diatoms. For example, *Nitzschia palea*, *Synedra ulna* and *Achnanthes affinis* can tolerate copper concentrations of up to 2.1 μg/L (Patrick & Reimer 1966).

As the toxicity of heavy metals to marine organisms is related to the free metal ion concentration, the high humic substance loading in Macquarie Harbour may be expected to form complexes with the heavy metals and reduce the toxicity of these metals. Carpenter et al (1991) found that the total copper concentrations are approximately twice the copper complexing capacity, suggesting little or no effective buffering of copper toxicity in the harbour. However, copper complexing capacity does increase with decreasing salinity. Coupled with the large influx of freshwater, the phytoplankton that inhabit the more freshwater euphotic zone may have a competitive advantage over brackish to marine phytoplankton species in Macquarie Harbour.

1.5.5 Benthic diatoms

The Macquarie Harbour diatom assemblages are dominated to varying degrees by brackish-marine taxa. However, freshwater taxa are present in significant abundance in most samples, their abundance presumably reflecting the varying influence of freshwater input. Most frustules are littoral benthic forms (some of which may be facultatively planktonic) with *Cyclotella hakanssoniae* the most common planktonic species, although this species was not recorded in the phytoplankton water column samples.

The sediment type is a major factor influencing the sediment diatom record. Kelly Basin is indicative of a depositional area and hence favourable for diatom frustule preservation. The higher sand content and sometimes high energy water movement at the fish farm site suggests this is an erosional zone and less favourable for frustule preservation. The absence of diatom valves at the King River site may be attributed to a poor preservation environment and/or an absence of living material. However, it is unlikely that poor preservation is the sole cause as there were no valves identified in surface sediments.

Fish farm (cluster groups 1 and 2)

Examined in isolation, the diatom stratigraphy at the fish farm site near Liberty Point suggests that some degree of change has occurred in the diatom community in recent times. Unfortunately, without absolute or relative dating it is difficult to suggest what period is covered by the 16 cm profile. The two basal core samples are dominated by the brackish-marine taxa *Cocconeis pelta* and *Navicula regularis* along with the fresh and fresh-brackish taxa *Cocconeis af. neothumensis* and *Achnanthes delicatula*. From 12 cm to the surface the relative abundance of *C. neothumensis* and *A. delicatula* is reduced. Examination of the diatom concentrations in the core revealed that this change is accompanied by a reduction in overall diatom concentrations and may, therefore, reflect reduced transport of freshwater diatoms to this site. Interestingly, the remaining surface samples, site 3B, and C, and remaining core sample D are somewhat similar to the two basal core samples, having higher diatom concentrations and a higher proportion of the aforementioned fresh and fresh-brackish taxa. These samples are consequently grouped with the two basal core samples in group 2.

It is reasonable to suggest that a complex depositional environment exists at this site. The differences between the site 3D surface sample and the remaining surface samples (sites 3A, B and D) may be explained by fairly rapid and localised sedimentation at site 3D. This is supported by the low diatom concentrations found in the group 1 samples, all of which where from site 3D.

Kelly Basin (cluster groups 3 to 5)

The differences between the surface sample and samples at depth are less obvious at Kelly Basin, although it is possible to distinguish two groups. The first of these groups (group 3) consists of the surface sediment samples while the second two groups (4 and 5) consisted of the core samples. Interestingly, the core samples from 6 to 10 cm clustered separately from those of 0 to 5 cm reflecting a change in the composition of depositing diatom species at some time in the recent past. The exact date of this change cannot be determined at present.

Generally, the changes in diatom frustules with depth at Kelly Basin are minor and, in effect, serve to highlight the changes evident at the fish farm site. The relatively high abundance of the planktonic diatom *Cyclotella hakanssoniae* provides further evidence that this site represents a more stable depositional environment than that at the fish farm. However, the benthic diatoms (brackish) which characterise the fish farm and Kelly Basin differ markedly, the fish farm site being dominated by *Cocconeis pelta, C. peltoides* and *Navicula regularis*, and Kelly Basin by *Achnanthes reversa* and *Cocconeis pediculus*. These differences most probably reflect the fish farm site's proximity to the harbour entrance whereas Kelly Basin is furthermost removed from the marine influence. It is somewhat surprising, therefore, that the relative abundances of fresh, fresh-brackish and brackish-marine are little different between the sites (group 1 samples notwithstanding).

Three factors may have contributed to the similarity between groups. Firstly, the broad groupings of fresh, fresh-brackish and brackish-marine may not have sufficient resolution to make differences apparent. It is apparent that the various taxa which comprise the fresh and fresh-brackish groupings at Kelly Basin and the fish farm do differ. *Cocconeis af. neothumensis*, *Achnanthes holsatica* and *Achnanthes delicatula* make up the bulk of the fresh and fresh-brackish diatoms at the fish farm, while *Cocconeis placentula*, *Diatoma balfouriana*, *Achnanthes delicatula* and *Achnanthes ploenensis v. gessneri* fulfil this role at Kelly Basin. Secondly, there may be some doubt as to the assigning of some taxa to the various groups, in particular, two taxa common in the surface samples at the fish farm, *Cocconeis af. neothumensis* and *Navicula af. halophila* (small form). In the case of C. *neothumensis*, its inclusion in the "fresh" grouping was based on the ecology of the taxon with which it displays affinity. This may or may not be valid. *N. halophila* (small form) was also included as a freshwater taxon and shares affinity with *N. halophila*, itself a brackish water diatom. Both taxa could be included as "unknown" in regard to salinity tolerance. Thirdly, the freshwater influence from rivers, streams and rainfall, obvious throughout the harbour from the phytoplankton results, may also affect the benthic diatom communities.

1.5.6 Zooplankton

Zooplankton are an important component of any aquatic community. They hold a pivotal position in the food chain, serving as prey for fish and macroinvertebrates and as top-down controllers of the phytoplankton community (Turner 1994). In turn, zooplankton distribution and abundance is affected by that of the phytoplankton and organisms higher in the food chain, and by the physical and chemical characteristics of the aquatic environment. In a study of the diversity and abundance of zooplankton communities in Bathurst Harbour (Edgar & Cresswell 1991), the lowest zooplankton abundances were recorded in winter. As the present study was conducted at the end of winter, the results should be considered to represent the lower extreme of species diversity and abundance within Macquarie Harbour. In addition, the mixing conditions in estuaries creates a high stress zone and species diversity in such a zone can be expected to be low (Arthur 1975).

Nauplii represent the youngest active developmental stage of copepods. As such they are probably more sensitive to environmental fluctuations than at any other stage of development (Faber, 1966). In Macquarie Harbour copepod nauplii were the numerically dominant zooplankton taxon and the only group present at every sampling site. Nauplii were also found to be the dominant taxon in Bathurst Harbour in August/September (Edgar & Cresswell 1991). The low numbers of mature copepods recorded in this study may have been due to seasonal effects and possibly sampling inefficiencies, where the fine mesh size used may have set up a pressure wave at the mouth of the net (Turner 1994) which would have allowed larger copepods with stronger swimming abilities to escape capture.

The most interesting result of the zooplankton survey was the presence of the calanoid *Sulcanus conflictus*. This monotypic endemic species was first described by Nicholls (1945) from a sample taken at the mouth of the Georges River, NSW, and later from the Swan River estuary, WA. As its name suggests, it is an important constituent of the 'conflict' zone where river meets sea, and is considered a euryhaline species (Nicholls 1945). In NSW and WA the species tends to be the dominant zooplankton at the time of year when it first appears. In this survey it was usually the second most abundant taxon after copepod nauplii and was most abundant at Farm Cove. *S. conflictus* was not recorded in the northern half of the harbour, possibly reflecting adverse physico-chemical conditions.

In both WA and NSW *S. conflictus* was associated with species of *Gladioferens*, another euryhaline calanoid copepod (Bayly 1994). *S. conflictus* was not recorded in a survey of Bathurst Harbour (Edgar & Cresswell 1991), where *Gladioferens* was recorded (the latter was not recorded in Macquarie Harbour). Nyan Taw and Ritz (1979) recorded in the upper reaches of the Derwent Estuary, the copepods *Gladioferens spinosus, Gladioferens pectinatus,* and *S. conflictus.* A possible explanation for the absence of *Gladioferens* in Macquarie Harbour may be diel vertical migration. Hays et al (1994) suggested that most large copepods move to lower levels in the water column during the day and ascend to nearer the surface at night.

The collection of the freshwater species *Calamoecia ampulla* at site 16 (Sarah Island) indicates that the freshwater surface layer in this part of the harbour is extensive and probably persists for much of the year.

Most members of the Harpacticoida are benthic, although there are a few marine planktonic forms including *Microsetella* sp., while *Euterpina* sp. are neritic (Raymont 1983). In this study *Microsetella* sp. was found at sites further from the shore than was *Euterpina* sp. The distribution of harpacticoids generally coincided with that of *S. conflictus*, although the harpacticoids identified in this study were marine genera (Watson & Chaloupka 1982).

The only cyclopoid genus identified was *Oithona* sp., a carnivorous marine copepod (Turner 1994). This species was restricted to sites 2 (Yellow Bluff) and 3 (Kelly Channel), close to the harbour mouth. Edgar and Cresswell (1991) found in their study of Bathurst Harbour that the small copepod *Oithona australis* prevailed in February and May.

The freshwater cladocera *Daphnia* sp. and *Bosmina meridionalis* were present at sites across the harbour, although not generally near river outlets. It is possible that these genera have some facility for surviving in estuarine waters.

Rotifers are confined to shore sites within the harbour, suggesting a preference for the shallower waters of these regions or a stronger freshwater influence at some sites. While most members of this phylum are freshwater species, there were also several brackish species but few fully marine species (Giere 1993).

Interestingly two common marine genera *Encentrum* and *Proales* (Giere 1993) were recorded in the southern half of the harbour but might have been expected in the region of the harbour mouth where salinities were higher. In general marine rotifer species are not well-recorded in Australian estuaries (Shiel 1995).

The other genera recorded during this study are all common freshwater genera. The soft bodied rotifers *Conochilus* and *Filinia* were found at site 19 closest to the mouth of King River. *Brachionus* sp. has a hard lorica which may have enabled it to survive closer to the harbour mouth. Other rotifers were found at sites 9 (Phillip Island) and 16 (Sarah Island), where a strong freshwater influence is suggested, especially at site 16 where freshwater cladocera were also present. The testate amoebae genera recorded in very low numbers at these sites are recognised to be predominantly freshwater organisms (Barnes 1982). As they mostly co-occurred with rotifers, this suggests that fauna at these sites were washed out from the rivers.

Although nematodes are regarded as a ubiquitous, mostly benthic phylum, in this study they were only found in the 'southern' half of the harbour. Their diversity can be influenced not only by sediment structure but also by salinity and pollution levels (Giere 1993). The absence of this taxon in the northern section of Macquarie Harbour may suggest an intolerance of the chemically polluted conditions associated with inflow from the King River (Department of the Environment 1975). Nematodes were not found at Farm Cove, where the highest numbers of *Sulcanus conflictus* and harpacticoids were recorded and nauplii numbers were also very high.

2 Heavy metal residues in Macquarie Harbour fish

2.1 Background

Much of the sediments and tailings transported from the Queen River have been deposited in a 250 ha delta at the mouth of the King River in Macquarie Harbour. Surface-water copper concentrations in Macquarie Harbour are typically <300 ppb although concentrations in excess of 1000 ppb have been detected (Koehnken 1996). Tailings derived from the Mount Lyell mine and the acid leachate generated by oxidisation of the tailings, contain copper, zinc, aluminium, iron, manganese and sulphate (McQuade et al 1995). Deposition of the tailings has led to elevated levels of copper, zinc, lead, iron and manganese in the bottom sediments in the harbour (Koehnken 1996).

Despite elevated metal concentrations in both the water column and sediments there is a paucity of information on the impact of heavy metals on the fish fauna of Macquarie Harbour or the possible effects of human consumption of these fish. De Blas (1994) assayed four species of fin-fish (brown trout, red cod, greenback flounder and white-spotted dogfish) and the Pacific oyster for cadmium, copper, mercury, lead and zinc. Of these metals, only mercury concentrations were higher than Australian Food Standards Code in some species. However, copper concentrations in the Pacific oysters far exceeded concentrations measured in oysters from the Derwent and Tamar Estuaries (de Blas 1994).

As part Project 13A of the MLRRDP Water Ecoscience has determined the trace metal concentrations in tissue of edible fish species. Analysis of metal concentrations was restricted to fish fillets as the primary objective of the study was to determine heavy metal concentrations in those parts of fish that are normally consumed by humans.

2.2 Methods

Fish for trace metal analysis were captured during the gill netting component of the Macquarie Harbour survey (see Section 1.4.2). Eight nets (78–127 mm mesh, 30–60 m long) were set overnight at five sites in Macquarie Harbour (figure 1.3): Neck Island (G1); Cosy Corner (G2); Table Head (G3); Double Cove (G4); and Kelly Basin (G5). Fish were identified, measured (mm) and weighed (g) prior to being scaled and filleted. Knives and filleting surfaces were washed with harbour water between processing each fish. Tissue samples were placed in individually labelled polythene bags, packed on ice at sea, frozen on return to shore and transported to the Australian Government Analytical Laboratories in Melbourne for determination of concentrations of copper, mercury, cadmium, lead, zinc and selenium. Determinations of fish tissue trace metal levels were conducted by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICPMS) according to recognised standard (NATA registered) methodologies.

Six species of fin-fish were analysed for trace metal concentrations, namely the short-finned eel *Anguilla australis*, brown trout *Salmo trutta*, Atlantic salmon *Salmo salar*, red cod *Pseudophycis bachus*, longsnout flounder *Ammotretis rostratus* and greenback flounder *Rhombosolea tapirina*. Edible shellfish were not considered for trace metal analyses as none could be found during the benthic macroinvertebrate survey.

2.3 Results

Tissue metal concentrations for individual fish collected at each site (table 2.1) and the mean tissue metal concentrations for each species (table 2.2) were generally below levels described by Australian Food Standards Code and Tasmanian regulations. The exception was for selenium in fish collected from four of the five sampling sites (mainly greenback flounder and red cod), which in many instances was above the recommended level of 1 mg/kg.

Table 2.1 Metal concentration in selected fish species. Concentrations have been tabulated from wetweights

Site	Species	Length (mm)	Weight (g)	Cadmium (mg/kg)	Copper (mg/kg)	Lead (mg/kg)	Mercury (mg/kg)	Selenium (mg/kg)	Zinc (mg/kg)
G1	Red cod	405	875	<0.01	0.24	0.013	0.44	1.3	3.9
	Longsnout flounder	260	225	<0.01	1.5	0.037	0.024	0.46	5.9
	Greenback flounder	310	350	<0.01	0.86	0.034	0.14	0.78	14
		270	200	<0.01	0.44	0.031	0.078	1.4	10
		270	200	<0.01	0.47	0.022	0.027	1.5	4.4
		265	200	<0.01	0.36	0.023	0.11	0.52	12
	Atlantic salmon	520	1650	<0.01	0.65	<0.01	0.039	0.3	3.6
G2	Red cod	320	500	<0.01	0.26	0.019	0.046	0.46	4.7
		272	250	<0.01	1	0.026	0.065	0.61	3.1
		395	825	<0.01	0.24	0.039	0.36	1.2	3
		347	600	<0.01	0.27	0.74	0.056	0.41	13
	Greenback flounder	205	100	<0.01	0.74	0.047	0.061	1.4	7.9
G3	Red cod	330	425	<0.01	0.19	0.022	0.12	0.7	2.7
	Greenback flounder	280	300	<0.01	0.16	0.01	0.026	1.6	10
		290	350	<0.01	0.11	0.017	0.17	1.5	3
		287	300	<0.01	0.097	0.019	0.12	0.84	9.7
		285	250	<0.01	0.33	0.015	0.084	0.6	5.4
		280	300	<0.01	0.3	0.015	0.2	1.2	8.2
	Brown trout	595	2100	<0.01	0.31	<0.01	0.68	0.64	3.4
G4	Red cod	370	550	<0.01	0.15	0.01	0.34	1.1	3.3
		385	775	<0.01	0.19	<0.01	0.34	0.92	2.1
		345	550	<0.01	0.18	0.013	0.54	0.89	3.1
G5	Brown trout	375	550	<0.01	0.42	<0.01	0.2	0.64	4.3
		350	450	<0.01	0.45	<0.01	0.7	0.82	4.6
	Short-finned eel	395	100	<0.01	0.3	0.019	0.37	0.74	8.2
		770	1150	<0.01	0.26	0.011	0.82	0.72	9.6

2.4 Discussion

In general the metal concentrations in the selected fish species were below recommended limits. The exceptions were one record for lead in red cod which was slightly above the acceptable levels listed in the Septmeber 1995 issue of the Australian Food Code (AFC), and for selenium concentrations which were in some instances above recommended levels, especially for red cod and greenback flounder. The other records for lead in red cod were much lower than the AFC recommended maximum levels. In addition, the method of sampling, analysis and reporting here differ from those recommended by the AFC. The AFC recommends taking a random subsample of several fish from a large collection and reporting the trace metal concentrations as an average value. With this method of reporting the lead levels in red cod would be well below the AFC recommended maximum concentrations.

Mammalian responses to selenium are variable. Selenium is present in air as a contaminant from fossil fuels and in domestic waste water arising from hair shampoos where it is used as a stabiliser. The most likely source of high selenium levels in Macquarie Harbour fish is via the food chain. Benthic invertebrate diversities are low in most of the harbour but nearshore samples collected in March 1996 (as part of the macroinvertebrate monitoring program recommended in Section 3) indicated areas of high invertebrate densities do occur. Most abundant taxa appeared to be filter-feeding mussels and polychaetes rather than deposit feeding species. In addition, most fish seine samples (Section 1) consisted of zoo-

Table 2.2 Summary of metal concentrations in selected fish species

Species	n		Length (mm)	Weight (g)	Copper (mg/kg)	Lead (mg/kg)	Mercury (mg/kg)	Selenium (mg/kg)	Zinc (mg/kg)
Red cod	9	Mean	352.0	594.4	0.3	0.099	0.256	0.84	4.32
		Std Err	14.0	67.2	0.1	0.08	0.062	0.11	1.11
		Min	272.0	250.0	0.2	0.01	0.046	0.41	2.1
		Max	405.0	875.0	1.0	0.74	0.54	1.3	13
Greenback flounder	10	Mean	274	255	0.39	0.023	0.102	1.13	8.46
		Std Err	9	25.22	0.08	0.0035	0.018	0.129	1.08
		Min	205	100	0.097	0.01	0.026	0.52	3
		Max	310	350	0.86	0.047	0.2	1.6	14
Brown trout	3	Mean	440	1033.33	0.39	<0.01	0.53	0.7	4.1
		Std Err	78	534.11	0.043	<0.01	0.16	0.06	0.36
		Min	350	450	0.31	<0.01	0.2	0.64	3.4
		Max	595	2100	0.45	<0.01	0.7	0.82	4.6
Short-finned eel	2	Mean	583	625	0.28	0.015	0.6	0.73	8.9
		Std Err	188	525	0.02	0.004	0.23	0.01	0.7
		Min	395	100	0.26	0.011	0.37	0.72	8.2
		Max	770	1150	0.3	0.019	0.82	0.74	9.6
Australian food code guidelines					10	0.5	0.5*	1.0	150

* Tasmanian Standards vary this to a maximum of 1.0 mg/kg

planktivorous fish. These observations indicate that most of the energy in the Macquarie Harbour food chain is derived from plankton in the water column. The two major energy pathways may be phytoplankton → zooplankton → small fish → large fish, and/or dissolved organic carbon (leached from terrestrial detritus) → heterotrophic bacteria → zooplankton → small fish → large fish. If selenium levels in the water column are relatively high then there is considerable scope for bioconcentration through the food chain.

According to the ANZECC (1992) Water Quality Guidelines, selenium exists in two states in the aquatic environment: selenium (IV), known as selenite (SeO_3^{2-}); and selenium (VI) known as selenate (SeO_4^{2-}). Most selenites are less water-soluble (and therefore less easily excreted by animals) than selenates and selenium (IV) is generally two to four times as toxic as selenium (VI) to freshwater and marine fish and invertebrates. The high selenium levels in Macquarie Harbour fish may therefore be due to selenium (IV).

At present it is not known what the source of selenium is in Macquarie Harbour and what the levels are in the sediments and water column. It is almost certainly derived from a mineral source, but whether this is natural weathering of rocks, or historical pollution from the Mount Lyell mine via the King River is unclear at present.

As these results were collected from a small sample size, some further investigations of selenium levels in local fish species may be required to better determine the possible risk to public health resulting from fish consumption.

3 Recommendations for future biological monitoring of Macquarie Harbour

3.1 Macquarie Harbour biological monitoring program

3.1.1 Background

As part of the MLRRDP an ongoing monitoring program aimed at assessing the ecological health of Macquarie Harbour is planned. The objective of such a monitoring program will be to establish the present status of the particular ecological community chosen for monitoring, to enable the detection of changes to this community following the implementation of remediation measures on the King and Queen Rivers and mine lease site.

For the purposes of developing a biological monitoring program, the Macquarie Harbour ecosystem can be divided into five component communities (with some overlap), namely:

- zooplankton;
- phytoplankton;
- fish;
- seagrass; and
- benthic macroinvertebrates

Although all these components are important parts of the Macquarie Harbour ecosystem, logistic and financial constraints decree that only one such community can be sampled as part of a monitoring program. Since the major aim of the monitoring program is to detect a gradual recovery in ecosystem health from the impact of mining residues in the harbour sediments and waters, the community chosen needs to meet the following criteria:

- Life histories of constituent taxa need to be in the order of several months to a few years so that they do not exhibit marked short term fluctuations in response to seasonal climatic changes;
- The taxa need to be reasonably persistent in a spatial sense (ie don't undergo great seasonal fluctuations in distribution and abundance due to factors such as migration);
- The taxa need to be relatively sedentary, rather than migratory, so that it is clear they can tolerate conditions at the sampling site;
- The taxa need to be in close association with potentially contaminated sediments on the bottom of the harbour rather than isolated from sediments, high in the water column;
- The costs of sampling the community and the identification of the constituent taxa need to be feasibly born by a monitoring agency and need to be competitive with other types of environmental monitoring; and
- The community chosen needs to be an important part of the Macquarie Harbour ecosystem with extensive links to other components so that observed changes will reflect changes in the health of the whole of harbour.

Benthic macroinvertebrate communities fit these criteria more closely than the other ecosystem components listed above. As a result, *benthic macroinvertebrates are the most commonly used ecosystem components in most marine impact assessment and monitoring programs and are the recommended community for the Macquarie Harbour biological monitoring program.*

3.1.2 Program design

In order to develop a cost-effective monitoring program, with sufficient sensitivity or power to detect a significant change in benthic macroinvertebrate communities, consideration must be given to several aspects of the sampling program. These factors are described below.

Statistical background

In statistical terminology, the biological variable to be monitored in the monitoring program, is known as the *dependent variable*. This may be total abundance, number of species, abundance of individual species, or other related measures.

In an impact detection or assessment study, the impact and non-impact zones are classed as two categories of an *independent variable* and are equivalent to treatments in an experiment. Sites to be sampled in such a study may be considered replicates, since they reflect the conditions of the zones. Individual measurements or collections made at each site are commonly termed samples.

In designing a monitoring program we need to be sure that the chosen design is sensitive enough to detect changes of a given level in the effects we wish to monitor. A measure of the sensitivity of the analysis to detect a significant effect if one exists is its *statistical power*. In any statistical test, a null hypothesis (H_0) of no significant effect is either accepted or rejected with a chosen level of probability of making an incorrect choice. This probability of making an incorrect choice is known as Type I error, also known as α (table 3.1), and the conventional level chosen is 0.05. This indicates that if there is less than a 5% chance we could have obtained that value when the null hypothesis is correct, we reject the null hypothesis.

Table 3.1 Summary table of statistical conclusions

	Statistical Conclusion	
Actual Situation	*Reject H_0*	*Retain H_0*
Impact	**Correct Decision** Impact exists and was detected	**Type II error** Failure to detect an impact
No Impact	**Type I error** False Alarm	**Correct Decision** No impact and none detected

In a conventional monitoring and impact design, Type II errors (β), represent the likelihood that we have failed to detect an impact when one truly exists. Therefore, 1 - β, represents our confidence in our conclusion that there was no impact because there truly wasn't one. Type I and Type II errors are inversely related and many workers opt for a power of 80% (ie β = 0.20) and α of 5% giving a ratio of β/α of 4:1.

The general form of the relationship between power and other key statistical parameters is:

$$\text{Power}(1-\beta) \propto \frac{\text{ES}\sqrt{n}}{\sigma}$$

where ES: the effect size (larger changes being easier to detect than smaller, more subtle, changes); n: the sample size (increasing sample size makes an analysis more sensitive - with reference to a monitoring design this usually mean more sites and sampling times); and σ: the level of background variation - the greater the background level of variation, the more difficult it will be to detect differences between treatments.

For any monitoring program, decisions need to be made on all these parameters.

The Macquarie Harbour monitoring program needs to cover both spatial and temporal changes in community structure. For the purpose of constructing an appropriate statistical design we divided the harbour up into three zones of increasing distance from the mouth of the King River and, therefore, presumed decreasing levels of impact from mining residues. Each of these zones constitutes a treatment in a one-factor analysis of variance (table 3.2). For a design with collections of single samples at a number of sites in these zones, the sites are replicates. If multiple samples are taken at each site, then the design becomes a one-factor nested analysis of variance with sites nested within treatments, and samples nested within sites (table 3.3).

Table 3.2 Analysis of variance table for a single factor design

Source of Variation	SS	DF	MS	F
Impact Zone	SSz	DFz = z - 1	SSz/DFz	MSz/MSe
Error	SSe	DFe = zn - z	SSe/DFe	
Total	SSt	DFt = zn - 1		

Table 3.3 Analysis of variance table for a two-level nested design

Source of Variation	SS	DF	MS	F
Impact Zone	SSz	DFz = z - 1	SSz/DFz	MSz/MSe
Sites within Zones	SSs	DFs = z(s - 1)	SSs/DFs	MSs/MSe
Error (samples within sites)	SSe	DFe = zs(n-1)	SSe/DFe	
Total	SSt	DFt = zsn - 1		

Note that in table 3.3, increasing the number of samples within sites does not change the power of the analysis to detect differences between zones. The degrees of freedom for that statistical test are determined solely by the number of zones. For this reason the single factor design in table 3.2 is recommended for the Macquarie Harbour monitoring program. In this design, costs will be decreased by minimising the number of samples at a site, and power increased by maximising the number of sites within a zone.

Variable selection

A number of dependent variables, such as total abundances, numbers of species, or abundances of individual species may be used in the monitoring program. However, these measures vary considerably in their sensitivity. For example, numbers of species per sample at a site, also known as species richness, can remain relatively constant in the face of great changes in the types and abundances of the species. Thus species richness is not considered a sensitive measure for impact monitoring and is not recommended as an appropriate dependent variable for the Macquarie Harbour monitoring program.

Many monitoring programs involve the recording of the abundances of one or more key species, or *indicator species*. Although this may lead to cost savings in that only one, or a small number, of species need be sampled and counted, potential problems are that the chosen species are unlikely to be sensitive to all types of impacts and may not be naturally distributed in all the desirable sampling locations. For these reasons, and given the very low densities of benthic invertebrates in Macquarie Harbour, monitoring of indicator species is not recommended.

The remaining parameter, total numbers of individuals (ie the total number of all individuals of all species in a sample) is sensitive to changes of abundances in more common or numerous species although not to changes in the identity of species. For measures that are sensitive to both species abundances and species identity, multivariate methods such as multidimensional scaling are the best available. However, at present there is no formal procedure for estimating the power of such analyses, and for this reason *it is recommended that numbers of individuals per sample be the parameter used for monitoring the effectiveness of the MLRRDP in Macquarie Harbour*. In addition, a monitoring program with sufficient statistical power to detect significant changes in total numbers of individuals is also likely to be sufficiently powerful to enable such changes to be detected with multivariate methods (especially as multivariate methods are likely to be more sensitive than univariate methods) should it be desirable to use these methods in the future.

The level of taxonomic discrimination has also been examined in recent marine benthic studies. For example, Warwick (1988a; 1988b) has found that impact designs using taxonomic levels higher than species (eg family, order, etc) have been sensitive enough to detect differences between zones of varying impact intensity. The main advantage of using higher order taxonomy is the substantial cost savings involved in not having to process samples to the species level. However, given the very low species richness and abundances of the Macquarie Harbour benthic invertebrate fauna, it is *recommended that samples be identified to the species level to provide a more detailed record of the potential recovery of the harbour*. If species richness in Macquarie Harbour is low due to mining impacts then it is likely that new species will colonise (or recolonise) the harbour if there is a gradual dissipation of benthic residues of copper (the most probable toxic residue). This recolonisation will only be clearly detected with species level identifications.

Site selection

The residues from mining activities appear to have settled throughout Macquarie Harbour (Department of the Environment 1975; Koehnken 1996) but there is a general trend of higher concentrations of heavy metals in sediments, particularly copper, near the mouth of the King River, and lower concentrations near the mouth of the Gordon River. Koehnken (1996) designated three categories of sediment copper concentrations in the harbour. These categories have been used to construct zones for biological monitoring (figure 3.1) as follows:

zone 1 >600 ppm copper;

zone 2 100 to 600 ppm copper south-eastern Macquarie Harbour

zone 3 100 to 600 ppm copper in the north-western tidal exchange

zone 4 <100 ppm copper

Zones 2 and 3 were considered separate zones, despite similar sediment copper concentrations, because zone 3 is likely to have coarser sediment characteristics due currents associated with its proximity to Macquarie Heads. The one sample collected from zone 3 also had over 200 individuals of a species of cirratulid polycheate. This abundance was an order of magnitude greater than any other species in any of the samples collected. This zone was subsequently excluded from further analyses.

Remediation measures at the Mount Lyell mine and in the Queen and King Rivers are likely to lead to a 60% decrease in the copper concentrations of water entering Macquarie Harbour from the King River (Dr L Koehnken, pers comm). Hydrodynamic studies (Koehnken 1996) have shown that King River water mixes with salt water entering the harbour through Macquarie Head and fresh surface waters from the Gordon River. This mixed water has a salinity approximately half that of sea water and tends to flow in a south-easterly fashion down the harbour. Due to its salinity, the water is also intermediate in density between seawater and freshwater and forms the middle layer of a halocline ranging between 3 to 10 metres. It is proposed that benthic invertebrate samples for the monitoring program be collected from this depth range. If invertebrate communities increase in abundance due to improvements in water quality, sampling in this depth zone should reflect such changes.

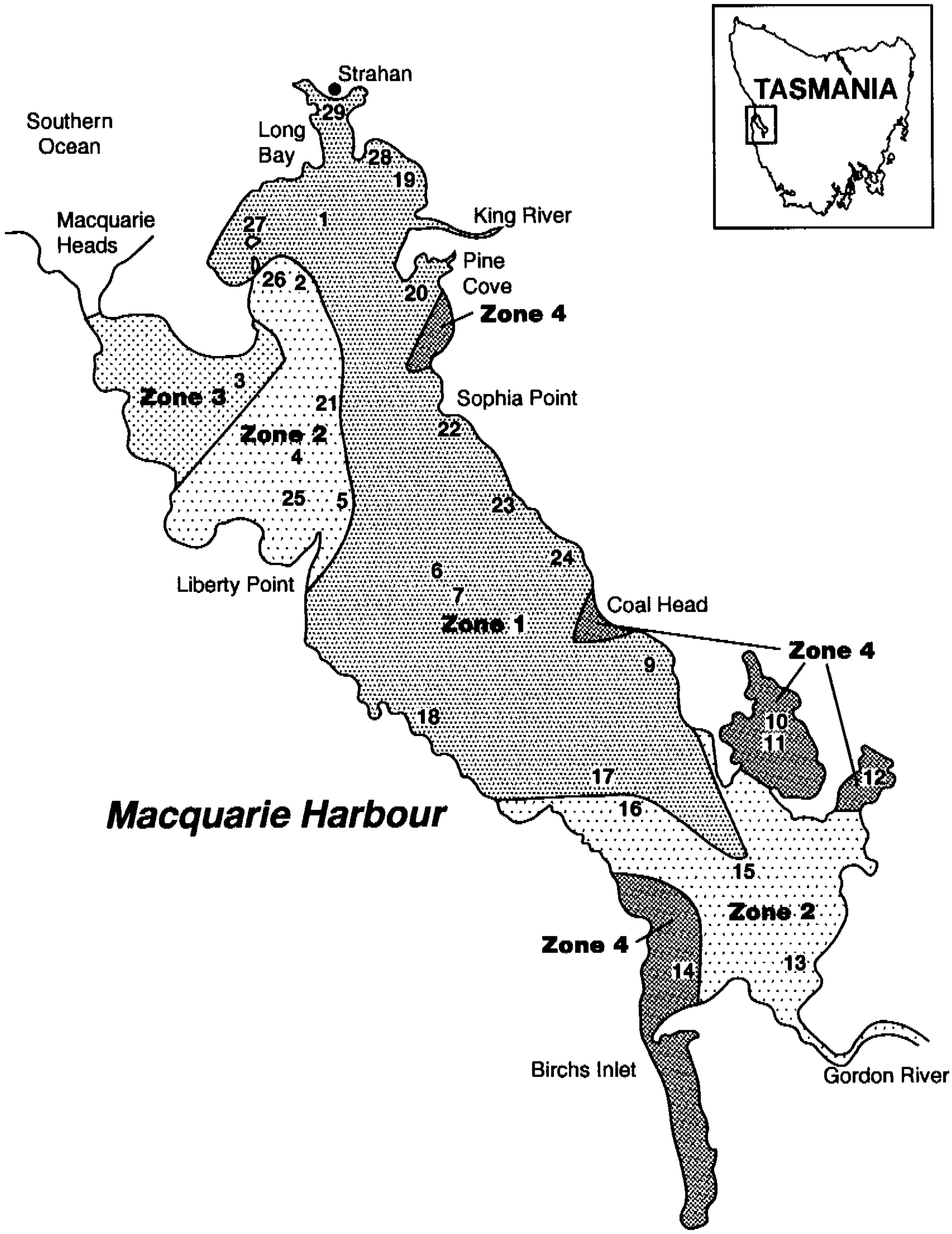

Figure 3.1 Pilot study sample sites in Macquarie Harbour and proposed impact zones for the future monitoring program (Zones are based on the sediment copper concentrations recorded in 1993 by Koehnken (1996))

Table 3.4 Means of numbers of individuals of benthic invertebrates per site for each zone

Zone	Mean no of individuals	No. of sites
1	1.14	14
2	6.00	9
4	9.40	5

Each of these zones was considered to be a treatment in a one-factor ANOVA, and sites sampled in each zone may be considered replicates (table 3.4).

The DESIGN module of the SYSTAT statistical software package was used to calculate the number of sites which need to be sampled per zone to achieve the chosen level of β for a one-factor analysis of variance. The module requires the standard deviation of the numbers of individuals across all sites, the number of zones (ie treatments), the means of each zone, and the chosen levels of α and β - in this case 0.05 and 0.20 respectively.

The data supplied by the pilot study indicated that the required sample size to detect an effect size of 80% difference in mean numbers of individuals between zones 1 and 2 (ie a large effect size), at $\alpha = 0.05$ and $\beta = 0.20$ (ie power = 0.80) was 13 (figure 3.2). This was also based on the assumption that if sediment copper levels in zone 1 drop to below 600 ppm, the benthic invertebrate communities will recolonise to a similar level of abundance and with a similar population variance to that found in zone 2.

Given the number of sites sampled in each of the three zones in the pilot study (table 3.4), an ANOVA would have sufficient power to detect differences between zones 1 and 2, and zones 1 & 4 (8 samples required), but not between zones 2 and 4 where about 60 samples would be required for a power of 0.80. Although increasing the number of sites per zone would allow differences in mean values between zones of 50% (ie ES, effect sizes) to be detected at a power of 0.80, such large sample sizes would be very expensive to process. In addition, as benthic invertebrate densities are likely to rise rather than decrease as potentially toxic sediments are gradually dispersed, the variance between samples is likely to decrease. Consequently, less samples may be required in the future to achieve a monitoring design of the same power. Alternatively, keeping the sample size constant, effect sizes less than 75% may be detectable.

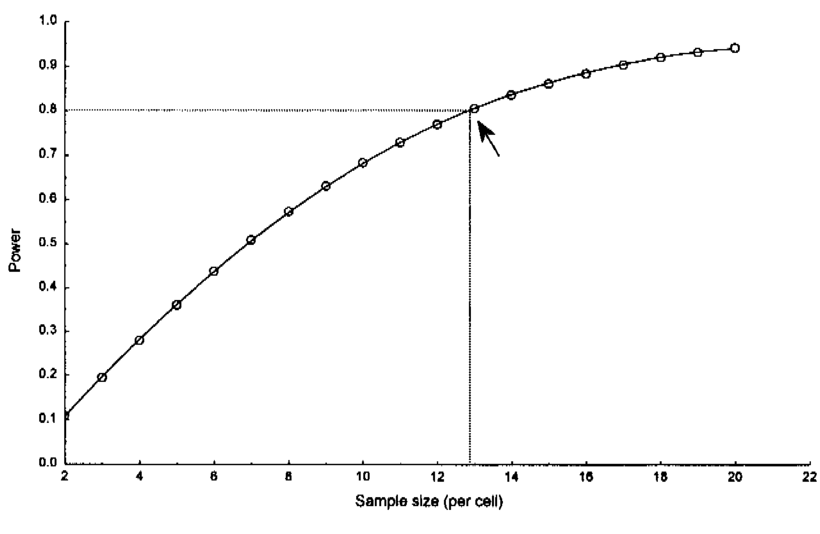

Figure 3.2 Plot of sample size versus power for a one-factor analysis of variance on numbers of individuals of benthic macroinvertebrates across impact zones in Macquarie Harbour (arrow denotes sample size with power > 0.8).

Temporal versus spatial variation
Winter abundances of many species, especially those with life cycles shorter than a few months, are likely to be lower than in summer due to lower ecosystem productivity at this time of year. Consequently there may be some improvements in the power of sampling programs conducted in summer rather than winter. If seasonal sampling is included in the MLRRDP, the appropriate statistical design is a two factor ANOVA (with fixed effects, assuming sampling is always conducted at the same times of year). The comparison of seasons between years provides another level of ANOVA, this time a three factor ANOVA with years as a third fixed factor (years are fixed since each is a fixed time step post-implementation of the MLRRDP).

A further point to note is that the pilot study, which was conducted in late August 1995 provided information on the spatial variation of benthic macroinvertebrate communities but no information on the levels of temporal variation. In the absence of data on seasonal variation, the statistical test for differences in macroinvertebrate abundances between seasons should be assumed to be of a similar magnitude to the spatial variation between zones. This is likely to be a conservative estimate, since increases in mean numbers per sample will decrease the frequency of samples with very few or no invertebrates. This is likely to lead to a decrease in the overall variation between samples and therefore, increased power.

The major aim of the monitoring program for Macquarie Harbour is to detect changes in the ecological health of the harbour following the implementation of measures to reduce the level of pollutants entering the harbour from the King River. Given this aim, the large size of the harbour, and limited funding, *it is recommended that seasonal sampling is not undertaken as part of the monitoring program.* The rate of recovery of the harbour after implementation of the MLRRDP is likely to be on the scale of decades, as heavy metals are gradually leached from the harbour sediments and flushed out the harbour mouth, or alternatively, covered by layers of non-contaminated sediment (an unlikely event given the bioturbatory activities of many benthic invertebrates). The time taken for a recovery to pre-impact conditions is unknown, but may be several centuries or greater. Thus there is little extra information to be gained from seasonal sampling.

Environmental variable selection
The effectiveness of the monitoring program may be greatly increased if data on a range of physical and chemical variables is simultaneously collected along with each sample. The appropriate variables are:

- major heavy metals, particularly copper, but including cadmium, mercury, lead, zinc, and selenium;
- sediment particle size;
- sediment organic matter content;
- sulphide concentrations;
- depth of sample site;
- salinity at the sample site;
- temperature; and
- pH

These variables would prove valuable in explaining trends in macroinvertebrate community data. However, analysis of all these parameters may quickly exhaust available funds and only a subset of the above are recommended for sampling. These are:

- sediment copper concentration;
- depth of sample site;
- sediment particle size;
- sediment organic matter content;
- salinity at the sample site;
- temperature
- pH

3.1.3 Summary of recommendations

The statistical design proposed here will detect an effect size of 80% difference between the means of numbers of individuals of benthic macroinvertebrates of two impact zones in Macquarie Harbour based on a sample area of 0.1 m^2 (the area sampled by a Smith-McIntyre Grab). It should be noted that there are no clear guidelines available as to what an appropriate effect size should be for a monitoring program. Sample size and cost are directly correlated and more sensitive designs are possible if monitoring agencies wish to provide increased funding. In developing the statistical design for the monitoring program, we have born in mind the likely level of available funds per annum. The recommended sampling design is listed in table 3.5.

Table 3.5 Recommended sampling details for the Macquarie Harbour biological monitoring program

Dependent variable	Numbers of individuals of benthic macroinvertebrates per sample
Level of taxonomic identification	Species
Size & type of sampling device	Smith-McIntyre Grab. Sample area = 0.1 m^2. Sample depth = 10cm
Number of sites per impact zone	13
Number of impact zones	3 zones as per figure 3.1
Depth range of samples to be collected	3–10 m depth - to coincide with the middle layer of the halocline
Number of samples per site	1
Number of sampling trips per year	1
Time of sampling each year	February/March
Environmental variables to be sampled	Sediment copper concentration; Depth of sample site; Sediment particle size; Sediment organic matter content; Salinity at the sample site; Temperature; and GPS co-ordinates
Sampling pattern	Sites to be chosen at random within zones on each sampling occasion, subject to the constraint that the average distance between sites is at least 2 km.

It is also recommended that the data collected in monitoring programs be subjected to analysis and interpretation using multivariate statistical methods. Appropriate techniques would be multidimensional scaling on a Bray-Curtis matrix of site dissimilarities and the fitting of vectors of maximum correlation of environmental variables in the ordination space. These vectors can be subjected to Monte-Carlo significance tests. The techniques can be implemented using the PATN (Belbin 1993), and DECODA (Minchin 1990), and similar techniques in the PRIMER (Plymouth Marine Laboratory UK, undated) software packages. The application of multivariate methods will reveal the relationship between the benthic invertebrate fauna at sites in Macquarie Harbour and the measured environmental variables. This information will be useful in the identification of key environmental variables controlling benthic macroinvertebrate communities in the harbour and, therefore, allow management activities to be effectively directed at the control of the most important variables.

Appendixes

Appendix A Summary length statistics for fish collected by seine netting

Species	Length (mm)				
	n	mean	std err	min	max
Retropinna tasmanica	115	47	0.6	34	67
Lovettia sealii	2	48	0	48	48
Galaxias maculatus	2	36.5	1.5	35	38
Atherinosoma microstoma	12	35	3.7	20	70
Kestratherina breviostris	110	60	1.9	32	100
Leptatherina presbyteroides	446	40	0.5	22	105
Hippocampus abdominalis	1	-	-	-	-
Aldrichetta forsteri	4	114	36.9	45	180
Pseudaphritis urvilli	2	45	6	39	51
Tasmanogobius lasti	1	37	-	37	37
Ammotretis rostratus	1	52	-	52	52
Rhombosolea tapirina	3	47	10.4	30	66

Appendix B Fish Species Recorded from Macquarie Harbour

Specific Name	Common Name
Squalus acanthias	Whitespotted dogfish
Raja sp.	Maugean skate
Anguilla australis	Short-finned eel
Oncorhynchus mykiss	Rainbow trout
Salmo trutta	Brown trout
Salmo salar	Atlantic salmon
Retropinna tasmanica	Tasmanian smelt
Lovettia sealii	Tasmanian whitebait
Galaxias maculatus	Common jollytail
Pseudophycis bachus	Red cod
Macruronus novaezelandiae	Blue grenadier
Genypterus tigerinus	Rock ling
Atherinosoma microstoma	Smallmouth hardyhead
Kestratherina brevirostris	Shortsnout hardyhead
Leptatherina presbyteroides	Silver fish
Hippocampus abdominalis	Bigbelly seahorse
Platycephalus bassensis	Sand flathead
Trachurus declivis	Cowanyoung
Nemadactylus macropterus	Jackass fish
Aldrichetta forsteri	Yellow-eye mullet
Pseudaphritis urvilli	Congolli
Tasmanogobius lasti	Lagoon goby
Ammotretis rostratus	Longsnout flounder
Rhombosolea tapirina	Greenback flounder

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