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A comparative survey of heavy metals in the mussel *Mytilus edulis* from Cockburn Sound and surrounding waters

A contribution to the
Southern Metropolitan Coastal Waters Study (1991-1994)

Environmental Protection Authority
Perth, Western Australia
Technical Series No. 56
October 1993

ISSN 0 7309 5644 X
ISBN 1030-0600

A comparative survey of heavy metals in the mussel *Mytilus edulis* from Cockburn Sound and surrounding waters

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Acknowledgments

The Western Australian Police Department particularly members of the Water Police Diving Squad assisted with the collection of the mussel samples. Sergeant Brian Binney organised and supplied divers, diving equipment and a dive boat.

Mr Peter Kiss from the Environmental Protection Authority (EPA), assisted with diving and mussel sorting on the boat.

The Western Australian Government Chemistry Centre analysed the samples and collated the results.

Murdoch University provided laboratory and freezer storage space.

Dr Chris Simpson provided advice and comment on numerous drafts of the manuscript. Mr Adrian Chegwidden, Dr Kevin Francesconi and Dr Victor Talbot reviewed and commented on the penultimate manuscript.

This assistance is gratefully acknowledged.

Summary

This report documents the results of a comparative survey, conducted in April 1989, of heavy metal concentrations in the mussel *Mytilus edulis* living in Cockburn Sound and Owen Anchorage and follows a previous survey, in 1977, showing mussels living in these waters to be contaminated with heavy metals.

The concentrations of Cu, Zn, Cd, Mn, Pb, Cr, Ni and Fe were measured in the tissue of *M. edulis,* at 27 sites throughout the study area. The results of the 1977 and 1989 surveys were analysed at three spatial scales: individual sites, four *localities* termed Owen Anchorage, Jervoise Bay, the Industrial Area (eastern side of Cockburn Sound) and Western Area (western side of Cockburn Sound) and the entire study area.

Heavy metal contamination of mussels, in Cockburn Sound and Owen Anchorage, has decreased since the 1977 survey, associated with substantial reductions in the total loads of heavy metals discharged directly into these waters over the same period. In 1989, the concentrations of Cu, Zn, Cd, Mn, Pb, Cr, and Fe (upper) in *M. edulis,* at nearly all the sites in the study area, were substantially lower than in 1977. In the four sampling *localities* there has been a downward trend in mean concentrations of these heavy metals since 1977. Over the entire study area, mean heavy metal concentrations were significantly lower.

The pattern of heavy metal contamination of mussels in the study area has changed since 1977, when the mean concentrations of Cu, Zn, Cd, Mn, Cr, and Fe(*upper*) in *M. edulis*, were significantly higher on the eastern side of Cockburn Sound compared to the western. By 1989 there were no significant differences in the mean concentrations of heavy metals between eastern and western sides of the Sound, reflecting reductions in loadings of heavy metals into these waters from industrial and municipal point sources along the eastern shoreline.

In 1977 the mean concentrations of Cu, Zn, Cd, Mn, Pb, Cr, and Fe in *M. edulis*, for the entire study area, exceeded levels of acceptable ecological contamination defined by Chegwidden (1979). By 1989 only the mean concentration of chromium exceeded these levels. Similarly, in 1977, the concentrations of Cd and Pb in *M. edulis* at several sites, exceeded the concentrations recommended by the Western Australian Health Department for these metals in seafoods. By 1989 the concentrations of all heavy metals surveyed in *M. edulis*, were below the recommended health standards.

The management initiatives to reduce the direct input of heavy metals into Cockburn Sound and surrounding waters have resulted in a significant reduction in heavy metal contamination of *M. edulis* living in these waters. The results indicate that heavy metal contamination of a marine embayment can be reversed within relatively short time periods provided the inputs of pollutants are reduced.

1. Introduction

As a result of widespread public concern about the deterioration in water quality of Cockburn Sound and Owen Anchorage during the early 1970s, the Western Australian State Government initiated the 1976-1979 Cockburn Sound Environmental Study (EPA, 1979). The study provided a comprehensive assessment of the marine environment within the protected waters of these embayments and acted as an umbrella for an array of environmental programs with the common objective of obtaining the necessary information to arrest the deterioration in the Sound and to provide the basis for future management of these waters. A survey of contaminants in the water, sediments and biota of the Sound, including heavy metal contamination in the tissue of the mussel, *Mytilus edulis* was undertaken by Chegwidden (1979).

Chegwidden (1979) concluded that Cockburn Sound and Owen Anchorage were contaminated with heavy metals as a result of discharges of industrial and domestic/municipal wastes into these waters since the late 1950s. Contamination was particularly high along the eastern shelf of Cockburn Sound, adjacent to the Kwinana industrial area, with elevated levels of heavy metals, hydrocarbons and enteric bacteria occurring in the water, sediments and biota. As a consequence of these findings, the Cockburn Sound Environmental Report contained a number of recommendations specifically aimed at reducing the input of pollutants into Cockburn Sound and surrounding waters. The implementation of these recommendations has resulted in industries improving their wastewater treatment processes or ceasing discharge, with the cumulative effect of considerably reducing heavy metal loadings into these waters.

Mussels bioaccumulate heavy metals and as such, concentrations in their tissues provide a integrated measures of the concentrations in the water column. This report describes the results of a comparative study, conducted in April 1989, of the heavy metal concentrations in the tissue of the mussel *Mytilus edulis,* collected from 27 sites in Cockburn Sound and Owen Anchorage (Figure 1). The survey provides an overview of the heavy metal contamination of mussels living in these waters and a means of identifying areas of significant contamination. Comparisons with the 1977 survey provide trends in the status of heavy metal contamination of mussels from these waters and a basis for determining the effectiveness of the management measures implemented in response to recommendations from the Cockburn Sound Environmental Study (1979).

2. Materials and methods

Where practicable, the sampling and analytical methods used in this study are consistent with the methodology of Chegwidden (1979).

Mussels were sampled at 27 sampling sites during April 1989, usually from fixed man-made structures such as posts, jetties and beacons (Figure 1). The sites were the same as those used in the 1977 study, except where mussels could no longer be found, or where the structure no longer existed, in which case the closest suitable location was selected (Appendix I). At each site, divers collected bulk samples of approximately 50 to 100 mussels from within the *upper* and *lower* one metre of mussels' vertical distribution on the collection structure.

Ten mussels with a shell length of between 55mm and 75mm were selected from each of the bulk samples and placed in a container of clean sea water for 48 hours to flush the digestive system of the mussels. Each sample was then divided into two sub-samples of five mussels. The shell length of each mussel was measured, then the mussel was shucked, drained and weighed (Appendix II). One sub-sample was used for heavy metal analyses, the other was then frozen and retained for future reference. Chegwidden (1979) conducted heavy metal analysis on five individual mussels, then averaged the individual results to provide a mean value. In this

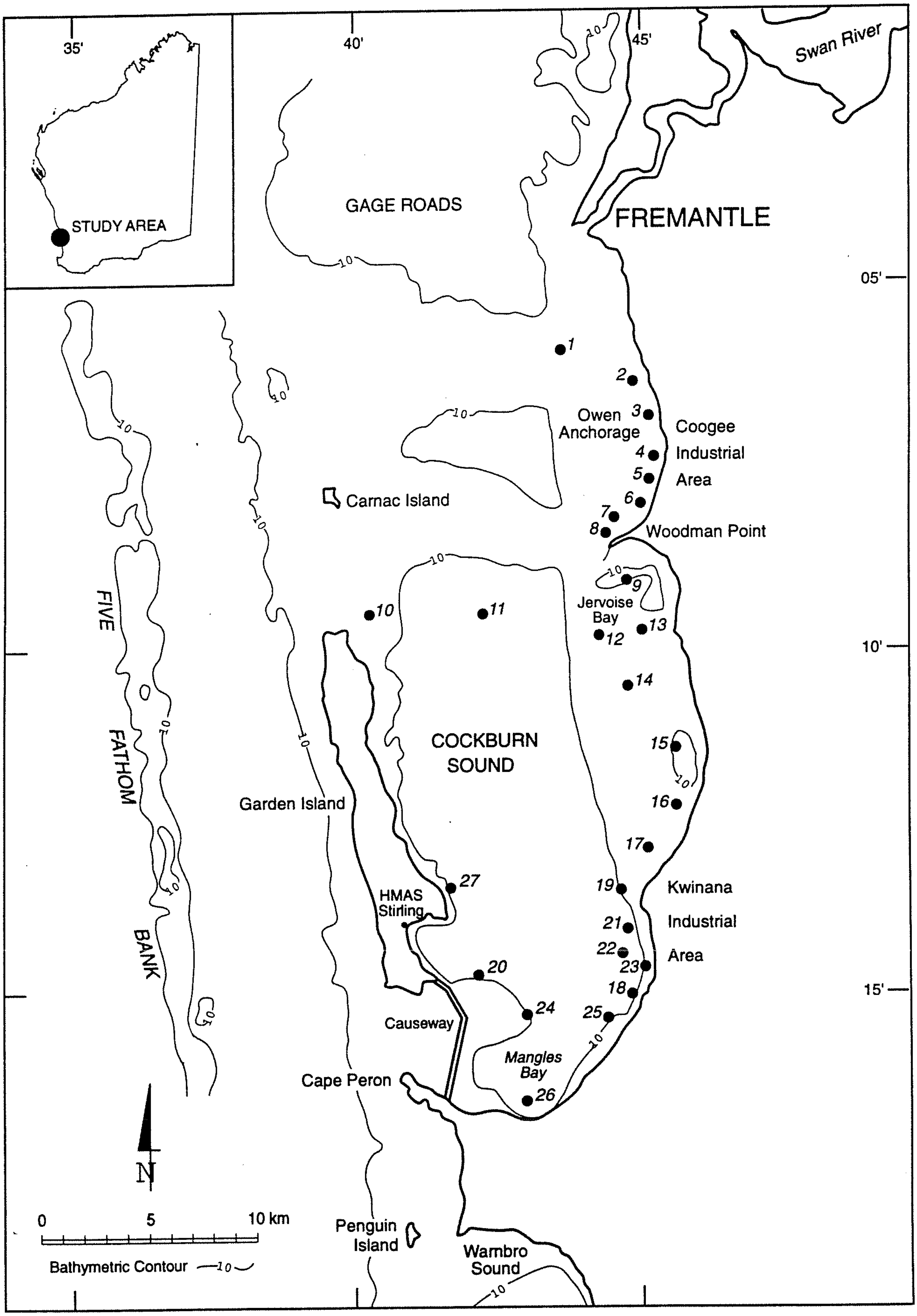

Figure 1. The study area showing the location of the 27 sampling sites.

study, the tissue of the five mussels in each sub-sample were homogenised to form a single bulk sample. Duplicate preparations of this material were then analysed to determine the concentrations of Cu, Zn, Cd, Fe, Mn, Pb, Cr and Ni.

Analyses were conducted at the Chemistry Centre of Western Australia using similar techniques where practicable, as Chegwidden (1979) and are briefly outlined here. The homogenised mussel tissue was digested in Aristar nitric acid and then analysed for heavy metal concentrations using a Atomic Absorption Spectrophotometer (AAS), with a nitrous oxide-acetylene flame for Cr and a air-acetylene flame for the other metals. Deuterium lamp background corrections were applied in the case of cadmium, lead and nickel. The AAS technique was routinely checked using standard reference samples. All heavy metal concentrations are expressed as $mgkg^{-1}$, wet weight.

To compare the distribution of heavy metal concentrations in the 1977 and 1989 surveys, the sampling sites were divided into groups from four *localities*: *Owen Anchorage* (sites 1, 2, 3, 5, 6, 7, 8); *Jervoise Bay* (sites 9, 12, 13, 14); *Industrial Area* (sites 15, 16, 17, 18, 19, 21, 22, 23, 25); and the *Western Area* (sites 10, 11, 20, 24, 26). Sites 4 and 27 were not used in the 1977 survey and therefore are excluded from these comparisons. The rationale for grouping the sites into these four *localities* is based on the history of pollutant loadings to the study area (Murphy,1979). Discharges to *Owen Anchorage* were primarily from agricultural processing industries such as tanneries, fellmongers and abattoirs. *Jervoise Bay* received discharges from the Woodmans Point Treatment Plant until 1984 and is now the site for boat maintenance and ship-building industries. The *Industrial Area*, on the eastern side of the Sound, receives discharges from the heavy industries of the Kwinana Industrial Area, such as oil refining, power generation and fertiliser production. The *Western Area*, adjacent to the shores of Garden Island, receives no direct industrial discharges.

2.1 Statistical treatment

Non-parametric statistical tests have been applied on the basis that the assumptions applying to parametric tests (e.g. normal distribution and homogeneity of variances) were not satisfied (Sokal and Rohlf, 1969). The Mann-Whitney U-test and Wilcoxon Signed Rank test, the non-parametric analogues of the student's t-test and paired t-test, were used to determine if pairs of sample means were significantly different (Snedecor and Cockrane, 1978). The Kruskal-Wallis test, the non-parametric equivalent of a one-way ANOVA, was used to determine if the variances between sample means were significantly different.

To determine if heavy metal concentrations in *M. edulis* were related to the vertical distribution of mussels on the sample collection structure, the mean concentrations of metals in *upper* and *lower* samples were compared using a Wilcoxon Signed Rank test, for the 1977 and 1989 surveys. There were no significant differences between the *upper* and *lower* mean concentrations of Cu, Zn, Cd, Mg, Pb, and Cr in the 1977 or 1989 surveys. However, although the mean concentrations of Fe in *upper* and *lower* samples in 1977 were not significantly different, the mean concentrations in *lower* samples in 1989, were significantly higher ($p<0.001$). Consequently, for all metals except Fe, the values from sites with paired samples were pooled to provide a mean site concentration. Metal concentrations at sites with a single sample were treated as means.

Heavy metal concentrations below the limit of detection [Ni 1.0 mg kg^{-1}, 1977; Pb 0.35 mg kg^{-1}, 1989] were excluded from statistical analyses. In 1977, individual mussels were analysed for Ni, limiting the quantities of mussel tissue available for analysis. Only three of the 24 sites sampled in 1977 (18, 19, 21), recorded concentrations of Ni above the limit of detection (Appendix 3). In 1989, larger bulked samples of mussel tissue provided a higher pre-concentration and hence the capacity to detect lower Ni tissue concentrations.

In 1989, duplicate analyses for Cr were not undertaken and consequently these results should be treated with caution.

3. Results

3.1 Copper

The concentration of copper in *M. edulis* in 1989, ranged from 0.9 mg kg^{-1} at site 11 to 2.6 mg kg^{-1} at site 19, representing an increase in the minimum values of 27% and a decrease in the maximum values of 82% over 1977 levels (Figure 2a). In 1989, the mean concentration of copper was lower at 15 of the 24 sites common to both surveys, with the largest reductions of over 90% occurring at sites 22 and 23.

The mean concentrations of copper in *M. edulis* in the four *localities* have declined since 1977, and was significantly lower ($p<0.01$) in the Industrial Area (Figure 3a). However, the decrease in concentration at site eight in Owen Anchorage from 6.3 mg kg^{-1} in 1977 to 1.5 mg kg^{-1} in 1989, has masked the upward trend in copper concentrations at the other six sites in this *locality* (Figure 2a). If site eight is omitted, then the mean concentration of copper in Owen Anchorage has increased significantly ($p<0.05$), from 1.1 mg kg^{-1} to 1.3 mg kg^{-1}.

In 1977, the mean concentration of copper in *M. edulis* in the Industrial Area was significantly higher ($p<0.05$) than in Owen Anchorage, Jervoise Bay and the Western Area while in these *localities* the mean concentrations were not significantly different (Figure 3a). In 1989 the mean concentrations in the four *localities* were not significantly different.

The mean concentration of copper in *M. edulis* for the 24 sites common to both surveys, was significantly lower in 1989 ($p<0.05$) compared with 1977 (Figure 4a).

3.2 Zinc

The concentration of zinc in *M. edulis* in 1989, ranged from 13 mg kg^{-1} at site 22 to 39 mg kg^{-1} at site 17, representing a decrease in the minimum and maximum values of 23% and 73% respectively over 1977 levels (Figure 2b). In 1989 the mean concentration of zinc was lower at 16 of the 24 sites common to both surveys, with the largest reductions of 87% and 77% occurring at sites 22 and 23 respectively. The mean concentrations increased at seven sites — four in Owen Anchorage.

The mean concentrations of zinc in *M. edulis* in all four *localities* have declined since 1977, and was significantly lower ($p<0.05$) in the Industrial Area (Figure 3b).

In 1977 the mean concentration of zinc in *M. edulis* in the Industrial Area was significantly higher ($p<0.05$) than Owen Anchorage, Jervoise Bay and the Western Area while in these *localities* the mean concentrations were not significantly different (Figure 3b). By 1989 the mean concentrations in the four *localities* were not significantly different.

The mean concentration of zinc in *M. edulis* for the 24 sites common to both surveys was significantly lower in 1989 ($p<0.01$) compared with 1977 (Figure 4a).

3.3 Cadmium

The concentration of cadmium in *M. edulis* in 1989 ranged from 0.09 mg kg^{-1} at site 5 to 0.36 mg kg^{-1} at site 23, representing a decrease in the minimum and maximum values of 55% and 94% respectively, over 1977 levels (Figure 2c). In 1989 the mean concentrations of cadmium were lower at all 24 sites common to both surveys, with the largest reduction of 95% at site 22.

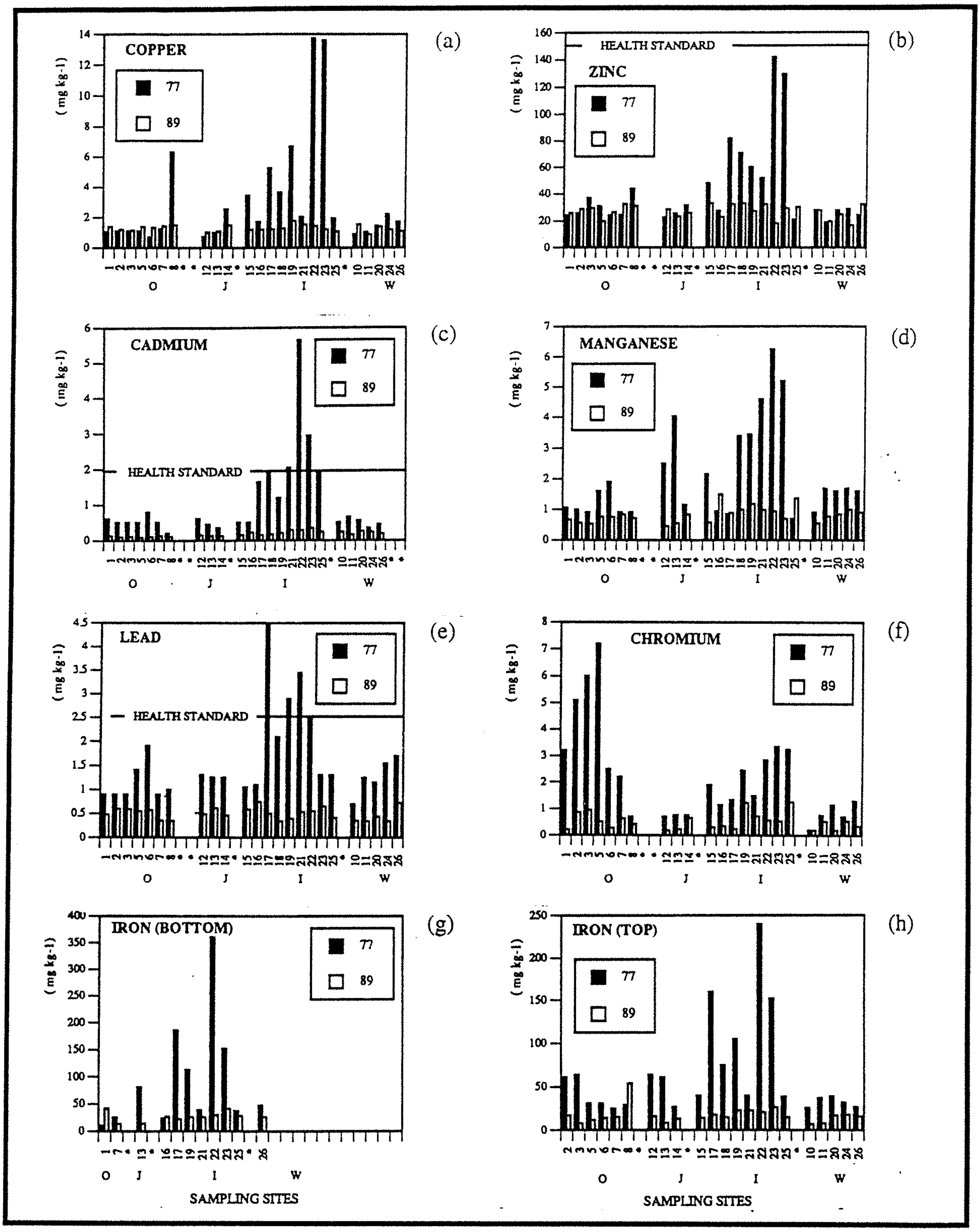

Figure 2. A comparison of the mean heavy metal concentrations in Mytilus edulis at sampling sites in Cockburn Sound and Owen Anchorage from the 1977 and 1989 surveys. Sites without comparative data are not included. Nickel has been omitted because the concentrations at most sites in 1977 were below the level of detection, making meaningful comparisons impossible. WA health standards are shown for cadmium, lead and zinc (copper, 70mg kg^{-1}). There are no health standards for manganese, chromium or iron. Sites are grouped into localities: Owen Anchorage (O); Jervoise Bay (J); Industrial Area (I); Western Area (W).

The mean concentrations of cadmium in *M. edulis* in the four *localities* have declined since 1977, and were significantly lower in Owen Anchorage ($p<0.01$), the Industrial Area ($p<0.01$) and the Western Area ($p<0.05$; Figure 3c).

In 1977 the mean concentration of cadmium in *M. edulis* in the Industrial Area was significantly higher ($p<0.01$) than Owen Anchorage, Jervoise Bay and the Western Area while in these *localities* the mean concentrations were not significantly different (Figure 3c). In 1989, the mean concentrations in the Industrial and Western Areas were significantly higher ($P>0.05$) than Owen Anchorage and Jervoise Bay.

The mean cadmium concentration in *M. edulis* for the 24 sites common to both surveys was significantly lower ($p<0.001$) in 1989 compared with 1977 (Figure 4a).

3.4 Manganese

The concentration of manganese in *M. edulis* in 1989, ranged from 0.48 mg kg^{-1} at site 13 to 2.00 mg kg^{-1} at site 25, representing a decrease in the minimum and maximum values of 0.04% and 72% respectively over 1977 levels (Figure 2d). In 1989 the mean concentrations of manganese were lower at 21 of the 24 sites common to both surveys, with the largest reduction of 85% at site 22.

The mean concentrations of manganese in *M. edulis* in the four *localities* have declined since 1977 and were significantly lower in Owen Anchorage ($p<0.01$), the Industrial Area ($p<0.05$) and the Western Area ($p<0.05$; Figure 3d).

In 1977 the mean concentrations of manganese in *M. edulis* in the four *localities* were not significantly different (Figure 3d). In 1989 there were no significant differences between Jervoise Bay, Owen Anchorage and the Western Area. The mean concentration in the Industrial Area however, was significantly higher ($p<0.01$) than Owen Anchorage and Jervoise Bay.

The mean concentration of manganese in *M. edulis* for the 24 sites common to both surveys was significantly lower ($p<0.001$) in 1989, compared with 1977 (Fig 4a).

3.5 Lead

The concentration of lead in *M. edulis* in 1989 ranged from less than 0.35 mg kg^{-1} (detection limit) at sites 7, 11, 18, 19, 22, 24 and 25, to 0.81 mg kg^{-1} at site 13, representing a decrease in the minimum and maximum values of 50% and 84% respectively, over 1977 levels (Figure 2e). In 1989 the mean concentrations of lead were lower at all 24 sites common to both surveys, with the largest reduction of 89% at site 17.

Since 1977 the mean concentrations of lead in *M. edulis* in all four *localities* have declined and are significantly lower ($p<0.05$) in Owen Anchorage, the Industrial Area ($p<0.01$) and the Western Area ($p<0.05$; Figure 3e).

In 1977 and 1989 the concentrations of lead in *M. edulis* from the four *localities* were not significantly different (Figure 3e).

The mean concentration of lead in *M. edulis* for the 24 sites common to both surveys was significantly lower ($p<0.001$) in 1989 compared with 1977 (Figure 4a).

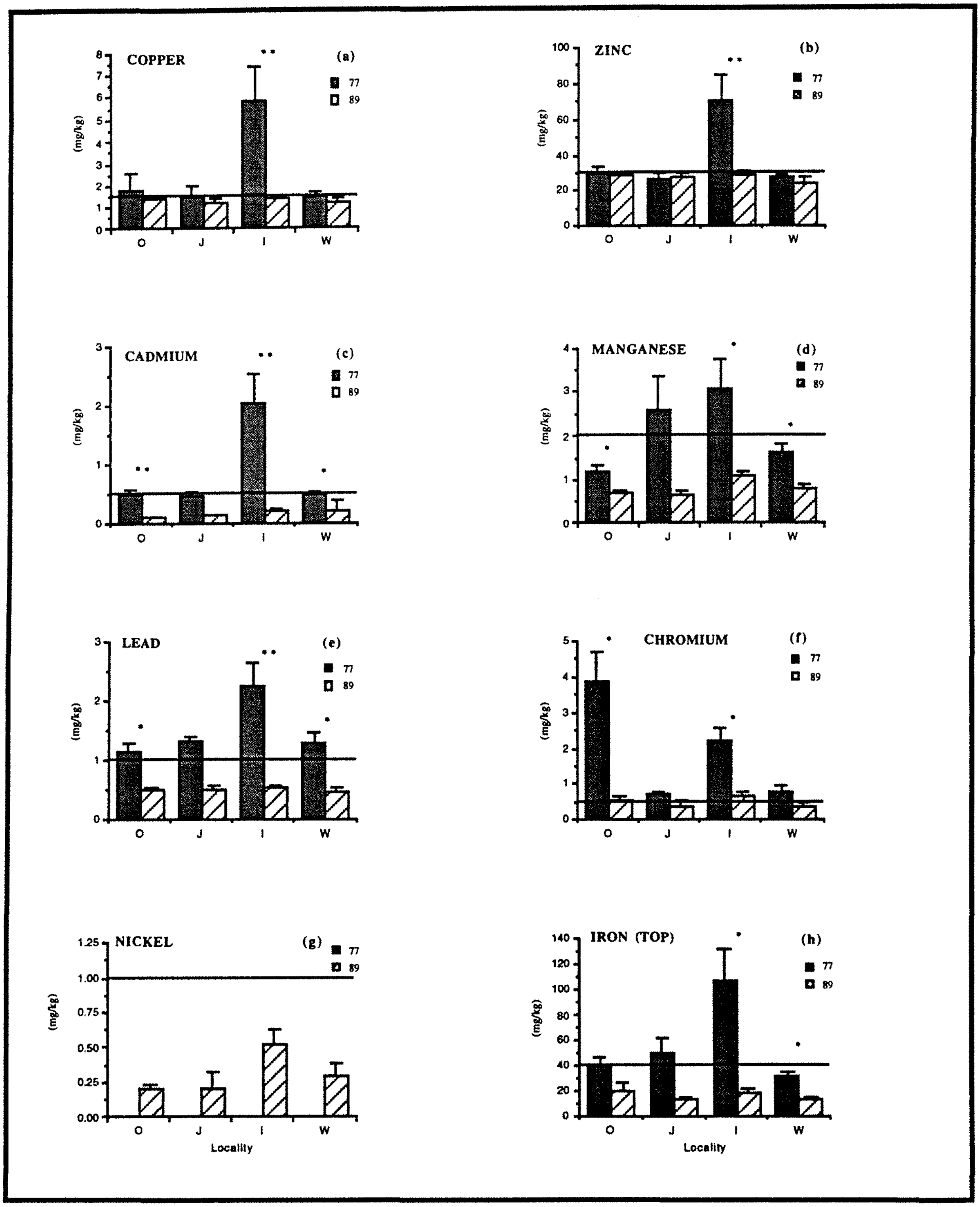

Figure 3. A comparison of the mean concentrations of heavy metals in Mytilus edulis at four localities within the study area, in 1977 and 1989. Vertical bars indicate standard errors. The horizontal line indicates the limit of acceptable contamination as defined by Chegwidden (1979). The concentrations of iron from the upper and lower samples of the mussels vertical distribution were significantly different and are shown separately. Sample sizes for lower mean iron concentrations are too small for valid comparisons and are not shown. The mean concentrations of nickel in 1977, have been omitted from the graph because only three sites were above the limit of detection. Significance levels: * 0.05 > P >0.01; ** 0.01 > P >0.001; *** 0.001 > P. (O) Owen Anchorage, (J) Jervoise Bay, (I) Industrial Area, (W) Western Area.

3.6 Chromium

The concentration of chromium in *M. edulis* in 1989 ranged from 0.07 mg kg^{-1} at site 10 to 2.10 mg kg^{-1} at site 19 representing a decrease in the minimum and maximum values of 65% and 71% respectively over 1977 levels (Figure 2f). In 1989 the mean concentrations of chromium were lower at all 23 sites common to both surveys, with the largest reduction of 93% at site 5.

The mean concentrations of chromium in *M. edulis* in each of the four *localities* have declined since 1977 and were significantly lower ($p<0.01$) in the Industrial Area and Owen Anchorage.

In 1977 the mean concentrations of chromium in *M. edulis* in Owen Anchorage and the Industrial Area were significantly higher ($p<0.01$) than Jervoise Bay and the Western Area (Figure 3f). In 1989 there was no significant difference between the four *localities*.

The mean concentrations of chromium in *M. edulis* at the 23 sites common to both surveys, were significantly lower ($p<0.001$) in 1989, compared with 1977 (Figure 4a).

3.7 Nickel

The concentration of nickel in *M. edulis* in 1989, ranged from 0.05 mg kg^{-1} at site 12 to 1.60 mg kg^{-1} at site 25, representing a decrease in the minimum and maximum values of 95% and 68% respectively over 1977 levels.

In 1977 there were insufficient samples with detectable concentrations of nickel for a valid statistical comparison with the 1989 survey. However, at the three sites common to both surveys and where the concentrations of nickel in 1977 were above the limit of detection, the mean concentration decreased by 84%, from 3.03 mg kg^{-1} in 1977 to 0.49 mg kg^{-1} in 1989.

In 1989 the mean concentration of nickel in *M. edulis* in the Industrial Area was significantly higher than Owen Anchorage and Jervoise Bay ($p<0.05$; Figure 3g). The mean concentrations in Owen Anchorage, Jervoise Bay and the Western Area were not significantly different.

3.8 Iron

The concentration of iron in *M. edulis* in *upper* samples in 1989 ranged from 7.2 mg kg^{-1} at site 10 to 54.0 mg kg^{-1} at site 8, representing a decrease in the minimum and maximum values of 69% and 75% respectively over 1977 levels (Figure 2h). The concentration of iron in *M. edulis* in *lower* samples in 1989 ranged from 12.0 mg kg^{-1} at sites 3 and 6, to 42.0 mg kg^{-1} at site 23 representing a decrease in the maximum values of 90% and a increase in the minimum values of 20% over 1977 levels (Figure 2g). In 1989 the concentrations of iron were lower at 21 of the 22 *upper* sites and 9 of the 11 *lower* sites common to both surveys. The largest reductions in the *upper* and *lower* concentrations was 92% at site 22.

Spatial and temporal comparisons of the *lower* mean iron concentrations in *M. edulis* were omitted because of insufficient *paired* samples.

Since 1977 the mean *upper* iron concentrations in *M. edulis* in the four *localities* have declined and were significantly lower ($p<0.05$) in the Industrial and Western Areas (Figure 3h).

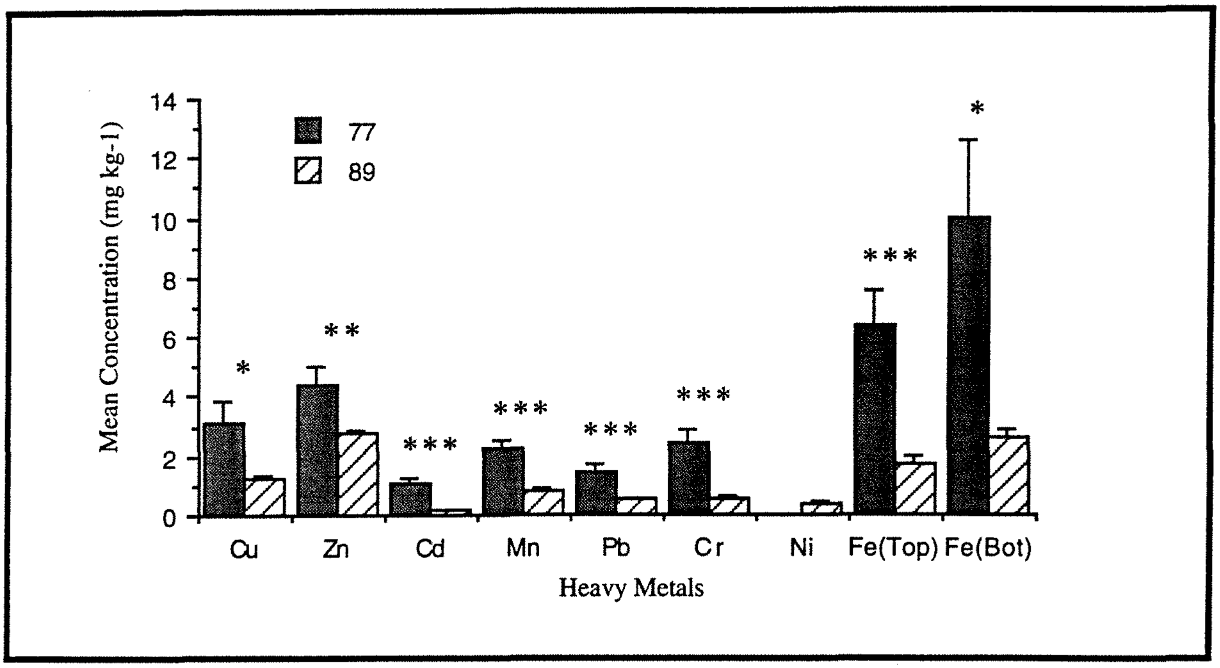

Figure 4a. A comparison of the mean concentrations of heavy metals in *Mytilus edulis* for all sites common to the 1977 and 1989 surveys. Vertical bars indicate standard errors. For graphical purposes the values for zinc and iron have been reduced by a factor of 10. The concentration of iron from the upper and lower samples of the mussels vertical distribution were significantly different and are shown separately. The mean concentrations of nickel in 1977 have been omitted from the graph because only three sites were above the limit of detection. Significance levels; * 0.05 > P >0.01; ** 0.01 > P >0.001; *** 0.001 > P.

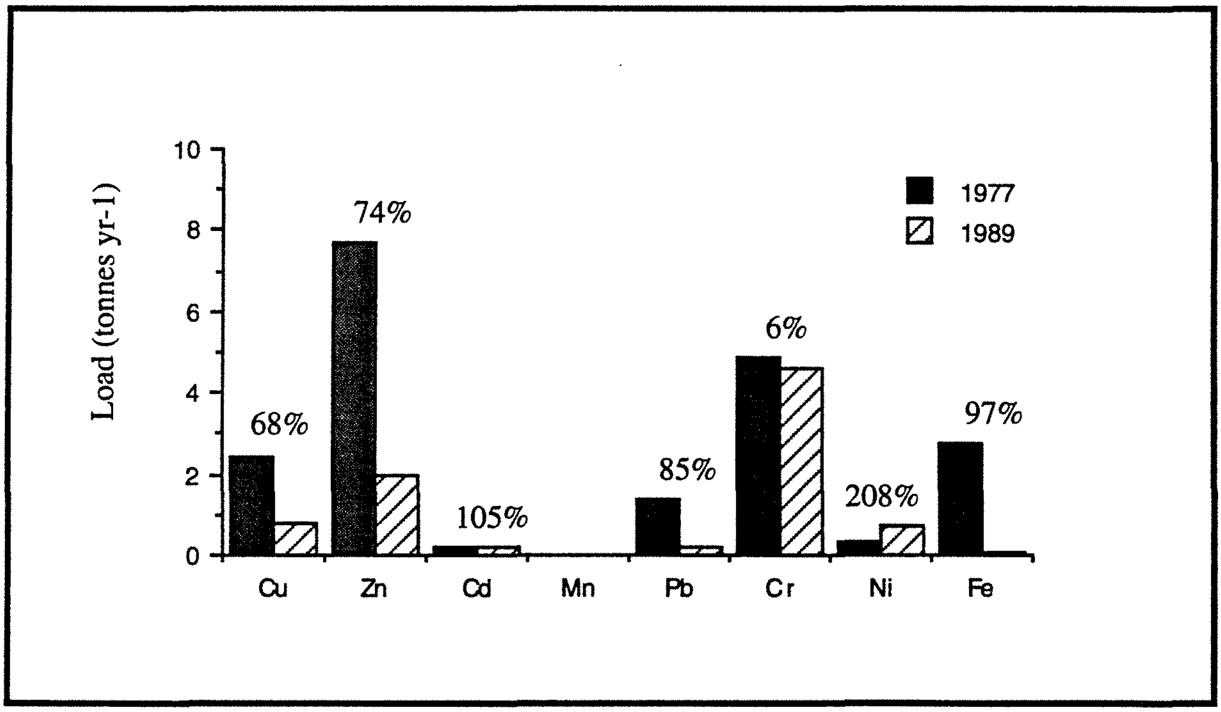

Figure 4b. A comparison of the total loads and the percentage changes of heavy metals discharged directly into the waters of the study area in 1977 and 1989. The loads for manganese are unavailable. For graphical purposes the value for iron has been reduced by a factor of 100 (Martinick *et al*, 1993).

In 1977 the *upper* mean iron concentration in *M. edulis* in the Industrial Area was significantly higher ($p<0.05$) than Owen Anchorage and the Western Area. The mean concentrations in Owen Anchorage, Jervoise Bay and the Western Area were not significantly different (Figure 3h). In 1989 there was no significant difference between the four *localities* .

In 1989 the mean concentrations of iron in *M. edulis* for the 22 *upper* ($p<0.001$)and 11 *lower* samples ($p<.05$), common to both surveys, were significantly lower compared to 1977 levels (Fig 4a).

4. Discussion

4.1 Temporal and spatial variation

The mean concentrations of Cu, Zn, Cd, Mn, Pb, Cr, and Fe in the tissue *M. edulis* for the entire study area were significantly lower in 1989 compared to 1977. These reductions are associated with substantial decreases in the total loadings of most metals over the same period (Figure 4b). Similarly, in all four sampling *localities* and nearly all the sites in the study area, the mean concentrations of these metals in *M. edulis* decreased (Figures 2 & 3). The notable exception to this downward trend was in Owen Anchorage where the concentrations of Cu and Zn increased at most sites (Figures 2a & 2b). Loadings of Cu and Zn discharged directly into these waters from industries along the shoreline of Owen Anchorage have increased by 10% (until 1988) and 42% respectively since 1977.

In 1977 the mean concentrations of Cu, Zn, Cd, Mn, Cr, and Fe (*upper*) in *M. edulis* were significantly higher on the eastern side of Cockburn Sound compared to the west. In 1989 there were no significant differences in mean concentrations of these metals between the eastern and western sides of the Sound, reflecting a substantial reduction in loadings of these metals to Cockburn Sound from industrial and municipal point sources along the eastern shoreline (Martinick *et al*, 1992).

4.2 Implications for public and environmental health

In 1977 the concentrations of cadmium, zinc and lead in *M. edulis* at a number of sites, particularly adjacent to the Kwinana industrial area, exceeded the concentrations recommended at the time by the National Health and Medical Research Council (NHMRC) and adopted by the Western Australian Health Department for metals in seafoods (Figure 2. NHMRC, 1979). Furthermore, the concentrations of chromium at other sites in Owen Anchorage were considered to be a cause of concern (Chegwidden, 1979). By 1989 the mean concentrations of Cu, Zn, Cd, Mn, Pb, Cr, and Fe in *M. edulis* at all sites in the study area are below the Western Australian health standards (Figure 2. NFA, 1993). These results suggest that the concentrations of these heavy metals in mussels from Cockburn Sound and Owen Anchorage, are not a public health problem.

The ecological effects related to the concentrations of heavy metals in the tissue of mussels are poorly understood. Chegwidden (1979) used the results of Australian and overseas studies of heavy metal concentrations in *M. edulis* as a first approximation of concentrations which may indicate ecologically unacceptable levels of heavy metal contamination. These are: copper, 1.5 mg kg^{-1}; Zinc, 30 mg kg^{-1}; cadmium, 0.5 mg kg^{-1}; manganese, 2.0 mg kg^{-1}; lead, 1.0 mg kg^{-1}; chromium, 0.5 mg kg^{-1}; nickel, 1.0 mg kg^{-1}; iron, 40.0 mg kg^{-1}.

In 1977 the mean concentrations of Cu, Zn, Cd, Mn, Pb, Cr, and Fe in *M. edulis* for the entire study area exceeded the levels defined by Chegwidden (1979), as indicative of unacceptable contamination of a marine environment (Figure 4a). Furthermore, in most localities in 1977, particularly the Industrial Area, the mean concentrations of most heavy metals exceeded the levels of acceptable contamination (Figure 3). By contrast, in 1989 the mean concentrations of all these heavy metals for the entire study area, except Cr, were substantially lower than unacceptable levels. For *localities*, only the mean concentration of Cr in the Industrial Area and Owen Anchorage, exceeded these levels. These results suggest that 1989 levels of heavy metal contamination in mussels in Cockburn Sound and surrounding waters are unlikely to be causing significant ecological impacts.

It is generally accepted that biostimulants and synthetic organic compounds which can cause long-term or irreversible ecological change, are a greater threat to the future viability of the marine environment, than non-synthetic toxics, such as heavy metals (GESAMP, 1990). Windom (1992), concluded that if discharges of heavy metals to the coastal environment were adequately regulated, then it was unlikely that heavy metal contamination would pose a significant threat to either marine biota or human health. It is evident from the comparisons of the results of the 1977 and 1989 surveys, that the management initiatives to reduce inputs of heavy metals into Cockburn Sound and Owen Anchorage have been effective and resulted in a significant reduction in heavy metal contamination of mussels living in these waters. Furthermore, these data support the conclusion that heavy metal contamination of mussels in the marine environment can decrease significantly over relatively short periods if the total loadings of these metals to the system are reduced.

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Appendix 1

Sampling sites and depths used in the 1977 and 1989 surveys.
(NS) Not sampled; (*) Information not recorded.

1977				1989			
Station Number	**Sampling Site**	**Depth of Sample(m)** T	B	**Station Number**	**Sampling Site**	**Depth of Sample(m)** T	B
1	Elbow	*	*	**1**	Fish Rock	NS	3.0
5	Robb Jetty Wreck	*	NS	**2**	Robb Jetty Groyne	1.0	NS
6	Power Station Inlet	*	*	**3**	Power Station Inlet	1.0	4.0
7	Anchorage Meatworks	NS	NS	**4**	OMEO Wreck	1.0	NS
8	Coogee Jetty	*	NS	**5**	Coogee Jetty	1.0	NS
9	Explosives Jetty	*	NS	**6**	Explosives Jetty	1.0	7.0
10	Jervoise Bay North Lead	*	*	**7**	Cement Barge Buoy	1.0	3.0
11	Cement Jetty	*	NS	**8**	Cement Jetty	1.0	*
12	Jervoise Bay South Lead	*	*	**9**	Cockburn Boat Ramp Jetty	1.0	NS
13	Beacon Head Dolphin	*	NS	**10**	Beacon Head Dolphin	1.0	7.0
14	No.2 Windmill	*	*	**11**	South Lead	1.0	NS
15	Woodman Point Channel Beacon	*	*	**12**	Woodman Point Channel Beacon	1.0	NS
16	Jervoise Bank Beacon	*	*	**13**	Jervoise Bank Beacon	1.0	9.0

Appendix 1. Continued

1977				1989			
Station Number	**Sampling Site**	**Depth of Sample(m) T**	**B**	**Station Number**	**Sampling Site**	**Depth of Sample(m) T**	**B**
17	Jervoise Bay-Medina Channel	*	*	**14**	Jervoise Bay-Medina Channel	*	1.0
18	Alcoa Jetty	*	*	**15**	Alcoa Jetty	1.0	11.0
19	SEC Intake Beacon	*	*	**16**	SEC Intake Pipe	NS	7.0
21	AIS Jetty	*	*	**17**	AIS Jetty	1.0	12.0
22	Kwinana Wreck	*	*	**18**	Kwinana Wreck	1.0	NS
24	James Point Spit	*	*	**19**	James Point Spit	1.0	11.0
25	Minstrel Channel North	*	*	**20**	Minstrel Channel North	1.0	NS
26	BP Jetty North	*	*	**21**	BP Jetty South	1.0	14.0
27	CSBP Jetty North	*	*	**22**	CSBP Jetty North	1.0	14.0
28	CSBP Jetty East	*	*	**23**	CSBP Jetty East	1.0	6.0
29	Southern Flats	*	*	**24**	Southern Flats	1.0	NS
30	CBH Jetty	*	*	**25**	CBH Jetty	1.0	17.0
31	Palm Beach Jetty	*	*	**26**	Palm Beach Jetty	1.0	6.0
33	Colpoys Buoy	NS	NS	**27**	Colpoys Buoy No. 1	1.0	19.0

Appendix 2

Individual and mean shell lengths, and total and mean tissue weights of *Mytilus edulis,* from *upper* (U) and *lower* (L) samples of the mussels vertical distribution at sites in Cockburn Sound and Owen Anchorage during April 1989. (NS) Not sampled.

STATION No	1		2		3		4		5		6		7	
LENGTH (mm)	T	B	T	B	T	B	T	B	T	B	T	B	T	B
1	NS	55	47	NS	56	61	57	NS	59	NS	60	56	65	62
2	NS	56	49	NS	58	61	62	NS	63	NS	63	60	65	67
3	NS	58	51	NS	58	64	63	NS	63	NS	65	63	67	68
4	NS	59	52	NS	62	64	64	NS	67	NS	65	67	72	69
5	NS	61	56	NS	67	68	66	NS	70	NS	66	68	78	73
MEAN LENGTH (mm)	NS	57.8	51.0	NS	60.2	63.6	62.4	NS	64.4	NS	63.8	62.8	69.4	67.8
TOTAL WEIGHT (gms)	NS	24.0	21.5	NS	32.0	32.4	31.6	NS	36.8	NS	29.1	29.1	44.4	36.7
MEAN WEIGHT (gms)	NS	4.8	4.3	NS	6.4	6.5	6.3	NS	7.4	NS	5.8	5.8	8.9	7.3

STATION No	8		9		10		11		12		13		14	
LENGTH (mm)	T	B	T	B	T	B	T	B	T	B	T	B	T	B
1	48	NS	50	NS	63	64	55	NS	66	52	58	50	63	NS
2	49	NS	51	NS	64	69	61	NS	67	55	60	53	67	NS
3	52	NS	52	NS	66	74	63	NS	69	60	60	56	67	NS
4	55	NS	52	NS	72	75	63	NS	72	60	74	60	73	NS
5	62	NS	55	NS	80	83	64	NS	77	62	77	66	75	NS
MEAN LENGTH (mm)	53.2	NS	52	NS	69.0	73.0	61.2	NS	70.2	57.8	65.8	57.0	69	NS
TOTAL WEIGHT (gms)	19.9	NS	15.1	NS	41.9	40.3	24.5	NS	43.2	26.1	44.7	25.4	45.6	NS
MEAN WEIGHT (gms)	4.0	NS	3.0	NS	8.4	8.0	4.9	NS	8.6	5.2	8.9	5.1	9.1	NS

STATION No	15		16		17		18		19		20		21	
LENGTH (mm)	T	B	T	B	T	B	T	B	T	B	T	B	T	B
1	62	65	NS	62	57	61	58	NS	70	71	68	NS	65	58
2	65	65	NS	62	60	62	59	NS	72	74	69	NS	70	61
3	67	66	NS	63	60	70	60	NS	75	79	70	NS	70	63
4	75	68	NS	68	64	70	63	NS	75	80	74	NS	72	65
5	77	70	NS	86	68	74	70	NS	90	84	80	NS	85	68
MEAN LENGTH (mm)	69.2	66.8	NS	68.2	61.8	67.4	62.0	NS	76.4	77.6	72.2	NS	72.2 63.0	
TOTAL WEIGHT (gms)	42.5	38.3	NS	42.1	29.3	30.1	34.14	NS	66.5 52.39		51.04 NS		51.04 27.41	
MEAN WEIGHT (gms)	8.5	7.7	NS	8.4	5.9	6.0	6.83	NS	13.3 10.48		10.21	NS	10.21 5.48	

STATION No	22		23		24		25		26		27	
LENGTH (mm)	T	B	T	B	T	B	T	B	T	B	T	B
1	69	68	58	55	50	NS	63	60	50	62	68	56
2	70	75	60	58	52	NS	64	65	52	72	72	57
3	72	77	63	62	53	NS	68	65	52	72	75	58
4	77	80	73	65	56	NS	70	66	55	72	80	69
5	80	81	79	73	57	NS	80	76	57	75	85	74
MEAN LENGTH (mm)	73.6	76.2	66.6	62.6	53.6	NS	69.0	66.4	53.2	70.6	76.0	62.8
TOTAL WEIGHT (gms)	48.42	51.14	45.22	31.74	18.18	NS	41.39	30.68	20.66	60.30	47.38	35.33
MEAN WEIGHT (gms)	9.68	10.23	9.04	6.35	3.64	NS	8.28	6.14	4.13	12.06	9.48	7.07

Appendix 3

Heavy metal concentrations in *Mytilus edulis*, collected in the *upper* (U) and *lower* (L) samples of the mussels vertical distribution, with results compared between 1977 and 1989. (*) Alternative sampling site to the 1977 survey; (NS) Not sampled; (<) Limit of detection; (#) non-replicated analyses.

Station Number	HEAVY METAL CONCENTRATIONS (mg kg^{-1})							
	Cu 77 89	Zn 77 89	Cd 77 89	Mn 77 89	Pb 77 89	Cr 77 89	Ni 77 89	Fe 77 89
1								
T	1.1 NS	27 NS	0.80 NS	0.90 NS	1.10 NS	2.80 NS	<1.00 NS	33 NS
B	1.0 *1.4	21 *26	0.40 0.13	1.20 0.67	0.70 *0.48	3.60 0.22	<1.0*0.33	10 *42
2								
T	1.1 1.2	26 29	0.50 0.10	1.00 0.56	0.90 0.60	5.10 0.87	<1.0 0.19	61 17
B	NS	NS	NS	NS	NS	NS	NS	NS
3								
T	1.1 1.1	37 34	0.50 0.10	0.90 0.50	0.90 0.62	6.00 1.20	<1.0 0.25	64 8
B	NS 1.2	NS 25	NS 0.11	NS 0.57	NS 0.57	NS 0.72	NS 0.23	NS 12
4								
T	NS 1.4	NS 30	NS 0.13	NS 0.78	NS 0.48	NS 0.74	NS 0.23	NS 22
B	NS	NS	NS	NS	NS	NS	NS	NS
5								
T	1.1 1.4	31 20	0.50 0.09	1.60 0.76	1.40 0.55	7.20 0.52	<1.0 0.26	31 12
B	NS	NS	NS	NS	NS	NS	NS	NS
6								
T	0.7 1.5	24 25	0.80 0.11	1.90 0.91	1.90 0.79	2.50 0.45	<1.0 0.18	31 14
B	NS 1.2	NS 28	NS 0.10	NS 0.60	NS 0.37	NS 0.11	NS 0.20	NS 12
7								
T	1.3 *1.4	29 *29	0.4 *0.12	0.9 *0.81	0.80 *0.37	2.4 *0.96	<1.0*0.15	25 *15
B	1.2 *1.5	20 *36	0.6 *0.15	0.9 *0.87	1.00 *<.35	2.0 *0.31	<1.0*0.06	25 *13
8								
T	6.3 1.5	44 31	0.20 0.11	0.90 0.72	1.00 0.35	0.70 0.43	<1.0 0.12	29 54
B	NS	NS	NS	NS	NS	NS	NS	NS
9								
T	NS 1.2	NS 26	NS 0.11	NS 0.66	NS 0.57	NS 0.22	NS 0.18	NS 15
B	NS	NS	NS	NS	NS	NS	NS	NS
10								
T	0.9 1.7	28 34	0.50 0.20	0.90 0.57	0.70 0.35	0.2 0.07	<1.0 0.12	26 7.2
B	NS 1.4	NS 22	NS 0.26	NS 0.54	NS 0.37	NS 0.33	NS 0.25	NS 16
11								
T	1.1 *0.9	19 *20	0.7 *0.15	1.8 *0.77	1.30 *<.35	0.7 *0.53	<1.0*0.17	37 *8.3
B	NS	NS	NS	NS	NS	NS	NS	NS
12								
T	0.8 1.1	23 32	0.60 0.17	2.50 0.52	1.50 0.39	0.7 #.2	<1.0 0.05	64 16
B	NS	NS	NS	NS	NS	NS	NS	NS
13								
T	1.1 1.3	25 27	0.60 0.13	4.40 0.48	1.20 0.42	0.7 0.14	<1.0 0.11	61 8.5
B	0.9 0.9	26 20	0.30 0.13	3.70 0.61	1.30 0.81	0.8 0.33	<1.0 0.19	81 14

Appendix 3. Continued

Station Number	HEAVY METAL CONCENTRATIONS (mg kg $^{-1}$)															
	Cu		Zn		Cd		Mn		Pb		Cr		Ni		Fe	
	77	89	77	89	77	89	77	89	77	89	77	89	77	89	77	89
14																
T	2.4	*1.5	29	*26	0.3	*0.13	1.2	* 0.84	1.50	*0.47	0.6	*0.65	<1.0	*0.42	27	*13
B	2.7	NS	35	NS	0.40	NS	1.10	NS	1.00	NS	0.90	NS	<1.0	NS	27	NS
15																
T	3.6	1.2	47	24	0.70	0.13	2.50	0.72	1.10	0.64	1.9	0.38	<1.0	0.26	40	14
B	NS		NS		NS		NS		NS		NS		NS		NS	
16																
T	NS		NS		NS		NS		NS		NS		NS		NS	
B	1.5	1.2	24	23	0.40	0.22	1.00	1.50	1.10	0.75	1.1	0.35	<1.0	0.36	23	27
17																
T	5.5	1.2	85	28	1.2	0.14	0.50	0.80	4.10	0.62	0.6	0.18	<1.0	0.15	160	18
B	5.0	1.3	79	39	2.1	0.17	1.20	0.98	4.80	0.40	2.1	0.32	<1.0	0.21	186	22
18																
T	3.7	*1.3	65	*33	1.8	*0.18	3.00	*1.0	1.90	*<.35	1.40	NS	2.3	*0.17	75	15
B	3.6	NS	77	NS	2.00	NS	3.80	NS	2.30	NS	2.40	NS	1.20	NS	168	NS
19																
T	5.7	2.6	56	33	1.10	0.27	2.70	1.60	3.10	0.45	2.1	2.10	2.80	1.40	105	23
B	7.7	1.2	65	22	1.30	0.15	4.20	0.76	2.70	<.35	2.8	0.39	3.50	0.10	113	26
20																
T	1.8	1.4	30	25	0.30	0.26	1.60	0.85	1.30	0.44	0.60	#.20	<1.0	0.12	39	17
B	1.1	NS	26	NS	0.80	NS	2.70	NS	1.00	NS	1.70	NS	<1.0	NS	38	NS
21																
T	2.1	1.9	52	33	1.70	0.30	4.20	1.10	2.20	0.55	1.70	1.10	3.40	0.89	40	23
B	2.0	1.2	52	32	2.40	0.27	5.00	0.86	4.70	0.54	1.30	0.34	5.00	0.22	39	26
22																
T	13.7	1.3	135	13	5.80	0.32	6.90	0.68	2.20	<.35	2.5	0.34	<1.0	0.19	240	21
B	13.8	1.6	149	24	5.50	0.26	5.60	1.20	2.80	0.76	3.2	0.82	<1.0	1.0	361	30
23																
T	12.9	1.1	127	26	2.30	0.36	6.60	0.65	0.80	0.78	3.6	0.33	<1.0	0.26	152	27
B	14.3	1.4	132	33	3.60	0.34	3.80	0.73	1.80	0.54	3.1	0.76	<1.0	0.86	152	42
24																
T	2.4	1.2	27	17	0.30	0.23	1.80	1.00	1.90	<.35	0.6	0.55	<1.0	0.49	32	18
B	2.0	NS	31	NS	0.40	NS	1.60	NS	1.20	NS	0.80	NS	<1.0	NS	27	NS
25																
T	1.9	1.2	25	29	2.00	0.23	0.80	0.73	1.80	<.35	3.3	0.33	<1.0	0.55	39	15
B	2.0	1.0	17	32	1.80	0.23	0.60	2.00	0.80	0.48	3.2	2.20	<1.0	1.60	37	28
26																
T	1.7	1.0	19	34	0.30	0.18	1.60	1.10	1.70	0.69	1.3	0.18	<1.0	0.61	27	16
B	1.7	1.2	30	31	0.60	0.20	1.60	0.70	1.70	0.77	1.3	0.52	<1.0	0.42	48	26
27																
T	NS	1.3	NS	24	NS	0.23	NS	1.50	NS	0.57	NS	0.35	NS	0.29	NS	17
B	NS	1.4	NS	24	NS	0.28	NS	0.84	NS	0.48	NS	0.31	NS	0.48	NS	22