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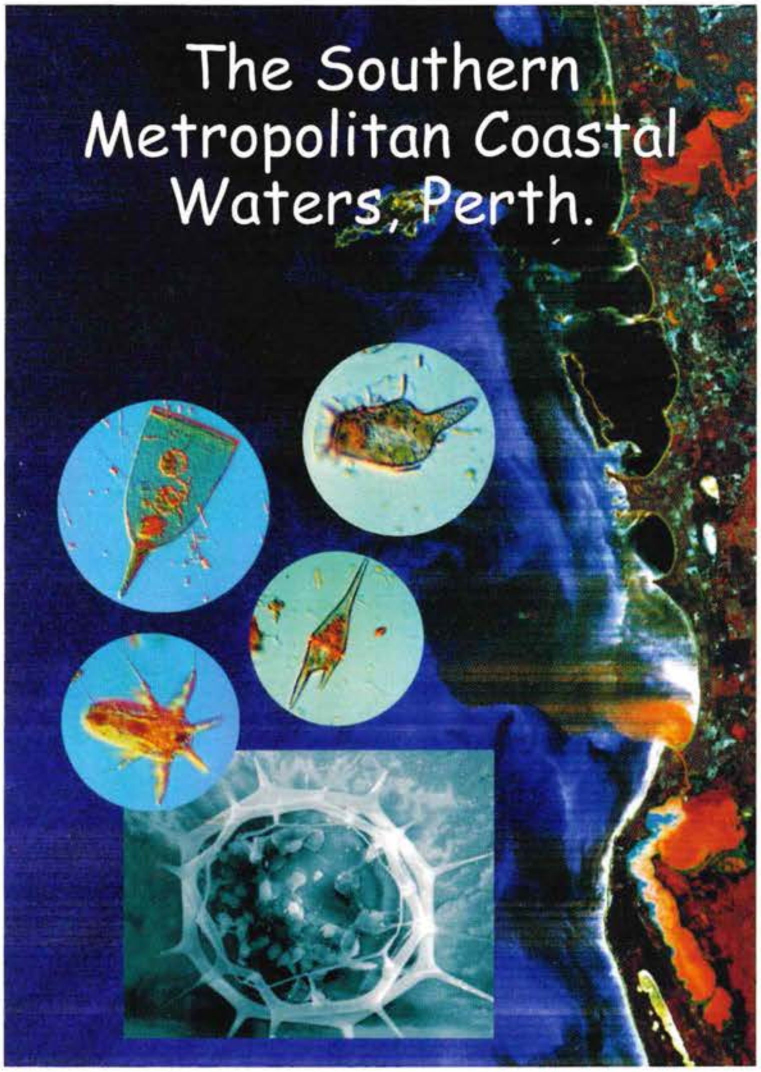
Phytoplankton and Zooplankton Dynamics in The Southern Metropolitan Coastal Waters, Perth.



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PHYTOPLANKTON AND ZOOPLANKTON DYNAMICS IN THE SOUTHERN METROPOLITAN COASTAL WATERS, PERTH, WESTERN AUSTRALIA

A report to the Department of Environmental Protection of Western Australia as part of the Southern Metropolitan Coastal Waters Study (1991-1994)

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November 1997

Technical Report Series: I Algal Research Group
School of Environmental Biology, Curtin University

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Front Cover

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Landsat thematic mapper colour image of the waters off Perth - courtesy of Department of Environmental Protection, Western Australia.

ABSTRACT

Marine biota integrate responses to environmental changes in different degrees. The plankton communities reflect water quality better than other biota, as they are at the base of nutrient and energy transfers. The structure and species composition of phytoplankton and zooplankton communities were investigated in relation to physical and chemical parameters in Cockburn Sound and Warnbro Sound, two shallow embayments of Perth coastal waters, by fortnightly sampling from August 1992 to August 1994.

Diatoms, dinoflagellates, chrysophytes and cyanobacteria were the dominant groups of phytoplankton. Summer and autumn phytoplankton assemblages were dominated by diatoms, winter and spring by silicoflagellates (chrysophytes). Dinoflagellates formed only a minor component of the assemblages throughout the year. The massive dominance of silicoflagellates during winter and spring is identified as a recent phenomenon not reported in any other temperate coastal waters of Australia. Considering the potential of silicoflagellate blooms to cause fish kills, further studies are recommended on these blooms.

The impact of estuarine eutrophication was amply reflected in characteristic phytoplankton blooms such as that of *Skeletonema costatum*. Phytoplankton were also identified as markers of Leeuwin Current influence. Phytoplankton biomass, measured by cell count and chlorophyll-a, was two and a half times higher in Cockburn Sound than in Warnbro Sound, and greater than that reported for comparable temperate coastal waters elsewhere in Australia. The high nitrogen loading in Cockburn Sound was identified as the predominant cause of the high biomass compared to Warnbro Sound. Multivariate analyses showed marked differences in phytoplankton community structure in Cockburn Sound and Warnbro Sound. Several species of potentially toxic dinoflagellates and diatoms were recorded, although they occurred in low numbers. Regular phytoplankton monitoring is recommended.

Copepods were the most abundant and diverse group of zooplankton, the other common groups being cladocerans and protozoans. From late spring to autumn the zooplankton assemblages were dominated by copepods and cladocerans. The late winter and early spring assemblages were dominated by radiolarians (protozoans).

Following the trend in distribution of phytoplankton, the structure of the zooplankton assemblages of Cockburn Sound and Warnbro Sound were statistically distinct. Zooplankton abundance in Cockburn Sound was more than twice that of Warnbro Sound. Planktonic eggs and larvae showed similar trends. Copepods, cladocerans and radiolarians were identified as the major potential grazers of phytoplankton. Among these, copepods were the most significant grazers of diatoms. Radiolarians may play a significant role in regulating silicoflagellate blooms. This needs to be further investigated.

There was a significant correlation between zooplankton and phytoplankton populations. The trophic interactions of these two groups need to be studied further.

ACKNOWLEDGMENTS

We wish to express our deepest gratitude to the following people and organisations:

Dr. Chris Simpson (formerly with the Department of Environmental Protection, now with the Department of Conservation and Land Management) and Dr. Ray Masini (D.E.P.) for providing us with the opportunity to undertake this pioneering study on the phytoplankton and zooplankton of Cockburn and Warnbro sounds.

Our skippers aboard the research vessels EX63, Diadema and Bidthangarra - Mr. Mike Lapwood, Mr. Charlie Maling, Mr. Steve Chase and Mr. Tim Daly, all of the D.E.P. All those who assisted with field work, Mr. Keith Helleren, Dr. Ray Masini, Mr. Mike Lapwood, Mr. Charlie Maling, Mr. Steve Chase, Mr. Tim Daly, and an assortment of unsuspecting work experience students.

Much thanks also to Mr. Geoff Bastyan and his team at the Centre for Water Research, Murdoch University for the analysis of chlorophyll samples.

Thanks to Mr. Sean Kelly (Curtin University) for much of the zooplankton analysis and to Dr. Rob Rippingale (Curtin University) and Mr. Wassle Hosja (Swan River Trust) for assistance with the identification of zooplankton and dinoflagellates respectively.

And finally, thanks to the School of Environmental Biology, Curtin University, for providing many of the facilities and resources which made this study possible.

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1 - INTRODUCTION

The tropical and subtropical waters around Australia are generally nutrient impoverished as a result of low terrestrial runoff, isolation from major ocean circulations and a lack of extensive upwelling systems (Hatcher 1994). In the offshore coastal waters of Perth, phytoplankton biomass has been considered to be low by world standards, possibly a result of the lack of a well-defined eastern boundary current flowing along the Western Australian coastline towards the equator; such currents induce upwelling and support high productivity on the west coasts of North and South America and Africa (Hatcher 1994).

This low biomass allows high light penetration through the water column during most of the year. Prior to the onset of anthropogenic inputs (wastes and nutrients) conditions suitable for high light penetration would have also prevailed in coastal embayments such as Cockburn and Warnbro sounds allowing the development and growth of extensive seagrass communities. Increased terrigenous and anthropogenic inputs into Perth's coastal waters might have been responsible for the dramatic increases in phytoplankton biomass. As a consequence of this, the seagrass communities appear to be restricted to lesser depths than would be expected in more pristine oligotrophic waters. Nearly an 80% reduction in the area of seagrass meadows in Cockburn Sound since the 1950s has been reported (Figure 1) (Anon 1991; Cary *et al.* 1991).

The first industries established themselves along the eastern shore of Cockburn Sound during the 1950s. At this time, very little was known about the environmental consequences of effluent discharge into the embayment and even less about the embayments' ability to assimilate and disperse these effluents (Anon 1991).

By the 1970s, the eastern shore of Cockburn Sound had become a major industrial centre, the embayment had also established itself as one of Perth's most popular recreational areas. After 20 years of unregulated effluent discharge (Anon 1991) the water quality of Cockburn Sound had degraded to such an extent that the area was no longer attractive to swimmers and beach users (Chiffings 1979).

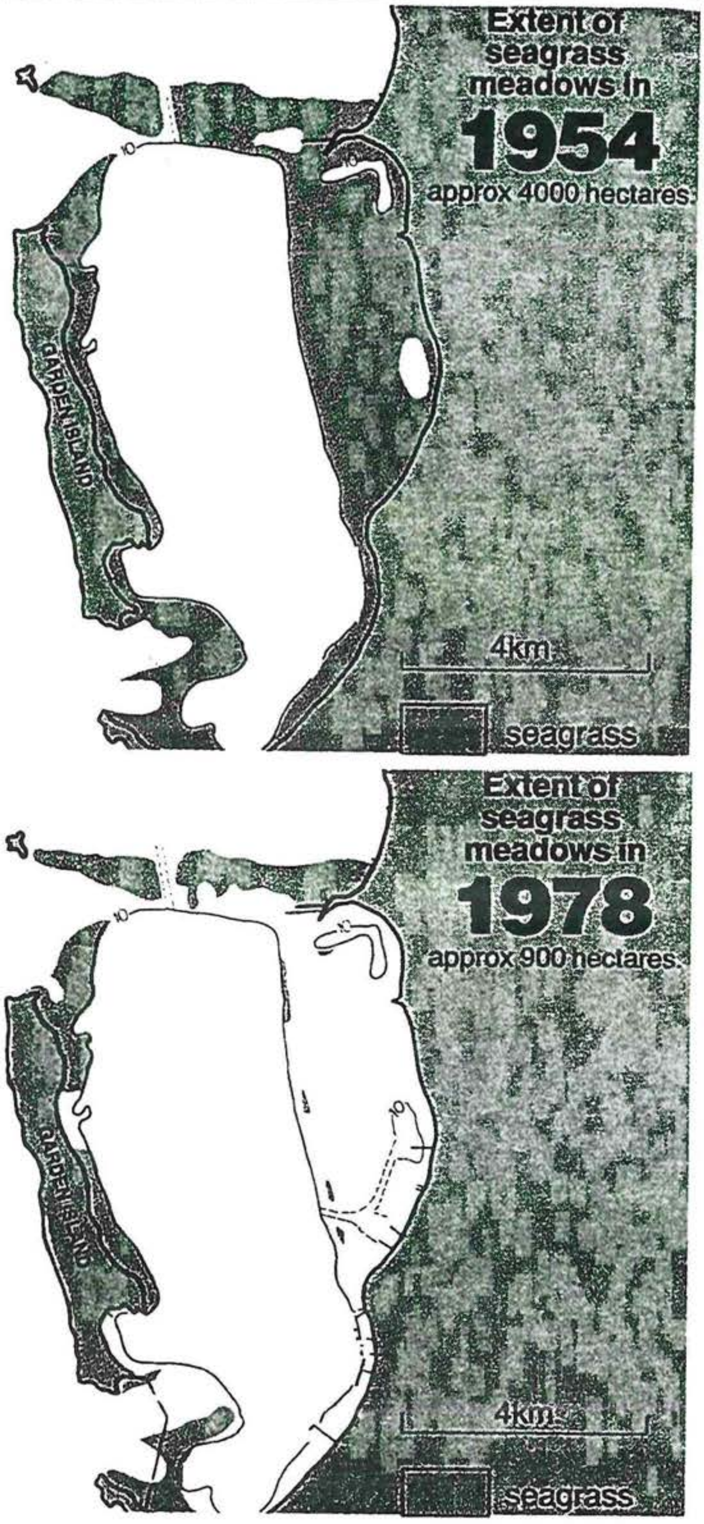


Figure 1: Changes in seagrass distribution in Cockburn Sound between 1962 and 1978 (from Anon 1991).

Cockburn Sound began to show signs of eutrophication as early as 1973 with the appearance of distinctly "coloured" water bodies within the embayment during autumn (Environmental Resources of Australia 1974a). In a subsequent report, (Environmental Resources of Australia 1974b), algal blooms were recorded during the spring and summer of 1973/74. During the same period, a general increase in the biomass of phytoplankton in Cockburn Sound compared to that of other coastal waters was also observed.

During this period, nutrient inputs into the waters of Cockburn Sound were high. Industrial effluents accounted for 79% of the total nitrogen load and 96% of the total phosphorous load into the embayment. The two main sources of these industrial effluents were CSBP & Farmers Ltd and Kwinana Nitrogen Company (KNC) (Chiffings 1979).

These inputs were significantly reduced after December 1982 when a steam scrubber was installed in the CSBP/KNC outfall, and again after July 1984 when secondary effluent began to be diverted from the Woodman Point sewage outfall (Hillman and Bastyan 1988). Both these events resulted in significant reduction in phytoplankton biomass as measured by chlorophyll-a (see section 2.5.2.2).

2 - PHYTOPLANKTON

Phytoplankton are the most important primary producers in marine environments. Estimates of the proportion of global productivity accounted for by marine phytoplankton varies from 20% (Morrisey 1995) to 25% (Jeffrey and Hallegraeff 1990) and 30% (Daly and Smith 1993). The most productive oceanic regions are those where upwellings occur, the coasts off Oregon and California (west coast of North America) Peru and Chile (west coast of South America), southern Africa and the waters of the sub-Antarctic. Continental shelf waters are responsible for 1.2% of global productivity (6% of total marine productivity) (Morrisey 1995), phytoplankton account for over 95% of marine photosynthesis (Daly and Smith 1993).

The community structure and biomass of phytoplankton populations are sensitive to changing environmental conditions, both natural (eg. seasonal) and unnatural (eg. anthropogenic impacts).

Short-term increases in nutrient loadings to coastal waters can result in rapid changes in phytoplankton populations with many species able to double their biomass in less than 24 hours under favourable conditions. Similarly, the diversity and species composition can change as a result of long-term alterations in environmental conditions caused by chronic waste inputs. Thus the biomass and species composition of phytoplankton populations are useful short- and long-term indicators of environmental change in their own right and, as a result of their effect on light penetration through the water column, as an indicator of potential light limitation impacts on benthic seagrass communities.

Information on species composition of phytoplankton communities of Perth's coastal waters is sparse. Chaney (1978) undertook a study of the phytoplankton communities in Cockburn Sound as part of the Cockburn Sound Environmental Study. Phytoplankton biomass, expressed as chlorophyll *a* concentrations, has been monitored for Perth coastal waters in several water quality surveys in the past, particularly in Cockburn Sound (Anon 1979; Chiffings 1979; Chiffings and McComb 1983; Hillman 1986; Hillman and Bastyan 1988; Cary *et al.* 1991).

In order to gain a better understanding of the phytoplankton communities in the southern metropolitan coastal waters of Perth and the factors that control these populations, intensive local-scale and complementary regional-scale studies were undertaken. The present report is the result of a two-year intensive local-scale study. Detailed analyses of species composition and abundance were conducted, focussing on the autecology of key species in view of the changes in species composition observed over recent years on a local scale and the increasing frequency of toxic red tide organism blooms on a global scale.

Results of this study show that phytoplankton biomass and productivity were 2.5 times greater in Cockburn Sound than in Warnbro Sound, that there has been a dramatic increase in the abundance of silicoflagellates in Perth's coastal waters since the late 1970s, that the coastal waters of Perth are periodically influenced by tropical waters via the Leeuwin Current, and that several potentially toxic taxa exist in the coastal waters of Perth.

2.1 - MATERIALS AND METHODS

Fortnightly cruises were conducted between August 17, 1992 and August 15, 1994 inclusive on board the D.E.P. research vessels EX63, Diadema or Bidthangarra. A total of 56 cruises were undertaken - 48 fortnightly cruises and an additional eight during the summer intensive survey December 23 1993 to March 30 1994 (see Appendix 1).

Initially four sites were sampled in each embayment. These sites corresponded to those used in previous southern metropolitan coastal waters studies (Cousins 1991) - CS11, CS9, CS6, CS4, WS7, WS5, WS4 and WS1 (Figure 2). During the February 10, 1994 cruise it was determined that two of the sites did not correspond to those of the previous studies. Site CS9 was about 750 m north of where it should have been and site WS4 about 1 500 m south of where it should have been; these sites were subsequently renamed CS12 and WS10 respectively. It was decided to continue sampling these sites and to begin sampling the original sites (CS9 and WS4) (Figure 2). Preliminary analyses of samples showed that the biota of sites CS9 and CS12 were very similar; after April 1994, site CS12 was no longer sampled. Because of its proximity to a mussel farm, site WS10 continued to be sampled, together with site WS4, until the end of the study.

In summary, sites CS12, CS11, CS6, CS4, WS10, WS7, WS5 and WS1 were sampled between August 17 1992 and January 27 1994; sites CS12, CS11, CS9, CS6, CS4, WS10, WS7, WS5, WS4 and WS1 between February 10 1994 and March 24 1994; and sites CS12, CS11, CS6, CS4, WS10, WS7, WS5, WS4 and WS1 between April 7 1994 and the end of the study, August 15 1994.

Water samples were collected from surface (1 m below surface) middle and bottom (1 m above bottom) waters at all sites except WS5 and WS1 where middle samples only were collected. Site depths were as follows; CS12 - 9 m, CS11 - 12 m, CS9 - 9 m, CS6 - 9 m, CS4 - 21 m, WS10 - 17 m, WS7 - 16 m, WS5 - 3.5 m, WS4 - 17 m and WS1 - 3.5 m.

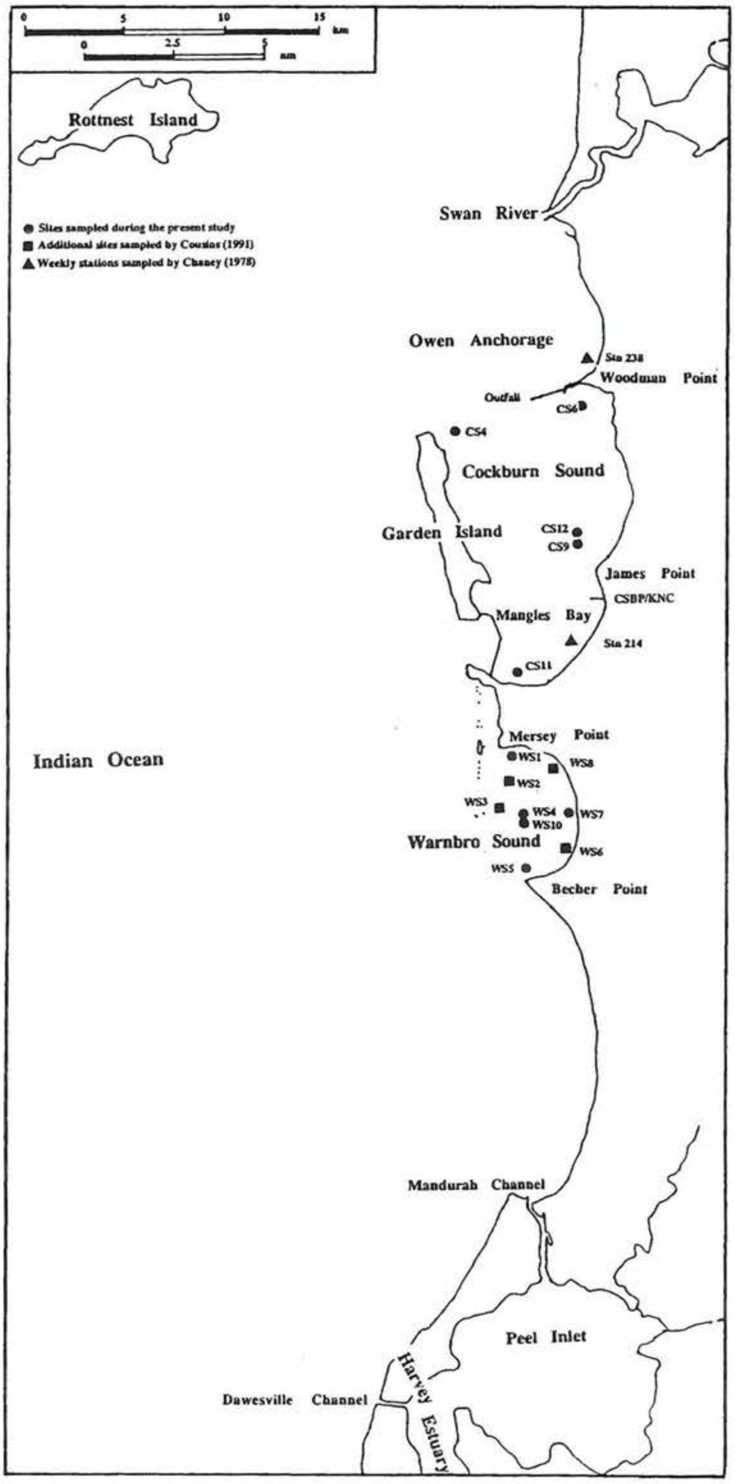


Figure 2: Regional map showing the location of all study sites in Cockburn and Warnbro sounds (including those of Chaney (1978) and Cousins (1991)).

A 10 L Niskin bottle was used to collect 20 L of water from each depth which was integrated into a 20 L bucket. Each 20 L sample was then well mixed and sub-sampled with 14 L being poured through a 10 μm phytoplankton net for phytoplankton analysis and 6 L being used for chlorophyll-a analysis.

2.1.1 - PHYTOPLANKTON SAMPLES

Phytoplankton samples were concentrated to a volume of 30 mL, transferred to labelled plastic vials, preserved with Lugol's solution and stored for analysis. These were analysed qualitatively and quantitatively using a Leitz Laborlux S photomicroscope and a Palmer nano-plankton counting cell at a magnification of 400x. For all samples a minimum of 500 phytoplankton cells were counted; from these counts, phytoplankton abundance and density were calculated. The phytoplankton were identified using a vast collection of specialised literature from Curtin University (eg. John (1983), Ricard (1987), Round *et al.* (1990), Hallegraeff (1991), Tomas (1993)). Phytoplankton data are presented in Helleren and John (1995a).

2.1.2 - CHLOROPHYLL-a SAMPLES

Six litres of water from each depth were passed through 4.7 cm Whatman glass microfibre filter papers under a slight negative pressure. After filtration, the papers were carefully removed, placed within a second unused paper, folded twice, wrapped in aluminium foil and sealed in a small labelled envelope. Chlorophyll samples were kept on ice in the field and subsequently frozen and stored for later analysis.

Chlorophyll-a concentration was measured spectrophotometrically after extraction with 90% acetone at the Center for Water Research, Murdoch University, Western Australia following the procedures of Jeffrey and Humphrey (1975).

2.1.3 - SECCHI DEPTH

Secchi depth was measured at each site. All measurements were made by the same observer on the non-shaded side of the boat, away from any churning caused by propellers.

2.2 - RESULTS and DISCUSSION

2.2.1 - DOMINANT ASSEMBLAGES

The phytoplankton of Cockburn Sound and Warnbro Sound were comprised of greater than 300 taxa representing a relatively high diversity for temperate coastal waters.

Four major groups of phytoplankton were identified: Bacillariophyta (diatoms), Dinophyta (dinoflagellates), Chrysophyta (silicoflagellates) and Cyanobacteria. Diatoms were the most diverse group, consisting of 263 taxa representing at least 59 genera (31 centric genera, 12 araphid genera and 16 raphid genera). Of these, 13 taxa require further identification to the species level. Dinoflagellates were less diverse with 66 taxa, representing at least 15 genera (8 of these taxa require further identification to the species level). There were 12 taxa of cyanobacteria (7 require further identification to the species level) and 2 taxa of silicoflagellates. Eighteen taxa belonging to minor groups including chlorococcales, chlorophytes, coccolithophorids and prymnesiophytes were also found. A complete list of taxa identified is given in Appendix 2.

In previous Cockburn Sound studies, the number of taxa found were considerably less than that for the present study. Between February and September 1991, Cousins (1991) found 95 taxa (74 diatoms, 18 dinoflagellates, 2 silicoflagellates and 1 cyanobacterium); and between July 1977 and August 1978, Chaney (1978) identified 61 taxa comprising 44 diatoms, 12 dinoflagellates and 5 unknowns from Cockburn Sound and Owen Anchorage. Greater taxonomic resolution and detailed examination of samples collected over a longer period probably account for the larger number of taxa reported in the present study.

The nutrient-poor continental shelf waters of Australia are generally dominated by nano-phytoplankton, 2 - 20 μm, (up to 95% of total chlorophyll) (Hallegraeff 1981, Jeffrey and Hallegraeff 1990, Hatcher 1994,). The nano-phytoplankton species composition of Australasian waters is remarkably similar and is generally comprised of prymnesiophytes (including coccolithophorids), prasinophytes, small non-thecate dinoflagellates, chrysophytes, cryptomonads, small diatoms and minute cyanobacteria (Jeffrey and Hallegraeff 1990).

In the waters of Cockburn and Warnbro sounds, nano-phytoplankton was sparse for most of the year. In the present study, the nano-phytoplankton was generally dominated by small diatoms (mainly chain-forming *Chaetoceros* spp.) although small cyanobacteria, small unidentified coccoid algae and a prymnesiophyte dominated on occasions. It is unlikely that either the sampling or preservation techniques were biased against the nano-phytoplankton as those which were recorded were often smaller than 10 µm and were well preserved. The only pico-phytoplankton taxa recorded from Cockburn and Warnbro sounds was the cyanobacterium *Synechococcus* sp.

Whether or not the nano- and pico- components of the phytoplankton in Cockburn and Warnbro sounds are minor or if sampling and/or preservation techniques were biased against these groups is not known at this stage although the former appears to be the case at least for the nanoplankton. Chaney (1978) also recorded very few nanoplankton, the only one being a small coccoid alga (designated Species 5) which dominated the phytoplankton during spring.

The majority of the taxa recorded are regarded as being cosmopolitan in temperate coastal marine waters. Several tropical taxa, generally characterised by their large size and/or elaborate structure, were also recorded, these taxa include a few species of diatom; *Coscinodiscus* (visible with the naked eye), *Bacteriastrum hyalinium, Rhizosolenia clevei* and *Chaetoceros coarctatus*; Round *et al.* (1990) also regard the following diatom genera as being primarily tropical or sub-tropical in origin: *Asteromphalus*, *Climacodium*, *Climacosphenia*, *Gossleriella*, *Podocystis*, *Toxarium* and *Trigonium*. A tropical species of *Ceratium* - a dinoflagellate, was also recorded. The timing of occurrence of these taxa coincides with the period of strongest flow of the Leeuwin Current suggesting that this current can influence the ecology of Perth's near-shore waters during autumn.

Other indicators of a tropical influence on Perth's coastal waters at this time included: associations between the symbiotic ciliate *Vorticella oceanica* and the diatom *Chaetoceros coarctatus* and the endosymbiotic cyanobacterium *Richelia intracellularis* and the diatom *Rhizosolenia clevei* both of which are common associations in tropical waters (Hallegraeff and Jeffrey 1993).

A tropical/sub-tropical cyanobacterium, *Oscillatoria erythraea* (*Trichodesmium erythraeum*) was also recorded in large numbers during late summer and autumn. This alga formed large slicks in both embayments as well as in offshore waters. *O. erythraea* has a wide distribution in tropical and subtropical waters (Carpenter and McCarthy 1975). *O. erythraea* has been recorded from the Philippines, the East Indian Archipelago, the east coast of South America, the Red Sea, the Arabian Sea, the East China Sea, Japan, the Sargasso Sea, North America and off the south coast of Ireland (Creagh 1985). In Australia, *Oscillatoria* blooms have been recorded in New South Wales, the Great Barrier Reef, the Dampier Archipelago and in Perth coastal waters (Cottesloe, Rottnest Island and Cockburn Sound) (Creagh 1985). Its occurrence in Perth coastal waters is likely to be due to southerly transportation in the Leeuwin current, hence it is not of local origin. Once it reaches the coastal waters of Perth, growth conditions appear to be favourable as the blooms are often sustained for several weeks.

Other taxa encountered in large numbers but not of local origin were the diatom *Skeletonema costatum* and the cyanobacterium *Nodularia spumigena*. *S. costatum* is the most common phytoplankton species blooming in the Swan River Estuary (Figure 2). Blooms of this diatom, occurring soon after early winter rains in the lower reaches of the Swan River estuary, are a well documented annual event (John 1987). *S. costatum* has also been recorded from the Peel-Harvey Estuary (Figure 2). *S. costatum* was recorded in large numbers at the mouth of the Swan River during the 1991 winter regional survey (Masini and Cousins 1995) but not at the mouth of the Peel-Harvey Estuary (Figure 3).

S. costatum proved to be a useful bio-indicator of the spatial influence of the Swan River outflow on the coastal waters of Perth as its distribution closely matched simulations of the buoyant outflow of the Swan River under similar wind conditions (Mills and D'Adamo in prep.) (Figure 3). A large bloom of *S. costatum* occurred during the present study in winter 1994. Consistent with the pattern of the Swan outflow, this bloom first appeared in northern Cockburn Sound during mid June, reached a peak throughout the embayment in early July (maximum counts of 2×10^6 cells L^{-1} at site 6-surface) and then dissipated in mid July and disappeared from the northern embayment during mid August. Over the same period, *S. costatum* numbers were much lower in Warnbro Sound. *S. costatum* was not found in Warnbro Sound during mid June, reached a peak at all sites in mid July (maximum counts of 3.3×10^5 cells L^{-1} at site 5-middle) and then dissipated, although present at all sites, during mid August (Figure 4).

Nodularia spumigena is an estuarine cyanobacterium which, prior to the opening of the Dawesville Channel (Figure 2) in April 1993, bloomed annually in the Peel-Harvey Estuary during spring and summer. Outflowing tides consisting of *N. spumigena* from the Peel-Harvey Estuary regularly spread into the waters of the Indian Ocean. *N. spumigena* does not survive in marine waters not being able to tolerate salinities greater than about 33 ‰.

N. spumigena also could be used as a bio-indicator of the spatial influence of the Peel-Harvey Estuary outflow on the coastal waters of Perth. During November 1992, *N. spumigena* was found at all sites in Warnbro Sound being most abundant in the southern and central embayment. Cell counts reached a peak of 1.6×10^6 cells L^{-1} in the southern part of the embayment in late November (Figure 5). *N. spumigena* was only found on one occasion in Cockburn Sound at the north eastern tip of Garden Island during late November; cell count was low, 4.3×10^3 cells L^{-1}. This distribution resembles the area of influence of Peel-Harvey waters which flow northwards passing the southern tip of Warnbro Sound and the western side of Garden Island.

There has not been any reported blooms of *N. spumigena* in the Peel-Harvey estuary since the opening of the Dawesville Channel (Chase 1995).

Diatom assemblages were generally dominated by relatively few taxa including: *Asterionellopsis glacialis* (= *Asterionella formosa* and *A. japonica*), *Cerataulina pelagica*, *Chaetoceros* spp., *Cylindrotheca closterium* (= *Nitzschia closterium*), *Eucampia cornuta*, *Guinardia flaccida*, *Leptocylindrus danicus*, *L. minimus*, *Nitzschia seriata*, *Rhizosolenia stolterfothii*, *R. styliformis*, *Thalassionema frauenfeldii*, *Thalassiosira pseudonana* and *Skeletonema costatum*.

Dinoflagellate assemblages were dominated by *Ceratium furca*, *C. lineatum*, *Dinophysis caudata* var. *pediculata*, *Mesoporos* sp., *Prorocentrum micans* and *Scrippsiella* sp. Silicoflagellate assemblages consisted of only two taxa, *Dictyocha octonaria* and *D. fibula* var. *rhombica*, and were almost exclusively dominated by *D. octonaria*.

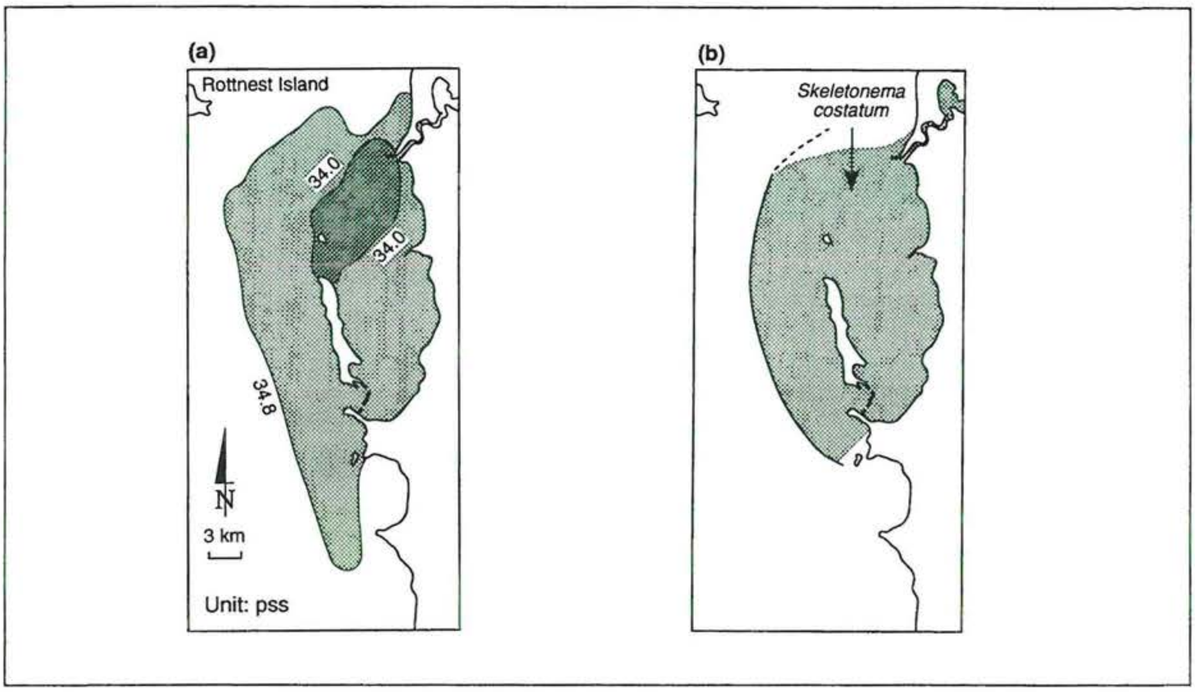


Figure 3: a) Simulation of the buoyant outflow of the Swan River (simulated surface salinity) under similar wind conditions as those recorded during the 1991 winter regional survey (Mills and D'Adamo in prep.) b) Spatial distribution of the diatom *Skeletonema costatum* during the 1991 winter regional survey (Masini and Cousins 1995).

Cyanobacteria were found sporadically throughout the study and generally occurred as monospecific blooms of *Oscillatoria erythraea*. The *Nodularia spumigena* found, as previously mentioned, were obviously transported northward from the Peel-Harvey estuary and were not in living condition. *Richelia intracellularis* and *Synechococcus* sp. were also abundant at times. Of the other algal groups, several dominated the phytoplankton at times, including an unidentified coccoid algae and a prymnesiophyte.

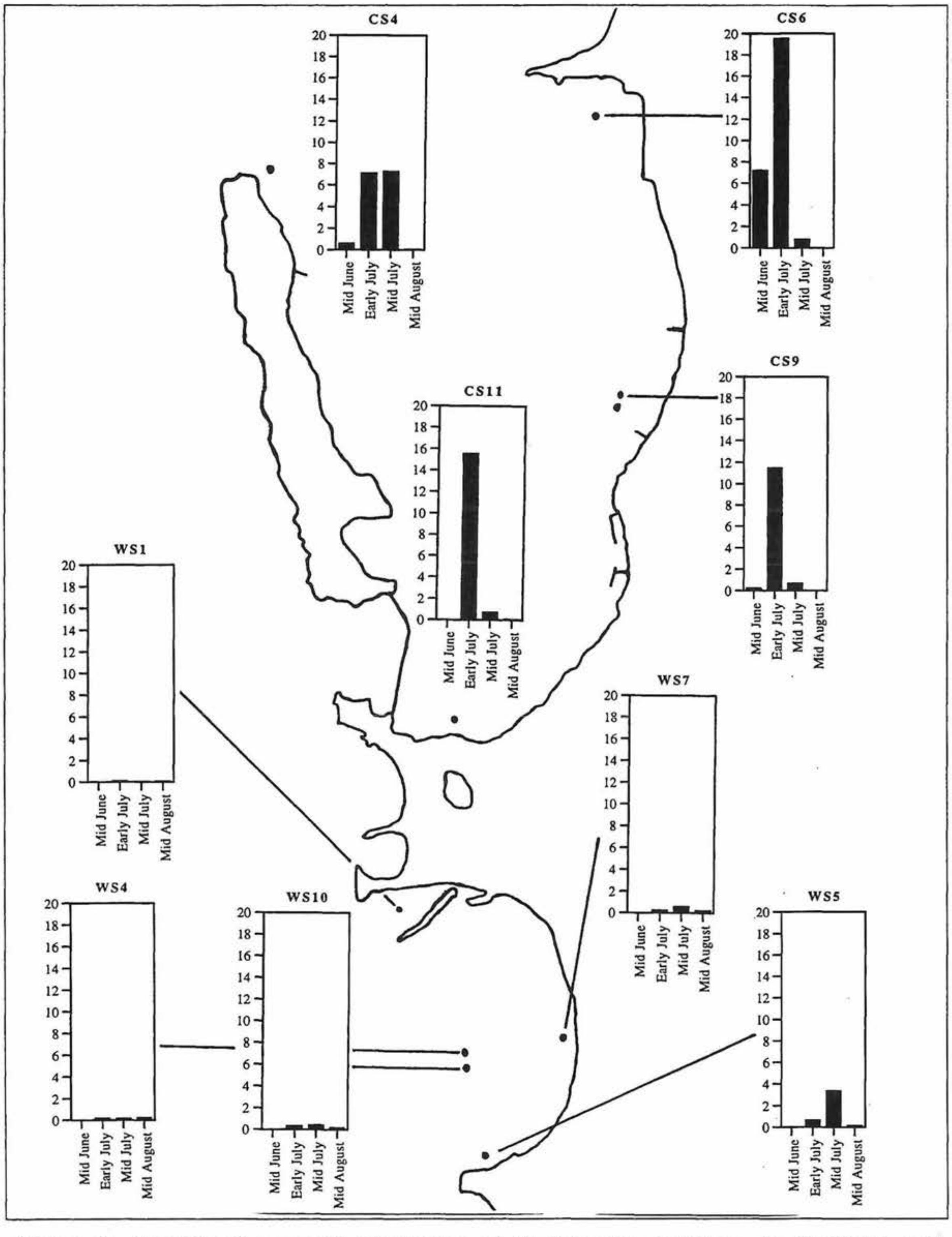


Figure 4: Spatial and temporal distribution of *Skeletonema costatum* in Cockburn and Warnbro sounds between mid June and mid August 1994. Vertical axis = Abundance (x 10^5 Cells L^{-1}).

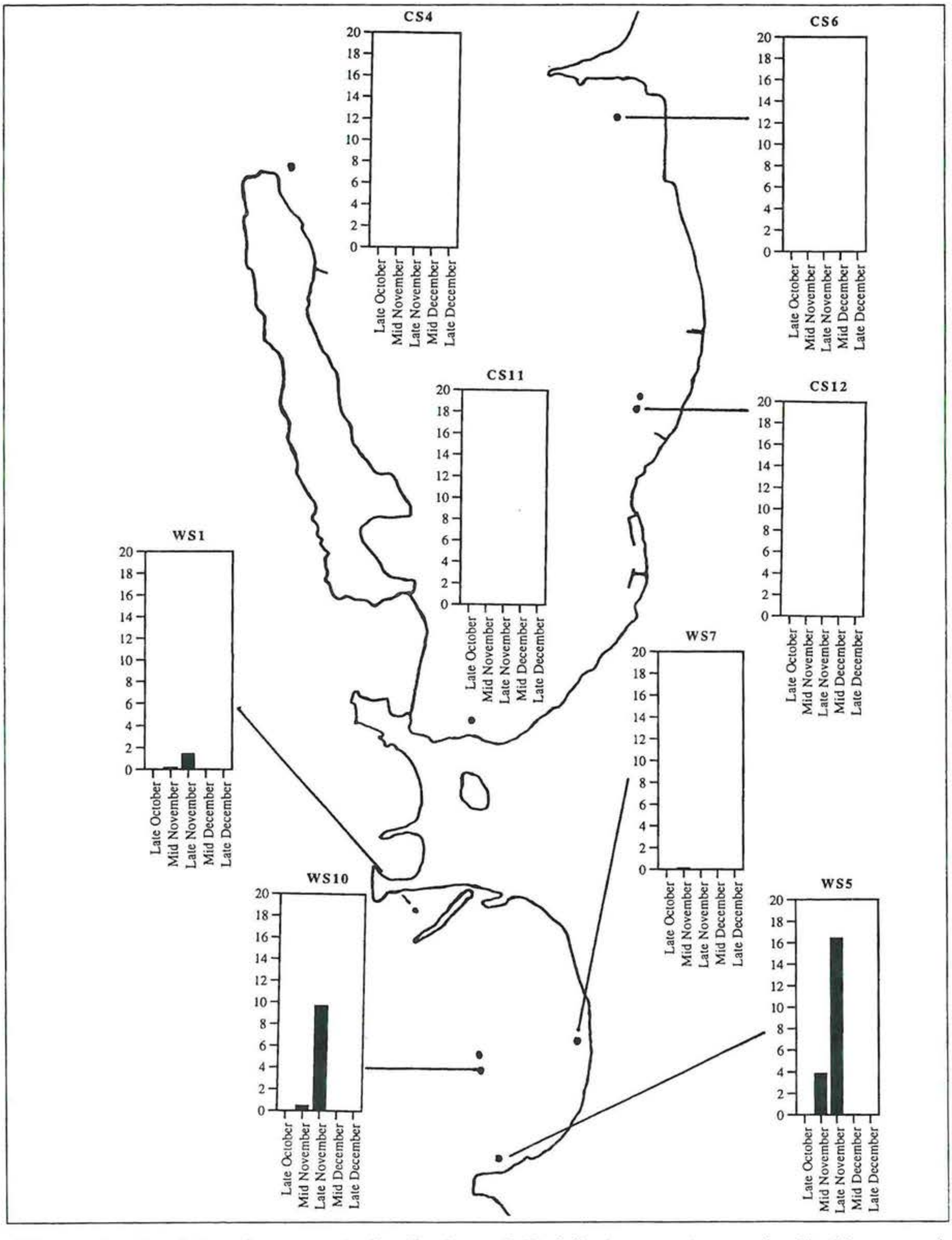


Figure 5: Spatial and temporal distribution of *Nodularia spumigena* in Cockburn and Warnbro sounds between late October and late December 1992. Vertical axis = Abundance (x 10^5 Cells L^{-1}).

2.2.2 - SPECIES SUCCESSION

Distinct seasonal patterns in phytoplankton assemblage succession common to both Cockburn Sound and Warnbro Sound have been recognised. These patterns were similar to those reported by Cousins (1991) and thus have been observed to re-occur over three annual cycles (1991 - 1994). Data were recorded over only one annual cycle in Sepia Depression (Cousins 1991), but the pattern was identical to the embayments and is considered likely to be common to Sepia Depression as well.

The basic annual pattern of species succession can be summarised as follows: summer and autumn assemblages were generally dominated by diatoms while winter and spring assemblages were usually dominated by the silicoflagellate *Dictyocha octonaria*. Dinoflagellates were present throughout the year usually at low abundances, blooms of the tropical cyanobacterium *Oscillatoria erythraea* were common in summer and autumn (Figures 6 and 7).

These seasonal patterns were generally the same for both embayments with the exception of occasional differences caused by regional effects, ie. *Oscillatoria erythraea* blooms in both Cockburn Sound and Warnbro Sound and *Skeletonema costatum* in Cockburn Sound). There was also some spatial heterogeneity within each embayment. This is to be expected in a shallow marine ecosystem with limited hydrological mixing. The resulting patchiness with respect to water quality creates a corresponding patchiness with respect to phytoplankton distribution.

Patchiness of phytoplankton communities is well documented in the literature. Stavn (1971) lists several factors responsible for phytoplankton patchiness, these include: physical/chemical boundary conditions such as light, temperature and salinity gradients; advective effects such as wind and water transport including small-scale variations due to turbulence; reproductive rates within phytoplankton populations; social behaviour within populations (more relevant to zooplankton); and coactive factors determined by interspecies competition.

Minor differences in vertical distribution were observed at most sites but these were primarily due to the presence of benthic species in bottom and sometimes middle samples rather than any large scale differences in the phytoplankton assemblage.

2.2.2.1 - DIATOMS

Diatom blooms generally occurred during spring and throughout summer, sometimes into autumn, with a succession of species dominating throughout the year (Figures 6 and 7).

In Cockburn Sound, diatom blooms were initiated during spring by small chain-forming species, usually *Leptocylindrus* sp. sometimes small *Chaetoceros* species as well. The 1992 spring bloom was initiated by *Leptocylindrus* sp. in mid spring, followed by a dominance of larger chain-forming species, *Leptocylindrus danicus* and *Rhizosolenia stolterfothii*, in late spring, then by the small centric diatom *Thalassiosira pseudonana* in late spring and early summer, the small chain-forming *Nitzschia seriata* in early and mid summer, and finally by small *Chaetoceros* species in late summer and early autumn as the bloom declined.

The 1993 spring bloom was not as clearly defined with a major peak in early spring dominated by *Leptocylindrus* sp. and small *Chaetoceros* species followed by larger chain-forming species, *L. danicus*, *L. minimus*, *N. seriata* and *R. stolterfothii* throughout mid and late spring, as the bloom declined. Throughout summer and autumn there were a series of small peaks which were generally dominated by the larger chain forming species, mainly *L. danicus*, interspersed with periods which were dominated by small *Chaetoceros* species, late summer - early autumn and late autumn. A large bloom of the small chain-forming diatom *Skeletonema costatum* occurred throughout early winter 1994, this was followed by a minor peak of small *Chaetoceros* species in mid winter.

The diatom assemblages of Warnbro Sound were characterised by a series of peaks throughout the year predominantly in spring, summer and early autumn. The 1992 spring bloom was initiated by a minor peak of *Leptocylindrus* sp. in mid spring followed by a period dominated by *N. seriata*, late spring through to late summer, in which there were two large peaks in abundance. There was a large peak of *L. minimus* during late summer which was followed by a period of low abundance dominated by small *Chaetoceros* species and *Cylindrotheca closterium* throughout early autumn.

Small *Chaetoceros* species continued to dominate throughout autumn with peaks in early and late autumn. Diatom abundance was low throughout winter, the assemblage was generally dominated by *L. danicus*. The 1993 spring bloom was poorly defined consisting of a series of small peaks throughout spring, summer and autumn.

The winter bloom was initiated by the chain-forming *Thalassionema frauenfeldii* and *Thalassiosira pseudonana*. *Leptocylindrus* sp. and small *Chaetoceros* species dominated throughout late winter and mid spring followed by larger chain-forming species, *L. minimus*, *L. danicus* and *R. stolterfothii* throughout late spring and early summer as the bloom declined. Several minor peaks, primarily small *Chaetoceros* species, *L. danicus* and *C. closterium*, occurred throughout the remainder of summer and autumn, prior to a small *Skeletonema costatum* bloom in early winter which was followed by a larger peak of large chain-forming species, *Rhizosolenia stolterfothii* and *R. setigera* in mid winter.

Generally, both the timing of diatom blooms and the composition and succession of diatom assemblages recorded for Cockburn and Warnbro sounds are similar to those reported from the temperate east coast of Australia. Diatom blooms are usually initiated during early spring by small chain-forming diatoms with other groups succeeding as the bloom progresses. Diatom abundance decreases during early summer, increasing during late summer and autumn and reaching a minimum in winter (Hallegraeff 1981, Hallegraeff and Reid 1986, Kingsford 1995). Although the timing and duration of diatom blooms may be reasonably consistent, Hallegraeff (1981) points out that the dominants and sub-dominants may vary from bloom to bloom and year to year. This is an important consideration as the progressive changes in species composition are due not only to broad-scale climatic factors such as light, temperature and turbulence, but also due to regional and local-scale factors such as the availability of organic and inorganic nutrients, organic chelators and vitamins and intraspecific and interspecific factors including grazing (Hallegraeff and Reid 1986).

2.2.2.2 - DINOFLAGELLATES

Dinoflagellates were never a major component of the phytoplankton assemblage with a maximum abundance of 5.6×10^4 cells L^{-1} in Cockburn Sound and 3.4×10^4 cells L^{-1} in Warnbro Sound. Although dinoflagellate abundance was consistently lower in Warnbro Sound they accounted for roughly the same proportion of the phytoplankton assemblages. Dinoflagellates rarely accounted for more than 20% of the phytoplankton assemblages of both Cockburn Sound and Warnbro Sound and often formed less than 5% of the assemblage. Dinoflagellates dominated the phytoplankton assemblage on only one occasion in Cockburn Sound (early September 1992) and on two occasions in Warnbro Sound (mid March 1993 and late December 1993) (Figures 6 & 7).

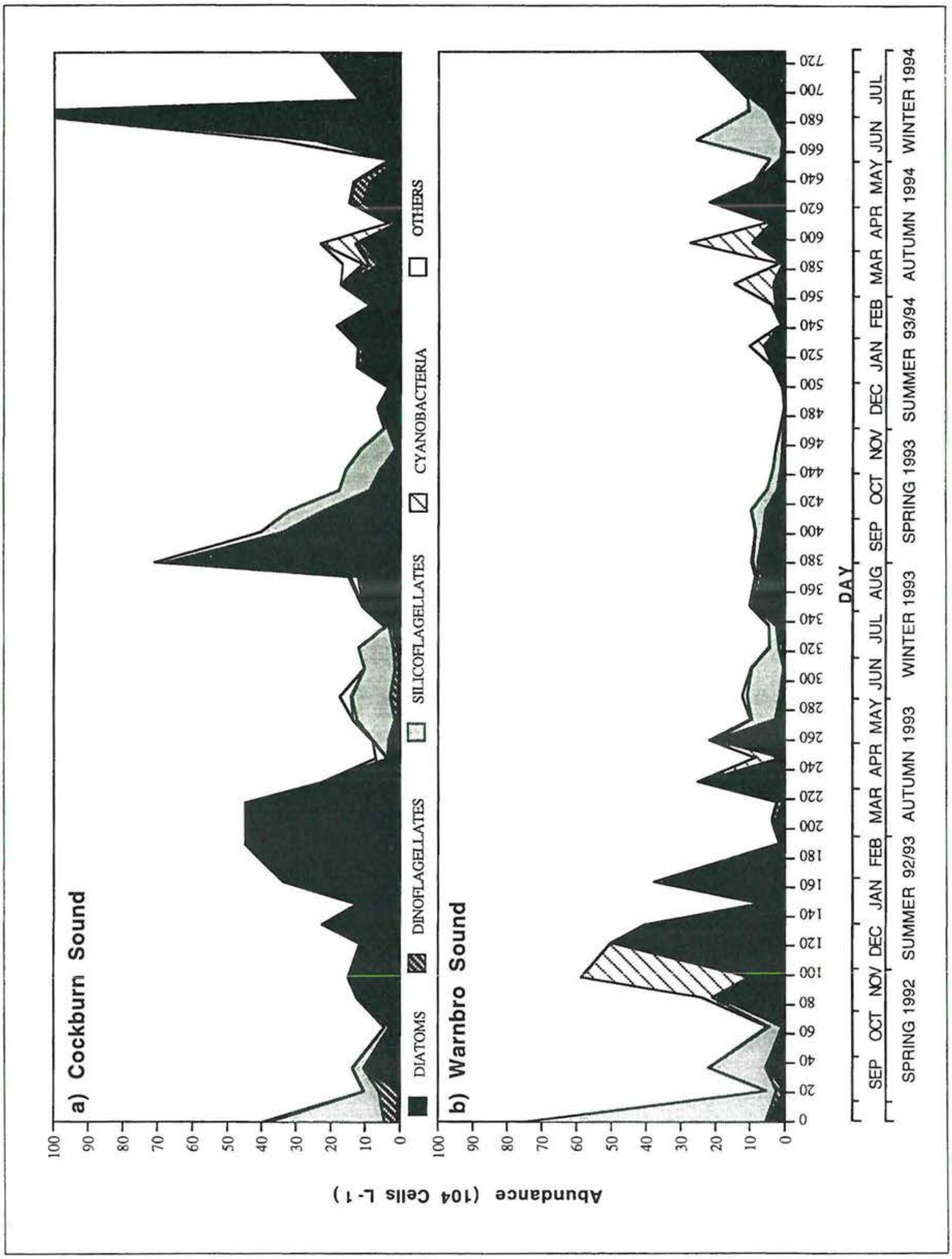


Figure 6: Timeseries plot showing abundance of the five major phytoplankton groups in Cockburn Sound and Warnbro Sound between August 1992 and August 1994.

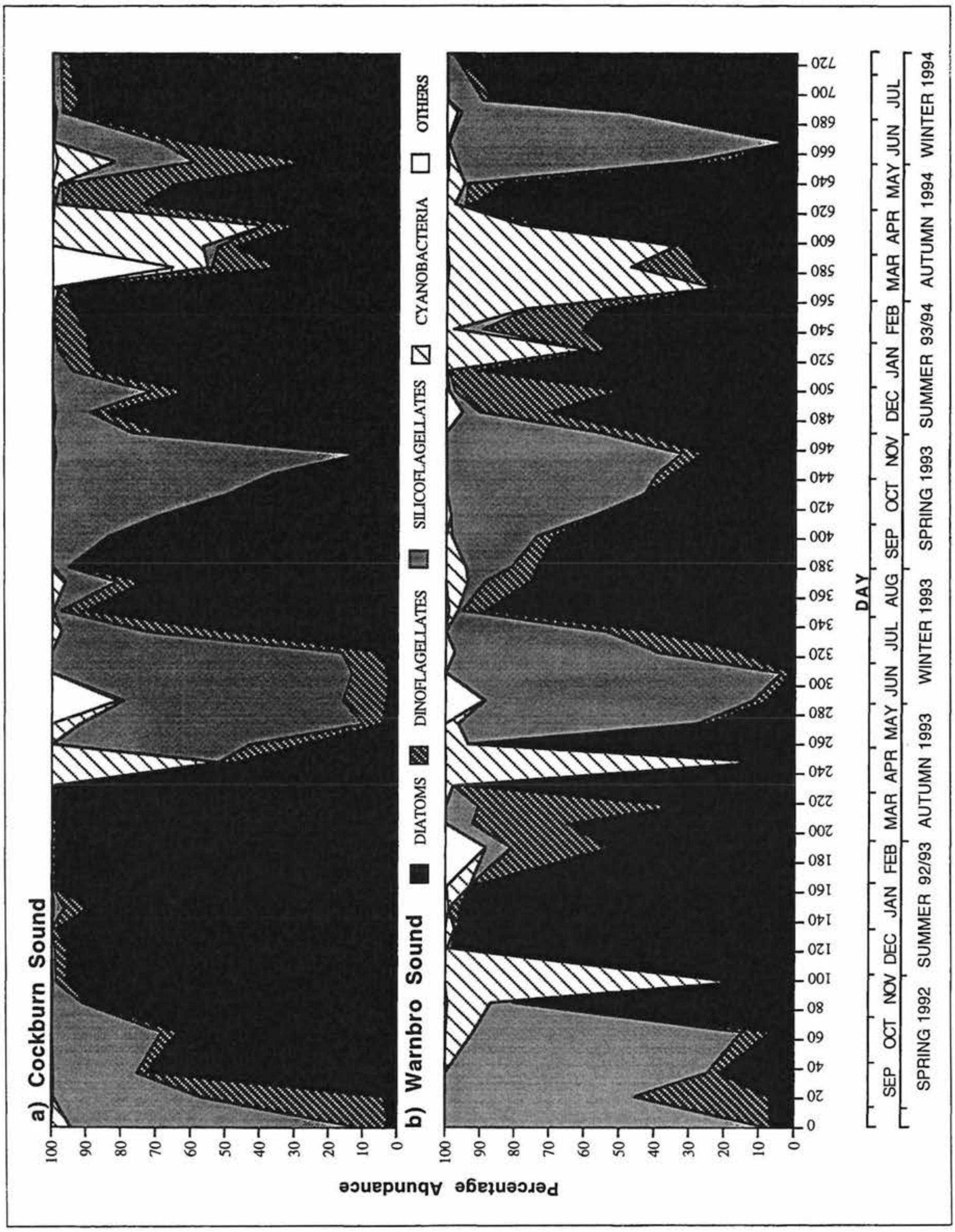


Figure 7: Timeseries plot showing relative abundance of the five major phytoplankton groups in Cockburn Sound and Warnbro Sound between August 1992 and August 1994.

There were some distinct seasonal patterns in dinoflagellate abundance but the years in which they occurred were not consistent between embayments. Peaks occurred in early September 1992 (both embayments), late March (1993 in Warnbro Sound, 1994 in Cockburn Sound), mid May 1994 (both embayments), early July (1993 in Warnbro Sound, 1994 in Cockburn Sound) and late August 1993 in Warnbro Sound only. Species succession within the dinoflagellate assemblage was much more stable than that of the diatoms with prolonged periods of dominance by the same species. Peaks in dinoflagellate abundance were generally dominated by *Mesoporos* sp. (early spring 1992 in both embayments) or species of *Ceratium*; *C. furca* in Cockburn Sound (late autumn and throughout winter 1993, summer 1993/94, late autumn - early winter 1994) and *C. furca* and *C. lineatum* in Warnbro Sound (late summer - early autumn 1993, mid winter 1993, mid - late summer 1993/94, early autumn 1994).

Throughout the remainder of the year dinoflagellate abundance and dominance was low, a variety of species dominated the dinoflagellate assemblages at different times but the species involved were relatively few.

The timing of dinoflagellate peaks in the present study were reasonably consistent with peak periods of dinoflagellate abundance reported in the literature for Australian coastal waters (Hallegraeff 1981, Hallegraeff and Reid 1986, Nielsen 1991, Heiskanen and Kononen 1994, Kingsford 1995) apart from mid winter peaks in 1993 (Warnbro Sound) and 1994 (Cockburn Sound) and a late winter peak in 1993 (Warnbro Sound). Chaney (1978) reported that dinoflagellates generally occupied a secondary role to diatoms although they occasionally reached abundances 20 - 30% of the phytoplankton assemblages. The dominant genera, *Prorocentrum*, *Protoperidinium*, *Ceratium*, *Mesoporos* and *Dinophysis* were the same as those recorded in the present study.

2.2.2.3 - SILICOFLAGELLATES

Silicoflagellates generally dominated the phytoplankton assemblages of Cockburn and Warnbro sounds during winter and spring. They were usually present throughout the rest of the year but in low abundances (Figures 6 & 7). The silicoflagellate assemblage consisted of only two species, *Dictyocha octonaria* and *D. fibula* var. *rhombica*, the former being dominant.

The only times when *D. fibula* var. *rhombica* dominated were generally when silicoflagellate abundances were low just prior to blooms during autumn, these periods of *D. fibula* var. *rhombica* dominance were more prolonged in Cockburn Sound.

Peaks in silicoflagellate abundance occurred in August 1992 in both embayments (3.3×10^5 cells L^{-1} in Cockburn Sound and 7.0×10^5 cells L^{-1} in Warnbro Sound), late September in Warnbro Sound (1.6×10^5 cells L^{-1}), May - July 1993 in both embayments (1.1×10^5 cells L^{-1} and 9.4×10^4 cells L^{-1} respectively), September - November 1993 in both embayments (1.0×10^5 cells L^{-1} and 4.1×10^4 cells L^{-1} respectively - an unusual spring bloom) and June - July 1994 in both embayments (1.1×10^5 cells L^{-1} and 2.5×10^5 cells L^{-1} respectively).

The 1993 silicoflagellate bloom was interrupted by a bloom of diatoms in mid winter. This diatom bloom continued into spring after which silicoflagellates dominated the assemblage once again. Although silicoflagellate dominance usually diminished by late spring, in this instance the silicoflagellates peaked in late spring and continued to dominate into early summer. An early summer silicoflagellate bloom was also reported by Cousins (Cousins and Masini 1992) for the summer of 1991/92.

In 1994, the winter bloom was cut short by a large bloom of the diatom *Skeletonema costatum* which originated in the Swan River Estuary to the north, silicoflagellates did not resume dominance after this bloom. Silicoflagellate abundance was at its lowest between mid-late spring and mid-late autumn (with the exception of the unusual spring bloom mentioned above), generally accounting for less than 5% of the phytoplankton assemblages in both embayments.

Although Cousins (1991) reported similar seasonal trends in silicoflagellate abundance as those for the present study, Chaney (1978) never recorded silicoflagellates in any great abundance. Silicoflagellates were generally more abundant in Warnbro Sound than in Cockburn Sound in both the present study and that of Cousins (1991).

Only the armoured stage of either *D. octonaria* or *D. fibula* var. *rhombica* were recorded in the present study, however both armoured and unarmoured stages of *D. octonaria* were recorded from Cockburn and Warnbro sounds by John, Cousins and Masini (1992).

Three silicoflagellate taxa have been recorded from Port Phillip Bay in Victoria; *D. fibula*, *D. octonaria* and *D. speculum* (Moestrup and Thomsen 1990, Wood and Beardall 1992). Wood and Beardall (1992) make no mention of the seasonality or abundance of these taxa only listing them in a species list. Naked stages, which could belong to either taxa, have been reported from Port Phillip Bay by Moestrup and Thomsen (1990).

The naked (unarmoured) stage of *D. speculum* has been recorded from Danish waters every year since 1983 first appearing at the beginning of May (late spring). *D. octonaria* has not been recorded from Danish waters, however, the preferred season for *D. speculum*, a closely related species, is early autumn, reasonably consistent with that of *D. octonaria* in the present study. The armoured stage of *D. speculum* is almost absent during spring with unarmoured stages being 100 times more abundant than the armoured stages (Moestrup and Thomsen 1990). A major monospecific bloom of *D. octonaria* was recorded off Newcastle (NSW) on the east Australian coast from February 9 - 18 1993, extending up to 3 km offshore (Hallegraeff pers. comm.).

Silicoflagellates are known to occur widely, particularly in temperate and polar regions, however they are not regarded as being dominant in the phytoplankton of present-day oceans (Van Valkenburg 1980, Takahashi 1987). They are a temperature-sensitive group (Van Valkenburg 1980) preferring temperatures less than 15°C (Travers and Travers 1968, Van Valkenburg and Norris 1970). They are abundant in the Southern Ocean and have also been recorded from the East Australian Current and Tasmanian coastal waters (Jeffrey and Carpenter 1974, Hallegraeff and Jeffrey 1984). Although relatively abundant in the East Australian Current, especially during autumn, they never comprise more than 10% of phytoplankton biomass (Jeffrey and Vesk 1990). Jeffrey and Hallegraeff (1990) report short bursts of silicoflagellates off the New South Wales coast during early autumn.

The seasonality of silicoflagellate occurrence reported for Cockburn and Warnbro sounds in the present study is reasonably consistent with that reported in the literature. There is however, a marked difference in silicoflagellate dominance and abundance between the southern metropolitan coastal waters of Perth and other temperate Australian coastal waters. The magnitude of abundance consistently observed since 1991 in Cockburn Sound and Warnbro Sound has not been recorded elsewhere in Australia.

2.2.2.4 - CYANOBACTERIA

At most times of the year cyanobacteria generally formed only a minor component of the phytoplankton assemblages of Cockburn and Warnbro sounds with abundances well under 1×10^3 cells L^{-1}. The cyanobacteria comprised a more significant component of the phytoplankton in Warnbro Sound than in Cockburn Sound although overall abundance was lower (Figures 6 & 7).

Peaks in cyanobacterial abundance occurred during autumn and were always associated with annual regional blooms of *Oscillatoria erythraea* (Figures 6 & 7). These *O. erythraea* blooms had an extremely patchy distribution, usually occurring in isolated "slicks", and abundances between sites in both embayments varied considerably.

O. erythraea is a filamentous, non-heterocystous, aggregate forming species of tropical-subtropical origin (Guo and Tester 1994). It is transported to the coastal waters of Perth from northern waters in the Leeuwin Current, where it regularly blooms each summer and autumn (Creagh 1985) as discussed in Section 2.2.1.

During the present study, *Oscillatoria* abundances were greatest in both embayments during early April 1994 with maximum abundance of 6.0×10^5 cells L^{-1} in Cockburn Sound and 4.9×10^5 cells L^{-1} in Warnbro Sound. These were considerably higher than the maximum abundance recorded in the autumn of 1993 (1.8×10^5 cells L^{-1} in Cockburn Sound, 2.0×10^5 cells L^{-1} in Warnbro Sound) and the autumn of 1991 (about 2.8×10^3 L^{-1} in Cockburn Sound) (Cousins 1991). Maximum abundances of *O. erythraea* were consistently recorded in surface waters.

Throughout the present study, *Oscillatoria* blooms usually occurred during periods of calm seas and light winds (personal observation). Originally it was assumed that rougher conditions disperse the blooms making them less obvious although still present. However, rough seas and high turbulence disrupt and destroy blooms by breaking up the bundles into which the trichomes (filaments) characteristically accumulate (Creagh 1985). These bundles are thought to act in a similar way to heterocysts, protecting the sites of nitrogen fixation (in this case the inner trichomes) from the harmful effects of exposure to oxygen.

Increased turbulence due to wave and wind action has been shown to break up these bundles causing a marked decrease in nitrogen fixation.

Creagh (1985) gives details of *Oscillatoria* density during a bloom in the Dampier Archipelago in 1984. Density was measured in terms of bundle numbers under three different bloom conditions; barely visible, clearly visible and dense. Densities measured were 1.2 x 10^5, 2.93 x 10^6 and 3.89 x 10^7 bundles L^{-1} respectively. These figures are difficult to compare to others measured as cells L^{-1}, however Carpenter and McCarthy (1975) estimated that, on average, *Oscillatoria* colonies contain 3.0 x 10^4 ± 7.8 x 10^3 cells, if these colonies are the same as bundles, Creagh's data translates to maximum cell counts of 4.51 x 10^9, 1.1x10^{11} and 1.46 x 10^{12} cells L^{-1}; a possible 7 500 to 2.5 million fold difference in *Oscillatoria* cell numbers in the northern waters of Western Australia where the blooms originate compared to the coastal waters of Perth. However, synchronous data need to be obtained from several locations along the Western Australian coastline to fully establish the extent and magnitude of these blooms.

Carpenter and McCarthy (1975) report maximum cell counts of 1.2 x 10^3 cells L^{-1} (at a depth of 25 m) during a *Oscillatoria thiebautii* bloom in the Sargasso Sea, the cell count 1 m below the surface was 8.3 x 10^2 cells L^{-1}. Carpenter and Price (1977) report maximum *Oscillatoria* cell counts of 3.0 x 10^5 cells L^{-1} and 6.5 x 10^4 cells L^{-1} from the Caribbean and Sargasso Seas respectively. These values are considerably lower than those reported in the present study.

Several other cyanobacterial taxa were recorded from both embayments, these played a minor role in Cockburn Sound with Cyanobacteria #1, *Richelia intracellularis*, *Spirulina* sp. and *Synechococcus* sp. generally accounting for less than 2% of the phytoplankton assemblage when present. In Warnbro Sound however, several cyanobacterial taxa played major roles in the phytoplankton assemblages at various times. The two main taxa were *Richelia intracellularis* and *Synechococcus* sp. These occasionally dominated the phytoplankton assemblage reaching maximum counts of 8.6 x 10^4 and 2.2 x 10^4 cells L^{-1} respectively.

Richelia intracellularis is an endosymbiotic cyanobacterium. It is the most commonly reported and most easily observed cyanobacterium living in association with marine diatoms (Villareal 1992). It has been reported as both an endo- and exo-symbiont occurring within or on cells of *Rhizosolenia*, *Hemiaulus*, *Bacteriastrum* and *Chaetoceros* (Villareal 1992). According to the literature, *R. intracellularis* has been reported as occurring in up to 12 species of *Rhizosolenia*, however, Sundström (1984) suggests that many of these reports are misidentifications and that most, if not all, of the *Richelia* hosts were varieties *Rhizosolenia clevei*.

Richelia endosymbionts within *Rhizosolenia* cells are easily visible under low magnification and always occur at the extremities of the cell (Villareal 1992). *Richelia* is mainly found in tropical and subtropical waters and, according to Marshal (1981), is only found in coastal waters when it is associated with intrusions of offshore waters. During early autumn 1994 in Warnbro Sound, *R. intracellularis* was found associated with the diatom *Rhizosolenia clevei*, an association common in tropical waters suggesting Leeuwin Current influence. Large numbers of free-living *Richelia* filaments were also found at this time. Summer blooms of *Richelia intracellularis* are an annual event in the central North Pacific gyre (Venrick 1974). Cell counts during these bloom events exceeded 1.0 x 10^5 cells L^{-1}, considerably less than those recorded in the present study. Venrick (1974) reported no clear relationship between the *Richelia* blooms and ambient nutrient levels conceding that a bloom-inducing factor could not be found.

Villareal (1992) reported that *Oscillatoria* and *Richelia-Rhizosolenia* blooms had not previously been recorded together and posed the question as to whether or not blooms of these two diazotrophs are mutually exclusive. The present study clearly illustrates that this is not the case, the two do co-occur.

Synechococcus sp. is a marine cyanobacterium which occurs in abundance in the picophytoplankton of temperate, subtropical and tropical oceans (Gallager *et al.* 1994; Ikeya *et al.* 1994). *Synechococcus* cell counts range from 10^6 cells L^{-1} in oligotrophic systems such as the Sargasso Sea to more than 10^9 cells L^{-1} in nutrient rich coastal embayments (Gallager *et al.* 1994). These are much greater than those recorded in the present study, maximum = 2.2 x 10^4 cells L^{-1}. *Synechococcus* has also been recorded in large numbers, up to 3.6 x 10^{10} cells L^{-1} in 1990, from the Peel-Harvey estuary (Hosja and Deeley 1994, Chase 1995).

It is possible that *Synechococcus* sp. is much more abundant in Cockburn and Warnbro sounds but may be heavily grazed as is suggested by Gallager *et al.* (1994).

2.2.2.5 - OTHERS

Of those phytoplankton grouped as "others", only three taxa ever occurred in an abundance of more than one percent in Cockburn Sound, two unidentified coccoid algae and a prymnesiophyte; and only four taxa ever occurred in an abundance of more than one percent in Warnbro Sound, an unidentified coccoid alga, a coccolithophorid and a prymnesiophyte.

In Cockburn Sound, there were only two peaks in the abundance of this group, one a prymnesiophyte bloom (3.3 x 10^4 cells L^{-1}) in early June 1993, average site abundances ranged from 2.2 x 10^4 cells L^{-1} at site 11 to 8.0 x 10^4 cells L^{-1} at site 6; and the other a bloom of the two unidentified coccoid alga (5.8 x 10^4 cells L^{-1}) in late March 1994, average site abundance for coccoid #1 ranged from 5.0 x 10^3 cells L^{-1} at site 6 to 1.3 x 10^5 cells L^{-1} at site 11, those for coccoid #2 ranged from 1.0 x 10^3 cells L^{-1} at site 9 to 1.5 x 10^4 cells L^{-1} at site 6 (Figures 6 and 7).

In Warnbro Sound, there was only one peak in the abundance of this group, a prymnesiophyte bloom (1.3 x 10^4 cells L^{-1}) in early June 1993. Average site abundances ranged from 6.0 x 10^3 cells L^{-1} at sites 1 and 5 to 1.8 x 10^4 cells L^{-1} at site 7 (Figures 6 and 7).

During 1994 in both embayments, prymnesiophyte abundance began to increase around June and July (up to 2.0 x 10^3 to 4.0 x 10^3 cells L^{-1}) suggesting that a winter prymnesiophyte bloom may be an annual event, however this increase was cut short by the *Skeletonema costatum* diatom bloom in July.

Chaney (1978) recorded an unknown bi-flagellate (designated species 4) which could possibly be the same as the prymnesiophyte recorded in the present study. Chaney's species 4 was abundant in Cockburn Sound throughout autumn, particularly late autumn when it accounted for 95% of the phytoplankton assemblage (~ 2.8 x 10^6 cells L^{-1}).

Although the prymnesiophyte bloom recorded in the present study occurred at a similar time (early winter) to that recorded by Chaney (late autumn) the magnitude (maximum count = 8.9×10^4 cells L^{-1}) and duration were considerably less.

Chaney also recorded small spherical cells (8 µm in diameter) which she considered to have possible affinities with coccoid chlorophytes; these were dominant throughout spring. The timing of Chaney's coccoid alga is the same as that recorded in the present study (mid spring), however their duration in the present study was much shorter, dominating the assemblage on only one occasion (late March 1994).

Two freshwater chlorococcales were found in the embayments samples, *Pediastrum* sp. on the eastern margin of Warnbro Sound during June/July 1993 and *Scenedesmus* sp. on the eastern margin of Cockburn Sound in August 1994, indicating obvious freshwater runoff into these areas.

2.2.3 - MULTIVARIATE ANALYSES AND EMBAYMENT SIMILARITY

A comparison of the taxa found in both embayments indicated a high degree of concordance in species composition with 64% of the phytoplankton taxa common to both Cockburn and Warnbro Sound. Twenty percent were exclusive to Cockburn Sound and 16% were exclusive to Warnbro Sound.

Multivariate analyses, based upon species abundance data, were conducted on all sites for each sampling period using Canonical Correspondence Analysis (Statistical Package = CANOCO; ter Braak 1986). These analyses indicated that there was a greater similarity between sites within embayments than between embayments. When clustered on biplot axes, sites in Cockburn Sound were clearly separated from sites in Warnbro Sound on 83% (39 out of 47) of occasions (Figure 8a). Sites from both embayments were reasonably well separated on 8.5% (four out of 47) of occasions (Figure 8b) and were poorly separated on 8.5% of occasions (Figure 8c). Periods where sites from both embayments were poorly separated generally corresponded to periods of silicoflagellate dominance.

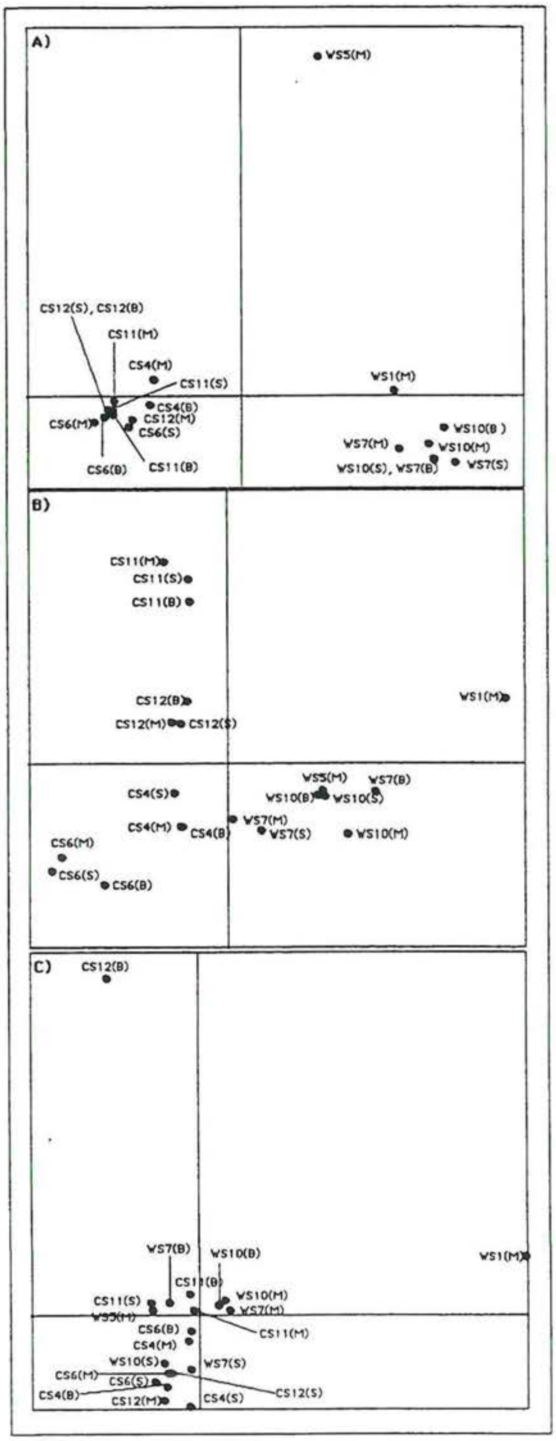


Figure 8: Typical biplot axes resulting from Canonical Correspondence Analysis showing a) periods of clear separation of embayments (eg. April 6, 1993), b) intermediate separation of embayments (eg. January 13, 1994) and c) poor separation of embayments (eg. October 7, 1993).

2.2.4 - BIOMASS

Phytoplankton biomass can be measured or estimated using several techniques including dry weight determination, analysis of carbon content, pigments, and cell counts. In the present study, phytoplankton biomass was estimated using chlorophyll-a analysis and cell counts. Chlorophyll-a analysis and cell counts are standard tools used in the estimation of phytoplankton biomass. However, chlorophyll-a analyses rely on relatively standardised techniques and are reasonably comparable between studies, the accuracy of cell counts is reliant on the technique used and as a result it is often difficult to compare estimations of phytoplankton biomass based on cell counts between studies. The relative frequency of various components are generally comparable. On the other hand, relying on chlorophyll-a alone may be misleading, as different groups of algae differ in chlorophyll-a content. For example, the ratio of chlorophyll-a:carbon is much lower in dinoflagellates than in other groups. Both chlorophyll-a and cell count taken together would give a balanced view of the biomass.

2.2.4.1 - PHYTOPLANKTON CELL COUNTS.

2.2.4.1.1 - Spatial Patterns.

Average cell counts for the current study ranged between 5.4 x 10^4 cells L^{-1} at site WS1 to 2.6 x 10^5 cells L^{-1} at site CS11. Within Cockburn Sound, site 4 (north-eastern tip of Garden Island) almost consistently had the lowest phytoplankton cell numbers. Sites 6, 9, 11 and 12 had similar cell numbers but generally followed a south to north trend with site 11 (Mangles Bay, southern end of the embayment) having the greatest phytoplankton cell numbers followed by sites 9 and 12 (industrial area near James point) with site 6 (Cockburn Power Boat Club, northern end of the embayment) having the lowest phytoplankton cell numbers.

Based upon pooled site data, site 4 had the lowest average cell numbers (1.5 x 10^5 cells L^{-1}) followed by site 12 (1.9 x 10^5 cells L^{-1}), site 9 (2.2 x 10^5 cells L^{-1}), site 6 (2.3 x 10^5 cells L^{-1}) and site 11 (2.6 x 10^5 cells L^{-1}) which had the highest average cell numbers (Figure 9). Anova and Scheffe test results ($p = 0.0079$), calculated using $\log_{10}$ transformed data, showed that sites 4, 12, 9 and 6 and sites 12, 9, 6 and 11 were not significantly different from each other (Table 1).

Table 1: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average phytoplankton cell counts for Cockburn Sound. Means which are not significantly different are linked.

CS11	(258 267)
CS6	(231 523)
CS9	(223 867)
CS12	(191 773)
CS4	(154 631)

Cockburn Sound was therefore divided into two distinct areas based on cell numbers: the eastern coastal strip (sites 6, 9, 11 and 12), and the western outer embayment (site 4). Throughout the study, phytoplankton cell numbers in the coastal strip sites were usually two to three times higher than those of site 4. Average pooled site data showed that the phytoplankton cell numbers of the coastal strip sites were only between 0.9 and 1.2 times higher than those of site 4, however these averages do not give a true indication of the relationships between sites as the range of cell numbers at each site was quite large (one to two degrees of magnitude). Obviously the coastal strip is more productive and is being enriched from various terrestrial nutrient sources, primarily industrial and sewage effluents. Site 4 is both further away from these terrestrial nutrient sources and receives greater oceanic exchange than the other sites.

Within Warnbro Sound, site 1 (northern tip near Mersey Point) consistently had the lowest phytoplankton cell numbers, sites 4, 7 and 10 (central embayment) all had similar cell numbers as did site 5 (southern tip near Becher Point). According to pooled site data, average phytoplankton cell numbers were highest at site 5 (1.5×10^5 cells L^{-1}), followed by site 10 (1.4×10^5 cells L^{-1}), site 7 (1.3×10^5 cells L^{-1}), site 4 (1.2×10^5 cells L^{-1}) and lowest at site 1 ($5. \times 10^4$ cells L^{-1}). However, for sites 5 and 10, this data was heavily biased by one sampling occasion (November 24, 1992) when the phytoplankton was dominated by *Nodularia spumigena* with cell numbers in excess of 1.1×10^6 and 1.7×10^6 cells L^{-1}, as previously discussed, this alga does not originate in the embayment.

If this sampling period is ignored for all sites, average cell numbers are as follows; site 1 still had the lowest average (5.2×10^4 cells L^{-1}), followed by sites 7 (1.2×10^5 cells L^{-1}), 5 (1.2×10^5 cells L^{-1}), 10 (1.2×10^5 cells L^{-1}) and 4 (1.2×10^5 cells L^{-1}) (Figure 9). Anova and Scheffe test results ($p = 0.009$), calculated using $\log_{10}$ transformed data, showed that sites 1 and 5 and sites 4, 5, 7 and 10 were not significantly different from each other (Table 2).

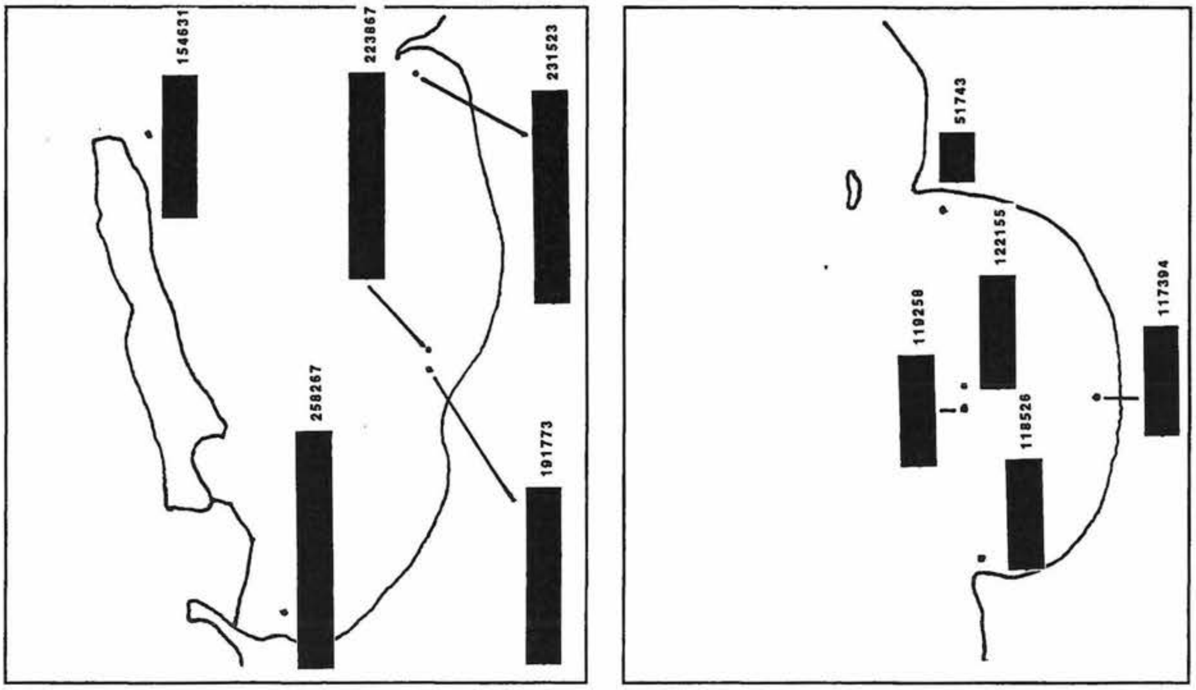


Figure 9: Average phytoplankton cell count for all sites in Cockburn and Warnbro sounds.

Table 2: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average phytoplankton cell counts for Warnbro Sound. Means which are not significantly different are linked.

WS7	(117 394)
WS4	(122 155)
WS10	(119 258)
WS5	(118 526)
WS1	(51 743)

*Note that the $\log_{10}$ transformation process alters the rank order of sites 10, 7, 5 and 4.

Cockburn Sound almost consistently had higher phytoplankton cell numbers than Warnbro Sound. According to pooled site data, site CS4 (the site with the lowest average cell number in Cockburn Sound) had almost 1.3 times the cell numbers of site WS4 (the site with the highest average cell number in Warnbro Sound). There was almost a three-fold difference in the average cell numbers between the lowest sites in both embayments (CS4 and WS1), more than a two-fold difference between the highest sites in both embayments (CS11 and WS4) and almost a five-fold difference between the highest Cockburn Sound site (CS11) and the lowest Warnbro Sound site (WS1).

Anova and Scheffe test results ($p = 0.0001$), calculated using $\log_{10}$ transformed data (November 24 1992 sampling occasion deleted), showed that sites WS1, WS5, WS10, and WS4, sites WS5, WS10, WS4, WS7, CS4, CS12, CS9 and CS6, and sites WS4, WS7, CS4, CS12, CS9, CS6 and CS11 were not significantly different from each other (Table 3).

Table 3: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average phytoplankton cell counts for Cockburn and Warnbro sounds. Means which are not significantly different are linked.

CS11	(258 267)	↑		
CS6	(231 523)	│	↑	
CS9	(223 867)	│	│	
CS12	(191 773)	│	│	
CS4	(154 631)	│	│	
WS7	(117 394)	│	│	
WS4	(122 155)	↓	│	↑
WS10	(119 258)		│	│
WS5	(118 526)		↓	│
WS1	(51 743)			↓

*Note that the $\log_{10}$ transformation process alters the rank order of sites 10, 7, 5 and 4.

Previous Studies.

High phytoplankton abundances, with respect to nearby coastal waters, were recorded during 1972 (ERA 1974a) although actual cell counts were not cited. A marked increase in phytoplankton abundance on the eastern side of the embayment was also reported.

Chaney (1978) sampled a site 1.6 km north-east of site 11 in Cockburn Sound (designated site 214) on a weekly basis between July 1977 and August 1978 (Figure 2). Average cell numbers at this site were 7.6×10^5 ($SD = 8.1 \times 10^5$) cells L^{-1}, almost 3 times greater than cell counts recorded at site 11 in the present study (Table 4), and 15 times those recorded by Cousins (1991) at site 11 during 1991 (Table 5). These high cell counts reflect the poorer water quality in the embayment during the 1970s.

Chaney recorded average cell counts of 2.4×10^2 ($SD = 3.4 \times 10^2$) cells L^{-1} from a site in Owen Anchorage (Table 4), immediately north of Cockburn Sound (Figure 2), more than 3 000 times less than the average cell count recorded in Cockburn Sound.

This supports data collected in earlier studies (ERA 1974 a, b) which showed considerably higher phytoplankton cell counts in Cockburn Sound compared to nearby, well flushed coastal waters.

Table 4: Annual and seasonal average phytoplankton cell count and chlorophyll-a concentration reported by Chaney (1978) for sites in Cockburn Sound (near site CS11) and Owen Anchorage.

	COCKBURN SOUND		OWEN ANCHORAGE	
SEASON	Cell count (Cells L^{-1})	Chlorophyll-a (μg L^{-1})	Cell count (Cells L^{-1})	Chlorophyll-a (μg L^{-1})
Annual	7.6 x 10^5±8.1 x 10^5	6.27±3.70	237±343	3.00±2.15
Summer	6.8 x 10^5±6.5 x 10^5	6.36±3.94	201±167	3.89±3.02
Autumn	1.7 x 10^6±1.1 x 10^6	6.87±3.89	503±678	2.95±1.77
Winter	6.2 x 10^5±5.3 x 10^5	5.67±3.04	217±360	2.70±2.12
Spring	3.1 x 10^5±2.9 x 10^5	6.42±4.39	135±86	2.65±1.61

Average cell counts recorded by Cousins (1991) for all sites were consistently lower by a factor of between 1.3 and 5.1 than those recorded in the present study (Table 5). Cousins analysed and counted phytoplankton samples at a magnification of 100x and it is possible that many of the smaller taxa recorded in the present study may have been overlooked.

However, trends in phytoplankton cell count between sites were similar to those of the present study with the coastal strip sites (11, 9 and 6) having the greatest cell count within Cockburn Sound and the central sites (7 and 4) and site 5 having the greatest cell count within Warnbro Sound.

Table 5: Average phytoplankton cell count and chlorophyll-a concentration recorded by Cousins (1991) for those Cockburn and Warnbro sound sites which were also included in the present study.

SITE	Cell count (Cells L^{-1})	Chlorophyll-a (μg L^{-1})
WS1	3.9 x 10^4±5.0 x 10^4	1.21±1.36
WS4	4.6 x 10^4±5.0 x 10^4	1.81±0.92
WS5	4.3 x 10^4±5.1 x 10^4	1.61±0.89
WS7	5.0 x 10^4±5.7 x 10^4	2.08±1.63
CS4	3.7 x 10^4±4.6 x 10^4	1.69±0.81
CS6	7.8 x 10^4±9.2 x 10^4	3.07±1.60
CS9	7.2 x 10^4±9.8 x 10^4	2.58±1.78
CS11	5.0 x 10^4±6.1 x 10^4	3.58±3.06

2.2.4.1.2 - Temporal Patterns.

The annual phytoplankton cycles of temperate waters are generally characterised by spring and autumn phytoplankton blooms (Nielsen 1991). Spring phytoplankton blooms are a well known and well documented event in temperate waters of the Northern Hemisphere (Jeffrey, Rochford and Cresswell 1990, Hallegraeff and Jeffrey 1993). These blooms are generally initiated by an increase in solar irradiation and the onset of temperature stratification during spring following deep winter mixing and internal nutrient regeneration (Hallegraeff and Jeffrey 1993).

Spring phytoplankton blooms are also relatively well documented in coastal south-eastern Australia (Hallegraeff and Reid 1986, Jeffrey and Hallegraeff 1990, Jeffrey, Vesk and Hallegraeff 1990, Hallegraeff and Jeffrey 1993) although the mechanisms with which they are initiated differ (Jeffrey, Vesk and Hallegraeff 1990, Hallegraeff and Jeffrey 1993). The spring phytoplankton blooms of temperate Australia are generally initiated by nutrient inputs from the Eastern Australian Current and Western Australian (Leeuwin) Current (Jeffrey, Rochford and Cresswell 1990).

In the present study, average phytoplankton cell counts for both embayments were generally highest during winter, corresponding to the period of silicoflagellate dominance, and lowest during summer or autumn (Table 6) (Figure 10). When those dates with high abundances of allochthonous phytoplankton (November 24 1992 - high abundances of *Nodularia spumigena* in Warnbro Sound; and July 6 1994 - high abundances of *Skeletonema costatum* in Cockburn Sound) were removed, average cell counts in Cockburn Sound were greatest during spring (followed by winter) and least in summer and in Warnbro Sound were greatest in winter (followed by summer) and least in spring (Table 6). Allochthonous material can therefore have a great affect on calculations of average cell count and average chlorophyll-a (as will be discussed next) and must be considered and removed from any calculations if necessary.

Even with this allochthonous phytoplankton ignored, it is apparent that the overall annual phytoplankton cycles of Cockburn and Warnbro sounds do not conform with those of other temperate regions around Australia and other parts of the world.

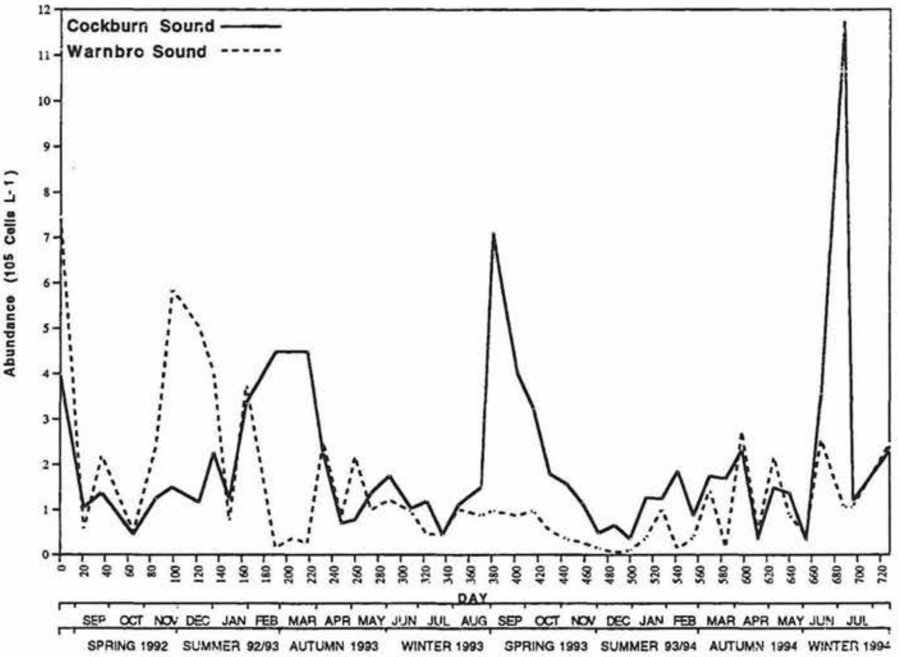


Figure 10: Timeseries plot showing average phytoplankton cell counts for Cockburn and Warnbro sounds (1992 - 1994).

The main reason for this is the high abundance of silicoflagellates during winter. Without these, the annual phytoplankton cycles of both embayments would be similar to that in other temperate regions of the world. Sea surface temperatures in Cockburn and Warnbro sounds do fall to around 15°C during winter (Figure 11) - the upper temperature range preferred by silicoflagellates - but obviously this alone is an inadequate reason to explain their recent (15 to 20 years) dramatic increase in abundance.

Previous Studies.

Although Chaney (1978) did not report high abundances of silicoflagellates during winter, the annual phytoplankton cycles of both Cockburn Sound and Owen Anchorage still deviated from that which would be expected for temperate Australian coastal waters, with greatest phytoplankton biomass being recorded during autumn and lowest during spring (Table 4). Cousins (1991) however, reported highest cell counts during spring in both Cockburn and Warnbro sounds and low counts in summer, winter counts were second highest due to high abundances of silicoflagellates (Table 7).

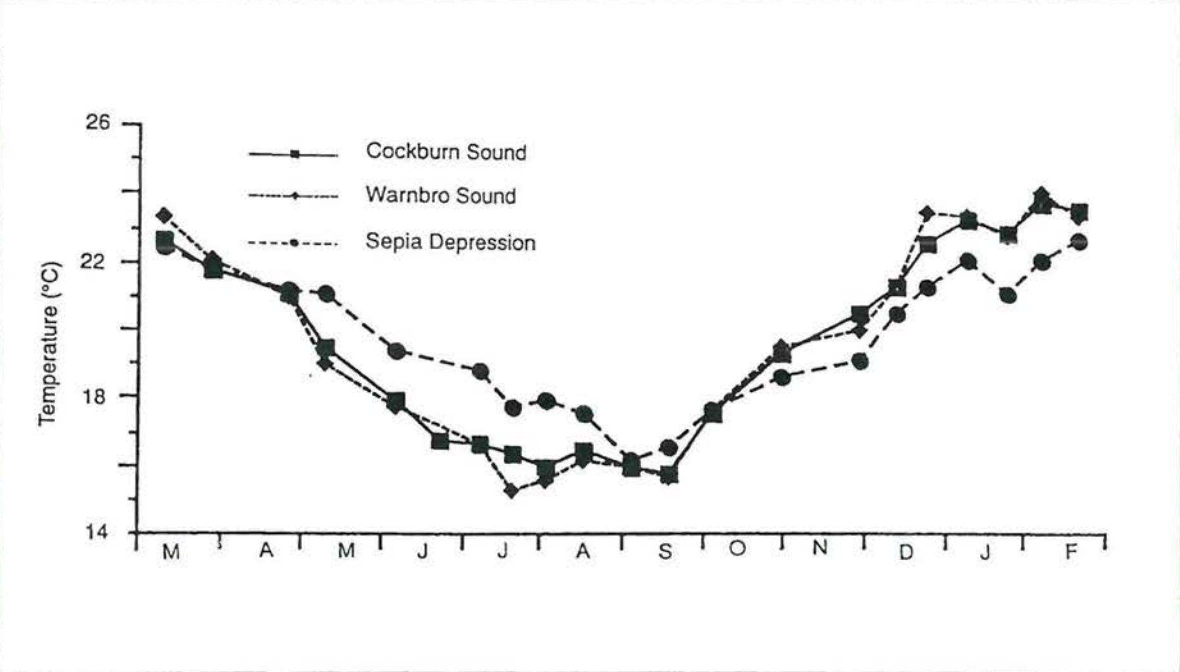


Figure 11: Timeseries plot showing sea-surface temperatures in Cockburn and Warnbro sounds and Sepia Depression (March 1991 - February 1992). (Cary, Masini and Simpson 1995).

Table 6: Annual and seasonal average phytoplankton cell count and chlorophyll-a concentration reported from the present study. Those values in italics represent averages after the deletion of unusual sampling dates (November 24 1992 and July 6 1994).

	COCKBURN SOUND		WARNBRO SOUND	
SEASON	Cell count (Cells L^{-1})	Chlorophyll-a ($\mu g\ L^{-1}$)	Cell count (Cells L^{-1})	Chlorophyll-a ($\mu g\ L^{-1}$)
Annual	$2.1 \times 10^5 \pm 2.2 \times 10^5$	1.85±0.78	$1.3 \times 10^5 \pm 1.6 \times 10^5$	0.76±0.44
	$1.8 \times 10^5 \pm 1.3 \times 10^5$	*1.81±0.76*	*$1.2 \times 10^5 \pm 1.3 \times 10^5$*	*0.76±0.44*
Summer	$1.6 \times 10^5 \pm 1.1 \times 10^5$	1.48±0.70	$1.2 \times 10^5 \pm 1.4 \times 10^5$	0.51±0.15
Autumn	$1.8 \times 10^5 \pm 1.1 \times 10^5$	1.85±0.86	$1.0 \times 10^5 \pm 6.2 \times 10^4$	0.72±0.28
Winter	$2.9 \times 10^5 \pm 3.9 \times 10^5$	2.38±0.65	$1.5 \times 10^5 \pm 1.9 \times 10^5$	1.27±0.63
	$1.8 \times 10^5 \pm 1.2 \times 10^5$	*2.32±0.64*	*$1.6 \times 10^5 \pm 2.0 \times 10^5$*	*1.32±0.64*
Spring	$2.1 \times 10^5 \pm 1.5 \times 10^5$	1.86±0.66	$1.5 \times 10^5 \pm 2.2 \times 10^5$	0.66±0.16
	$2.2 \times 10^5 \pm 1.6 \times 10^5$	*1.74±0.57*	*$8.9 \times 10^4 \pm 8.7 \times 10^4$*	*0.63±0.10*

Table 7: Annual and seasonal average phytoplankton cell count and chlorophyll-a concentration reported by Cousins (1991) for those Cockburn and Warnbro sound sites which were also included in the present study.

	COCKBURN SOUND		WARNBRO SOUND	
SEASON	Cell count (Cells L^{-1})	Chlorophyll-a ($\mu g\ L^{-1}$)	Cell count (Cells L^{-1})	Chlorophyll-a ($\mu g\ L^{-1}$)
Annual	$5.9 \times 10^4 \pm 7.6 \times 10^4$	2.73±2.00	$4.4 \times 10^4 \pm 5.2 \times 10^4$	1.63±1.14
Summer	$1.8 \times 10^3 \pm 5.9 \times 10^2$	1.79±0.77	$3.6 \times 10^3 \pm 1.1 \times 10^3$	0.50±0.19
Autumn	$3.3 \times 10^4 \pm 7.4 \times 10^4$	1.98±0.86	$4.3 \times 10^3 \pm 2.7 \times 10^3$	1.08±0.31
Winter	$7.3 \times 10^4 \pm 7.7 \times 10^4$	3.72±3.13	$8.3 \times 10^4 \pm 4.9 \times 10^4$	2.40±1.39
Spring	$1.6 \times 10^5 \pm 2.5 \times 10^4$	3.96±1.36	$9.3 \times 10^4 \pm 4.2 \times 10^4$	2.22±0.53

No seasonal data are available prior to Chaney (1978) as these studies were all conducted over the summer period. However, taking into account the seasonality demonstrated by Cousins (1991) and Chaney (1978) as well as that in the present study, it is likely that the high phytoplankton cell counts recorded by earlier studies during the summer months were indicative of near minimum values suggesting that, at times, water quality in the embayment could have been much worse than reported.

2.2.4.1.3 - Vertical Patterns.

Vertical stratification of phytoplankton is a well documented phenomenon in poorly mixed waters. It is usually caused by strong gradients of temperature and/or salinity. Vertical stratification with respect to phytoplankton cell count and chlorophyll-a concentration was observed to a small degree within both embayments during the present study; phytoplankton cell counts tended to be greatest in surface, and to a lesser extent, middle waters in Cockburn Sound. In Warnbro Sound cell counts appeared to be more evenly spread between surface, middle and bottom layers (site WS10, in the middle of Warnbro Sound showed the greatest cell count most often at the bottom). However, in Cockburn and Warnbro sounds, there are no true haloclines or thermoclines as a result of their relative shallowness. Obviously some other factor is responsible for the observed vertical differences, this will be discussed further in section 2.2.4.2.3. There appeared to be no seasonal patterns in the vertical distribution of phytoplankton cells in either embayment. The low percentage of dinoflagellates, which are well known to show vertical migration, may explain the lack of strong vertical differences in cell count.

Previous Studies.

Chaney (1978) reported marked vertical stratification of phytoplankton cell count and chlorophyll-a concentration in Cockburn Sound with maximum cell counts and chlorophyll-a concentrations occurring more often in surface or middle waters than in bottom waters, similar to what was found in the present study. Studies prior to Chaney (1978) collected integrated water samples; no data on vertical phytoplankton distribution are available.

2.2.4.2 - CHLOROPHYLL - a

Chlorophyll-a concentrations in Australian waters generally range from 0.05 - 0.5 $\mu g\ L^{-1}$ in oceanic tropical and subtropical regions to up to 1.5 $\mu g\ L^{-1}$ in the temperate and southern oceans (Table 8) (Jeffrey and Hallegraeff 1990).

Coastal regions tend to show greater seasonal variation in chlorophyll-a concentration, Jeffrey and Hallegraeff (1990) give a range of 0.1 - 8.0 $\mu g\ L^{-1}$ for a coastal station off Sydney, and a range of 2 to 19 $\mu g\ L^{-1}$ from the entrance to the upper reaches of Sydney Harbour (Table 8).

2.2.4.2.1 - Spatial Patterns.

Chlorophyll-a concentration in the present study ranged between 0.11 and 5.21 $\mu g\ L^{-1}$ in Warnbro Sound and 0.14 and 17.34 $\mu g\ L^{-1}$ in Cockburn Sound. Average chlorophyll-a concentrations ranged between 0.41 $\mu g\ L^{-1}$ at site WS1 to 2.51 $\mu g\ L^{-1}$ at site CS11.

Trends in chlorophyll-a concentration were similar to those for cell counts with site 4 in Cockburn Sound almost consistently having the lowest chlorophyll-a concentration followed by the coastal strip sites ; and site 1 in Warnbro Sound almost consistently having the lowest chlorophyll-a concentration followed by site 5 and the central embayment sites (Figure 2).

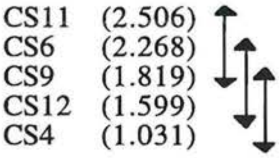
Table 8: Chlorophyll-a concentration reported from Cockburn Sound and Warnbro Sound in the present study compared with Owen Anchorage (Cousins 1991) and other global regions. Values quoted represent ranges or means in parentheses (±SD). Sources are listed below the Table.

Location	Chl-a ($\mu g\ L^{-1}$)	Comments
Antarctica (Ross Sea)[1]	(1.65±3.24) - (22.6±19.3)	Spring 1978
Antarctica (Weddell-Scotia Sea)[2]	(0.29) - (2.82)	Summer 1988-89
Antarctica (Weddell Sea)[3]	0.1 - 0.8	Summer and Autumn 1991
Antarctica (Weddell Sea)[4]	(0.06) - (4.00)	Summer 1989
Australia (Tropical and sub-tropical Oceans)[5]	0.05 - 0.5	Annual range
Australia (Temperate and southern Oceans)[5]	≤ 1.5	Annual range
Baltic Sea (Skagerrak/Kattegat Front)[6]	(0.38±0.1) - (6.52±5.55)	1984 - 1993
Cockburn Sound[7]	**(1.85±0.78)**	**Annual average 1992-1994**
Cockburn Sound[7]	**0.14 - 17.34**	**Range 1992-1994**
Indian Ocean (eastern)[8]	(0.15±0.052)	Spring 1991
Manukau Harbour, New Zealand[9]	(2.4) - (9.3)	1991 - 1992
North Pacific (western)[8]	(0.11±0.028)	Autumn 1991
Owen Anchorage[10]	**(3.00±2.15)**	**Annual average 1991**
South Atlantic Bight (inner shelf waters)[11]	(7.4±1.2) - (11.4±2.9)	Summer 1985-87
	(4.6±1.1) - (6.4±1.8)	Winter 1985-87
South Atlantic Bight (outer shelf waters)[11]	(3.0±1.1) - (8.3±5.3)	Summer 1985-87
	(2.2±0.2) - (4.6±2.3)	Winter 1985-87
South-east Asia[8]	(0.29±0.206)	Spring 1991
Strait of Magellan[12]	0.43 - 2.54	Summer 1991
Strait of Magellan[13]	0.17 - 4.55	Spring-Summer 1991
Sydney (Coastal station)[5]	0.1 - 8.0	Annual range
Sydney Harbour)entrance - upper Harbour)[5]	2 - 19	Annual range
Tai Tam Bay, Hong Kong[14]	0.5 - 34	Summer 1989 - Spring 1991
Warnbro Sound[7]	**(0.76±0.44)**	**Annual average 1992-1994**
Warnbro Sound[7]	**0.11 - 5.21**	**Range 1992-1994**

1) - Arrigo and McClain (1994)
2) - Figueiras *et al.* (1994)
3) - Kang and Fryxell (1993)
4) - Gleitz *et al.* (1994)
5) - Jeffrey and Hallegraeff (1990)
6) - Heilmann *et al.* (1994)
7) - Present Study
8) - Odate and Fukuchi (1994)
9) - Vant and Budd (1993)
10) - Cousins (1991)
11) - Verity *et al.* (1993)
12) - Saggiomo *et al.* (1994)
13) - Iriarte *et al.* (1993)
14) - Chiu *et al.* (1994)

Within Cockburn Sound, based upon pooled site data, site 4 had the lowest average chlorophyll-a concentration (1.03 $\mu g\ L^{-1}$) followed by site 12 (1.60 $\mu g\ L^{-1}$), site 9 (1.82 $\mu g\ L^{-1}$), site 6 (2.27 $\mu g\ L^{-1}$) and site 11 (2.51 $\mu g\ L^{-1}$) which had the highest average chlorophyll-a concentration (Figure 12). Anova and Scheffe test results ($p = 0.0001$) showed that sites 4, 12 and 9, sites 12, 9 and 6 and sites 9, 6 and 11 were not significantly different from each other (Table 9).

Table 9: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average chlorophyll-a concentration for Cockburn Sound. Means which are not significantly different are linked.



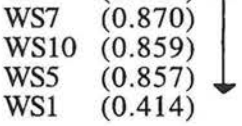
CS11	(2.506)
CS6	(2.268)
CS9	(1.819)
CS12	(1.599)
CS4	(1.031)

Although the difference between site 4 and the coastal strip sites was not as apparent in chlorophyll-a concentration as with cell count, the pooled chlorophyll-a concentrations for the coastal strip sites were, on average, 1.7 to 3 times greater than those for site 4, confirming the distinction observed for cell count.

Within Warnbro Sound, the pooled chlorophyll-a concentration of site 5 and the central embayment sites were, on average, almost 2.5 times those of site 1 (Figure 2). Based on pooled site data, site 1 had the lowest average chlorophyll-a concentration (0.41 $\mu g\ L^{-1}$) followed by site 5 (0.86 $\mu g\ L^{-1}$), site 10 (0.86 $\mu g\ L^{-1}$), site 7 (0.87 $\mu g\ L^{-1}$) and site 4 (1.00 $\mu g\ L^{-1}$) (Figure 12). Anova and Scheffe test results ($p = 0.0001$) showed that sites 5, 10, 7 and 4 were not significantly different from each other, all were significantly different from site 1 (Table 10).

The average chlorophyll-a concentration within Cockburn Sound was, on average, 2.75 times higher than that in Warnbro Sound (range = 0.8x to 6.5x). According to pooled site data, site CS4 (the site with the lowest average chlorophyll-a concentration in Cockburn Sound) had about the same chlorophyll-a concentration as site WS4 (the site with the highest average chlorophyll-a concentration in Warnbro Sound).

Table 10: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average chlorophyll-a concentration for Warnbro Sound. Means which are not significantly different are linked.



WS4	(1.002)
WS7	(0.870)
WS10	(0.859)
WS5	(0.857)
WS1	(0.414)

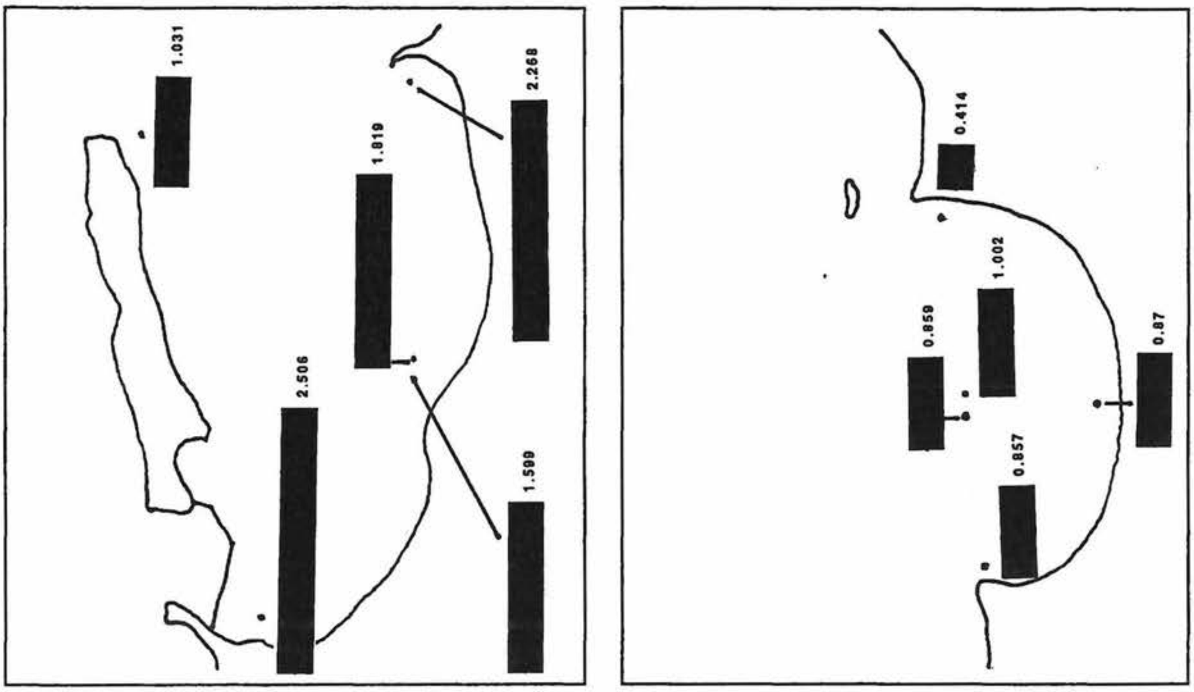


Figure 12: Average chlorophyll-a concentration for all sites in Cockburn and Warnbro sounds (1991 - 1994).

There was almost a 2.5 times difference in the chlorophyll-a concentration between the lowest sites in both embayments (CS4 and WS1), a 2.5 times difference between the highest sites in both embayments (CS11 and WS4) and a six-fold difference between the highest Cockburn Sound site (CS11) and the lowest Warnbro Sound site (WS1). Anova and Scheffe test results ($p = 0.0001$) showed that sites WS1, WS5, WS10, WS7, WS4 and CS4, sites WS5, WS10, WS7, WS4, CS4, CS12 and CS9, sites CS12, CS9 and CS6, and sites CS9, CS6 and CS11 were not significantly different from each other (Table 11).

Previous Studies.

Considerable data are available on chlorophyll-a concentrations in Cockburn Sound and nearby coastal waters from surveys conducted during the autumn of 1973 (ERA 1974a), the summer of 1973/74 (ERA 1974b), late spring to early autumn 1973/74 (Meagher and LeProvost 1975), winter 1977 to winter 1978 (Chaney 1978; Chiffings 1979), the summers of 1979/80, 1980/81, 1982/83 (Chiffings and McComb 1983), 1984/85 (Hillman 1986), 1986/87 (Hillman and Bastyan 1988), 1989/90 (Cary *et al.* 1991) and late summer to early spring 1991 (Cousins 1991). Most of these studies have three sites in common; one approximately 1.6 km north-east of CS11 (site 214), one midway between CS12/9 and CS6 and another in Owen Anchorage (Figure 2).

Table 11: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average chlorophyll-a concentration for Cockburn and Warnbro sounds. Means which are not significantly different are linked.

CS11	(2.506)
CS6	(2.268)
CS9	(1.819)
CS12	(1.599)
CS4	(1.031)
WS4	(1.002)
WS7	(0.870)
WS10	(0.859)
WS5	(0.857)
WS1	(0.414)

Results of chlorophyll-a analyses showed similar trends to those found in the present study with highest chlorophyll-a concentrations in the south-eastern part of the embayment (CS11) and lower concentrations further northward (CS12/9). Chlorophyll-a concentrations at the Owen Anchorage site were always less, often less than half, those of Cockburn Sound.

Chaney recorded an average chlorophyll-a concentration of 3.00 µg L-1 (SD = 2.15) from a site in Owen Anchorage (Table 4). This value is half of that recorded in Cockburn Sound (6.27 µg L^{-1} (SD = 3.70) from site 214) but does not differ nearly as much as cell count (more than 3 000 times greater in Cockburn Sound). Several factors may account for this large inconsistency between cell count and chlorophyll-a concentration.

Trends in chlorophyll-a concentration recorded by Cousins (1991) between sites were similar to those of the present study with the coastal strip sites (11, 9 and 6) having the greatest average values within Cockburn Sound and the central sites (7 and 4) and site 5 having the greatest average values within Warnbro Sound (Table 5).

During the present study, both annual and seasonal average chlorophyll-a concentrations for Warnbro Sound were within the range of those expected for temperate regions around Australia, however the annual range of values (0.11 - 5.21 µg L^{-1}) was greater (Tables 6 and 8). For Cockburn Sound, annual and seasonal averages were greater than those expected for temperate regions around Australia (Tables 6 and 8), the annual range of values (0.14 - 17.34 µg L^{-1}) was considerably greater.

2.2.4.2.2 - Temporal Patterns.

In the present study, average chlorophyll-a concentration for both embayments were highest during winter, corresponding to the period of silicoflagellate dominance, and lowest during summer (Table 6) (Figure 13). This is in contrast to the annual phytoplankton cycle regarded as typical for temperate coastal waters.

The allochthonous material discussed in the previous section did not have the same influence on average chlorophyll-a concentration as it did on average cell count. These allochthonous 'blooms' were in a state of decay, particularly the *Nodularia spumigena* bloom in Warnbro Sound, and would have contributed relatively little to the overall chlorophyll-a concentration.

Previous Studies.

Seasonal.
During 1977 and 1978, chlorophyll-a concentration in Cockburn Sound was greatest in autumn followed by spring, summer and winter; in Owen Anchorage it was greatest in summer followed by autumn, winter and spring (Table 4) (Chaney 1978). In 1991 average chlorophyll-a concentrations in Cockburn Sound were highest during spring followed by winter, autumn and summer; in Warnbro Sound they were highest in winter followed by spring, autumn and summer (Table 7) (Cousins 1991).

No seasonal data are available prior to Chaney (1978) as these studies were all conducted over the summer period.

Again it is apparent that both in the present study and in previous studies, that the annual phytoplankton cycles of Cockburn and Warnbro sounds (and Owen Anchorage) do not conform to that which would be expected, ie. spring and autumn maxima. In the earlier studies, there was also considerable variation between Cockburn Sound and Warnbro Sound and Owen Anchorage.

Chaney (1978) attributed differences between Cockburn Sound and Owen Anchorage to differences in their nutrient regimes. For example, blooms of chain forming diatoms in Cockburn Sound during late autumn and early winter were probably triggered by nutrient release from sediments stirred up during the first storms of autumn and winter. Nutrient stores in Owen Anchorage were much lower than those in Cockburn Sound so the blooms did not occur there.

While there are obviously local effects which would be partially responsible for the unusual annual cycles historically recorded in Cockburn and Warnbro sounds, the fact that this has also been recorded from Owen Anchorage suggests the likelihood of regional influences. If differences between the annual cycles of Cockburn Sound and other nearby areas in the past have been due to differences in nutrient regimes, then the similarity between Cockburn Sound and Warnbro Sound in the present study may indicate either an increased similarity in nutrient regime (unlikely in view of obvious differences in biomass) or that both embayments are being overridingly influenced by regional factors.

Whether or not the annual cycles of these areas are influenced primarily by local or regional factors should be high on a list of priorities for future research.

Annual.

Chlorophyll-a data for Cockburn Sound collected during the previous studies outlined in section 2.2.4.2.1 as well as those from the present study are summarised in Figure 14. High chlorophyll-a concentrations prior to the installation of the KNC steam scrubber in 1982 are evident. Note the two different average values for the summer of 1977/78, the greater of the two is from Chaney (1978) and is based on 11 weekly samples over the summer period, the lower value is from Chiffings (1979) and is based on only 3 of Chaney's sampling periods.

Limited data are available prior to 1977 however Meagher and LeProvost (1975) recorded chlorophyll-a values consistently within the range of 5 - 10 $\mu g\ L^{-1}$ for the period November 1974 to April 1975.

During the summer study of 1977/78 (Chiffings 1979), several cruises throughout Cockburn Sound were also undertaken, mean values in the Sound ranged from 1 - 5 µg L^{-1} with a maximum mean station value of 14 µg L^{-1}. Weekly values recorded at station 214 ranged from 1.2 - 18.0 µg L^{-1}, those for station 238 (Owen Anchorage) from 0.4 - 9.5 µg L^{-1} (Chaney 1978; Chiffings 1979). Chiffings (1979) reported a maximum chlorophyll-a value of 110 µg L^{-1} recorded at the peak of a bloom in Cockburn Sound.

Chaney (1978) recorded an average chlorophyll-a concentration of 6.27 µg L^{-1} (SD = 3.70) from Cockburn Sound (from site 214) between July 1977 and August 1978 (Table 4), almost twice that recorded from site CS11 by Cousins (1991) (Table 5) and 2.5 times that recorded from site CS11 during the present study.

Summertime chlorophyll-a concentrations in Cockburn Sound after the installation of the KNC steam scrubber in 1982 and the diversion of secondary wastes from the Woodman Point sewage outfall in 1984 fell considerably (Figure 14). Those for the summers of 1982/83, 1984/85 and 1986/87 were not significantly different from each other; data for subsequent summers suggests that chlorophyll-a concentrations are on the increase once more.

Average chlorophyll-a concentration recorded by Cousins (1991) for all sites were consistently higher by a factor of between 1.3 and 2.7 than those recorded in the present study (Table 5). These values are much more similar than those for cell count, again emphasising the greater accuracy and comparability of chlorophyll-a concentration as an estimate of biomass compared to cell count (chlorophyll-a samples for both studies were analysed at the same laboratory using the same technique). It is likely that these differences in chlorophyll-a concentration are due to the greater sampling frequency and greater study duration in the present study resulting in lower average values.

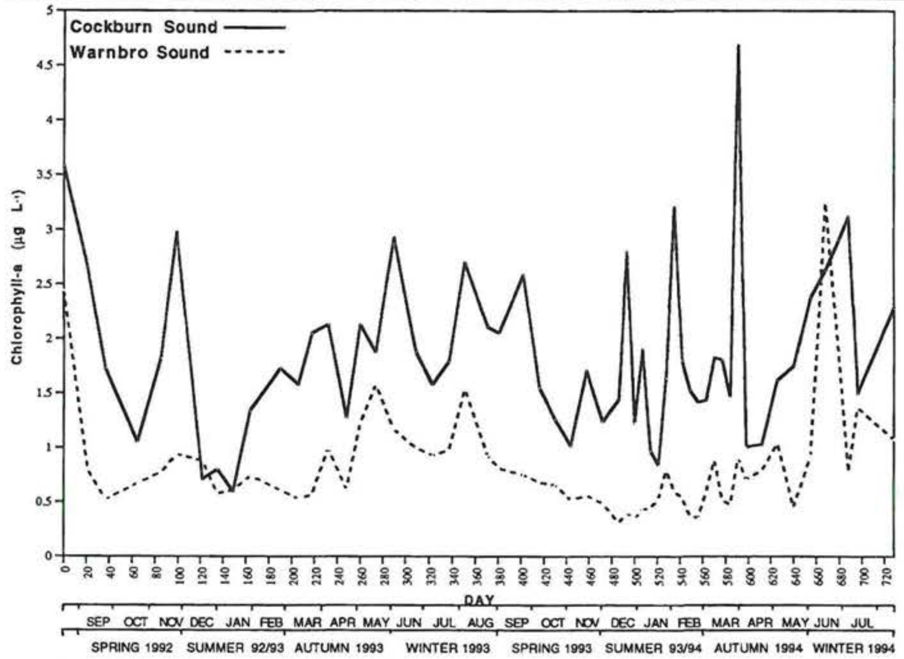


Figure 13: Timeseries plot showing average chlorophyll-a concentration for Cockburn and Warnbro sounds (1991 - 1994).

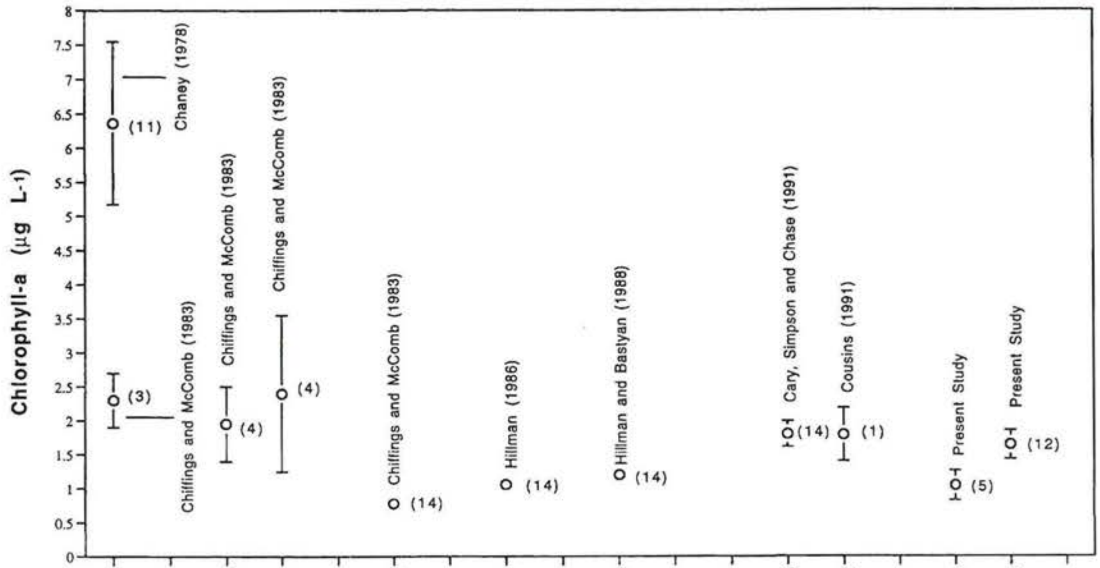


Figure 14: Chlorophyll-a data from Cockburn Sound as reported in previous studies and the present study.

As for phytoplankton cell count, it is likely that the summer chlorophyll-a concentrations measured in the studies prior to Cousins (1991) represent near minimum values, suggesting that, at times, water quality in the embayment could have been much worse than reported.

2.2.4.2.3 - Vertical Patterns.

Phytoplankton cells are generally considerably denser than the water in which they are found and therefore have a natural tendency to sink. In deep waters this tendency to sink becomes a problem as cells can quickly be removed from the euphotic zone. In other waters this may be a problem as cells may sink into waters with sub-optimum temperatures, salinities or nutrient concentrations. Various strategies are employed by the phytoplankton in order to either maintain their buoyancy or to minimise their tendency to sink. Such strategies include the possession of elaborate structures designed to increase surface area such as the setae of *Chaetoceros* species, the regulation of ionic concentrations of the cytoplasm or the regulation of gas vacuoles. Physical factors such as water movement also assist the suspension of phytoplankton cells.

The optimum position in the water column for phytoplankton growth is often a compromise between several factors including available light, temperature, salinity and available nutrients. As was mentioned earlier, there are no haloclines or thermoclines in Cockburn or Warnbro sounds, so these factors can be considered to be of little or no importance with respect to the vertical stratification of phytoplankton in the present study. There are however, strong gradients with respect to available light and nutrients within Cockburn and Warnbro sounds.

As for cell count, chlorophyll-a concentration in Cockburn Sound in the present study, tended to be greatest in surface and middle waters with the exception of site 4 for which chlorophyll-a concentration was greatest at the bottom of the water column (20 m) most of the time. In Warnbro Sound, chlorophyll-a concentration was almost consistently greatest at the bottom of the water column. There appeared to be no seasonal patterns in the vertical distribution of chlorophyll-a concentration in either embayment.

Previous Studies.

Cousins (1991) presents no data on vertical phytoplankton or chlorophyll-a distribution as only integrated depth samples were collected. Chaney (1978) reported marked vertical stratification of phytoplankton cell count and chlorophyll-a concentration in Cockburn Sound with maximum cell counts and chlorophyll-a concentrations occurring more often in surface or middle waters than in bottom waters, similar to what was found in the present study. Studies prior to Chaney (1978) collected integrated water samples; no data on vertical phytoplankton distribution are available.

Increased light attenuation in Cockburn Sound (due largely to the greater phytoplankton biomass) could account for the apparent concentration of phytoplankton cells and chlorophyll-a in surface and middle waters. The bottom waters in the Cockburn Sound basin are generally oxygen deficient, an environment conducive to nutrient release. Under conditions of low light attenuation, these bottom waters would be more productive than middle or surface waters but as light attenuation increases the cell count and chlorophyll-a maxima shift upward in a compromise between light and nutrient availability.

As previously mentioned, site 4 in Cockburn Sound, being further away from any terrigenous nutrient sources and having greater oceanic exchange, is considerably less productive than the rest of the embayment. It stands to reason that light attenuation at this site would be less than in the rest of the embayment therefore permitting phytoplankton cell count and chlorophyll-a maxima at a greater depth (see section 2.4). The phytoplankton cell count and chlorophyll-a maxima observed in bottom waters at this site confirm this. The apparent low productivity and greater water clarity at this site may also be enhanced by the nearby mussel farm.

The phytoplankton cell count and chlorophyll-a maxima in the bottom waters of Warnbro Sound again suggests lower light attenuation which is consistent with lower nutrient inputs and lower productivity as indicated by lower cell numbers and chlorophyll-a concentrations compared to Cockburn Sound.

2.2.4.3 - CELL COUNT vs CHLOROPHYLL- a

Relationships between cell count and pigment concentration are difficult to determine because of the large variation in cell size (up to 2 - 3 orders of magnitude) and cellular pigment content in marine phytoplankton communities.

Cell count and pigment concentration are difficult to correlate when the phytoplankton assemblage often contains numerous small cells with low pigment concentrations as well as large cells with high pigment concentrations or vice versa. Such correlations do become evident during large scale or prolonged monospecific blooms.

Whilst there were several monospecific blooms recorded in the present study, these were short-lived and restricted in distribution, eg. *Nodularia* and *Skeletonema*, and/or were in a state of decay, eg. *Nodularia* and *Oscillatoria*. No significant correlations between cell count and chlorophyll-a concentration were found during these blooms.

Silicoflagellates, which often showed widespread dominance of the phytoplankton assemblages of both Cockburn and Warnbro sounds during winter, were significantly positively correlated with chlorophyll-a concentration at most sites in Cockburn Sound and at all sites in Warnbro Sound except sites 1 and 5 over the two annual cycles included in the present study (Table 12). When these correlations were repeated using data from silicoflagellate bloom periods only, r^2 values increased on almost all occasions; however, because of the reduced sample size, considerably fewer of these correlations were significant (Table 12). Silicoflagellates showed significant correlations with average data (all sites averaged) for both embayments over the two annual cycles ($\alpha = 0.05$ for Cockburn Sound; $\alpha = 0.01$ for Warnbro Sound) but not for the silicoflagellate bloom periods, again due to the decreased sample size.

When the data were temporally averaged (a three-point running average was applied to smooth out "lumpiness" in the timeseries plots (Figure 15)), silicoflagellates showed significant correlations with chlorophyll-a during both annual and bloom periods for Cockburn Sound ($\alpha = 0.01$) and during the annual period only for Warnbro Sound ($\alpha = 0.01$).

Table 12: Results of correlations between silicoflagellates and chlorophyll-a concentration over the annual cycle and during silicoflagellate bloom periods showing the sample size (n), the r^2 value and the significance of the correlation (NS = not significant, * = significant at $\alpha = 0.05$, ** = significant at $\alpha = 0.01$). Results are shown for all sites and depths as well as for average site data, average data and for temporally averaged data (RA). Sites CS9 and WS4 have been excluded due to the low sample size during silicoflagellate bloom periods.

		Annual			Bloom	
SITE	n	r^2	Sig.	n	r^2	Sig.
CS12(S)	38	-0.272	NS	10	0.592	NS
CS12(M)	36	0.456	**	9	0.680	*
CS12(B)	35	0.397	*	8	0.391	NS
CS12	38	0.250	NS	10	0.561	NS
CS11(S)	47	0.422	**	10	0.762	*
CS11(M)	45	0.465	**	9	0.674	*
CS11(B)	43	0.274	NS	8	0.426	NS
CS11	47	0.453	**	10	0.800	**
CS6(S)	47	0.056	NS	10	0.444	NS
CS6(M)	45	0.054	NS	9	-0.095	NS
CS6(B)	45	-0.168	NS	9	-0.158	NS
CS6	47	0.098	NS	10	0.194	NS
CS4(S)	44	0.863	**	10	0.961	**
CS4(M)	44	0.775	**	9	0.916	**
CS4(B)	45	0.172	NS	10	0.274	NS
CS4	44	0.749	**	10	0.914	**
CS	40	0.389	*	10	0.515	NS
CS(RA)	38	0.422	**	9	0.881	**
WS10(S)	46	0.474	**	13	0.326	NS
WS10(M)	45	0.707	**	12	0.750	**
WS10(B)	45	0.568	**	12	0.573	NS
WS10	46	0.532	**	13	0.419	NS
WS7(S)	46	0.897	**	13	0.957	**
WS7(M)	45	0.794	**	12	0.887	**
WS7(B)	45	0.602	**	10	0.776	**
WS7	46	0.798	**	13	0.819	**
WS5(M)	45	0.292	NS	12	0.416	NS
WS1(M)	46	0.202	NS	13	0.163	NS
WS	47	0.609	**	14	0.560	NS
WS(RA)	45	0.546	**	13	0.155	NS

Dinoflagellates showed significant positive correlations with chlorophyll-a at nearly all sites in Cockburn Sound and at no sites in Warnbro Sound over the two annual cycles (Table 13). Diatoms, cyanobacteria and other phytoplankton showed few significant correlations with chlorophyll-a (Table 13). Total phytoplankton showed significant positive correlations with chlorophyll-a at most sites in Cockburn Sound and at a few sites in Warnbro Sound over the two annual cycles (Table 13).

Table 13: Results of correlations between chlorophyll-a and major phytoplankton groups. NS = not significant, * = significant ($\alpha = 0.05$), ** = significant ($\alpha = 0.01$).

SITE	Diatoms	Dinoflagellates	Cyanobacteria	Other	Total
CS12(S)	NS	*	NS	NS	*
CS12(M)	NS	**	NS	NS	*
CS12(B)	NS	*	*	NS	**
CS12	NS	**	**	NS	**
CS11(S)	NS	**	NS	NS	NS
CS11(M)	NS	**	NS	NS	*
CS11(B)	NS	**	NS	NS	*
CS11	NS	**	NS	NS	*
CS9(S)	NS	NS	NS	NS	NS
CS9(M)	NS	NS	NS	NS	NS
CS9(B)	NS	NS	NS	NS	NS
CS9	NS	NS	NS	NS	NS
CS6(S)	NS	NS	NS	NS	NS
CS6(M)	NS	**	NS	NS	NS
CS6(B)	**	NS	NS	NS	**
CS6	NS	**	NS	NS	NS
CS4(S)	NS	**	NS	NS	**
CS4(M)	NS	**	NS	NS	**
CS4(B)	*	*	NS	NS	**
CS4	NS	**	NS	NS	NS
CS	NS	**	NS	NS	NS
CS(RA)	NS	NS	NS	NS	NS

SITE	Diatoms	Dinoflagellates	Cyanobacteria	Other	Total
WS10(S)	NS	NS	NS	NS	NS
WS10(M)	NS	NS	NS	NS	NS
WS10(B)	NS	NS	NS	NS	NS
WS10	NS	NS	NS	NS	NS
WS7(S)	NS	NS	NS	NS	**
WS7(M)	NS	NS	NS	NS	*
WS7(B)	NS	NS	NS	NS	NS
WS7	NS	NS	NS	NS	**
WS5(M)	*	NS	*	NS	**
WS4(S)	NS	NS	NS	NS	NS
WS4(M)	NS	NS	NS	NS	*
WS4(B)	NS	NS	NS	NS	NS
WS4	NS	NS	NS	NS	NS
WS1(M)	NS	NS	NS	NS	NS
WS	NS	NS	NS	NS	**
WS(RA)	NS	NS	NS	**	NS

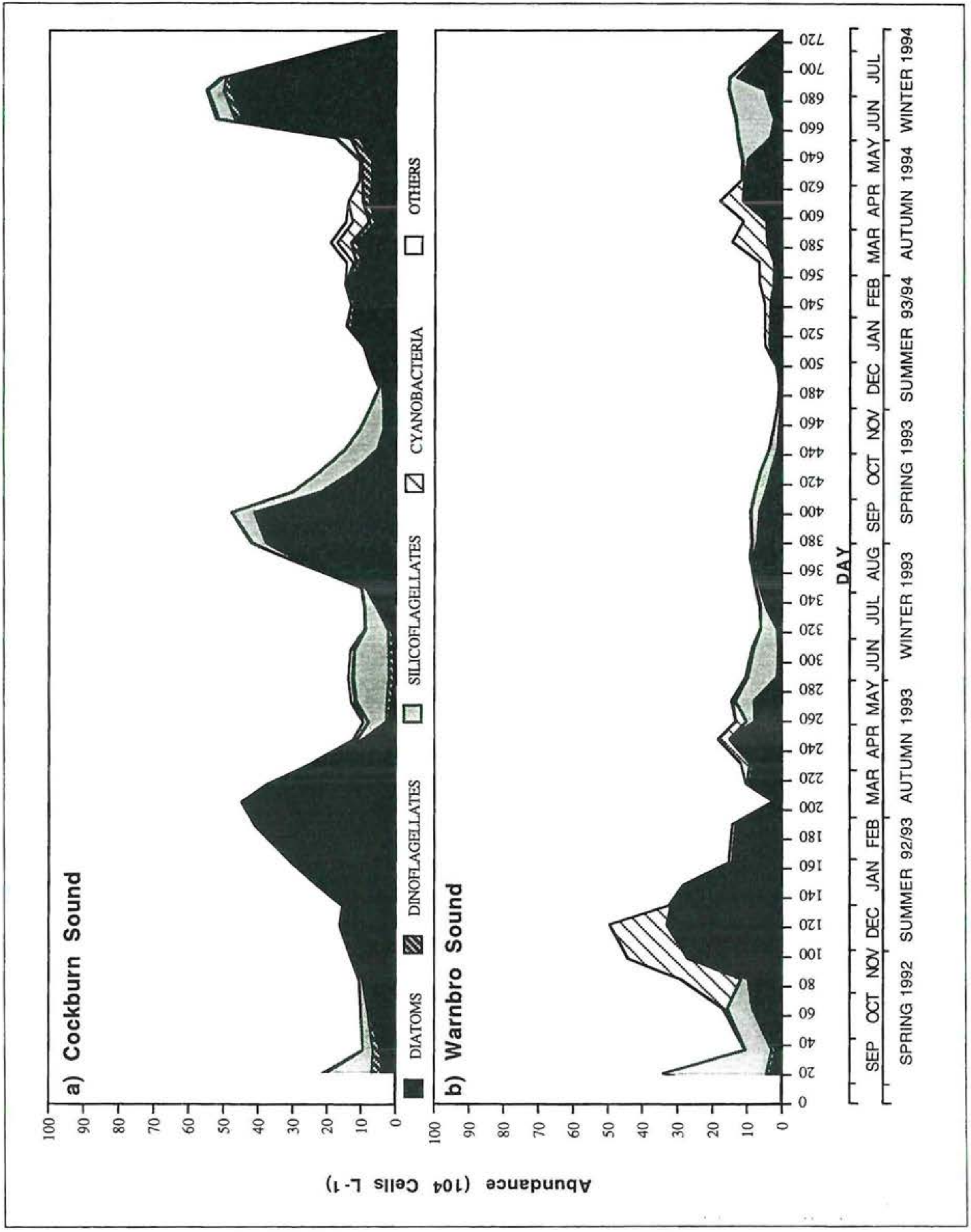


Figure 15: Temporally averaged timeseries plot showing abundance of the five major phytoplankton groups in Cockburn Sound and Warnbro Sound between February 1991 and August 1994.

Chaney (1978) found a significant positive correlation between cell count and chlorophyll-a concentration in Cockburn Sound ($\alpha = 0.01$) but not in Owen Anchorage. She attributed this lack of correlation to the above mentioned factors as well as the large amounts of detrital material present in Owen Anchorage which made cell counts difficult. In contrast, Cousins (1991) reported a significant positive correlation between cell count and chlorophyll-a concentration in both Cockburn and Warnbro sounds ($\alpha = 0.05$).

2.2.4.4 - SECCHI DEPTH

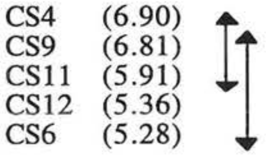
It has already been shown that the phytoplankton biomass of Cockburn Sound is considerably greater than that of Warnbro Sound and it would therefore be expected that secchi depth in Cockburn Sound would be less than in Warnbro Sound.

Although the measurement of secchi depth is more suited to still, freshwater systems (secchi depth tends to be highly dependant on prevailing light and weather conditions), it does provide a realistic interpretation of water clarity in both embayments.

Within Cockburn Sound, site 4 had the highest average secchi depth (6.90 m) compared to sites 6, 9, 11 and 12 (5.28, 6.81, 5.91 and 5.36 m respectively) (Figure 16). This is consistent with previous data suggesting that light attenuation at site 4 is less than that of the other Cockburn Sound sites. Anova and Scheffe test results ($p = 0.0003$) show that the average secchi depths of sites 4, 9 and 11 and sites 6, 9, 11 and 12 were not significantly different from each other (Table 14).

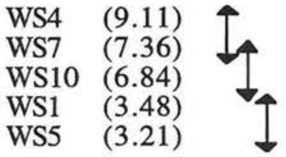
Within Warnbro Sound, sites 1 and 5 had the lowest average secchi depths (3.48 and 3.21 m respectively), not surprising considering that the shallow bottom was almost always visible. Site 4 had the highest average secchi depth (9.11 m) followed by sites 7 and 10 (7.36 and 6.84 m respectively) (Figure 16). Anova and Scheffe test results ($p = 0.0001$) show that sites 1 and 5, sites 4 and 7 and sites 7 and 10 were significantly different from each other (Table 15).

Table 14: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average secchi depth for Cockburn Sound. Means which are not significantly different are linked.



CS4	(6.90)
CS9	(6.81)
CS11	(5.91)
CS12	(5.36)
CS6	(5.28)

Table 15: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average secchi depth for Warnbro Sound. Means which are not significantly different are linked.

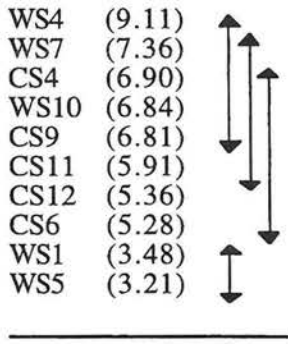


WS4	(9.11)
WS7	(7.36)
WS10	(6.84)
WS1	(3.48)
WS5	(3.21)

With the exception of site CS4, secchi depth was generally lower in Cockburn Sound than in Warnbro Sound (excluding sites 5 and 1). According to pooled site data, the Cockburn Sound coastal strip sites all had average secchi depths less than those of site CS4 and the central Warnbro Sound sites. This is also consistent with a lower light attenuation in Warnbro Sound as compared to Cockburn Sound.

Anova and Scheffe test results ($p = 0.0001$), showed that sites WS4, WS7, WS10, CS4 and CS9; sites WS7, WS10, CS4, CS9 and CS11, and sites WS10, CS4, CS6, CS9, CS11 and CS12 were not significantly different from each other. Sites WS1 and WS5 were not significantly different from each other, but were significantly different from all other sites (Table 16).

Table 16: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average secchi penetration for Cockburn and Warnbro sounds. Means which are not significantly different are linked.



WS4	(9.11)
WS7	(7.36)
CS4	(6.90)
WS10	(6.84)
CS9	(6.81)
CS11	(5.91)
CS12	(5.36)
CS6	(5.28)
WS1	(3.48)
WS5	(3.21)

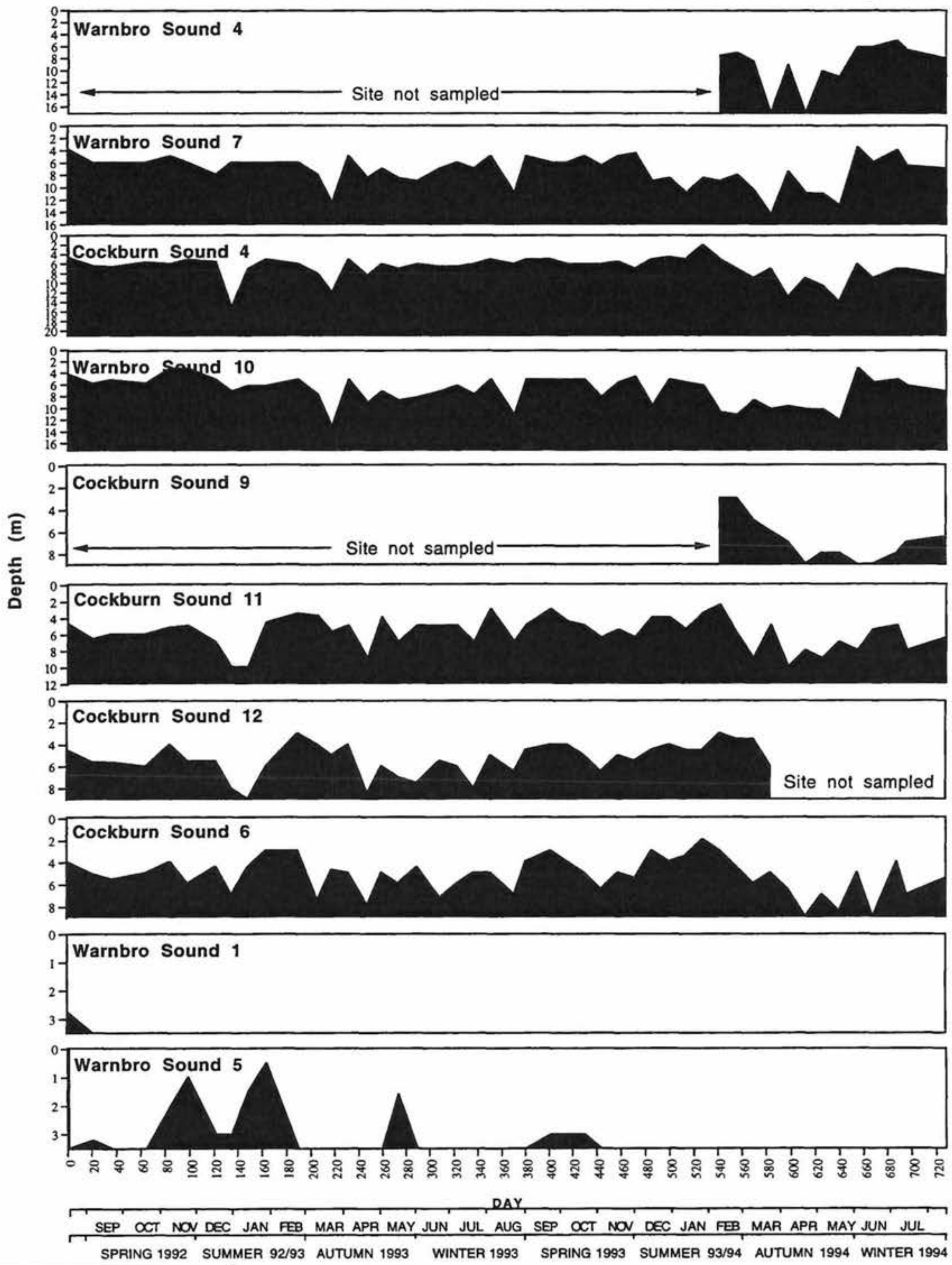


Figure 16: Timeseries plot showing secchi depth for all sites in Cockburn and Warnbro sounds. Secchi depth shown as white area.

Secchi depth showed no consistent seasonal trends in either embayment (Figure 16). None of the previous studies cited measured secchi depth. The increased availability of sophisticated portable light meters has made secchi depth a rather obsolete measurement, at least in marine waters; its usefulness in this study extends no further than reinforcing biomass data which shows greater light attenuation in Cockburn Sound than in Warnbro Sound.

2.2.5 - PRODUCTIVITY

In general, the oceanic regions of the World are oligotrophic, characterised by low nutrient concentrations and low light attenuation, the waters surrounding Australia are also generally nutrient impoverished. Within Australia's 200 nm zone nitrate concentrations rarely exceed 1.0 μM (62 μg L^{-1}), those for phosphate rarely exceed 0.2 μM (19 μg L^{-1}) (Table 17). Primary productivity values for oligotrophic oceanic regions are generally less than 0.250 g C m^{-2} d^{-1} (Hatcher 1994); open ocean regions in the tropics have productivity values generally ranging between 0.050 and 0.100 g C m^{-2} d^{-1} whilst those of high latitudes range between 0.150 and 1.250 g C m^{-2} d^{-1} (Barnes and Hughes 1982) (Table 18). Daily productivity values in the mixed layer of the open ocean around Australia range from 0.05 - 0.5 g C m^{-2} d^{-1} (Table 18) (Hatcher 1994).

Primary production in the water column is characterised by extreme 'patchiness' or variability in space and time. Phytoplankton production can be influenced by several factors including light availability, temperature, nutrient concentrations and grazing by zooplankton. Theoretical and empirical observations indicate that of all these factors, the supplies of inorganic N and P are the most important (Hatcher 1994). Phytoplankton productivity is also influenced by the structure of the phytoplankton assemblage as various phytoplankton groups respond differently to varying conditions.

Table 17: Past and present nutrient data for Cockburn Sound, Warnbro Sound and Owen Anchorage, as well as for other Australian waters. Sources and comments are listed below the table.

	NO_3^- (µg L^{-1})	NH_4^+ (µg L^{-1})	TN (µg L^{-1})	PO_4^{3-} (µg L^{-1})	TP (µg L^{-1})
Australian Waters[1a]	> 22.14			> 1.2	
Australian 200 nm Zone[1b]	< 62			< 19	
Cockburn Sound 1977-78[2a]	2 - 11	1 - 95		5 - 239	8 - 576
Cockburn Sound 1977-78[2b]	2 - 79	2 - 194	<200 - 62	20 - 275	32 - 627
Cockburn Sound 1977-78[3]	7±5	31±30	173±61	105±45	119±57
Cockburn Sound 1978[4]	8 - 70	10 - 90	180 - 370	90 - 200	40 - 200
Cockburn Sound 1982-83[3]	7±3	16±16	339±96	56±14	86±15
Cockburn Sound 1984-85[5]	6±4	16±7	497±119	15±9	40±16
Cockburn Sound 1986-87[6]	4±2	21±10	346±162	9±4	47±52
Cockburn Sound 1990-91[7]	7±2	10±8	252±35	3±2	34±3
Cockburn Sound 1991[8]			41 - 236		5 - 27
Dawesville Channel (outer)[11]	4 - 22	2 - 12	30 - 170		18 - 26
Dawesville Channel[11]	4 - 21	5 - 44	50 - 600		17 - 68
Dawesville Channel (inner)[11]	6 - 24	4 - 16	50 - 750		20 - 103
Harvey Estuary[11]	5 - 440	5 - 500	100 - 2 10		10 - 230
Owen Anchorage 1977-78[2a]	2 - 11	2 - 30		1 - 73	14 - 300
Owen Anchorage 1977-78[2b]	2 - 35	6 - 80	<200 - 108	2 - 60	20 - 240
Owen Anchorage 1982-83[3]	5±3	14±10	432±164	39±15	73±31
Owen Anchorage 1984-85[5]	4±2	13±10	495±144	8±5	30±9
Owen Anchorage 1986-87[6]	3±1	13±10	275±103	5±4	34±42
Owen Anchorage 1990-91[7]	6±1	3±0.6	233±24	1±0.6	31±1.5
Peel Inlet[11]	5 - 490	5 - 250	100 - 2 20		2 - 120
Perth Coastal Waters[1b]	0.44 - 4.43			0.31 - 0.61	
Perth Coastal Waters[12a]			5.3		4.0
Perth Coastal Waters[12b]			3.8		3.0
Perth Coastal Waters[12c]			5.2		3.0
Perth Coastal Waters[12d]			4.2		3.2
Swan River (Lower - 0 m)[9a]	10 - 40 (25)	10 - 51 (40)			500 - 1 300 (900
Swan River (Lower - 14.5 m)[9a]	10 - 40 (25)	20 - 85 (50)			100 - 1 100 (800
Swan River (Lower - 0 m)[9b]	40 - 1 900 (1 000)	10 - 220 (11			100 - 1 750 (1 35
Swan River (Lower - 14 m)[9b]	10 - 800 (200)	20 - 200 (85			100 - 1 200 (700
Swan River (Lower)[10a]			403 - 2 72		47 - 465
Swan River (Lower)[10b]			158 - 1 02		32 - 226
Warnbro Sound 1991[8]			49 - 262		7 - 25
Warnbro Sound 1977-78[2a]	2 - 11			1 - 12	1 - 50

1a - Range of values. Australia's richest areas. (Jeffrey, Rochford & Cresswell 1990).
1b - Range of values. (Jeffrey, Rochford & Cresswell 1990).
2a - Range of values. Result of 9 cruises August 1977 - December 1978 (Chiffings 1979).
2b - Range of values. Result of weekly sampling August 1977 - December 1978 (Chiffings 1979).
3 - Average ± Std. Dev. Summer 1982-83 (Chiffings and McComb 1983).
4 - Range of values. Weekly sampling March - October 1978 (Chaney 1978).
5 - Average ± Std. Dev. Summer 1984-85 (Hillman 1986).
6 - Average ± Std. Dev. Summer 1986-87 (Hillman and Bastyan 1988).
7 - Average ± Std. Dev. Summer 1990-91 (Cary *et al.* 1991).
8 - Range of values. Autumn-Winter 1991 (Cousins 1991).
9a - Range of values with(average). Summer 1974 (Jack 1987).
9b - Range of values with (average). Winter 1974/75 (Jack 1987).
10a - Range of values. Winter/Spring 1980 (John 1983).
10b - Range of values. Summer/Autumn 1980/81 (John 1983).
11 - Range of values. Jan 1993 - May 1995 (Chase 1995).
12 - Median Values: a) Nearshore-summer b) Nearshore-winter c) Offshore-summer d) Offshore-winter (Carey *et al.* 1995)

Table 18: Phytoplankton primary productivity from different marine waters around the World. Values are expressed as either ranges or means (± SD). Sources are listed below the table.

Location	Productivity (mg C m^{-2} d^{-1})	Comments
Antarctic Regions[1]	9.86 - 907.4	
Antarctica (Ross Sea)[2]	(0.99±0.82) - (3.9±2.72)	Spring 1978
Antarctica (Weddell Sea)[3]	<200	Autumn 1986, Ice-covered waters
Arabian Sea[4]	300 - 1 000	
Australia (200 nm zone)[5]	< 250	
Baltic Sea (Northern)[6]	<1.8	Spring 1988
Baltic Sea (Skagerrak/Kattegat Front)[7]	(575±232) - (908±412)	1984 - 1993
	521	Estimated Annual Average
Cockburn Sound[8]	33 600	Maximum value, autumn 1978
Cockburn Sound[9]	603	Annual average 1992-1994
Coral Sea[10]	264 - 600	
Great Australian Bight[10]	437	Summer months
Gulf of Carpentaria[10]	3 190	Summer months
Indian Ocean (110°E) [10]	888	
Indian Ocean (southern) [10]	3 120	
Open Ocean[5]	50 - 500	
Open Ocean (High latitudes)[11]	150 - 1 250	
Open Ocean (Oligotrophic regions)[5]	<250	
Open Ocean (Tropical)[11]	50 - 100	
Pacific Ocean (near Strait of Magellan) [12]	195	Summer 1991
Peel / Harvey Estuary[13]	4 660	Winter bloom
Sargasso Sea (western) [14]	96 - 261 (141)	Winter
	69 - 589 (333)	Spring
Shelf Seas & Neritic Waters[5]	350 - 1 000	
Strait of Magellan[12]	195 - 1170	Summer 1991
Subtropical Areas[1]	13.7 - 2 498	
Sydney Harbour (estuary)[15]	260	Annual average
Sydney Harbour (upper estuary) [15]	3 040	Annual average
Tasmanian Waters[10]	336 - 2 880	
Tasman Sea[10]	1 176	Summer months
Upwelling Regions[5]	500 - 3 150	
Warnbro Sound[9]	243	Annual average 1992-1994
Westerschelde Estuary (Netherlands)[16]	270 - 2460	Spring - Autumn 1989

1) Walsh (1969)
2) Arrigo and McClain (1994)
3) Gleitz *et al.* (1994)
4) Jochem *et al.* (1993)
5) Hatcher (1994)
6) Lignell *et al.* (1993)
7) Heilmann *et al.* (1994)
8) Cousins (1991)
9) Present Study
10) Jeffrey and Hallegraeff (1990)
11) Barnes and Hughes (1982)
12) Saggiomo *et al.* (1994)
13) Revelante and Gilmartin (1978)
14) Malone *et al.* (1993)
15) Lukatelich and McComb (1986)
16) Van Spaendonk *et al.* (1993)

Phytoplankton populations are generally characterised by boom and bust cycles. Phytoplankton growth booms and busts as nutrients become available and are exploited, and as grazer communities respond. The result of this is a succession of phytoplankton groups and, within those groups, a succession of phytoplankton species. The factors that limit productivity of different populations during this succession may be quite different (Hatcher 1994).

Nutrient levels in Cockburn and Warnbro sounds were greater than those regarded as being typical of Australian coastal waters. In previous studies nitrate and phosphate concentrations in Cockburn Sound have been recorded up to 1.2 and 14.0 times greater (respectively) than those considered to be typical maximum values for Australian waters within the 200 nm zone, and up to 3.5 and 230 times greater (respectively) than those of Australia's richest waters (Table 17). Nitrate and phosphate values previously reported for Warnbro Sound were 0.2 and 0.6 times less (respectively) than those considered to be typical maximum values for Australian waters within the 200 nm zone, and 0.5 and 10.0 times (respectively) those of Australia's richest waters (Table 17).

Maximum nitrate concentrations indicative of Perth coastal waters were up to 1 100 times less than those recorded in Cockburn Sound and 180 times less than those recorded in Warnbro Sound and Owen Anchorage (Table 17). Maximum phosphate concentrations indicative of Perth coastal waters were up to 10 000 times less than those recorded in Cockburn Sound and 3 000 times less than those recorded in Warnbro Sound and Owen Anchorage (Table 17). However, nutrient concentrations recorded in Cockburn Sound are presently, and have consistently been in the past, considerably less than those recorded from the lower Swan River estuary and from the Peel-Harvey estuary, especially winter/spring concentrations (Table 17).

Productivity was not measured directly during the present study. However, it was estimated empirically, as is the case with any abundance-based estimates of productivity, several assumptions were made as follows:

1. Phytoplankton standing crop (expressed as chlorophyll-a) was the annual average for both embayments.
2. Zooplankton standing crop was taken to be the annual average adult copepod abundance in each embayment (expressed as animals L^{-1}) and was used to represent the grazing pressure of the entire zooplankton community.
3. Zooplankton grazing rate = 0.10 μg chl-a $animal^{-1}$ day^{-1} (Jorgensen 1991).
4. Settling/advective loss = 5% of phytoplankton biomass day^{-1} (Jorgensen 1991).
5. Phytoplankton Carbon:Chlorophyll-a ratio = 50:1 (Hillman 1986).

The doubling time of phytoplankton populations can be estimated by dividing the phytoplankton standing crop by the combined losses due to grazing and settling/advection, assuming that the phytoplankton standing crop remains relatively constant on a day to day basis. When calculated in this manner, the phytoplankton doubling times for Cockburn and Warnbro sounds are quite similar at around 2.3 days (Table 19). Although the doubling times for the phytoplankton populations were the same in both embayments, the phytoplankton standing crop was about 2.5 times higher in Cockburn Sound than in Warnbro Sound, subsequently the production per cubic metre was also about 2.5 times higher in Cockburn Sound (40.20 mg C m^{-3} d^{-1} compared to 16.20 mg C m^{-3} d^{-1}) (Tables 19 and 20).

Table 19: Comparison of phytoplankton standing crop, zooplankton grazing pressure, and phytoplankton doubling times in Cockburn Sound and Warnbro Sound.

		Cockburn Sound	Warnbro Sound
Average Depth (m)		15	15
Volume (L)		1.5×10^{12}	0.3×10^{12}
Chlorophyll-a standing crop (μg Chl-a L^{-1})		1.85	0.76
Settling/Advective loss (μg Chl-a L^{-1} d^{-1})	(1)	0.093	0.038
Copepod standing crop (animals L^{-1})		7.1	2.8
Grazing loss (μg Chl-a L^{-1} d^{-1})	(2)	0.710	0.285
Total loss (μg Chl-a L^{-1} d^{-1})	(3)	0.803	0.323
Phytoplankton doubling time (days)	(4)	2.30	2.35

Equation 1: Settling/Advective loss = 5% phytoplankton biomass day^{-1}.
Equation 2: Grazing loss = 0.10 μg Chl-a $animal^{-1}$ day^{-1}.
Equation 3: Total loss = Settling/(Advective loss + Grazing loss).
Equation 4: Phytoplankton doubling time = Standing crop / Total loss

Table 20: Comparative productivity of phytoplankton in Cockburn Sound and Warnbro Sound.

Productivity		Cockburn Sound	Warnbro Sound
Daily rates			
μg Chl-a L^{-1} d^{-1}	(5)	0.80	0.32
μg C L^{-1} d^{-1}	(6)	40.20	16.20
mg C m^{-3} d^{-1}		40.20	16.20
mg C m^{-2} d^{-1}	(7)	603.00	243.00
Annual rates			
g C m^{-2} yr^{-1}		220.10	88.50
tonnes C yr^{-1}	(8)	22 009.00	1 771.00

Equation 5: Productivity = Standing crop / Doubling time.
Equation 6: Phytoplankton Carbon:Chlorophyll ratio = 50:1
Equation 7: Productivity m^{-3} = Productivity m^{-2} x Average depth of embayment.
Equation 8: Annual production = Daily production L^{-1} x 365 days x Volume of embayment

The spatial distribution of productivity values obtained support cell count and chlorophyll-a data from both Chaney's and the present study. The highest values were obtained from the southern portion of the embayment between Mangles Bay and James Point (in the vicinity of site 11), followed by the mainland coastal area (sites 9 and 6), with the mid-embayment, Garden Island (site 4) and near-oceanic sites having the lowest productivity values (Figure 2). Although the estimated productivity for Cockburn Sound in the present study is similar only to Chaney's minimum value, it is still a reasonable estimate considering that it does not take into account any seasonal or spatial variation and that phytoplankton productivity during Chaney's study would have been considerably higher taking into account the greater phytoplankton biomass (Table 4).

Chaney (1978) measured phytoplankton productivity at 19 sites within Cockburn Sound during September 1978 using the C^{14} technique. Productivity values ranged from 48 mg C m^{-3} d^{-1} to 818 mg C m^{-3} d^{-1} with an average of 231 mg C m^{-3} d^{-1} ± 170. Chaney also measured productivity in Cockburn Sound on a monthly basis between March and October 1978 using the O_2 production technique. Productivity was greatest during autumn and least during winter. The values obtained were extraordinarily high (ranging between 5 280 and 33 600 mg C m^{-2} d^{-1}), much higher than that estimated in the present study (603 mg C m^{-2} d^{-1}, Table 20) and considerably higher than values indicative of nutrient-rich upwelling regions (Table 18). It is unlikely that these figures represent accurate productivity measurements.

Phytoplankton productivity in Cockburn Sound, as estimated in the present study, is relatively low by world standards, fitting well within the range of values expected for shelf seas and neritic waters and at the bottom of the range of values expected for upwelling regions, it was greater than that expected for open ocean regions and Australian coastal waters in general (within the 200 nm zone) (Table 18). On the other hand, the productivity estimated for Warnbro Sound was similar to values which would be expected in Australian coastal waters and oceanic regions (Table 18).

Cockburn Sound is approximately five times larger than Warnbro Sound by volume (Table 19) and therefore the primary production of Cockburn Sound attributable to phytoplankton (22 009 t C y^{-1}) is about 12.4 times greater than that of Warnbro Sound (1 771 t C y^{-1}) (Table 20).

As mentioned earlier, the productivity of phytoplankton, and most other primary producers for that matter, is primarily determined by light availability, water temperature and macro-nutrient availability. Other factors such as micro-nutrient availability can also be important, however these are considered to be secondary factors and generally do not override the effects of the primary limiting factors described above. Nitrogen is the macro-nutrient most limiting plant growth in these waters (Anon 1979, Chiffings and McComb 1983, Hillman and Bastyan 1988).

Apart from the size difference of the two embayments, they have similar bathymetry, sediment types, habitat types and have similar seasonal patterns and ranges in water temperature and global radiation. The major difference between them is the magnitude of nutrient loads they receive from anthropogenic sources; Cockburn Sound is currently estimated to receive a daily load during summer of between 1 300 and 3 200 kg of nitrogen compared to Warnbro Sound which receives about 50 kg N d^{-1} (Muriale and Cary 1995). Given the similarity in the physical and biological characteristics of the embayments, it would appear that the difference in their respective nutrient loadings is the most likely cause of the different phytoplankton productions.

The carbon to nitrogen to phosphorus ratio of phytoplankton is generally considered to be about 106:16:1 on a molar basis (Redfield 1958) but data collected by Bastyan and Hillman (unpublished; cited in Bastyan and Paling 1995) suggest that the C:N:P ratio of the phytoplankton of Cockburn Sound is more like 106:10.4:1 and supports the general assumption that the growth of phytoplankton is nitrogen limited. The nitrogen requirement to meet the measured production in the two embayments can be calculated by applying these C:N ratios (Table 21).

Table 21: Annual nitrogen requirements to support phytoplankton production in Cockburn and Warnbro sounds.

	Cockburn Sound	Warnbro Sound
Chl-a (µg L^{-1})	1.85	0.76
Annual production (tonnes C yr^{-1})	22 010	1 770
Nitrogen requirement (tonnes N yr^{-1}) (9)	2 522 - 3 865	203 - 311
Nitrogen requirement (tonnes N d^{-1})	6.91 - 10.59	0.56 - 0.85

Equation 9: Nitrogen requirement = Application of C:N molar ratios (106:16 - 106:10) to Annual carbon production.

These estimated nitrogen requirements for maintaining the current level of primary production in Cockburn Sound are similar to the range 5.9 - 9.1 t N d^{-1} calculated from Bastyan and Paling (1995) after correcting an error in the C:N:P ratio used in their calculations.

2.2.6 - POTENTIALLY TOXIC PHYTOPLANKTON

Some dinoflagellates and diatoms are capable of producing powerful toxins which affect organisms which feed upon them, either directly or indirectly, including humans who eat shellfish that have ingested these algae. Many of these phytoplankton species are cosmopolitan and some were identified in the present study, but generally at relatively low abundances.

The dinoflagellates *Alexandrium* and *Gymnodinium* spp. were found in Cockburn and Warnbro sounds and some strains are known to cause Paralytic Shellfish Poisoning (PSP). *Alexandrium* spp. occurred at all sites in both embayments except at the most southerly end of Cockburn Sound (site 11) and was most common during spring; the maximum abundance (~9.0×10^3 cells L^{-1}, 2.2% of total abundance) was recorded in bottom samples from Jervoise Bay in early spring 1993. *Gymnodinium* spp. were found at all sites and were most common during autumn and winter, but rarely exceeded 1.0×10^3 cells L^{-1}.

The dinoflagellates *Prorocentrum micans* and *Dinophysis acuminata* were found in both embayments and are known to be responsible for Diarrhetic Shellfish Poisoning (DSP). *P. micans* occurred at average cell counts of 8.0×10^2 and 4.0×10^2 cells L^{-1} in Cockburn Sound and Warnbro Sound respectively over the sampling period. The maximum recorded abundance of 2.4×10^4 cells L^{-1} (~3.5 % of total abundance) occurred near James Point (Cockburn Sound, site CS12) in late winter 1992. *D. acuminata* was commonly found throughout the year at average cell counts of 2.3×10^2 and 1.4×10^2 cells L^{-1} at Cockburn Sound and Warnbro Sound respectively and reached maximum cell counts of 1.2×10^4 cell L^{-1} (~1.2 % of total abundance) in surface waters near Mangles Bay (Cockburn Sound, site CS11) during mid-winter 1994.

Blooms of the tropical cyanobacterium *Oscillatoria erythraea* are often sustained for several weeks in the coastal waters of Perth. Toward the final stages of these blooms, large amounts of purple pigments become visible indicating that the cells of this cyanobacterium become lysed. In the past, human health problems ("Trichodesmium fever") have been associated with *O. erythraea* contact (Satô *et al* 1963) and Hawser *et al* (1991) have described a highly neurotoxic effect of *Oscillatoria* (*Trichodesmium*) samples on mice. *Oscillatoria thiebautii*, whist non-toxic to harpactacoid copepods, has been shown to cause significant mortality to calanoid and cyclopoid copepods and to brine shrimp. *O. erythraea*, when used in place of *O. thiebautii* in similar experiments, was shown to be non-toxic (Guo and Tester 1994).

No toxins have yet been isolated from and/or characterised for *Oscillatoria* (Guo and Tester 1994). Samples analysed from blooms which occurred during this study were shown to be non-toxic.

Several species of the toxigenic diatom genus *Pseudonitzschia* have been recorded from Perth coastal waters (Hallegraeff 1994a, John pers. observations). Accurate identification of these taxa requires electron microscopic studies, and several taxa which are similar to *Pseudonitzschia australis* were recorded. Further work is required to ascertain the exact identity of these taxa.

Outbreaks of PSP and DSP have had serious repercussions on the viability of shellfish aquaculture industries in Europe, Asia and America. The low abundances of the causative phytoplankton species and the absence of any reported poisonings of humans in local waters suggests that there is no current cause for undue concern, but the presence of these species is indicative of the potential for problems to occur in the future.

Other species that were also recorded in the present study such as the dinoflagellates *Dinophysis caudata, D. rotundatum*, *Scrippsiella*, and *Amphidinium* have been implicated as the cause of fish mortalities or have been the cause of public health concerns elsewhere, but their toxicity status remains largely unresolved.

2.3 - SUMMARY

High nutrient inputs and the associated increase in phytoplankton biomass have, in the past, been responsible for an 80% reduction in the area of seagrass meadows in Cockburn Sound. Remedial measures undertaken during the early 1980s reduced these nutrient inputs and an improvement in water quality was apparent. However, recent studies indicate that water quality within Cockburn Sound may, once again, be deteriorating.

The following are the conclusions of the phytoplankton component of the present study based on a two-year fortnightly sampling program between August 1992 and August 1994.

1. More than 300 phytoplankton taxa were recorded, primarily consisting of diatoms, dinoflagellates, silicoflagellates and cyanobacteria, represent a moderately diverse flora for coastal temperate regions. However there was relatively very few nano- and pico-phytoplankton.

   The number of taxa found in the present study was much greater than that found in previous studies, however this may reflect higher frequency of sampling and more detailed taxonomic analysis.

   The very low percentage of nano- and picophytoplankton and possible reasons are discussed. The abundance and distribution of nano- and pico-phytoplankton in Cockburn and Warnbro sounds as well as in the coastal waters off Perth warrants further investigation.

2. Most of the phytoplankton taxa encountered were cosmopolitan in temperate coastal waters. The occurrence of several tropical taxa of diatom, dinoflagellate and cyanobacteria indicated the influence of the Leeuwin Current on the coastal waters of Perth. The presence of large numbers of silicoflagellates may indicate a Southern Ocean influence.

3. Annual blooms of the tropical cyanobacterium *Oscillatoria erythraea* are a common occurrence in the waters off Perth. These blooms are often sustained for several weeks before decaying and must have a considerable effect on the local ecology.

Further work is required to investigate the origin and distribution of this alga and its influence on the ecology of Cockburn and Warnbro sounds in terms of potential toxicity especially with respect to the pilchard (*Sardinella lemuru*), white bait (*Hyperlophus vittatus*) and mussel (*Mytilus edulis*) fisheries (to date, the blooms have been non-toxic), palatability to grazers, and its effect on the nutrient budget (do they fix or consume nitrogen in these waters?).

4. Another tropical cyanobacterium, *Richelia intracellularis*, also warrants further investigation. Blooms of this cyanobacterium reported in Warnbro Sound during early autumn 1994 were considerably larger than any that have been found in the literature. As this bloom was not recorded during 1993, it is not known whether it is an annual or occasional event. This cyanobacterium is diazotrophic and, when present in large numbers, may have an impact on the ecology of the embayment. When present as an endosymbiont, it may also increase the palatability of certain taxa of diatom. *Richelia intracellularis* is non-toxic.

   The co-occurrence of *Richelia intracellularis* and *Oscillatoria erythraea* blooms appear to have been recorded for the first time.

5. Silicoflagellates, whilst abundant in the Southern Ocean, are generally not recorded in abundance in any other coastal Australian waters. Their dominance of the phytoplankton assemblage during winter and spring in the coastal waters of Perth is only a recent phenomenon having begun sometime between the late 1970s and the early 1990s.

   Dictyocha speculum blooms (naked and skeletal stages) have been associated with fish kills in Denmark (garfish and farmed trout) and France (trout). A major bloom of *D. octonaria* off the east coast of Australia during 1993 was also associated with massive fish kills.

There are two possible explanations for the apparent recent (< 15 years) dominance of silicoflagellates during winter compared to the dominance by other flagellates during 1978. The literature suggests that high concentrations of heavy metals can inhibit algal growth, with the diatoms, dinoflagellates and cyanobacteria most sensitive and the green flagellates the least sensitive (Hallegraeff 1994b). During the late 1970s, loadings of heavy metals to Cockburn Sound and Owen Anchorage were higher than current loadings (Muriale and Cary 1995) and the apparent dominance by flagellates during 1978 may reflect a competitive advantage given to them as a result of heavy metal pollution. Alternatively, the current dominance and broad-scale distribution of silicoflagellates may be an indication of chronic, low-level anthropogenic influences operating at a regional scale which either stimulate silicoflagellate growth (silicoflagellates have been linked to eutrophication in European waters) or reduce grazing pressure. Data from elsewhere in the state are needed to confirm this.

The distribution, abundance and timing of silicoflagellate blooms should be investigated in other areas of the south and west coast during winter to put the local patterns into a broader perspective and provide insight into the potential cause(s) of the recurring blooms, as well as any possible risk to pilchard and white bait fisheries in Cockburn and Warnbro sounds.

6. Other taxa present in Cockburn and Warnbro sounds not of local origin included the diatom *Skeletonema costatum* and the cyanobacterium *Nodularia spumigena. N. spumigena* cells were not in living condition being unable to tolerate the high salinity of sea water, with the Dawesville Channel now open, high abundances of this cyanobacterium in Perth coastal waters are not likely to re-occur. Blooms of *S. costatum* in the coastal waters off Perth are likely to become an annual event if trends toward increased eutrophication persist.

7. Disregarding regional effects caused by the influence of the Peel-Harvey and Swan River estuaries and the Leeuwin Current, distinct seasonal patterns in the succession of phytoplankton assemblages were recognised, with summer and autumn assemblages dominated by diatoms, winter and spring assemblages dominated by silicoflagellates and dinoflagellates forming a minor part of the phytoplankton assemblage throughout the year.

The timing of peaks in the abundance of these major groups was consistent with that reported in the literature.

However, the overall phytoplankton cycle which, including the work of Cousins (1991), has been observed over three annual cycles (1991 - 1994), does not conform to that of other temperate regions of Australia and the World. The main reason for this is the dominance of silicoflagellates during winter and spring.

8. A comparison of the taxa found in both embayments indicated a high degree of commonality in species composition with 64% of the phytoplankton taxa common to both Cockburn and Warnbro Sound. Twenty percent were exclusive to Cockburn Sound and 16% were exclusive to Warnbro Sound.

   Multivariate analyses, based upon species abundance, indicated that there was greater similarity between sites within embayments than between embayments. Sites between embayments were most similar during periods of high silicoflagellate abundance.

   This commonality in phytoplankton assemblages and the seasonal successional patterns in the two embayments (and Sepia Depression) suggest that factors common to the region control species assemblages and the successional pattern of these assemblages.

   The differences in phytoplankton abundance and biomass in the sub regions of the study area suggest that factors specific to these sub-regions control abundance and biomass. Further, spatial patterns of highest phytoplankton abundance and biomass near the areas of nutrient discharge within Cockburn Sound indicate a direct relationship between nitrogen discharge and phytoplankton biomass.

9. Trends in phytoplankton biomass, measured as cell count and chlorophyll-a, for Cockburn Sound were consistent with those of previous studies. Biomass was highest along the eastern (coastal) boundary of the embayment, especially in the Mangles Bay area, and lowest in the northern and north-western areas where the embayment adjoins the open coastal waters of the Indian Ocean.

Within Warnbro Sound, phytoplankton biomass was lowest at the northern end (near Mersey Point) and highest in the remainder of the embayment.

Phytoplankton biomass (both cell count and chlorophyll-a) in Cockburn Sound was consistently higher than that of Warnbro Sound by a factor of about 2.5. This supports data collected in earlier studies (ERA 1974 a, b) which showed considerably higher phytoplankton cell counts in Cockburn Sound compared to nearby, well flushed coastal waters.

10. The exaggerated effect of allochthonous phytoplankton on biomass estimates using cell counts and to a lesser extent chlorophyll-a concentration was demonstrated. Allochthonous phytoplankton material must be taken into account when performing calculations or making comparisons.

The observations of large surface slicks of species such as *O. erythraea* and *N. spumigena*, apparently advected into the embayments from neighbouring waters, indicates that the presence of high abundances of phytoplankton in a particular environment does not necessarily imply that the phytoplankton grew in that area in response to a local stimuli. These advected species raise chlorophyll-a concentrations, complicating the interpretation of water quality monitoring programs and can lead to a false conclusion that water quality has deteriorated due to local factors (eg. waste inputs).

11. Vertical stratification with respect to phytoplankton cell count and chlorophyll-a concentration in both Cockburn and Warnbro sounds was explained in terms of a compromise between light attenuation and nutrient availability. In Cockburn Sound, where light attenuation was high, phytoplankton biomass was distributed closer to the surface whereas in Warnbro Sound, where light attenuation was lower, phytoplankton biomass was distributed mainly in bottom waters closer to the nutrient-rich sediment.

12. Both annual and seasonal chlorophyll-a averages and ranges for Cockburn Sound were greater than those expected for temperate regions around Australia. Annual and seasonal average chlorophyll-a concentrations for Warnbro Sound were within the range of those expected for temperate regions around Australia, however the annual range of values was greater.

    Summertime chlorophyll-a concentrations in Cockburn Sound fell considerably after the installation of the KNC steam scrubber in 1982 and the diversion of secondary wastes from the Woodman Point sewage outfall in 1984. Concentrations for the summers of 1982/83, 1984/85 and 1986/87 were not significantly different from each other; data for subsequent summers suggests that chlorophyll-a concentrations are on the increase once more.

13. Nutrient levels in Cockburn and Warnbro sounds are considerably greater than those regarded as being typical of Australian coastal waters. However, they are consistently less than those recorded from the Swan and Peel-Harvey estuaries.

14. Empirical calculations of phytoplankton doubling times were similar for both Cockburn and Warnbro sounds at around 2.3 days.

15. Phytoplankton productivity per cubic metre, based on empirical calculations, was about 2.5 times higher in Cockburn Sound than in Warnbro Sound.

    Spatial estimates of phytoplankton productivity made by Chaney (1978) support cell count and chlorophyll-a data from both Chaney's and the present study. The highest values were obtained from the southern portion of the embayment between Mangles Bay and James Point (in the vicinity of site 11), followed by the mainland coastal area (sites 9 and 6), with the mid-embayment, Garden Island (site 4) and near-oceanic sites having the lowest productivity values.

Phytoplankton productivity in Cockburn Sound, as estimated in the present study, was relatively low by world standards, fitting well within the range of values expected for shelf seas and neritic waters and at the bottom of the range of values expected for upwelling regions. However, it was greater than that expected for open ocean regions and Australian coastal waters in general (within the 200 nm zone). On the other hand, the productivity estimated for Warnbro Sound was similar to values which would be expected in Australian coastal waters and oceanic regions.

16. Cockburn Sound is currently estimated to receive a daily nitrogen load during summer between 26 and 64 times greater than that of Warnbro Sound. Given the similarity in the physical and biological characteristics of the embayments it would appear that the difference in their respective nutrient loadings is the most likely cause of the different phytoplankton productions.

Estimated nitrogen requirements for maintaining the current level of primary production in Cockburn Sound are similar to those calculated in previous studies. Estimated nitrogen requirements exceeded nitrogen inputs by a factor of around 3.9 times.

17. Several potentially toxic dinoflagellate, cyanobacteria and possibly diatom taxa were identified. Although their biomass was relatively low, at least with respect to the dinoflagellates, and as yet there have been no reported human poisonings or fish kills in local waters, the presence of these species is indicative of future potential.

Further work is required to investigate the distribution and abundance of these taxa and also to resolve their taxonomy and toxic potential. Since it is known that these taxa are present in Perth's coastal waters, regular monitoring of phytoplankton should be conducted to detect any increases in abundance or toxicity of these taxa as well as to detect the presence of other potentially toxic taxa, especially in areas utilised for shellfish harvesting (commercial and recreational) and subject to nutrient enrichment.

The presence of distinct seasonal phytoplankton assemblages, together with recurring, cyclical patterns of succession of these assemblages allows diverse phytoplankton populations to be characterised and described simply, facilitating the development of efficient and focussed biological monitoring programs. This information is a prerequisite for the development of a phytoplankton species succession and growth model.

3 - ZOOPLANKTON

Zooplankton are the primary grazers of phytoplankton assemblages. The zooplankton assemblages are sensitive to changing environmental conditions just as phytoplankton. Therefore zooplankton populations are potentially useful indicators of environmental change in their own right and, additionally, as a potential control on phytoplankton populations. There have been no intensive studies of zooplankton populations of Perth's coastal waters, although some work was conducted during the early 1970s (ERA 1971 a, b) with the intent of using the abundance of selected species as indices of water residence times in Cockburn Sound.

In order to gain a better understanding of the nature of zooplankton communities in the southern metropolitan coastal waters of Perth and the factors that control these populations, intensive local-scale studies have been undertaken as part of the Southern Metropolitan Coastal Waters Study. The specific objective of these studies was to characterise the seasonal and inter-annual variation in the zooplankton assemblages in Cockburn and Warnbro sounds over the period August 1992 to August 1994. These studies, which complement the phytoplankton data, also provide information useful in developing a phytoplankton species succession and growth model for these waters.

3.1 - MATERIALS AND METHODS

Fortnightly cruises were conducted between August 17, 1992 and August 15, 1994 inclusive on board the D.E.P. research vessels EX63, Diadema or Bidthangarra. A total of 56 cruises were conducted - 48 fortnightly, and an additional eight during the summer intensive survey (December 23 1993 to March 30 1994) (Appendix 1). Zooplankton samples were collected from the same locations as phytoplankton samples (Section 2.1) between 8:00 am and 4:00 pm.

Zooplankton samples were collected using a 180 μm net towed at a speed not exceeding 5. Samples were collected from surface (1 m below surface), middle and bottom (1 m above bottom) waters at all sites except WS5 and WS1 where middle samples only were collected.

Between August 17, 1992 and January 13, 1993 inclusive, zooplankton samples were collected using a Clarke-Bumpus zooplankton sampler with a close-open-close messenger-operated system allowing discrete samples to be taken at each depth. Loss of this net on January 28, 1993 prevented further zooplankton sampling until April 6, 1993. From this date onwards, the samples were collected using a standard zooplankton net (diameter = 30 cm). For consistency, zooplankton tows generally lasted two minutes. Both nets were equipped with flow meters by which filtered volume could be determined, allowing quantitative analysis of samples. Flow meters were calibrated on a regular basis by towing the net frame (net removed) over a known distance (ie. a known volume).

Zooplankton samples were concentrated to a volume of 30 ml, transferred to labelled plastic vials, preserved with the addition of 5% borax-buffered formaldehyde and stored for analysis. The samples were analysed qualitatively and quantitatively using a Leitz Laborlux S photomicroscope and a Sedgwick-Rafter counting cell at a magnification of 40 - 100x. Zooplankton abundance and density were calculated from these counts.

The zooplankton were identified using a number of specialised literature; (eg. Wickstead 1965, Newell and Newell 1973, Barnes 1987). Photographs were taken of most specimens. In most instances, zooplankton taxa were identified to, at least, the Order level. Zooplankton data are presented in Helleren and John (1995b).

This report summarises the results of monthly samples

3.2 - RESULTS and DISCUSSION

3.2.1 - DOMINANT ASSEMBLAGES

A total of 124 taxa were recorded from Cockburn Sound and Warnbro Sound belonging to the invertebrate phyla Annelida, Arthropoda, Bryozoa, Chaetognatha, Ciliophora, Cnidaria, Ctenophora, Echinodermata, Mollusca, Nematoda, Platyhelminthes, Sarcodina and the vertebrate phylum Chordata. In addition, 22 invertebrate taxa could not be identified.

Arthropod taxa were the most common including 90 taxa of crustaceans accounting for over 72 % of all the taxa recorded. The crustaceans were comprised of amphipods, cirripedes, cladocerans, copepods, decapods, isopods, mysids, and ostracods, and of these, copepods were the most abundant in terms of both species diversity and abundance. The second most diverse group was the decapods but they were never as abundant as the copepods.

Twenty five copepod taxa were identified at the Order level and for enumeration, the individuals were grouped into 5 size classes (Class I = < 0.5 mm, Class II = 0.5 - 0.75 mm, Class III = 0.75 - 1.0 mm, Class IV = 1.0 - 1.25 mm, Class V = > 1.25 mm). All copepod nauplii, regardless of developmental stage and size were grouped together.

Only three groups ever dominated the zooplankton assemblages of both embayments; copepods, cladocerans and protozoans. All others were grouped under the heading "others", specific zooplankters within this group will be discussed as required (Figures 17 and 18).

Copepods numerically dominated the zooplankton of Cockburn and Warnbro sounds. According to pooled data, copepods dominated the assemblages of both embayments on 75% of occasions; the relative abundance of copepods ranged from 18% to 87% in Cockburn Sound and from three percent[1] to 78% in Warnbro Sound.

Copepod assemblages were generally dominated by calanoid copepods (Figure 19) although all three orders (cyclopoida, calanoida, harpactacoida) were present in both embayments and on almost all occasions. Based on average pooled data, calanoid copepods occupied 60% of the adult copepod assemblage in Cockburn Sound and 69% in Warnbro Sound, and cyclopoid copepods occupied 34% and 21% respectively, harpactacoid copepods occupied seven percent and nine percent respectively (Figure 20). Over 80% of adult copepods were in the two smallest size classes (<0.75 mm) (Figure 21); this pattern was similar for each of the copepod orders.

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[1] This value of 3% was recorded during a large radiolarian bloom, generally, copepod relative abundance in Warnbro Sound did not fall below 11%.

The dominance of the zooplankton community by copepods is typical of temperate coastal waters (Martin 1965, Ikeda 1977, White and Roman 1992, Kivi *et al.* 1993, Sautour and Castel 1993, Kiørboe and Nielsen 1994).

Cladocerans were the second most abundant zooplankters in both embayments and consisted predominantly of one species, *Penilia avirostris*, and 7 taxa of *Podon*. According to pooled data, cladocerans dominated the zooplankton assemblage of Cockburn Sound on eight percent of occasions and co-dominated with copepods on a further eight percent of all occasions; in Warnbro Sound, cladocerans dominated on one occasion only; the relative abundance of cladocerans ranged from one percent to 46% in Cockburn Sound and from one percent to 64% in Warnbro Sound.. According to average pooled data, *Penilia* adults comprised 77% and 88% of the cladoceran assemblages in Cockburn and Warnbro Sounds respectively whilst all *Podon* taxa combined generally comprised around 22% and 11% of the cladoceran assemblages respectively (Figures 22 and 23).

The third major zooplankton group was the Protozoa of which, the radiolarians were the major group. Radiolarians dominated the zooplankton assemblages of Cockburn Sound on two occasions; in Warnbro Sound, radiolarians dominated on four occasions, tintinnids on one occasion; the relative abundance of protozoans ranged from zero percent to 71% in Cockburn Sound and from zero percent to 92% in Warnbro Sound.

Of the remaining zooplankters grouped as "others", molluscs (usually mussel veliger larvae), tunicates and polychaetes were common, but were minor components of the zooplankton assemblage, comprising less than 10% of the total.

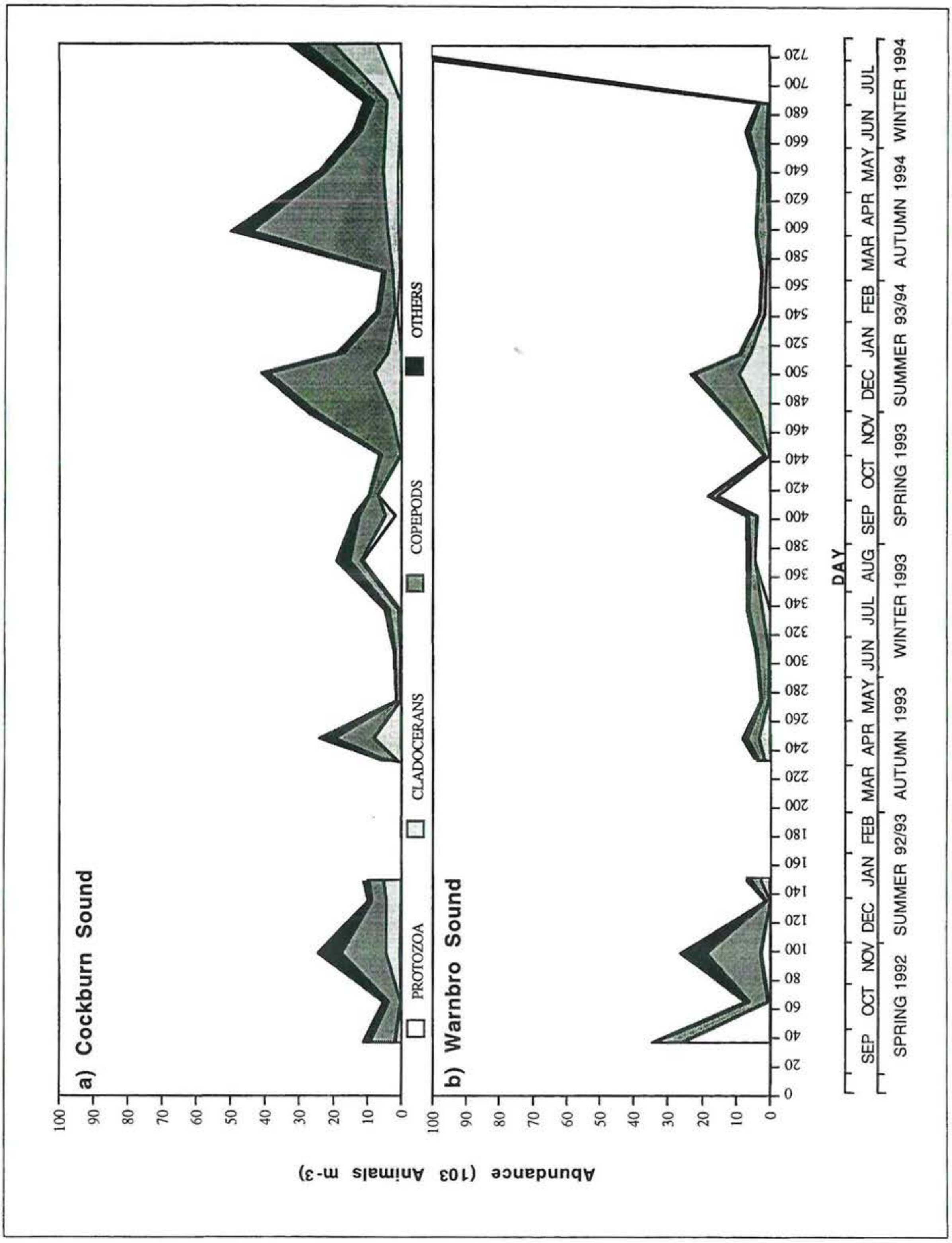

Figure 17: Timeseries plot showing abundance of the major zooplankton groups in Cockburn Sound and Warnbro Sound between August 1992 and August 1994.

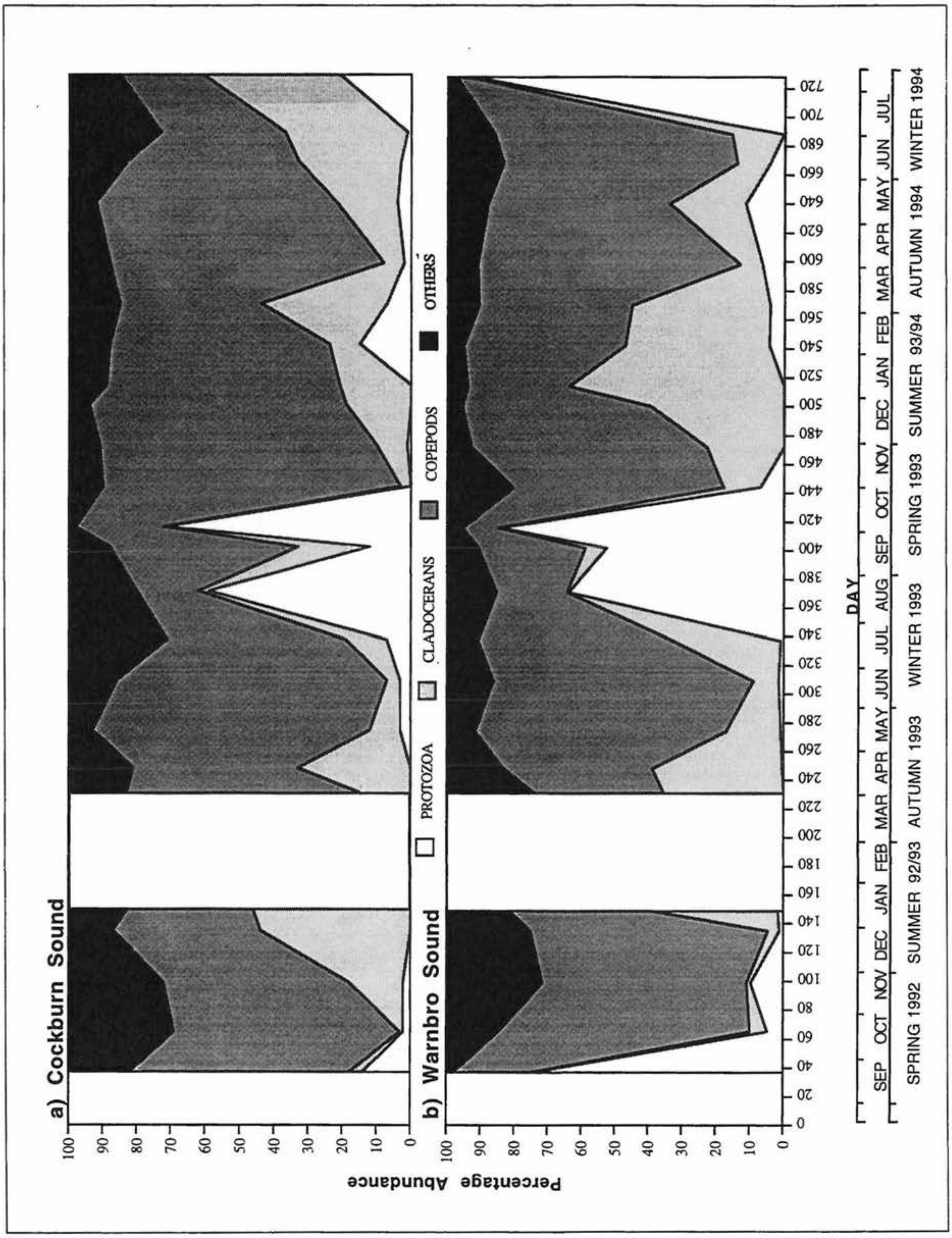

Figure 18: Timeseries plot showing relative abundance of the major zooplankton groups in Cockburn Sound and Warnbro Sound between August 1992 and August 1994.

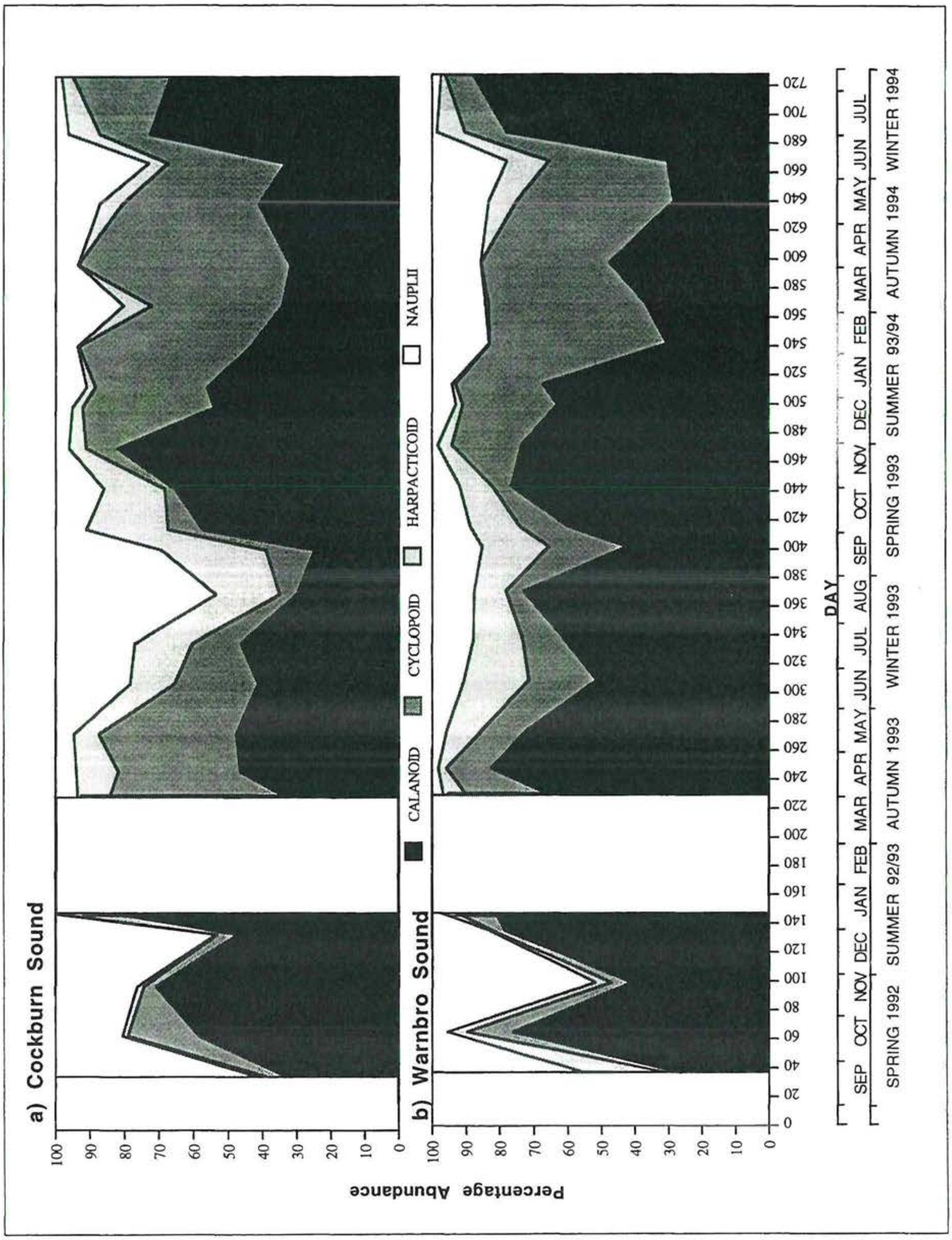

Figure 19: Timeseries plot showing relative abundance of copepod orders and nauplii in Cockburn Sound and Warnbro Sound between August 1992 and August 1994.

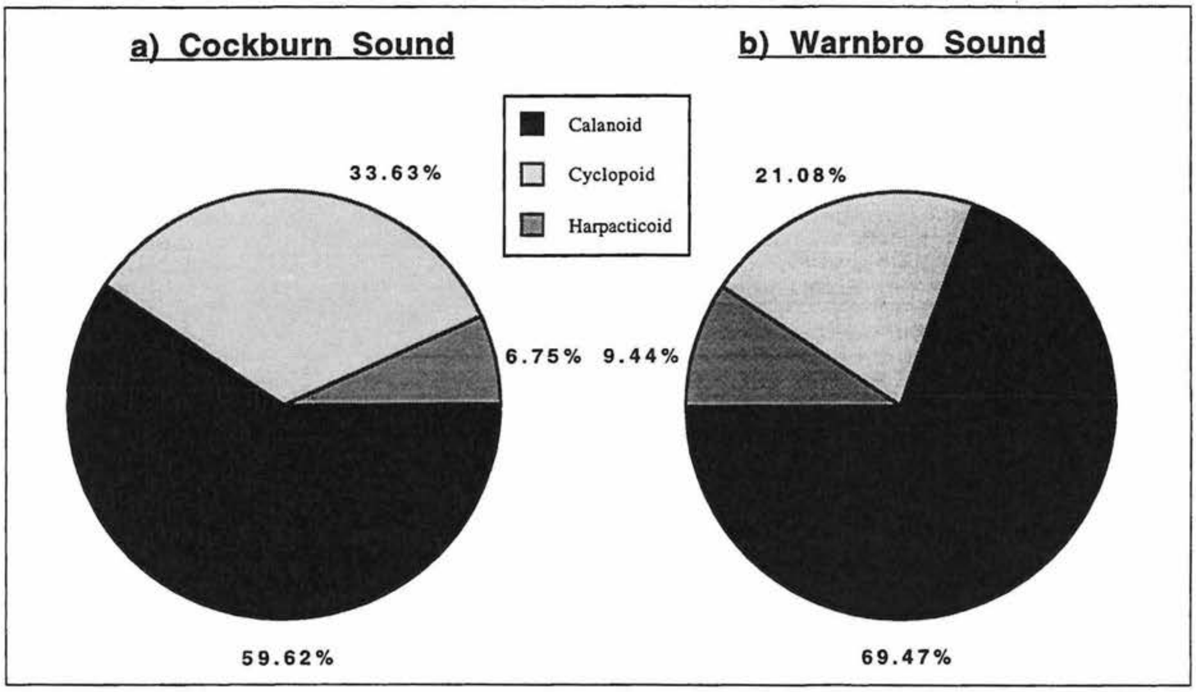

Figure 20: Percentage distribution of copepod orders in Cockburn Sound and Warnbro Sound.

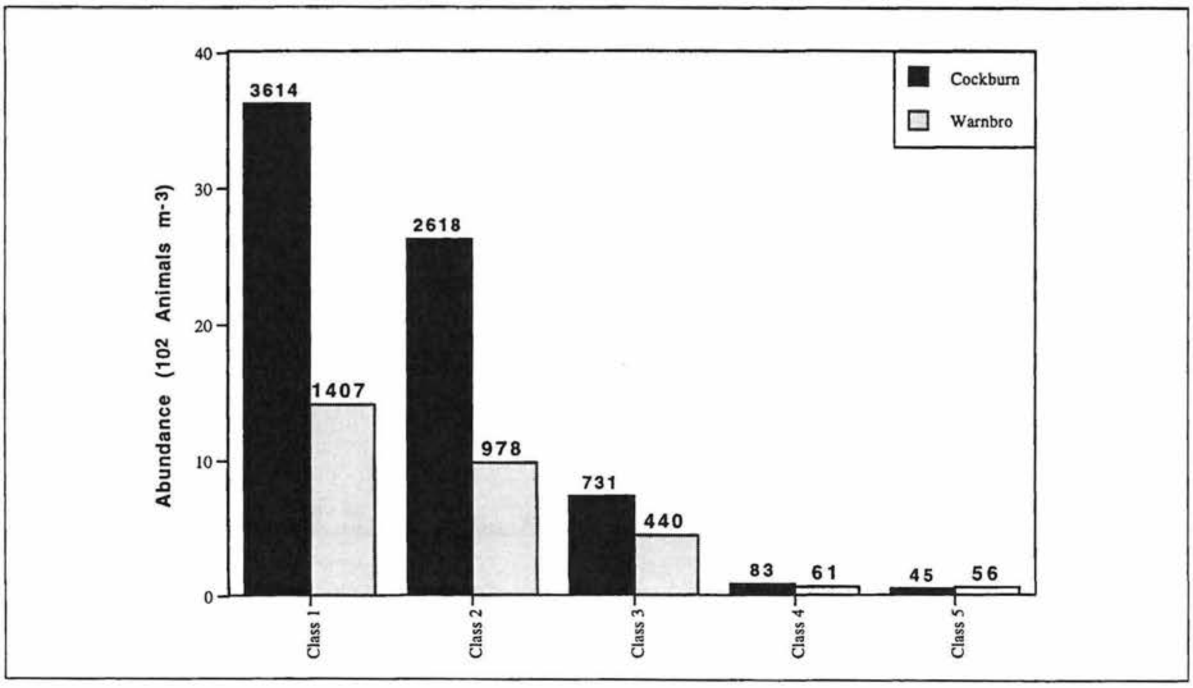

Figure 21: Relative abundance of copepod size classes in Cockburn Sound and Warnbro Sound.

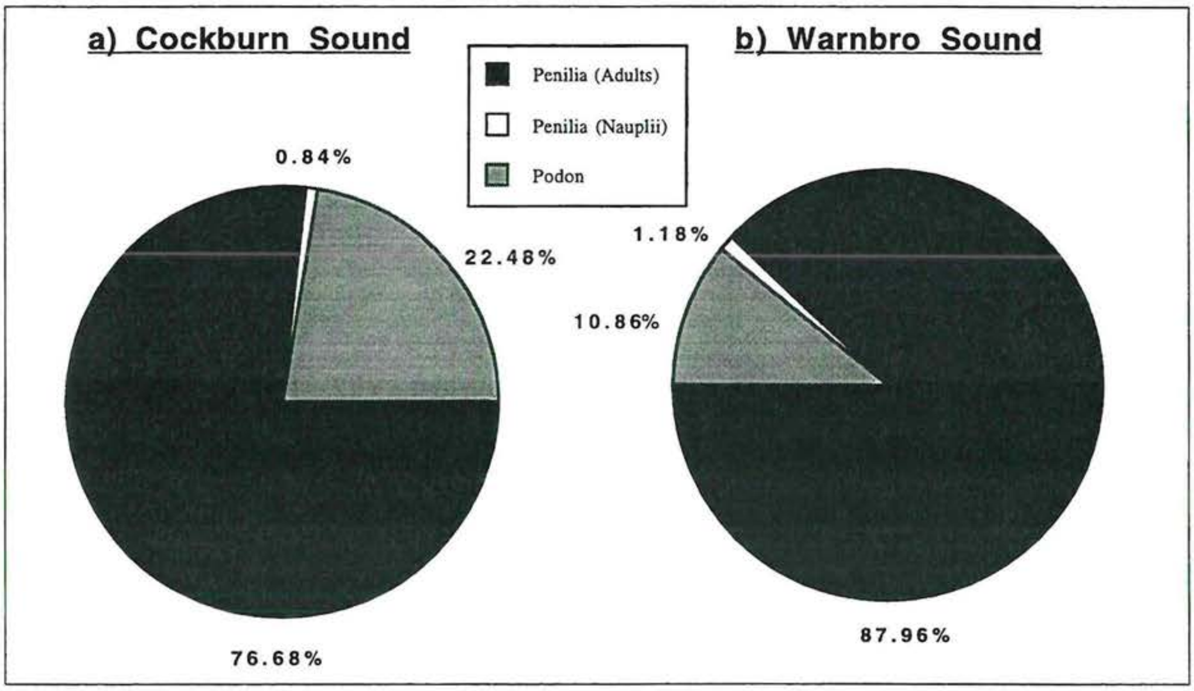

Figure 22: Percentage distribution of cladocerans in Cockburn Sound and Warnbro Sound.

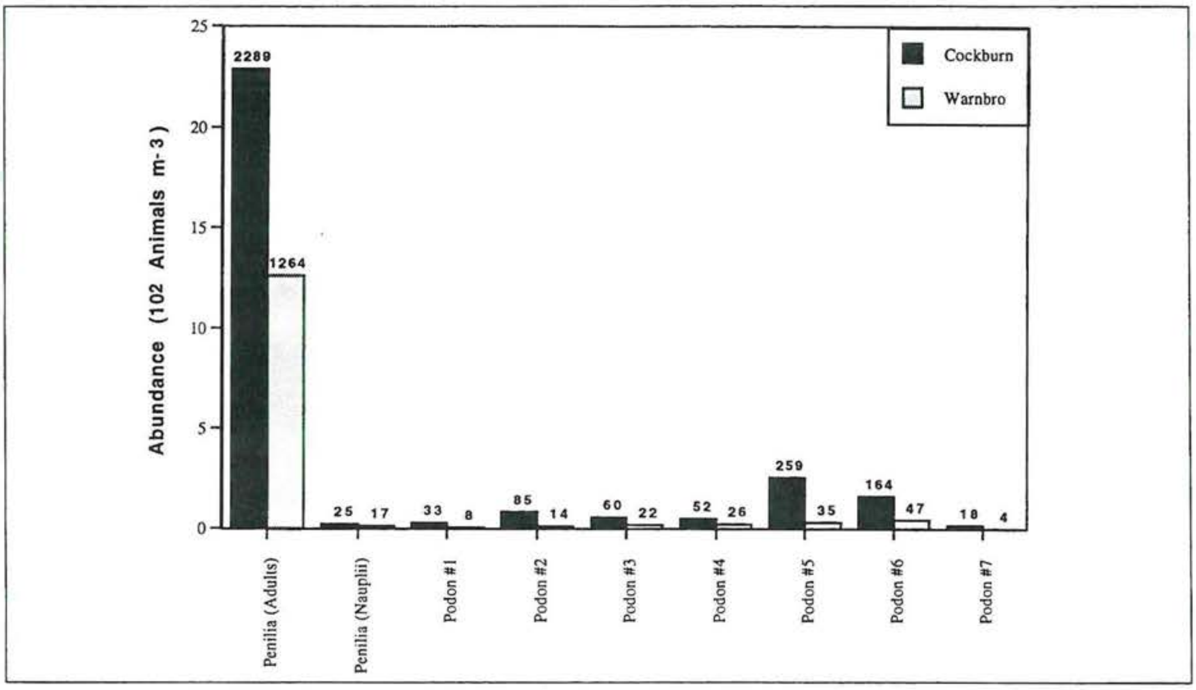

Figure 23: Relative abundance of cladoceran taxa in Cockburn Sound and Warnbro Sound.

3.2.2 - SUCCESSION AND ABUNDANCE

In temperate systems, zooplankton biomass and abundance undergo marked seasonal changes. Typically the mesozooplankton shows a unimodal seasonal distribution, with a peak abundance and biomass during late spring and summer (Kiørboe and Nielsen 1994). In the present study, distinct seasonal patterns in zooplankton assemblage succession and abundance have been recognised. As previously mentioned, copepods dominated the assemblages of both embayments for most of the study. Summer and autumn assemblages were generally dominated by copepods and cladocerans, copepods being the most abundant; early winter assemblages were dominated by copepods (and cladocerans to a lesser extent) with late winter and early spring assemblages dominated by radiolarians; copepods and cladocerans dominated late spring assemblages (Figures 17 and 18).

These seasonal patterns were generally the same for both embayments, the only major differences being in magnitude. There was some spatial heterogeneity, just as for phytoplankton, within each embayment.

Both holoplankton and meroplankton components were similar to those found in other temperate coastal regions of the World and of Australia, particularly eastern Australia off the New South Wales coast (Kingsford 1995) except for the large radiolarian blooms in late winter and early spring, especially in Warnbro Sound.

Trends in overall zooplankton abundance were largely determined by copepod, cladoceran and radiolarian peaks, being greatest during late spring/early summer and winter. In Cockburn Sound, copepod and cladoceran peaks also occurred during autumn. During the remainder of the year, zooplankton abundance was generally low (Figures 17 and 18).

With the exception of winter abundance peaks of radiolarians, these trends are similar to those described by Martin (1965, 1970) for Narragansett Bay (USA), White and Roman (1992) for Chesapeake Bay (USA), Kivi *et al.* (1993) for the Baltic Sea, Kiørboe and Nielsen (1994) for coastal Denmark waters and Kingsford (1995) for coastal New South Wales waters.

Similarities in zooplankton succession and abundance off the New South Wales coast (near Sydney) and Perth include: overall low abundances in winter increasing toward the end of winter, highest larval abundance during spring, a rapid increase in cladoceran numbers during summer, and abundant cladocerans and copepods in autumn (Kingsford 1995).

Based on pooled site data, zooplankton abundance was typically greater in Cockburn Sound than in Warnbro Sound. However, extremely high abundances of radiolarian protozoans (up to 2.7×10^5 m^{-3}) were encountered throughout Warnbro Sound (excluding site 1) on August 15, 1994. The maximum radiolarian abundance recorded in Cockburn Sound on the same day (1.2×10^4 m^{-3}) was an order of magnitude lower. This sampling day was considered to be atypical (see Figure 17) and when this was excluded from calculations, average zooplankton abundance in Cockburn Sound was 2.3 times higher than in Warnbro Sound.

The lowest zooplankton abundance in Cockburn Sound was typically found in the north-western corner (CS4 - average abundance = 9.2×10^3 m^{-3}), and when this site was excluded the difference between Cockburn Sound and Warnbro Sound increased to approximately 2.6 times. Within Cockburn Sound, zooplankton abundance tended to be highest at site 6 in Jervoise Bay (2.0×10^4 m^{-3}), which was twice that at the north-western corner, followed by CS9 (1.5×10^4 m^{-3}), CS12 (1.4×10^4 m^{-3}) and CS11(1.1×10^4 m^{-3}) (Figure 24).

Anova results ($\alpha = 0.05$, $p = 0.2398$), calculated using $\log_{10}$ transformed data (August 15 1994 date removed), showed no significant difference in mean abundances among the 5 Cockburn Sound sites.

The low relative abundance of zooplankton in the north-west of Cockburn Sound where exchange with offshore waters is greatest, is consistent with the findings of ERA (1971a, b) which showed that the highest zooplankton abundances within Cockburn Sound were associated with waters that had the longest residence times in the embayment.

Within Warnbro Sound, the greatest average zooplankton abundance was recorded at site 10 in the centre of the embayment (9.5 x 10^3 m^{-3}), followed by site 7 on the central coast (8.2 x 10^3 m^{-3}), site 5 at the southern tip of the embayment (5.9 x 10^3 m^{-3}), site 1 at the northern tip of the embayment (4.9 x 10^3 m^{-3}) and site 4 in the central embayment (3.5 x 10^3 m^{-3}) although this site is better off ignored due to the small number of sampling dates (6) analysed.

Anova results ($\alpha = 0.05$, $p = 0.0405$), calculated using $\log_{10}$ transformed data (August 15 1994 date removed), showed a significant difference in mean abundances among the 5 Warnbro Sound sites, however post-hoc analyses (ie. Scheffe test) showed no significant difference.

Ignoring radiolarian peaks, Cockburn Sound almost consistently had greater zooplankton abundance than Warnbro Sound. A comparison of pooled site averages yield very similar results as those obtained for phytoplankton. The Cockburn Sound site with the lowest zooplankton abundance (CS4) was similar to the Warnbro Sound site with the highest abundance (WS10) (0.98 times less compared to 1.3 times greater for phytoplankton). There was almost a three-fold difference in average abundance between the lowest sites in each embayment (CS4 and WS4, a two-fold difference if site WS4 is ignored and site WS1 used instead) the same as found for phytoplankton; more than a two-fold difference between the highest sites in both embayments (CS6 and WS10) the same as found for phytoplankton; and nearly a six-fold difference between the highest Cockburn Sound site (CS6) and the lowest Warnbro Sound site (WS4), (a four-fold difference if site WS4 is ignored and site WS1 used instead), compared to a five-fold difference found for phytoplankton.

Anova and Scheffe test results ($\alpha = 0.05$, $p = 0.0001$), calculated using $\log_{10}$ transformed data (August 15 1994 date removed), showed that all Warnbro Sound sites together with all Cockburn Sound sites except CS6 were not significantly different from each other. Site CS6 was not significantly different from the rest of the Cockburn Sound sites and sites WS10, WS7 and WS4. (Table 22).

Table 22: Scheffe test summary table of rank order means ($\alpha = 0.05$). Average zooplankton abundance for Cockburn and Warnbro sounds (August 15 1994 date removed). Means which are not significantly different are linked.

WS4	(3 535)	↑	
WS1	(4 826)	│	
WS5	(5 883)	│	↑
WS7	(8 189)	│	│
CS4	(9 395)	│	│
WS10	(9 470)	│	│
CS11	(11 886)	│	│
CS12	(14 928)	│	│
CS9	(17 508)	↓	│
CS6	(20 128)		↓

These data, illustrating greater zooplankton abundance in Cockburn Sound compared to Warnbro Sound, support earlier data collected during the early 1970s (ERA 1971a, b) showing higher zooplankton abundances in Cockburn Sound than in adjacent waters.

3.2.2.1 - COPEPODS

Peaks in copepod abundance occurred during late spring/early summer in both embayments. Autumn peaks in copepod abundance were recorded in Cockburn Sound in 1993 and 1994 but not in Warnbro Sound. Throughout the remainder of the year, copepod numbers were reasonably constant (Figure 17). Spring/summer copepod assemblages were generally dominated by calanoids whilst autumn assemblages were generally dominated by cyclopoids (Figure 19).

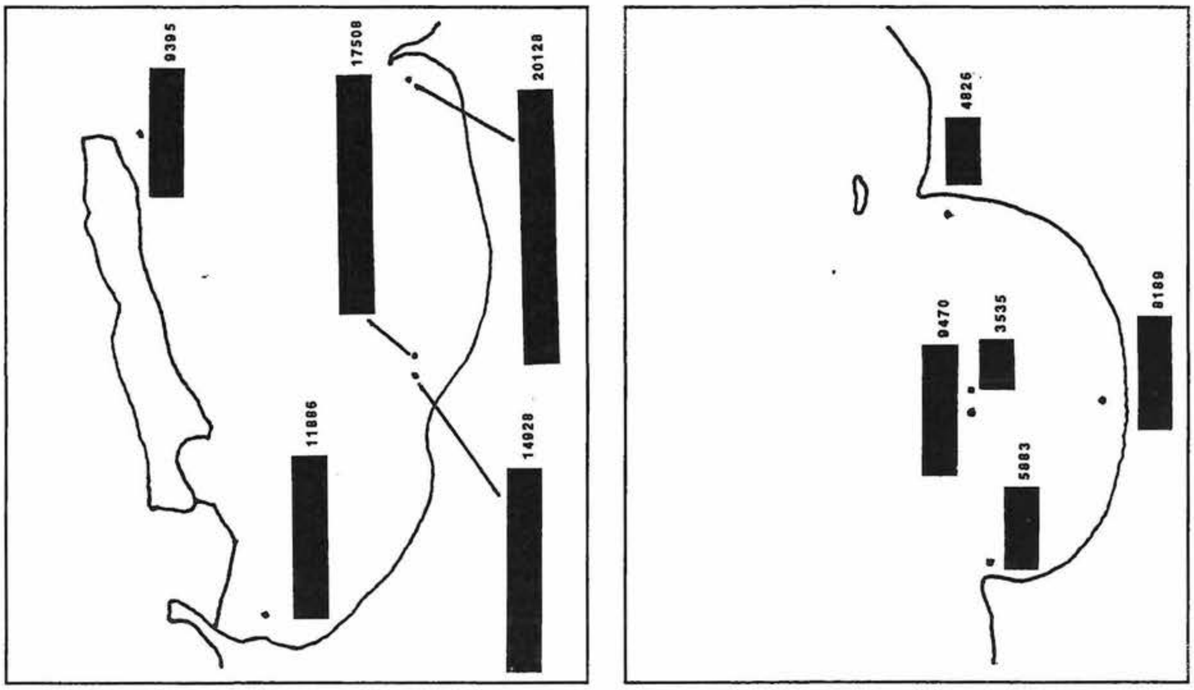

Figure 24: Average zooplankton abundance for all sites in Cockburn and Warnbro sounds.

The 1992/93 late spring/early summer copepod bloom peaked in late November 1992 and was generally dominated by calanoids and nauplii in both Cockburn and Warnbro sounds. Copepod abundance in Cockburn Sound ranged from 1.1 x 10^3 m^{-3} at site CS12 (surface) to 7.5 x 10^4 m^{-3} also at site CS12 (bottom), site averages ranged from 3.7 x 10^3 m^{-3} at site CS4 to 2.9 x 10^4 m^{-3} at site CS12. Copepods dominated the zooplankton assemblages at all sites occupying between 35% and 68% (average = 55%) of the total assemblages. Nauplii comprised a significant portion of the copepod assemblage accounting for between seven percent and 55% (average = 30%) of all copepods.

Copepod abundance in Warnbro Sound ranged from 5.4 x 10^2 m^{-3} at site WS1 to 4.9 x 10^4 m^{-3} at site WS10 (middle), site averages ranged from 5.4 x 10^2 m^{-3} at site WS1 to 2.1 x 10^4 m^{-3} at site WS10. Copepods dominated the zooplankton assemblages at all sites occupying between 51% and 67% (average = 60%) of the total assemblages. Nauplii comprised a major portion of the copepod assemblage accounting for between 32% and 58% (average = 46%) of all copepods.

The late spring/early summer 1993/94 copepod bloom peaked slightly later than the previous year, and was generally dominated by calanoid and cyclopoid copepods in Cockburn Sound and by calanoid copepods in Warnbro Sound. However, where the magnitude of the peaks during the 1992/93 bloom were similar for both sounds, that of the 1993/94 bloom was almost 3 times greater in Cockburn Sound than in Warnbro Sound.

Copepod abundance in Cockburn Sound ranged from 1.1 x 10^4 m^{-3} at site CS11 (surface) to 5.5 x 10^4 m^{-3} at site CS12 (middle), site averages ranged from 1.3 x 10^4 m^{-3} at site CS11 to 4.8 x 10^4 m^{-3} at site CS12. Copepods dominated the zooplankton assemblages at all sites occupying between 62% and 87% (average = 76%) of the total assemblages. Nauplii generally comprised a minor portion of the copepod assemblage never accounting for more than 10% (average = four percent) of all copepods.

Copepod abundance in Warnbro Sound ranged from 5.5 x 10^3 m^{-3} at site WS5 to 2.5 x 10^4 m^{-3} at site WS7 (middle), site averages ranged from 5.5 x 10^3 m^{-3} at site WS5 to 1.4 x 10^4 m^{-3} at site WS7. Copepods dominated the zooplankton assemblages at all sites occupying between 49% and 62% (average = 57%) of the total assemblages. Nauplii generally comprised a minor portion of the copepod assemblage rarely accounting for more than 10% (average = seven percent) of all copepods.

Autumn peaks in copepod abundance were only observed in Cockburn Sound, the first of these, in mid April 1993, was minor with abundances ranging from 7.3 x 10^2 m^{-3} at site CS4 (surface) to 3.0 x 10^4 m^{-3} at site CS11 (middle); site averages ranged from 1.4 x 10^3 m^{-3} at site CS4 to 1.5 x 10^4 m^{-3} at site CS11. Copepods dominated the zooplankton assemblages at all sites occupying between 33% and 61% (average = 49%) of the total assemblages. Nauplii generally comprised a minor portion of the copepod assemblage accounting for between three percent and 16% (average = eight percent) of all copepods. Copepod assemblages were dominated by calanoids and cyclopoids.

During the same period in Warnbro Sound, although copepods still dominated the zooplankton assemblages (average = 48%), copepod abundance reached a maximum of only 7.5 x 10^3 m^{-3} at site WS7 (surface) (average = 3.4 x 10^3 m^{-3}). The copepod assemblage was dominated by calanoids, nauplii never accounted for more than one percent of the copepod assemblage.

The second autumn peak in Cockburn Sound, in early April 1994, was the largest copepod bloom observed throughout the study. Copepod abundance ranged from 8.8 x 10^2 m^{-3} at site CS4 (bottom) to 9.1 x 10^4 m^{-3} at site CS6 (middle), site averages ranged from 3.5 x 10^3 m^{-3} at site CS4 to 7.7 x 10^4 m^{-3} at site CS6. Copepods dominated the zooplankton assemblages at all sites occupying between 74% and 98% (average = 84%) of the total assemblages. Nauplii comprised between one percent and 18% (average = seven percent) of the copepod assemblage. During the same period in Warnbro Sound, although copepods still dominated the zooplankton assemblages (average = 79%), their abundance reached a maximum of only 1.1 x 10^4 m^{-3} at site WS5 (average for embayment = 4.6 x 10^3 m^{-3}). The copepod assemblage was dominated by calanoids and cyclopoids, nauplii occupied a more significant component of the copepod assemblage ranging from five percent to 28% (average = 14%).

The timing of these copepod peaks is consistent with that reported in the literature. Several authors (Martin 1965, Nielsen 1991, Kivi *et al.* 1993, Sautour and Castel 1993) report high abundances of copepods during spring/summer and low abundances during winter from several temperate regions. No reports of autumn copepod blooms could be found in the literature to support those observed in Cockburn Sound during the present study.

The abundance of copepods observed in the present study appears to be quite high by World standards, Anderson (1994) states that in nutrient-rich areas, copepods exist in vast numbers up to 1.0 x 10^4 - 2.5 x 10^4 m^{-3}. While copepod abundance in both Cockburn and Warnbro sounds was generally less than 1.0 x 10^4 m^{-3}, peaks in both Sounds exceeded 1.0 x 10^4 m^{-3} and in Cockburn Sound exceeded 2.5 x 10^4 m^{-3}.

3.2.2.2 - CLADOCERANS

Peaks in cladoceran abundance generally followed the same trends as copepods with spring/summer peaks in both sounds and additional autumn peaks in Cockburn Sound. There was a small autumn peak in Warnbro Sound in 1993. During 1994 in Cockburn Sound, the autumn peak extended into winter. Throughout the remainder of the year, cladoceran numbers were reasonably constant (Figure 17).

Although trends in abundance were similar for both copepods and cladocerans, cladocerans were never as abundant as copepods, rarely occurring in numbers greater than 1.0×10^4 m^{-3} and generally less than 5.0×10^3 m^{-3}. The abundance of cladocerans in Cockburn Sound was generally at least twice that of Warnbro Sound, same as the trend found for the copepods (Figure 22).

The 1992/93 spring/summer cladoceran bloom was more prolonged and of a greater magnitude in Cockburn Sound than in Warnbro Sound beginning in late November and proceeding until mid January, in Warnbro Sound, this bloom was confined to a single peak in mid January.

During late November 1992 in Cockburn Sound, cladoceran abundance was high (primarily due to large numbers encountered at sites CS6 and CS12), the cladoceran assemblage was dominated by both *Penilia avirostris* and *Podon* spp. At this time cladocerans accounted for between four percent and 29% (average = 13%) of the zooplankton assemblage. Cladoceran abundance ranged from 1.6×10^2 m^{-3} at site CS12 (surface) to 1.9×10^4 m^{-3} also at site CS12 (bottom); average site abundances ranged from less than 6.0×10^2 m^{-3} at sites CS4 and CS11 to 8.8×10^3 m^{-3} at site CS12. During the same period in Warnbro Sound, cladoceran abundance was low ranging from zero to 7.0×10^2 m^{-3}; cladoceran assemblages were dominated by both *P. avirostris* and *Podon* spp. and generally accounted for less than two percent of the zooplankton assemblage.

Cladoceran abundance increased in Cockburn Sound in late December with abundances in excess of 2.1 x 10^4 m^{-3} at sites CS4 (bottom) and CS6 (bottom); average site abundances ranged from around 2.0 x 10^3 m^{-3} at sites CS11 and CS12 to around 8.0 x 10^3 m^{-3} at sites CS4 and CS6. Cladocerans dominated the zooplankton assemblage at several sites accounting for between one percent and 79% (average = 37%) of the total assemblage. *P. avirostris* was the dominant cladoceran at most sites. Conversely, cladoceran abundance decreased during late December in Warnbro Sound, to less than 1.5 x 10^2 m^{-3}. The cladoceran assemblage was dominated by both *P. avirostris* and *Podon* spp.

In Cockburn Sound, cladoceran abundance increased further during early-mid January with average site abundances ranging from around 2.0 x 10^3 m^{-3} at site CS4 to around 6.5 x 10^3 m^{-3} at site CS6. Individual abundances ranged from 1.1 x 10^2 m^{-3} at site CS4 (surface) to 1.3 x 10^4 m^{-3} at site CS12 (bottom). Cladocerans dominated the zooplankton assemblages at several sites accounting for between 13% and 55% (average = 33%); cladoceran assemblages at all sites were dominated by *P. avirostris*. There was a peak in cladoceran abundance in Warnbro Sound during this period, although abundances were generally half those of Cockburn Sound. Cladoceran abundance ranged from less than 1.5 x 10^2 m^{-3} at sites WS1 and WS5 to 4.5 x 10^3 m^{-3} at site WS10 (bottom), average site abundances at sites WS7 and WS1 were 1.4 x 10^3 m^{-3} and 3.7 x 10^3 m^{-3} respectively. *P. avirostris* dominated the cladoceran assemblages at all sites which accounted for between five percent and 54% (average = 28%) of the zooplankton assemblage.

The 1993 autumn bloom in Cockburn Sound was of a greater magnitude than the previous spring/summer bloom and peaked during mid April with abundances ranging from 90 m^{-3} at site CS4 (surface) to more than 1.6 x 10^4 m^{-3} at site CS11 (middle). Average site abundances ranged from 4.0 x 10^2 m^{-3} at site CS4 to 8.0 x 10^3 m^{-3} at site CS11. *P. avirostris* dominated at most sites, with cladocerans accounting for between seven percent and 42% (average = 27%) of the total zooplankton assemblages. There was a small autumn peak in Warnbro Sound at the same time, less than half the size of the Cockburn Sound peak, but greater than the previous Warnbro Sound spring / summer bloom. Cladoceran abundance ranged from 1.9 x 10^2 m^{-3} at site WS10 (middle) to 6.1 x 10^2 m^{-3} at site WS7 (middle), all sites were dominated by *P. avirostris*. Cladocerans accounted for between 24% and 46% (average = 34%) of the total zooplankton assemblages.

Between the 1993 autumn peak and the 1993/94 spring/summer peak, there was a small cladoceran peak in both embayments. The first of these occurred in Warnbro Sound during mid winter with abundances ranging from 38 m^{-3} at site WS5 to 3.8 x 10^3 m^{-3} at site WS10 (bottom). Average site abundances ranged from 38 m^{-3} at site WS5 to 2.3 x 10^3 m^{-3} at site WS10. *P. avirostris* dominated at all sites, cladocerans accounted for between four percent and 41% (average = 29%) of the total zooplankton assemblages. During the same period, in Cockburn Sound, cladoceran abundance was generally less than 1.0 x 10^3 m^{-3}.

The second small peak occurred in Cockburn Sound during early spring with abundances ranging from 3.5 x 10^2 m^{-3} at site CS11 (surface) to 8.3 x 10^3 m^{-3} at site CS6 (surface). Average site abundances ranged from 9.7 x 10^2 m^{-3} at site CS4 to 6.0 x 10^3 m^{-3} at site CS6. *Podon* spp. dominated at all sites, with cladocerans accounting for between two percent and 24% (average = 16%) of the total zooplankton assemblages. During the same period in Cockburn Sound, cladoceran abundance was generally less than 7.0 x 10^2 m^{-3}.

The 1993/94 spring/summer blooms peaked during late December 1993 and were of a similar magnitude in both embayments. The cladoceran assemblages were dominated by *P. avirostris* in both embayments. In Cockburn Sound, abundances ranged from 1.0 x 10^3 m^{-3} at site CS11 (surface) to 2.0 x 10^4 m^{-3} at site CS6 (surface). Average site abundances ranged from 3.1 x 10^3 m^{-3} at site CS11 to 1.5 x 10^4 m^{-3} at site CS6. Cladocerans accounted for between six percent and 33% (average = 17%) of the total zooplankton assemblages.

In Warnbro Sound, abundances ranged from 3.0 x 10^3 m^{-3} at site WS5 to 1.7 x 10^4 m^{-3} at site WS7 (middle), average site abundances ranged from 3.0 x 10^3 m^{-3} at site WS5 to 9.9 x 10^3 m^{-3} at site WS10. Cladocerans dominated the zooplankton assemblages at several sites accounting for between 32% and 47% (average = 39%) of the total zooplankton assemblages. In Warnbro Sound, cladoceran abundance declined after this peak and remained low until a small peak in late winter 1994. In Cockburn Sound however, their abundance, after initially declining, began to increase during mid-late autumn, peaking in late autumn before increasing again to a large late winter peak (the largest cladoceran peak recorded).

During the late autumn peak in Cockburn Sound, cladoceran abundance reached a maximum of 1.6 x 10^4 m^{-3} at site CS6 (surface), average site abundances ranged from 6.7 x 10^2 m^{-3} at site CS11 to 8.8 x 10^3 m^{-3} at site CS6. *Penilia avirostris* dominated the cladoceran assemblages which accounted for between seven percent and 37% (average = 18%) of the total zooplankton assemblages. The large cladoceran peak during late winter (mid August 1994) was also dominated by *P. avirostris*. Cladoceran abundance ranged from 4.4 x 10^2 m^{-3} at site CS4 (middle) to 2.6 x 10^4 m^{-3} at site CS9 (bottom). Average site abundances ranged from 2.6 x 10^3 m^{-3} at site CS4 to 1.8 x 10^4 m^{-3} at site CS9. Cladocerans dominated the zooplankton assemblages at several sites accounting for between eight percent and 54% (average = 35%) of the total zooplankton assemblage.

The late winter peak in Warnbro Sound was of a much lesser magnitude than that of Cockburn Sound but was again dominated by *P. avirostris*. Cladoceran abundance ranged from 1.0 x 10^2 m^{-3} at site WS1 to 1.3 x 10^4 m^{-3} at site WS10 (middle). Average site abundances ranged from 1.0 x 10^2 m^{-3} at site WS1 to 4.8 x 10^3 m^{-3} at site WS10, never accounting for more than five percent of the total zooplankton assemblage.

The seasonal cladoceran peaks observed in the present study were reasonably consistent with that reported in the literature with the exception of the observed winter peaks, especially that of 1994. High abundances of cladocerans during late spring, summer and early autumn have been reported by Martin (1965) for Narragansett Bay (USA), Nielsen (1991) for coastal waters of Denmark, Kivi *et al.* (1993) for the Baltic Sea, Sautour and Castel (1993) for Marennes-Oléron Bay (France) and Kingsford (1995) for coastal waters off New South Wales.

Penilia avirostris is the only marine cladoceran which is abundant and cosmopolitan in distribution. It is frequently abundant in warm and productive coastal waters of the tropics and subtropics and occurs seasonally in large numbers in polluted coastal temperate waters (Wong *et al.*, 1992). Peaks in the abundance of *P. avirostris* recorded in the present study occurred during summer and autumn, consistent with that reported in the literature (Martin 1965, Wong *et al.* 1992, Kingsford 1995, Onbé and Ikeda 1995).

In coastal waters off Sydney, *P. avirostris* density often exceeds 5.0 x 10^4 m^{-3} during summer and early autumn, however, during winter, it is rarely found (Kingsford 1995). In the present study, the maximum abundance in Cockburn and Warnbro Sounds was 2.5 x 10^4 m^{-3} and 1.6 x 10^4 m^{-3} respectively. In Narragansett Bay (USA), *P. avirostris* has been recorded at abundances of up to 1.1 x 10^2 m^{-3} (Martin 1965); whilst in the eutrophic Tolo Harbour (Hong Kong), average autumn densities reach 1.5 x 10^4 m^{-3}, comparable to those recorded in the present study (Wong *et al.* 1992).

3.2.2.3 - PROTOZOA

Protozoan assemblages consisted of radiolarians, foraminiferans, and several tintinnid taxa. Peaks in protozoan abundance occurred in early spring and early summer 1992, late winter - early spring 1993 and late winter 1994 (Figure 17). The largest protozoan peaks, the winter/spring peaks, were generally comprised almost entirely of radiolarians and coincided with the decline of winter silicoflagellate blooms.

The 1992 spring bloom, dominated by tintinnids, consisted of a single peak in early spring and was an order of magnitude greater in Warnbro Sound than in Cockburn Sound. In Cockburn Sound, maximum protozoan abundance was around 3.6 x 10^3 m^{-3} at site CS6 (surface), protozoans accounted for between one percent and 47% (average = 15%) of the zooplankton assemblage. In Warnbro Sound, protozoan abundance ranged from 4.1 x 10^2 m^{-3} at site WS1 to 5.8 x 10^4 m^{-3} at site WS10 (surface), average site abundances ranged from 4.1 x 10^2 m^{-3} at site WS1 to 4.0 x 10^4 m^{-3} at site WS10. Protozoans accounted for between eight percent and 87% (average = 54%) of the total zooplankton assemblage, dominating at most sites.

Protozoan abundance fell dramatically in both embayments during mid spring, to less than 1.0 x 10^2 m^{-3} and 6.0 x 10^2 m^{-3} in Cockburn Sound and Warnbro Sound respectively, before increasing during early summer to about 10% of the magnitude of the early spring bloom. Tintinnids continued to dominate protozoan assemblages during this period. Between mid summer 1992/93 and mid winter 1993, protozoan abundance was low in both embayments, generally less than 1.0 x 10^2 m^{-3}. Protozoan assemblages were not dominated by any particular group during this period.

Between mid winter and late spring 1993, protozoan assemblages in both embayments were dominated by radiolarians; there were two peaks, one in late winter and one in mid spring. Radiolarians dominated the zooplankton assemblages of most sites during these peaks. During the late winter peak, their abundance reached a maximum of 1.0×10^4 m^{-3} in Warnbro Sound and 3.7×10^4 m^{-3} in Cockburn Sound; during the mid spring peak protozoan maxima were 2.9×10^4 m^{-3} and 1.9×10^4 m^{-3} respectively.

Protozoan abundance was once again low between late spring 1993 and mid summer 1994 with abundances at all sites generally less than 1.0×10^2 m^{-3}, no particular group dominated the assemblages.

Between mid summer and late autumn 1994, protozoan assemblages comprised entirely of foraminiferans. Abundances fluctuated up to 3.9×10^3 m^{-3} in Cockburn Sound and 9.5×10^2 m^{-3} in Warnbro Sound.

During late winter 1994, there was a large radiolarian bloom in Warnbro Sound at all sites except site WS1. Protozoan abundances ranged from 2.0×10^4 m^{-3} at site WS10 (bottom) to 2.7×10^5 m^{-3} also at site WS10 (middle). Average site abundances ranged from 7.4×10^4 m^{-3} at site WS5 to 1.3×10^5 m^{-3} at site WS10. Radiolarians dominated the zooplankton assemblages at all sites except WS1, accounting for between 84% and 98% of the total assemblage. There was also a protozoan peak in Cockburn Sound during late winter 1994, but an order of magnitude less than that in Warnbro Sound. Protozoan assemblages were dominated by radiolarians reaching a maximum of 1.2×10^4 m^{-3} at site CS11 (surface) and dominated the zooplankton assemblages of a few sites.

Planktonic foraminifera and radiolaria are widely distributed in most of the World oceans (Anderson 1993) but there is little available information on their ecology in nearshore coastal waters anywhere in the World. Anderson (1993) states that in highly productive regions, abundances of radiolaria can reach more than 1.0×10^4 m^{-3}, this figure is almost four times less than maximum radiolarian abundances in Cockburn Sound and more than 27 times less than the maximum abundances in Warnbro Sound.

Caron *et al.* (1995) reports typical abundances of radiolaria in oceanic waters of less than one individual m^{-3}, clearly much less than that recorded in the present study. Kingsford (1995) reports that radiolaria first appear in the zooplankton off the coast of New South Wales during autumn but does not elaborate on their abundance or dominance. Other studies of temperate zooplankton communities (eg. Kivi *et al.* 1993, Martin 1965) make no mention of radiolarian abundance making further comparisons difficult. From the data available on the distribution of radiolaria in the open ocean, spatially and vertically, it appears that they prefer cooler waters as they are found throughout the water column at high latitudes and at progressively deeper waters as latitude decreases (Anderson 1993). No information has been obtained on radiolaria in coastal waters but the high abundances during winter and low abundance or absence throughout the rest of the year found during the present study also suggest a preference for low temperatures. However, the distribution pattern of radiolaria in Perth coastal waters need to be investigated further.

Ciliates, tintinnids in particular, are a significant and often dominant component of the microzooplankton in marine waters. They are important consumers of nano- and pico-phytoplankton and play an important role in linking microbial processes to higher trophic levels (Nielsen and Kiørboe 1994, Pierce and Turner 1994).

In Buzzards Bay (USA) the abundance of tintinnids has been linked to eutrophication, with abundances increasing with increased inputs of nutrients and hydrocarbons (Pierce and Turner 1994). However, in the present study, tintinnids were more abundant in Warnbro Sound (maximum abundance = 5.8×10^4 m^{-3}) than in Cockburn Sound (maximum abundance = 3.6×10^3 m^{-3}). Maximum tintinnid abundance reported by Pierce and Turner was 3.3×10^6 m^{-3}, there appeared to be no seasonal trends with abundances often varying by an order of magnitude between sampling periods (two weeks). Other studies in coastal temperate regions showed maximum tintinnid abundances during spring, as in the present study (Ferrier-Pagés and Rassoulzadegan 1994, Nielsen and Kiørboe 1994). Ferrier-Pagés and Rassoulzadegan (1994) report maximum tintinnid abundances in the Mediterranean Sea of around 5.0×10^2 m^{-3}.

During the analysis of samples for the present study, large numbers of tintinnids were occasionally found in phytoplankton samples - more than those found in the corresponding zooplankton samples. Although no enumerations were made of these samples, this suggests that there have been some bias against tintinnids in the collection and possibly preservation of zooplankton samples. Stoecker, Gifford and Putt (1994) found that ciliate counts from the North Atlantic and subarctic Pacific Oceans were, on average, 56% higher in samples preserved with Lugol's solution compared to samples preserved with buffered formaldehyde. In the light of this, it appears that the preservation technique used for zooplankton samples in the present study may have resulted in large ciliate losses. Since they are considered to be significant grazers of phytoplankton and may play a role as indicators of eutrophication, the taxonomy, abundance and distribution of ciliates, tintinnids in particular, in the coastal metropolitan waters of Perth require further investigation.

3.2.2.4 - EGGS AND LARVAE

Zooplankton larvae, especially crustacean nauplii, are among the principal foods of larval fish (Burkart *et al.* 1995). Information on the timing of larval recruitment for the major zooplankton groups can provide a useful tool for the management of fisheries and the management of commercially important invertebrate groups such as crabs, lobsters and mussels. Information on the timing of larval recruitment may also assist in combating the spread of nuisance species such as the exotic fan worm, *Sabella*, which has spread over much of Port Phillip Bay, Victoria, and has recently been discovered in Cockburn Sound (Australian and New Zealand Environment and Conservation Council 1995).

The abundance of larvae and eggs in Cockburn Sound was higher and almost twice that found in Warnbro Sound for most groups apart from the echinoderm larvae (Table 23). The average number of echinoderm eggs was higher in Cockburn Sound than in Warnbro Sound whereas the larvae were more commonly encountered in Warnbro Sound and occurred in similar numbers, on average, in both embayments. A recent study comparing the benthic fauna of the deep basins of Cockburn and Warnbro sounds found higher abundances of echinoderms in Warnbro Sound than in Cockburn Sound and additionally, a north-south gradient of decreasing abundance of echinoderms within Cockburn Sound (Cary *et al.* 1995).

The seasonal timing of peak abundance of eggs and larvae in the two embayments are presented in Table 23. The timing of occurrence of eggs and larvae varied amongst the zooplankton groups and also between embayments for some groups.

Mollusc, polychaete and copepod larvae were very common, occurring at all sites on practically all sampling occasions. Peaks in abundance occurred during early winter and late spring in both embayments for molluscs (lamellibranch veligers), during summer and autumn in Cockburn Sound and during winter and spring in Warnbro Sound for polychaete larvae, and during late winter and early spring in both embayments for copepod nauplii.

Cirripede nauplii, crab zoea and echinoderm eggs and larvae were also common, being encountered at all locations on most occasions. Peaks in the abundance of cirripede nauplii, crab zoea and echinoderm eggs occurred during autumn and winter, early summer, and spring and autumn respectively in both embayments. In Cockburn Sound, peaks in the abundance of echinoderm larvae occurred during late winter and late spring; in Warnbro Sound they peaked during autumn.

Cirripede cypris, penaeid nauplii and *Penilia* juveniles occurred at most sites but on less than half the sampling occasions. Peaks occurred in winter and summer in both embayments for cirripede cypris and penaeid nauplii respectively, and in autumn for *Penilia* juveniles in Cockburn Sound and late winter/early spring for *Penilia* juveniles in Warnbro Sound. Crab megalopa were only encountered on one occasion in each embayment, during mid autumn in Cockburn Sound and during early summer in Warnbro Sound.

Abundant copepod nauplii in spring has been reported in a few other similar studies (Kivi *et al.* 1993, White and Roman 1992). Kingsford (1995) report low abundances in late winter increasing into spring; abundant cirripede cypris in winter (Martin 1965, Sautour and Castel 1993), and abundant polychaete larvae in autumn (Martin 1965) and winter (Kingsford 1995).

Table 23: Seasonal timing of peak abundance of eggs and larvae in Cockburn Sound and Warnbro Sound between August 1992 and August 1994.

	Seasonal Peaks		Mean abundance when present (individuals m^{-3})		Comments and number of times found out of 24 sampling occasions.
Group	Cockburn Sound (CS)	Warnbro Sound (WS)	CS	WS	
Cirripede nauplii	autumn winter	autumn winter	404	29	Common. Found at all sites. CS 24, WS 21
Cirripede cypris	winter	winter	136	12	Uncommon. Found at most sites. CS 9, WS 4
Copepod nauplii	late winter early spring	late winter early spring	1 127	639	Very common. Found at all sites. CS 24, WS 24
Crab megalopa	mid autumn	early summer	182	13	Rare. 1 site in each Sound. CS 1, WS 1
Crab zoea	early summer	early summer	108	52	Common. Found at all sites. CS 18, WS 20
Echinoderm eggs	spring autumn	spring autumn	106	87	Common. Found at most sites. CS 17, WS 16
Echinoderm larvae	late spring late winter	autumn	76	79	Common. Found at all sites. CS 15, WS 22
Lamellibranch veligers	late spring early winter	late spring early winter	652	395	Very Common. Found at all sites. CS 24, WS 24
Penaeid nauplii	summer	summer	31	15	Uncommon. 1 site in CS, 2 sites in WS. CS 10, WS 7
Penilia juveniles	autumn	late winter early spring	200	91	Uncommon. Found at all sites. CS 11, WS 8
Polychaete larvae	autumn summer	winter spring	191	58	Very common. Found at all sites. CS 23, WS 23

3.2.3 - MULTIVARIATE ANALYSES AND EMBAYMENT SIMILARITY

A comparison of the taxa found in both embayments, excluding copepods, indicated a high degree of commonality in species composition with 71% of the taxa common to both Cockburn Sound and Warnbro Sound. Fourteen percent were exclusive to Cockburn Sound and 15% were exclusive to Warnbro Sound.

Multivariate analyses, based upon species abundance data, were conducted on all sites for each sampling period analysed using Canonical Correspondence Analysis (Statistical Package = CANOCO; ter Braak 1986). As for phytoplankton, these analyses indicated that there was a greater similarity between sites within embayments than between embayments. When clustered on biplot axes, sites in Cockburn Sound were clearly separated from sites in Warnbro Sound on all bar two of the 24 occasions analysed, mid summer 1993 and early winter 1993.

3.2.4 - LONG TERM CHANGES

Paucity of data from the early 1970s precludes any meaningful long-term comparisons. However, the data clearly demonstrates that copepods dominated the zooplankton assemblages of Cockburn Sound.

The copepods *Acrocalanus/Paracalanus* and the cladoceran *Penilia* were the dominant species present during May 1971 and these typically occurred at densities of approx 4.0×10^3 m^{-3} and 3.0×10^3 m^{-3} in surface waters in Mangles Bay and the southern end of the deep basin respectively and at densities of approximately 1.3×10^3 m^{-3} and 5.0×10^2 m^{-3} in the northern deep basin and eastern edge of the basin respectively. Eight other species were each recorded at densities of approximately 1.0×10^2 m^{-3} at the same time (ERA 1971a, b).

In the present study, *Penilia avirostris* was also found at lower densities in the northern part of the embayment (1.9 x 10^2 m^{-3}; site 4) than in the southern end (4.8 x 10^2 m^{-3}; site 11) during May 1993/94. However the abundances were lower than found during 1971. The average abundance of *Penilia* in Cockburn Sound over the study period was 2.3 x 10^3 m^{-3} and was consistently higher along the eastern margin (2.9 x 10^3 m^{-3}) than at the north-western end (9.9 x 10^2 m^{-3}). This is more consistent with both the patterns and abundances recorded during the early 1970s. Data from the present study was generated from 24 monthly cruises and provides a more reliable estimate of abundance compared with the 1970s data which was collected on two days, with two days interval.

3.3 - SUMMARY

Detailed data on zooplankton dynamics and distribution pattern are presented for the first time. Zooplankton can be effective regulators of phytoplankton. However, excessive phytoplankton biomass, related to the loss of seagrass meadows, cannot be effectively regulated by zooplankton grazers. Therefore, changes in phytoplankton biomass would be reflected in the zooplankton assemblages which in turn are good indicators of environmental change.

The 124 zooplankton taxa identified represent the major invertebrate phyla expected to be found in temperate coastal waters. The most common phylum was the Arthropoda, accounting for more than 72% of all taxa. The most common group within the Arthropoda were the crustaceans of which the copepods were the most abundant in terms of both species diversity and abundance. The only groups which dominated the zooplankton assemblages of both Cockburn and Warnbro sounds were copepods, cladocerans and protozoans (tintinnids and radiolaria).

2. Both holoplankton and meroplankton components of the zooplankton assemblages were similar to those found in other temperate coastal regions of Australia and the World. The dominance of zooplankton assemblages by copepods is typical of temperate coastal waters.

3. Distinct seasonal patterns in zooplankton assemblage succession and abundance were recognised. These patterns were generally the same for both embayments, the only major differences being in magnitude.
   Summer, autumn, early winter and late spring assemblages were generally dominated by copepods and cladocerans with copepods being the most abundant; late winter and early spring assemblages were dominated by radiolarians.

The consistent similarity between surface, middle and bottom samples suggests that the degree of vertical stratification in abundance was small and diel migration was limited.

4. High abundances of *Penilia avirostris* were indicative of eutrophication. Abundances recorded in the present study were comparable to those recorded from the eutrophic Tolo Harbour in Hong Kong, but less than abundances regularly recorded off the New South Wales coast during summer.

5. High abundances of radiolaria may also be indicative of eutrophication. However, the exact cause of radiolarian blooms in Cockburn and Warnbro sounds during winter is unknown and warrants further investigation.

6. An apparent bias against tintinnids in the zooplankton sampling and/or preservation technique was outlined. These techniques need to be critically assessed, and altered, if necessary, for future studies. The distribution and abundance of tintinnids in the coastal waters of Perth should be investigated further.

7. Zooplankton larvae and eggs also showed distinct seasonal trends in abundance.

   Being among the major food sources of larval fish, information on the timing of peaks in the abundance of zooplankton larvae is vital for the management of recreational and commercial fisheries. The abundance of this portion of the zooplankton community also provides recruitment information necessary for the management of shellfish and crustacean fisheries.

8. A comparison of the taxa found in both embayments indicated a high degree of commonality in composition. Multivariate analyses, based upon the relative abundance of zooplankton taxa, indicated (as for the phytoplankton) that there was greater similarity between sites within embayments than between embayments.

9. Trends in zooplankton abundance within both embayments were similar to those for phytoplankton with the coastal sites in Cockburn Sound having a consistently greater abundance than at the north-western tip. The central Warnbro Sound sites, and to a lesser extent site 5 at the southern tip, had a greater zooplankton abundance than site 1 at the northern tip of the embayment. The low relative abundance of zooplankton in the north-west corner of Cockburn Sound, where exchange with offshore waters is greatest is consistent with the findings of ERA (1971a, b) which showed that the highest zooplankton abundances within Cockburn Sound were associated with waters that had the longest residence times in the embayment.

   Trends between Sounds were also similar to those of phytoplankton with zooplankton abundances in Cockburn Sound generally 2.3 times greater than those of Warnbro Sound.

10. Zooplankton larvae and eggs showed similar trends in abundance as adults with numbers in Cockburn Sound being almost twice those in Warnbro Sound for most groups.

    While echinoderm eggs were more abundant in Cockburn Sound, echinoderm larvae were more commonly encountered in Warnbro Sound in abundances similar to Cockburn Sound. This supports data collected during benthic fauna surveys pointing to higher abundances of echinoderm larvae in Warnbro Sound compared to Cockburn Sound. Reasons for this are not known and should be investigated further.

4 - PHYTOPLANKTON - ZOOPLANKTON INTERACTIONS

Interaction between phytoplankton and zooplankton assemblages can be bi-directional having either a positive or negative result on their standing crops. For example, heavy grazing pressure exerted by high zooplankton abundance can negatively impact on phytoplankton by reducing standing crops; or conversely, excretion of inorganic nutrients into the water column by zooplankton can stimulate phytoplankton growth and is therefore a positive interaction. In laboratory experiments, Sterner (1986) demonstrated that enhanced phytoplankton growth due to nitrogen regeneration by zooplankton and mortality due to zooplankton grazing can act upon each other simultaneously, in effect, cancelling each other out.

An inverse relationship between the standing crop of phytoplankton and the standing stock of grazers has been described from scales of metres and days to thousands of kilometres and years; however, a causal link between grazing intensity and phytoplankton abundance has only been demonstrated in a few ecosystems at the smaller time and space scales while at larger scales, it remains hypothetical (Robertson and Hatcher 1994).

Phytoplankton are a major food source for zooplankton and therefore their high standing crops and growth rates support high zooplankton abundances and allow heavy grazing pressures to be maintained, whereas low phytoplankton abundance and growth rates will only sustain low zooplankton abundances. Conversely, in areas where grazing pressure is naturally low, phytoplankton growth may be largely unchecked. Wong *et al.* (1992), concluded from a study of grazing impacts in Tolo Harbour, Hong Kong, that phytoplankton communities in coastal areas are often underexploited by zooplankton grazing.

Some phytoplankton taxa are selectively grazed in preference to others providing a distinct advantage or disadvantage to certain phytoplankton taxa depending on whether they are a preferred food source or not. Factors responsible for such selective grazing include: size, morphology, and chemical composition of the phytoplankton taxa and/or the structure of the zooplankton community in terms of size and/or feeding preferences, ie. herbivorous or omnivorous.

High abundances of particular phytoplankton taxa may, in some cases, be more indicative of its unpalatability to grazers rather than conditions suitable for rapid growth.

The primary productivity of Cockburn and Warnbro sounds is phytoplankton dominated. Changes in relative phytoplankton abundance, measured as chlorophyll-a concentrations, can be used as a principal ecosystem response to nutrient inputs. An understanding of the interaction between phytoplankton populations and zooplankton grazers may highlight the need to focus on nutrient inputs and phytoplankton biomass.

Sections 2 and 3 described the results of an intensive two year study of the phytoplankton and zooplankton populations in Cockburn and Warnbro sounds. In this section the two data sets are integrated to identify relationships between these two groups to highlight the trophodynamics of phytoplankton populations in these waters.

4.1 - GRAZER COMMUNITIES

Of the three major zooplankton groups identified from Cockburn and Warnbro sounds, (copepods, cladocerans and protozoans), all would be significant grazers of phytoplankton having an impact proportional to their abundance at any one time. Copepods are generally regarded as being among the most significant grazers of phytoplankton (Ikeda 1977, Anderson 1994), although their food habits are often quite diverse ranging from herbivory to carnivory and omnivory (Ikeda 1977, Adrian and Frost 1993, Kleppel 1993).

Considering their dominance during most of the year, the copepods would probably be the most significant grazers in the present study. Cladocerans, *Penilia avirostris* in particular, would be the second most significant grazers, followed by the protozoa (radiolaria and tintinnids). Of the minor groups of zooplankton present, polychaete and mollusc larvae, and tunicates also graze on phytoplankton. However, their low abundances suggest that their impact on phytoplankton populations in the study area would be relatively low compared to the dominant groups above.

4.1.1 - PHYTOPLANKTON AS A FOOD SOURCE FOR GRAZER COMMUNITIES

Of the major phytoplankton groups identified during this study (section 2.2), the diatoms were the most abundant and would be the most abundant food source for the planktonic grazing community. The diatom-copepod link has long been regarded as a key element in the reconstruction of pelagic food chains; and, in productive areas (such as upwelling regions - and possibly Cockburn Sound), it is well known that diatoms play a major role in copepod diets (Kleppel 1993). However, recent studies (Kleppel 1993) suggest that copepod diets are often varied encompassing a broad range of different food types.

Whilst Nielsen (1991) regards certain species of dinoflagellate (*Ceratium* spp. - a dominant taxa in the present study) to constitute a poor source of food for copepods, they appear to be readily grazed by the cladoceran *Podon polyphemoides*. Over the range of particle sizes characteristic of those grazed by copepods (incorporating most diatom and dinoflagellate taxa), Kleppel (1993) estimates that, as a food source, dinoflagellates provide 2 to 6 times more protein, 2.5 to 3.5 times more carbohydrate and 1.1 to 3 times more lipid than diatoms of an equivalent volume. In the present study, dinoflagellates were never a major component of the phytoplankton assemblage and would probably constitute a secondary food source to diatoms during most of the year.

Little is known of the relative palatability of silicoflagellates to zooplankton grazers. However, the abundant silicoflagellate population in both embayments during winter is a potentially large food source to those zooplankters able to exploit it. The cyanobacteria would be considered to be the least favoured food source for zooplankton grazers as some are potentially toxic, eg. *Oscillatoria thiebautii* to calanoid and cyclopoid copepods (Guo and Tester 1994), although Gallager *et al.* (1994) suggests that *Synechococcus* sp. may be heavily grazed by certain members of the zooplankton community.

4.2 - TROPHIC INTERACTIONS

When data were averaged over the entire study period, phytoplankton and zooplankton abundances showed a significant positive correlation (Figures 25 and 26). The correlation was strong ($r^2 = 0.672$) suggesting that either one group is controlling the standing crop of the other or that common site-specific factors are influencing both populations.

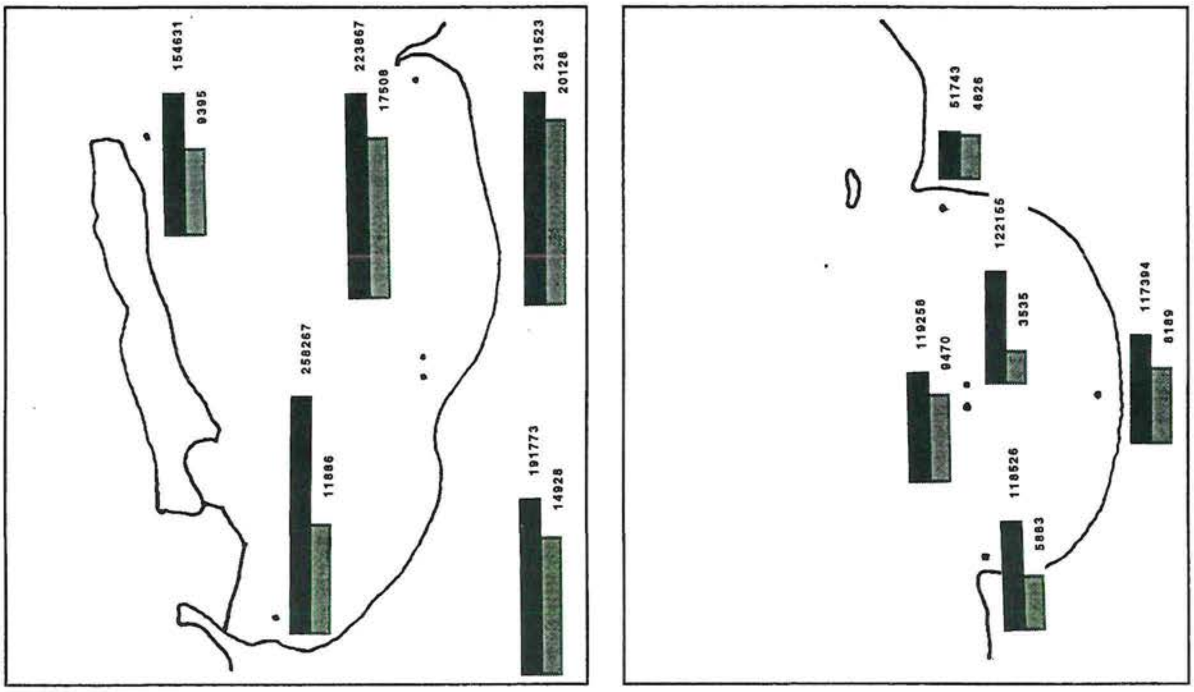

Figure 25: Average phytoplankton and zooplankton abundance for all sites in Cockburn and Warnbro sounds. ■ = Phytoplankton ▨ = Zooplankton.

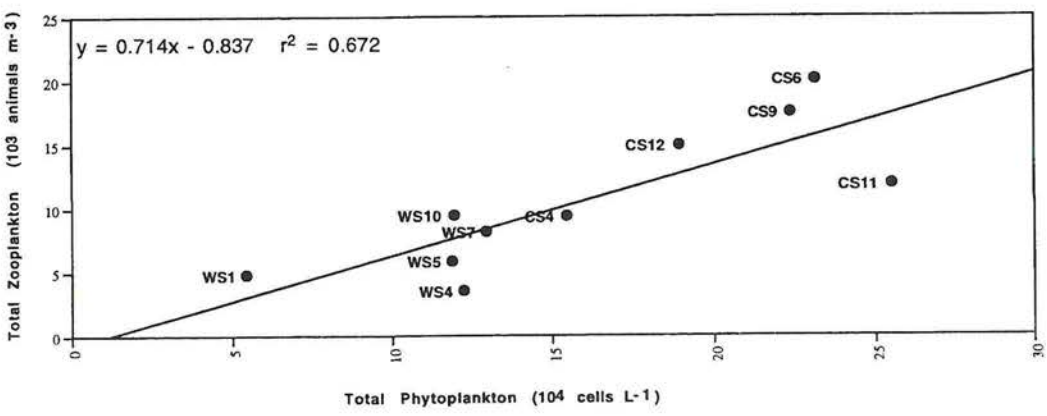

Figure 26: Scatter plot showing correlation between phytoplankton and zooplankton abundance in both embayments averaged over the study period.

The composition of the phytoplankton and zooplankton assemblages of both embayments were very similar suggesting that the types of trophic interactions between the zooplankton and phytoplankton would be general to both embayments.

Although some relationship between phytoplankton and zooplankton abundance was evident according to averaged site data, there were very few statistically significant relationships between any of the major phytoplankton and zooplankton groups using raw data at any site in either embayment. To account for any lag effects in zooplankton response times, analyses were repeated using data offset by 1, 2 and 3 months; analyses were also repeated using temporally averaged data (eg. Figure 15) to even out the data. Results of these analyses also showed no consistent significant correlations between the abundances of the major phytoplankton and zooplankton groups or between chlorophyll-a concentration and any of the zooplankton groups.

Although the potential for interaction between various groups of zooplankton and phytoplankton has been identified in this and other similar studies conducted elsewhere, seasonal changes in abundances of each of these groups are not solely determined by predator:prey interactions; other confounding influences such as predator:predator interactions are also very important and will tend to mask all but the strongest and most simplistic predator:prey interactions.

However, an assessment of the timeseries plots of phytoplankton and zooplankton abundance (Figures 6 and 17 respectively) does reveal some possible inter-relationships between particular phytoplankton and zooplankton groups, primarily between copepods/cladocerans and diatoms and between radiolaria and silicoflagellates.

Peaks in copepod and cladoceran abundance generally occurred during spring and summer in both embayments (sections 3.2.2.1 and 3.2.2.2) corresponding to the period of peak diatom abundance (section 2.2.2.1). This suggests that both copepods and cladocerans may be preferentially grazing on diatoms and is supported by an observed increase in copepod and cladoceran abundance in Cockburn Sound during late winter 1994 coinciding with a rapid decline in a monospecific bloom of the diatom *Skeletonema costatum* during early winter. Neither of these events were observed in Warnbro Sound (Figures 6 and 17). The preferential grazing of *S. costatum* by copepods will be discussed further in section 4.2.1.1.

Increases in radiolarian abundance occurred during late winter in both embayments (section 3.2.2.3) coinciding with decreasing density of silicoflagellates which dominated the phytoplankton assemblages throughout the region during winter (section 2.2.2.3). Radiolarian abundance peaked in early spring and declined to low numbers by the end of spring, a pattern that would be expected if the radiolarians were grazing on the silicoflagellates. Additionally, the magnitude of the radiolarian peaks during late winter was related to the magnitude of the preceding silicoflagellate bloom (Figure 27) which is also indicative of a significant relationship between the two groups. The feeding ecology of radiolaria will be discussed further in section 4.2.1.3.

There were no apparent associations between the abundance of dinoflagellates and any of the major zooplankton groups. Dinoflagellate abundance remained relatively low throughout the study period (section 2.2.2.2). Given the high nutritional status of dinoflagellates (section 4.1.1), the possibility that the abundance remains low throughout the year due to selective grazing by the grazing community rather than because of unfavourable environmental conditions, cannot be ruled out. Likewise, there were no apparent associations between the abundance of cyanobacteria and "other" phytoplankton and any of the major zooplankton groups.

4.2.1 - DOMINANT GRAZERS

4.2.1.1 - Copepods

Of all the herbivorous zooplankton, the copepods are the most numerous and important (Anderson 1994), although, as a group, their diets are diverse (Ikeda 1977, Adrian and Frost 1993). Adrian and Frost (1993) report an increasing amount of evidence that omnivory among the planktonic copepods is a common phenomenon. They also state however, that the degree of omnivory, at least among the cyclopoid copepods, varies according to the size of the animal, with the smaller species being able to cover their energy requirements with an exclusively phytoplankton diet whilst the larger species need to supplement their diets with a variety of zooplankton prey.

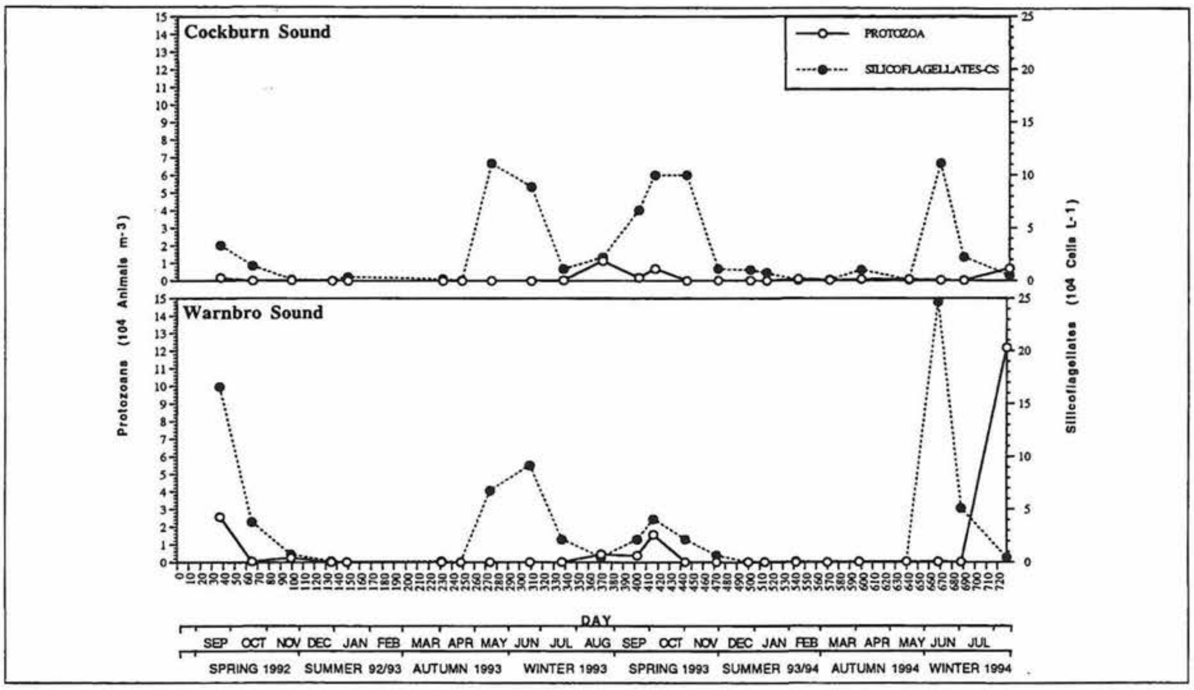

Figure 27: Average silicoflagellate and protozoan abundance for Cockburn and Warnbro sounds between August 1992 and August 1994.

In the present study, over 80% of adult copepods were in the two smallest size classes, less than 0.75 mm in length (section 3.2.1), suggesting that the majority of copepods in the embayments would be herbivorous or at least depend largely on the phytoplankton to meet their energy needs and would therefore be exerting a substantial grazing pressure on the phytoplankton assemblages. Copepods are capable of feeding on suspended particles between 5 µm and 100 µm (Boyd 1976). Kiørboe and Nielsen (1994) suggest that they can extract particles of up to 200 µm in size. This suggests that almost the entire phytoplankton assemblage at any one time would be available for copepod grazers as very few taxa encountered had a length or diameter greater than 200 µm, and most were less than 50 µm. However, many of these smaller taxa formed chains and/or possessed large setae, as in the case of some *Chaetoceros* species, which may affect their availability to grazing copepods.

Selective grazing by copepods has been demonstrated in Narragansett Bay, USA, where several copepod taxa were shown to feed selectively on the diatom *Skeletonema costatum* leaving other species untouched until *S. costatum* abundance fell below a certain threshold (Martin 1965, 1970).

Martin (1970) also observed that not only did the copepods show a preference for *Skeletonema* but they also showed a preference for the longer chains, removing them from the water first.

4.2.1.2 - Cladocerans

Nielsen (1991) considers the cladocerans to be a frequently ignored component of zooplankton assemblages. Cladoceran assemblages in the present study were generally dominated by *Penilia avirostris*, and followed similar seasonal trends as the copepods (section 3.3.2) suggesting that, they too, may be preferentially grazing upon diatoms.

In Tolo Harbour, Hong Kong, cladocerans, *P. avirostris* in particular, were found to graze only a small portion of the phytoplankton standing crop (Wong *et al.* 1992), however the relatively high abundance of cladocerans compared to other zooplankton groups in the present study and compared to that of Wong *et al.*, suggest that they are likely to be a significant component of the grazer community.

As previously mentioned, *P. avirostris* is widely distributed in the world's temperate oceans where small phytoplankton species dominate. *P. avirostris* is capable of growing and reproducing in waters where phytoplankton concentrations are relatively low (Paffenhoffer and Orcutt, 1986).

Gut content analyses of four cladoceran species (*P. avirostris*, one species of *Podon* and two species of *Evadne*) from the inland Sea of Japan revealed that, despite differences in their feeding mode, they all fed mainly on centric diatoms (Uye and Onbé 1993). Although little other information has been found on the feeding habits of species of *Podon*, the results of gut content analyses in Nielsen (1991) suggest that they may be significant grazers of dinoflagellates, *Ceratium* spp. in particular.

P. avirostris has a preference for small particles including small diatoms, microflagellates and bacteria (Wong *et al.*, 1992). Wong *et al.* (1992) cite other studies in which *P. avirostris* is reported to be limited to feeding on particles less than 30 µm in diameter, preferring centric diatoms.

As for copepods, the size structure of the phytoplankton community is such that throughout the year, the majority of phytoplankton taxa would be within the size range preferred by *Penilia*.

It is likely that the apparent close association between copepods and cladocerans is possible because, although both seem to be preferentially grazing upon diatoms, the cladocerans may be exploiting particles in a smaller size range than the copepods.

4.2.1.3 - Protozoans

The dominant protozoans in the present study were tintinnids and radiolarians (section 3.2.2.3). Whilst tintinnids have been recognised as significant consumers of the pico- and nano- sized fractions of plankton assemblages, linking microbial and metazoan food webs (Nielsen and Kiørboe 1994, Pierce and Turner 1994) little information is available on the feeding habits of radiolarians.

Caron *et al.* (1995) report that the planktonic sarcodines (acantharia, radiolaria and foraminifera) are a trophically diverse group preying on a variety of organisms ranging from bacteria to macroscopic metazoans. Planktonic radiolaria are opportunistic predators, using adhesive surfaces on their feeding rhizopodia to snare prey. The smaller skeleton-bearing species (those observed in the present study) utilise supporting skeletal structures to capture relatively large prey including copepods, copepod nauplii, pteropods, trochophore larvae and larvaceans as well as smaller prey including tintinnids, non-loricate ciliates, acantharians, diatoms and silicoflagellates (Anderson 1993).

Given the relatively high abundance of radiolaria encountered during late winter compared to other zooplankton groups in the present study and to other regions of the world (section 3.2.2.3), they have the potential to exert a significant grazing pressure on the phytoplankton communities of the embayments. Their relationship with silicoflagellates, if any, remains unresolved.

Phytoplankton and zooplankton abundance data were analysed in section 2.6 to provide an insight into the overall primary productivity of the two embayments. In the absence of information on the feeding ecology of much of the zooplankton community, it was assumed that the grazing community at any one time could be represented by the adult copepod population, most of which were in the two smallest size groups and considered to be entirely or mostly herbivorous.

4.3 - SUMMARY

Phytoplankton-zooplankton interactions in Cockburn and Warnbro sounds have never been previously investigated. The following conclusions are theoretical, based upon empirical field data. Without appropriate grazing experiments, it is difficult to assess the interaction between the two.

1. Copepods, cladocerans and protozoans (tintinnids and radiolarians) were identified as the major potential grazers of phytoplankton in Cockburn and Warnbro sounds. Due to their numerical abundance during most of the year, the copepods would be the most significant grazers followed by the cladocerans and protozoans.

2. Diatoms were identified as potentially the major food source of zooplankton grazer communities. Although usually present in low abundances, dinoflagellates could possibly be a major food source for cladocerans, particularly *Podon* spp., as suggested by Nielsen (1991).

   The suggestion that dinoflagellate densities may be kept low by grazing pressure rather than unsuitable environmental conditions or a competitive disadvantage imposed by another phytoplankton group requires further investigation. If this is the case, the likelihood of an increase in the abundance of toxic or potentially toxic dinoflagellate species is reduced while the grazing pressure is maintained. Any disruption of the grazing food chain, such as through the introduction of toxicants (eg. pesticides), could therefore have a dramatic effect on the density and/or composition of the dinoflagellate assemblage.

   The palatability of silicoflagellates to zooplankton grazers is unknown and requires investigation due to their high abundance during winter and spring and subsequent potential as a food resource. Cyanobacteria were considered to be a minor food source.

3. Several phytoplankton-zooplankton interactions were apparent. At the coarsest level, the correlation between average phytoplankton and zooplankton abundances over the study period is indicative of predator:prey interaction or common controlling factors. At a finer level of resolution, two different associations were evident. The first was between copepods/cladocerans and diatoms. Copepods and cladocerans showed similar seasonal trends in abundance and were both most abundant at the time when diatoms dominated the phytoplankton assemblages. These similarities suggest that all three groups were responding to the same stimuli or there were predator:prey interactions operating between each of the two zooplankton groups and the diatoms. Although both these zooplankton groups appear to be grazing on diatoms, it is possible that they are not in direct competition. The dominant cladoceran, *Penilia avirostris*, has a preference for small particles (<25 µm) which would allow these two groups to coexist if the dominant copepods were exploiting a larger size class of diatoms.

   The second association was evident between the silicoflagellates and the radiolarians. Although only one documented instance of radiolarians grazing on silicoflagellates could be found in the literature, the late winter initiation of radiolarian blooms and the positive relationship between the magnitude of silicoflagellate and radiolarian blooms is indicative of grazing interaction. It is possible that these radiolarian grazers may play an important role in limiting the magnitude and duration of silicoflagellate blooms.

   The apparent increase in silicoflagellate numbers in the two embayments since the late 1970s may be due to insufficient grazing pressure. This could result from an inability of grazers to multiply fast enough to keep up with increased silicoflagellate production or alternatively, it is possible that the growth rates of silicoflagellates have remained relatively constant but there has been a decline in the numbers of silicoflagellate grazers and hence grazing pressure. In either case, the interaction between silicoflagellates and radiolarians appears important, but is poorly understood world-wide and should be investigated further.

4. As previously stated in section 3.6, the distribution and abundance of tintinnids in the coastal waters of Perth require further investigation. If, as suggested, there is a bias against this group due to preservation technique, a large group of significant grazers of pico- and nano-phytoplankton assemblages has possibly been overlooked.

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APPENDIX 1 - SAMPLE DATES

1)	August	17	1992
2)	September	07	1992
3)	September	23	1992
4)	October	21	1992
5)	November	10	1992
6)	November	24	1992
7)	December	17	1992
8)	December	30	1992
9)	January	14	1993
10)	January	28	1993
11)	February	23	1993
12)	March	10	1993
13)	March	24	1993
14)	April	06	1993
15)	April	22	1993
16)	May	04	1993
17)	May	18	1993
18)	June	03	1993
19)	June	22	1993
20)	July	06	1993
21)	July	20	1993
22)	August	03	1993
23)	August	23	1993
24)	September	02	1993
25)	September	23	1993
26)	October	07	1993
27)	October	21	1993
28)	November	04	1993
29)	November	18	1993
30)	December	02	1993
31)	December	16	1993
32)	December	23	1993
33)	December	30	1993
34)	January	06	1994
35)	January	13	1994
36)	January	20	1994
37)	January	27	1994
38)	February	03	1994
39)	February	10	1994
40)	February	17	1994
41)	February	24	1994
42)	March	03	1994
43)	March	10	1994
44)	March	17	1994
45)	March	24	1994
46)	March	30	1994
47)	April	07	1994
48)	April	21	1994
49)	May	05	1994
50)	May	19	1994
51)	June	03	1994
52)	June	16	1994
53)	July	06	1994
54)	July	14	1994
55)	August	15	1994

APPENDIX 2 - LIST OF PHYTOPLANKTON TAXA

DIATOMS

Achnanthes spp. (2)
Actinoptychus spp. (2)
Amphora decussata
Amphora hyalina
Amphora ostrearia
Amphora spp. (9)
Asterionellopsis glacialis
Asteromphalus spp. (2)
Auliscus sculptus
Bacillaria paradoxa
Bacillaria spp. (2)
Bacteriastrum hyalinium
Bellerochea sp.
Biddulphia sinensis
Biddulphia toumeyi
Biddulphia spp. (2)
Campylodiscus robertsianus
Campylodiscus samonenes
Campylodiscus spp. (2)
Cerataulina pelagica
Cerataulina sp.
Chaetoceros spp. (70)
Climacodium sp.
Climacosphenia moniligera
Climacosphenia sp.
Cocconeis heteroideae
Cocconeis pseudomarginata
Cocconeis scutellum
Cocconeis sp.
Corethron spp. (2)
Coscinodiscus spp. (5)
Cyclotella sp.
Cylindrotheca closterium
Detonula sp.
Diploneis bombus
Diploneis chersonensis
Diploneis ovalis
Diploneis suborbicularis
Diploneis vacillans
Ditylum sp.
Druridgia compressa
Entomoeoneis spp. (2)
Eucampia cornuta
Eucampia zodiacus
Eucampia spp. (2)
Falcula sp.
Gossleriella sp.
Gramatophora marina
Gramatophora oceanica
Guinardia flaccida
Gyrosigma balticum

DIATOMS (cont.)

Gyrosigma spp. (2)
Leptocylindrus danicus
Leptocylindrus minimus
Leptocylindrus spp. (2)
Licmophora flabellata
Licmophora gracilis
Licmophora lyngbyei
Licmophora spp. (3)
Lithodesmium undulatum
Lithodesmium sp.
Mastogloia cocconeiformis
Mastogloia spp. (3)
Mastoneis biformis
Melosira moniliformis
Navicula cincta
Navicula punctata
Navicula punctulata
Navicula robertsiana
Navicula spp. (22)
Nitzschia levidensis
Nitzschia longissima
Nitzschia panduriformis
Nitzschia punctata
Nitzschia seriata
Nitzschia seriata (large)
Nitzschia spp. (14)
Odontella aurita
Odontella spp. (2)
Paralia sulcata
Pinnularia sp.
Pleurosigma salinarum
Pleurosigma spp. (4)
Podocystis sp.
Podosira sp.
Rhizosolenia clevei
Rhizosolenia imbricata
Rhizosolenia imbricata var. shrubsolei
Rhizosolenia setigera
Rhizosolenia shrubsolei
Rhizosolenia stolterfothii
Rhizosolenia styliformis
Rhizosolenia spp. (5)
Skeletonema costatum
Stephanodiscus #1
Streptotheca #1
Striatella unipunctata
Surirella ovalis
Synedra #1
Synedra crystalina
Thalassionema frauenfeldii
Thalassionema nitzschiodes

DIATOMS (cont.)

Thalassiosira pseudonana
Thalassiosira spp. (2)
Thalassiothrix sp.
Toxarium sp.
Triceratium favus
Triceratium sp.
Trigonium alternans
Trigonium reticulum
Trigonium shadboltianum
Unidentified diatoms (12)

DINOFLAGELLATES

Alexandrium spp. (3)
Amphidinium spp. (3)
Ceratium azoricum
Ceratium buceros
Ceratium candelabrum
Ceratium furca
Ceratium fusus
Ceratium lineatum
Ceratium tripos
Ceratium spp. (4)
Dinophysis acuminata
Dinophysis caudata var. pediculata
Dinophysis rotundatum
Dinophysis spp. (2)
Ebria tripartita
Gymnodinium aff. splendens
Gymnodinium spp. (3)
Katodinium rotundatum
Mesoporos sp.
Oxytoxum sp.
Polykrikos sp.
Prorocentrum lima
Prorocentrum micans
Protoperidinium aff. curtipes
Protoperidinium aff. marielebouriae
Protoperidinium bipes
Protoperidinium claudicans
Protoperidinium roseum
Protoperidinium steinii
Protoperidinium spp. (10)
Pseliodinium sp.
Pyrocystis lunula
Pyrocystis spp. (3)
Scrippsiella spp. (3)
Unidentified dinoflagellates (8)
Unidentified dinoflagellate cyst

SILICOFLAGELLATES

Dictyocha fibula var. rhombica
Dictyocha octonaria

CYANOBACTERIA	OTHER
Nodularia spumigena	Pediastrum sp.
Oscillatoria erythraea	Scenedesmus sp.
Richelia intracellularis	Unidentified algae (2)
Spirulina sp.	Unidentified bi-flagellates (2)
Synechococcus sp.	Unidentified occoid algae (3)
Unknown cyanobacteria (7)	Unidentified coccolith
	Unidentified epiphytic alga
	Unidentified filamentous alga
	Unidentified flagellate
	Unidentified prymnesiophyte

APPENDIX 3 - LIST OF ZOOPLANKTON TAXA

SARCODINA

Foraminiferan (1)
Radiolarian (1)

CILIOPHORA

Vorticella (1)
Tintinnids (6)

CNIDARIA

Hydroids (2)
Medusa (2)

CTENOPHORA

Ctenophore (1)

PLATYHELMINTHES

Turbellarians (2)

NEMATODA

Nematodes (2)

ANNELIDA

Nereid nectochaete (1)
Polychaete (1)
Polychaete larva (1)
Polychaete larva (spionidae) (1)

MOLLUSCA

Gastropod (1)
Lamellibranch veliger (1)

CRUSTACEA

Branchiopoda
Penilia avirostris
Penilia avirostris larva
Podon spp. (7)
Ostracoda
Ostracod (1)
Copepoda
Calanoid Copepods (13)
Cyclopoid Copepods (4)
Harpactacoid Copepods (6)
Pontellid Copepod nauplius (2)

CIRRIPEDIA

Cirripede cypris (1)
Cirripede nauplii (5)

MALACOSTRACA

Amphipods (5)
Anomuran zoea (1)
Caprella (1)

MALACOSTRACA (cont.)

Carideans (8)
Crab megalopa (1)
Crab zoea (6)
Euphausiid calyptopis (2)
Isopods (5)
Lucifer (1)
Lucifer mysis (1)
Lucifer protozoea (1)
Mysids (9)
Penaeids (3)
Penaeid nauplius (1)
Penaeid protozoea (1)
Squilla sp (alima larva) (1)

BRYOZOA

Bryozoan (1)
Bryozoan larva (1)

ECHINODERMATA

Echinoderm auricularia larva (1)
Echinoderm bipinnaria larva (1)
Echinoderm ophiopluteus larva (1)

CHAETOGNATHA

Chaetognatha (1)

CHORDATA

Ascidian (1)
Ascidian tadpole (2)
Fish eggs (5)
Larvacean (1)
Tunicate (1)

UNKNOWN

Eggs (5)
Trochophore-type larva (1)
Unknown zooplankters (21)