Water quality in Cockburn Sound

Results of the 1989/90 summer monitoring programme

A contribution to the Environmental Management Strategy of Cockburn Sound and Surrounding Waters

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Summary

The water quality of Cockburn Sound and Owen Anchorage was monitored at 11 sites over the summer of 1989/90. The sites and sampling regime were consistent with three previous summer surveys since 1982/83. The physical, biological and chemical characteristics of the water column were measured, at approximately weekly intervals, between 29 December 1989 and 29 March 1990.

The water quality of Cockburn Sound (expressed as mean phytoplankton concentration and mean light attenuation coefficient) has declined significantly since the 1986/87 survey. In 1989/90, phytoplankton levels increased by approximately 59 % and light penetration decreased by approximately 10 %. Comparisons with historical data indicate that the mean phytoplankton concentration of the Sound in 1989/90 was significantly greater than the mean of the three summer periods prior to this survey but not significantly different from the mean of the three summer periods before 1982/83. These data suggest that, if this trend continues, the water quality of Cockburn Sound will soon return to the poor condition of these waters of the 1970s.

The mean nitrogen load entering Cockburn Sound from the CSBP outfall during the 1989/90 study increased to 1883 kg/day, a 67 % increase from the 1986/87 study. A significant positive correlation exists between mean daily nitrogen loads, from the CSBP outfall, and mean phytoplankton concentration in Cockburn Sound for each summer monitoring period since 1982/83. Furthermore, a significant positive correlation exists between mean phytoplankton concentration at three sites in the general vicinity of the CSBP outfall in 1989/90, and mean phytoplankton concentrations in Cockburn Sound and the entire study area. These data suggest that nitrogen from the CSBP outfall was the primary determinant of water quality in Cockburn Sound during the 1989/90 summer monitoring programme. It follows that if the water quality of Cockburn Sound is to improve, the nitrogen loading from this source must be significantly reduced.

Inorganic N:P ratios in the water column were similar to the 1986/87 study levels suggesting that, in general, phytoplankton growth in Cockburn Sound remains nitrogen limited. However, the data also indicate that parts of the Sound may be phosphorus limited at times.

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1. Introduction

Prior to establishment of industry on the shores of Cockburn Sound in 1954, the extensive shallow banks (less than 10 m depth) that fringe the mainland and the eastern side of Garden Island were covered in healthy seagrass meadows (Anon.1979; Fig.1). Increased nutrient loading, primarily associated with industrial wastes and sewage discharge resulted in increased algal growth. More epiphytes grew on the leaves of the seagrasses and the frequency of phytoplankton blooms increased both of which shaded the seagrass and starved them of light. Between 1954 and 1978, approximately 80% of the seagrass meadows in Cockburn Sound were lost (Anon. 1979). Since 1978, the remaining meadows have continued to decline, albeit at a slower rate, and currently the seagrasses in Cockburn Sound remain, in general, in a relatively poor condition (EPA, unpublished data).

The Cockburn Sound Environmental Study (1976-79) report recommended that a significant reduction of nutrient loads into the Sound was necessary if water quality was to improve and dieback of the remaining seagrasses was to stop (Anon. 1979). The study identified two major sources of nitrogen; the combined outfall of the Kwinana Nitrogen Company (KNC) and CSBP & Farmers Ltd (CSBP), and the Water Authority of Western Australia's (WAWA) wastewater outfall (now only used as an emergency outfall) off Woodman Point (Fig. 1). In accordance with these recommendations, KNC installed a steam scrubber in late December 1982, which removed a large proportion of the nitrogen from their effluent. On 12 July 1984, the WAWA diverted the primary treated effluent away from the Sound into 20 m water depth 4 km off Cape Peron (Fig. 1). Currently, KNC/CSBP remains the single largest direct discharger of nutrients into Cockburn Sound.

To assess the effects of the reduced nitrogen loads into Cockburn Sound following implementation of the Cockburn Sound Environmental Study recommendations, the Department of Conservation and Environment, now the Environmental Protection Authority, initiated a long-term monitoring programme. The programme was designed to monitor, every two to three years, the physical, biological and chemical characteristics of the water column in summer when, historically, phytoplankton blooms were most frequent.

Chlorophyll *a* concentration, as a measure of phytoplankton abundance, and light attenuation, as a measure of water clarity, is measured at eight sites in Cockburn Sound, two sites in Owen Anchorage and a site near the north end of Garden Island (Fig. 1). The mean values of these parameters for Cockburn Sound are used as indices of ecosystem 'health'. Surveys were conducted during the summer of 1982/83 (Chiffings and McComb, 1983), 1984/85 (Hillman, 1986), and 1986/87 (Hillman and Bastyan, 1988). The fourth survey in this series was conducted over the summer of 1989/90 and is the subject of this report.

The first survey in 1982/83 found that phytoplankton concentrations and light attenuation in Cockburn Sound had decreased dramatically compared with the late 1970s and this improvement in water quality was mainly attributed to the reduced nitrogen loads from KNC (Chiffings and McComb, 1983). During the 1984/85 study, phytoplankton levels and light attenuation were not significantly different from those of the 1982/83 study suggesting that the Sound had reached a new trophic equilibrium in response to several years of relatively stable nitrogen loads (Hillman, 1986). Similar conclusions were reached following the 1986/87 study which found that, although the water quality had declined slightly (in terms of mean phytoplankton concentrations and mean light attenuation), it was not significantly different from the previous two surveys (Hillman and Bastyan, 1988). This decline, however, was coincident with a slight increase in the amount of nitrogen into the Sound from the KNC/CSBP outfall. A further conclusion of this study was that whereas the Cockburn Sound Study showed that nitrogen was the major nutrient limiting phytoplankton growth during the late 1970s (Chiffings, 1979), the 1986/87 study indicated that both nitrogen and phosphorus were alternating as the limiting nutrient during the summer of 1986/87 and suggested that, by 1989, phosphorus could become the nutrient limiting phytoplankton growth in Cockburn Sound.

This report outlines the results of the fourth survey of the water quality in Cockburn Sound carried during the summer of 1989/90.

2. Methods

The location of the sampling sites and the sampling regime were consistent with the previous three surveys and involved approximately weekly sampling at 11 sites between 29 December 1989 and 29 March 1990. Eight sites were in Cockburn Sound, two in Owen Anchorage, and one between Garden Island and Carnac Island (Figure 1).

Five litre surface, mid-depth and bottom water samples were collected at each site using a Niskin bottle. Two litres of the water collected at each depth was filtered through a 1.2 µm G/FC Millipore filter paper and the filter paper retained for subsequent chlorophyll *a* analysis. The remaining three litres of each depth sample was placed in a large plastic container, mixed thoroughly and subsampled for subsequent nutrient analyses. Samples for inorganic nutrient analyses were filtered through 1.2 µm G/FC Millipore filter paper at a maximum negative pressure of 75 KPa. Water samples were placed in 150 ml polyethylene bags ("Whirlpak", Nasco Kansas, USA.). In the field, all samples were temporarily stored in darkness on ice, and upon return to the laboratory, were frozen until the analyses were conducted.

Nutrient and chlorophyll *a* analyses were conducted by the Nutrient Analysis Laboratory, School of Biological and Environmental Sciences, at Murdoch University. Orthophosphate was analysed by the single solution method (Major *et al.* 1972); nitrate and nitrite after copper-cadmium reduction with a Technicon Autoanalyser 11; and ammonia by the phenol-prusside method (Dal Pont *et al.* 1974). Total nitrogen and phosphorus were from sulphuric and perchloric acid digests respectively; followed by analysis for ammonia and phosphate by the methods given above. Chlorophyll *a* was analysed after 24 hours in 90% acetone at 750 nm, 664 nm, and 630 nm according to the methods of Jeffrey and Humphrey (1975).

Light intensity (400-700 nm) profiles of the water column were measured using a Li-cor Integrating Quantum Sensor (LI-192S) and a Li-cor Underwater Quantum Meter (LI-188B). Light measurements were measured at 0.5 m (0-2 m depth) and 1.0 m (>2 m depth) intervals. Light attenuation coefficients (log base 10) were calculated for the top six metres of the water column, to compare with the results of previous surveys. It should be noted here that the first three sampling periods, 1977/78, 1979/80 and 1980/81 determined the light attenuation coefficient by measuring light penetration throughout the entire water column. Since the 1982/83 it has been measured using the top 6 metres of the water column only.

Seawater temperature (±0.05° C) and salinity (±0.05 ppt) were measured at 0.5 m (0-2 m depth) and 1.0 m (>2 m depth) intervals using a salinity-temperature meter (Yeo-Kal Model 602). The probe was immersed for 15 minutes in 0.1 M HCL before use each day to minimise instrument drift which, if this procedure is followed, is less than 0.1 ppt per day (D A Mills, pers. comm.). To determine salinity drift and offset, four samples of seawater were collected during each sampling day and subsequently measured for salinity on an inductive salinometer at the CSIRO Marine Laboratory in Perth. Results were adjusted accordingly. The temperature sensor was calibrated with a high precision mercury thermometer (±0.01° C).

For comparative purposes, mean phytoplankton concentration and light attenuation coefficient in Cockburn Sound before 1982 were calculated from the data of Chiffings (1979) for similar summer periods and for a set of eight stations at the same locations or close to those used during the summer surveys after 1982 (sites 4-11). Before 1982, the water quality in Cockburn Sound was monitored on a monthly basis and, as such, data for the summer periods prior to 1982 are fewer ($n \leq 4$) than the subsequent 14 weekly surveys ($n=14$).

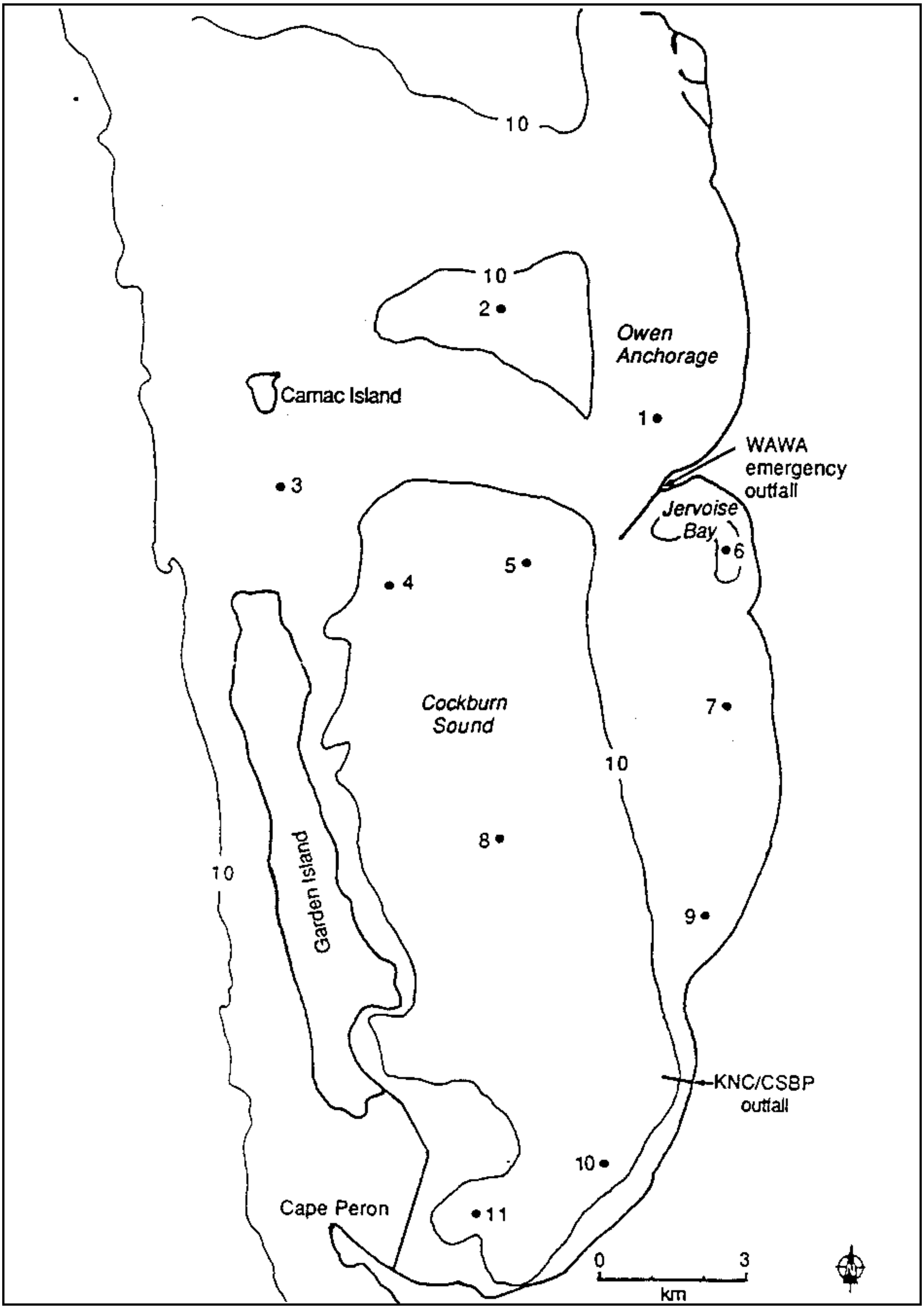

Figure 1. Location map of Cockburn Sound and Owen Anchorage showing the study sites.

3. Results

3.1 Water quality parameters

Mean water quality parameters at the 11 sites in the study area for the 14 week survey are shown in Table 1. In general the sites along the eastern shoreline of Cockburn Sound (sites 6, 7, 9, 10, 11) were higher in mean inorganic nutrient concentrations and phytoplankton abundance, expressed here as chlorophyll *a* concentrations and light penetration was lower, expressed here as mean light attenuation coefficient.

3.1.1 Phytoplankton concentrations

Vertically integrated phytoplankton concentrations at 11 sites in Cockburn Sound and Owen Anchorage during the summer monitoring period of 1989/90 ranged from 0.25 μgl^{-1} at site 2 to 5.84 μgl^{-1} at site 7. Mean chlorophyll *a* concentrations for the eight Cockburn Sound sites for the study period ranged from 0.86 μgl^{-1} to 3.20 μgl^{-1} (Fig. 2).

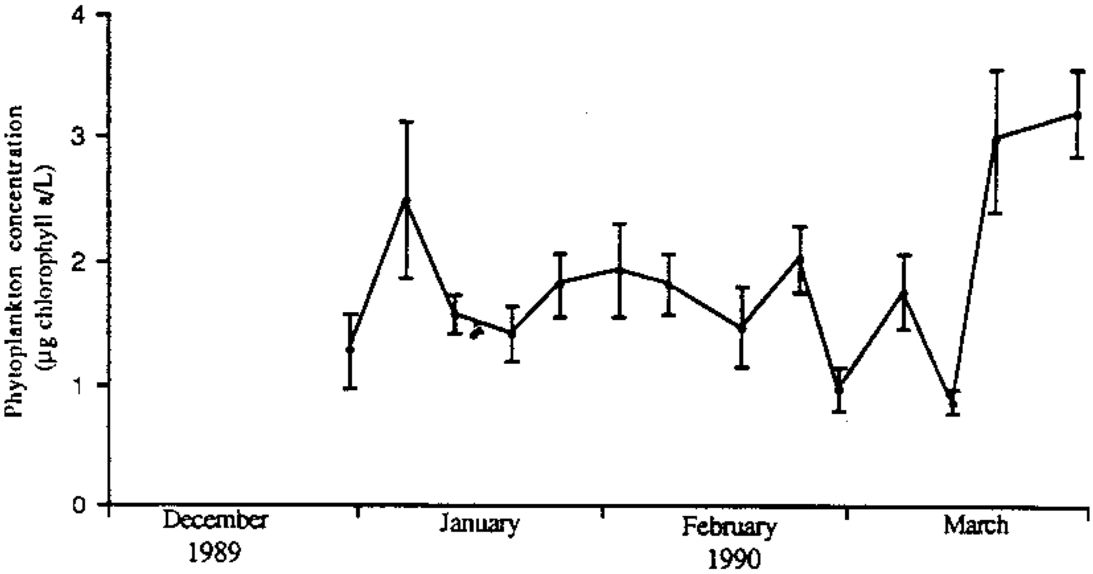

Figure 2. Mean phytoplankton concentrations for eight sites in Cockburn Sound during the summer of 1989/90. Error bars are standard errors.

Mean phytoplankton concentrations for the entire 14 week study period for each of the 11 sites are shown in Table 1 and ranged from 0.6 μgl^{-1} at site 3 to 2.7 μgl^{-1} at site 7. Mean phytoplankton concentration along the eastern margin of the Cockburn Sound (sites 6,7,9,10,11) was significantly higher (x=2.30 μgl^{-1}, se=0.10; F=49.4, $p<0.05$) than the mean of the three sites (sites 4,5,8) in the central and western part of the Sound (x=1.07 μgl^{-1}, se=0.14). By comparison, the mean of the three sites in Owen Anchorage (sites 1,2) and near Garden Island (site 3) was 0.77 μgl^{-1}.

Longer-term trends of mean phytoplankton concentrations for the eight sites in Cockburn Sound during seven summer periods since 1977/78 are shown in Figure 3. The 1989/90 mean chlorophyll *a* value of 1.83 μgl^{-1} (se=0.18) for the eight sites in Cockburn Sound was significantly higher than the mean values of 1986/87 (x=1.15 μgl^{-1}, se=0.12), 84/85 (x=1.25 μgl^{-1}, se=0.10) and 82/83 (x=0.80 μgl^{-1}, se=0.09; paired t-tests; $p<0.05$) and represents an increase of about 71 % over the overall mean value of 1.07 μgl^{-1} for the summer periods between 1982 and 1987. In comparison, the 1989/90 level was 86 % of the mean chlorophyll *a* level of the three summer 'surveys' before 1982 (x=2.13 μgl^{-1}, se=0.09).

Sites	1		2		3		4		5		6		7	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate-P	2	(0.5)	1	(1)	1	(1)	2	(1)	2	(1)	1	(0.5)	2	(1)
Organic-P	32	(7)	30	(8)	28	(6)	29	(7)	32	(10)	31	(8)	34	(11)
Total-P	33	(8)	31	(8)	30	(6)	31	(6)	33	(10)	32	(8)	36	(11)
Ammonia-N	3	(3)	2	(2)	2	(1)	4	(5)	5	(4)	7	(6)	3	(4)
Nitrate-N	6	(4)	5	(1)	7	(5)	5	(2)	5	(2)	8	(5)	5	(2)
Organic-N	250	(87)	209	(59)	214	(113)	187	(46)	198	(66)	247	(78)	258	(67)
Total-N	260	(88)	216	(59)	222	(111)	197	(48)	207	(64)	262	(77)	266	(69)
Chlorophyll *a*	1.0	(0.4)	0.7	(0.4)	0.6	(0.3)	0.8	(0.4)	1.1	(0.6)	2.2	(1.1)	2.7	(1.6)
Inorganic N:P atomic ratio	14.6	n/a	13.1	n/a	16.2	n/a	15.4	n/a	16.2	n/a	24.6	n/a	14.8	n/a
Organic N:P atomic ratio	18.1	n/a	16.2	n/a	17.05	n/a	14.8	n/a	14.8	n/a	19.3	n/a	17.7	n/a
Light attenuation coefficient	0.14	(0.02)	0.10	(0.02)	0.09	(0.03)	0.10	(0.03)	0.10	(0.05)	0.13	(0.04)	0.13	(0.03)

Sites	8		9		10		11		xsa		xcs		xoa	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate-P	2	(1)	4	(4)	7	(4)	6	(3)	3	(2)	3	(2)	1	(0.6)
Organic-P	29	(9)	31	(10)	32	(12)	32	(12)	31	(2)	31	(2)	30	(2)
Total-P	32	(10)	35	(10)	39	(13)	37	(11)	34	(3)	34	(3)	31	(1.5)
Ammonia-N	8	(11)	22	(25)	24	(15)	9	(9)	8	(8)	10	(8)	3	(0.6)
Nitrate-N	6	(6)	11	(9)	8	(5)	10	(8)	7	(2)	7	(2)	6	(1)
Organic-N	220	(95)	260	(95)	249	(105)	253	(88)	231	(26)	234	(29)	224	(22)
Total-N	235	(96)	294	(118)	282	(106)	272	(88)	247	(33)	252	(35)	233	(24)
Chlorophyll *a*	1.3	(0.5)	2.2	(1)	2.3	(0.8)	2.1	(1.1)	1.5	(0.8)	1.8	(0.7)	0.8	(0.2)
Inorganic N:P atomic ratio	9.6	n/a	28.5	n/a	11.2	n/a	8.7	n/a	15.7	n/a	16.1	n/a	14.6	n/a
Organic N:P atomic ratio	17.05	n/a	20.8	n/a	19.3	n/a	19.5	n/a	17.7	n/a	17.9	n/a	17.1	n/a
Light attenuation coefficient	0.10	(0.03)	0.13	(0.03)	0.12	(0.03)	0.11	(0.02)	0.11	(0.02)	0.12	(0.02)	0.11	(0.03)

Table 1. Mean water quality parameters measured at each site during the 1989/90 14-week summer monitoring programme of Cockburn Sound. Values are means and standard deviations; n=14; xsa=mean of the study area; xcs=mean of Cockburn Sound; and xoa=mean of Owen Anchorage; n/a = not applicable.

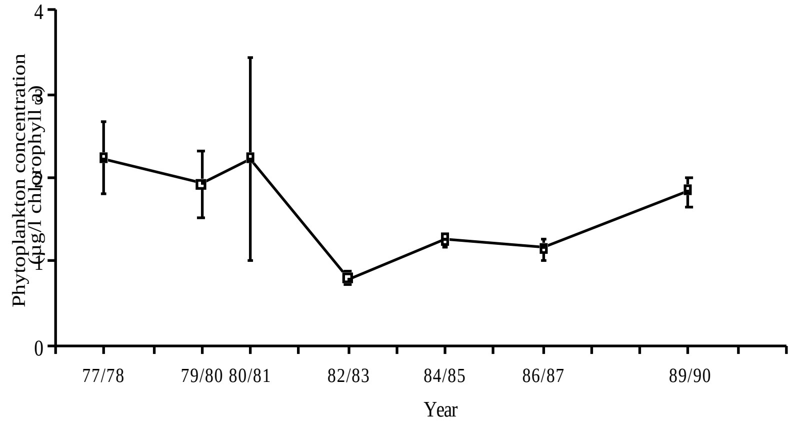

Figure 3. Mean phytoplankton concentration in Cockburn Sound during the summer monitoring periods in* 1977/78 (*n*=4), 1979/80 (*n*=4), 1980/81 (*n*=4) 1982/83 (*n*=14), 1984/85 (*n*=14), 1986/87 (*n*=14) and 1989/90 (*n*=14). *Error bars are standard errors.

3.1.2 Light Attenuation coefficients

Vertical light attenuation coefficients measured at 11 sites in Cockburn Sound and Owen Anchorage during the summer monitoring period of 1989/90 ranged from 0.03 m^{-1} at site 3 to 0.229 m^{-1} at site 5. Mean light attenuation coefficients for the entire 14 week study period for each of the 11 stations ranged from 0.089 m^{-1} at site 3 to 0.135 m^{-1} at site 1. Mean light attenuation coefficient along the eastern margin of the Sound (sites 6,7,9,10,11) was significantly greater (x=0.123 m^{-1}, se=0.004; F=21.7, $p<0.05$) than the mean of the three sites (sites 4,5,8) in the central and western part of the Sound (x=0.103 m^{-1}, se=0.004). By comparison, the mean of the three sites in Owen Anchorage (sites 1, 2) and near Garden Island (site 3) was 0.109 m^{-1}.

Longer-term trends of mean light attenuation coefficients for the eight sites in Cockburn Sound during seven summer periods since 1977/78 are shown in Figure 4.

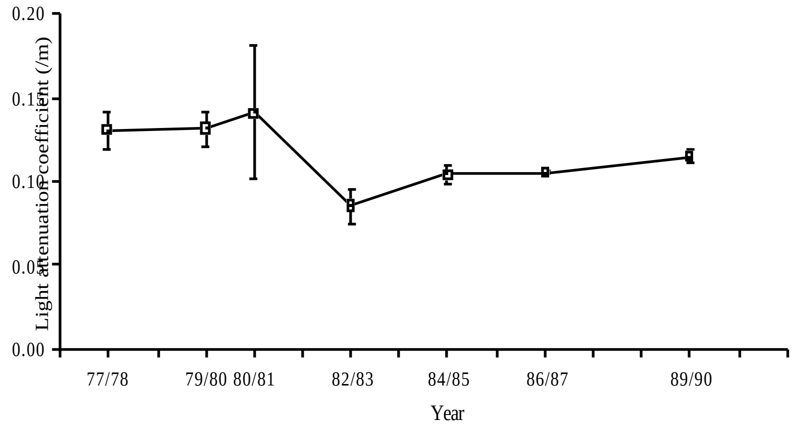

Figure 4. Mean light attenuation coefficient in Cockburn Sound during the summer monitoring periods in* 1977/78 (*n*=4), 1979/80 (*n*=4), 1980/81 (*n*=4) 1982/83 (*n*=14), 1984/85 (*n*=14), 1986/87 (*n*=14) and 1989/90 (*n*=14). *Error bars are standard errors. For convenience, attenuation coefficients are plotted

as positive values.

There was a significant increase in the mean light attenuation coefficient of Cockburn Sound during 1989/90 (x=0.115 m^{-1}, se=0.004) compared to 86/87 (x=0.103 m^{-1}, se=0.003), 84/85 (x=0.105 m^{-1}, se=0.005) and 82/83 (x=0.085 m^{-1}, se=0.010; paired t-tests; $p<0.05$), indicating a significant decrease in water clarity and therefore light penetration. The mean light attenuation coefficient of Cockburn Sound in 1989/90 represents an increase of about 17 % over the overall mean value of about 0.098 m^{-1} for the summer periods between 1982 and 1987 and is about 14 % less than the mean value of the surveys prior to 1982/83 (x=0.134 m^{-1}, se=0.004).

3.1.3 Nutrients

(i) *Spatial variation in 1989/90*

Mean orthophosphate-P concentrations at the 11 sites in Cockburn Sound and Owen Anchorage for the entire monitoring period ranged from 1 µg l^{-1} at sites 2, 3 and 6 to 7 µg l^{-1} at site 10. Mean orthophosphate-P concentration along the eastern margin of the Sound sites 6,7,9,10,11 was not significantly different than the mean of the three sites (sites 4,5,8) in the central and western part of the Sound.

Mean organic-P concentrations at the 11 sites in Cockburn Sound and Owen Anchorage for the entire monitoring period ranged from 28 µg l^{-1} at site 3 to 34 µg l^{-1} at site 7. Mean organic-P concentration along the eastern margin of the Sound (sites 6,7,9,10,11) was not significantly different than the mean of the three sites (sites 4,5,8) in the central and western part of the Sound.

Mean ammonium-N concentrations at the 11 sites in Cockburn Sound and Owen Anchorage for the entire monitoring period ranged from 2 µg l^{-1} at site 3 to 24 µg l^{-1} at site 10. Although the mean ammonium-N concentration along the eastern margin of the Sound (sites 6,7,9,10,11) was over twice the mean of the three sites (sites 4,5,8) in the central and western part of the Sound, it was not significantly different due to the high variation in ammonium-N concentration at these eastern sites.

Mean nitrate-N concentrations at the 11 sites in Cockburn Sound and Owen Anchorage for the entire monitoring period ranged from 5 µg l^{-1} at site 2, 4, 5 and 7 to 11 µg l^{-1} at site 9. The mean nitrate-N concentration along the eastern margin of the Sound (sites 6,7,9,10,11) was significantly greater (x=8.6, se=1.0; F=5.49, $p<0.05$) than the mean of the three sites (sites 4,5,8) in the central and western part of the Sound (x=5.3, se=0.3).

Mean organic-N concentrations at the 11 sites in Cockburn Sound and Owen Anchorage for the entire monitoring period ranged from 187 µg l^{-1} at site 4 to 260 µg l^{-1} at site 9. The mean organic-N concentration along the eastern margin of the Sound (sites 6,7,9,10,11) was significantly greater (x=253.5, se=2.5; F=43.6, $p<0.05$) than the mean of the three sites (sites 4,5,8) in the central and western part of the Sound (x=201.7, se=9.7).

(ii) *Temporal Variation*

Mean orthophosphate-phosphorus, organic phosphorus, ammonium-nitrogen and organic nitrogen concentrations at the eight sites in Cockburn Sound during the 1989/90 survey were significantly less than the mean values recorded at these sites in 1986/87 (paired t-tests, $p<0.05$). In contrast, mean nitrate-nitrogen concentration in 1989/90 was significantly higher than in 1986/87.

Longer-term trends in the nutrient characteristics of the water during the summer survey periods are shown at representative sites in Cockburn Sound (sites 7,10) and Owen Anchorage (site 1) in

Site 1

Parameter	1977/78		1982/83		1984/85		1986/87		1989/90	
Orthophosphate-P	36	(7)	39	(15)	8	(5)	5	(4)	2	(0.5)
Organic-P	22	(12)	45	(20)	22	(8)	29	(41)	32	(7)
Total-P	74	(57)	73	(31)	30	(9)	34	(42)	33	(8)
Ammonium-N	13	(6)	14	(10)	13	(10)	13	(10)	3	(3)
Nitrate-N	3	(2)	5	(3)	4	(2)	3	(1)	6	(4)
Organic-N	150	(67)	414	(159)	478	(143)	259	(104)	250	(87)
Total-N	172	(58)	432	(164)	495	(144)	275	(103)	260	(88)
Chlorophyll a	3.2	(2.2)	0.6	(0.2)	0.6	(0.4)	0.4	(0.3)	1.0	(0.4)
Inorganic atomic N:P ratio	1.1	n/a	1.0	n/a	15.3	n/a	17.2	n/a	14.6	n/a
Organic atomic N:P ratio	-	-	34.3	n/a	52.9	n/a	41.6	n/a	18.1	n/a
Vertical light attenuation coefficient	0.16	(0.03)	0.13	(0.06)	0.11	(0.02)	0.08	(0.02)	0.14	(0.02)

Site 7

Parameter	1977/78		1982/83		1984/85		1986/87		1989/90	
Orthophosphate-P	72	(19)	66	(22)	12	(6)	6	(5)	2	(1)
Organic-P	25	(18)	33	(18)	26	(10)	32	(36)	34	(11)
Total-P	96	(28)	99	(31)	37	(11)	38	(38)	36	(11)
Ammonium-N	12	(11)	14	(12)	9	(8)	9	(6)	3	(4)
Nitrate-N	4	(3)	7	(5)	4	(3)	3	(3)	5	(2)
Organic-N	210	(79)	409	(213)	504	(178)	297	(144)	258	(67)
Total-N	208	(80)	429	(217)	517	(175)	310	(142)	266	(69)
Chlorophyll a	4.4	(2.6)	0.9	(0.6)	1.3	(0.5)	1.3	(0.8)	2.7	(1.6)
Inorganic atomic N:P ratio	0.7	n/a	1.3	n/a	6.0	n/a	11.1	n/a	14.8	n/a
Organic atomic N:P ratio	-	-	38.7	n/a	46.7	n/a	31.9	n/a	17.7	n/a
Vertical light attenuation coefficient	0.16	(0.02)	0.11	(0.02)	0.11	(0.02)	0.12	(0.02)	0.13	(0.03)

Site 10

Parameter	1977/78		1982/83		1984/85		1986/87		1989/90	
Orthophosphate-P	105	(45)	56	(14)	15	(9)	9	(4)	7	(4)
Organic-P	22	(20)	29	(18)	25	(11)	38	(50)	32	(12)
Total-P	119	(57)	86	(15)	40	(16)	47	(52)	39	(13)
Ammonium-N	31	(30)	16	(16)	16	(7)	21	(10)	24	(12)
Nitrate-N	7	(5)	7	(3)	6	(4)	4	(2)	8	(5)
Organic-N	142	(47)	320	(103)	476	(116)	321	(164)	249	(105)
Total-N	173	(61)	339	(96)	497	(119)	346	(162)	282	(106)
Chlorophyll a	5.2	(3.5)	1.2	(0.8)	1.9	(0.8)	1.4	(0.8)	2.3	(0.8)
Inorganic atomic N:P ratio	0.8	n/a	0.7	n/a	7.75	n/a	8.4	n/a	11.2	n/a
Organic atomic N:P ratio	-	-	31.2	n/a	49.1	n/a	33.9	n/a	19.3	n/a
Vertical light attenuation coefficient	0.14	(0.03)	0.09	(0.01)	0.11	(0.02)	0.10	(0.02)	0.12	(0.03)

Table 2. Comparison of water quality parameters at three sites in Cockburn Sound/Owen Anchorage during summer periods in 1977/78 (n=4), 1982/83 (n=14), 1984/85 (n=14), 1986/87 (n=14), and 1989/90 (n=14). Values are means and standard deviations. Data from Chiffings (1979); Chiffings and McComb (1983); Hillman (1986) and the present study. n/a = not applicable.

previous surveys, continuing the trend since 1977/78. In contrast, mean organic phosphorus has remained relatively constant over the past decade.

Mean ammonium-N concentration in 1989/90 decreased at sites 1 and 7 but increased slightly at site 10 over 1986/87 levels. Since 1977/78, mean nitrate-N concentrations generally decreased up to 1986/87, then increased in 1989/90. In comparison, mean organic-N concentrations have been relatively variable since 1977/78. Organic N:P ratios have decreased steadily since 1984/85 whereas inorganic N:P ratios, relatively constant between 1977/78 and 1982/83, increased sharply in 1984/85 and remained at about these levels.

3.2 Changes in nutrient inputs to Cockburn Sound since 1976-79

Mean daily loads (kg) of nitrogen from the KNC/CSBP outfall for the summer of 1989/90 are compared with loads from the KNC/CSBP and WPTP outfalls for corresponding periods in previous surveys in Table 3. Mean daily loads for the study period of 1989/90 increased by about 67 % over mean loads for the previous survey in 1986/87 and, since the 1982/83 survey, mean loads have increased steadily from 563 kg/day to 1883 kg/day in 1989/90.

Table 3. Changes in nitrogen loads (kg/day) to Cockburn Sound from Woodman Point Treatment Plant (WPTP) and the KNC/CSBP outfalls. Total nitrogen (TN) includes inorganic and organic nitrogen. Total inorganic nitrogen (TIN) includes ammonium-N and nitrate-N. Data for the last four studies are presented two ways: the mean for the entire study period (all days), and the mean load on days when the plants were discharging (operational).

	Woodman Point Treatment Plant		KNC/CSBP Outfall		Data Source
	TIN	TN	TIN (all days)	TIN (operational)	
October 1977	-	-	3015	-	1
Jan-Feb 1978	1124	1422	-	-	1
March 1981	1560	-	1593	-	2
March 1982	-	-	257	-	3
Nov 1982-Feb 1983	-	2004	563 (KNC only)	1061 (KNC only)	4
Dec 1984-Mar 1985	0	0	974	1018	5
Dec 1986-April 1987	0	0	1128	1215	5
Dec 1989-Mar 1990	0	0	1883	1883	6

1. Murphy (1979) Data for KNC are mean values from one week's intensive sampling at three-hourly intervals. Data for WPTP are mean values from a four week continuous sampling programme.
2. Mean value from one week's intensive sampling by DCE at three-hourly intervals.
3. Talbot (1983) Sampling carried out from 12/11/82 to 22/11/82.
4. Chiffings and McComb (1983)- The total for KNC was calculated from daily figures over the period of the study.
5. Hillman and Bastyan (1988)- The total for the KNC/CSBP outfall was calculated from daily figures for the period of the study.
6. Present study- The total for the CSBP outfall was calculated from daily figures for the period of the study from CSBP's self monitoring data.

3.2.1 Short-term variability

Daily loads of nitrogen and phosphorus from the CSBP outfall for the 1989/90 summer monitoring period are shown in Figure 5. Daily variation in nitrogen loading was considerable and ranged from 264 kg to 6440 kg. Daily phosphorus loads in the same period ranged from 28 kg to 604 kg. These variations were due to fluctuations in effluent concentration which, in turn, are due to both alterations in the production process and discontinuities in pumping of waste (Chiffings and McComb, 1983).

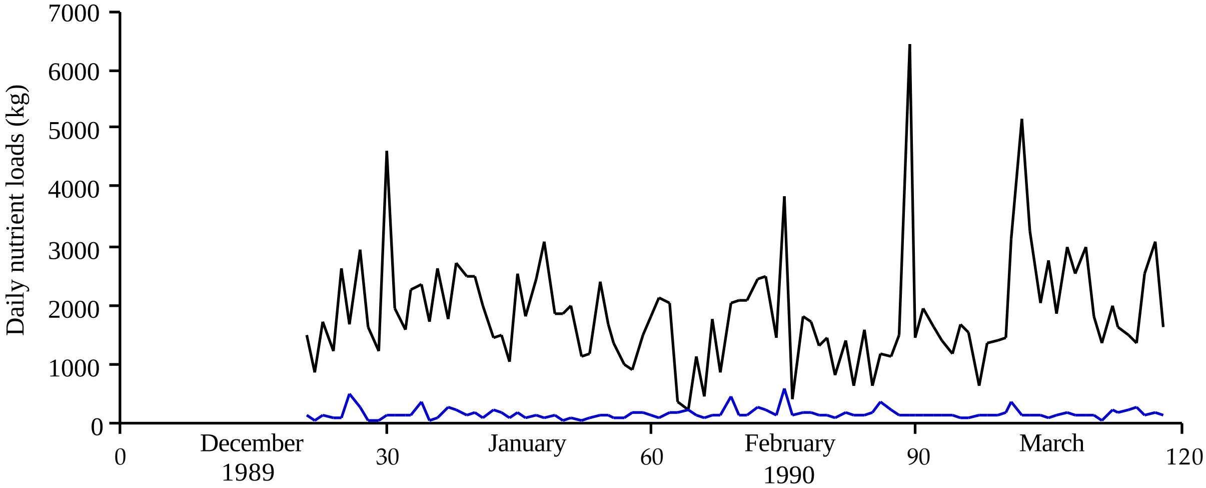

Figure 5. Daily nitrogen (upper) and phosphorus (lower) loads (kg) to Cockburn Sound from the CSBP outfall over the 1989/90 summer monitoring period. Data supplied by CSBP & Farmers Limited.

4. Discussion

The results of the 1989/90 summer monitoring programme indicate that the water quality of Cockburn Sound was significantly lower than any of the previous summer periods since 1982/83. This was expressed as a significant increase (71%) in mean phytoplankton abundance (expressed as mean chlorophyll *a* concentration) and a corresponding decrease (17 %) in mean water clarity (expressed as mean light attenuation coefficient). Comparisons between the 1989/90 survey and the surveys prior to the 1982, when the water quality of Cockburn Sound was at its lowest recorded level, indicate that the water quality of the Sound, in 1989/90, was approaching the levels of the late 1970s.

Comparisons between the 1989/90 survey and the previous survey in 1986/87 indicate that there was a 59% increase in phytoplankton and a 10% decrease in water clarity. This decline in water quality during the summer of 1989/90 coincided with a 67 % increase, from the 1986/87 study, in nitrogen loading from the KNC/CSBP outfall suggesting that nitrogen loading from this source is directly related to water quality in Cockburn Sound. A significant positive correlation exists between the mean daily nitrogen load from the KNC/CSBP outfall and mean chlorophyll *a* concentration for the eight sites in Cockburn Sound over the four summer monitoring programmes since 1982/83 (Fig. 6). These data further support the conclusion that nitrogen from the KNC/CSBP outfall is the primary determinant of phytoplankton abundance in Cockburn Sound.

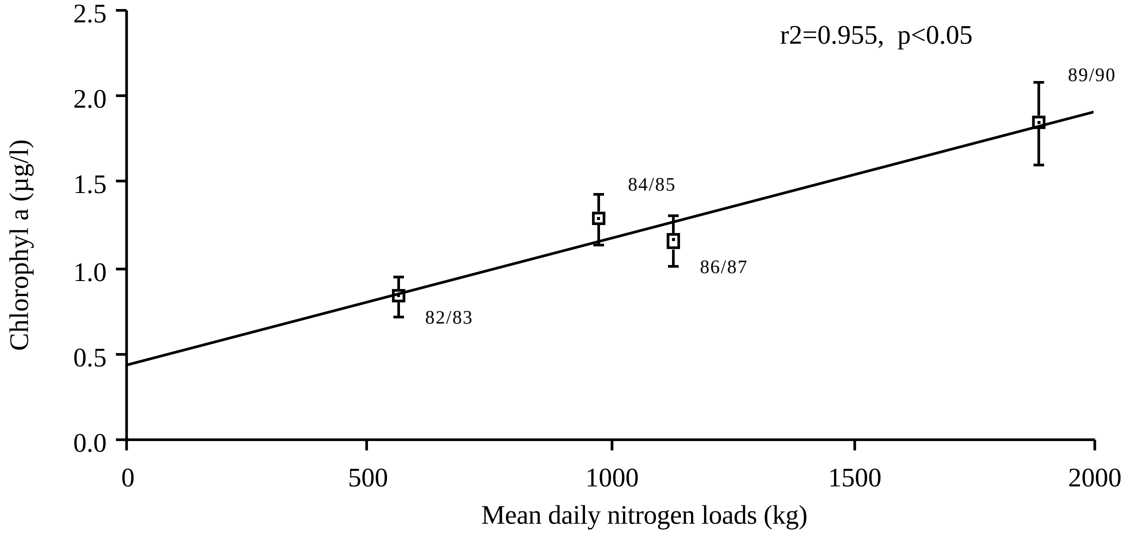

Figure 6. Correlation between mean daily nitrogen loads from the KNC/CSBP outfall and mean chlorophyll a concentration in Cockburn Sound.

During this study, phytoplankton levels were consistently highest along the entire eastern shore of Cockburn Sound (Table 1). Mean phytoplankton concentrations at sites (7, 9 and 10) in the vicinity of the KNC/CSBP outfall are significantly positively correlated with mean phytoplankton abundance in Cockburn Sound (r^2=0.916, n=14, $p<0.001$) and the entire study area (r^2=0.902, n=14, $p<0.001$). Comparable data collected in May 1990, two months after the present survey finished, again showed the highest phytoplankton levels in the vicinity of the KNC/CSBP outfall (Figure 7). Phytoplankton abundance decreased further north and northwest of this point source suggesting that the patterns observed during the summer survey of 1989/90 are temporally stable. These data further suggest that phytoplankton abundance in Cockburn Sound is strongly influenced by the discharge of nutrients from the KNC/CSBP outfall.

The high inorganic atomic N:P ratios of 1986/87 were maintained in 1989/90 (Figure 8a, Appendix I). This trend is probably due to the continued low concentrations of orthophosphate (Figure 8b) and the relatively constant total inorganic nitrogen levels (Table 2, Appendix I); maintained because, although there was a decrease in ammonium-N concentrations, nitrate-N levels increased.

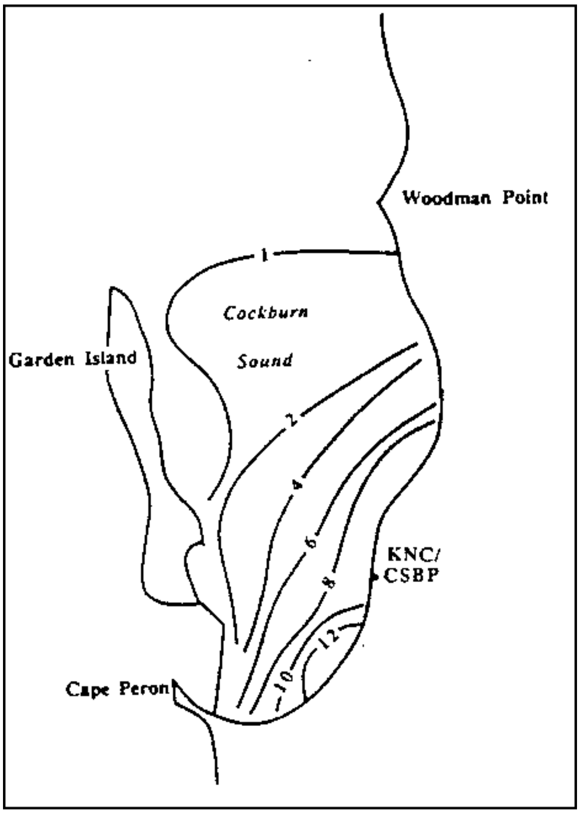

Figure 7. Chlorophyll a concentrations (µg/L) in Cockburn Sound on May 16, 1990.

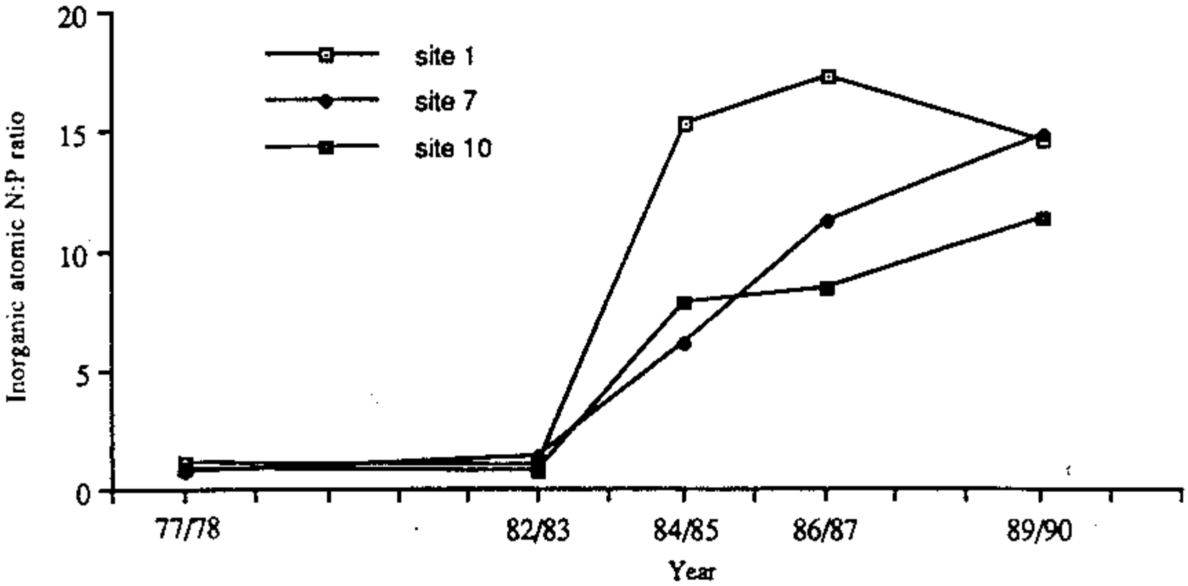

Figure 8a. Mean inorganic atomic N:P ratios at sites 1, 7 and 10.

The high inorganic N:P ratios, at site 6 (Jervoise Bay) and site 9 (the closest northerly site to the KNC/CSBP outfall and therefore the site most likely to be influenced by the outfall in summer) are greater than 22:1 indicating that these sites are phosphorus limited (Table 1). In contrast, sites 8, 10 and 11 located in the southern end of the Sound have N:P ratios equal to or less than 11:1 suggesting that these sites are nitrogen limited. The N:P ratio at the remaining sites range between these two extremes suggesting alternation between phosphorus and nitrogen limitation.

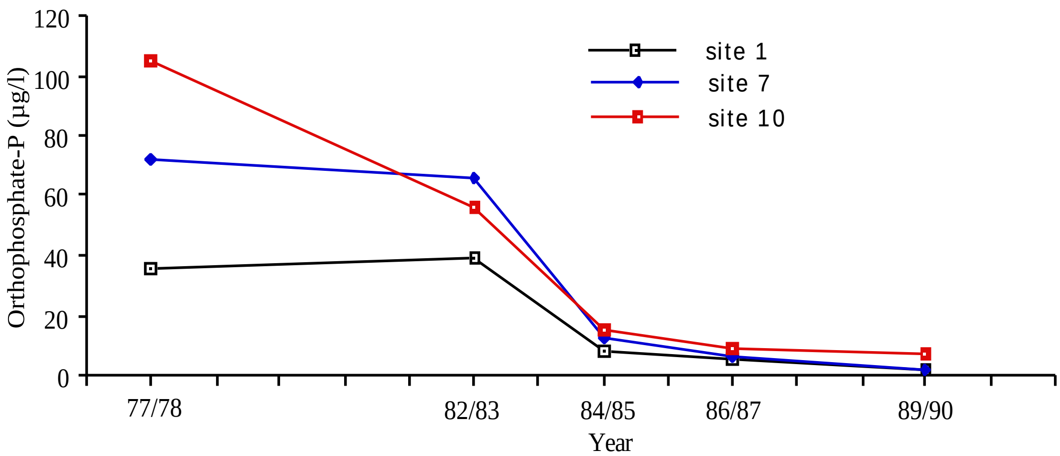

Figure 8b. Mean orthophosphate-P concentrations (µg/L) at sites 1, 7 and 10.

Small-scale temporal and spatial variations in inorganic N:P ratios make the true situation more complex and different parts of the Sound may still be nitrogen limited one week and phosphorus limited the next. Thus inputs of inorganic nitrogen or phosphorus may be controlling phytoplankton levels in Cockburn Sound at different times.

High inorganic N:P ratios occurred at sites 6 and 9. The high inorganic N:P ratio at site 9 can probably be explained by the high inorganic nitrogen to phosphorus ratio of the effluent from CSBP (about 30:1) which is discharged upwind of this site in summer. Although nutrients from CSBP are likely to be contributing to the inorganic N:P ratio at site 6, if this was the only source of nutrients then site 7, further south of site 6 and closer to the CSBP outfall, would also be expected to have a similarly high N:P ratio. This was not the case and suggests that another source of nitrogen exists at the northern end of the Sound. A recent study of groundwater nutrient inputs to the nearshore waters off metropolitan Perth found that the highest concentration of nitrogen enters Perth's coastal waters in the vicinity of site 6 (Appleyard, 1990). Although the source is minor in comparison to the direct discharge of nutrients to Cockburn Sound, it may partially explain the anomalous N:P values in Jervoise Bay. Apart from site 6, the lower N:P ratio of sites further away from the CSBP outfall may be explained by advection and dilution of the effluent and removal of nitrogen from the water column as a result of biological uptake.

Although the inorganic N:P ratio in the water column in Cockburn Sound varied considerably during the study (x=16.1, sd=7.1), the organic N:P ratio was relatively constant (x=17.9, sd=2.2; Table 1). There is no significant correlation between inorganic N:P and the organic N:P ratio in the water column in either Cockburn Sound or for the entire study area. The assumption here is that the organic matter in the water column is mainly phytoplankton and this assertion is supported by the significant positive correlation between mean chlorophyll *a* concentrations for Cockburn Sound and mean light attenuation coefficient (r^2=0.941, *n*=7, $p<0.002$). The organic N:P ratio was higher than the inorganic N:P ratio in the water column for all sites except site 9 (the site most likely to be influenced by the CSBP outfall in summer), sites 4 and 5 in the north western part of Cockburn Sound and at site 6 in Jervoise Bay.

Although nitrogen loading from the CSBP outfall during 1989/90 increased by about 67 % over 1986/87 levels, mean inorganic N:P ratios in Cockburn Sound were similar. In contrast, mean chlorophyll *a* concentration increased by 59 % suggesting that phytoplankton uptake removed most of the additional nitrogen load, further supporting the conclusion that the Sound remains predominantly nitrogen limited.

Although there appears to be a strong association between the nitrogen loading from the KNC/CSBP outfall and the water quality in Cockburn Sound, other nitrogen sources entering the Sound also need to be considered. As discussed above, groundwater nitrogen discharge in the vicinity of Woodman Point may be a significant influence on the water quality of the Jervoise Bay area. Chiffings (1979) listed air emissions, groundwater, coastal exchange, nitrogen fixation and rainfall, in decreasing order of importance, as other sources of nitrogen entering the Sound. Although all these sources were taken into account in this study, in total, they were relatively minor (about 28 % of the total loading) compared to the inputs from industrial effluent and sewage. To what extent the loading from these minor sources have changed significantly over the past 10 years is unknown.

Seasonal variation in phytoplankton abundance in Cockburn Sound has been measured by Hillman (pers. comm.) and indicate that, in some years at least, levels between May and November are higher than levels measured during the previous summer monitoring periods. This finding is consistent with the results of a survey undertaken in May 1990 which found chlorophyll *a* concentrations in excess of 12 μgl^{-1} in Cockburn Sound (Figure 7) compared to the maximum value of 5.84 μgl^{-1} found during the 1989/90 survey. Thus the mean water quality measured over an entire year in Cockburn Sound may be considerably lower than the level determined in the summer monitoring programmes.

5. Conclusions

The mean inorganic nitrogen load entering Cockburn Sound from the KNC/CSBP outfall has increased to 1883 kg/day, a 67 % increase from the 1986/87 study.

Water quality (expressed as phytoplankton and light penetration) has declined significantly since the 1986/87 study with phytoplankton levels increasing by approximately 59 % and light penetration decreasing by approximately 10 %.

There is a significant positive correlation between nitrogen loading from the KNC/CSBP outfall and mean phytoplankton concentration in Cockburn Sound.

If nitrogen inputs into Cockburn Sound continue to increase, then the water quality of Cockburn Sound will rapidly return to the degraded state observed during 1970s, when the Sound was in its poorest recorded condition.

6. Acknowledgements

Water samples were analysed for nutrient content at the nutrient analysis laboratory, School of Biological and Environmental Sciences, Murdoch University. Daily records of nitrogen and phosphorus loads were provided by Kwinana Nitrogen Company and CSBP & Farmers Ltd.

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Appendix 1

Comparison of water quality parameters at eight stations during Cockburn Sound studies of 1982/83, 1984/85, 1986/87 and 1989/90.

Mean nutrient levels, chlorophyll levels and attenuation coefficients during Cockburn Sound Studies 1982-83, 1984-85, 1986-87 and 1989-90 for sites 2-6 inclusive, 8, 9 and 11 (see Table 2 for sites 1, 7 and 10).

Water Quality Parameter	Site 2							
	1982-83		1984-85		1986-87		1989-90	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate phosphorus	16	(6)	5	(2)	4	(3)	1	(1)
Organic phosphorus	22	(8)	20	(7)	30	(44)	30	(8)
Total phosphorus	38	(12)	24	(6)	33	(46)	31	(8)
Ammonia-nitrogen	8	(6)	7	(5)	11	(6)	2	(2)
Nitrate-nitrogen	5	(5)	3	(1)	2	(1)	5	(1)
Organic nitrogen	206	(101)	446	(118)	225	(98)	209	(59)
Total nitrogen	309	(98)	445	(119)	238	(99)	216	(59)
Chlorophyll *a*	0.3	(0.5)	0.5	(0.2)	0.3	(0.2)	0.7	(0.4)
Inorganic N:P atomic ratio	2.1	n/a	5.7	n/a	15.0	n/a	13.1	n/a
Organic N:P atomic ratio	34.8	n/a	55.3	n/a	35.4	n/a	16.2	n/a
Attenuation coefficient	0.06	(0.01)	0.09	(0.02)	0.09	(0.01)	0.1	(0.02)

Water Quality Parameter	Site 3							
	1982-83		1984-85		1986-87		1989-90	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate phosphorus	12	(7)	5	(1)	4	(3)	1	(1)
Organic phosphorus	25	(9)	18	(8)	27	(42)	28	(6)
Total phosphorus	36	(14)	23	(8)	31	(43)	30	(6)
Ammonia-nitrogen	10	(16)	11	(8)	9	(5)	2	(1)
Nitrate-nitrogen	6	(5)	4	(2)	4	(2)	7	(5)
Organic nitrogen	291	(94)	469	(122)	274	(167)	214	(113)
Total nitrogen	308	(94)	484	(122)	282	(167)	222	(111)
Chlorophyll *a*	0.2	(0.3)	0.4	(0.2)	0.3	(0.2)	0.6	(0.3)
Inorganic N:P atomic ratio	3.6	n/a	7.1	n/a	16.8	n/a	16.2	n/a
Organic N:P atomic ratio	31.7	n/a	64.0	n/a	49.4	n/a	17.05	n/a
Attenuation coefficient	0.06	(.01)	0.09	(0.02)	0.09	(0.01)	0.09	(0.03)

Water Quality Parameter	Site 4							
	1982-83		1984-85		1986-87		1989-90	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate phosphorus	23	(7)	7	(3)	5	(3)	2	(1)
Organic phosphorus	28	(10)	21	(10)	32	(43)	29	(7)
Total phosphorus	52	(13)	28	(11)	36	(45)	31	(6)
Ammonia-nitrogen	9	(6)	10	(7)	12	(9)	4	(5)
Nitrate-nitrogen	7	(7)	3	(2)	3	(2)	5	(2)
Organic nitrogen	314	(101)	443	(112)	277	(174)	187	(46)
Total nitrogen	330	(103)	455	(115)	292	(172)	197	(48)
Chlorophyll *a*	0.4	(0.3)	0.6	(0.2)	0.6	(0.2)	0.8	(0.4)
Inorganic N:P atomic ratio	1.6	n/a	4.6	n/a	14.7	n/a	15.4	n/a
Organic N:P atomic ratio	28.6	n/a	54.2	n/a	34.5	n/a	14.8	n/a
Attenuation coefficient	0.06	(0.01)	0.09	(0.02)	0.09	(0.01)	0.10	(0.03)

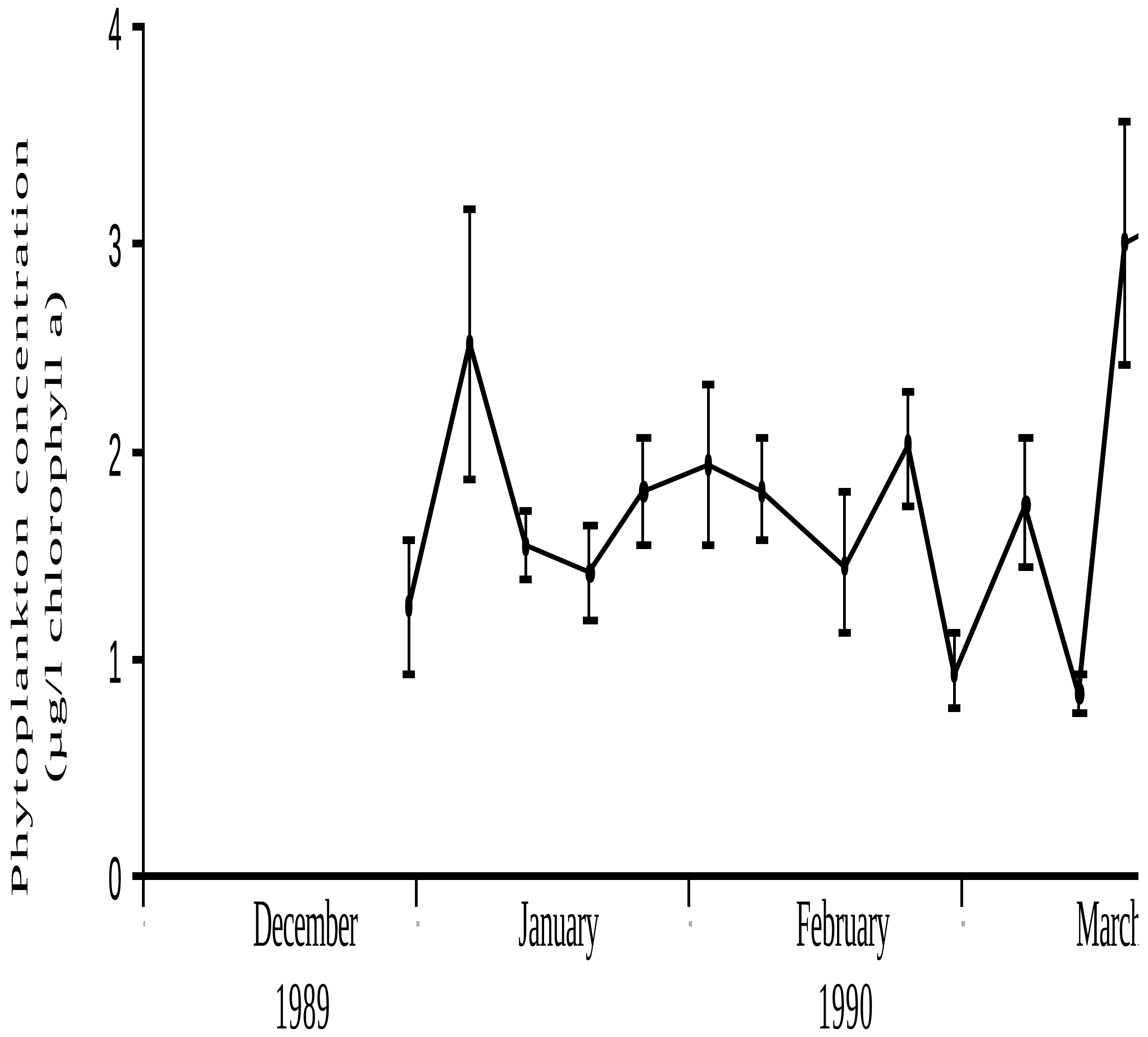
Water Quality Parameter	Site 5							
	1982-83		1984-85		1986-87		1989-90	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate phosphorus	32	(12)	7	(3)	5	(4)	2	(1)
Organic phosphorus	29	(10)	23	(10)	36	(49)	32	(10)
Total phosphorus	61	(17)	29	(9)	39	(50)	33	(10)
Ammonia-nitrogen	15	(10)	11	(6)	12	(7)	5	(4)
Nitrate-nitrogen	5	(4)	3	(1)	3	(2)	5	(2)
Organic nitrogen	360	(142)	485	(89)	289	(114)	198	(66)
Total nitrogen	380	(145)	499	(90)	304	(113)	207	(64)
Chlorophyll *a*	0.6	(0.5)	0.8	(0.3)	0.7	(0.3)	1.1	(0.6)
Inorganic N:P atomic ratio	1.6	n/a	5.7	n/a	12.9	n/a	16.2	n/a
Organic N:P atomic ratio	32.1	n/a	56.7	n/a	36.3	n/a	14.8	n/a
Attenuation coefficient	0.08	(0.02)	0.09	(0.02)	0.10	(0.01)	0.10	(0.04)

Water Quality Parameter	Site 6							
	1982-83		1984-85		1986-87		1989-90	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate phosphorus	52	(18)	9	(5)	5	(4)	1	(0.5)
Organic phosphorus	37	(19)	31	(15)	34	(38)	31	(8)
Total phosphorus	89	(30)	39	(15)	39	(40)	32	(8)
Ammonia-nitrogen	19	(25)	7	(3)	12	(7)	7	(6)
Nitrate-nitrogen	8	(7)	5	(3)	6	(6)	8	(5)
Organic nitrogen	396	(180)	524	(137)	284	(149)	247	(78)
Total nitrogen	424	(173)	536	(139)	302	(149)	262	(77)
Chlorophyll *a*	1.1	(0.9)	1.6	(0.8)	1.4	(0.6)	2.2	(1.1)
Inorganic N:P atomic ratio	1.4	n/a	4.2	n/a	15.2	n/a	24.6	n/a
Organic N:P atomic ratio	30.1	n/a	42.3	n/a	31.0	n/a	19.3	n/a
Attenuation coefficient	0.08	(0.02)	0.13	(0.04)	0.11	(0.01)	0.13	(0.04)

Water Quality Parameter	Site 8							
	1982-83		1984-85		1986-87		1989-90	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate phosphorus	34	(7)	9	(4)	4	(3)	2	(1)
Organic phosphorus	27	(8)	24	(10)	36	(52)	29	(9)
Total phosphorus	60	(10)	34	(11)	40	(52)	32	(10)
Ammonia-nitrogen	9	(5)	15	(13)	13	(12)	8	(11)
Nitrate-nitrogen	5	(6)	4	(4)	2	(1)	6	(6)
Organic nitrogen	286	(126)	499	(153)	331	(173)	220	(95)
Total nitrogen	300	(122)	518	(161)	346	(171)	235	(96)
Chlorophyll *a*	0.4	(0.3)	1.0	(0.4)	0.8	(0.4)	1.3	(0.5)
Inorganic N:P atomic ratio	1.0	n/a	4.6	n/a	12.7	n/a	9.6	n/a
Organic N:P atomic ratio	26.6	n/a	48.0	n/a	36.1	n/a	17.05	n/a
Attenuation coefficient	0.07	(0.01)	0.09	(0.01)	0.10	(0.02)	0.10	(0.03)

Water Quality Parameter	Site 9							
	1982-83		1984-85		1986-87		1989-90	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate phosphorus	75	(18)	17	(11)	9	(8)	4	(4)
Organic phosphorus	32	(7)	26	(10)	41	(51)	31	(10)
Total phosphorus	106	(21)	43	(13)	50	(52)	35	(10)
Ammonia-nitrogen	26	(15)	27	(27)	31	(18)	22	(25)
Nitrate-nitrogen	13	(9)	12	(15)	13	(12)	11	(9)
Organic nitrogen	453	(213)	473	(108)	323	(143)	260	(95)
Total nitrogen	492	(213)	512	(120)	367	(148)	294	(118)
Chlorophyll *a*	1.0	(0.8)	1.5	(0.7)	1.7	(1.1)	2.2	(1.0)
Inorganic N:P atomic ratio	1.2	n/a	6.0	n/a	31.7	n/a	28.5	n/a
Organic N:P atomic ratio	34.8	n/a	45.2	n/a	33.0	n/a	20.8	n/a
Attenuation coefficient	0.10	(0.03)	0.11	(0.02)	0.12	(0.01)	0.13	(0.03)

Water Quality Parameter	Site 11							
	1982-83		1984-85		1986-87		1989-90	
	X	(SD)	X	(SD)	X	(SD)	X	(SD)
Orthophosphate phosphorus	54	(14)	13	(8)	6	(4)	6	(3)
Organic phosphorus	22	(10)	23	(12)	46	(83)	32	(12)
Total phosphorus	76	(13)	36	(13)	52	(86)	37	(11)
Ammonia-nitrogen	13	(11)	10	(6)	15	(10)	9	(9)
Nitrate-nitrogen	6	(4)	5	(3)	4	(3)	10	(8)
Organic nitrogen	261	(86)	487	(103)	327	(101)	253	(88)
Total nitrogen	279	(86)	502	(107)	345	(98)	272	(88)
Chlorophyll *a*	1.1	(0.6)	1.5	(0.8)	1.3	(0.7)	2.0	(1.1)
Inorganic N:P atomic ratio	0.7	n/a	2.9	n/a	12.3	n/a	8.7	n/a
Organic N:P atomic ratio	39.0	n/a	57.6	n/a	33.0	n/a	19.5	n/a
Attenuation coefficient	0.09	(0.02)	0.10	(0.02)	0.10	(0.01)	0.11	(0.02)



Phytoplankton concentration
(µg/l chlorophyll a)
4
3
2
1
0
December
January
February
March
1989
1990