The water quality of the southern metropolitan coastal waters of Perth, Western Australia: The influence of regional and local scale forcings

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

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The water quality of the southern metropolitan coastal waters of Perth, Western Australia: The influence of regional and local scale forcings

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Abstract

This report describes the results of an intensive twelve month water quality monitoring program undertaken in the southern metropolitan coastal waters of Perth between March 1991 and February 1992 and complementary regional surveys undertaken in August 1991 (winter) and March 1992 (summer). Regional and local influences on water quality are discussed and the implications for future management of these waters outlined. Inorganic N:P ratios suggest that nitrogen is the primary nutrient limiting plant growth in the nearshore coastal waters of Perth. Background concentrations of inorganic nutrients and chlorophyll *a* (outside of anthropogenic influences) are low and support the generally accepted view that Perth's coastal waters are oligotrophic by world standards. Regional survey and monitoring results show winter to be characterised by lower water clarity and higher nutrient and chlorophyll *a* concentrations than summer. Satellite imagery and regional nitrate/nitrite-N, salinity and water temperature data highlight the scales of influence and timing of estuarine outflows and Leeuwin Current incursions. Estuarine plumes, particularly from the Peel-Harvey Estuary can affect the quality of Perth's coastal waters over scales of up to 100 kilometres during 3-4 months in winter. Approximately 1300 tonnes of nitrogen enter Perth's coastal waters via estuarine outflows, a load almost double that discharged to the area from the Cape Peron sewage outfall over the same period. Annual cycles of temperature and salinity in Cockburn and Warnbro sounds compared with offshore waters in Sepia Depression highlight the 'trapped' nature of the waters of the two embayments. Total Kjeldahl nitrogen and total phosphorus concentrations of the three water bodies were strongly correlated over the annual period, suggesting a 'common' controlling factor. In summer, water quality, as indicated by chlorophyll *a* and inorganic nitrogen concentrations and light attenuation coefficients, is primarily determined by local forcings such as sewage and industrial wastewater discharges and groundwater inflows. In winter, estuarine nitrogen discharges overshadow most local influences and can elevate nitrogen concentrations over a significant portion of the southern metropolitan coastal waters of Perth. The results of this study highlight the need to acknowledge the temporal variability and spatial scales of influence of a number of anthropogenic and natural forcings. In particular nitrogen inputs from industrial and domestic point and diffuse sources and from the catchments of the Peel-Harvey and Swan-Canning estuaries need to be considered together with the influence of natural factors such as Leeuwin Current incursions.

1. Introduction

The Department of Environmental Protection of Western Australia is undertaking a study of the southern metropolitan coastal waters of Perth to develop an understanding of the cumulative environmental impacts of waste discharges to these waters (Simpson *et al.* 1993). A secondary objective is to provide inventory and quantitative baseline data for future environmental protection and management. The overall goal of the Southern Metropolitan Coastal Waters Study (1991-1994) is to develop a comprehensive environmental management strategy to ensure the long-term 'health' of the coastal marine environment off Perth (Simpson *et al.* 1993).

One measure of the environmental health of an aquatic ecosystem is provided by the quality of its waters. Water quality can be described in terms of chemical, physical and biological indicators, and spatial and temporal patterns in these water quality data can be used to detect sources of contaminants and determine the zones of influence and the degree of seasonality in these influences.

Previous water quality surveys of the coastal waters of Perth have found low and relatively stable nutrient concentrations during the non-winter months as compared to the winter months when nutrient concentrations were characteristically higher and more variable. The high ambient nutrient concentrations in winter have been attributed to industrial and groundwater discharge and release from sediments during winter storms (Chiffings 1979,1987; CSIRO, unpublished data) and estuarine outflows (Johannes *et al.* 1994). Since these studies were conducted, satellite-derived remote sensed imagery has provided a more regional perspective and highlighted the presence of two generic influences on Perth's coastal waters; estuarine outflows and the periodic intrusion of tropical water from the north. The outflows of the Peel-Harvey and Swan-Canning estuaries can be readily identified from images of sea surface temperature (SST) and colour (Figure 1; Simpson *et al.* 1993; Mills *et al.* 1994) and SST images clearly identify the presence of the Leeuwin Current in nearshore waters of the study area, particularly during autumn and winter (Godfrey and Ridgeway, 1985; Mills *et al.* 1994).

At a more local-scale (km's), the major sources of contaminants are industrial and domestic point sources, contaminated groundwater and surface runoff (Muriale and Cary, 1995). Industrial outfalls have discharged wastes into Cockburn Sound and Owen Anchorage since the 1950s (Anon., 1979; Murphy, 1979). A sewage outfall into Cockburn Sound was decommissioned in 1984 and primary-treated domestic wastewater is currently discharged via the Cape Peron outfall into 22 m of water, four kilometres offshore in Sepia Depression (Figure 1). Contaminants in groundwater and surface run-off enter the nearshore waters of the study area particularly in locations adjacent to industrial and urban development (Martinick *et al.* 1993). In contrast, industrial or domestic waste has never been discharged directly into Warnbro Sound. This area, along with the nearby waters around the Shoalwater Islands, was declared a Marine Park in 1992.

The objectives of the present study were to characterise the water quality of the region, determine the main controlling influences on this water quality and identify the temporal and spatial scales of these influences in Perth's southern coastal waters. Companion studies include assessments of: long-term changes in water quality of these waters (Cary *et al.* 1995b), seasonal changes in species composition and abundance of phytoplankton and zooplankton (Cousins, 1991; Helleren and John, 1995) and regional patterns in phytoplankton species composition and abundance (Masini and Cousins, 1992).

This report is a contribution to the Southern Metropolitan Coastal Waters Study (1991-1994).

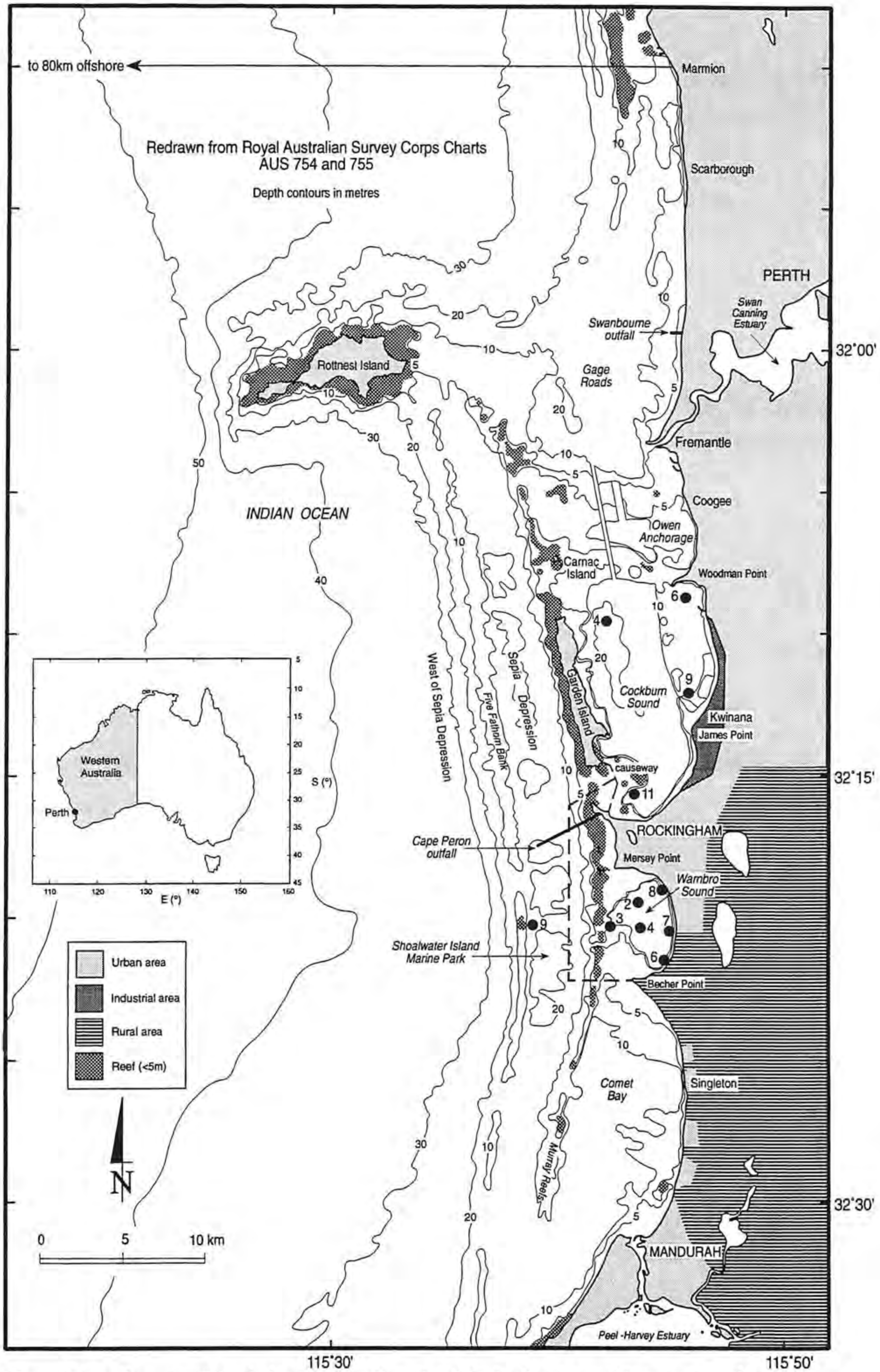

Figure 1. Location map of the study area. Sampling sites of the local water quality survey are shown.

2. Methods

2.1 Study area

The study area covers the region between Marmion and Mandurah and west to the 100 m bathymetric contour (Figure 1), although most sites were located south of Rottnest Island and east of the 30 m contour (Figure 2). The study area contains the sheltered embayments of Cockburn Sound and Warnbro Sound, the semi-enclosed waters of Owen Anchorage, Gage Roads and Comet Bay, Sepia Depression to the west of the Garden Island Ridge System and the offshore waters of the inner-continental shelf.

Cockburn and Warnbro sounds have central basins 15-20 m deep and are bordered by shallow banks and sills providing considerable protection from ocean swells. Circulation and flushing in both embayments is restricted, particularly in Cockburn Sound where water exchange occurs mainly through the northern opening with limited exchange through the southern end due to the presence of a solid-fill causeway with two narrow openings (Steedman and Craig, 1983; Hearn, 1991; D'Adamo, 1992). Owen Anchorage consists of a small basin, up to 12 m deep, receiving substantial protection from ocean swells by Success Bank to the north and by the Garden Island Ridge System to the west. Comet Bay, south of Warnbro Sound, is a broad expanse of shallow water ranging in depth from 5 to 15 m. The Murray Reefs provide only minor protection from swell, and wave energy reaching the coastline of Comet Bay is relatively high. Sepia Depression is a long-shore trough 15-22 m deep and 5 km wide, bordered by Five Fathom Bank to the west which provides some protection from ocean swell. The area west of Sepia Depression includes the inner and mid-continental shelf and is fully exposed to ocean swell.

2.2 Water quality

Local surveys

Water quality surveys were undertaken at approximately 14 day intervals between March 1991 and February 1992. Six sites were sampled in Warnbro Sound, four in Cockburn Sound and one in Sepia Depression, the latter an indication of the quality of the coastal waters immediately west of Warnbro Sound (Figure 1). The location of sites in Cockburn Sound were identical to previous water quality sampling programmes (Cary *et al.* 1991).

The general sampling procedure consisted of collecting 10-litre water samples from 1 m below the water surface, at mid-depth and from 1 m above the seabed using a Niskin bottle (General Oceanics). The three water samples from each site were bulked and a subsample (approximately 6 l) filtered through a 1.2 µm G/FC Millipore filter paper, at a maximum negative pressure of 75 kPa, for inorganic nutrient determinations. The filter paper was blotted dry, wrapped in aluminium foil to shield it from light, stored on ice and subsequently frozen for storage prior to chlorophyll *a* analysis. Water samples for total nutrient determinations were not filtered. All water samples were stored in Whirlpaks, in darkness on ice in the field, and stored frozen in the laboratory. Within approximately 30 days of collection analyses were conducted for chlorophyll *a*, total Kjeldahl-nitrogen (TKN), total-phosphorus (TP), nitrate/nitrite-nitrogen (NO_3+NO_2-N), ammonium-nitrogen (NH_4-N) and orthophosphate-phosphorus (PO_4-P) at the Marine and Freshwater Research Laboratory, Institute for Environmental Science, Murdoch University. Analytical methodologies are outlined briefly below. Chlorophyll *a* concentrations (±0.06 $\mu g\ l^{-1}$) were determined spectrophotometrically (Jeffrey and Humphrey, 1975), PO_4-P (±4 $\mu g\ l^{-1}$) was analysed by the single solution method of Major *et al.* (1972), NO_3+NO_2-N (±2 $\mu g\ l^{-1}$), after copper-cadmium reduction, with a Technicon Autoanalyser 11 (Technicon Industrial Systems, Tarry Town, New York), NH_4-N (±5 $\mu g\ l^{-1}$) by the phenol-prusside method (Dal Pont *et al.* 1974),

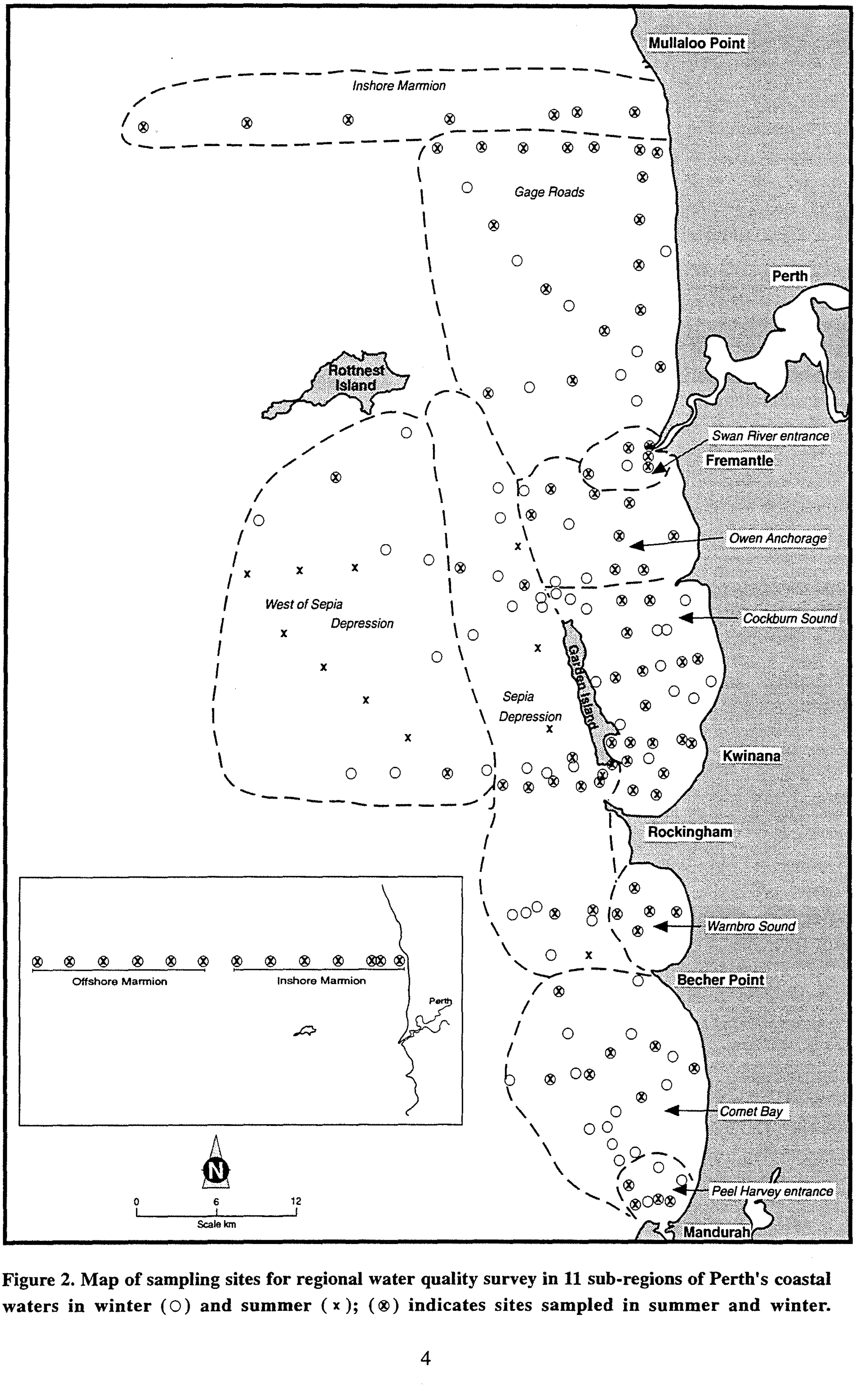

Figure 2. Map of sampling sites for regional water quality survey in 11 sub-regions of Perth's coastal waters in winter (○) and summer (x); (⊗) indicates sites sampled in summer and winter.

TKN (±200 µg l^{-1}) by analysing for NH_4-N after sulphuric acid digestion (Anon., 1985) and TP (±10 µg l^{-1}) by analysing for PO_4-P after perchloric acid digestion (Anon., 1985).

Between March 1991 and July 1991, nutrient sampling was restricted to TKN and TP. From August 1991 to March 1992 additional samples were collected and analysed for the suite of inorganic nutrients (NO_3+NO_2-N, NH_4-N and PO_4-P). On one occasion (15 August, 1991) TKN analyses were performed on filtered water samples. Dissolved organic nitrogen (DON) concentrations were calculated by subtracting the NH_4-N content from the TKN content of the filtered samples.

Seawater temperature (±0.05 °C) and salinity (±0.05 pss) were measured at 1 m intervals through the water column using a salinity-temperature meter (Yeo-Kal Model 602). The instrument was calibrated against water of known salinity and a high-precision mercury thermometer. Before use the probe was soaked in 0.1 M HCl for 10 minutes to clean the platinum electrode thereby minimising instrument 'drift'. High-precision salinity determinations were made in the laboratory, using an inductive salinometer, on water samples that had been collected in the field at the beginning and end of each day. The precise measurements were compared with salinity recorded in the field to check for instrument drift, and if it did occur, field data were normalised assuming a constant rate of drift through the day.

Photosynthetically available radiation (PAR, 400-700 nm waveband), was measured (±5 %) at 1 m intervals through the water column using an Integrating Quantum Sensor (Li-Cor 192S) and an Underwater Quantum Meter (Li-Cor 188B). The light attenuation coefficient was calculated as the slope of the line of best fit through the plot of $\log_{10}$ PAR versus depth and expressed as positive values in units of m^{-1}. Secchi depth was recorded as the depth (m) at which a 0.2 m diameter disc with black and white quadrants disappeared when viewed from above the water surface.

2.3 Summer and winter regional surveys

Regional water quality surveys were conducted at 154 sites during winter and at 101 sites during summer (Figure 2). The surveys were timed to coincide with LANDSAT TM satellite over-passes; the winter surveys were undertaken between 13-22 August 1991 and the summer surveys over two periods between 9-13 March and 23-27 March 1992. At most sites, surface (0 to 1 m below the water surface) and bottom samples (1 to 2 m above the seabed) were taken at least two times during both winter and summer. Surface samples were also taken at twelve sites along a transect west of Marmion to 80 km offshore during both winter and summer. Water samples were collected and analysed for TKN, (NO_3+NO_2)-N, NH_4-N, PO_4-P as described above for the 'local surveys'. Temperature and salinity profiles and Secchi depths were also measured. Unfiltered water samples for chlorophyll *a* determinations were stored in 15 ml PYREX screw-cap glass tubes and maintained on ice and in darkness prior to analysis. Samples were analysed within 12-24 h of collection using an *in-vivo* fluorometric method (Turner Designs Fluorometer Model 10-005) after returning sample temperatures to approximately 20 °C and the addition of dichlorophenylmethylurea (DCMU) to achieve a concentration of 10 µM DCMU (Slovacek and Hannan, 1977). This method was calibrated against the trichromatic method of Jeffrey and Humphrey (1975) for both the winter and summer surveys by concentrating the phytoplankton in a water sample using a 10 µm mesh size plankton net, serially diluting the sample with filtered water to obtain a range of chlorophyll *a* concentrations and subsampling for fluorometric and spectrophotometric analyses as described above. The relationship between the two methods was linear for the site where the calibration samples were taken but independent comparisons suggest that the broadscale influence of the estuarine plumes, and the associated tannins and other fluorescent substances in estuarine waters, led to chlorophyll *a* being overestimated. This effect was most pronounced in winter, particularly in the nearshore regions most affected by estuarine outflows and as such the results, particularly during August 1991, at best only provide a broad indication of chlorophyll *a* concentrations throughout the region.

2.4 'Background' water quality

Background values were determined for selected water quality parameters; total inorganic nitrogen [(NO_3+NO_2-N) + (NH_4-N)], total inorganic phosphorus (PO_4-P) and chlorophyll *a* concentrations, and light attenuation coefficient. Determination of background conditions was restricted to the 'coastal waters' to the south of Perth, defined here as the zone where currents are wind dominated. To the west of this zone waters from the tropics are commonly encountered flowing southward throughout the year in opposition to the mean wind stress. During summer, the boundary between these two water masses lies close to the continental shelf break some 30-50 km offshore and between the 50 and 200 m depth contours. During winter this boundary moves shoreward and is typically some 10-30 km offshore in waters 30-50 m deep (Cresswell, 1991; Mills *et al.* 1994). The coastal waters were further divided into 'offshore' and 'nearshore', the latter defined as waters east of the Garden Island Ridge and including the reefs running parallel to the shore and the embayments of Cockburn and Warnbro sounds. Seasonality was considered by grouping data into 'summer' (December to March) and 'winter' (July to September) periods. The background conditions were characterised using data from areas considered unaffected by anthropogenic or estuarine influences, but still broadly representative of the study area.

There was a paucity of suitable data for winter as estuarine outflows typically extend over much of the coastal waters between July and September. The 'winter' background nutrient concentrations were based on the mean concentration of surface and bottom waters at 32 sites on a single days sampling conducted in mid-September, 1993 (Buckee *et al.* 1994; when estuarine flows were low) and are therefore temporally limited. Winter background TIN was derived from NO_3+NO_2-N concentrations measured by Buckee *et al.* (1994) with the addition of 1 μgN l^{-1} to account for the low NH_4-N concentrations typically found in these waters (Cary and Masini, 1995; Cary *et al.* 1995a). There were insufficient data to determine background conditions for chlorophyll *a* or light attenuation during winter.

Nearshore summer background conditions for nutrients and chlorophyll *a* were derived from the mean concentration in surface, middle and bottom waters at five sites within Warnbro Sound over 16 weeks during the summer of 1993/94 (Cary and D'Adamo, 1995). Background light attenuation was derived from light measurements at 1 m intervals from surface to bottom at the three deepest sites sampled by Cary and D'Adamo (1995) in Warnbro Sound.

Offshore summer background conditions were derived from data collected at two sites 5-7 km west of Sepia Depression (Cary and D'Adamo, 1995) and are temporally compatible with data used to generate 'nearshore' summer background conditions.

3. Results

3.1 Regional water quality

The study area was arbitrarily divided into 11 sub-regions based on bathymetry, degree of exposure, proximity to rivers and an understanding of local circulation patterns. The locations of the sub-regions and the sampling sites within them are shown in Figure 2. Water quality data collected within each sub-region were pooled to typify that sub-region and provide a basis for spatial and seasonal comparisons. Data collected during the winter and summer surveys are summarised in Tables 1 and 2 respectively.

Table 1. Summary of data from the winter regional water quality survey, 13-23 August 1991. N = number of sites; n = number of samples; x = mean; se = standard error.

a) WINTER KJELDAHL-N ($\mu g\ l^{-1}$)

Sub-Region			Surface						Bottom			
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	6	9	64	614	284	75.1	4	7	48	135	98	13.9
Owen Anchorage	9	17	48	158	110	7.6	8	15	96	158	110	9.4
Cockburn Sound	20	32	72	410	176	12.1	19	29	88	268	176	8.9
Gage Roads	17	17	72	205	157	9.1	-	-	-	-	-	-
Inshore Marmion	6	6	143	284	174	22.6	-	-	-	-	-	-
Offshore Marmion	6	6	119	158	134	6.2	-	-	-	-	-	-
Peel Harvey entrance	6	20	174	755	422	44.3	7	13	127	370	258	18.8
Comet Bay	14	25	72	567	118	25.2	9	17	80	300	148	11.3
Sepia Depression	11	21	64	174	93	8.1	8	12	64	143	117	9.0
Warnbro Sound	5	10	58	119	79	5.5	5	5	48	111	89	11.5
West of Sepia Depression	4	4	103	151	117	11.5	-	-	-	-	-	-

b) WINTER NITRATE-N ($\mu g\ l^{-1}$)

Sub-Region			Surface						Bottom			
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	6	11	3	495	163	49.5	4	7	3	11	7	0.8
Owen Anchorage	9	19	1	115	11	5.8	8	19	2	12	6	0.6
Cockburn Sound	31	80	1	28	7	0.8	28	80	2	49	14	1.5
Gage Roads	22	40	2	17	7	0.7	-	-	-	-	-	-
Inshore Marmion	6	6	1	11	5	2	-	-	-	-	-	-
Offshore Marmion	6	6	2	12	7	2	-	-	-	-	-	-
Peel Harvey entrance	7	30	3	200	74	12.6	7	20	3	60	34	3.9
Comet Bay	19	80	2	150	24	3	12	40	2	53	24	2.6
Sepia Depression	23	82	2	83	21	2	17	29	3	39	24	2.8
Warnbro Sound	6	16	1	7	3	0.5	5	23	3	65	18	3.4
West of Sepia Depression	7	7	3	10	6	1.1	4	4	3	8	6	1.2

c) WINTER AMMONIUM-N ($\mu g\ l^{-1}$)

Sub-Region			Surface						Bottom			
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	6	9	1	92	28	12.3	4	7	1	2	1	0
Owen Anchorage	7	16	1	1	1	0.7	7	16	1	1	1	0
Cockburn Sound	20	33	1	15	3	0.7	21	33	1	44	9	2.2
Gage Roads	18	18	1	1	1	0	-	-	-	-	-	-
Inshore Marmion	6	6	1	3	2	0.4	-	-	-	-	-	-
Offshore Marmion	6	6	1	1	1	0	-	-	-	-	-	-
Peel Harvey entrance	7	14	1	21	4	1.4	7	11	1	13	3	1.1
Comet Bay	14	24	1	4	1	0.1	9	16	1	2	1	0.1
Sepia Depression	11	22	1	10	2	0.4	6	9	1	5	2	10.6
Warnbro Sound	5	10	1	1	1	0	5	5	1	1	1	0
West of Sepia Depression	4	4	1	1	1	0	-	-	-	-	-	-

d) WINTER PHOSPHATE-P ($\mu g\ l^{-1}$)

Sub-Region			Surface						Bottom			
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	6	11	2	62	23	7.4	4	10	1	7	3	0.9
Owen Anchorage	9	20	1	8	2	0.5	8	17	1	5	2	0.3
Cockburn Sound	25	30	1	9	2	0.4	25	37	1	25	4	1.0
Gage Roads	20	48	1	21	2	0.6	14	13	1	1	1	0
Inshore Marmion	6	6	1	5	2	1	-	-	-	-	-	-
Offshore Marmion	6	6	1	1	1	1	-	-	-	-	-	-
Peel Harvey entrance	7	15	10	77	47	5.8	7	16	2	32	18	3
Comet Bay	15	48	1	47	11	1.5	13	32	5	17	10	0.7
Sepia Depression	21	44	1	14	5	0.7	17	41	1	9	3	0.5
Warnbro Sound	5	13	1	7	3	0.6	5	10	1	9	4	1.0
West of Sepia Depression	5	7	1	1	1	0	3	3	1	1	1	0

e) WINTER Inorganic N:P ratios

Sub-Region			Surface						Bottom			
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	6	9	1	27	9	2.1	4	7	1	4	3	0.5
Owen Anchorage	7	16	1	14	5	0.8	7	15	1	9	5	0.7
Cockburn Sound	20	28	1	35	10	1.9	19	24	2	21	9	1.3
Gage Roads	17	17	3	12	6	0.6	-	-	-	-	-	-
Inshore Marmion	6	6	1	14	4	3.3	-	-	-	-	-	-
Offshore Marmion	6	6	4	13	8	1.7	-	-	-	-	-	-
Peel Harvey entrance	7	14	2	3	3	0.1	7	11	1	4	2	0.4
Comet Bay	13	23	1	3	2	0.2	9	15	1	5	3	0.4
Sepia Depression	11	21	2	16	5	0.8	6	8	3	6	3	0.4
Warnbro Sound	5	10	1	4	2	0.4	5	5	1	6	3	0.9
West of Sepia Depression	4	4	4	10	6	1.4	-	-	-	-	-	-

Table 1. (cont'd)

f) WINTER — CHLOROPHYLL *a* (μg l^{-1})

Sub-Region	Surface						Bottom					
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	5	11	4.12	9.78	6.38	0.44	4	8	3.49	6.84	5.93	0.74
Owen Anchorage	13	29	0.13	9.36	4.58	0.46	10	20	1.81	7.26	4.44	0.45
Cockburn Sound	34	86	1.00	17.75	5.85	0.34	29	63	0.76	20.27	4.31	0.38
Gage Roads	26	47	0.76	23.63	8.32	0.94	-	-	-	-	-	-
Inshore Marmion	6	15	1.6	11.88	2.81	0.81	-	-	-	-	-	-
Offshore Marmion	6	11	0.97	1.18	0.99	0.04	-	-	-	-	-	-
Peel Harvey entrance	7	21	2.65	43.34	17.71	2.69	7	22	1.39	10.86	6.45	0.7
Comet Bay	17	39	2.23	24.05	7.54	0.76	14	33	0.55	8.73	4.04	0.45
Sepia Depression	22	45	0.97	5.17	2.47	0.17	14	28	0.97	5.17	2.4	0.21
Warnbro Sound	5	13	1.81	4.33	4.07	0.82	4	8	1.39	5.59	3.65	0.52
West of Sepia Depression	8	10	1.6	2.65	1.89	0.17	3	3	1.18	1.39	1.23	0.05

g) WINTER — TEMPERATURE (°C)

Sub-Region	Surface						Bottom					
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	6	6	15.01	16.41	15.88	0.29	6	6	16.42	16.91	16.79	0.08
Owen Anchorage	9	9	15.81	17.02	16.21	0.17	9	9	15.82	17.01	16.3	0.16
Cockburn Sound	27	27	15.55	16.91	15.99	0.07	27	27	15.31	16.74	16.01	0.09
Gage Roads	23	23	15.98	19.33	17.01	0.18	23	23	15.96	18.05	16.82	0.13
Inshore Marmion	6	6	16.06	20.19	18.53	0.6	6	6	16.12	19.86	18.47	0.59
Offshore Marmion	6	6	19.95	20.19	20.11	0.04	6	6	13.95	20.17	17.29	0.96
Peel Harvey entrance	6	6	15.85	17.25	16.63	0.22	6	6	16.15	16.5	16.36	0.06
Comet Bay	9	9	15.87	17.25	16.59	0.13	9	9	15.55	17.25	16.64	0.19
Sepia Depression	11	11	16.5	17.67	16.85	0.11	11	11	16.59	17.4	16.91	0.12
Warnbro Sound	6	6	15.35	15.65	15.45	0.06	6	6	15.2	15.75	15.43	0.16
West of Sepia Depression	7	7	17.6	19.62	18.66	0.2	3	3	17.25	18.91	18.25	0.24

h) WINTER — SALINITY (pss)

Sub-Region	Surface						Bottom					
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	6	6	14.10	34.57	28.69	3.3	6	6	34.74	35.00	34.96	0.06
Owen Anchorage	9	9	34.24	35.05	34.52	0.12	9	9	34.34	35.52	34.69	0.11
Cockburn Sound	24	24	34.10	35.00	34.27	0.05	24	24	34.18	35.05	34.58	0.05
Gage Roads	22	22	33.86	35.39	34.96	0.07	22	22	34.77	35.29	35.06	0.04
Inshore Marmion	6	6	35.25	35.39	35.33	0.02	6	6	35.05	35.38	35.29	0.05
Offshore Marmion	6	6	35.43	35.45	35.44	0	6	6	35.39	35.77	35.57	0.05
Peel Harvey entrance	7	7	22.00	33.26	26.8	1.88	7	7	34.97	35.07	34.98	0.02
Comet Bay	9	9	28.52	34.70	33.03	0.72	9	9	34.62	35.72	35.09	0.11
Sepia Depression	10	10	34.77	35.2	34.99	0.05	10	10	34.92	35.23	35.07	0.04
Warnbro Sound	5	5	34.42	34.53	34.49	0.02	5	5	34.43	34.92	34.64	0.09
West of Sepia Depression	7	7	35.32	35.52	35.41	0.03	7	7	35.22	35.52	35.38	0.05

i) WINTER — SECCHI (m)

Sub-Region	N	n	min	max	x	se
Swan Canning entrance	5	11	1	6	4	0.5
Owen Anchorage	15	22	2	8	7	0.4
Cockburn Sound	36	93	4	10	6	0.1
Gage Roads	27	71	2	14	6	0.1
Inshore Marmion	7	14	4	14	8	1.1
Offshore Marmion	6	11	11	15	13	0.3
Peel Harvey entrance	7	37	1	3	2	0.1
Comet Bay	20	100	1	5	4	0.1
Sepia Depression	27	94	4	11	6	0.2
Warnbro Sound	5	30	4	8	5	0.2
West of Sepia Depression	19	31	5	11	8	0.4

Table 2. Summary of data from the summer regional water quality survey, 9-13 and 23-27 March 1992. N = number of sites; n = number of samples.

a) SUMMER NITRATE-N a (µg l^{-1})

Sub-Region	Surface						Bottom					
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	4	7	3	9	5	0.9	4	4	2	3	3	0.3
Owen Anchorage	7	9	1	14	3	1.4	6	6	1	8	3	1.1
Cockburn Sound	17	27	1	17	3	0.6	16	16	1	8	4	0.6
Gage Roads	17	27	1	73	5	2.8	16	21	1	9	2	0.4
Inshore Marmion	7	8	1	14	4	1.6	1	1	8	8	8	0
Offshore Marmion	6	10	1	16	3	1.5	-	-	-	-	-	-
Peel Harvey outflow	4	7	1	8	3	0.9	4	6	1	11	3	1.3
Comet Bay	4	8	1	6	3	0.6	4	7	-	-	3	1.3
Sepia Depression	9	14	1	29	7	2.3	10	12	1	9	4	0.8
Warnbro Sound	5	7	1	5	3	0.5	5	6	2	14	6	1.8
West of Sepia Depression	9	15	1	4	2	0.3	9	11	1	42	6	3.6

b) SUMMER CHLOROPHYLL *a* (µg l^{-1})

Sub-Region	Surface						Bottom					
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	3	6	0.40	1.7	1.2	0.02	3	3	0.4	0.7	0.5	0.09
Owen Anchorage	9	11	0.3	1.6	0.6	0.12	3	6	0.3	1.3	0.7	0.2
Cockburn Sound	20	29	0.4	3.6	1.4	0.16	15	15	0.9	3.4	1.8	0.19
Gage Roads	17	25	0.1	1.3	0.5	0.06	17	23	0.3	4.4	0.9	0.19
Inshore Marmion	7	11	0.1	1.8	0.5	0.14	2	2	1.0	1.0	1.0	0.08
Offshore Marmion	6	7	0.1	0.3	0.1	0.02	-	-	-	-	-	-
Peel Harvey entrance	4	7	0.3	2.3	1.3	0.37	3	3	0.1	1.6	1.2	0.2
Comet Bay	4	7	0.3	3.8	1.2	0.49	3	3	1.1	6.3	3.0	1.7
Sepia Depression	17	24	0.3	2.0	0.8	0.11	3	5	0.1	0.7	0.5	0.13
Warnbro Sound	4	8	0.3	0.8	0.6	0.08	-	-	0.3	1.6	0.8	0.29
West of Sepia Depression	11	20	0.1	0.6	0.2	0.04	13	14	0.1	1.0	0.5	0.07

c) SUMMER TEMPERATURE (°C)

Sub-Region	Surface						Bottom					
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	4	4	23.41	23.86	23.69	0.10	4	4	22.46	22.8	22.68	0.08
Owen Anchorage	5	5	23.21	23.69	23.61	0.11	5	5	22.07	22.53	22.90	0.24
Cockburn Sound	14	14	23.54	24.77	23.96	0.08	14	14	22.34	22.39	22.76	0.11
Gage Roads	20	20	22.85	23.77	23.39	0.07	20	20	21.14	23.11	22.27	0.14
Inshore Marmion	6	6	20.9	22.74	21.71	0.31	6	6	20.88	22.72	21.71	0.31
Offshore Marmion	5	5	21.45	21.84	21.70	0.07	5	5	11.78	19.46	15.10	1.34
Peel Harvey entrance	3	3	23.45	23.6	23.55	0.05	3	3	23.05	23.55	23.25	0.15
Comet Bay	7	7	23.25	23.8	23.51	0.08	7	7	22.65	23.28	22.99	0.09
Sepia Depression	7	7	23.3	23.75	23.43	0.06	7	7	22.6	22.9	22.66	0.06
Warnbro Sound	5	5	24.05	24.15	24.13	0.03	5	5	22.8	24.17	23.33	0.25
West of Sepia Depression	11	11	21.29	22.56	21.56	0.09	11	11	21.02	21.94	21.44	0.10

d) SUMMER SALINITY (pss)

Sub-Region	Surface						Bottom					
	N	n	min	max	x	se	N	n	min	max	x	se
Swan Canning entrance	4	4	32.46	36.76	35.23	0.95	4	4	33.34	36.27	35.52	0.73
Owen Anchorage	6	6	36.28	36.34	36.30	0.01	6	6	36.29	36.84	36.43	0.10
Cockburn Sound	16	16	36.21	36.52	36.25	0.07	16	16	36.27	36.51	36.39	0.02
Gage Roads	19	19	36.04	36.31	36.19	0.02	19	19	35.94	36.33	36.14	0.03
Inshore Marmion	7	7	35.90	36.27	36.04	0.05	7	7	35.84	36.28	36.02	0.06
Offshore Marmion	5	5	35.92	35.99	35.97	0.01	5	5	35.27	35.89	35.67	0.11
Peel Harvey entrance	3	3	36.59	36.64	36.62	0.02	3	3	36.61	36.63	36.62	0.01
Comet Bay	7	7	36.33	36.57	36.46	0.03	7	7	36.41	36.59	36.51	0.03
Sepia Depression	7	7	36.16	36.41	36.28	0.03	7	7	36.15	36.48	36.35	0.04
Warnbro Sound	5	5	36.46	36.51	36.29	0.20	5	5	36.50	36.51	36.50	0.0
West of Sepia Depression	11	11	35.97	36.16	36.07	0.02	11	11	35.9	36.19	36.08	0.03

e) SUMMER SECCHI (m)

Sub-Region	N	n	min	max	x	se
Swan Canning entrance	4	7	4	6	6	0.2
Owen Anchorage	8	9	6	9	7	0.4
Cockburn Sound	18	31	5	9	7	0.2
Gage Roads	17	30	4	14	8	0.5
Inshore Marmion	7	14	4	15	10	1.3
Offshore Marmion	6	12	7	20	12	0.8
Peel Harvey entrance	4	8	3	7	5	0.5
Comet Bay	8	16	5	9	7	0.4
Sepia Depression	24	32	6	16	10	0.5
Warnbro Sound	5	10	5	11	9	0.9
West of Sepia Depression	11	15	9	14	12	0.5

Winter

Total Kjeldahl nitrogen concentrations were generally low and close to the level of detection except in surface waters near the entrances of the Swan-Canning and Peel-Harvey estuaries (Table 1a). The TKN concentrations in surface waters were much higher than in bottom waters near the estuarine entrances, but in other regions the degree of vertical stratification was generally much weaker and often reversed with highest concentrations in bottom waters.

The concentration of NO_3-N ((NO_3+NO_2)-N will be referred to as NO_3-N in the results and discussion) at individual sites ranged from 1 to 495 $\mu g\ l^{-1}$ and was typically highest in the surface waters at the entrances of the estuaries followed by Owen Anchorage and Comet Bay which are adjacent to these entrances (Table 1b; Figure 3a). Sepia Depression, immediately to the north-west of Comet Bay also had relatively high NO_3-N concentrations. Nitrate-N concentrations in surface waters were low in the nearshore embayments of Cockburn Sound and Warnbro Sound and in the offshore and northern parts of the study area. In bottom waters, NO_3-N concentrations ranged from 2 to 65 $\mu g\ l^{-1}$ and patterns were generally similar to surface waters (Figure 3b). Exceptions were the relatively high concentrations in Cockburn Sound and Warnbro Sound and the low concentrations in bottom waters at the entrance to the Swan-Canning Estuary.

Ammonium-N concentrations were considerably lower than NO_3-N concentrations, ranging from 1 to 92 $\mu g\ l^{-1}$ (Table 1c). Mean concentrations in all sub-regions were less than 5 $\mu g\ l^{-1}$ apart from surface waters near the entrance to the Swan-Canning Estuary and the bottom waters of Cockburn Sound.

Phosphate-P concentrations in both surface and bottom waters showed the same overall pattern as NO_3-N, ranging from 1 to 77 $\mu g\ l^{-1}$ (Table 1d) and were highest in the vicinity of the estuarine outflows and in Comet Bay and lowest in the embayments and the northern and offshore areas.

Mean inorganic N:P ratios ranged from 2 to 10 on a weight basis and were highest in Cockburn Sound and the Swan-Canning entrance and lowest in Warnbro Sound and Comet Bay (Table 1e). Mean inorganic N:P ratios in bottom waters were 5 or less in all areas apart from Cockburn Sound which was 9.

Chlorophyll *a* concentrations ranged from 0.13 to 43.34 $\mu g\ l^{-1}$ and were highest in the vicinity of the Peel-Harvey and Swan-Canning estuary entrances and in the adjacent Gage Roads and Comet Bay (Table 1f). Lowest concentrations occurred in the offshore and northern waters. In general, there was little difference in the chlorophyll *a* concentration of surface and bottom waters.

Surface water temperatures ranged from about 15 °C in the southern nearshore waters to 20 °C in the northern and offshore waters. Bottom water temperatures were generally lower than at the surface except at, and adjacent to, the estuary entrances (Table 1g). Surface water salinities were lowest in the vicinity of the estuaries and highest in the northern and offshore waters. The salinity of bottom waters was higher than surface waters and the mean salinity of all sub-regions was greater than 34 pss (Table 1h). Secchi depths ranged from 1 m to 15 m with lowest values occurring in the vicinity of the estuary entrances and adjacent waters and highest values in northern and offshore waters (Table 1i).

Summer

The water quality parameters measured during the summer regional survey were confined to NO_3-N, chlorophyll *a*, temperature, salinity and Secchi depth (Table 2). Mean NO_3-N concentrations for surface and bottom waters of the sub-regions were generally low and ranged from 2 to 8 $\mu g\ l^{-1}$ (Table 2a). Three locations in the study area showed elevated concentrations, with the highest (73 $\mu g\ l^{-1}$) recorded in the surface water of a site near the Swanbourne sewage outfall, (Figure 3d). High NO_3-N concentrations were also recorded at a site near the Cape Peron

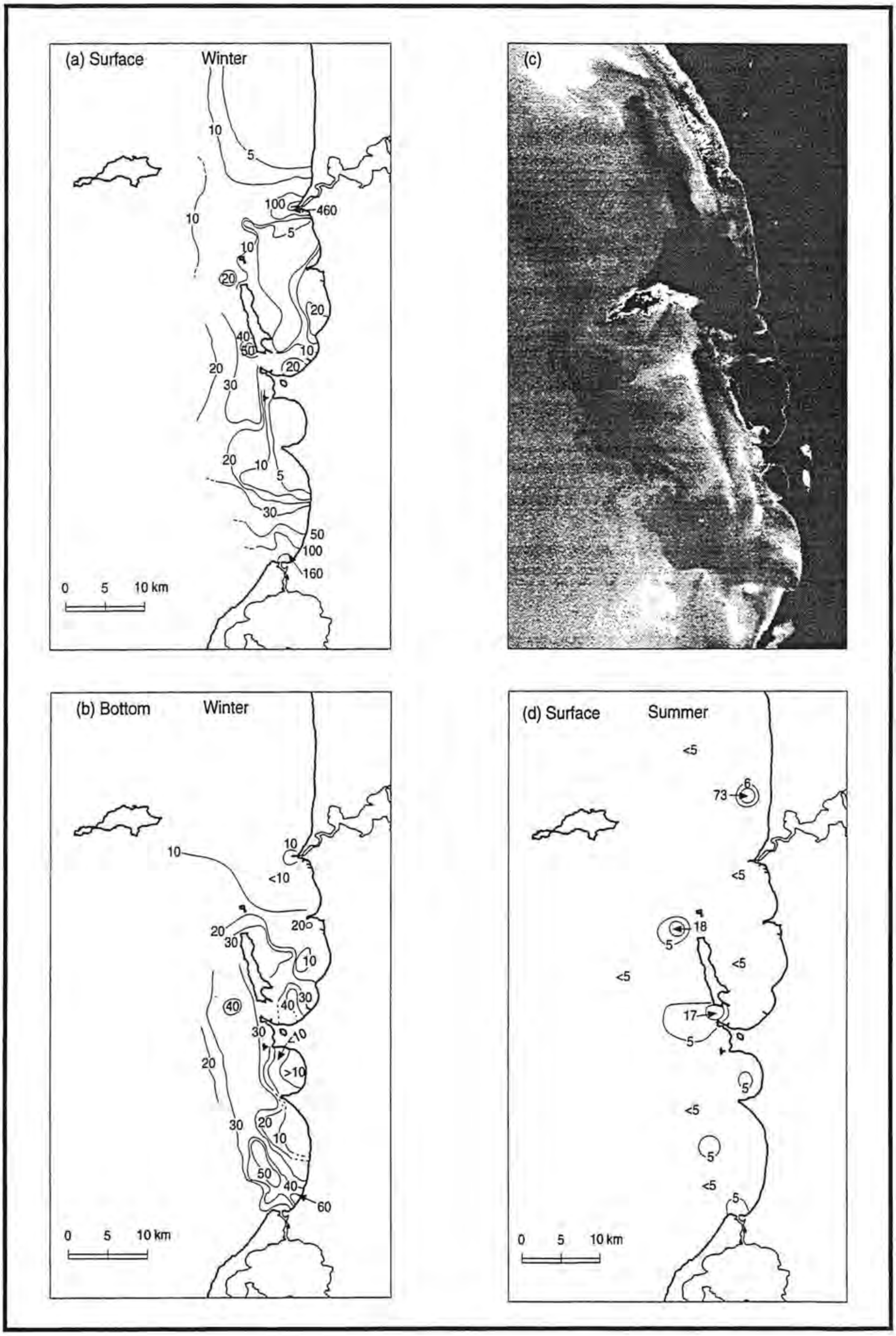

Figure 3. Nitrate-N concentrations (μgL^{-1}) over the study region on 13 and 14 August 1991 in (a) surface and (b) bottom waters; (c) Landsat Thematic Mapper image of the waters off Perth recorded from an altitude of 720 km 0930 hrs, 14 August 1991 showing outflows of the Swan-Canning and Peel-Harvey estuaries; (d) Nitrate-N concentrations (μgL^{-1}) in surface waters on 9 March 1992 (summer).

sewage outfall in Sepia Depression, and at another site near the northern opening into Cockburn Sound (Figure 3d). Nitrate-N concentrations in bottom waters were generally similar to surface waters except at the locations where high surface concentrations were recorded. An anomalously high reading of 42 $\mu g\ l^{-1}$ was recorded at a site west of Sepia Depression. Chlorophyll *a* concentrations ranged from 0.1 to 6.3 $\mu g\ l^{-1}$, and were highest in the vicinity of Cockburn Sound, the Peel-Harvey and Swan-Canning estuary entrances and Comet Bay (Table 2b). Highest concentrations in bottom waters occurred in Cockburn Sound, Comet Bay and Gage Roads. The lowest chlorophyll *a* concentrations were found in offshore waters.

Surface water temperatures ranged from about 20.9 to 24.8 °C and were lowest in the northern and offshore waters and highest in Warnbro and Cockburn sounds. Vertical and onshore-offshore gradients in water temperatures were recorded with higher temperatures on the surface than the bottom and warmer waters inshore than offshore (Table 2c). Surface salinities ranged from about 32.5 to 36.8 pss with lowest salinities in the vicinity of the Swan-Canning Estuary entrance and in the offshore waters. Highest salinities occurred in the embayments and nearshore areas. Bottom salinities were higher and had similar spatial patterns to the surface waters (Table 2d). Secchi depths ranged from 1 m to 20 m with lowest values occurring in the nearshore southern waters and highest values in northern and offshore waters (Table 2e).

Continental Shelf Transect (Inshore and Offshore Marmion)

In winter, lowest NO_3-N concentrations occurred within 15 km of the coastline and 35-45 km offshore. Highest values occurred at sites 15 to 35 km and 65 to 85 km offshore (Figure 4a,b). Nitrate-N concentrations ranged from 1 $\mu g\ l^{-1}$ at site V2 to 11 and 12 $\mu g\ l^{-1}$ at sites V5 and V11 respectively (Figure 4b). Temperature and salinity in winter was lowest at inshore sites, increased sharply at about 15 km offshore, decreased slightly around 35 km offshore, increased again and then remained largely constant over the inner continental shelf sites. Temperature and salinity ranged from around 17.5 °C and 35.25 pss in the nearshore waters to 20 °C and 35.45 pss in offshore waters (Figure 4c,d). In summer NO_3-N, salinity and temperature showed opposite trends to winter with highest levels in nearshore waters and lowest in offshore waters (Figure 4e,f,g).

3.2 Local water quality

Results of the intensive local-scale water quality surveys are shown in Figure 5. For comparative purposes the data were grouped into periods of '*estuarine-flow*' (July to September) and '*non estuarine-flow*', in recognition of the strong seasonal influence of the outflows from the Swan-Canning and Peel-Harvey estuaries (Table 3).

Physical data

Mean water temperatures over the 12 months ranged from about 15.8 to 23.8 °C in Cockburn Sound, 15.3 to 24.0 °C in Warnbro Sound and 16.2 to 22.7 °C at the site in Sepia Depression (Figure 5g). Water temperatures of all three waterbodies followed a similar seasonal pattern and were lowest between July and September and highest between December and February. Temperatures in Cockburn Sound, Warnbro Sound and Sepia Depression were significantly correlated during the 12 month study and during the period of non estuarine-flow (Table 3). In all three water bodies, water temperatures were significantly lower during the period of estuarine-flow than during the non estuarine-flow period (Table 4).

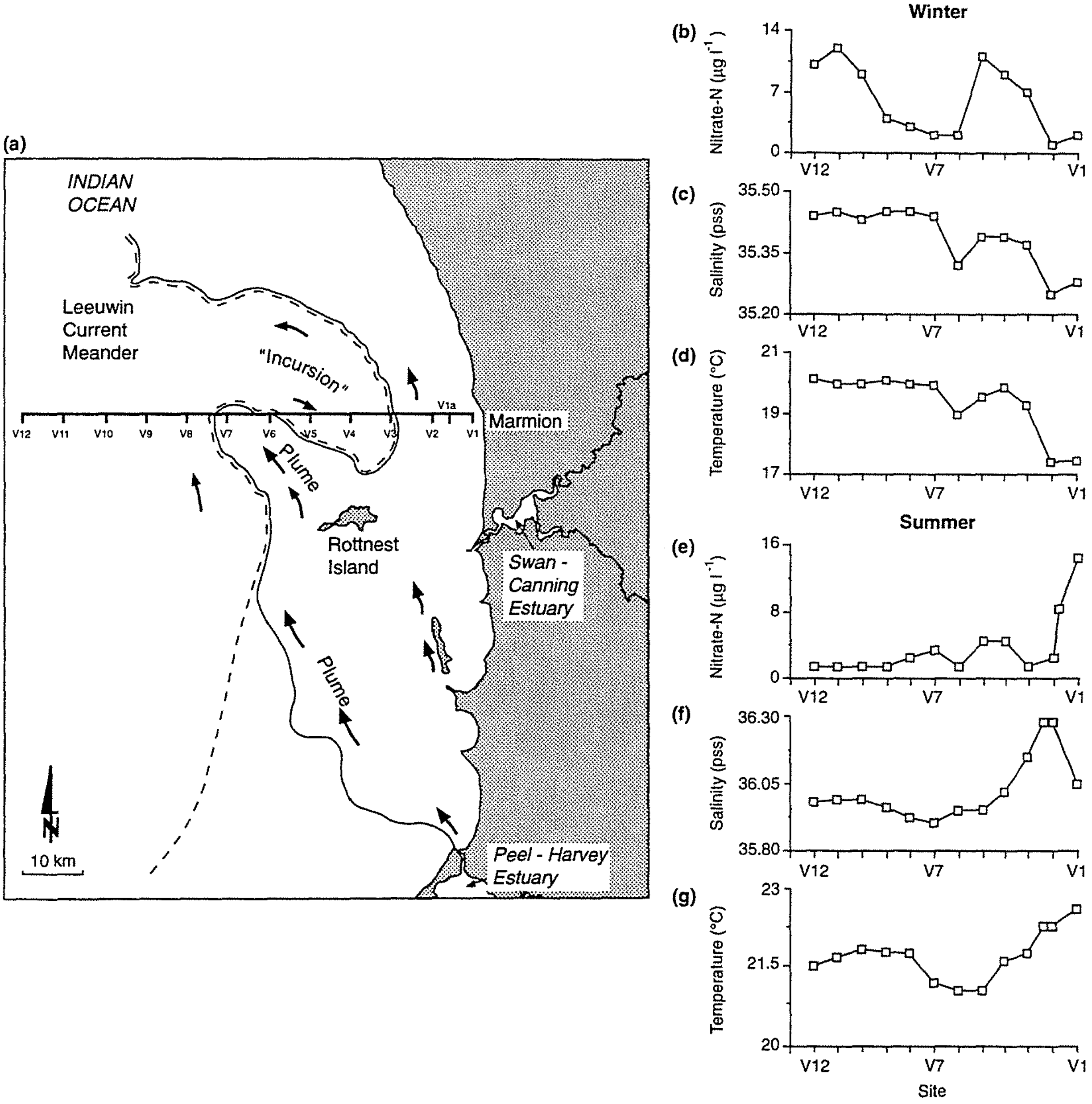

Figure 4. Location map showing (a) the offshore transect in relation to the Leeuwin Current and Peel-Harvey outflow plume as inferred from a Landsat TM image on 14 August 1991 and water quality parameters measured along the transect on 14 August 1991 (b-d) and 9 March (e) and 11 March 1992 (f,g).

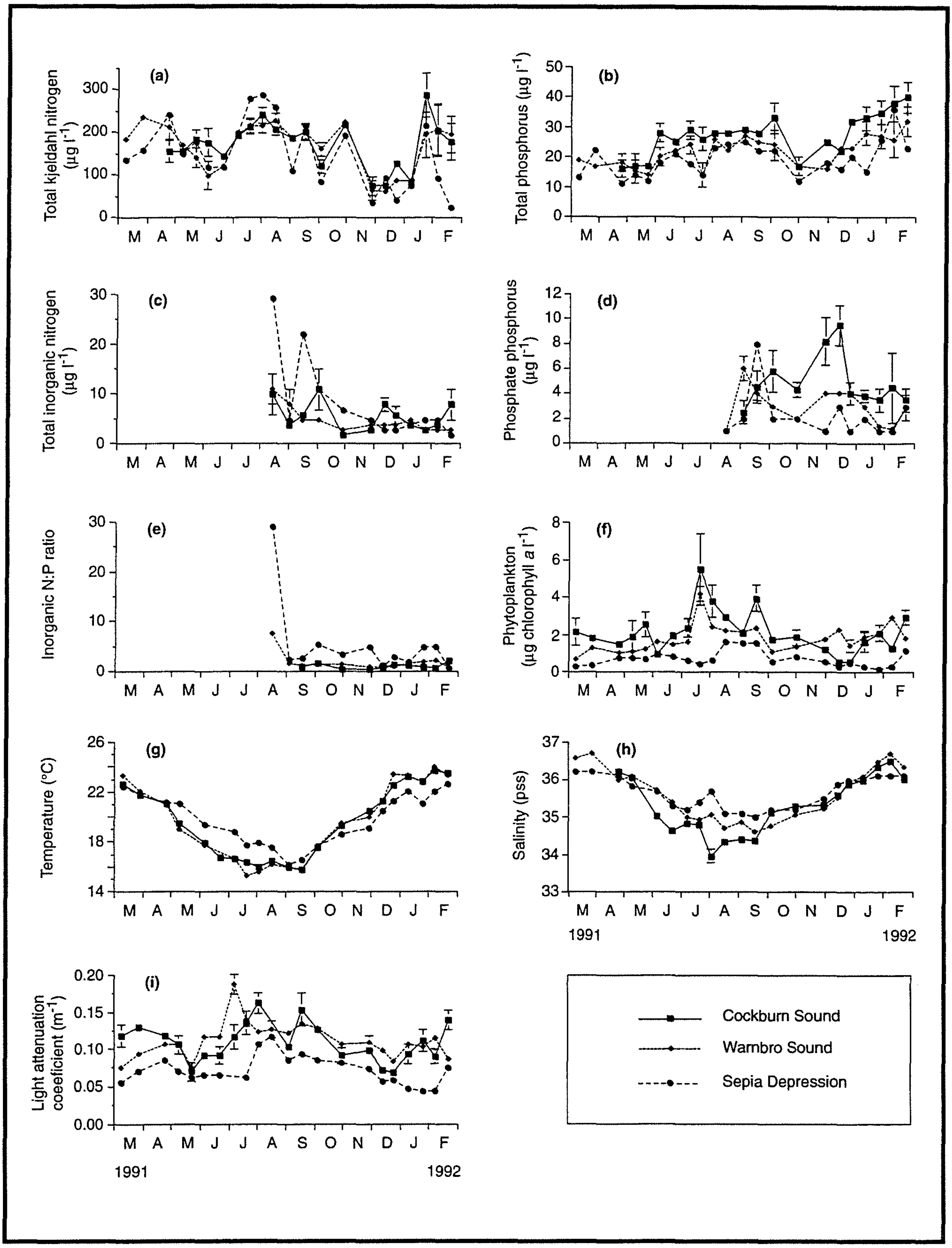

Figure 5. Annual cycles of selected water quality parameters for Cockburn Sound, Warnbro Sound and Sepia Depression. Vertical bars indicate 1 standard error of the mean.

Table 3. Significance of correlations between Cockburn Sound (CS); Warnbro Sound (WS) and Sepia Depression (SD) over the annual, estuarine-flow (July - September) and non estuarine-flow (October - June) periods for a range of water quality parameters. CS (4 sites); WS (6 sites); SD (1 site). n = number of data points used. NS = no significant correlation.

	Annual period			Estuarine-flow period			Non estuarine-flow period		
	March 91 - Feb 92			July 91 - Sept 91			March-June 91 and Oct 91 - Feb 92		
	CS/WS (n)	WS/SD (n)	CS/SD (n)	CS/WS (n)	WS/SD (n)	CS/SD (n)	CS/WS (n)	WS/SD (n)	CS/SD (n)
Total Kjeldahl nitrogen (µg l^{-1})	$p \leq 0.0001$ (20)	$p<0.0008$ (21)	$p<0.0002$ (19)	$p<0.03$ (6)	$p<0.001$ (6)	$p<0.03$ (5)	$p<0.02$ (14)	$p<0.04$ (15)	$p<0.04$ (14)
Total phosphorus (µg l^{-1})	$p \leq 0.0001$ (20)	$p<0.003$ (20)	$P<0.0001$ (20)	$p<0.03$ (6)	NS	$p<0.007$ (5)	$p<0.0001$ (14)	$p<0.02$ (15)	$p<0.0005$ (14)
Total inorganic nitrogen (µg l^{-1})	NS	NS	NS	NS	NS	NS	NS	NS	$p<0.002$ (9)
Orthophosphate phosphorus (µg l^{-1})	NS	NS	NS	-	NS	-	NS	NS	NS
Chlorophyll *a* (µg l^{-1})	$p<0.0006$ (21)	NS	NS	$p<0.03$ (6)	NS	NS	NS	NS	NS
Temperature (°C)	$p<0.0002$ (20)	$p<0.0002$ (20)	$p<0.0002$ (20)	NS	NS	NS	$p<0.0001$ (14)	$p<0.0003$ (14)	$p<0.0002$ (14)
Salinity (pss)	$p<0.0002$ (19)	$p<0.0002$ (21)	$p<0.0002$ (19)	NS	NS	NS	$p<0.0005$ (13)	$p<0.0002$ (15)	$p<0.0003$ (13)
Light attenuation coefficient (m^{-1})	NS	$p<0.04$ (22)	$p<0.006$ (22)	NS	NS	NS	NS	NS	NS

Table 4. Water quality parameters in Cockburn Sound (4 sites), Warnbro Sound (6 sites) and Sepia Depression (1 site) during the estuarine-flow (July-September) and non estuarine-flow (November-May) periods. Results of statistical comparisons between river and non river-flow periods are also shown: * = .01< p≤ .05; ** = .001< p≤ .01; *** = p≤ .001; ns = no significant difference. se = standard error. n = number of data points.

	COCKBURN SOUND				WARNBRO SOUND				SEPIA DEPRESSION			
	Estuarine-flow		Non estuarine- flow		Estuarine-flow		Non estuarine flow		Estuarine-flow		Non estuarine- flow	
	mean (se)	n	mean (se)	n	mean (se)	n	mean (se)	n	mean (se)	n	mean (se)	n
Total Kjeldahl nitrogen (µg l^{-1})	206 (8)	6	152 (21)	12	207 (6)	6	141 (20)	12	225 (27)**	6	120 (21)	12
Total phosphorus (µg l^{-1})	28 (1)	6	28 (3)	12	23 (2)	6	22 (2)	12	21 (2)	6	19 (2)	12
Total inorganic nitrogen (µg l^{-1})	7 (2)	3	5 (1)	7	8 (1.7)**	3	4 (0.28)	7	19 (7)**	3	4 (0.5)	7
Orthophosphate phosphorus (µg l^{-1})	-	-	6 (1)	7	4 (1)	3	3 (1)	7	4 (2)	3	2 (0.4)	7
Inorganic N:P ratio (by weight)	-	-	1:1	7	3:1	3	1:1	7	11:1	3	3:1	7
Chlorophyll *a* (µg l^{-1})	3.5 (0.61)**	6	1.7 (0.21)	12	2.5 (0.36)*	6	1.6 (0.18)	12	1.1 (0.23)*	6	0.5 (0.08)	12
Temperature (°C)	16.2 (0.14)	6	22.1 (0.41)	11	15.9 (0.20)	6	22.1 (0.49)	11	17.5 (0.39)	6	21.4 (0.30)	11
Salinity (pss)	34.44 (0.13)	6	35.90 (0.14)	10	34.86 (0.07)	6	36.16 (0.14)	11	35.25 (0.11)	6	36.00 (0.06)	11
Attenuation coefficient (m^{-1})	0.14 (0.01)**	6	0.10 (0.01)	12	0.14(0.01)***	6	0.10 (0.003)	12	0.10 (0.007)*	6	0.07 (0.006)	12

Mean salinities over the 12 month period ranged from 34.0 to 36.5 pss in Cockburn Sound, 34.6 to 36.7 pss in Warnbro Sound and 35.1 to 36.1 pss in Sepia Depression (Figure 5h). The salinity of all waterbodies followed a similar seasonal pattern with lower and more variable salinities in August/September and higher salinities between January and March. Cockburn Sound had consistently lower mean salinities in winter than Warnbro Sound (Figure 5h). Salinities in Cockburn Sound, Warnbro Sound and Sepia Depression were significantly correlated during the 12 month study and during the period of non estuarine-flow (Table 3). Seawater salinities were significantly lower during the period of estuarine-flow than during the non estuarine-flow period in all three water bodies (Table 4).

Mean light attenuation coefficients over the 12 month period ranged from 0.07 to 0.16 m^{-1} in Cockburn Sound, 0.08 to 0.19 m^{-1} in Warnbro Sound and 0.04 to 0.12 m^{-1} in Sepia Depression (Figure 5i). In general, mean attenuation coefficients of the three waterbodies followed a similar seasonal pattern with higher and more variable light attenuation coefficients between July and September and lower values throughout the rest of the year. Light attenuation coefficients of

September and lower values throughout the rest of the year. Light attenuation coefficients of Cockburn Sound and Sepia Depression and of Warnbro Sound and Sepia Depression were significantly correlated during the study period. There was no significant correlation between the three regions during the periods of estuarine-flow and non estuarine-flow (Table 3) but light attenuation coefficients were significantly higher during the period of estuarine-flow than during the non estuarine-flow period in all three water bodies (Table 4).

Nutrients

Mean TKN concentrations over the 12 month period ranged from 74 to 287 µg l^{-1} in Cockburn Sound, 61 to 236 µg l^{-1} in Warnbro Sound and 40 to 287 µg l^{-1} at the site in Sepia Depression (Figure 5a). Total Kjeldahl-N concentrations in Cockburn Sound, Warnbro Sound and Sepia Depression were significantly correlated during the 12 month study period and during the periods of estuarine-flow and non estuarine-flow, with lowest levels in November/December and highest levels in July/August and January (Table 3). Mean TKN concentrations were significantly higher during the estuarine-flow period than during the non estuarine-flow period at the site in Sepia Depression (Table 4). TKN concentrations of filtered water samples collected on 15 August 1991 ranged from 85 to 89 % of the TKN of unfiltered water samples. Dissolved organic nitrogen (DON) comprised 79 to 83 % of the total nitrogen content in the three water bodies.

Mean TP concentrations over the 12 month period ranged from 16 to 40 µg l^{-1} in Cockburn Sound, 14 to 32 µg l^{-1} in Warnbro Sound and 11 to 36 µg l^{-1} at the site in Sepia Depression (Figure 5b). In general mean TP concentrations in all three water bodies followed a similar seasonal pattern with lowest levels between November and February and highest levels between June and September and January/February. Total-P concentrations in Cockburn Sound, Warnbro Sound and Sepia Depression were significantly correlated during the 12 month study period, the period of non estuarine-flow and during the period of estuarine-flow (except between Warnbro Sound and Sepia Depression)(Table 3). There were no significant differences in TP concentrations between the estuarine-flow and non estuarine-flow periods in either of the three water bodies (Table 4). Approximately 93 % of the total phosphorus content of the waters in Warnbro Sound and Sepia Depression on 15 August 1991 was in a dissolved form. Dissolved organic phosphorus (DOP) comprised approximately 88 % of the total phosphorus content in the these water bodies.

Mean TIN concentrations over the 12 month period ranged from 4 to 10 µg l^{-1} in both Cockburn and Warnbro sounds and from 2 to 29 µg l^{-1} at the site in Sepia Depression (Figure 5c). The TIN in the three water bodies was mainly comprised of NO_3+NO_2-N as the NH_4-N concentrations were typically about 1 µg l^{-1}. In general, mean TIN concentrations followed a similar seasonal pattern with lowest levels occurring between November and February and highest levels in August/September. Total inorganic nitrogen concentrations in the three areas were not significantly correlated during the 12 month study period or during the period of estuarine-flow, however TIN concentrations in Cockburn Sound and Sepia Depression were significantly correlated during the period of non estuarine-flow (Table 3). Total inorganic nitrogen concentrations were higher during the period of estuarine-flow than during the non estuarine-flow period in Warnbro Sound and at the site in Sepia Depression (Table 4).

Mean PO_4-P concentrations followed no apparent seasonal pattern and ranged from 4 to 10 µg l^{-1} in Cockburn Sound, 1 to 6 µg l^{-1} in Warnbro Sound and 1 to 8 µg l^{-1} at the site in Sepia Depression (Figure 5d). Orthophosphate-P concentrations in Cockburn Sound, Warnbro Sound and Sepia Depression were not significantly correlated during the 12 month study period or during the periods of estuarine-flow and non estuarine-flow (Table 3). There were no significant seasonal differences in the mean PO_4-P concentrations between any of the three water bodies (Table 4).

Mean inorganic N:P ratios (by mass) were less than 2 in Cockburn Sound, ranged from 1 to 8 in Warnbro Sound and 1 to 29 in Sepia Depression between August and February (Figure 5e). The highest mean inorganic N:P ratios in Warnbro Sound and Sepia Depression occurred in August (winter data missing for Cockburn Sound), but no statistically significant seasonal differences were detected (Table 4).

Chlorophyll *a*

Mean chlorophyll *a* concentrations over the 12 month period ranged from 0.6 to 5.5 µg l^{-1} in Cockburn Sound, 0.8 to 4.2 µg l^{-1} in Warnbro Sound, and 0.2 to 1.7 µg l^{-1} at the site in Sepia Depression (Figure 5f). Chlorophyll *a* concentrations in all three water bodies were generally highest and most variable between July and September. In Cockburn Sound during summer, the lowest mean chlorophyll *a* values were consistently found at the north-westerly most site (x = 0.85 µg l^{-1}, se = 0.27; site 4) and high values at the three remaining sites located in the eastern and southern parts (x = 1.8 µg l^{-1}, se = 0.18; n=3). In Warnbro Sound, lowest chlorophyll *a* values were also found at the north-westerly most sites (x = 1.72, se = 0.09; sites 2 and 3) and high values at the four remaining sites located in the eastern and southern parts of Warnbro Sound (x = 2.2 µg l^{-1}, se = 0.04; n=4). Chlorophyll *a* concentrations in Cockburn Sound and Warnbro Sound were significantly correlated over the 12 month study period and during the period of estuarine-flow. There were no correlations between the chlorophyll *a* concentrations of the embayments and Sepia Depression during the 12 month study period or during the periods of estuarine-flow and non estuarine-flow (Table 3). Chlorophyll *a* concentrations were significantly higher and approximately double in estuarine-flow periods compared to non estuarine-flow periods in all three water bodies (Table 4).

3.3 Background water quality

Background values (median and 90th percentile) for selected water quality parameters in nearshore and offshore coastal waters during 'summer' and 'winter' are presented in Table 5. The median total inorganic nitrogen (TIN) concentration of the coastal waters was less than 6 µg l^{-1} and 90 % of all samples were less than 9 µg l^{-1}, with no differences between nearshore and offshore during summer or winter. Median total inorganic phosphorus (TIP) concentration in nearshore coastal waters was marginally higher (by approximately 1 µg l^{-1}) during summer than during winter or in offshore waters during either season. The least variation in TIP was found in offshore waters during summer, but this is based on only nine data points. The summer background chlorophyll *a* concentration in nearshore waters was over double that found in offshore waters. A similar pattern was evident in water clarity during summer; the median value for the light attenuation coefficient of nearshore waters was almost double that of offshore waters (Table 5).

Table 5. Median and 90th percentile (in parentheses) background levels for selected water quality parameters for the 'nearshore' and 'offshore' coastal waters in summer and winter. (n) = number of data points.

Water quality parameter	Nearshore coastal waters				Offshore coastal waters			
	Summer	(n)	Winter	(n)	Summer	(n)	Winter	(n)
Total inorganic nitrogen (µg l^{-1})	5.3 (8.0)	(80)	3.8 (7.5)	(24)	5.2 (8.3)	(32)	4.2 (7.3)	(32)
Total inorganic phosphorus (µg l^{-1})	4.0 (5.0)	(22)	3.0 (5.3)	(25)	3.0 (3.4)	(9)	3.2 (5.1)	(32)
Chlorophyll *a* (µg l^{-1})	0.43 (0.76)	(80)	-		0.18 (0.39)	(34)	-	
Light attenuation coefficient (m^{-1})	0.071 (0.087)	(46)	-		0.04 (0.045)	(30)	-	

4. Discussion

Inorganic N:P ratios suggest that nitrogen is the primary nutrient limiting plant growth in the nearshore coastal waters off Perth and this is consistent with the findings of other studies conducted in these waters (Anon., 1979; Chiffings and McComb, 1983; Chiffings 1987; Hillman and Bastyan, 1988; Cary *et al.* 1991; Bastyan *et al.* 1994; Cary *et al.* 1995b) and in coastal waters of many other parts of the world (Paasche, 1988). Background levels of inorganic nitrogen (outside of anthropogenic influences) are low, but elevated total inorganic nitrogen concentrations were recorded over large areas in the winter regional survey and at localised points during the equivalent survey conducted during summer.

The results of the present study can provide an insight into the factors that influence the water quality of the region, particularly inorganic nitrogen and chlorophyll *a* concentrations and light attenuation, and the relative spatial scales and seasonal timing of these influences.

4.1 Regional survey

The results of the regional water quality surveys highlight the broadscale influence of estuarine outflows and the Leeuwin Current on the water quality of Perth's coastal waters during winter.

The high (>100 $\mu g\ l^{-1}$) NO_3-N concentrations associated with low salinity water near the estuarine entrances coupled with the gradient in nutrient concentration and salinity between the estuarine entrances and offshore waters suggest that estuarine outflows strongly influence the inorganic nitrogen content of the coastal waters off Perth during winter. A satellite image of the region taken during the winter survey (Figure 3c), which shows large areas of stained water apparently emanating from the Peel-Harvey and Swan River estuaries, further supports this suggestion and also highlights the potential extent of these influences and the degree of connectivity between water bodies within the region. For example, the staining evident to the northwest of Rottnest Island is linked to the Peel-Harvey Estuary mouth indicating that the scale of effect of the estuarine plumes on the water quality of Perth's coastal waters can exceed 100 kilometres (Figure 3a,b,c; Table 1 and 2).

Approximately 1300 tonnes of nitrogen enters Perth's coastal waters via estuarine discharges during a 3-4 month period in winter and this load is almost double that discharged from the Cape Peron sewage outfall over the same period. Most of this nitrogen originates from rural catchments that have been extensively cleared for agriculture and is therefore 'anthropogenic' in nature rather than 'natural' (Deeley, 1995). Deeley (1995) estimated that these estuarine-derived nitrogen loadings have increased 10 fold since the 1960s. Currently loads from these sources comprise approximately 50 % of the total annual nitrogen loading to the southern metropolitan coastal waters of Perth (Martinick *et al.* 1993; Muriale and Cary, 1995). Non-tidal outflows from the Swan-Canning and Peel-Harvey estuaries commence at approximately the same time (Donahue *et al.* 1994; Deeley *et al.* 1995), indicating that the relative timing of their effects on the coastal waters are similar. The entrances to these estuaries, however, are approximately 45 km apart and it is therefore likely that their relative influences will differ at any location within their combined zone of influence. Numerical simulations of water circulation patterns support this assertion and show that, under a southerly wind, buoyant water discharges from the Peel-Harvey Estuary move northward through Comet Bay and into Sepia Depression and Warnbro Sound (Figure 6a; Mills and D'Adamo, 1995). Under a northerly wind regime, numerical simulations indicate that discharges from the Swan-Canning Estuary move southwards through Owen Anchorage and into Cockburn Sound (Figure 6b; Mills and D'Adamo, 1995). Field studies confirmed that, under a south-southwesterly wind regime, water originating from the Peel-Harvey Estuary entered Warnbro Sound within 1-2 days (D'Adamo *et al.* 1995a) and, under a predominantly northerly wind regime, water originating from the Swan-Canning Estuary entered Cockburn Sound also in the order of 1-2 days (D'Adamo *et al.* 1995b). The wind field regularly swings through the full 360° cycle every 7-10 days during winter/spring (Breckling, 1989) and this causes a significant occurrence of both northerly and southerly winds. In turn this leads to a northward/southward oscillation of nutrient-laden estuarine plumes along the coastal strip and hence affects the water quality of the entire region.

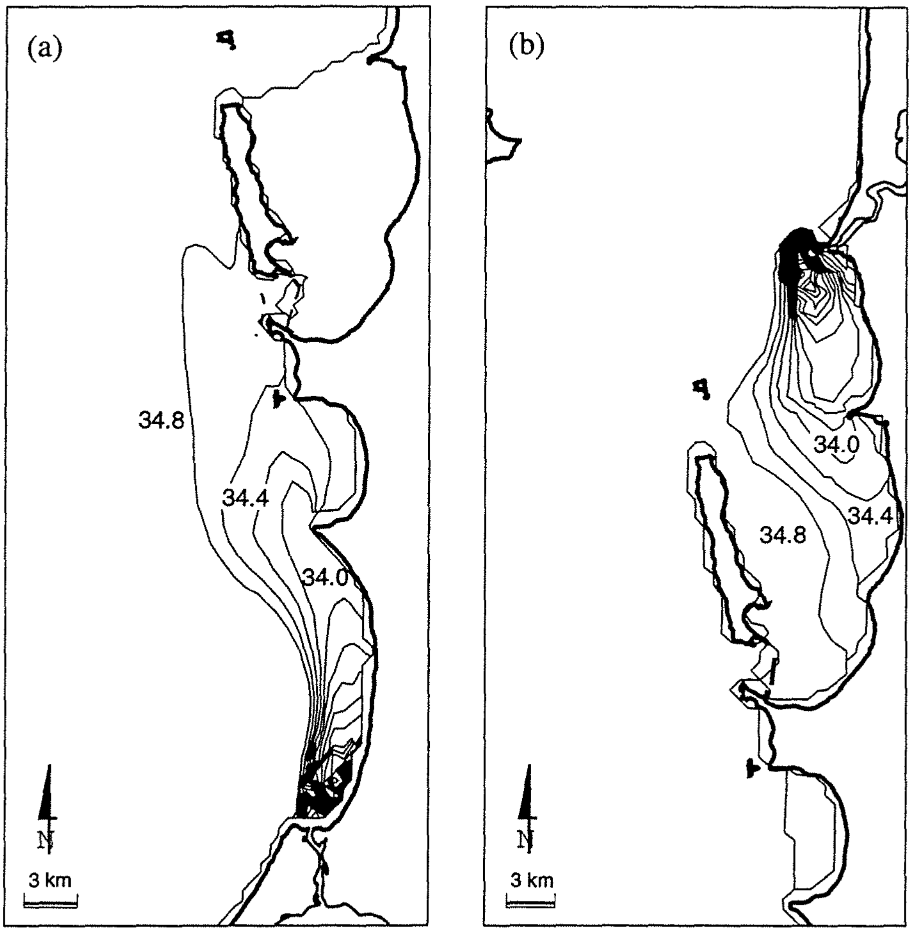

Figure 6. Three dimensional hydrodynamic simulation showing water movement from (a) the Peel-Harvey Estuary under a south-west wind at 7.5 m s^{-1} after 2.5 days and (b) the Swan-Canning Estuary under a north wind at 3.5 m s^{-1} after 2 days. Contours are at 0.2 pss intervals. (from Mills and D'Adamo, 1995).

Chiffings (1987), in the late 1970s, found a similar seasonal pattern in nutrient concentrations to that reported in the present study but attributed the winter peaks in inorganic nitrogen concentrations to be due, in part, to lower phytoplankton growth rates and to the release of nutrients from sediments during periods of persistent storm activity. Elevated nutrient concentrations were found in waters overlying seagrass meadows immediately after significant winter storm events (CSIRO, unpublished data). High concentrations of nutrients have been found in the interstitial pore water of sediments in the study area and it was estimated from these data that disturbance of the top 20 cm during storms could generate a pulse release of 20 mgN m^{-2}, which would increase ambient water column nitrogen concentrations by 2 $\mu g\ l^{-1}$ in a water column 10 m deep (Rosich *et al.* 1994). The magnitude of these pulse releases seems too small to account for the widespread occurrence of nitrogen concentrations that were often 15-20 µg l^{-1} above background during winter in the present study.

The influence of estuarine outflows is also reflected in the distribution of estuarine phytoplankton species in the coastal waters. *Skeletonema costatum* is the dominant phytoplankton species in the Swan-Canning Estuary (John, 1994), and was present in high numbers at the Swan-Canning Estuary entrance during the winter survey, and although *Skeletonema* blooms in the Peel-Harvey Estuary are common (Lukatelich, 1987), this species was absent at the Peel-Harvey Estuary entrance during the present study, making it a useful bio-indicator of the influence of the Swan-Canning Estuary. A contour plot of the abundance of this species in the study region under a northerly wind regime during the winter regional survey period (Masini and Cousins, 1992), produced a pattern very similar to the salinity contours produced in the numerical simulation of the Swan River Estuary outflow under a similar northerly wind regime (Figure 6b). This similarity provides further support that the elevated nutrients characteristic of Perth's nearshore waters during winter are related to estuarine influences. Further, this also suggests that estuarine-derived phytoplankton can have a bearing on phytoplankton species composition and abundance, and hence chlorophyll *a* concentrations, in the study region during winter.

The Leeuwin Current also appears to be influencing the water quality of the region in winter with meanders of the Current observed approximately 18 kilometres off the coast at Marmion (Figure 4). Mills *et al.* (1994) have shown that meanders of the Leeuwin Current can come to within 1-2 kilometres of the coast at times. On 14 August 1991, the warm waters of a meander of the Leeuwin Current had higher NO_3-N levels than the nearshore coastal waters influenced by the estuarine plumes (Figure 4a,b,c,d). Thompson (1984) and Cresswell (1995) found similar NO_3-N concentrations (ranging up to 13 µg l^{-1}) in the surface 50 metres of the Leeuwin Current to those reported in the present study. In contrast, nutrient data collected in the Leeuwin Current off Geraldton (approximately 360 km north of Perth) suggest that the current is not nutrient-rich and has NO_3-N concentrations of approximately 3 µg l^{-1} (Pearce *et al.* 1992). Although NO_3+NO_2-N concentrations of 11-12 µg l^{-1} were found in association with the waters of the Leeuwin Current during the present study, the data are limited and the nutrient status of the Current remains unresolved. However, the findings of the present study suggest that the Leeuwin Current can influence the coastal waters of Perth at times, and given the potential scale of a Leeuwin Current incursion into shelf waters (Mills *et al.* 1994), the nutrient status of the Current warrants further investigation.

The summer regional survey found that, apart from the areas around sewage outfalls and in close proximity to the estuarine entrances, NO_3-N levels in the surface waters were generally less than 5 µg l^{-1} (Figure 3d) which is within median background conditions.

Two of the three localised areas of elevated (> 5 µg l^{-1}) NO_3-N concentrations found in Sepia Depression and Gage Roads during the summer regional water quality surveys are close to the outlets of the Cape Peron and Swanbourne sewage outfalls respectively (Figure 3d). The Cape Peron outfall discharges primary treated sewage with a total nitrogen concentration of 50 mg l^{-1} at a rate of approximately 107 million litres d^{-1}. The Swanbourne outfall discharges 52 million litres d^{-1} of secondary treated sewage with a nitrogen concentration of 25 mg l^{-1} (Water Authority of Western Australia, unpublished data). The close proximity of the sewage outlets to these two sites of above-background nitrogen concentrations suggest that a significant proportion of the inorganic nitrogen present at these locations originated from the outfalls. The elevated TIN concentration in summer at the third site located near the northern opening to Cockburn Sound, is consistent with the findings of Bastyan *et al.* (1994) during the summer of 1992/93 however the cause of the elevated inorganic nitrogen concentrations is unclear.

4.2. Annual cycle

The results of the regional water quality surveys discussed above allow the seasonal patterns evident in many of the water quality parameters in the three sub-regions of the study area to be viewed from a broader perspective.

Physical

Annual cycles of temperature in all three areas were linked but Sepia Depression was warmer than Cockburn and Warnbro sounds during autumn and winter and cooler during spring and summer, by about 2 °C. These differences can be explained by the differential heating and cooling of the relatively 'trapped' water in the two embayments and the moderating influence of offshore oceanic waters on Sepia Depression. Mean salinities also showed a pronounced seasonal cycle with highest values in summer and lowest in winter with the greatest annual range occurring in Cockburn Sound and the least in Sepia Depression. The lower mean salinity of Cockburn Sound than Warnbro Sound during late autumn and winter can be explained by the greater influence of the fresh-water outflow of the Swan-Canning Estuary on the salinity of Cockburn Sound waters. The salinities of the two embayments were similar during summer and were higher than in Sepia Depression. The difference can be explained by the differential evaporation of the relatively 'trapped' water in the two basins.

In contrast to the unimodal annual cycles of temperature and salinity in the two basins the annual cycle of light attenuation of the water column was bimodal with a primary maxima in winter and a secondary maxima in summer. This annual pattern in light attenuation was similar to the pattern for chlorophyll *a* (Figure 5f,i). A significant positive correlation exists between light attenuation coefficient and chlorophyll *a* during summer using data from all three water bodies investigated in the present study (Cary *et al.* 1995b). Burt *et al.* (1995) found that light attenuation through the water column in Owen Anchorage/Gage Roads was correlated to swell waves and chlorophyll *a* concentration, and that plumes from the Swan-Canning Estuary also have intermittent localised effects on the water clarity of the area. Although no measurements of dissolved organic compounds or suspended sediments were taken in the present study, field observations by the authors in winter, coupled with interpretation of satellite imagery, indicated an obvious discolouration associated with the estuarine plumes. During autumn and spring there is less resuspension of sediments by swell- and wind-waves (Burt *et al.* 1995), estuarine outflows are minimal and chlorophyll *a* concentrations are low; conditions that result in less light attenuation and hence clearer water during these periods.

Chlorophyll *a*

The correlation in chlorophyll *a* concentrations between the embayments over the annual period is largely due to the elevated concentrations found in winter in both embayments. The high chlorophyll *a* concentrations found during the estuarine-flow period in the present study are consistent with the findings of Chiffings (1987) and Burt *et al.* (1995) and may be due to enhanced growth stimulated by estuarine- or sediment-derived nutrients, estuarine-derived phytoplankton, resuspended benthic microalgae or a combination of these factors. Studies of phytoplankton in these waters have shown persistent seasonal cycles of succession with monospecific silicoflagellate blooms during winter giving way to cycles of diatom blooms during summer (Cousins and Masini, 1992; Helleren and John, 1995). The commonality in phytoplankton composition of the embayments during winter suggests that the controls on growth of the dominant silicoflagellate operate at a regional-scale, and as this species has a salinity optimum below 35 pss (Helleren and John, 1994) the estuarine influences on these waters may be a factor contributing to this dominance. The mean chlorophyll *a* concentrations and salinities of the three sub-regions during winter were inversely related. Cockburn Sound had the highest chlorophyll *a* and lowest salinity and Sepia Depression the lowest chlorophyll *a* and highest salinity, providing further evidence that estuarine outflows have a significant influence on the water quality of the region at this time of year.

The lack of correlation in chlorophyll *a* between the embayments during the non estuarine-flow period suggests that 'local' scale rather than 'regional' scale forcings dominate water quality during this period. The elevated chlorophyll *a* concentrations in summer at the three sites in the east and south of Cockburn Sound were also found to be elevated over summer in previous studies, and are associated with increased nutrient loading to these waters from groundwater and industrial discharges (Chiffings, 1987; Cary *et al.* 1991; Bastyan *et al.* 1994). In Warnbro Sound consistently lower chlorophyll *a* concentrations were found at the western sites during summer and are likely due to dilution by Sepia Depression waters which have a significantly lower chlorophyll *a* content (Mills and D'Adamo, 1995). The data presented in Table 4 indicate that Cockburn Sound and Warnbro Sound had very similar chlorophyll *a* levels during the non-winter period in the present study. Cary *et al.* (1995b) however suggested that the elevated chlorophyll *a* concentrations in Warnbro Sound during the 1991/92 summer were atypical and that based on seven years of data Warnbro Sound has an average phytoplankton concentration of around 0.7 $\mu g\ l^{-1}$ during summer which is 3 times lower than the concentration typically found in Cockburn Sound at the same time. Relationships between nitrogen loading to Cockburn Sound and chlorophyll *a* concentrations (Cary *et al.* 1995b) provide good evidence to show that phytoplankton in Cockburn Sound are locally generated and directly proportional to the inorganic nitrogen load from point and diffuse sources during summer. The low chlorophyll *a* concentrations that typify Warnbro Sound during the non estuarine-flow period are due to low nitrogen loading to these waters from local point or diffuse sources (Muriale and Cary, 1995; Cary *et al.* 1995b) and probably represent close to 'natural' levels.

Nutrients

The mean TKN concentrations of the water bodies were similar to the analytical error term for this parameter (±200 $\mu g\ l^{-1}$) however the TKN concentrations of the three water bodies showed a bimodal pattern, peaking in summer and in winter and were strongly correlated suggesting that this variation is not an analytical artefact, rather it reflects a factor or process that is 'common' to these three areas (Figure 5; Table 3). Comparisons of TKN concentrations of filtered and unfiltered water samples indicate that only a small proportion ($\leq$15 %) of nitrogen present is in a particulate form and that the majority is in a dissolved organic form ($\geq$79 %). The winter peak in TKN was associated with high TIN concentrations whereas during summer, when TIN was low, the peak in TKN must have been due to elevated DON or particulate nitrogen. Particulate nitrogen concentrations are generally low in these waters and DON is consistently the dominant form of nitrogen (Hillman unpublished; Masini unpublished). Dissolved organic nitrogen can be comprised of humic-type compounds (presumably estuarine-derived), and also recently excreted or exuded amino acids, purines, urea etc (Mantoura *et al.* 1988) which must originate from living or dead plant and animal material. Due to the lack of estuarine-flow during the summer period it is unlikely that the apparent DON peak in summer is estuarine-derived, but more likely to be from marine plant and animal exudates. Schell (1974) reported that approximately 10 % of nitrogen assimilated by phytoplankton was released back to the water column as DON in 48-hour experiments. In the present study, white amorphous aggregations (marine snow) were evident in the water column throughout the study area, especially during calm conditions in summer (Authors personal observations). This material has been attributed to exudates from decomposing and/or stressed marine biota such as phytoplankton and zooplankton (Lancelot and Mahot 1987; Herndl and Peduzzi, 1988; Herndl *et al.* 1992), and these visual observations further support the suggestion that the DON present in summer has a local origin. The total nitrogen concentration at Parker Point, Rottnest Island over an annual cycle was higher during summer than winter (Masini, 1990) and approximately 95 % of the total nitrogen was DON (Masini unpublished). The sampling site at Rottnest Island is well offshore and distant from estuarine discharges, supporting the suggestion that elevated TKN concentrations in the region during summer are due to elevated DON concentrations and that the DON is marine- and not estuarine-derived.

McCarthy (1981) comments on the striking uniformity of DON concentrations found in vastly different regions world-wide and suggests that this material is rather refractory in both a chemical and biological sense. Although nothing is known of the fluxes between the inorganic and organic nitrogen pools in the water column of the Perth region, it seems likely that the inorganic fraction is the most readily available for plant growth and should remain the focus of water quality investigations.

The highest TIN concentrations were recorded in the winter period and in light of the findings of the regional survey it seems likely that this nitrogen was derived from the Swan-Canning and Peel-Harvey estuary outflows. The greatest variation in TIN concentrations within the embayments and between them occurred during the winter period and coupled with the associated variation in salinity at this time it appears that the TIN was associated with depressed salinity waters. The Leeuwin Current has slightly depressed salinities compared to the surrounding oceanic waters but the greatest source of low salinity water to the nearshore (<30 m) region off Perth during winter is the estuarine outflows (D'Adamo and Mills, 1995), further supporting the link between elevated TIN and estuarine outflows.

The pattern just described for nitrogen applies equally well to phosphorus in these waters. Approximately 5 % of the total phosphorus pool was PO_4-P, and a small proportion (~7 %) was in the particulate form indicating that the majority (~88 %) was in a dissolved organic (DOP) form. Most of the DOP in water consists of high molecular weight, refractile and enzyme resistant material which is considered unlikely to be available for plant growth (Nalewajko and Lean, 1980). The strong correlations in TP concentrations between regions over the study period also suggests that, as with the TKN data, the cause of this variation is a factor or process that is 'common' to the region; during the period of estuarine-flow phosphorus concentrations are likely to be influenced by these outflows, but during the summer period biological influences are likely to be important.

Phosphate-P concentrations were often higher in Cockburn Sound than in the other water bodies and there were no apparent correlations between the three water bodies for this parameter suggesting that inorganic phosphorus concentrations are controlled by local- rather than regional-scale forcings. The direct discharge of phosphorus from industrial outfalls into Cockburn Sound is likely to be the dominant local influence and the cause of the generally elevated concentrations found in the waters of Cockburn Sound as opposed to the other regions. The higher relative availability of phosphorus compared with nitrogen in the Sound (see below) means that it is not rapidly stripped from the water column by plants and explains why PO_4-P is commonly found at higher and more variable (eg. large standard errors) concentrations in Cockburn Sound than in the other water bodies.

The inorganic N to P ratios of the water column reflect the relative availability of nitrogen and phosphorus for plant growth and indicate that of these two nutrient species nitrogen is the one likely to limit plant growth at any particular time. This finding is consistent with other water quality surveys of these waters conducted since 1977 which are summarised by Cary *et al.* (1995b). Cary *et al.* (1995b) also found that the highest N:P ratios typically occur during the winter period and largely reflect the availability of TIN which also peaked at that time. The high N:P ratios during the period of estuarine-flow suggest that phosphorus is the limiting macro-nutrient for plant growth, but it is equally likely that growth at this time of year is controlled by physical factors such as the relatively low light availability and water temperatures, rather than by inorganic nutrient availability.

Background conditions

The low background nutrient concentrations reported in this study during both 'summer' and 'winter' support the view that these waters are oligotrophic by world standards (Kirkman, 1981; Johannes *et al.* 1994). The low nutrient status throughout the year in areas away from anthropogenic or estuarine influences are indicative of a lack of significant up-welling of nutrient-rich oceanic waters, and as such, are considered 'atypical' for the western shore of a continental landmass in the southern hemisphere (Codispoti, 1983; Pearce, 1991). The 'summer' background conditions for nearshore coastal waters, established from limited water quality data collected in Warnbro Sound during summer, are supported by water quality data collected near Busselton in Geographe Bay, a seagrass dominated system some 150 km south of Warnbro Sound (Walker *et al.* 1994). The background conditions for offshore coastal waters are supported by 30 years of data from a site off Rottnest Island (Pearce *et al.* in prep.) and are similar to values found by Rochford (1980) for offshore waters off southwest Australia. Although background conditions have not been established for 'spring' and 'autumn', the results of this and other studies (eg. Cary *et al.* 1995b) suggest that estuarine influences on the nutrient status of Perth's coastal waters are very localised during the non-winter months and therefore the background conditions for summer are likely to be indicative of 'spring' and 'autumn' as well.

Summary of major findings

- Inorganic N:P ratios suggest that nitrogen is the primary nutrient limiting plant growth in the nearshore coastal waters of Perth.
- Mean background concentrations of nutrients and chlorophyll *a* (outside of anthropogenic influences) are low and support the generally accepted view that Perth's coastal waters are oligotrophic by world standards.
- The regional water quality surveys highlight the regional influence of estuarine outflows and the possible influence of the Leeuwin Current on the water quality of Perth's nearshore coastal waters.
- Satellite imagery, in combination with nitrate/nitrite-nitrogen, salinity and water temperature data from the winter regional water quality survey highlight the scale of influence and timing of the estuarine outflows. These plumes, particularly from the Peel-Harvey Estuary can affect the water quality of Perth's coastal waters over scales of up to 100 kilometres during 3-4 months in winter. During this period approximately 1300 tonnes of nitrogen enters Perth's coastal waters from this source, a load almost double that discharged from the Cape Peron sewage outfall over the same period.
- Annual cycles of temperature and salinity in the two embayments compared with Sepia Depression reflect the 'trapped' nature of the waters of the two embayments. The TKN and TP concentrations of the three water bodies were strongly correlated suggesting a 'common' controlling factor. The annual data for Cockburn and Warnbro sounds and Sepia Depression support the regional data with winter having a lower water clarity and higher nutrient and chlorophyll *a* concentrations than summer.

- In summer the water quality, as measured by chlorophyll *a* and inorganic nitrogen concentrations and light attenuation coefficients, is primarily determined by sewage and industrial wastewater discharges and groundwater inflows. In winter, estuarine discharges overshadow most local influences and can elevate nitrogen levels over a significant portion of the southern metropolitan coastal waters of Perth.

5. Conclusions

Local-scale forcings, such as sewage and industrial wastewater outfalls, together with diffuse sources such as groundwater, discharge nitrogen into the system throughout the year. Regional-scale forcings, unlike the local-scale forcings, are largely episodic and operate principally during brief periods in winter, and over-shadow local-scale forcings at this time. Regional-scale forcings include estuarine outflows which inject both nutrients and phytoplankton into the coastal waters, storm events which resuspend sediments resulting in the release of nitrogen and microalgae and the Leeuwin Current which can have a broad-scale influence on the coastal waters of Perth.

The results of this study highlight the need to acknowledge the temporal variability and spatial scales of influence of a number of anthropogenic and natural forcings. In particular nitrogen inputs from industrial and domestic point and diffuse sources and from the catchments of the Peel-Harvey and Swan-Canning estuaries need to be considered together with the influence of natural factors such as Leeuwin Current incursions.

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