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Review of productivity levels of Western Australian coastal and estuarine waters for mariculture planning purposes

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Cover pictures courtesy of Dalcon Environmental
Top left - *Chaetoceros curvisetus*, a chain-forming diatom
Top right - *Coscinodiscus* sp. a diatom
Centre bottom - *Dictyocha octonaria* a silicoflagellate and the one responsible for the winter blooms in Cockburn and Warnbro sounds

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Review of productivity levels of Western Australian coastal and estuarine waters for mariculture planning purposes.

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Abstract

*The measurement of chlorophyll-*a *(a simple estimate of phytoplankton biomass) is often used as an indicator of water quality. Chlorophyll measurements are relatively sparse for most of the Western Australian continental shelf, although there are areas such as the Perth metropolitan coastal zone, Wilson Inlet and the Albany harbours where some intensive studies have been undertaken.*

This review of both published and unpublished chlorophyll concentrations in Western Australian waters has shown a high degree of variability in space (both horizontally and vertically) and time, and statistics on the seasonal distribution of chlorophyll have been derived for those regions with sufficient chlorophyll data. Conclusions from these in situ *observations have been supported by satellite remote sensing of ocean colour using archived Coastal Zone Colour Scanner (CZCS) satellite imagery.*

South-eastern Indian Ocean waters are generally nutrient- and chlorophyll-poor, with chlorophyll concentrations generally well below 1 µg/L and, therefore, probably unsuitable for successful bivalve aquaculture. These concentrations are much lower than in the upwelling regions off the west coasts of southern Africa and South America because of the warm low-nutrient Leeuwin Current. Chlorophyll levels in coastal areas and semi-enclosed water bodies on the Western Australian coast are generally higher than in the open ocean, with seasonal mean chlorophyll concentrations sometimes exceeding 2 µg/L and occasionally reaching 5 µg/L. Such elevated chlorophyll levels are, however, largely due to natural input of nutrients regionally exacerbated by anthropogenic influences like agriculture runoff and sewage. Present chlorophyll levels in these regions should be viewed as transient, being influenced by potentially varying nutrient loadings, as further industrial development occurs and countered by remedial management practices. Peak chlorophyll levels in Western Australia's coastal waters generally occur in winter with the lowest concentrations in summer and autumn.

An atlas is presented depicting seasonal chlorophyll concentrations for those regions where data coverage is adequate: Perth metropolitan waters, the Peel-Harvey system, Wilson Inlet and the Albany harbours region. Due to the high level of phytoplankton patchiness, more detailed in situ *chlorophyll (and other) measurements are recommended in specific areas where future aquaculture ventures are proposed.*

The Helleren and Pearce (2000) source document, which assembles much of the available original chlorophyll data, is appended as a pdf file on CD in the pocket on the back cover of this report. Please read the Readme file on the CD before accessing the pdf file.

1.0 Introduction

Planning for bivalve culture industries and environmental management of mariculture impacts in Western Australian waters, require detailed information on background levels of water productivity. In contrast with the west coasts of southern Africa and South America (where there are northwards cool currents with upwelling of nutrient-rich waters onto the continental shelf and consequent highly productive coastal waters), the Western Australian coastal environment is dominated by the tropical, nutrient-poor (and hence low productivity) southward Leeuwin Current (Pearce 1991). Localised enhanced productivity may, however, occur in areas with significant terrestrial runoff, industrial nutrient input (Simpson *et al.* 1992), localised upwelling (although, in Western Australia's south-western waters, this may not necessarily result in nutrient enrichment - Gersbach *et al.* 1999), inshore recycling of detrital material (Kirkman 1984, Johannes *et al.* 1994), re-suspended sediments (Department of Environmental Protection 1996), submarine groundwater discharge (Johannes and Hearn 1985) and/or the interaction of internal tides with bottom topography (Hallegraeff and Jeffrey 1984).

A simple method of comparing the productivity of different regions is by measuring the level of chlorophyll in the water column, as this gives an indication of the biomass of phytoplankton, the drifting (and typically microscopic) plants that form the base of the marine food chain. As pointed out by the Department of Environmental Protection (1996), phytoplankton (or chlorophyll) concentrations are in fact better indicators of the trophic status of a water body than are nutrients because of nutrient uptake by plankton or macroalgae. Conversion from chlorophyll-*a* levels to algal biomass cannot be reliably made due to the large variability of the phytoplankton composition in Western Australian coastal waters. As a very approximate estimate, Ryther (1963) suggests that standing crop (or biomass, in μg/m^3 dry weight) is about 0.1 times the chlorophyll-*a* concentration in μg/L, but such conversions should be used with caution.

Australian waters generally exhibit low productivity levels with typical ranges for chlorophyll-*a* concentrations being 0.05-0.5 μg/L for oceanic tropical and subtropical regions, and up to 1.5 μg/L for temperate and southern oceans (Jeffrey and Hallegraeff 1990). However, because of estuarine and/or terrestrial (urban, industrial and agricultural) runoff, coastal areas tend to show both higher and more variable chlorophyll concentrations.

Historical studies of chlorophyll levels in the coastal waters of Western Australia have largely been localised surveys for environmental management of nutrient-affected areas. As yet, no comprehensive review of chlorophyll levels in the region currently exists, nor has there been an overview of the productivity of the State's coastal waters to assist the developing mariculture industries.

Terms of reference

The Western Australian Aquaculture Development Council has requested an assessment of the temporal and spatial variability of chlorophyll concentrations along the Western Australian coastline to aid the selection of suitable areas for aquaculture. The specific terms of reference of this study are:

a) To provide an overview of chlorophyll levels for continental shelf and coastal waters using historical satellite (Coastal Zone Colour Scanner - CZCS) data.

b) To compile available chlorophyll data for the key sites with mariculture potential around the State (Figure 1) identified as:
   - Recherche Archipelago
   - Albany harbours (King George Sound, Princess Royal Harbour, Oyster Harbour)
   - Wilson Inlet
   - Geographe Bay
   - Leschenault Inlet
   - Peel-Harvey Inlet
   - Cockburn Sound and Perth metropolitan coastal waters
   - Jurien Bay
   - Abrolhos Islands
   - Lower Shark Bay
   - Exmouth Gulf
   - Dampier Archipelago

   The sites range from open-shelf (Dampier and Recherche archipelagos, Abrolhos Islands), through coastal ocean (Jurien Bay, Geographe Bay, Perth metropolitan waters); semi-enclosed bays (Exmouth Gulf, Shark Bay, Cockburn Sound, Albany harbours) and water bodies almost completely-enclosed (Peel-Harvey, Leschenault and Wilson inlets).

   Areas such as the Swan River estuary have not been included on the assumption that existing community usage and environmental constraints would preclude aquaculture development. Similarly, areas such as the Kimberley have been excluded due to the constraints of the physical environment on the satellite data.

c) To provide an atlas of chlorophyll levels for coastal and estuarine waters based on the compiled data, with observations on seasonal variations where available.

d) To provide a reference list of data sources and their status for further analysis if required.

This report reviews all available published and unpublished information about chlorophyll levels in the selected coastal regions off Western Australia, and evaluates historical ocean colour satellite imagery (which gives estimates of chlorophyll levels, although the accuracy of the derived chlorophyll concentrations is not particularly high and data coverage in the Western Australia area has been sporadic). For those regions where sufficient *in situ* data are available, seasonal patterns are presented graphically to depict the areas and periods of higher productivity as an aid to planning for mariculture projects. While we have attempted to include all sources of data, there may well be unpublished student theses (at various levels from Honours projects to Doctoral dissertations) at local universities which we have not uncovered in this search. There is currently no comprehensive index to such theses.

2.0 Background: chlorophyll in the ocean

Chlorophyll is the green pigment found in all photosynthetic organisms (primary producers). Photosynthesis in phytoplankton is associated with light in the wavelengths of 400-720 nm, much the same as in terrestrial plants. Phytoplankton contain many photosynthetic pigments (Barnes and Hughes, 1988, list 31 different pigments) allowing access to the full spectrum of light available for photosynthesis. By containing different pigments, or different concentrations of pigments, particular phytoplankton groups can specialise to exploit wavelengths not utilised by other groups. The most important photosynthetic pigment, and the only one present in all phytoplankton groups, is chlorophyll-*a* which exhibits peak light absorption at 430 and 662 nm (Jeffrey *et al.* 1997). Whilst many researchers also measure chlorophylls -*b* and -*c*, chlorophyll-*a* tends to be the standard measure due to its occurrence in all phytoplankton groups. Where we refer simply to "chlorophyll" in this report we imply chlorophyll-*a*.

Phytoplankton are the major primary producers in most marine ecosystems, forming the basis of many marine food webs, and chlorophyll concentration is now a universally accepted measure of phytoplankton abundance or standing stock in marine waters (Jeffrey and Hallegraeff 1990). Primary productivity (the amount of new organic material being created) is related to phytoplankton biomass as well as to the radiation incident at the sea surface (light), water temperature, nutrients, some photosynthetic parameters and the depth distribution of the phytoplankton (Barale and Doerffer 1993). Highly productive regions tend to have a high phytoplankton biomass (and associated high chlorophyll levels) and will therefore be able to support larger populations of organisms at higher trophic levels than would areas with low productivity. In this report, we loosely use the term "high productivity" as effectively synonymous with high phytoplankton (and chlorophyll) concentrations. Nielsen (1963) discusses these concepts in more detail.

Phytoplankton distributions are very patchy and can change rapidly over short periods of hours to days. These variations, coupled with the time/resources involved in the sampling and analysis of the samples, (sorting, counting and identification), can make direct measurement of phytoplankton density difficult. In addition, conversion of phytoplankton abundance to biomass is unreliable especially in mixed populations. However, the amount of chlorophyll present in marine ecosystems is well established as an indicator of phytoplankton standing stock (Parsons *et al.* 1984, Jeffrey and Hallegraeff 1990) and chlorophyll sampling and analysis are much easier than phytoplankton enumeration. Measuring the chlorophyll distribution therefore enables the temporal (diurnal/seasonal/inter-annual) and spatial (inshore/offshore/alongshore) variability of oceanic productivity to be assessed (Jeffrey *et al.* 1997). However, as pointed out by Helleren and John (1997), changes in phytoplankton species composition can result in somewhat different chlorophyll-*a* concentrations for the same phytoplankton biomass, and it is often useful to have complementary cell counts as well.

Chlorophyll concentrations can be measured in various ways (Parsons *et al.* 1984, Jeffrey *et al.* 1997, Jeffrey and Hallegraeff 1990). The precision of the different methods varies with the actual technique used, the volume of seawater filtered and, in some cases, the method of calculation and the chlorophyll concentration itself. Methods for measuring chlorophyll concentrations are:

a) **Chromatography:** This is the most precise method and involves chromatography of extracted pigments. It can yield information about all chlorophyll pigments, carotenoids and chlorophyll degradation products. High performance liquid chromatography (HPLC) is gradually replacing thin-layer chromatography (TLC).

b) **Chemical extraction:** In this method, a known volume of seawater is passed through a fine filter which collects all phytoplankton material. The filter paper is macerated in an organic solvent (usually acetone) and the chlorophyll pigment dissolves into the solvent. The concentration of chlorophyll in the solvent can then be estimated by measuring light absorbance through the solution at various wavelengths with a spectrophotometer. This technique is fairly time consuming and generally cannot be done *in-situ*, but gives chlorophyll-*a* concentrations accurate to about ±5% if no chlorophyll degradation products are present.

c) **Fluorometry:** When chlorophyll molecules are excited by photons of light they fluoresce, especially in the red wavelength. The chlorophyll concentration can be determined using a fluorometer to measure this fluorescence and a calibration curve derived from chlorophyll standards. Flow-through fluorometers can be used to measure fluorescence *in situ*, but the results are less accurate (about ±50%) than using extracted samples (Jeffrey and Hallegraeff 1990, Jeffrey *et al.* 1997). Comparison of chlorophyll concentrations measured by spectrophotometer and by fluorometer in the northern metropolitan waters of Perth by Helleren and Pearce (2000) shows a high correlation between the two datasets (r^2 value of 0.84).

d) **Remote sensing:** Chlorophyll concentrations can also be estimated from satellite and/or airborne colour imagery, by measuring the upwelling radiation from the ocean surface in the visible wavelengths of the electromagnetic spectrum (see section 4.0). The accuracy of near-surface phytoplankton pigment concentrations derived from older ocean colour data is estimated at between 35% and 100%, but new sensors and better correction algorithms should provide more accurate estimates in the future. For further information on the use of remotely-sensed data for chlorophyll determination, see Shannon (1985), Barale and Schlittenhardt (1993) and Wallace and Campbell (1998).

3.0 Literature review and data analysis

Relatively little information is available on chlorophyll concentrations in Western Australian coastal waters except for localised studies around Perth, a couple of popular estuaries, the Albany region and the North-West Shelf. Much of the published literature is historical, some dating back 40 years, and there is also a body of literature in the form of unpublished data reports, contract reports and student theses. The bibliographies by Hodgkin and Majer (1978), Crossland and Wells (1985) and Cary and Ryall (1992) have been helpful in tracking down references. Some of the chlorophyll data in the coastal waters off Perth have been compiled and summarised by Helleren and John (1997). In a companion report to the present one, Helleren and Pearce (2000) have assembled much of the available original data as a “source document” for chlorophyll in Western Australian waters, also calculating seasonal summaries and listing the analytical techniques used. The only data specifically omitted in Helleren and Pearce (2000) were recent unpublished chlorophyll surveys which were still being analysed by the original authors for publication. As a further guide to the viability of potential local bivalve ventures, a second related report by Saxby (submitted) reviews environmental data from a number of sites (globally) where bivalve aquaculture has been successful.

In this section, both the published literature on chlorophyll levels in Western Australian coastal waters as well as unpublished chlorophyll data are summarised by region, presenting the seasonal concentrations where possible. To set the results in perspective, the larger-scale south-eastern Indian Ocean is dealt with first, and then the individual coastal areas as specified in section 1.0 under the terms of reference. Units have been standardised as μg/L, which is numerically equivalent to mg/m^3.

While it would be desirable to present the results in terms of medians rather than arithmetic means because of the large variability and log-normal distribution of the chlorophyll data, many of the results we are reviewing are available only as means in the source documents, and, therefore, for consistency we have continued this presentation. In some cases, extreme values may bias the means, but the standard deviations will generally give an indication of such variability.

3.1 South-eastern Indian Ocean

As described earlier, the wind-driven upwelling regimes off the west coasts of southern Africa and South America result in much higher productivity than off the Western Australian coast. Phytoplankton production off south-western Australia is about 200 mg C/m^2/day compared with over 500 mg C/m^2/day off southern Africa and Chile/Peru (Figure 2 from Pearce 1991). Zooplankton abundance is also correspondingly higher in the upwelling regimes than off the Western Australian coast.

Nitrate and silicate concentrations in Western Australian shelf waters are also low, generally less than 2 µM and 3 µM respectively (Pearce *et al.* 1985), compared with 16-30 µM (nitrate) and 7-48 µM (silicate) in the coastal upwelling areas off other west coasts (Rochford 1980). Rochford (1980) concluded that "Australian marine waters ... must in an overall sense be regarded as one of the most nutrient poor marine regions in the world".

Chlorophyll concentrations in the south-eastern Indian Ocean were presented by Humphrey (1966) and Humphrey and Kerr (1969) as part of Australia's contribution to the International Indian Ocean Expedition (IIOE). Humphrey (1966) analysed chlorophyll data from the south-eastern Indian Ocean in the area from 90° to 140°E and between 10°N and 50°S, collecting samples from 335 stations between October 1959 and October 1962. Although samples were collected at depths of 0, 25, 50, 75, 100 and 150 m, the only data presented were those at the surface and 150 m, whilst data from the other depths were used to calculate depth-averaged chlorophyll concentrations in the water column. The methods used and the raw data for these early cruises are presented in data reports published by CSIRO (1962a, 1962b, 1963a, 1963b, 1963c, 1964a, 1964b, 1964c, 1966a and 1966b).

The surface and column chlorophylls were averaged over 5-degree latitude/longitude squares and by season (summer/winter). Over the whole sampled region, surface chlorophyll-*a* concentrations were higher during winter (0.12 µg/L) than in summer (0.08 µg/L), and the depth-averaged values were 23 and 15 mg/m^2 respectively. At most stations, Humphrey (1966) found chlorophyll maxima at depths of around 75 m, often associated with pycnoclines or thermoclines, with regionally-averaged values at that depth of 0.19 µg/L in winter and 0.14 µg/L in summer (this has obvious implications for remote sensing of chlorophyll in the open ocean, as satellite colour sensors can sample only the upper 30 m or so of the water column and will therefore miss these subsurface chlorophyll peaks). There was a gradient in chlorophyll concentrations from far offshore (about 0.05 µg/L) to coastal areas (> 0.1 µg/L in summer and double this in winter) (Humphrey 1966). There were also higher concentrations (> 0.2 µg/L) at 45°S in the Southern Ocean in both summer and winter.

Using similar sampling methods to those of Humphrey (1966), Humphrey and Kerr (1969) analysed chlorophyll measurements taken between latitudes 10° and 30°S along the 110°E line of longitude, again down to 150 m depth. Their results largely verified the earlier conclusions of Humphrey (1966), with the highest concentrations occurring between June and August, and the depth-maximum between 70 and 100 m.

When Humphrey's (1966) surface chlorophyll concentrations were adjusted using corrected extinction coefficients (Jeffrey and Humphrey 1975, Humphrey 1978), the concentrations were reduced by 23%, giving an amended range of concentrations. The original and amended data for the five-degree squares closest to the Western Australian coast are summarised in Helleren and Pearce (2000 Table 62).

Adjusted surface chlorophyll-*a* concentration (µg/L) for five-degree latitude/longitude squares off the Western Australian coastline, recalculated from data presented in Humphrey (1966) by Helleren and Pearce (2000 Table 62) are presented below.

Region	**Summer**	**Winter**
South-east Indian Ocean	0.06	0.09
South coast (120°-125°E)	0.06	
South coast (115°-120°E)	0.08	
South-west cape (35°-40°S)	0.05	0.18
South-west coast (30°-35°S)	0.07	0.14
Batavia coast (25°-30°S)	0.05	0.08
Gascoyne coast (20°-25°S)	0.05	0.12
South Pilbara coast (20°-22°S)	0.23	0.17
Central Pilbara coast (15°-20°S)	0.03	0.07
North Pilbara coast (15°-20°S)	0.05	0.12
Kimberley coast (125°-130°E)	0.08	0.16

It is evident from Figure 14 that these open-ocean chlorophyll levels are about an order of magnitude less than in the upwelling regions of the Benguela (southern Africa) and Humboldt (south America) current systems; particularly during the upwelling months when average chlorophyll levels off southern Africa approach 3 µg/L. More localised measurements can yield even greater contrasts: surface chlorophylls sampled by Brown and Henry (1985) in the southern Benguela upwelling zone, for example, were over 6 µg/L for much of the year.

The IIOE data were combined with other chlorophyll measurements, collected between 1951 and 1971, in an atlas showing vertical chlorophyll sections and horizontal charts by Krey and Babenerd (1976). Contours were drawn after the data had been binned into five-degree latitude/longitude squares for six-monthly periods: May to October (representing winter) and November to April (summer). Despite this large-scale averaging, the patchiness of the sampling in space and time and the recognition that the "important near-coastal areas are under-represented", surface chlorophylls in both the winter and summer charts showed higher concentrations on the Western Australian continental shelf compared with offshore regions. A region of chlorophyll concentration exceeding 0.3 µg/L is depicted between Shark Bay and Perth in winter (Figure 3). Whereas, in summer the maximum coastal concentration is shown as 0.2-0.3 µg/L in a band extending northwards onto the North-West Shelf. There is little data available for along the south coast. Further south in the Southern Ocean, higher chlorophyll levels are again found.

3.2 Recherche Archipelago

The Recherche Archipelago is a group of small islands near Esperance on the south coast of Western Australia. The only environmental information for this area appears to be from a single survey undertaken after the bulk carrier *Sanko Harvest* ran aground and broke up on a reef near Hood Island in February 1991 releasing fertiliser and oil into the water. A total of six sets of water samples (some at three depths, others at mid-depth only) were taken for chlorophyll analysis at four sites: two of which were about 4 km from the stricken vessel, while the other two were on the coast (Kinhill 1991; Helleren and Pearce 2000 Table 1).

The chlorophyll concentrations at the coastal sites were below 0.5 µg/L, but the two oceanic sites near the vessel had concentrations of 1.0-1.7 µg/L, with 4.2 µg/L the maximum observed. This pattern was consistent with nutrient levels in the water at that time as the fertiliser dissolved and dispersed. Under normal conditions, without such artificial elevation of nutrient concentrations, it would appear that chlorophyll values in the archipelago are probably well below 1 µg/L.

3.3 Albany harbours

Oyster Harbour and Princess Royal Harbour are almost entirely closed water bodies with only narrow passages into King George Sound, which in turn is a semi-enclosed embayment with relatively open access to the ocean off Albany. The two smaller harbours are shallow (2-5 m) with a maximum depth of 10 m near the channel entering Princess Royal Harbour. Since 1962, when the harbours were collectively considered to be in pristine condition, there was a steady deterioration in water quality and in the health and coverage of the once-extensive seagrass beds (Environmental Protection Authority 1990). A summary of chlorophyll concentrations from all the surveys in the Albany harbours region is given in Helleren and Pearce (2000 Table 5).

The first study of chlorophyll distribution in Princess Royal Harbour was by Atkins *et al.* (1980), comprising 24 stations sampled approximately monthly between December 1978 and November 1979. Most of the stations were evenly distributed through the harbour, as well as two sites adjacent to sewage outlets and a single "control" site 2 km offshore in King George Sound. Where the water depth exceeded 3 m both surface and bottom samples were taken. The results were presented as averages for the harbour, the two special sites, and the offshore station: the data are listed in Helleren and Pearce (2000 Table 2). The highest concentrations were from the harbour sites in December 1978, when the site average was 3.8 µg/L, and again in February and March 1979 (2.5 and 2.4 µg/L respectively), suggesting that summer was the season with the highest chlorophyll levels; otherwise all the concentrations were about 1 µg/L or less. The overall mean at the offshore marine site in King George Sound was 0.97 µg/L, at the two sewage outfall sites 1.01 µg/L, and in Princess Royal Harbour 1.43 µg/L. Atkins *et al.* (1980) concluded that the so-called "control" station in King George Sound was probably influenced by waters discharging from the harbour.

To date, the most comprehensive study of water quality (including chlorophyll) has been the Albany Harbours Environmental Study (AHES) carried out between 1988 and 1989. Water quality measurements were made in the two harbours as well as in King George Sound, between December 1987 and February 1989, with monthly sampling in summer and twice-monthly in winter (Hillman *et al.* 1991, Environmental Protection Authority 1990). Chlorophyll samples were taken on 25 occasions over the 15-month period during the AHES. The position of the station in King George Sound was not shown in Hillman *et al.* (1991); the five stations in each of the other two harbours were fairly evenly distributed.

The survey-averaged results from the AHES, which were presented graphically in Hillman *et al.* (1991 Figure 9, reproduced here as Figure 4), show the mean concentrations in each survey to have been generally less than 1 µg/L, with elevated chlorophyll levels of up to 3 µg/L found only in Oyster Harbour between May and August 1988. These elevated levels were presumed to have been associated with increased nutrients from riverine inputs and seagrass decay during that season. The average chlorophyll concentrations in Princess Royal Harbour and Oyster Harbour were, respectively, about twice and three times the mean value from the more open King George Sound, these ratios being reasonably well maintained during the entire 15-month period.

Hillman *et al.* (1991) re-analysed their data from Princess Royal Harbour for the 12-month period December 1987 to November 1988 for comparison with the results from the earlier Atkins *et al.* (1980) report to assess any detectable changes in water quality over the nine-year interval. Estimating values for both studies from Hillman *et al.* (1991 Figure 13), the 1978/79 annual mean value was 1.41 µg/L (with a range of means from 0.57 µg/L to 3.74 µg/L), compared with the average concentration of 0.59 µg/L (range of means from 0.28 µg/L to 0.77 µg/L) for the 1987/88 survey. Chlorophyll concentrations in the later study were, therefore, appreciably lower than those a decade earlier. While temperatures and salinities from the two periods were similar, suggesting similar rainfall and runoff, the monthly mean phosphate and ammonium concentrations were significantly lower in the later study. In a similar comparison, data collected from 16 sites in Princess Royal Harbour over a five-day period in February 1988 by Hillman *et al.* (1990) gave an average chlorophyll concentration of 0.4 µg/L (and 0.5 µg/L in Oyster Harbour), compared with an average of 2.5 µg/L during the same month in 1979 observed by Atkins *et al.* (1980). This again represented a marked reduction in chlorophyll levels between 1979 and 1988, both results being interpreted by Hillman *et al.* (1990,1991) as an indication of successful strategies to improve the water quality in Princess Royal Harbour during the intervening period.

The most recent study by the Water and Rivers Commission (unpublished data, listed in Helleren and Pearce 2000 Table 4) involved two sites in King George Sound and five each in Oyster and Princess Royal harbours, sampled between March and December 1997. Helleren and Pearce (2000) also computed the site-averages and the monthly averages over all sites in each harbour, however, many concentrations were quoted simply as "< 0.5 µg/L" so the calculated averages may be unreliable. The highest individual concentrations were 2.6 and 3.0 µg/L in March 1997, but all the site-averages were below 1 µg/L, except for the bottom sample at site 5 in Oyster Harbour, presumed to be the same as Hillman *et al.*'s (1991) site 10 at the northern end of the harbour near the King River.

3.4 Wilson Inlet

Wilson Inlet is a shallow estuary on the south coast east of Albany. Water depth in the inlet is mostly between 3 and 4 m, with the channel to the sea usually closed from about January to July (Lukatelich *et al.* 1984). Early sampling by Humphries *et al.* (1982) gave monthly surface chlorophyll data for two sites within Wilson Inlet and three sites located in its tributaries for the period January to December 1980. The location of these sites is not known but it is assumed that the two sites within the inlet are close to sites 7 and 9 as used by Lukatelich *et al.* (1984). The data are presented in Helleren and Pearce (2000 Table 6) but are very difficult to interpret due to the inconsistency of sampling dates and the large number of zero values which were presumably below some (unknown) detection limit. Chlorophyll concentrations were patchy, ranging from zero to almost 11 µg/L at the mouth of the Denmark River in August 1890, and no consistent spatial or temporal pattern could be derived.

During a later study, water samples were taken at three sites (station 1 in the entrance to the estuary where the water depth was less than about a metre, and stations 5 and 8 with depths of about 1.5 m and 3 m respectively, midway along the southern bank) at about six-week intervals between July 1982 and June 1983 (Lukatelich *et al.* 1984). There were also three intensive sampling surveys covering 16 sites throughout the estuary in July and December 1982 and April 1983.

Digitising the chlorophyll concentrations from Lukatelich *et al.* (1984 Figure 15) gave mean surface values (averaged over all sites) ranging from 1.57 µg/L in October 1982 to 4.92 µg/L in September 1982, mean surface-bottom averages for all sites ranged from 1.90 µg/L during October 1982 to 9.13 µg/L during November/December 1982 (because of an extremely high value of 20.4 µg/L at the lagoon entrance - see Helleren and Pearce 2000 Table 7). The chlorophyll concentration was generally highest at the entrance to the inlet and was almost consistently higher in bottom waters than at the surface, most likely a result of contamination by benthic and epiphytic microalgae but possibly also due to vertically-migrating phytoplankton (Luke Twomey pers. comm.). There were no clear seasonal trends (Lukatelich *et al.* 1984). Averaging the chlorophyll data over the whole period yields the following means and standard deviations (µg/L):

Site	Surface	Depth averages
Entrance (site 1)	3.85 ± 1.40	7.00 ± 5.94
Midway (site 5)	2.60 ± 2.82	6.63 ± 4.87
Midway (site 8)	1.93 ± 0.85	3.19 ± 1.81

There was clearly a horizontal gradient between relatively high chlorophyll levels in the mouth of the estuary to much lower values along the southern bank within the estuary. There were also large differences between the surface and bottom concentrations on occasion, despite the shallowness of the water and generally little evidence of thermal or haline stratification (although Kalnejais 1998 has subsequently described a vertical layering with fresh river water overlying salty ocean water when the bar is open in spring).

As a result of particularly low rainfall and the subsequent breaching of the sand bar between the inlet and the ocean for the shortest length of time on record, the 1982/83 study by Lukatelich *et al.* (1984) was deemed to have occurred during an atypical year and was repeated in July 1984 and April 1985 in order to obtain some understanding of the inter-annual variability likely to be encountered (Lukatelich *et al.* 1986). Again these data were presented graphically (their Figure 13), so the digitised data presented in Helleren and Pearce (2000 Table 7) are only approximate. Mean surface values for all sites were 8.45 µg/L in July 1984 and 1.59 µg/L during April 1985, and the mean bottom values were 7.87 µg/L in July 1984 and 1.67 µg/L during April 1985. The chlorophyll concentrations in July 1984 were found to be much higher than those from two years previously and were attributed to higher riverine nutrient loadings. The April concentrations, however, were similar in both surveys. Unfortunately, the sampling was too irregular and the variability too great in these studies to show any consistent seasonal or spatial pattern in the inlet.

Unpublished data from weekly sampling at the water surface and near the bottom from 11 sites in Wilson Inlet between November 1994 and April 1998 from the Water and Rivers Commission of Western Australia (WRC) data base, are presented in Helleren and Pearce (2000 Table 8). As with the Albany harbours data, many of these records were below the detection limit used (1 µg/L prior to March 1995 and 0.5 µg/L thereafter). Averaging over the full three and one-half year period gave the lowest surface values of 1.67 µg/L at site 14 (at the easternmost end of the inlet), 1.67 µg/L at site 2 (the entrance), and the highest mean concentration was 3.10 µg/L at site 35 (in the centre of the inlet). At the seabed, the mean concentrations ranged from 1.72 µg/L at site 2 (estuary entrance) to 2.57 µg/L at site 35 (excluding values from sites 5 and 8 which were only sampled in 1991, and site 1 which was sampled on only four occasions in December 1994 and January 1995). The maximum value recorded over the entire study was 65 µg/L in September 1995 at the surface at site 7, near the mouth of the Denmark River.

Helleren and Pearce (2000 Tables 9 and 10) summarised the site-averaged results by season for the period summer 1995 to autumn 1998. Based on the results from 1995, 1996 and 1997, the chlorophyll concentration is consistently highest in spring and lowest during the summer months (Figure 5). Kalnejais (1998) showed the distinct peak between September and November resulting from a seasonal phytoplankton bloom (mainly dinoflagellates and diatoms), with extreme values during spring exceeding 10 µg/L, sometimes at the surface and sometimes near the bottom.

The reported chlorophyll levels in Wilson Inlet are relatively high, comparable with those in the Peel-Harvey system and Cockburn Sound, both of which are considered to be eutrophied. This appears to be due to the seasonal opening of the inlet and consequent exchange of inlet and open-ocean waters, leading to an episodic release of nutrients from the sediments and consequent dramatic elevation in chlorophylls during spring (Twomey and Thompson submitted). More recent sampling throughout the lagoon (Luke Twomey, pers. comm.) has suggested that the present chlorophyll concentrations may in fact be somewhat lower than the WRC data.

3.5 Geographe Bay

There do not seem to be any offshore chlorophyll measurements for Geographe Bay. Walker *et al.* (1987) presented some limited chlorophyll data from the Vasse and Wonnerup estuaries and from the ocean entrance of these two estuaries collected in May 1987. Chlorophyll concentrations at the two Vasse Estuary sites were 6.9 µg/L and 10.4 µg/L respectively, those at the two Wonnerup Estuary sites were 60.7 µg/L and 14.5 µg/L respectively, and the ocean entrance site was 1.7 µg/L (the data are listed in Helleren and Pearce 2000 Table 11). The concentrations within the estuaries were much higher than the ocean site because of the permanent presence of the floodgates preventing mixing with oceanic water.

Limited data were also presented graphically for four sites in the Vasse Estuary on five sampling days between September and November 1988 by Davis (1989). Chlorophyll concentrations have been read from Davis (1989 Figure 7) and the data presented in Helleren and Pearce (2000 Table 11) are therefore approximate. Chlorophyll concentration ranged from 5 µg/L at site 3 (in the central part of the estuary) in mid-October to 117 µg/L at site 3b (very close to site 3) in November. Site averages ranged from 20 µg/L at site 3 to 46 µg/L at site 3b, while the average chlorophyll concentration over the whole study period was 33 µg/L. These values are again very high, commensurate with high nutrient loadings indicating that the estuary is nutrient-enriched.

A small amount of unpublished chlorophyll data has also been obtained from the Water and Rivers Commission data base for a site in the Vasse Drain, three sites in the Vasse Estuary, two sites in the Vasse River, one site in the Wonnerup Estuary, and one site in the Wonnerup Inlet sampled during January, February and March of 1998 (Helleren and Pearce 2000 Table 13). Concentrations varied from 1.8 µg/L at the Wonnerup Inlet site in February to 94 µg/L at one of the Vasse Estuary sites in March.

In an investigation into the "health" of Geographe Bay, sampling of chlorophyll (and other parameters) was undertaken at eight sites over shallow seagrass meadows along the shoreline of Geographe Bay from south of Bunbury south to Dunsborough by McMahon *et al.* (1997); see also Helleren and Pearce (2000 Table 12). Two sites (Dunsborough and Forrest Beach) were viewed as reference sites, the other six being potential 'impact' sites offshore of drainage systems. All sites were in approximately 5 m water depth and about 500 m from shore. The surveys were conducted fortnightly over the summers of 1993/94 and 1994/95 at all eight sites. The four sites along the southern shore of the bay (including one reference site) were also surveyed in April and September 1994. The mean chlorophyll concentrations (µg/L), with the ranges in parentheses, during each survey period over these four sites were:

Date	Mean (range)
Jan 1994	0.19 (0.12-0.22)
April 1994	0.13 (0.08-0.18)
Sept 1994	0.25 (0.12-0.49)
Jan 1995	0.16 (0.09-0.13)

The chlorophyll concentration was always less at the reference site (Dunsborough) than at the three impacted sites. The highest concentration measured was 0.63 µg/L at the Vasse-Wonnerup ocean entrance site in winter 1994, the lowest was 0.08 µg/L off Dunsborough in autumn 1994, and the overall mean was 0.22 µg/L. With so few samples, it is difficult to derive any realistic seasonal variation; suffice it to say that the values are comparable with open-shelf concentrations off Perth (see 3.8 below).

The data from all the above studies are too sparse to draw any conclusions about seasonal variability of chlorophyll in Geographe Bay.

3.6 Leschenault Inlet

Some chlorophyll data have been obtained from the WRC for several sites in Leschenault Inlet and its tributaries during four surveys between January and March 1998 (Helleren and Pearce 2000 Table 14); the positions of the sites, unfortunately, are not provided. Chlorophyll concentrations in the tributaries ranged from below the detection limit of about 1 µg/L, in the Brunswick River and the single Parkfield site during February, to 94 µg/L in the Vasse Estuary site 3 in March. Many of the concentrations recorded were well above 20 µg/L.

3.7 Peel-Harvey Inlet

The Peel-Harvey system has had a long history of eutrophication, with massive blooms of algae and phytoplankton caused by raised nutrient levels from agricultural fertilisers in the catchment area (Hodgkin *et al.* 1985). Prior to the opening of the Dawesville Cut in 1994, exchange with the open ocean was via a long and narrow channel, restricting effective flushing of the system. Water depths in both the Peel and Harvey water bodies are about 1 m.

The Peel-Harvey Estuarine System Study was undertaken between 1976 and 1980 to determine the causes of algal growth in the estuary and to understand the dynamics of the ecosystem (Hodgkin *et al.* 1980). Water sampling showed that chlorophyll levels escalated rapidly with the onset of diatom blooms in winter and *Nodularia* blooms during the spring/summer months; chlorophyll concentrations during these blooms could exceed 40 µg/L in Peel Inlet and 100 µg/L in Harvey Estuary, compared with “background” values which tended to vary between 1 and 10 µg/L depending on time and location (Hodgkin *et al.* 1980).

Black *et al.* (1981) sampled chlorophyll and nutrients from six sites in the open ocean outside the estuary channel and six sites distributed throughout Peel Inlet (no locations are given) during seven surveys between April 1979 and April 1980 (Helleren and Pearce 2000 Table 15). Mean concentrations outside the estuary only exceeded 1 µg/L in October and December, but the sampling was too sporadic to show any reliable seasonal pattern. In the inlet, however, average chlorophyll levels reached 8.7 µg/L in April 1980 and were all above 1 µg/L.

Lavery *et al.* (1990, 1993) measured chlorophylls in the Peel-Harvey estuarine system on four occasions in the summer of 1989/90, in conjunction with Landsat passes (see 4.3.2 below). Observations were also made on four occasions between December 1989 and February 1990 at five sites in the Harvey Estuary, 15 sites in the Peel Inlet, two sites at the confluence of these two water bodies, one site inside the estuary channel, one in the channel itself, and one site in the ocean outside the estuary. The surface chlorophylls in both water bodies were highly variable both in space and time (Helleren and Pearce 2000 Table 16). Survey-averaged chlorophyll concentrations for the Harvey Estuary ranged from 18.4 µg/L in February 1990 to 198.0 µg/L in December 1989; while those in Peel Inlet ranged from 6.0 µg/L to 65.1 µg/L in the same two months. The chlorophyll concentrations in the Peel Inlet were consistently lower than those of the more restricted Harvey Estuary, whilst concentrations in the confluence area were intermediate.

The lowest and highest concentrations in µg/L inside the two estuaries were:

Date	**Peel (15 sites)**		**Harvey (5 sites)**	
	min	**max**	**min**	**max**
14 Dec 1989	29	110	85	280
24 Jan 1990	11	208	42	186
31 Jan 1990	4	103	81	210
25 Feb 1990	2	11	8	31

The lowest values for the Peel Inlet were in the deeper central part of the inlet (near the channel, as may be expected) and in the eastern sites; the highest concentrations occurred in the western sites near the entrance to Harvey Estuary. There was little evident spatial variation in chlorophyll concentrations for the Harvey Estuary sites. There was a generally decreasing trend in chlorophyll concentrations through the channel from inside to outside, with the outer site having a maximum chlorophyll concentration of 5 µg/L in January 1990.

The Dawesville Cut, a 1.5 km long channel (200 m wide and 5 m deep) linking the northern end of the Harvey Estuary to the sea, was opened in April 1994 to improve the flushing of the estuarine system and so reduce nutrient levels and the attendant algal blooms (Hodgkin *et al.* 1985). Water quality measurements were made in the estuary system and in the open ocean outside the cut to compare conditions before and after its construction.

Chase (1995) compared surface and bottom chlorophyll data from the Peel-Harvey Estuary and associated coastal waters between November 1993 (six months prior to the opening of the cut) and August 1995 (17 months after the opening of the cut). Sampling was undertaken at three sites in each of the Peel and Harvey water bodies consistent with sites used in prior studies, on a fortnightly basis (or weekly during periods of substantial river flow), and 10 sites in coastal waters adjacent to the cut were sampled approximately monthly between March 1994 and May 1995. These sites were grouped (apparently with the addition of some other sites as sampled by the WRC) into Peel Estuary (three sites), Harvey Estuary (three sites), northern outer oceanic (three sites), southern outer oceanic (two sites), northern inner oceanic (four sites), southern inner oceanic (four sites), as well as three sites within the channel (data summarised in Helleren and Pearce 2000 Table 18). Graphical time-series data for the inner, outer and cut sites, the Peel Inlet sites (surface and bottom) and the Harvey Estuary sites (surface and bottom) were presented by Chase (1995; reproduced here as Figure 6) but these have been difficult to digitise.

The summarised data show that overall average chlorophyll concentrations in the Peel and Harvey estuaries dropped from 7.0 to 3.5 µg/L and from 5.1 to 3.3 µg/L, respectively, in surface waters after the opening of the Dawesville Cut, although Chase (1995) found there was no statistical significance in these values. Bottom waters in the Peel Estuary also showed a reduction in the average chlorophyll level from 1.7 to 0.4 µg/L, whilst that for the Harvey Estuary showed a slight increase in the average from 2.3 to 2.8 µg/L (Helleren and Pearce 2000 Table 18). Again these differences were not statistically significant. Prior to the opening of the cut, average chlorophyll concentrations in both estuaries were highest during spring and lowest during winter; after the opening, average chlorophyll concentrations were greatest in summer and lowest in spring. The opening of the Dawesville Cut resulted in decreases in average chlorophyll values in the Harvey Estuary for all seasons except winter (a dramatic decrease was observed in spring), whereas in the Peel Estuary there were slight increases during all seasons except spring. Average chlorophyll concentrations for the offshore (oceanic) sites were typical of open-ocean values and so were lower than those for the estuarine sites. The average chlorophyll concentrations at the inner oceanic sites were greater than those of the outer oceanic sites, and concentrations in the cut itself were between those for the estuarine and oceanic sites.

In a longer-term and more comprehensive study, Wilson *et al.* (1997) compared chlorophyll concentrations in the Peel-Harvey system between July 1991 and August 1993 (before the opening of the Cut) with those from July 1994 to April 1997 (after the opening). Samples were collected from surface and bottom waters at three locations in each of the Peel Inlet and the Harvey Estuary on a weekly basis during winter rainfall periods, fortnightly from the end of the rainfall period until December, and monthly from then until the start of the winter rainfall again. These data, which presumably include that of Chase (1995), are presented in Pearce and Helleren (2000 Table 19) and summarised in their Table 20 (reproduced below):

Comparison of seasonal mean chlorophyll concentrations (µg/L) and standard deviations in the Peel-Harvey system before and after construction of the Dawesville Cut, after Wilson *et al.* (1997).

Peel Inlet		**Station 2**	**Station 7**	**Station 4**
Summer	pre	30.15 ± 54.82	26.91 ± 33.99	23.78 ± 61.98
	post	2.91 ± 2.29	2.39 ± 1.51	4.01 ± 4.37
Autumn	pre	2.28 ± 1.75	1.46 ± 0.89	2.00 ± 1.84
	post	1.14 ± 1.57	1.23 ± 1.07	2.79 ± 2.62
Winter	pre	7.21 ± 12.05	9.44 ± 13.95	4.69 ± 6.95
	post	2.76 ± 5.81	5.99 ± 10.87	4.31 ± 7.17
Spring	pre	102.79 ± 119.30	65.65 ± 112.71	53.41 ± 90.28
	post	2.84 ± 12.41	2.14 ± 1.55	3.25 ± 2.67
Harvey Estuary		**Station 58**	**Station 1**	**Station 31**
Summer	pre	65.74 ± 109.65	80.33 ± 133.91	78.27 ± 122.45
	post	2.52 ± 1.62	4.87 ± 3.31	6.81 ± 4.34
Autumn	pre	2.72 ± 1.68	2.88 ± 2.02	4.78 ± 3.57
	post	1.52 ± 1.30	3.43 ± 2.81	5.47 ± 4.00
Winter	pre	10.99 ± 21.86	8.80 ± 17.72	8.38 ± 16.95
	post	2.27 ± 3.01	6.15 ± 7.89	8.98 ± 15.23
Spring	pre	97.41 ± 143.87	85.32 ± 101.15	102.26 ± 117.26
	post	1.71 ± 2.79	3.73 ± 5.00	5.85 ± 7.45

Prior to the opening of the cut, individual chlorophyll concentrations in Peel Inlet ranged from 0.1 to 563.0 µg/L, with an average concentration over all stations and seasons of 31.0 ± 71.8 µg/L. Variability was high with the greatest concentrations being recorded in spring (at all three stations) followed by summer, with much lower concentrations in autumn and winter. The high variability was evidenced by the low median values for each site with respect to the means and the high standard deviations which were generally double the means. Median values ranged from 2.8 to

7.5 µg/L, in general, at least an order of magnitude less than the mean values. Using averaged surface and bottom data, chlorophyll concentration was greatest at sites 2 and 7 (near the confluence with the Harvey Estuary and in the centre of the inlet respectively) on most occasions and least at site 4 (near the entrance of the Serpentine and Murray rivers). Concentrations at surface sites were generally greater than those of bottom sites.

Chlorophyll concentrations in the Harvey Estuary before the cut was opened were similarly extremely variable, ranging from 0.3 to 567.7 µg/L, with an average concentration of 46.35 ± 93.22 µg/L, and having a similar seasonal pattern to that of Peel Inlet. During winter, depth-averaged chlorophyll concentrations were generally greatest at site 58 (near the confluence with the Peel Inlet) followed by site 1 (in the centre of the Estuary) and site 31 (at the south end of the Estuary near the entrance of the Harvey River), but this trend reversed in summer. There were no clear spatial trends in autumn or spring.

After the opening of the Dawesville Cut, variability of chlorophyll in the Peel Inlet was still high but extreme and average values were much lower. Seasonal variability was less marked than in pre-channel years but average chlorophyll concentrations were generally greatest during winter; this differs from Chase's (1995) result, but is likely to be more representative because of the extra two years of new data. Using averaged surface and bottom data, chlorophyll concentration was usually greatest at site 4 and least at sites 7 and 2 (the opposite pattern to the pre-cut distribution). Chlorophyll levels at surface sites still tended to be higher than those of bottom sites. There was some indication of inter-annual variability but no consistent pattern between the three sites (see Helleren and Pearce 2000 for details). High chlorophyll concentrations in the summer of 1992/93 were caused by *Nodularia spumigena* blooms continuing on into that period from spring, while low rainfall recorded during 1993 and 1994 resulted in significantly lower chlorophyll concentrations for those years compared with 1991.

Chlorophyll concentrations in the Harvey Estuary have, likewise, decreased after the opening of the cut. As in the Peel Inlet, summer concentrations and the previously high variability have been substantially reduced (Wilson *et al*. 1997), and highest chlorophyll concentrations tended to occur in winter. Again, this is slightly different from Chase's (1995) seasonal pattern.

Generally, the opening of the cut has led to appreciably lower chlorophyll concentrations in Peel Inlet from the previously high values in spring and summer, and has prevented subsequent *Nodularia* blooms (Wilson *et al.* 1997). There has been little change during the lower-chlorophyll seasons of autumn and winter.

3.8 Cockburn Sound and Perth metropolitan coastal waters

Several comprehensive studies, both published and unpublished, from coastal waters around Perth and in Cockburn Sound have incorporated chlorophyll measurements (the sites are shown in Figure 7). These surveys have included the Southern Metropolitan Coastal Waters Study (SMCWS) which commenced in 1991 and ran until 1994 (Simpson *et al.* 1993, Department of Environmental Protection 1996), and the Perth Coastal Waters Study (PCWS, July 1992 to December 1994, Lord and Hillman 1995). This region therefore has appreciably more detailed chlorophyll information than anywhere else in Western Australia. Nevertheless, it is worth quoting Buckee *et al.*'s (1994) conclusion to the water quality component of the PCWS: "... this work should be regarded as a pilot study in that the establishment of a data set for estimating long term background values and spatial trends, with statistical rigour, would require a data collection exercise spanning several years to decades. Given the paucity of historical data and the limited resources the values ... should be viewed as first estimates that will undoubtedly be refined with additional data acquisition in the future."

The water quality component of the PCWS was conducted over the period June 1993 to March 1994, with the objectives to better understand and predict the ecological response to nutrient additions to coastal marine environments associated with discharge from sewage outfalls (Buckee *et al.* 1994). The PCWS comprised several components, during three of which (the Model Validation Plume Surveys, the Event Surveys and the Regional Surveys) chlorophyll concentrations in the water column were measured.

The SMCWS was undertaken to develop an understanding of the impacts and environmental consequences of contaminant inputs to the southern waters off Perth, covering the region between Fremantle and Mandurah (Department of Environmental Protection 1996). Chlorophyll concentrations in Cockburn Sound were measured monthly between January 1991 and January 1992 (Cousins 1991, Cousins *et al.* in prep.) and fortnightly between August 1992 and August 1994 (Helleren and John 1997, Department of Environmental Protection 1996). In addition, two shelf-scale water quality surveys were undertaken during August 1991 and March 1992 (Department of Environmental Protection 1996), comprising 100 sites between the mouth of the Peel-Harvey estuary (south of Perth) to Sorrento (north of Perth) and across the continental shelf to 70 km offshore. There are some differences between summarised chlorophyll concentrations (and other parameters as well) in the SMCWS progress report (Simpson *et al.* 1993) and the final report (Department of Environmental Protection 1996); we have used data from the latter.

Both for convenience and because of historical precedent, we have subdivided the metropolitan waters into (a) Cockburn and Warnbro sounds (including Owen Anchorage), (b) the three metropolitan ocean outfalls (Cape Peron, Beenyup and Swanbourne) and (c) wider regional shelf surveys covering a much larger area of the continental shelf. The data are analysed in smaller regions by Helleren and Pearce (2000).

3.8.1 Cockburn and Warnbro sounds

Cockburn Sound and Warnbro Sound are perhaps the best documented regions along the Western Australian coastline with respect to chlorophyll information. Many of the studies have involved both Cockburn and Warnbro Sounds, so the two coastal embayments are dealt with together here. There are presently a number of mussel farms operating in Cockburn Sound, so the possible impact of those ventures on the chlorophyll concentration should be borne in mind.

Cockburn Sound is a relatively shallow (10-20 m) semi-enclosed basin just south of the Swan River, exchange with the open ocean is often limited and may depend on the degree of (seasonal) stratification (Hearn 1991, D'Adamo 1992). There is a high level of nitrogen input to the sound, both from industrial effluent and contaminated groundwater, resulting in eutrophication and therefore high phytoplankton biomass (Department of Environmental Protection 1996) and loss of the originally extensive seagrass meadows (Simpson *et al.* 1992, Kirkman 1997). Warnbro Sound, by comparison, is largely open to the ocean, has little or no direct nutrient input, and is essentially an uncontaminated water body. Water depths are 10-15 m in Warnbro Sound. All the available chlorophyll data for Cockburn Sound and Warnbro Sound are tabulated and summarised in Helleren and Pearce (1999, Tables 22 to 33 and 34 to 38 respectively).

Although major ecological studies of the water quality in Cockburn Sound date back to the early 1970s, these early studies did not include chlorophyll measurements. In an early report to the Fremantle Port Authority on the eutrophication of Cockburn Sound, Meagher and Le Provost (1975) presented chlorophyll profile data for 17 sites (sampled at 2 m depth intervals) taken on a total of six occasions over the summer period November 1974 to April 1975; the results for each site and sampling date are tabulated in Helleren and Pearce (1999 Table 22). The data suggest that the analytical methods may have been imprecise, with many apparently constant chlorophyll concentrations throughout the water column.

Time-averaged chlorophyll concentrations over all six surveys by Meagher and Le Provost at the various sites were reasonably constant between 2.5 and 5.5 µg/L, with the higher values at stations 10 and 13 near the south-eastern shore of Cockburn Sound off Rockingham. There was clearly a high degree of both spatial and temporal variability, with concentrations at individual stations varying between 1.2 and 22.1 µg/L, the latter being a surface measurement at site 7 midway down the eastern shore in March 1995. High variability with depth was reflected in the station standard deviations as, for example, stations 2 to 7 in March 1975 when both the depth-averages and standard deviations were very high.

In 1976 the Cockburn Sound Study (1976-1979) was initiated (Department of Conservation and Environment 1979), including an 18-month (July 1977-December 1978) investigation of phytoplankton biomass. As part of the this study, Chaney (1978) and Chiffings (1979) reported chlorophyll concentrations for inshore sites in Mangles Bay (southern end of Cockburn Sound) and just north of Woodman Point, with weekly samples between July 1977 and August 1978. These data are tabulated in Helleren and Pearce (2000 Tables 24 and 42). As pointed out by Helleren and John (1997), this was the first study to cover the full year and enable any seasonal pattern to be assessed. Estimating the weekly concentrations from Chaney (1978 Figures 3.3 and 3.5) for the two sites, showed that variability was high: individual concentrations at both sites varied by more than an order of magnitude (0.6-16.9 µg/L in Mangles Bay and 0.4-9.4 µg/L at Woodman Point), with large spikes occurring throughout the period. Seasonal averages and standard deviations (µg/L) have been derived by Helleren and John (1997) and are listed below:

Season	**Mangles Bay**	**Woodman Point**
Annual	5.97 ± 3.72	2.72 ± 1.98
Summer	6.09 ± 4.00	3.43 ± 2.69
Autumn	6.53 ± 4.00	2.37 ± 1.45
Winter	5.24 ± 2.98	2.57 ± 2.21
Spring	6.30 ± 4.33	2.67 ± 1.52

The highest average concentration in Mangles Bay (Cockburn Sound) was in autumn and the lowest in winter, whereas at the Woodman Point site in Owen Anchorage, the highest chlorophyll levels were in summer and the lowest in winter/spring. Generally, the concentrations in Cockburn Sound were more than twice those in Owen Anchorage. Chaney (1978) concluded that the reasons for this difference were probably related to the high levels of nutrients in the system and the "considerable heterogeneity" of the productivity both with depth and horizontal location in the sound. Chlorophyll profiles taken over the water depth at two-hourly intervals revealed large changes both in absolute levels and in vertical structure (Chaney 1978): vertical gradients of up to 6 µg/L per metre depth were encountered, with variations throughout the water column.

Concurrent with this pioneering work, chlorophyll and nutrient concentrations were measured during a study to describe seasonal changes in phytoplankton communities in Cockburn Sound and adjacent waters between August 1977 and November 1978 (Chiffings 1979, Chiffings and McComb 1981). Nine cruises were undertaken incorporating 22 sites in Cockburn Sound, five sites in Owen Anchorage, a single site south-west of the southern tip of Garden Island in the Sepia Depression, and another site in the centre of Warnbro Sound (Helleren and Pearce 2000 Tables 23, 34, 39 and 41). Sampling was at two or three depths, depending on the total water depth at each station; at the single stations off Garden Island and in Warnbro Sound, three replicate samples were taken (Chiffings 1979). The original data are not available, but Chiffings (1979) presented spatially- and depth-averaged values for each of the four areas.

The highest "cruise-averaged" chlorophyll concentrations in Cockburn Sound were found in October 1977 (4.8 µg/L) and September 1978 (4.2 µg/L), with a similar pattern but slightly lower concentrations in Owen Anchorage. Minimum values over all sites were 1.8 µg/L in Cockburn Sound in December 1977 and March 1978, while in Owen Anchorage the minima were approximately 1 µg/L in December 1977, May 1978 and November 1978. Concentrations were relatively low in Warnbro Sound with the only marked peak being in July 1978 (2.6 µg/L). Offshore, in the Sepia Depression, the chlorophyll levels were all well below 1 µg/L, with the higher concentrations between March and July. The high variability in Cockburn Sound was reflected in large standard deviations and ranges presented in Chiffings (1979) and Helleren and Pearce (2000): the highest individual concentrations were 10.2 µ g/l in October 1977, 13.8 µg/L in July 1978 and 12.5 µg/L in September 1978. Chiffings (1979) even reported an extremely high chlorophyll concentration of 110 µg/L at the peak of a phytoplankton bloom in the sound, although this was not included in his tabulated results. In the other three areas, maxima rarely exceeded 5 µg/L.

Seasonal means (µg/L) derived from Chiffings (1979) were:

Site	**Cockburn**	**Owen A.**	**Warnbro**	**Sepia**
Annual	3.1	2.7	0.9	0.4
Summer	2.5	2.1	0.8	0.2
Autumn	2.3	1.7	0.8	0.5
Winter	3.4	3.6	1.9	0.5
Spring	3.8	3.1	0.3	0.3

A series of monitoring programs was initiated to track changes in the water quality (as an index of ecosystem "health" — Cary *et al.* 1991) of Cockburn Sound during the summers of 1979/80 (Chiffings and McComb 1983), 1980/81 (Chiffings and McComb 1983), 1982/83 (Chiffings and McComb 1983), 1984/85 (Hillman 1986), 1986/87 (Hillman and Bastyan 1988) and 1989/90 (Cary *et al.* 1991) - see Helleren and Pearce (2000 Tables 25 and 43). During each of these studies, weekly samples were collected from eight sites in Cockburn Sound, two sites in Owen Anchorage and one site north of Garden Island. A marked spatial pattern was found during the 1989/90 survey (Cary *et al.* 1991), with the mean chlorophyll concentration from stations along the eastern margin of Cockburn Sound (2.30 µg/L) being significantly higher than the mean concentration for the central and western sound (1.07 µg/L), which, in turn, was much higher than the mean concentration for the Owen Anchorage and Garden Island sites (0.77µg/L).

While seasonal patterns cannot be derived because these were all summer surveys, Cary *et al.* (1991) showed a great improvement in water quality in Cockburn Sound between 1980 (average chlorophyll concentration > 2 µg/L) and 1982 (< 1 µg/L), followed by a gradual deterioration again (1.83 µg/L) in 1989.

Associated with remote sensing observations from Landsat (section 4.3.2 below), Pattiaratchi *et al.* (1991,1994) measured chlorophyll concentrations on a grid of stations across Cockburn Sound in summer/autumn of 1990 (Helleren and Pearce 2000 Table 26). Both surface and depth-integrated samples were taken. The minimum and maximum surface concentrations (and depth-integrated in brackets) were:

Date	**Minimum**	**Maximum**
31 Jan 1990	0.51 (0.56)	2.48 (3.19)
25 Feb 1990	0.28 (0.44)	2.12 (1.38)
13 Mar 1990	0.23 (0.28)	1.48 (1.50)
7 May 1990	0.33 (0.44)	2.67 (3.26)

The lowest concentrations were within the range 0.2-0.5 µg/L and the highest concentrations were within the range 1.5-2.5 µg/L. There was little indication of temporal change (the surveys were all within a period of four months). The higher concentrations were generally observed in the southern regions of the sound where exchange with open ocean waters were relatively restricted. Unfortunately, the original logsheets with the positions of these stations have apparently been mislaid, and different site references were used in each survey, so we are unable to draw any further conclusions about the spatial distribution of chlorophyll from this study.

The chlorophyll sampling reported by Cousins (1991) and Cousins *et al*. (in prep.) for the SMCWS was on a fortnightly basis between from four sites within Cockburn Sound (CS4, CS6, CS9 and CS11); these were the same as stations 4, 6, 9 and 11 used in the summer programs mentioned above (see also Cary and Masini 1995). Sampling was also undertaken at eight sites distributed evenly through Warnbro Sound (WS1-WS8) and at site WS9 in the Sepia Depression just outside the sound, these being considered as "low impact" sites in comparison with those of Cockburn Sound.

Individual chlorophyll concentrations in Cockburn Sound ranged from 0.23 µg/L at site CS4 (near the north-western entrance to the sound, where water exchange with the open ocean is relatively good) in December 1991, to an anomalously high value of 10.15 µg/L at site CS11 (in Mangles Bay at the southern extremity of the sound) in July 1991. Site-concentration averages for the year-long period ranged from 1.15 µg/L at site CS4 to 2.58 µg/L at site CS11; large standard deviations again showing high variability about these mean values. Monthly averages, over all sites combined, ranged from 0.57 µg/L, during December, to 5.49 µg/L, during July. This winter enrichment indicating a marked seasonal pattern. The grand average for all the Cockburn Sound sites over the full period was 2.05 µg/L (Helleren and Pearce 2000 Table 27).

In Warnbro Sound, individual chlorophyll concentrations ranged from 0.17 µg/L at site WS1 (in Safety Bay at the northern limit of the sound) in February 1991, to 5.67 µg/L at site WS7 (close inshore near the coast) in July 1991 (Helleren and Pearce 2000 Table 34). The overall site averages for the year-long period showed a similar pattern, ranging from 0.93 µg/L at WS1 to 1.72 µg/L at WS7, furthest from the open ocean. The highest site-averaged monthly concentration was 4.07 µg/L during July and the lowest was 0.37 µg/L in January 1991, with a reasonably distinct seasonal pattern and an overall mean (all sites, full period) of 1.44 µg/L. These values are appreciably lower than those measured at the same time in Cockburn Sound, where the overall mean was 2.05 µg/L. At the offshore station (WS9 in Sepia Depression) chlorophyll concentrations were lowest in January 1992 (0.17 µg/L) and highest in August 1991 (1.66 µg/L), with a well-defined seasonal pattern. The site average was 0.75 µg/L over the whole period (Helleren and Pearce 2000 Table 40). These values were appreciably lower than those in either of the sounds.

Also associated with the SMCWS, Helleren and John (1997) measured chlorophyll concentration from five sites within Cockburn Sound and four of the original eight sites in Warnbro Sound (WS1, WS4, WS5 and WS7) on a fortnightly basis between August 1992 and August 1994 (Helleren and Pearce 2000 Tables 28 and 36). These sites were the same as those in Cousins (1991), with additional sites CS12 (in the centre of Cockburn Sound near site CS9) and WS10 (near WS4 in the centre of Warnbro Sound). Chlorophyll concentrations were measured at three depths (surface, middle and bottom) at each site.

The individual concentrations in Cockburn Sound ranged from 0.14 µg/L at CS4 to 17.34 µg/L at CS6 (near Woodman Point), with depth-averaged site means ranging from 1.01 µg/L at site CS4 to 2.52 µg/L at site CS11. These values were in general agreement with the earlier studies by Cousins (1991) and Cousins *et al.* (in prep.) - Helleren and Pearce (2000 Table 28). Chlorophyll concentrations were greater during winter than in summer (Figure 8) and there were no obvious vertical trends. In Warnbro Sound, individual chlorophyll concentrations ranged from 0.11 to 5.21 µg/L (both at WS7), with the site averages varying between 0.41 µg/L (range 0.14 to 1.90) at site WS1 and 1.00 µg/L (0.30 to 4.09) at site WS4 (Helleren and Pearce 2000 Table 36). Seasonal chlorophyll concentrations were greatest during winter (1.4-2.2 µg/L) and lowest during summer (0.5-1.3 µg/L - Helleren and Pearce 2000 Table 38). These values were generally half those of the concentrations in Cockburn Sound over the same period, and (again) there were no consistent vertical gradients. These seasonal trends were different from those reported by Chaney (1978, where chlorophyll concentrations were greatest during spring rather than winter which is characteristic of temperate waters), most likely because of the winter dominance and abundance of silicoflagellates reported in the later studies.

Helleren and John (1997) derived seasonal patterns for both Cockburn and Warnbro sounds from Cary and Masini (1995) as well as their own data (means in µg/L with standard deviations):

	Cary and Masini (1995) data		**Helleren and John (1997) data**	
Season	**Cockburn**	**Warnbro**	**Cockburn**	**Warnbro**
Annual	2.05 ± 1.43	1.44 ± 0.97	1.85 ± 1.55	0.83 ± 0.66
Summer	1.62 ± 0.87	1.31 ± 1.04	1.58 ± 1.32	0.50 ± 0.25
Autumn	2.01 ± 1.11	0.95 ± 0.32	1.88 ± 1.40	0.78 ± 0.49
Winter	2.92 ± 2.35	2.12 ± 1.12	2.36 ± 1.71	1.38 ± 0.97
Spring	2.21 ± 1.22	1.65 ± 0.70	1.86 ± 1.83	0.71 ± 0.35

Both sets of results show appreciably higher levels in Cockburn Sound than in Warnbro Sound. The highest concentrations in both embayments were generally in winter and the lowest in summer. The variability, reflected in the standard deviations, was lower for Cary and Masini (1995) data than for Helleren and John (1997); these differences may simply be attributed to natural chlorophyll patchiness in space and time, and differences in sampling sites and frequency.

As part of the PCWS Regional Surveys, synoptic views of the nutrient and chlorophyll levels over the Perth continental shelf area were provided by sampling chlorophyll levels in Cockburn Sound. Sampling was undertaken at nine sites during September 1993 and at three sites during February 1994, to represent winter and summer conditions respectively (Buckee *et al.* 1994). Chlorophyll concentrations in the September survey ranged from 0.84 to 1.60 µg/L in surface waters (with a median value of 1.30 µg/L) and from 0.63 to 5.2 µg/L in bottom waters (median 1.10 µg/L). Examination of the raw data in Buckee *et al.* (1994 Appendix B) suggests that the bottom samples in the centre of the sound (16-20 m depth) had appreciably more chlorophyll than the surface samples, presumably because of the stronger vertical stratification and therefore weaker vertical mixing in that season (D'Adamo 1992). During the 1994 summer survey, chlorophyll concentrations ranged from 0.78 to 1.04 µg/L in surface waters (median 0.90 µg/L) and from 0.76 to 1.18 µg/L in bottom waters (no median quoted) and, in contrast with the winter survey, there was little distinction between surface and bottom samples.

Helleren and John (1997) examined the long-term trend in chlorophyll levels in Cockburn Sound over the 16-year period 1977 to 1994. Their study extended beyond the results presented by Cary *et al.* (1991) and was subsequently re-examined by Helleren and Pearce (2000). Following the high chlorophyll levels prior to 1980, when seasonal values were sometimes over 6 µg/L (Figure 9), mean chlorophylls have fallen to about 2 µg/L (ignoring the anomalous levels in winter 1991), however, these values will be susceptible to any future changes in nutrient inputs and water circulation/exchange in the sound.

All the time-series data for Cockburn and Warnbro Sounds have been combined into a single seasonal pattern by Helleren and Pearce (2000 Tables 29 and 38) reproduced below:

Season	Cockburn	Warnbro
Annual	1.88 ± 1.53	1.02 ± 0.82
Summer	1.51 ± 1.22	0.82 ± 0.78
Autumn	1.90 ± 1.37	0.82 ± 0.46
Winter	2.43 ± 1.80	1.60 ± 1.07
Spring	1.91 ± 1.76	0.99 ± 0.64

Weekly chlorophyll measurements were undertaken at four sites around the rim of Cockburn Sound by Lemmens *et al.* (1996) in a study of the filtering capacity of seagrass meadows over the summers of 1990/91 to 1993/94. Sampling was undertaken at three depths at each station. The mean chlorophyll concentrations at each site over all samples were 2.22 µg/L at site 1 (Woodman Point), 0.85 µg/L at site 2 (near the original Cary and Masini 1995 station 4 at the northern tip of Garden Island), 1.89 µg/L at site 4 (off Rockingham) and 1.82 µg/L at site 5 (midway up the eastern shore of the sound). This pattern effectively matches the previous studies, with greatest flushing by low-chlorophyll ocean waters at site 2 and highest concentrations along the nutrient-richer eastern shore. Some inter-annual variability was evident, mainly at sites 1 and 2 in the north of the sound.

3.8.2 Metropolitan ocean outfalls

Three sewage outfalls presently discharge into the Perth coastal environment: Beenyup (or Ocean Reef), some 20 km north of Perth, Swanbourne and Cape Peron (between Cockburn and Warnbro sounds) (Lord and Hillman 1995). As part of the model validation plume surveys of the PCWS, chlorophyll was sampled around these outfalls during the spring of 1993 and the summer of 1994. Additional measurements were made around the Beenyup outfall during "event" surveys to study the sea breeze cycle in summer and the effect of a winter storm (Buckee *et al.* 1994). As pointed out by Buckee *et al.* (1994), as there is no chlorophyll-*a* present in the sewage effluent itself, elevated concentrations would be due to phytoplankton processes in the water.

The model validation surveys off Cape Peron were carried out in June 1993 ("winter") and March 1994 ("summer"). The corresponding surveys off Swanbourne were in September 1993 and January 1994, and those at Beenyup were in August 1993 and February 1994 (Buckee *et al.* 1994, Helleren and Pearce 2000 Table 45). The mean chlorophyll concentrations (µg/L, with standard deviations and ranges) from a number of stations around each outfall, derived from Buckee *et al.* (1994), are summarised below. The maximum and minimum chlorophyll values given by Buckee *et al.* (1994 Table 11) do not always correspond to the raw data in their Appendix B; we have used the raw data.

Outfall site		Summer	Winter
Cape Peron	Surface	0.45 ± 0.20 (0.12-1.18)	0.46 ± 0.16 (0.04-0.69)
	Bottom	0.45 ± 0.15 (0.08-0.94)	0.49 ± 0.15 (0.08-0.77)
Swanbourne	Surface	0.30 ± 0.07 (0.16-0.46)	0.49 ± 0.13 (0.25-0.86)
	Bottom	0.32 ± 0.08 (0.20-0.50)	0.71 ± 0.28 (0.35-1.70)
Beenyup	Surface	0.70 ± 0.20 (0.16-1.10)	1.33 ± 0.28 (0.93-1.90)
	Bottom	0.74 ± 0.24 (0.16-1.32)	1.32 ± 0.33 (0.80-1.90)

As reflected in these averages, there was little difference between surface and bottom chlorophyll concentrations at most stations. Winter concentrations at both Beenyup and Swanbourne were higher than those in summer (although there was no seasonal difference evident at Cape Peron). It is interesting that chlorophyll levels at Beenyup were appreciably higher than those from the southern outfalls in both summer and winter.

Previous measurements off Cape Peron presented in Buckee *et al.* (1994) show pre-discharge chlorophyll concentrations of between 0.1 and 1.6 µg/L for 1981 (Binnie and Partners 1981) and between 0.1 and 1.7 µg/L for 1984 (Le Provost *et al.* 1984). Post-discharge chlorophyll concentrations ranged from 0.1 to, an extreme high of, 191 µg/L for the period 1984-1986 (Le Provost *et al.* 1984, 1986), between 0.1 and 0.7 µg/L for the period 1987 to 1991 (Water Authority of Western Australia 1991), and between 0.2 and 3.1 µg/L for 1992 (Halpern *et al.* 1992). Earlier measurements near the Beenyup plume by the Water Authority of Western Australia, presented in Buckee *et al.* (1994), gave chlorophyll concentrations of between 0.3 and 3.4 µg/L for the period 1988-1992. These values indicate the high degree of variability (probably patchiness in both time and space on a variety of scales) that can occur.

The sea breeze-event survey incorporated 35 sites and was conducted over three discrete time periods to capture different phases of the sea breeze cycle. These time periods were defined as a morning session (0700-1200 hours), an afternoon session (1500-2100) and a night session (0000-0645) (Buckee *et al.* 1994 - the raw data for the morning session are not listed in that report). The ranges and mean chlorophyll concentrations (µg/L ± standard deviations) were (Helleren and Pearce 2000 Table 46):

Period	**Surface**	**Bottom**
Morning	no mean (0.16-1.10)	no mean (0.16-1.32)
Afternoon	0.51 ± 0.14 (0.12-0.86)	0.53 ± 0.16 (0.10-0.92)
Night	0.66 ± 0.35 (0.32-2.10)	0.64 ± 0.34 (0.30-2.10)

During the winter storm-event survey, 35 sites were sampled on 9 August 1994 (prior to the storm), four sites on 11 August (the morning of the storm), three sites on 12 August and three sites on 14 August; the ranges and means (± standard deviations) were (Helleren and Pearce 2000 Table 46):

Date	**Surface**	**Bottom**
9 August	0.47 ± 0.26 (0.10-1.02)	0.49 ± 0.27 (0.08-1.10)
11 August	1.09 ± 0.42 (0.80-1.70)	1.12 ± 0.44 (0.78-1.76)
12 August	9.47 ±16.05(0.12-28.0)	0.25 ± 0.04 (0.22-0.30)
14 August	0.17 ± 0.05 (0.12-0.20)	0.23 ± 0.13 (0.10-0.36)

There was some increase in chlorophyll levels from the morning to the afternoon/night during the sea breeze-exercise in February, but the winds were relatively weak and it is difficult to assess the significance of the increase. During the storm-event survey, however, when winds exceeded 25 knots on the night of 10 August and generated 5 m seas (Buckee *et al.* 1994), there was a significant rise in the chlorophyll levels near the Beenyup outfall within a day. A day or two later, chlorophylls dropped back to pre-storm levels (excepting the anomalous and presumably faulty spike in the surface sample on 12 August - examination of the raw data for all the quantities sampled in Buckee *et al.* (1994 Appendix B) suggests this value may in fact be 0.28 instead of 28).

Following completion of the PCWS, the Water Corporation of Western Australia initiated an ongoing program to monitor several water quality parameters around the Cape Peron and Beenyup sewage outfalls. The Perth Long-term Ocean Outfall Monitoring Program (PLOOM) commenced in March 1996 and is currently still running. Temperature, salinity, depth-integrated chlorophyll and nutrients are sampled at about monthly intervals at four stations near each of the two outfalls: site 1 is 4 km south of the outfall, site 2 is directly over the outfall, sites 3 and 4 are 4 and 8 km, respectively, north of the outfall (Thompson 1997, 1998). The water depth at the Cape Peron outfall is about 20 m, twice that at Ocean Reef, and the Cape Peron outfall is also more than twice as far offshore as the Ocean Reef pipeline. The water samples are taken from the upper 60% of the water column.

Analysing the results of the first year's measurements, Thompson (1997) found a strong seasonal pattern at the Cape Peron outfall, with peak chlorophyll concentrations of 1-2 µg/L (at the various stations) in August and lowest levels of about 0.2 µg/L in December. The annual means at the four stations were very consistent. Variability was much higher at the Ocean Reef outfall with no discernible seasonal pattern.

The raw data for the two-year period March 1996 to May 1998 were obtained, courtesy of the Water Corporation and University of Tasmania, and monthly means were computed to show the seasonal variations (Figure 10). The monthly mean chlorophyll concentrations at Ocean Reef were approximately equal to or higher than those at the Cape Peron outfall in all months except July and August, and the weaker seasonality in the north was confirmed.

The seasonal mean, standard deviation and range (µg/L) at each site were computed by Helleren and Pearce (2000 Table 47) as:

Outfall site	**Cape Peron**	**Ocean Reef (Beenyup)**
Summer	0.31 ± 0.16	0.73 ± 0.45
Autumn	0.67 ± 0.38	1.08 ±.0.86
Winter	0.95 ± 0.34	0.77 ± 0.70
Spring	0.88 ± 0.43	1.05 ± 0.80
Annual	0.70 ± 0.42	0.92 ± 0.73

Winter/spring is clearly the period of raised chlorophyll levels at Cape Peron, while at Beenyup the peaks are in autumn and spring, and the concentrations are generally higher at the northern Beenyup outfall. Thompson (1998) suggests these results may be due to a variety of possible causes, including the shallower water, closer proximity to the coast, higher nutrient levels and/or greater stratification at the northern outfall.

3.8.3 Wider regional shelf surveys

Apart from the measurements in specific locations described above, larger-scale regional studies have also been undertaken along the continental shelf off metropolitan Perth.

Shelf-scale regional surveys, during August 1991 and March 1992, were conducted as part of the SMCWS. These shelf-scale surveys incorporated data from the Peel-Harvey estuary, south of Perth, to Sorrento, north of Perth, and out to 70 km offshore (Department of Environmental Protection 1996; Helleren and Pearce 2000 Table 17). The whole area was subdivided into regions, in each of which a number of stations were sampled and the results averaged for surface and bottom concentrations. The winter chlorophyll levels were appreciably higher than the summer levels in all regions, and inshore concentrations were clearly higher than concentrations further out on the continental shelf (Figure 11). In winter, surface concentrations were generally higher than those near the bottom, however, during summer, the reverse tended to be the case, although the differences were generally small. The somewhat anomalously high winter concentrations were attributed, by the Department of Environmental Protection (1996), to outflow from the Peel-Harvey system drifting northwards, meteorological conditions and the presence/absence of the Leeuwin Current.

The highest concentrations in the August survey (during the period of winter rainfall and therefore higher discharges from the Swan and Peel estuaries) were off the mouths of the Peel Inlet (17.7 µg/L at the surface) and the Swan River (6.4 µg/L). Jack (1987) has shown that surface chlorophyll concentrations just upstream of the Swan River mouth, average about 5 µg/L (range 2-11) in summer and 11 µg/L (2-24) in winter, with bottom values being about 5 µg/L (range 2-7) in both seasons. A similar study by John (1987) found the seasonal mean chlorophylls (µg/L, with standard errors) in the lower Swan estuary to be:

Winter	**Spring**	**Summer**	**Autumn**
7.5 ± 1.8	7.3 ± 2.7	3.7 ± 0.2	5.8 ± 0.9

He attributed this variation to the seasonal interchange between fresh (winter) and saline (summer) waters with the strongly seasonal rainfall and runoff distribution. As shown above (section 3.7), chlorophyll concentrations in the Peel Inlet can exceed 300 µg/L during plankton or *Nodularia* blooms (Hodgkin and Birch 1991), so tidal outflow from the inlet can have a marked influence on chlorophyll levels outside the estuary mouth.

During the winter surveys, apart from the estuary mouths, elevated concentrations were effectively constrained to the coastal strip some 10 km wide. The highest concentrations were in the regions immediately north of the Peel-Harvey estuary (Comet Bay at 7.5 µg/L) and the Swan River (Gage Roads at 8.3 µg/L). Probably due to internally-generated phytoplankton blooms, Cockburn Sound (5.8 µg/L) had higher chlorophyll levels than the adjacent coastal regions of Warnbro Sound (4.1 µg/L) and Owen Anchorage (4.6 µg/L). Further offshore, the chlorophyll concentrations were effectively halved. The longest transect was off Marmion, some 25 km to the north of Perth but possibly still within the range of influence of the Swan River. Chlorophyll concentrations across the inner shelf were relatively low and, as would be anticipated, were at or below 1 µg/L further offshore.

By contrast, the summer situation showed much lower concentrations (Figure 11b), presumably reflecting reduced outflow from the estuaries. The highest chlorophyll levels were again just outside the estuary mouths and in Cockburn Sound. This seasonal change is in line with the other surveys discussed above.

During the PCWS, regional studies were conducted between 13 and 15 September 1993 (the so-called "winter" survey) and between 9 to 10 February 1994 (representing summer); the raw data are in Buckee *et al.* (1994) and in Helleren and Pearce (2000 Tables 52 to 54). The actual stations sampled during the winter and summer surveys were quite different, and the stations were grouped differently in Buckee *et al.*(1994 Appendix B).

For the winter survey, the mean chlorophyll concentrations (µg/L, with standard deviations and ranges) were summarised by Helleren and Pearce (2000 Table 52) for each region as:

Region (number of sites)	**Surface**	**Bottom**
Tim's Thicket to Rottnest (24)	0.29 ± 0.16 (0.12-0.89)	0.47 ± 0.26 (0.09-1.20)
Swanbourne to Hillarys (30)	0.49 ± 0.13 (0.25-0.86)	0.71 ± 0.28 (0.35-1.70)
Hillarys to Yanchep (17)	0.31 ± 0.17 (0.18-0.82)	0.45 ± 0.14 (0.19-0.70)
Beenyup to shelf edge (22)	0.39 ± 0.20 (0.13-0.90)	0.43 ± 0.19 (0.13-0.85)
Cockburn to Warnbro (24)	0.83 ± 0.50 (0.16-2.00)	1.35 ± 1.09 (0.24-5.20)

For the summer survey, the mean chlorophyll concentrations (µg/L, with standard deviations and ranges) were summarised by Helleren and Pearce (2000 Table 53) for each region as:

Region (number of sites)	**Surface**	**Bottom**
Swanbourne to Yanchep (18)	0.47 ± 0.44 (0.24-2.10)	0.47 ± 0.42 (0.18-1.74)
Fremantle to Rottnest (10)	0.35 ± 0.34 (0.16-1.16)	(only 1 sample: 0.30 µg/L)
Cape Peron to shelf edge (21)	0.20 ± 0.08 (0.08-0.36)	0.20 ± 0.09 (0.08-0.42)
Fremantle to Mandurah (26)	0.35 ± 0.34 (0.12-1.42)	0.37 ± 0.36 (0.12-1.54)

These regions are too large and too different to be comparable between seasons.

Possibly for this reason, Buckee *et al.* (1994) combined the stations differently, dividing the coastal waters into nearshore (< 25 m depth) and offshore (> 25 m) as well as by north and south. As a guide, the 25 m isobath is about 6 km offshore (Figure 4 in Buckee *et al.* 1994). The median chlorophyll concentrations (µg/L, and ranges) were:

Winter (no. of sites)		**Surface**	**Bottom**
Northern	nearshore (10)	0.34 (0.24-0.82)	0.35 (0.16-0.67)
	offshore (20)	0.22 (0.16-0.38)	0.40 (0.13-0.67)
Southern	nearshore (19)	0.44 (0.21-1.10)	0.97 (0.27-1.80)
	offshore (19)	0.18 (0.12-0.34)	0.39 (0.09-0.77)

Summer (no. of sites)		**Surface**	**Bottom**
Northern	nearshore (8)	0.41 (0.18-2.10)	0.42 (0.28-1.74)
	offshore (10)	0.29 (0.24-0.52)	0.25 (0.18-0.72)
Southern	nearshore (19)	0.20 (0.08-0.60)	0.22 (0.08-0.70)
	offshore (22)	0.20 (0.12-1.16)	0.20 (0.12-0.38)

In almost all cases, the nearshore waters contained more chlorophyll than did the deeper offshore waters, probably a reflection both of nearshore (local) productivity and the presence of the low-nutrient Leeuwin Current along the outer shelf (Pattiaratchi *et al.* 1990, and in press). The northern region tended to have lower chlorophyll concentrations than the southern area in winter but higher in summer. In winter, the bottom waters had somewhat higher chlorophyll concentrations than the surface waters. In summer there was little vertical difference, probably due to better vertical mixing by the strong summer sea breezes. Some of these conclusions may not be real, bearing in mind the single sampling period for each season and the natural patchiness in the water.

The results from these regional surveys have been neatly put into perspective in Figure 12 (after Lord and Hillman 1995). In the summer survey, both the absolute concentrations and variability were higher in the northern waters than the southern areas, while in winter the reverse was the case. This may well reflect the seasonal change in the alongshore currents (Pattiaratchi *et al.* 1995), with the coastal current system transporting Swan River outflow waters northward during the summer months and southwards in winter. Absolute concentrations were higher in Cockburn Sound than either the northern or southern waters in both seasons.

A year-long study (March 1994 to March 1995) of physical water properties, nutrients and chlorophyll concentrations at four stations north and west of Hillarys marina by Lemmens and Thompson (in prep.) showed, that chlorophyll concentrations in this area were an order-of-magnitude lower than those in Cockburn Sound. The stations were in a box-grid, divided as north-south and inshore-offshore. Estimated annual mean concentrations from Lemmens and Thompson (in prep. Figure 4) were about 0.41 µg/L at both inshore stations and about 0.26 µg/L at the two offshore sites (Helleren and Pearce 2000 Table 49). Lemmens and Thompson found no distinct seasonal variation in the chlorophyll levels. The highest individual concentrations were 1.24 and 1.55 µg/L at the inshore stations in July/August 1994, and 1.83 and 2.27 µg/L for the offshore sites near the reef system on the same day in March.

Similar results have been obtained from a geographically larger grid of four stations between Trigg and Ocean Reef as part of an ongoing monitoring project for the Perth outfalls (Kinhill 1998). Chlorophyll concentrations (as well as other parameters) are being sampled both in the water column and sediment in water depths of about 10 m. Sampling, in April (three days), June (three days) and September 1997 (two days), again showed that chlorophyll levels were generally low and that offshore sites had lower chlorophyll levels than the inshore sites. The mean concentrations (µg/L, and ranges) over the three surveys at each site were:

Site	Mean (range)
3-Mile Reef (north-offshore)	0.36 (0.09-1.78)
Centaur Reef (south-offshore)	0.61 (0.25-1.32)
Ocean Reef (north-inshore)	1.67 (0.53-2.86)
Marmion (south-inshore)	1.66 (0.83-4.70)

These results were obtained essentially in autumn, winter and spring, but the series is too short to suggest any seasonal pattern; the values are higher than those found by Lemmens and Thompson (in prep.).

As part of a national project to provide surface-truth measurements for the recently-launched SeaWiFS ocean colour sensor, CSIRO Marine Research and Curtin University School of Physical Sciences conducted monthly transects out to 40 km west of Hillarys boat harbour (Figure 22). These surveys ran from October 1996 to December 1998 (Pearce and Lynch in prep.). Among other physical, chemical and bio-optical measurements, depth-averaged chlorophyll concentrations were measured at nine stations (H0 to H40, the suffix denoting the distance offshore in km) with 5 km spacing. Nominal water depths at the stations varied from 7 (closest inshore) to 90 m, and sampling was by pumping through a flexible hose to give a vertically-integrated sample. Chlorophyll analysis was by both the spectrophometric and fluorometric methods. The data have been summarised in Helleren and Pearce (2000 Table 51).

This has been the only study to date which consistently sampled chlorophylls across the continental shelf off southern Western Australia over an extended period, to show seasonal variability of the inner- and outer-shelf waters. Station-averaged chlorophyll concentrations over the 27 surveys ranged from 0.24 µg/L, at the outermost station H40, to 0.70 µg/L at the station nearest the coast H0) (Figure 13). The highest chlorophyll concentrations (exceeding 0.4 µg/L) were restricted to the shallow (< 15 m depth) region less than 10 km from the coast, whereafter mean chlorophyll levels were reasonably steady at between 0.2 and 0.3 µg/L across the shelf.

Monthly means averaged across the whole transect indicated a seasonal cycle with a strong peak exceeding 1 µg/L in June (Figure 13). The seasonal statistics for selected stations across the transect were (Helleren and Pearce 2000 Table 51):

Stn	H0	H5	H10	H20	H40
SU	0.52 ± 0.22	0.41 ± 0.09	0.15 ± 0.05	0.16 ± 0.10	0.17 ± 0.15
AU	0.66 ± 0.32	0.40 ± 0.20	0.35 ± 0.22	0.28 ± 0.13	0.22 ± 0.09
WI	0.95 ± 1.02	0.34 ± 0.17	0.39 ± 0.17	0.52 ± 0.30	0.43 ± 0.21
SP	0.69 ± 0.38	0.48 ± 0.26	0.20 ± 0.15	0.26 ± 0.14	0.15 ± 0.08

Despite the high level of variability, there was a clear seasonal cycle with a winter peak at all stations except H5, where the highest value was in spring.

3.9 Jurien Bay

No data have been located.

3.10 Abrolhos Islands

The only chlorophyll data in the vicinity of the Houtman Abrolhos Islands appears to be some transects between Geraldton and the islands sampled by Hatcher (unpublished data) in 1982/83; see Helleren and Pearce (2000 Table 55a). Most of the chlorophyll concentrations were below 0.1 µg/L. The highest concentration measured was 0.14 µg/L in the lagoon of the Easter Group in May and again in July 1983.

3.11 Shark Bay

Kimmerer *et al.* (1985) sampled chlorophyll along a transect between Cape Inscription through Hopeless Reach into the southern extremity of Hamelin Pool in June 1983 (data in Helleren and Pearce 2000 Table 56). The concentrations were all low, varying from 0.04 µg/L in Hamelin Pool to 0.63 µg/L in Hopeless Reach (this was to some extent an "outlier", with the next highest concentration being 0.29 µg/L near the Faure Sill). The concentrations across the western (deeper) part of Shark Bay, which is more flushed by ocean waters, were uniformly low at 0.08-0.09 µg/L.

A time-series experiment was carried out by Peterson and Black (1991) in January/February 1987. Chlorophyll concentrations were measured to examine changes in phytoplankton over a shallow intertidal flat near Monkey Mia, on the western shore of Hopeless Reach (data in Helleren and Pearce 2000 Table 57). The chlorophyll concentrations over a three- to four-hour period varied between 0.03 and 0.08 µg/L, and there was a decline in the concentration of approximately 25% over the sampling period as the incoming tide flooded past the measuring site.

It appears, therefore, that while there may be some localised productivity, the waters of Shark Bay are generally very low in chlorophyll, in line with the open ocean waters.

3.12 Exmouth Gulf

Exmouth Gulf is large (approximately 40 km wide and 80 km long) and relatively shallow. The only available chlorophyll information appears to be from a single survey of the gulf in September/October 1994 (McKinnon and Ayukai 1996; see Helleren and Pearce 2000 Table 59). Three replicate samples were taken at mid-depth for chlorophyll analysis at 10 stations distributed across the gulf. The chlorophyll concentrations were low (0.15-0.35 µg/L), with the two highest values being from stations near the eastern shore of the gulf.

Although Coral Bay (23°S), at Ningaloo Reef, is not included in the terms of reference of the present report, a study investigating sewage disposal in the bay has some chlorophyll data. Simpson and Field (1995) measured chlorophyll levels at 27 sites between September and October 1994 (reproduced in Helleren and Pearce 2000 Table 58). The concentrations ranged from 0.07 µg/L at site CB22 (near Monks Head in the open ocean south of Coral Bay) to 0.28 µg/L at site CB25 (close inshore near Mauds Landing, north of Point Maud). The average chlorophyll concentration over all stations in the study period was 0.15 µg/L. These concentrations were considered to be low, as may be expected for tropical waters. The chlorophyll levels were higher at sites in the inner part of Bills Bay, consistent with high groundwater nutrient inputs into this region from nearby tourist facilities (Simpson and Field 1995).

Chlorophyll data for four regions within Coral Bay sampled on 26 March 1998 were presented by Lord and Associates (1998). The ranges of values presented for the four regions were: Mauds Landing 1.1-1.3 µg/L, northern Bills Bay 1.4-1.7 µg/L, southern Bills Bay 0.9-1.0 µg/L, and Monks Head 0.6-0.7 µg/L. Again, these concentrations were relatively low, although higher than the Simpson and Field (1995) data discussed above.

3.13 Dampier Archipelago

Some extensive chlorophyll measurements were made in the Dampier area in the mid-1980s by the Environmental Protection Authority, but were not published at the time. The data were printed on hard-copy as well as archived to magnetic tape from a now-obsolete DEC-10 computer, but neither the printout nor the tape have been located so accessing these data may no longer be possible.

3.14 North-West Shelf

Apart from the Dampier work referred to above, some chlorophyll measurements have also been made further offshore on the North-West Shelf. Although there is some localised nutrient enrichment on the shelf, Rochford (1977) suggested that it was not due to upwelling, but he was unable to ascertain the cause.

Hallegraeff and Jeffrey (1984) collected chlorophyll data from 46 stations across the North-West Shelf in June 1980, December 1982 and June 1983 (Helleren and Pearce 2000 Table 60). Depth-integrated chlorophyll concentrations were quoted in mg/m^2, which we have converted to µg/L by dividing the concentration by the water column depth sampled. Total water column chlorophyll concentrations ranged between 10 and 55 mg/m^2 (equivalent to 0.2-1.1 µg/L), with cruise mean values of 0.49, 0.60 and 0.43 µg/L. The nanoplankton (< 15 µm) component of the phytoplankton accounted for between 53 and 97% of total chlorophyll.

Tranter and Leech (1987) reported vertically-integrated chlorophyll concentrations at six stations along each of two transects across the North-West Shelf during eight cruises between July 1982 and November 1983; Helleren and Pearce (2000 Table 61) have converted these to absolute concentrations. The depth range sampled was 40-150 m. Station-averaged chlorophyll levels were between 0.2 and 0.6 µg/L, and the highest individual sample was 1.04 µg/L at mid-shelf in June 1983. These values were higher than those in the Indian Ocean subtropical gyre (< 0.05 µg/L) but much lower than those in the classical upwelling regions. On the North-West Shelf, nutrient enrichment is apparently from below as slope water intrudes onto the continental shelf in summer when the Leeuwin Current is weak - the phytoplankton is therefore mainly near the bottom and below the thermocline (and therefore unlikely to be seen in colour satellite imagery). No elevated phytoplankton concentrations were observed at the surface offshore of the 40 m isobath. Both Hallegraeff and Jeffrey (1984) and Tranter and Leech (1987) found subsurface chlorophyll maxima at depths of 40-100 m in summer (associated with pycnoclines) and at more uniform depth distribution in winter. The concentration dropped from about 0.4 µg/L, along the inner shelf, to half that value beyond the shelf break. No consistent seasonal pattern was evident.

During a survey of the biological and chemical properties of the water near the Montebello Islands in September 1995 (Furnas and Mitchell 1998), chlorophyll samples were taken at a number of stations near an oil platform. The depth-averaged mean and median concentrations were 0.26 and 0.27 µg/L respectively. The vertical profile from a single station in 25 m of water was plotted, showing little change with depth.

3.15 South-west coast

A series of chlorophyll measurements by Ayvazian and Hyndes (unpublished data - listed by permission in Helleren and Pearce 2000 Table 44) along a large stretch of the coast between Geraldton and Esperance, do not fit into any of the other geographic regions specified and so are dealt with separately here. Inshore chlorophyll concentrations were measured at 23 beach sites over the period March 1991 to December 1992; the sites are shown in Ayvazian and Hyndes (1995). The sampling interval was irregular and each site was visited infrequently, so no seasonal pattern can be derived. The highest chlorophyll concentrations were 2.7 µg/L in Koombana Bay (Bunbury, in Geographe Bay - Figure 1) in April 1991, 2.6 µg/L off Jurien Bay in October 1992, 4.6 µg/L at Esperance in February 1991, 3.3 µg/L in Shoalwater Bay (just south of Cockburn Sound) in June 1992, and 3.6 µg/L at Barracks Beach (Garden Island) in August 1992. Otherwise, the concentrations were generally in the range of zero to 2 µg/L, typical of west coastal waters. More representative sampling would be required to reveal any true regional chlorophyll enhancement through the natural patchiness.

4.0 Ocean colour measurements from space: CZCS and Landsat

4.1 Introduction to remote sensing of ocean colour

Satellite remote sensing is presently the only feasible method of monitoring large areas of the ocean surface on a regular basis. One of the properties of the ocean that can be measured by remote sensing is colour, which is influenced by the concentration of phytoplankton (and associated pigments) as well as other particulate matter in the water. As the phytoplankton concentration (and hence the chlorophyll level) increases, ocean colour changes from blue to green (Hovis *et al*. 1980). Colour satellite imagery can therefore be used in studies of surface phytoplankton distributions (and hence areas of enhanced productivity), coastal ocean circulation (using the colour as a tracer), and dispersion of river and outfall plumes.

In the open ocean, so-called "Case 1" waters (where the reflectance is determined solely by absorption - Hooker *et al.* 1993), the dominant contributor to ocean colour is phytoplankton. Remotely-sensed colour imagery enables chlorophyll concentrations to be estimated with some reliability. In coastal, "Case 2", waters on the other hand, the reflectance (and hence the colour of the water) is also influenced by scattering due to suspended sediment and land-derived organic matter, so separation of the chlorophyll component is more complex (Simpson 1993). In shallow coastal waters, since visible light can penetrate well into clear ocean water, there can also be a potential contribution of reflection from the seabed to the water-leaving radiance, as well as from "mixed" pixels which include some land (Wallace and Campbell 1998). Further, because 80-90% of the signal received by the satellite arises from the atmosphere, corrections must be applied to yield valid estimates of the water-leaving radiance and hence the chlorophyll concentration in the water (Feldman *et al.* 1989).

It must also be borne in mind that direct chlorophyll measurements in the south-eastern Indian Ocean have shown (section 4.1) that the highest chlorophyll concentrations are generally found at about 75 m depth (Humphrey 1966), well below the depth able to be sampled by the CZCS. In the generally well-mixed shelf waters, surface chlorophyll estimates will be more representative of the water column, although, as shown by Chaney (1978), chlorophyll profiles can occasionally show large vertical gradients.

Satellites with different spatial resolutions and different re-visit periods have been used for ocean colour work. The first dedicated ocean colour measurements were made between 1978 and 1986 by the CZCS, which was suitable for large-scale studies such as open-ocean and continental shelf waters. Higher-resolution colour imagery, more appropriate for coastal waters, is available from the Thematic Mapper (TM) sensor on the Landsat-4 and -5 satellites launched in July 1982 and March 1984 respectively.

For further information on the feasibility and application of ocean colour measurements to coastal monitoring in Australia, see Wallace and Campbell (1998) and Pearce and Pattiaratchi (1997). Smith and Pearce (1997) have compiled a detailed bibliography of satellite remote sensing in Western Australia.

4.2 The Coastal Zone Colour Scanner

4.2.1 The satellite and sensor

The CZCS was an ocean colour sensor on the Nimbus-7 satellite which was launched in October 1978 and operated until mid-1986 when it failed. The original design life was one year (Feldman *et al.* 1989). It was the first space-borne instrument designed specifically for measuring ocean colour, thus providing a means for estimating the concentration of phytoplankton pigments in the near-surface waters of the ocean from space. There were four spectral bands in the visible part of the spectrum, and the pixel size was 800 m (at nadir) with a swath width of about 1600 km (Hovis 1982).

As Nimbus-7 was an experimental (as opposed to an operational) satellite, the CZCS was operated intermittently on demand. The coverage in the south-eastern Indian Ocean was therefore very patchy in both space and time. Coverage is further restricted as radiation in the visible wavelengths is unable to penetrate cloud, so there are many data gaps especially towards the end of the useful life of the sensor.

Based on experience gained from early analyses of CZCS imagery for various parts of the global ocean, a re-compilation of the complete CZCS data set was prepared using a consistent set of procedures and interactive quality control (Feldman *et al.* 1989). This dataset was made available on CD-ROM in the form of global monthly composites over the period 1978 to 1986 and "represents the most comprehensive source of ocean colour measurements to date" (Tran *et al.* 1993). Field studies have suggested that the accuracy of near-surface phytoplankton pigment concentrations derived from CZCS data is at best 35% for Case 1 waters (under ideal conditions - John Parslow pers. comm.), and within a factor of 2 generally (Feldman *et al.* 1989).

The effective spatial resolution of the re-processed CD-ROM dataset is nominally 18 km, approximately 36 pixels in a 1 degree latitude/longitude square. The width of the continental shelf off Western Australia varies between about 10 km, off Ningaloo Reef near Exmouth, to over 150 km on the widest part of the North-West Shelf. Therefore, the 18 km CZCS pixels are wider than the continental shelf in some areas, and are certainly larger than some of the areas being examined in the present terms of reference (Section 1). The CZCS dataset is inapplicable for shallow nearshore waters and semi-enclosed regions such as Shark Bay because of coastal pixel contamination and bottom reflectance. Nevertheless, the data are useful in showing the larger-scale distribution and seasonality of chlorophyll in Western Australia's poorly-surveyed waters.

A monthly climatology was also prepared on the CD by averaging the individual monthly files over all years. In regions such as the ocean off Western Australia where the data are comparatively sparse, these monthly means may not be very reliable but are included here as an indication of possible seasonal trends. As there is some question about the ability of CZCS data to adequately resolve inter-annual variability of chlorophyll in the ocean (Hooker *et al.* 1993, John Parslow pers. comm.), only the monthly climatology has been used in this report.

4.2.2 Previous CZCS results in Western Australian waters

To date, little use has been made of the CZCS data archive for local Western Australian waters. Lockhart (1994) examined the seasonal variability of chlorophyll in a block centred on latitude 21.4°S and longitude 114.8°E, near Exmouth, for the years 1980 to 1982 using monthly CZCS composites. While there was a high level of scatter in the monthly values between years, chlorophyll concentrations were generally higher (up to 3 µg/L) between January and June than in the spring months (1-2 µg/L). Based on this rather limited time-series, Lockhart (1994) concluded that there was a biannual chlorophyll cycle off Exmouth as a result of vertical mixing (causing a breakdown of thermal stratification) in winter and solar radiation during summer. An unpublished analysis of the CZCS dataset by Parslow and Rathbone (1997) using least-squares fitting of time series models with seasonal and inter-annual components, showed that chlorophyll concentrations in the Leeuwin Current region were highest in May-June.

On a more regional scale, Pattiaratchi *et al.* (1990, and in press) analysed individual full-resolution CZCS images between Shark Bay and Cape Leeuwin for March and May 1981 to examine the interaction between the Leeuwin Current and the water on the continental shelf. They showed that the shelf waters had higher concentrations of chlorophyll than the Leeuwin Current, and that as the current meandered onto the shelf it tended to entrain the more productive shelf waters and effectively export the chlorophyll from the shelf region.

4.2.3 CZCS data analysis for this study

At a gross scale, chlorophyll concentrations have been extracted from the CZCS climatology for the west coasts of Australia, southern Africa and South America to compare productivity in the Benguela (Africa) and Humboldt (America) upwelling regions with that in the Leeuwin Current. Chlorophyll concentrations have been averaged for pixels 2 to 5 offshore (*i.e.* ignoring the 18 km pixel nearest the coast to avoid possible seabed and coastal effects), in 10-degree latitude bands centred on the upwelling regions off each of the three coasts. A simple quality control has been exercised by computing for each region the average chlorophyll concentrations and root-mean-square (RMS) values in 1-degree bands by four pixels cross-shelf (representing 24 pixels), and then ignoring areas where the RMS exceeds two (arbitrarily selected by inspection).

While not too much emphasis should be placed on individual months because of the limitations in CZCS data coverage and accuracy, appreciably higher chlorophyll levels were found in the Humboldt and Benguela Current upwelling regions than off Western Australia (Figure 14), as evident in the annual mean chlorophyll concentrations, below, derived from the satellite data:

Region	Latitude band	Chlorophyll (µg/L)
W. Australia	25°-35°S	0.25
S. Africa (Benguela)	20°-30°S	1.69
S. America (Humboldt)	6°-16°S	0.86

The seasonal patterns are also quite different. In the Benguela (Africa) region, summer/autumn upwelling leads to increased productivity between January and May. The pattern is less clear off South America (Humboldt), although if the anomalous value for July is excepted, the highest chlorophylls occur between late spring and summer. In the Leeuwin (Western Australia) region, by contrast, peak productivity is found in winter (May to August), and chlorophyll levels are very low for the remainder of the year (Figure 14). This effectively matches the seasonal pattern derived from *in situ* sampling along Western Australia's continental shelf discussed above.

For a more detailed analysis of Western Australia's waters, monthly mean CZCS-derived chlorophyll data for the area 17°-37°S and 110°-122°E (the eastern limit of the Indian Ocean datafile) have been extracted from the global data available on the CD-ROM set. These data have been analysed to show the spatial and temporal distribution of chlorophyll concentrations around the Western Australian coast. Because Nimbus-7 was not an operational satellite and the CZCS was only switched on to record over specific areas and particular times, there are many and large gaps in the data for the south-eastern Indian Ocean. As an indication of the data coverage for Western Australian waters, Figure 15 illustrates the percentage of data for each 1-degree latitude band between 110° and 122°E (or the coast) for each month over the eight-year period. Clearly, northern regions of the Western Australian coast were better covered than the southern areas, with a distinct drop in observations south of about latitude 26°S (Shark Bay). The "best" years were 1981 and 1982 (Lockhart 1994). It is evident too that the chlorophyll climatology, derived from these individual monthly data sets, must be viewed with caution in some areas and some months.

Despite these limitations, the climatological chlorophyll images (Figure 16) clearly illustrate the higher chlorophyll concentrations on the continental shelf compared with those of the open ocean, as found by Pattiaratchi *et al.* (in press). Offshore chlorophylls were generally low at < 0.1 µg/l, peaking at 0.2-0.4 µg/l in July/August in agreement with the *in situ* measurements of Humphrey and Kerr (1969). On the continental shelf, the concentration was also low during the summer months but exceeded 0.5 µg/L off the mid-west coast in May and July, as found by Parslow and Rathbone (1997). For reasons given earlier, the apparently high chlorophylls in the shallow waters of Shark Bay and Geographe Bay, as well as near the Abrolhos Islands, were probably due to the shallow water/land effects, although they could also indicate some enhanced productivity in those areas. There were relatively high concentrations along the south coast and in the Southern Ocean as well, typical for that latitude band around the globe.

The raised chlorophyll concentrations on the continental shelf, as well as the higher productivity in the autumn/winter months, are graphically illustrated in the zonal chlorophyll transects for two selected latitudes (Figure 17). Along both these transects, the seabed deepened to below 50 m within about 5 km (about 1/4 of a pixel) of the shore, so the apparent coastal enrichment was not an artefact of the imagery. Clearly, the chlorophyll concentration fell rapidly with distance offshore, and beyond the first two pixels (36 km) it was generally down to low oceanic levels of less than 0.2 µg/L. The highest concentrations were in May and August. Results elsewhere along the coast showed a similar pattern, and were supported by time-series plots over the eight-year archive presented by Marinelli (in prep.), where the same seasonal pattern appeared in different years, despite the data gaps, and suggested that the monthly climatology was probably realistic. There was evidence of inter-annual variability particularly in the first five pixels on the continental shelf; this is being investigated in detail by Marinelli (in prep.).

4.3 Landsat

4.3.1 The satellite and sensors

The Landsat-4 and -5 satellites are polar-orbitors with altitudes of about 700 km and repeat periods of 16 days (Matra Marconi 1993). They carry the Thematic Mapper (TM) which has three bands in the visible range, three in the near- and mid-infrared regions, and one band in the thermal infrared region of the spectrum. Pixel size is 30 m (appreciably smaller than the CZCS ground resolution) and the swath width is 185 km. Applications to the marine environment are discussed by, for example, Robinson (1985) and Pattiaratchi *et al.* (1991, 1994).

4.3.2 Results for Western Australian waters

Landsat TM data have been used locally in studies of chlorophyll distributions in Cockburn Sound and the Peel-Harvey estuarine system (Figure 1).

The Cockburn Sound project modelled chlorophyll concentrations by developing appropriate algorithms from TM data in conjunction with *in situ* measurements undertaken specifically for the purpose between January and May 1990 (Pattiaratchi 1992, Pattiaratchi *et al.* 1991, 1994). Three (out of 10) images were selected for analysis coincident with the surface measurements at a total of 39 sites. The TM radiance data in spectral bands 1 and 3 were corrected for atmospheric effects and a block of 5x5 pixels around each *in situ* site was analysed. Although, as may be expected, there was a reasonable amount of scatter in the results, a significant correlation with both surface chlorophyll concentrations (which ranged between 0.2 and 2.7 µg/L) and Secchi Disk depths (range 4-15 m) enabled prediction algorithms to be derived for these parameters. The standard errors were ± 0.3µg/L and ± 1.2 m respectively.

The main benefit of the satellite imagery is the ability to map the water quality over large areas simultaneously. The selected images showed a large degree of spatial variability, but higher chlorophyll concentrations occurred in the southern areas of Cockburn Sound, which had limited exchange with open-ocean waters. The higher chlorophyll levels in shallow nearshore waters were apparently due to seabed reflectance contaminating the water-leaving radiances (Pattiaratchi *et al.* 1994). Temporal differences were also found between the sampling dates.

In a similar study in the shallow Peel-Harvey estuary, Lavery *et al.* (1990,1993) assessed the potential of Landsat TM for monitoring water quality (including chlorophyll concentrations and Secchi Disk depths) in estuarine waters. Field measurements were carried out in the estuary on four occasions between December 1989 and February 1990 (see section 3.7) to coincide with Landsat TM overpasses. As in the Cockburn Sound study, the *in situ* chlorophyll concentration was significantly correlated with the TM (corrected) radiances in the Case 2 waters of the estuary. The contrast between the colour of the estuarine water and that of the low chlorophyll water entering from the open ocean, enabled some features of the circulation and dispersion to be followed. An anticlockwise eddy was mapped during the January 1990 survey. This study was before the Dawesville Cut had been opened, and both present-day chlorophyll levels and distribution patterns in the estuary will be different as a result of the enhanced flushing through the cut.

5.0 Atlas of seasonal chlorophyll levels

While much of the chlorophyll data around the Western Australian coastline is too patchy (in both time and space) to yield meaningful results, seasonal patterns can be derived for those areas which have been adequately sampled. In this section, a series of charts (Figures 18 to 22) have been prepared summarising average chlorophyll concentrations for each of the four seasons. The same chlorophyll scale has been used throughout to facilitate comparison between and within regions.

Albany harbours: Historically there was a large reduction in chlorophyll levels in Princess Royal Harbour between 1979 (with high summer and autumn concentrations) and 1988. By 1989 concentrations were generally well below 1 µg/L in both Princess Royal Harbour and in King George Sound.

Currently, chlorophyll concentrations are low in both Oyster and Princess Royal harbours, as well as in King George Sound (Figure 18). Seasonally, there is a peak in chlorophyll levels in winter in these two water bodies. However, in Oyster Harbour both autumn and winter show higher chlorophyll concentrations, slightly exceeding 2 µg/L, as well as greater variability (reflected in the standard deviation bars).

There are currently aquaculture leases in Oyster Harbour (mussels and oysters) and the south-western waters of King George Sound (mussels only), with further development anticipated along the western shore of the Sound (Tina Thorne, pers. comm.). An earlier lease in eastern Princess Royal Harbour is no longer operational, but a new lease has been applied for.

Wilson Inlet: For reasons that are not presently clear, much higher concentrations are found in Wilson Inlet (Figure 19) than in most of the other water bodies reviewed in this report. Peak chlorophyll levels of 3-4 µg/L and the highest variability clearly occur in spring at all the Wilson Inlet sites presented. Only in summer does the mean concentration fall below 1 µg/L at most stations. Spatially within the inlet (at least for the stations with sufficient data to adequately define the seasonal cycle), there is little variation between sites despite the periodic opening of the estuary entrance to the ocean.

Peel-Harvey estuary: Since the opening of the Dawesville Cut in 1994, chlorophyll concentrations in the Peel-Harvey system have been substantially reduced, particularly during the previously-high chlorophyll seasons of summer and spring. Nevertheless, the concentrations are much higher (Figure 20) than in the other water bodies discussed in this report, suggesting that the estuary is still in an eutrophied condition. Since the opening in 1994, seasonal mean chlorophyll levels in Peel Inlet have varied between 1 and 8 µg/L, while in Harvey Estuary the concentrations are even higher. There is no consistent seasonal pattern in the surface and bottom waters of either estuary. Geographically, there are increasing chlorophyll levels down the Harvey Estuary and (although less clearly) the Peel Inlet with distance away from the Dawesville Cut.

Perth metropolitan area and Cockburn Sound: The southern metropolitan waters of Perth have been intensively monitored over the past two decades. In the relatively uncontaminated waters of Warnbro Sound, the seasonally-averaged concentrations are generally between 1 and 2 µg/L, with highest chlorophylls in winter and, in some areas, spring as well (Figure 21). This is the same seasonal pattern that occurs offshore in the open ocean where the concentrations are almost universally below 1 µg/L and the variability is low.

In parts of Cockburn Sound, on the other hand, in the late 1970s chlorophyll concentrations averaged around 5 µg/L, reflecting the high industrial nutrient loadings at the time. Recent sampling, however, shows that the chlorophyll levels in Cockburn Sound have fallen dramatically (by about half), and in many areas are now only marginally higher than those in Warnbro Sound. As may be expected, lowest concentrations are in the north-western region of the sound, where exchange with the open ocean is greatest and where the winter peak matches much of Warnbro Sound. In the southern and eastern parts of Cockburn Sound, the chlorophyll levels are between 1 and 3 µg/L, with a somewhat mixed seasonal pattern. The concentrations are highest in spring/summer near Woodman Point (site CS6), autumn/winter and autumn and spring at the two stations midway down the eastern part of the sound (CS9 and CS12), and clearly in winter near the Causeway (CS11) at Rockingham (Figure 21). Some of this apparent seasonal and spatial variability may be due to different sampling periods at each station and possibly the hydrodynamics/circulation of the sound resulting in the consequent variable local residence times.

There are existing mussel leases off the north-eastern tip of Garden Island (near site CS4, Figure 21) and the south-eastern shore of the sound where chlorophyll levels are relatively low. New leases are proposed (Tina Thorne pers. comm.) just north of site CS11, where the chlorophyll concentration is appreciably higher.

Ocean outfall sites and shelf waters: Chlorophyll concentrations in the open continental shelf waters off Perth are low (Figure 22). Only close inshore does the concentration reach 1 µg/L in winter. Beyond about 5 km offshore the chlorophyll levels, almost without exception, are below 0.5 µg/L, with a small winter peak at most sites. Near the two outfall sites, the levels are higher at about 1 µg/L in autumn and spring (north) and winter/spring (south).

Other areas: Insufficient sampling has been undertaken to show even broad seasonal patterns elsewhere along the coast.

Chlorophyll concentrations on the offshore North-West Shelf generally average between 0.2 and 0.5 µg/L; there are no inshore (coastal) observations for the North-West Shelf region. Further south, concentrations in Exmouth Gulf are similar to those of the North-West Shelf, while chlorophylls in Coral Bay and Shark Bay are even lower at 0.1-0.3 µg/L. There are very high chlorophylls in some of the estuaries and drains entering Geographe Bay, but the coastal waters of the Bay itself experience normal oceanic chlorophyll concentrations.

Sporadic coastal sampling between Geraldton and Esperance indicated similar levels, with some concentrations being over 1 µg/L and occasionally exceeding 2 µg/L, but the data were too sparse for these results to be interpreted meaningfully. A single survey in the Recherche Archipelago found low concentrations in this area, except for elevated levels around a sunken fertiliser carrier.

6.0 Summary and conclusions

Chlorophyll is accepted as a valid and easily measured indicator of water quality. As has been pointed out in many of the papers and reports reviewed here, chlorophyll concentrations in Western Australian waters are highly variable in both space (horizontally and vertically) and time. From the results of the Perth Coastal Waters Study, Lord and Hillman (1995) concluded that there was a naturally high variability of phytoplankton populations (reflected in chlorophyll levels) in local waters, with a small-scale “patchiness” in which concentrations can vary by a factor of 3 within a distance of 500 m. In addition, chlorophyll monitoring has been very sporadic, so for most of Australia’s 8200 km coastline there are no measurements or so few as to preclude any realistic assessment even about seasonal patterns.

Nevertheless, for those areas with adequate chlorophyll sampling (Albany harbours, Wilson Inlet, Peel-Harvey system and Perth coastal waters) and aided by satellite remote sensing of ocean colour, we have been able to draw some conclusions about the major chlorophyll distribution and variability by appropriate averaging, both temporally and spatially. We have, however, found that some of the published and unpublished chlorophyll data for Western Australian coastal waters are of questionable reliability.

Large-scale oceanographic sampling, Coastal Zone Colour Scanner (CZCS) satellite imagery and local *in situ* measurements have all demonstrated that south-eastern Indian Ocean waters are nutrient- and chlorophyll-poor, with chlorophyll concentrations generally well below 1 μg/L. By contrast, chlorophyll concentrations in the upwelling regions off the west coasts of southern Africa and South America are between three and seven times higher than concentrations in the Leeuwin Current-dominated Western Australian shelf waters. Analysis of historical CZCS imagery has shown that on-shelf meandering of the low-nutrient Leeuwin Current entrains the more productive shelf waters and so effectively exports chlorophyll from the continental shelf.

Chlorophyll levels are generally higher close inshore, but tend to exceed 1 μg/L only in regions where nutrient concentrations have been artificially raised by agricultural runoff or industrial/sewage effluent. Compared with temperate waters elsewhere in the world where phytoplankton cycles generally show spring and autumn blooms (Helleren and John 1997), this review has shown that in the south-eastern Indian Ocean and Western Australian coastal waters, peak chlorophylls generally occur in winter, with the lowest concentrations in summer and autumn. In some areas, such as Cockburn Sound, Warnbro Sound and adjacent waters, this winter maximum is probably due to the dominance of silicoflagellates during that season, while riverine input may also be a contributor. There are regions, however, where a different seasonal pattern seems to exist but this may be a result of inadequate sampling.

Parslow (pers. comm.) has suggested that, although there is a high degree of variability, mean chlorophyll levels in the oceanic and coastal waters of Western Australia effectively fall into four categories:
(i) chlorophyll < 0.2 μg/L is characteristic of offshore/oligotrophic waters;
(ii) chlorophyll < 1 μg/L is found in most coastal waters not subject to anthropogenic enrichment;
(iii) chlorophyll > 1 μg/L generally occurs in shelf waters or estuaries subject to nutrient enrichment;
(iv) chlorophyll > 10 μg/L would be typical of highly eutrophied estuaries.

In regions with industrial and municipal contamination, such as the Albany harbours and in Cockburn Sound, previously high chlorophyll concentrations have been appreciably reduced by stringent management practices. The opening of the Dawesville Cut has lowered the earlier very high nutrient and chlorophyll concentrations in the Peel-Harvey system. It is clear that the present chlorophyll levels in all these well-studied water bodies should be viewed as transient, being influenced both by potentially varying nutrient inputs as further industrial development occurs and countered by remedial management practices.

The question may be raised: are more productive (higher chlorophyll) regions desirable for aquaculture development? As discussed above, elevated chlorophylls in many areas may well be due to raised nutrient levels resulting from anthropogenic influences such as industrial or municipal wastes, with the possibility of contamination by harmful chemicals. Increased productivity may also lead to undesirable effects such as eutrophication, fouling of cages, etc. There may be unpalatable phytoplankton species present, *e.g. Nodularia* (blue-green algae) in the

Peel-Harvey system, which may not necessarily increase productivity further up the food chain and such areas of high chlorophyll could be prime candidates for potentially toxic phytoplankton species.

In a detailed review of factors influencing bivalve growth, Saxby (submitted) found that successful aquaculture of bivalves requires chlorophyll levels consistently above 1 µg/L, although for best results the mean annual concentration should exceed 2 µg/L. On this basis, it is clear that most sections of the Western Australian coast may not be sufficiently productive for successful bivalve aquaculture, although some localised and semi-enclosed water bodies may well be suitable provided other criteria are also taken into account. We recommend that site-specific nutrient/chlorophyll monitoring should be undertaken if aquaculture ventures are planned in regions which have not as yet been examined in any detail. It would be desirable to study the phytoplankton dynamics (possibly including zooplankton) to determine spatial and temporal changes in species composition, and perhaps even undertake direct productivity measurements.

While analysis of coarse-resolution CZCS imagery has demonstrated the potential value of satellite remote sensing for monitoring oceanic and open-shelf chlorophyll distributions, higher-resolution ocean colour imagery from satellites such as Landsat can be profitably used to complement *in situ* measurements for comparative studies in coastal embayments and estuaries. New satellite colour sensors, including SeaWiFS, will provide excellent opportunities for mapping temporal and spatial variability along Western Australia's continental shelf, provided the appropriate (and very necessary) atmospheric corrections and chlorophyll algorithms have been refined for local conditions. In particular, the spectral bands on SeaWiFS will enable the development of algorithms for better discrimination of Case 2 (nearshore-estuarine) waters, although the 1 km nominal pixel size and bottom reflectance may still be limiting for shallow inshore waters.

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8.0 References

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9.0 Figures

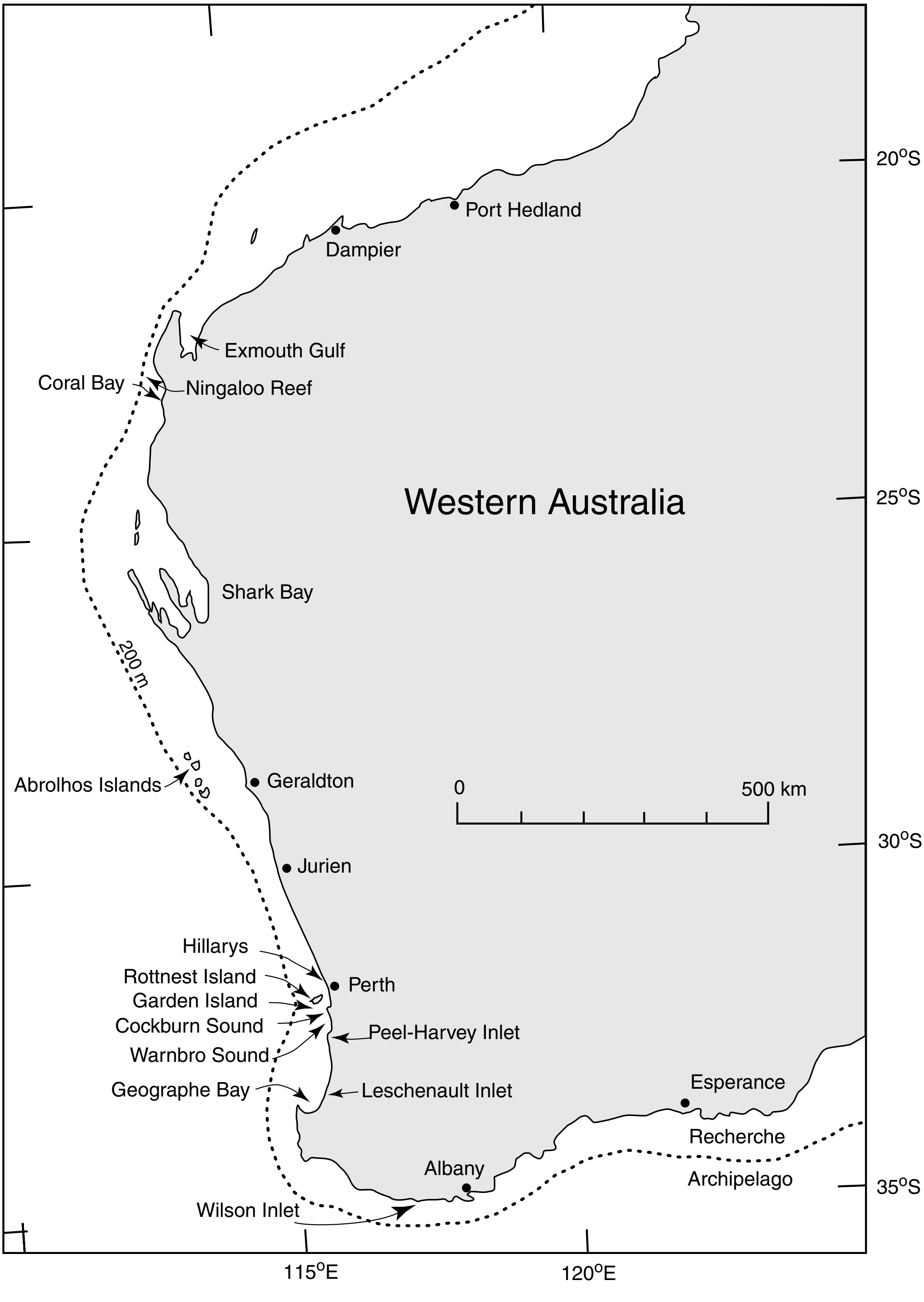
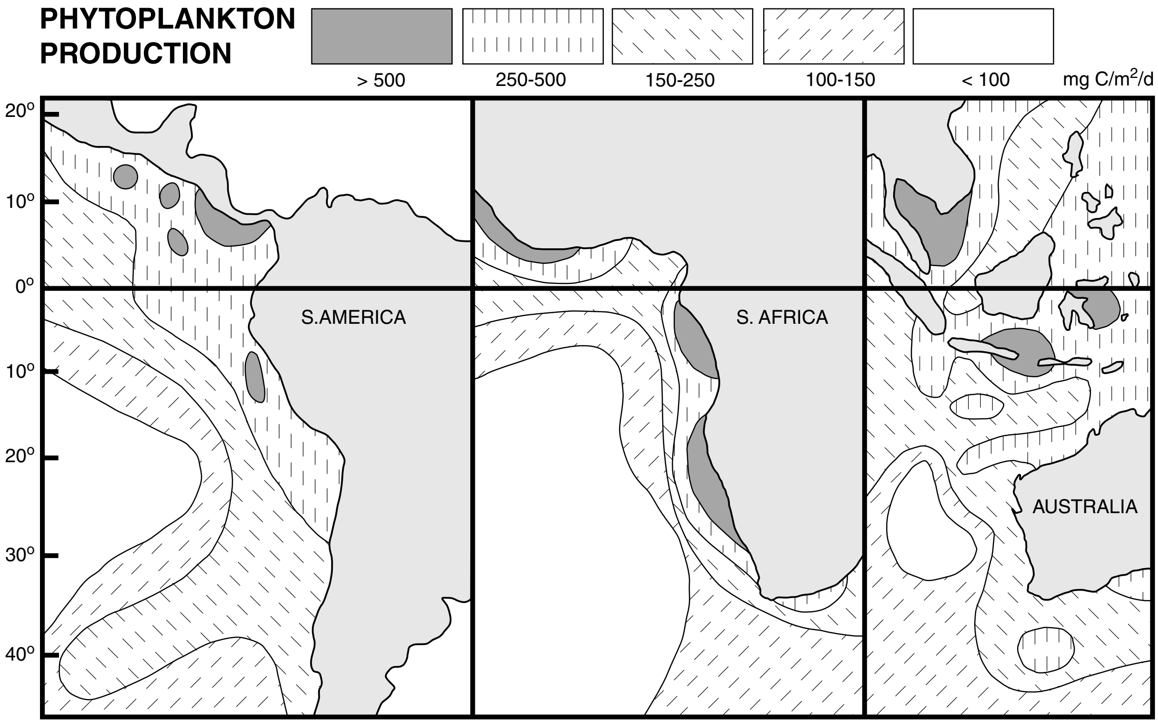


Figure 1 Location chart of the main sites mentioned in the text. The dotted line represents the 200 m contour (approximately the edge of the continental shelf).



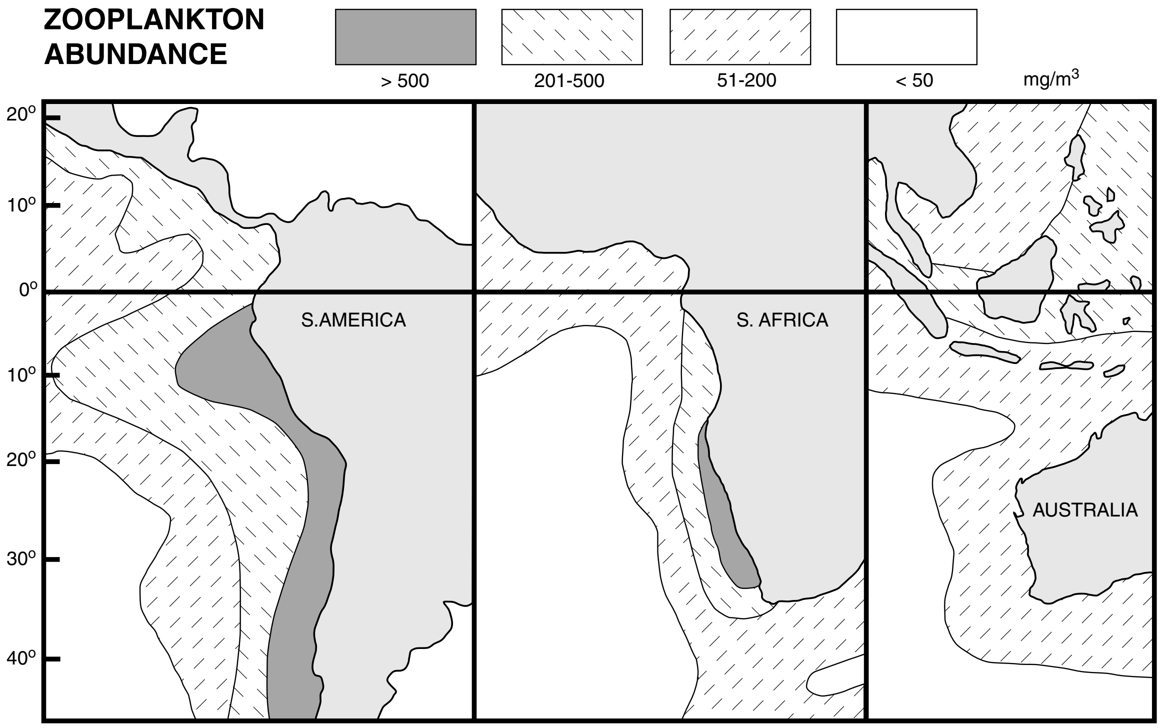


Figure 2 Phytoplankton production (mg C/m²/day) (upper panel) and zooplankton abundance (µg/L) (lower panel) off the west coasts of South America, South Africa and Western Australia. After Pearce (1991), adapted from FAO (1981).

Figure 3 Surface chlorophyll concentrations (µg/L) in the south-eastern Indian Ocean in summer (November to April) (left) and winter (May to October) (right) from Krey and Babenerd (1976).

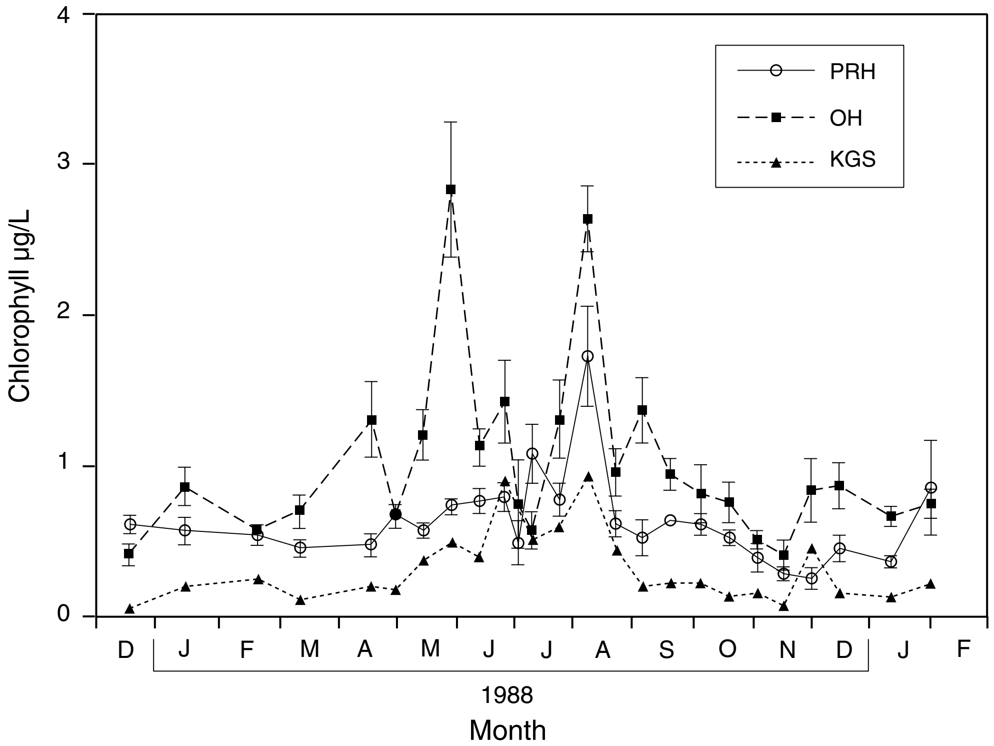


Figure 4 Average chlorophyll concentrations from Oyster Harbour (OH, filled squares), Princess Royal Harbour (PRH, open circles) and King George Sound (KGS, filled triangles) between December 1987 and February 1989, adapted from Hillman *et al.* (1991). The data have been digitised from Hillman *et al.* (1991, Figure 9) by Helleren and Pearce (2000).

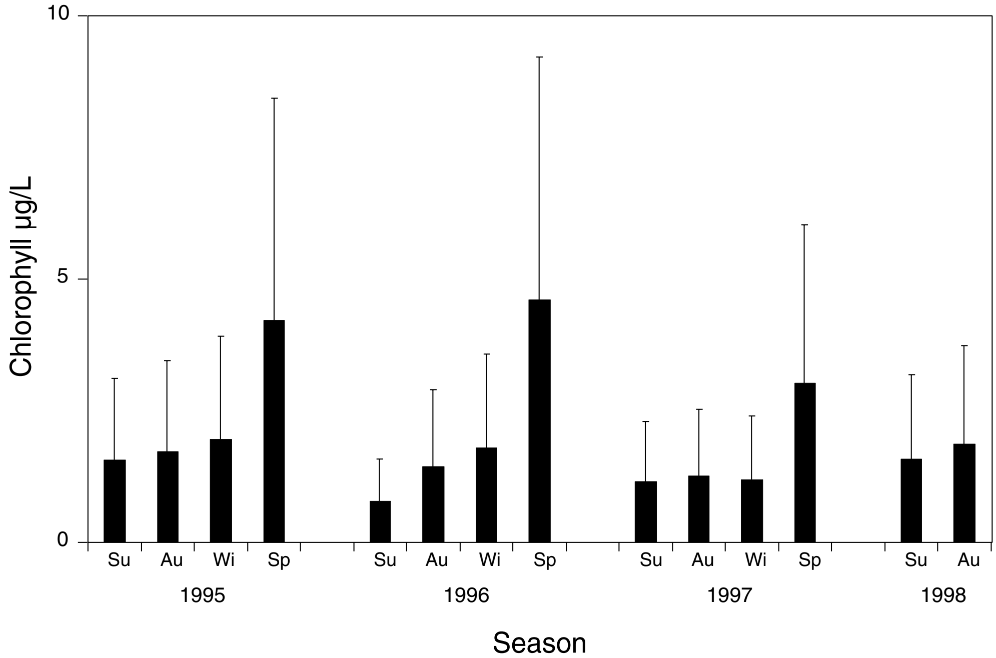


Figure 5 Bar chart of seasonal mean chlorophyll-*a* concentrations and standard deviations in Wilson Inlet, averaged over 11 sites between 1995 and 1998 (unpublished Water and Rivers Commission data, adapted from Helleren and Pearce 2000), where Su = summer, Au = autumn, Wi = winter and Sp = spring.

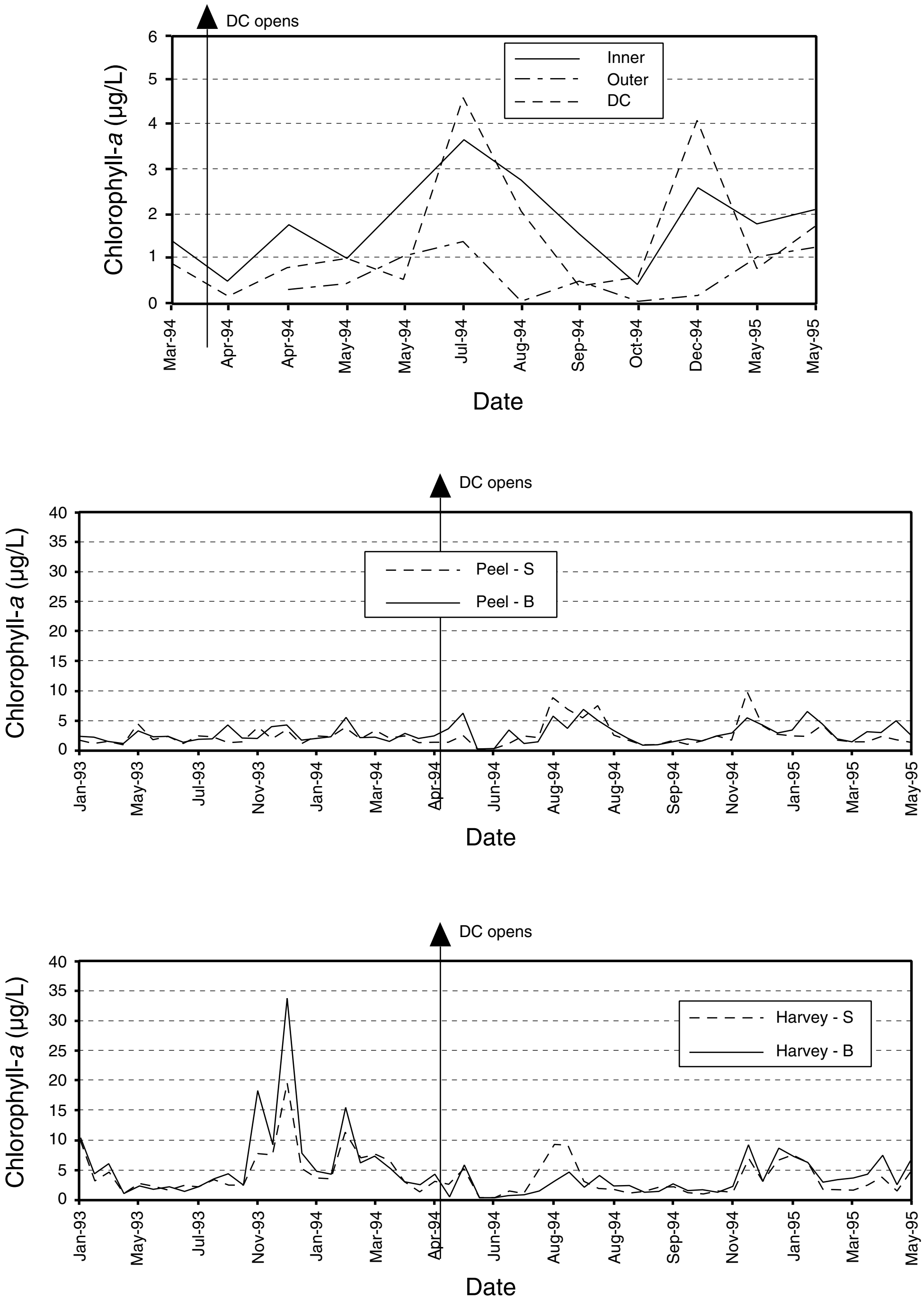


Figure 6 Mean chlorophyll concentrations before and after the opening of the Dawesville Cut in April 1994. (a) the open ocean, with inner stations solid line, outer stations dashed line, stations in the Cut dotted line. Both (b) Peel Inlet and (c) Harvey estuary, with surface data dashed and bottom values solid. Adapted from Chase (1995). Note the change of vertical axis scale between (a) and (b, c).

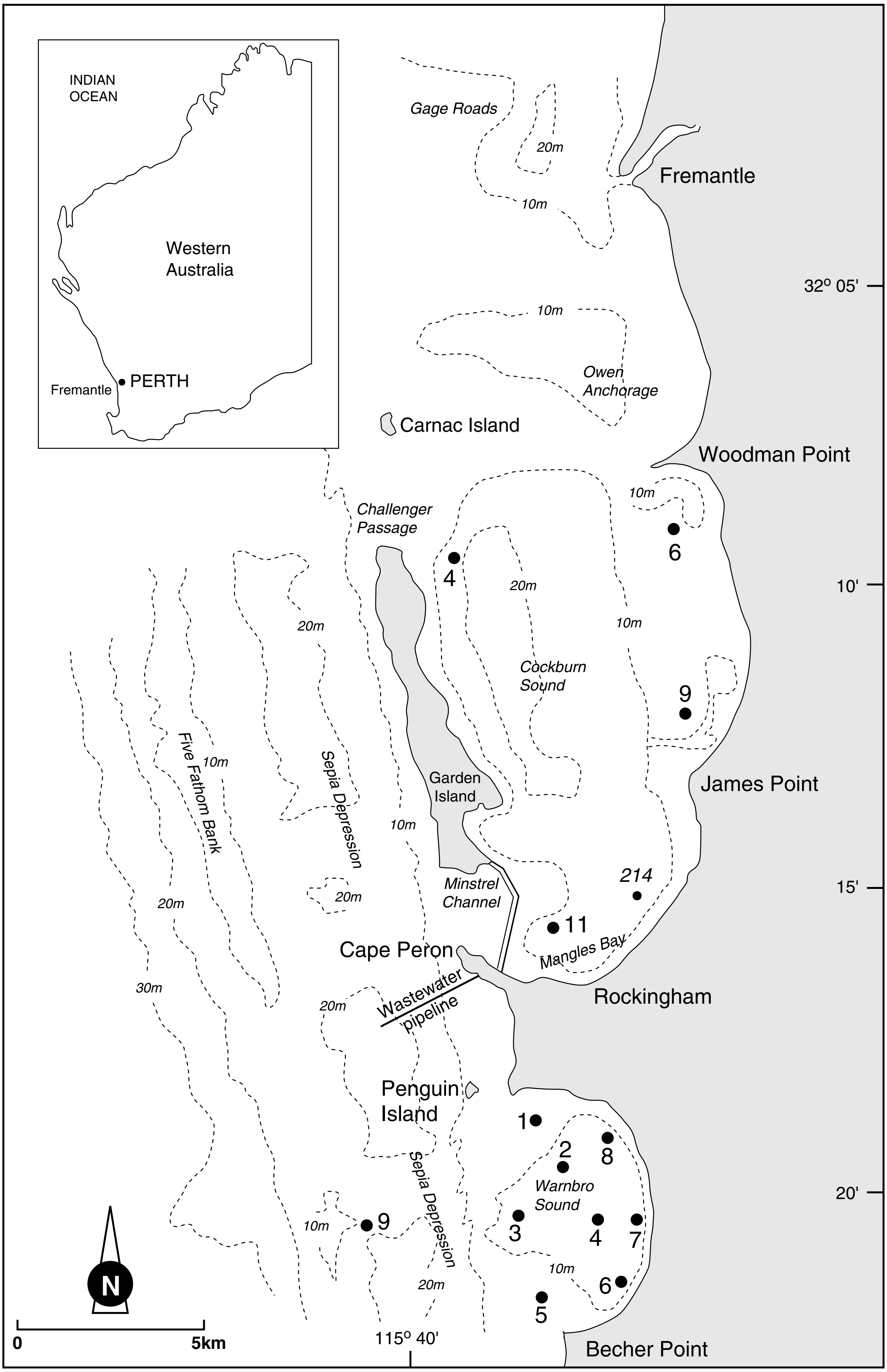


Figure 7 Location chart of place names and station positions in the Perth southern metropolitan area, adapted from Cary and Masini (1995). Station 214 was sampled during the earlier Chiffings (1979) study.

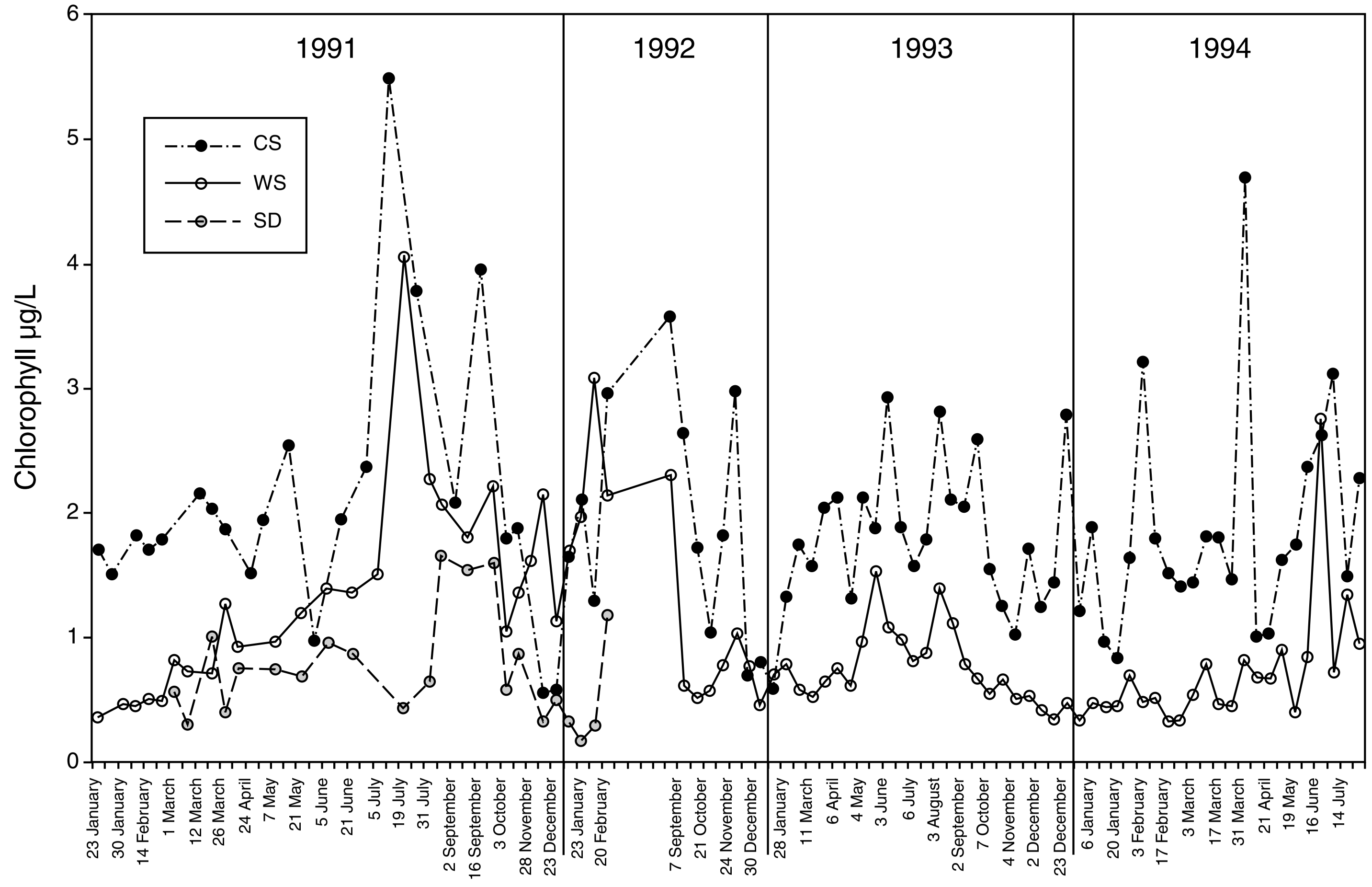


Figure 8 Mean chlorophyll concentrations in Cockburn Sound (CS, solid circles), Warnbro Sound (WS, open circles) and Sepia Depression (SD, grey circles 1991-92 only) between 1991 and 1994. The data are from Cousins (1991), Cary and Masini (1995) and Helleren and John (1997).

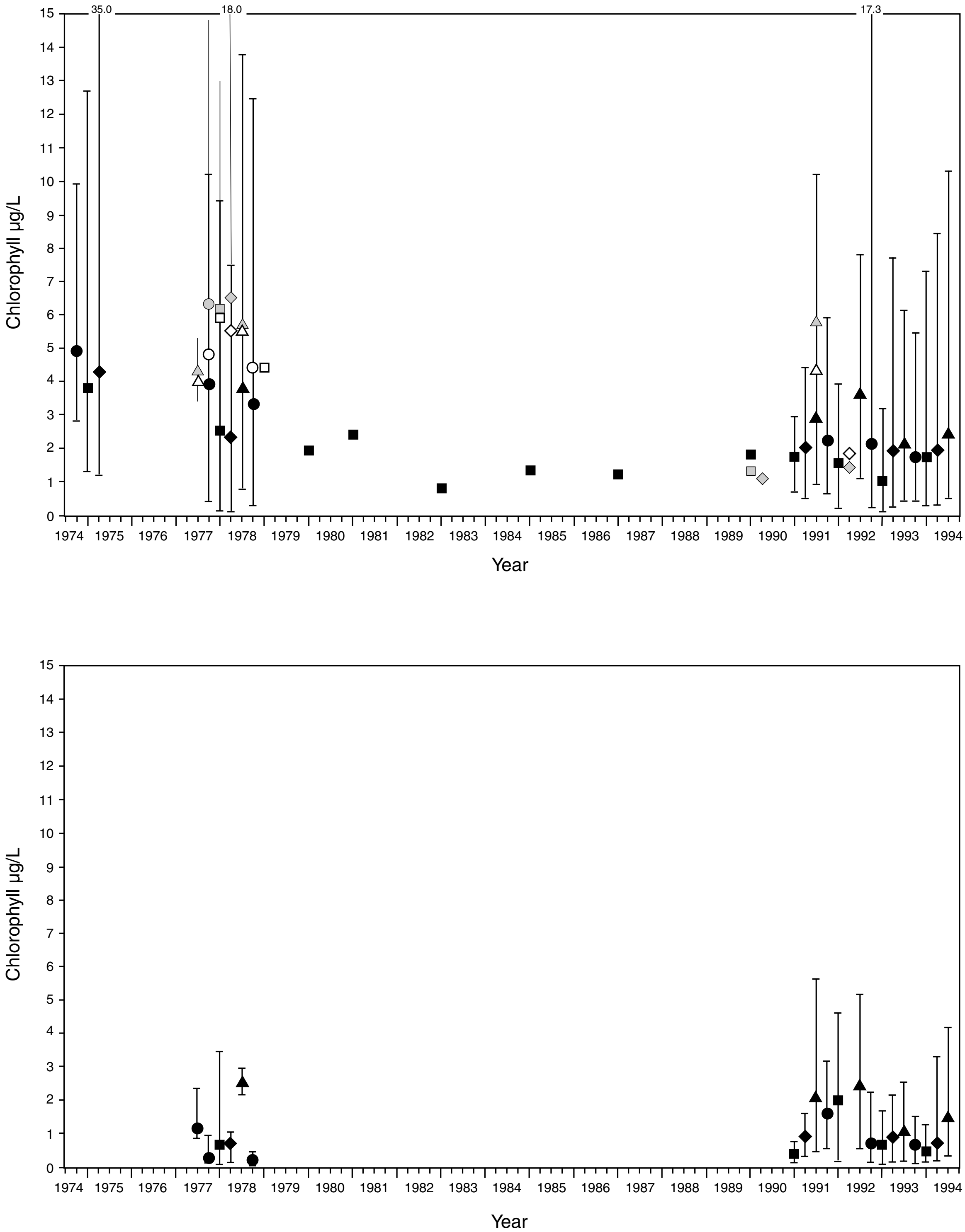


Figure 9 Seasonal mean chlorophyll concentrations and ranges for Cockburn Sound (upper panel) and Warnbro Sound (lower panel) between 1974 and 1994. Where squares represent summer, diamonds autumn, triangles winter and circles spring. *(For a more detailed explanation of the symbols, please refer to Helleren and Pearce 2000 Figure 41).*

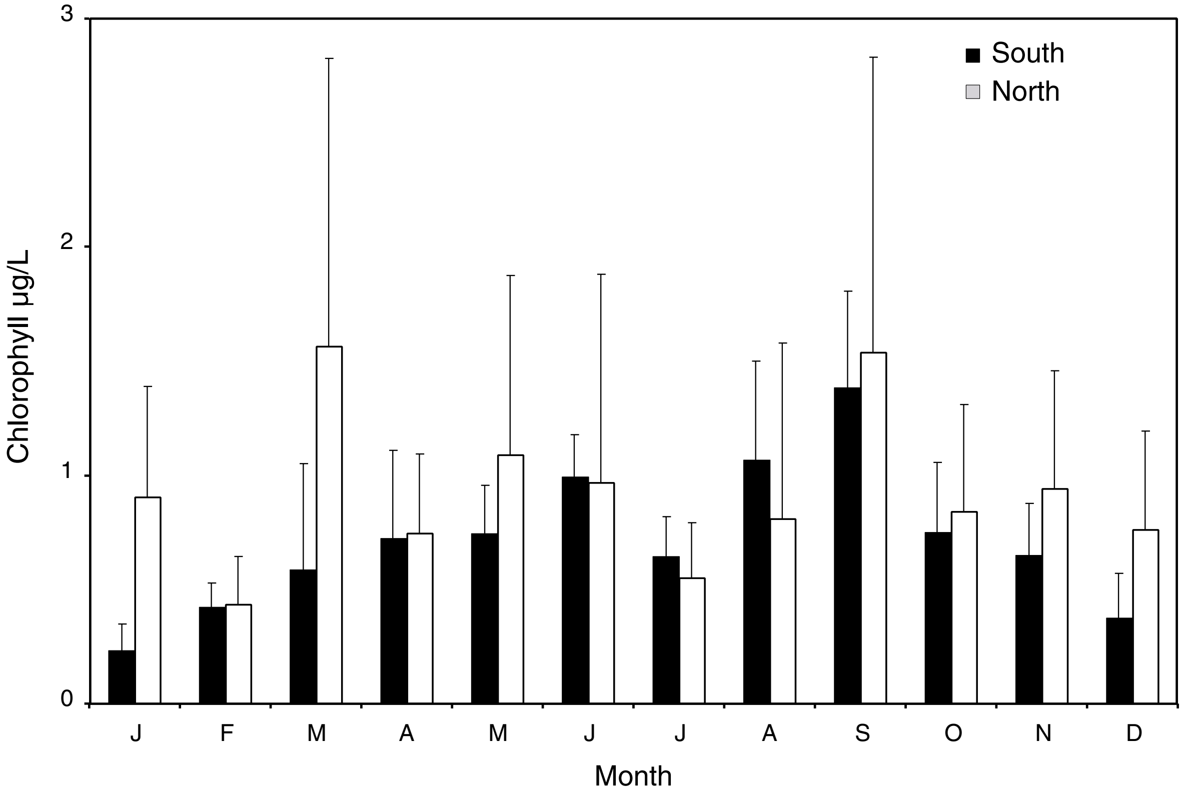


Figure 10 Monthly mean chlorophyll concentrations and standard deviations at the Ocean Reef ("north", pale bars) and Cape Peron ("south", black bars) outfalls between March 1996 and May 1998, derived from raw data kindly provided by the Water Corporation of Western Australia and the University of Tasmania as part of the PLOOM surveys (Thompson 1998).

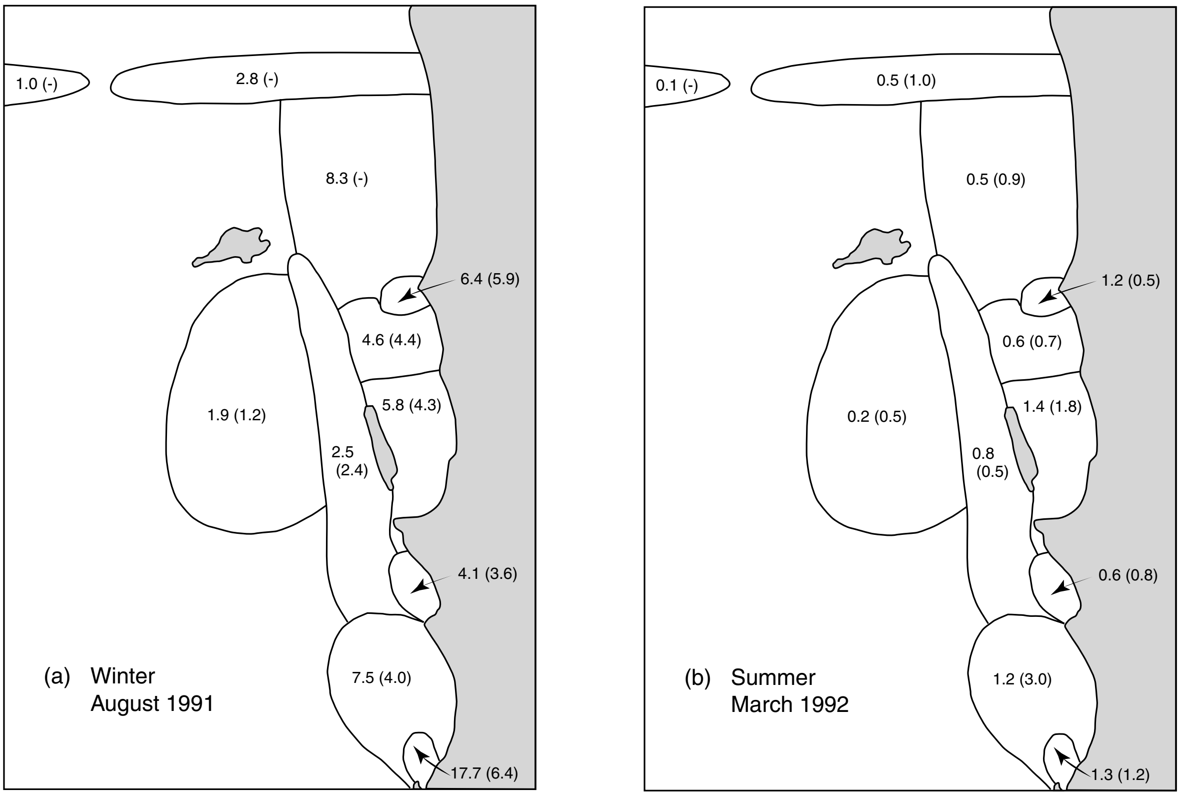


Figure 11 Regional distributions of surface and bottom (in brackets) chlorophyll concentrations (µg/L) in the Perth coastal waters in (a) winter, and (b) summer, adapted from the shelf-scale surveys undertaken as part of the SMCWS (from Tables 4.7-2 and 4.7-3 in Department of Environmental Protection 1996).

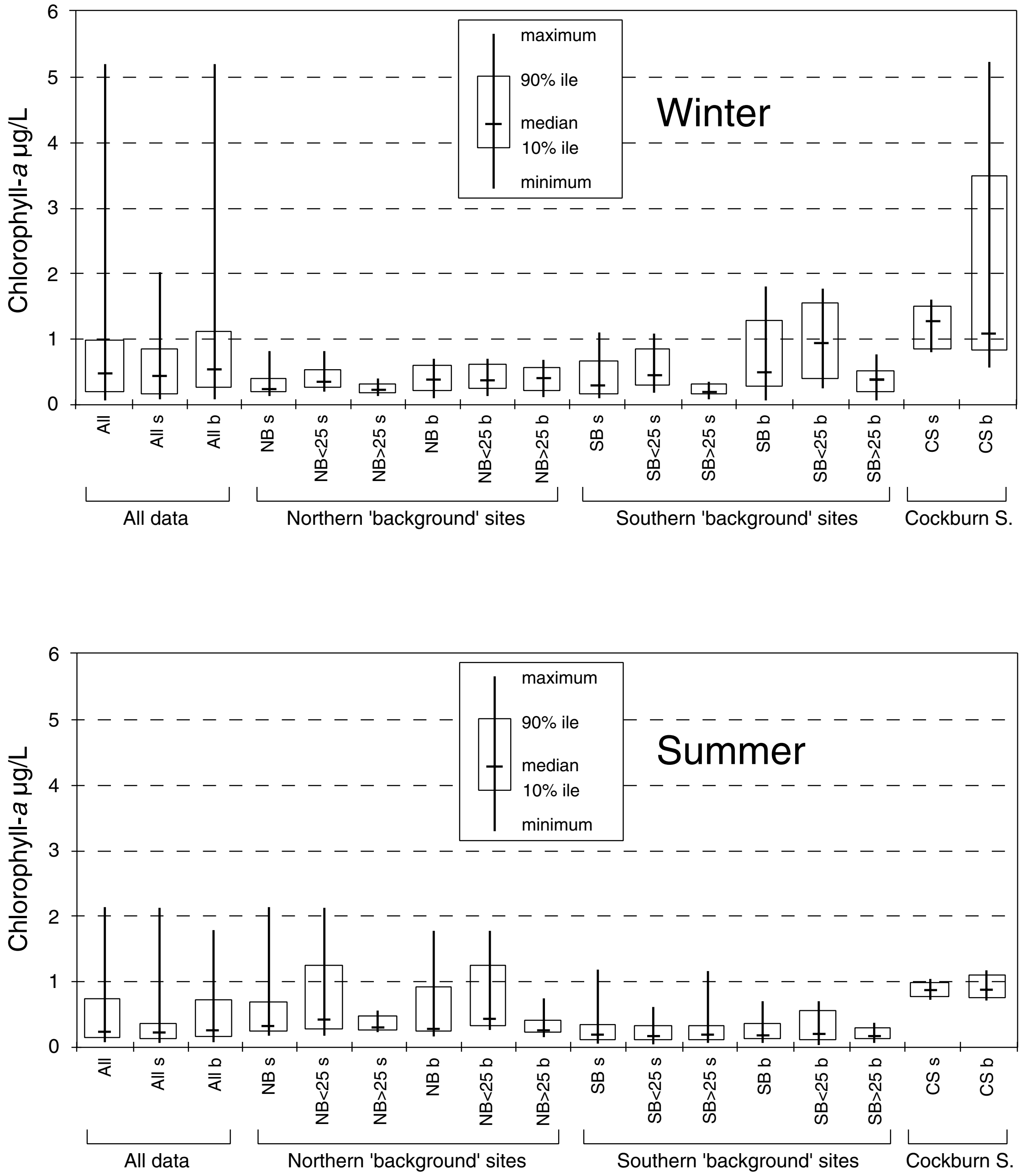


Figure 12 Summary of chlorophyll levels from the Perth Coastal Waters Study in winter (September 1993) (upper panel) and summer (February 1994) (lower panel) surveys, reproduced from Lord and Hillman (1995).

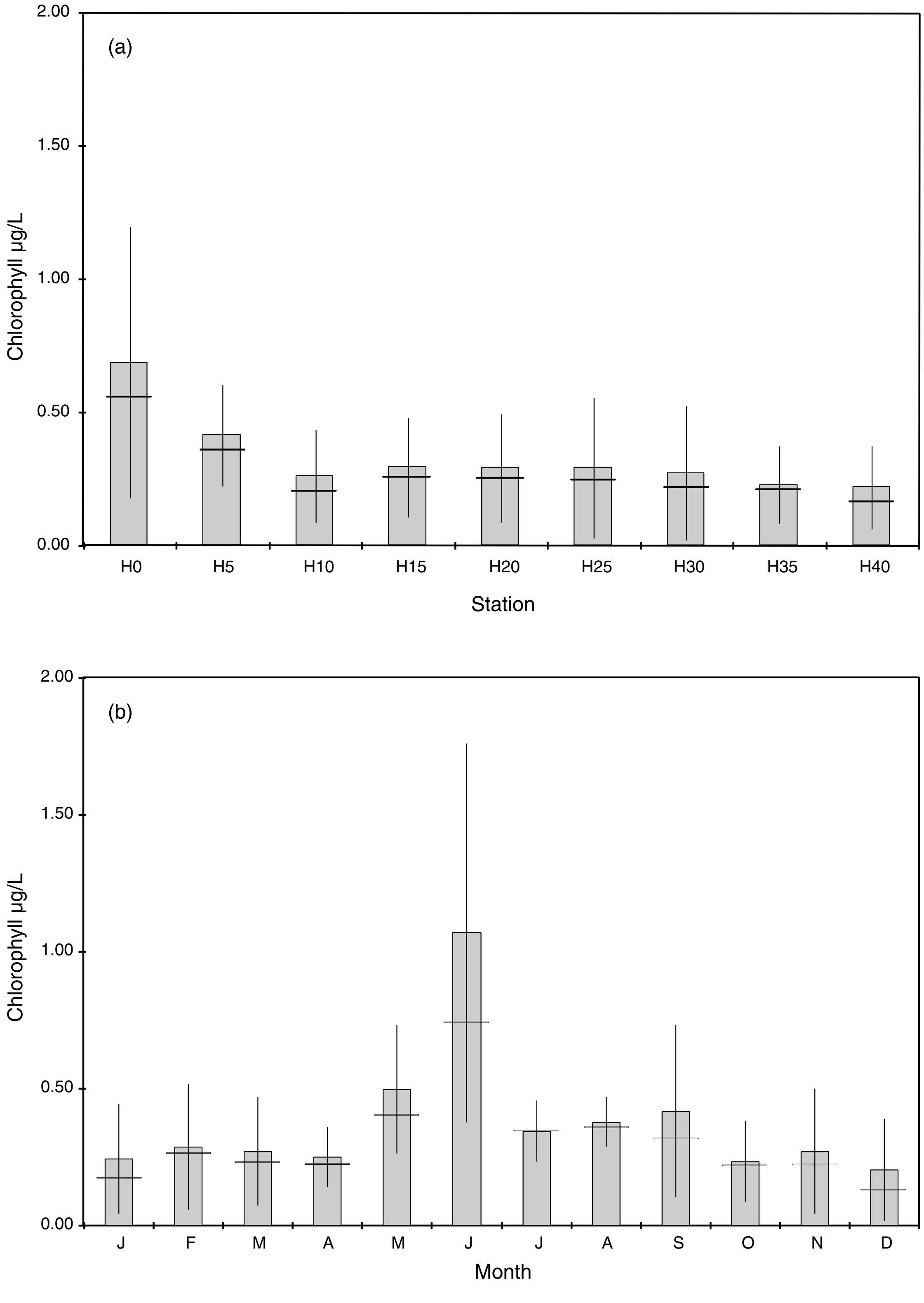


Figure 13 (a) Time-averaged chlorophyll concentrations with standard deviations and medians (horizontal lines) at each station between the coast (station H0) and the outermost station (H40) along the Hillarys transect. (b) Monthly mean chlorophyll concentrations, standard deviations and medians for all Hillarys transect stations H0 to H40 combined.

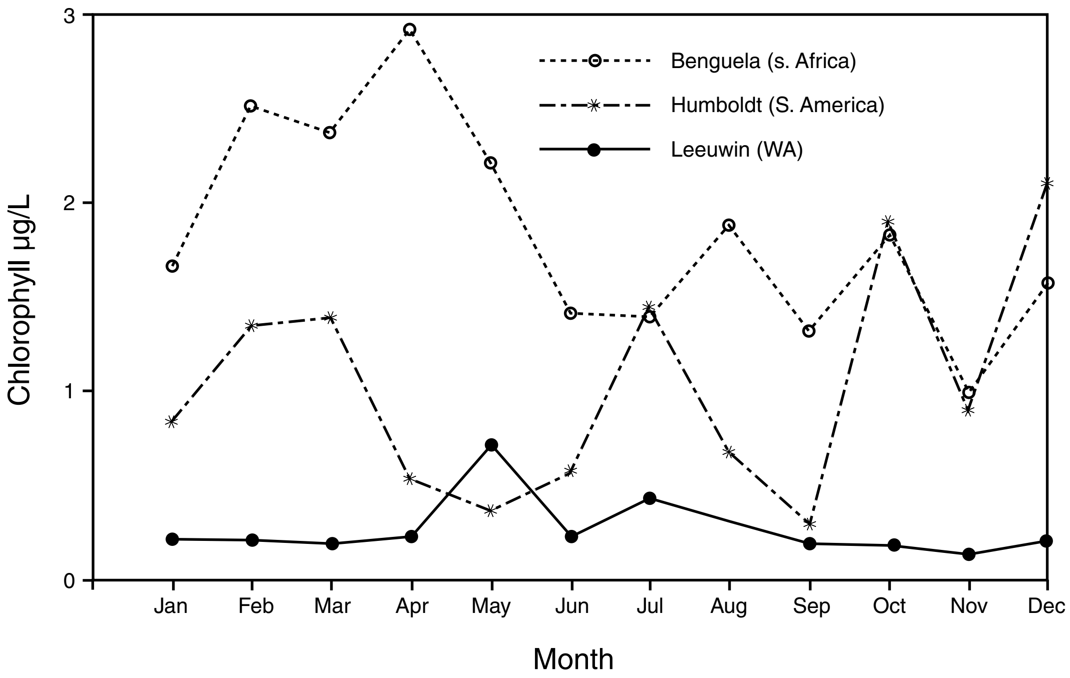


Figure 14 Monthly mean chlorophyll concentrations for 10-degree latitude bands centred on the upwelling regions off South America (Humboldt) (6°-16°S, asterisks), southern Africa (Benguela) (20°-30°S, open circles) and Western Australia (Leeuwin) (25°-35°S, solid circles), derived from the CZCS satellite climatology (see section 4.2.3).

	1979											
	J	F	M	A	M	J	J	A	S	O	N	D
-10.5						8					6	
-11.5						9				5	8	
-12.6						9	6		7	8	8	
-13.6					7	8	9	8	9	9	9	
-14.7					9	8	*	9	9	*	9	7
-15.7					8	9	*	*	9	9	9	8
-16.8					9	9	*	9	9	*	*	9
-17.8					*	*	*	*	9	*	*	9
-18.9					9	*	*	*	*	9	*	9
-20					9	*	*	*	9	*	*	9
-21					9	*	*	*	*	9	*	*
-22.1					*	*	*	*	*	9	*	9
-23.1					*	*	*	*	9	9	*	8
-24.2					*	*	*	*	9	6	*	6
-25.2					9	*	7	8	9	5	*	
-26.3									8		6	
-27.3						7						
-28.4												
-29.4											5	
-30.5											5	
-31.6											5	
-32.6											6	
-33.7											7	
-34.7												
-35.8												
-36.8												
-37.9												
-38.9												

	1980											
	J	F	M	A	M	J	J	A	S	O	N	D
-10.5						9				5		
-11.5						9				5		
-12.6	6				5	9				5		
-13.6	8				9	9	9		5	5		
-14.7	8				9	9	9		6	5		
-15.7	7				*	9	9		8	5		
-16.8	7				9	8	8		9	5		
-17.8	6				9	8	9		9	5	5	
-18.9	6				9	9	9	7	9	6	6	
-20					9	9	9	7	*	9	7	
-21					9	9	9	6	*	9	9	
-22.1					8	*	8		*	*	*	
-23.1	6				6	9	9		*	*	*	
-24.2	7				9	9	5		*	*	9	6
-25.2	6				7	8	5		*	9	9	7
-26.3					5	6	8		*	9	7	9
-27.3						5	6		*	9	5	*
-28.4	5								*	8	5	*
-29.4	5								*	8	7	*
-30.5									9	6	6	*
-31.6									9	7	5	*
-32.6	5								*		5	*
-33.7	6								9	8	6	9
-34.7	5				5				9	8	8	8
-35.8	6								9	7	7	7
-36.8	5								9	5	7	
-37.9									9	5	5	5
-38.9									9	5	5	7

	1981											
	J	F	M	A	M	J	J	A	S	O	N	D
-10.5			5	9	9	*	*	9	8	9	6	
-11.5			8	9	*	*	*	9	8	9		
-12.6			9	9	*	*	*	9	9	9		6
-13.6			*	*	*	*	*	9	8	*	5	5
-14.7			*	9	*	*	*	9	8	*		6
-15.7			*	9	*	*	*	9	8	*		8
-16.8			*	9	*	9	9	9	8	*	6	6
-17.8			*	*	*	9	8	*	9	*	7	6
-18.9			*	*	*	9	8	*	9	*	7	
-20		6	*	*	*	9	9	*	9	*	8	
-21	5	7	*	*	*	9	*	*	*	*	9	
-22.1	5	9	*	*	*	9	*	*	*	*	9	
-23.1	8	*	*	*	*	*	*	9	9	*	9	
-24.2	*	*	*	9	*	9	*	*	9	*	9	6
-25.2	*	*	*	*	*	9	9	*	8	*	9	7
-26.3	9	*	*	9	*	9	7	*	6	*	9	6
-27.3	9	*	*	9	*		7	9		*	9	8
-28.4	9	*	*	9	*		7	8		*	9	6
-29.4	9	*	*	*	*			8		*	*	
-30.5	*	*	*	*	*			7		9	9	
-31.6	*	*	*	9	9			5		9	9	
-32.6	*	*	9	9	*					9	7	
-33.7	*	*	9	8	9					*	7	
-34.7	*	9	*	8	8					9	8	
-35.8	*	7	9	7	7					9	7	
-36.8	9		9	6	7					9		
-37.9	9		9	7	6					9		
-38.9	9		7							6		

	1982											
	J	F	M	A	M	J	J	A	S	O	N	D
-10.5					7		9		9		9	8
-11.5					7		9		9		9	9
-12.6					7		9		9		9	8
-13.6					7		9		9		8	6
-14.7			5	6	8		*		9			6
-15.7			8	7	8		9	8	9			6
-16.8			9	8	8		9	9	9			
-17.8			9	9	8		*	9	*			
-18.9			9	*	9		*	8	9			
-20		7	9	9	9		*	9	*			
-21	7	9	9	9	*		*	8	*			
-22.1	9	9	9	*	*		9	7	*			
-23.1	9	9	*	*	*		8	6	*			
-24.2	*	8	*	*	*		9	9	*		9	
-25.2	*	8	*	*	*		9	5	*		9	
-26.3	9	9	*	*	*		5		9		7	
-27.3	9	*	*	*	9		6	7	9			
-28.4	9	9	9	*	9		8	8	7		5	
-29.4	8	9	*	*	7		8	9	8		6	
-30.5	8	9	*	*	7		7	9	8		9	
-31.6	9	8	*	9	5		8	8	8		*	5
-32.6	9	8	9	9	6		6	5	7		*	
-33.7	7	7	9	8					5		*	
-34.7	8	6	8		5		8	6	7		9	5
-35.8	5		7					5	5		9	
-36.8			5								9	6
-37.9			5								9	8
-38.9											9	6

	1983											
	J	F	M	A	M	J	J	A	S	O	N	D
-10.5					8		9	9	*			
-11.5					8		9	9	*			
-12.6					9		9	9	9			
-13.6					9		*	9	*			
-14.7					9		9	9	*			
-15.7					9		7	9	*			
-16.8					9		7	*	*			
-17.8					9		9	*	9			
-18.9					*		9	*	*			
-20			5		*		8	*	9			
-21			6	5	*			*	5			
-22.1				8	*			*				
-23.1				9	*			*				
-24.2			7	*	*			*				
-25.2			7	*	9			8				
-26.3			9	*	5							
-27.3			9	*	5							
-28.4			8	*								
-29.4	7		6	*								
-30.5	9		7	*								
-31.6	9	5	8	*								
-32.6	9	6	8	9								
-33.7	9		8	9								
-34.7	8	6	8	8								
-35.8	9		7									
-36.8	9		7									
-37.9	8		6									
-38.9	8		6									

	1984											
	J	F	M	A	M	J	J	A	S	O	N	D
-10.5								5	9	9	6	
-11.5								6	8	8		
-12.6								6	9	8		
-13.6								5	9	7		
-14.7									*	7		
-15.7									*	8		
-16.8									*	8		
-17.8									*	8		
-18.9									*	8		
-20									*	9		
-21									*	9		
-22.1									9	9		
-23.1									*	8		
-24.2									*	8		
-25.2									9	7		
-26.3									*	7		
-27.3									*	8		
-28.4									*	7		
-29.4									9	7	6	
-30.5									8		7	
-31.6											7	
-32.6											7	
-33.7											6	
-34.7											5	5
-35.8												
-36.8												
-37.9												
-38.9												

	1985											
	J	F	M	A	M	J	J	A	S	O	N	D
-10.5	5		6	9	5							
-11.5	7		6	9								
-12.6	7		7	*								
-13.6	9		8	*								
-14.7	9		9	*								
-15.7	9		9	*								
-16.8	7		9	*								
-17.8	5		9	*								
-18.9			9	*								
-20		6	9	9								
-21		9	9	9								
-22.1		9	9	9								
-23.1		*	*	*								
-24.2		*	*	*								
-25.2		9	*	*								
-26.3		*	*	*								
-27.3	7	9	*	*								
-28.4	9	*	*	*								
-29.4	9	*	*	9								
-30.5	8	*	*	9								
-31.6	9	9	9	9								
-32.6	*	7	7	*								
-33.7	8	4	7	9								
-34.7	8	5	9	9								
-35.8	8	7	9	9								
-36.8	8		7	9								
-37.9	9		2	9								
-38.9	8			8								

	1986					
	J	F	M	A	M	J
-10.5				7	9	9
-11.5				8	9	9
-12.6				9	9	*
-13.6				9	8	9
-14.7				9	8	9
-15.7				9	8	8
-16.8				7	8	7
-17.8				7	8	7
-18.9				7	8	8
-20				6	7	8
-21	7					9
-22.1	8			7		9
-23.1				9		*
-24.2				8		*
-25.2				*		*
-26.3				*		8
-27.3				*		7
-28.4				*		7
-29.4				*		7
-30.5	6			*		8
-31.6	6			*		8
-32.6				*		
-33.7				*		
-34.7				9		
-35.8				9		
-36.8				9		
-37.9				8		
-38.9				6		

Figure 15 Proportions of valid monthly CZCS data in each 1-degree latitude band between 10° and 40° south and for longitudes between 110°E and the coast off Western Australia. An asterisk signifies 100% coverage (no data gaps) in that latitude band and month, "9" represents 90-100%, "8" 80-90%, etc.; coverage less than 50% has been left blank.

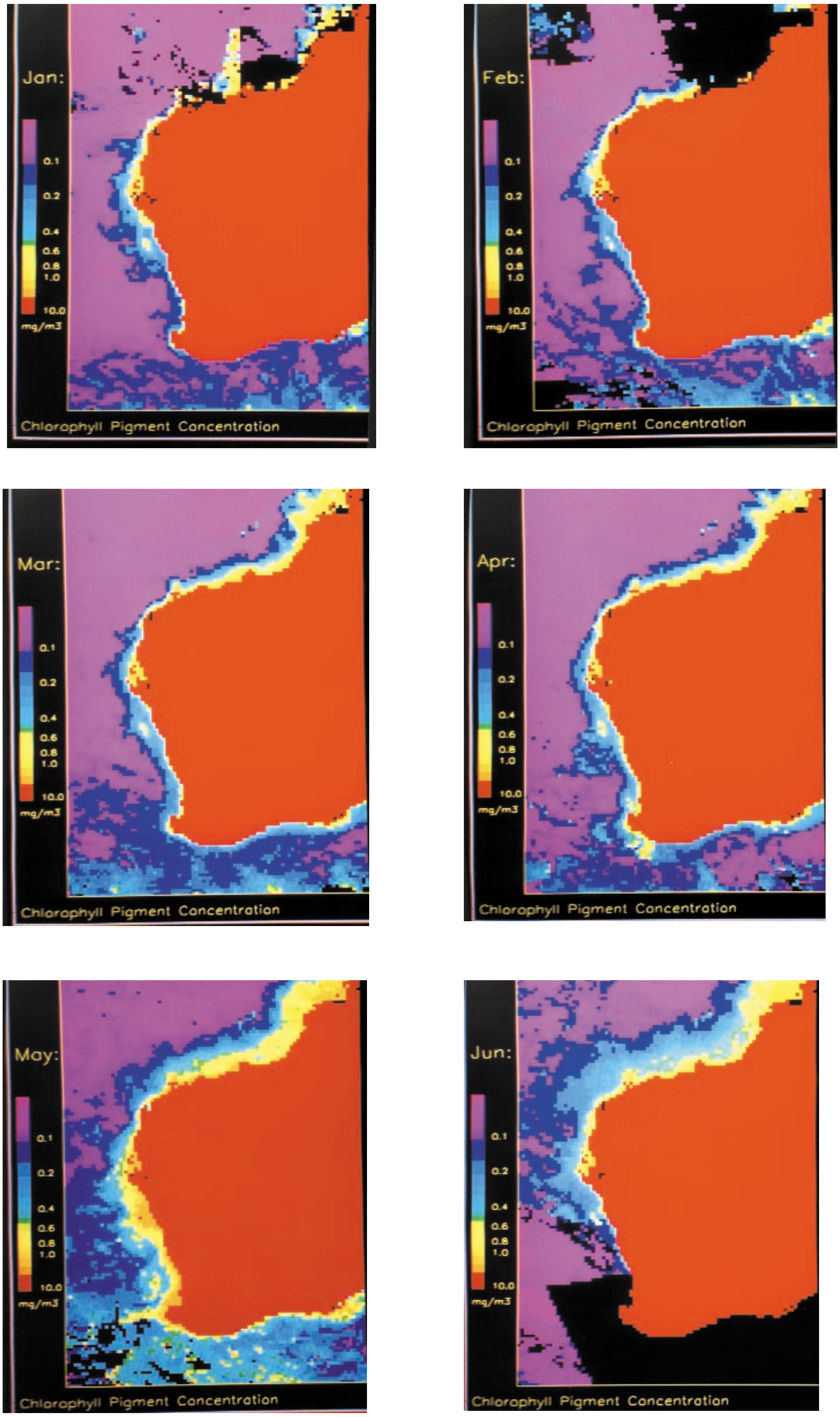


Figure 16 Colour images of the chlorophyll concentrations off Western Australia derived from the CZCS monthly climatology. Land is shown in red. The logarithmic colour scale shows the concentration in mg/m^3 (= µg/L) ranging from the highest chlorophyll concentrations in red/yellow to the lowest in mauve. Black areas have no valid data over the whole eight-year period.

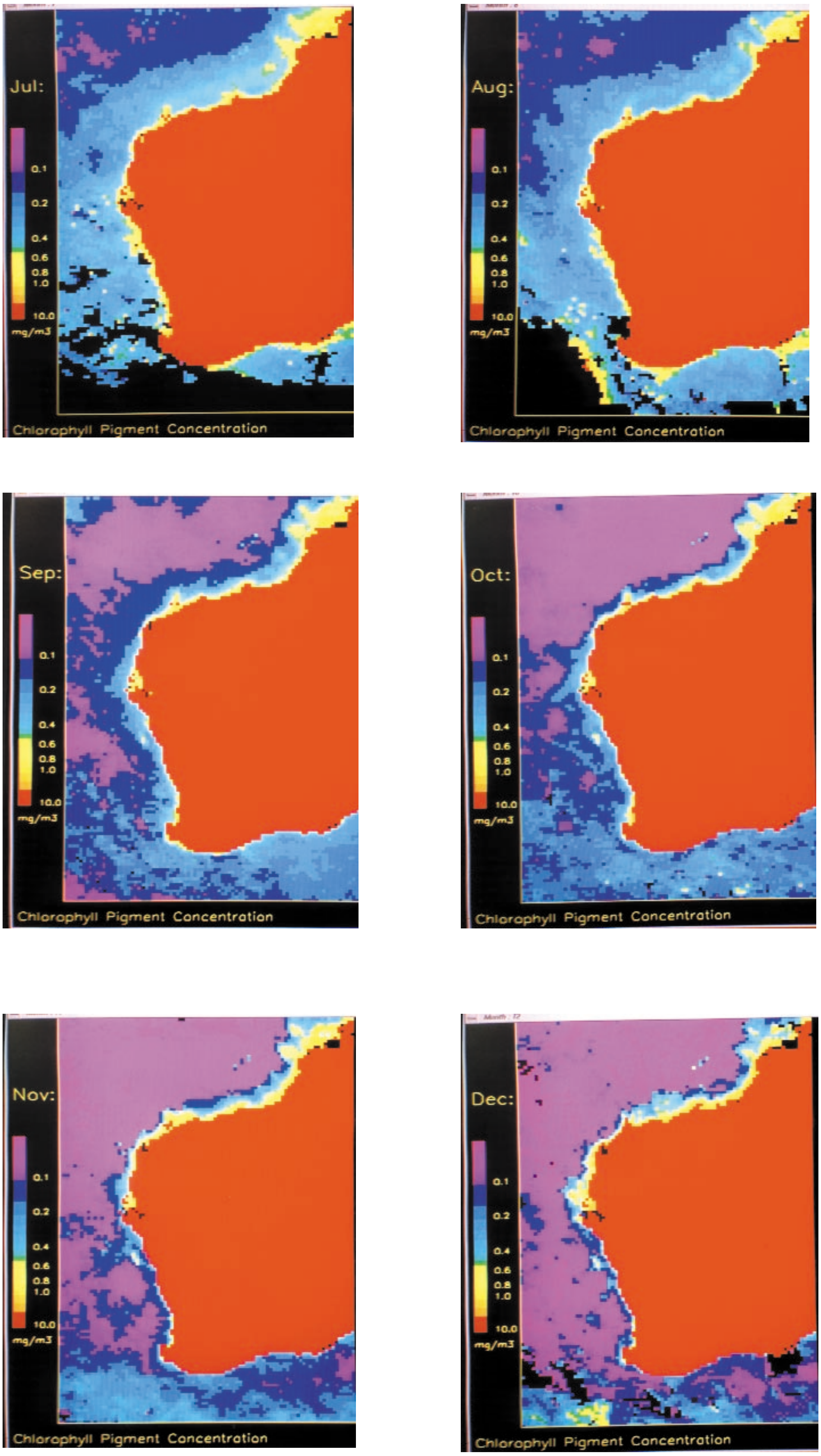


Figure 16 Continued.

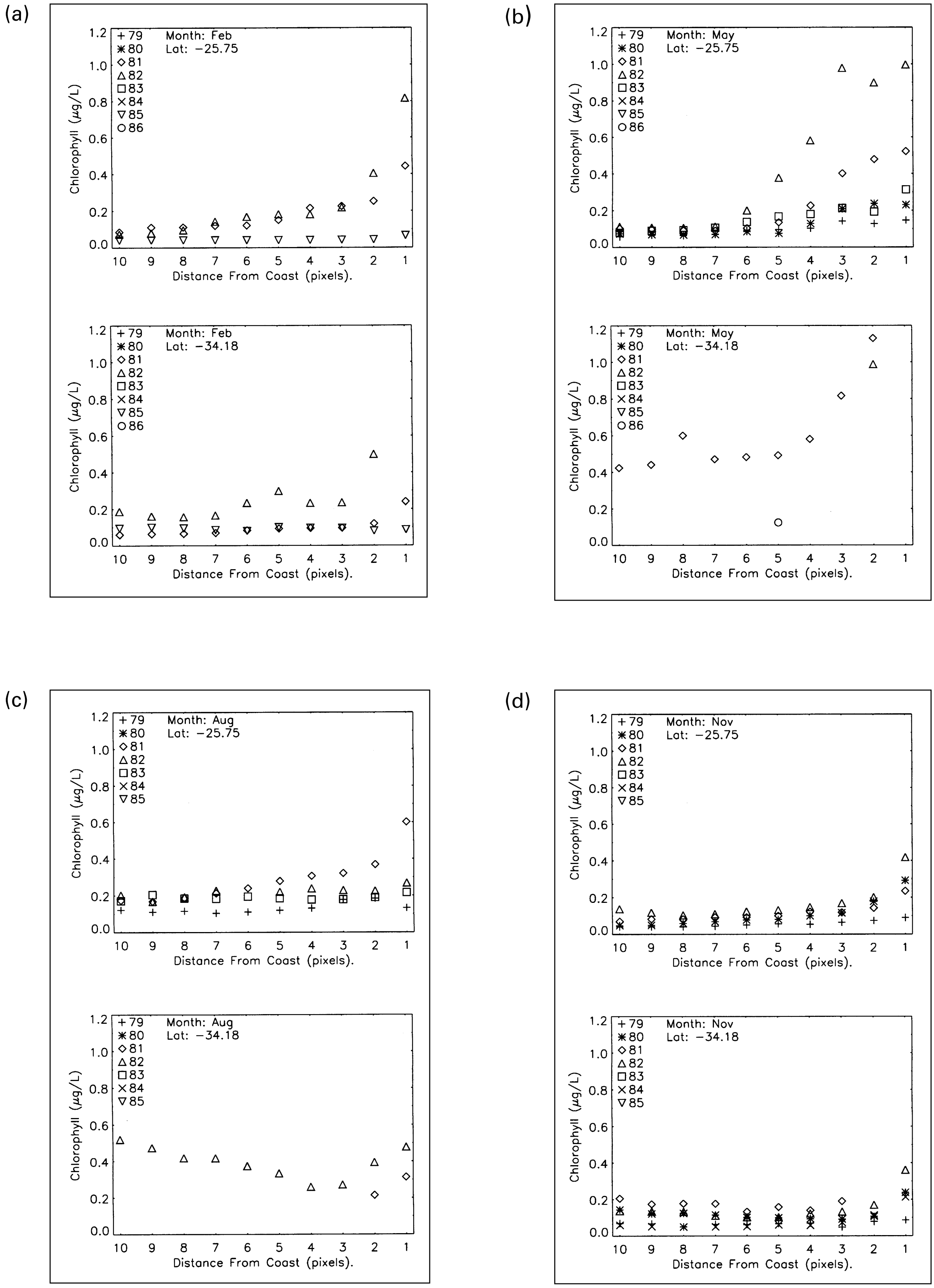


Figure 17 Sample chlorophyll transects due west of Shark Bay (25.75°S) and Cape Leeuwin (34.18°S), for the months of (a) February - representing summer, (b) May - autumn, (c) August - winter and (d) November - spring, between 1979 and 1986 (different symbols) derived from the CZCS climatology (Marinelli in prep.). The pixel size is about 18 km. Note that there are many gaps in the data coverage.

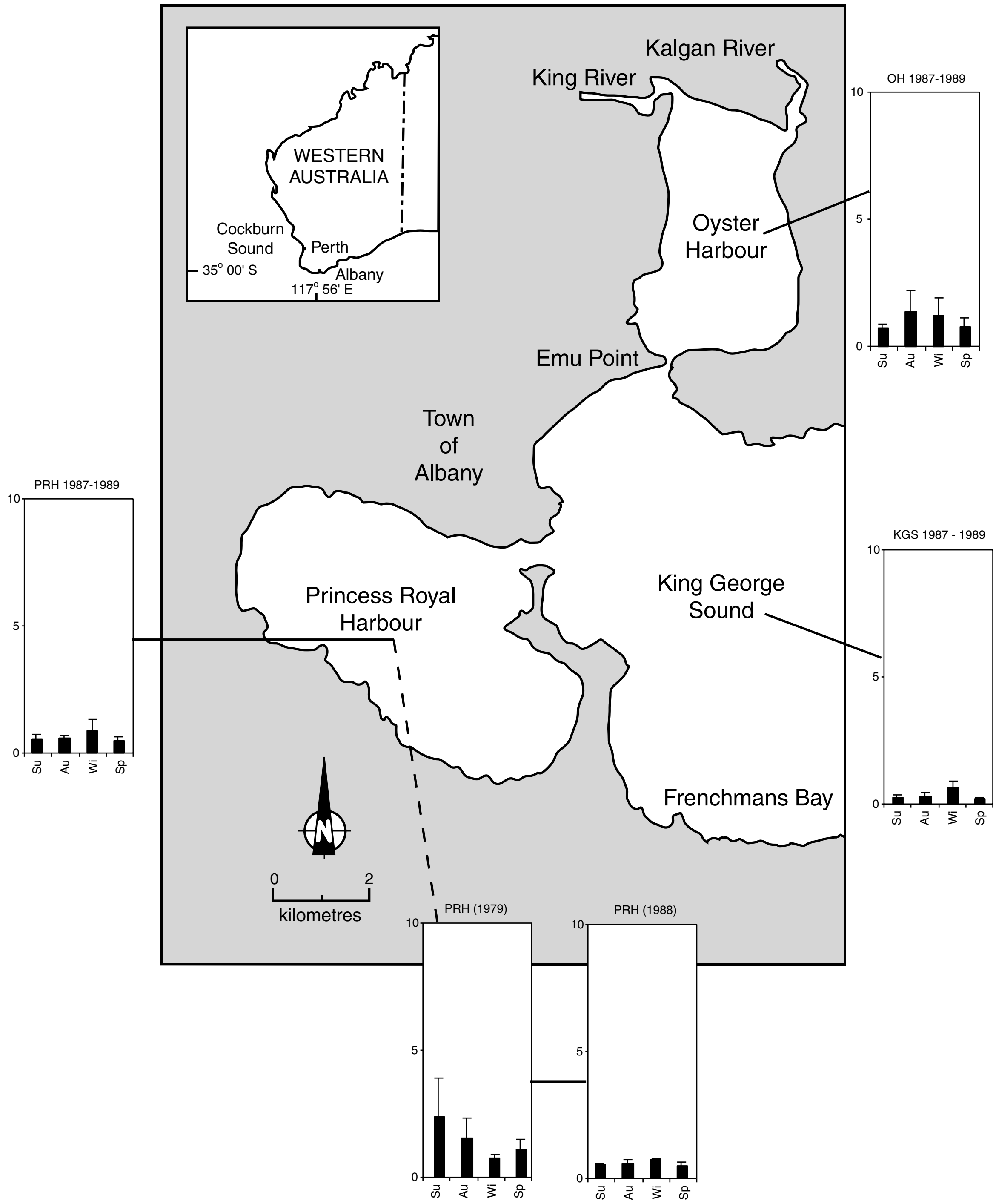


Figure 18 Seasonal chlorophyll concentrations in the Albany harbours region. The four seasons are defined as Summer = December-January-February, and so on. The vertical chlorophyll axis runs from 0 to 10 µg/L, and the bars depict the means and standard deviations. The base map has been adapted from Hillman *et al.* (1991). The two lower panels compare conditions in Princess Royal Harbour between 1979 (Atkins *et al.* 1980) and 1988 (Hillman *et al.* 1991), while the three upper panels are the more recent chlorophyll data collected between 1987 and 1989 (Hillman *et al.* 1991).

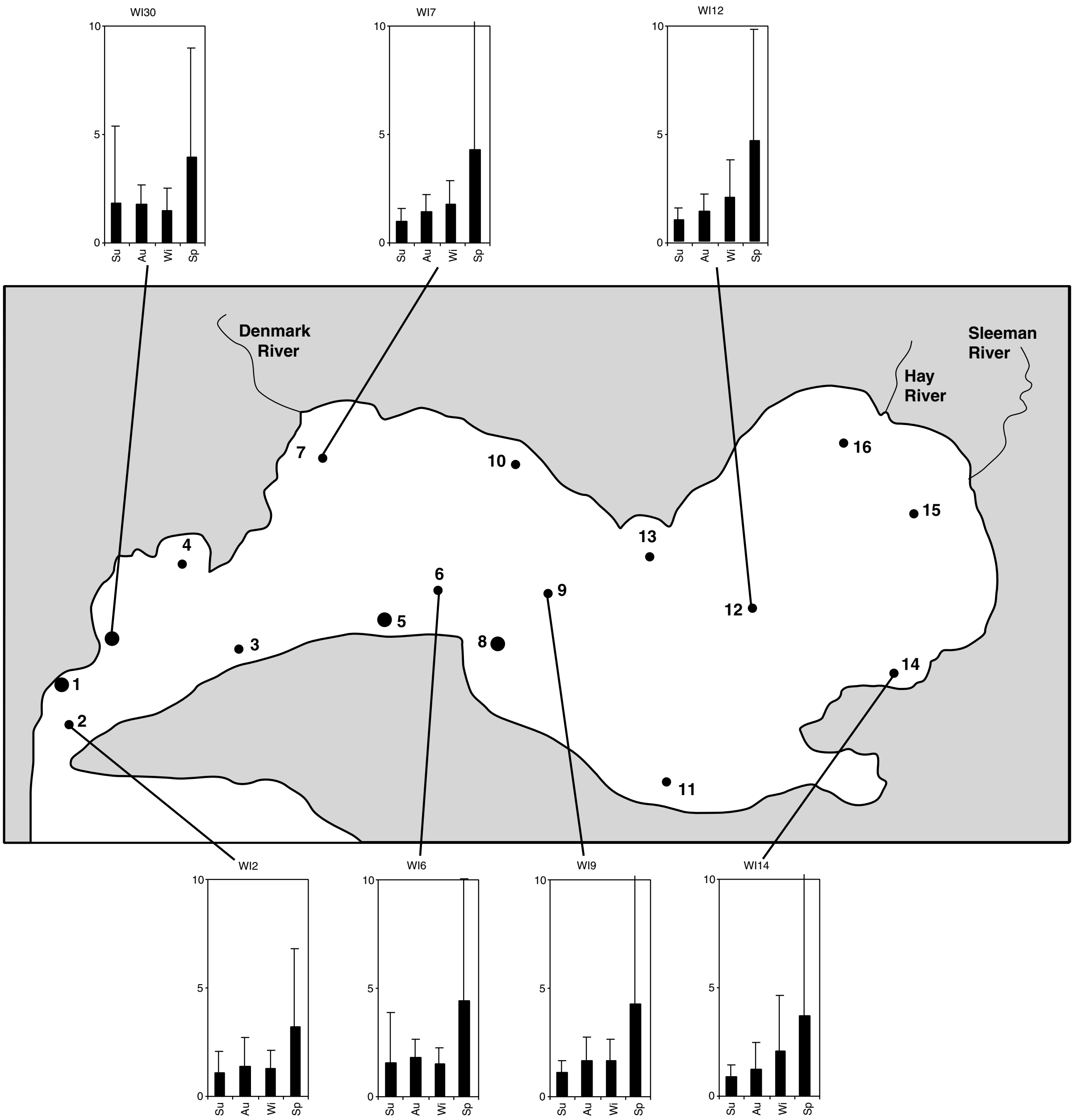


Figure 19 Seasonal depth-averaged chlorophyll concentrations in Wilson Inlet. The four seasons are defined as Summer = December-January-February, and so on. The vertical chlorophyll axis runs from 0 to 10 µg/L, and the bars depict the means and standard deviations. The base map has been adapted from Lukatelich *et al.* (1984), and the (unpublished) data are by courtesy of the Water and Rivers Commission covering the period 1994 to 1998.

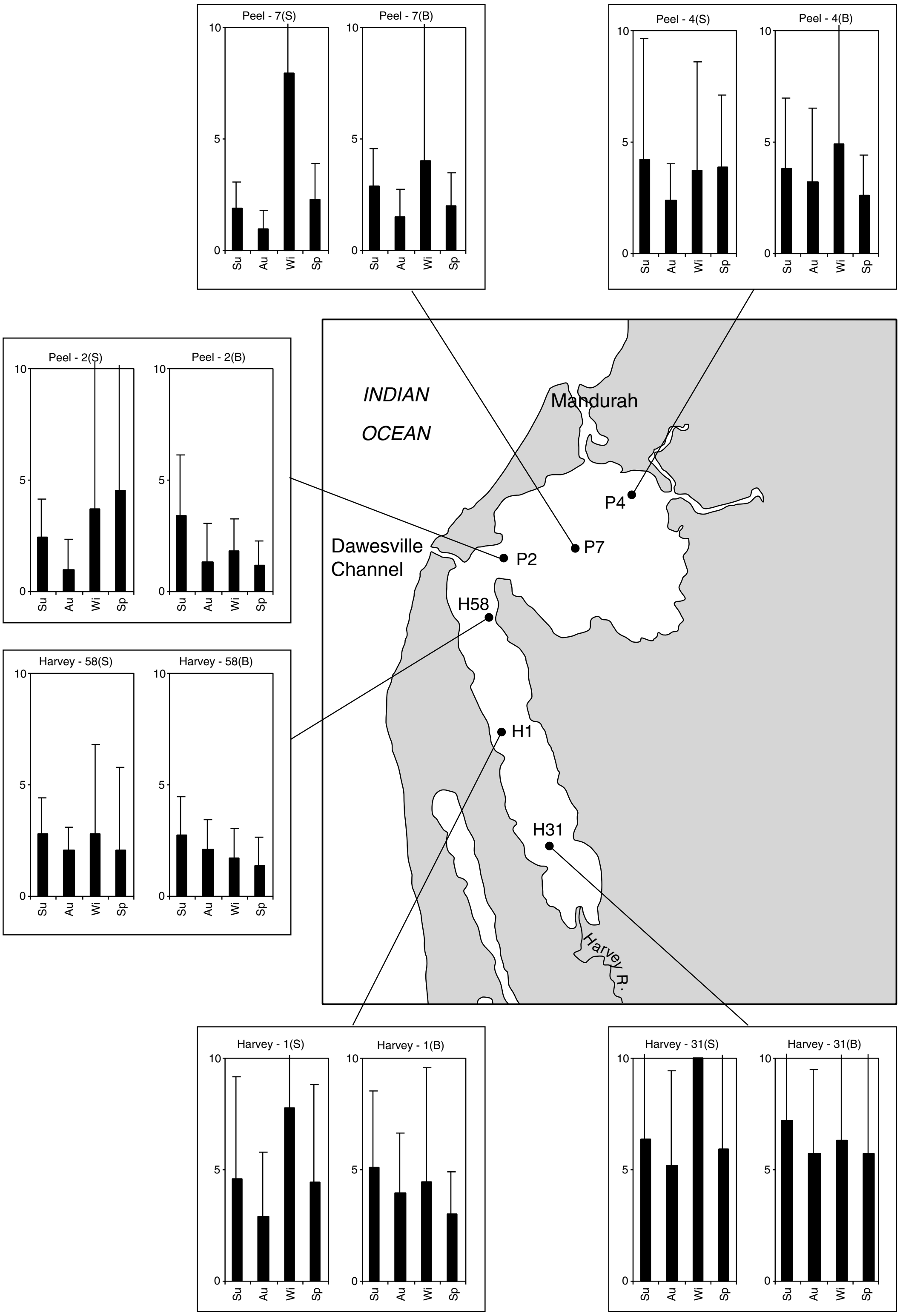


Figure 20 Seasonal chlorophyll concentrations in the Peel-Harvey estuary system after the opening of the Dawesville Cut. The four seasons are defined as Summer = December-January-February, and so on. The vertical chlorophyll axis runs from 0 to 10 µg/L, and the bars depict the means and standard deviations. The left panel of each pair shows the surface chlorophyll concentrations and the right panel concentrations at the bottom. The base map has been modified from Wilson *et al*. (1997).

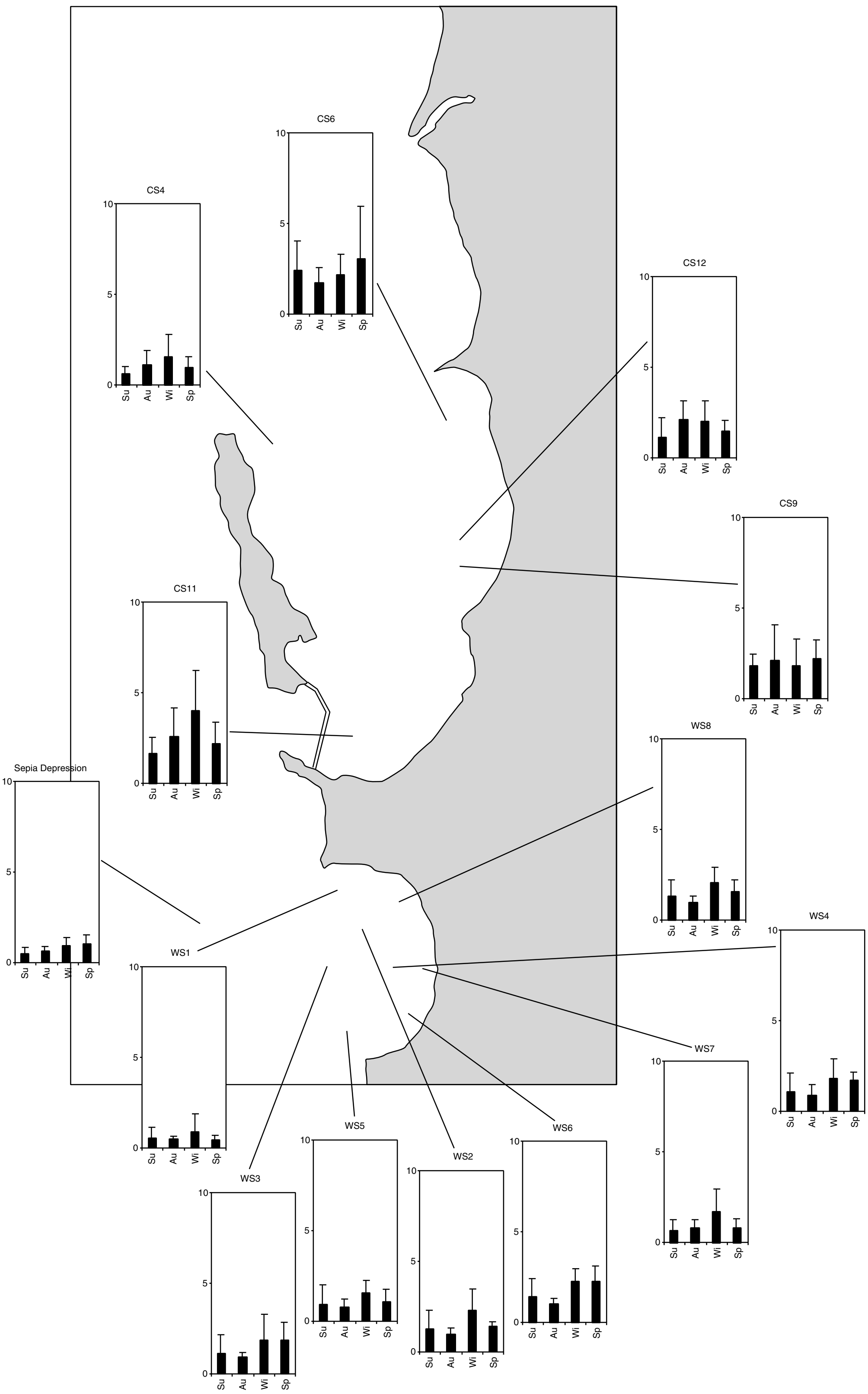


Figure 21 Seasonal chlorophyll concentrations in the Cockburn Sound/Warnbro Sound region. The four seasons are defined as Summer = December-January-February, and so on. The vertical chlorophyll axis runs from 0 to 10 μg/L, and the bars depict the means and standard deviations. The base map has been adapted from Cary and Masini (1995), and the data are for the period 1991 to 1994 from Cary and Masini (1995) and Helleren and John (1995).

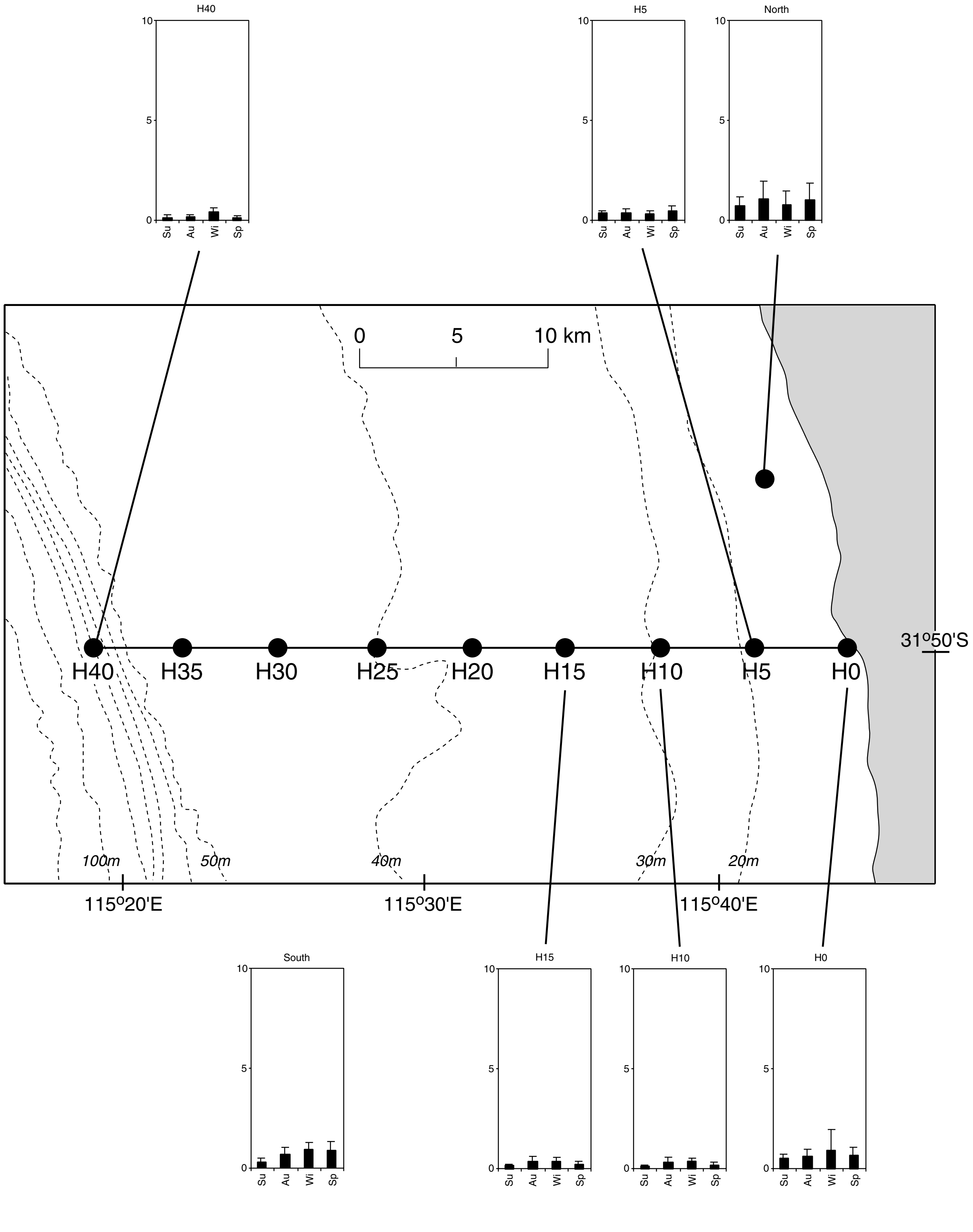


Figure 22 Seasonal chlorophyll concentrations in the wider Perth metropolitan waters, from the Hillarys transect and the two PLOOM stations. The four seasons are defined as Summer = December-January-February, and so on. The vertical chlorophyll axis runs from 0 to 10 µg/L, and the bars depict the means and standard deviations. The northern and southern charts are for the Beenyup (Ocean Reef) and Cape Peron outfall sites, respectively, for the period 1996-1998 (unpublished data courtesy of the Water Corporation and Peter Thompson), while stations H0 to H40 are from unpublished CSIRO data 1996 to 1998 (Pearce and Lynch in prep.).

The CD-ROM in the sleeve below contains the reference source document Helleren and Pearce 2000 referred to in Fisheries WA Research Report 123, 'Review of productivity levels of Western Australian coastal and estuarine waters for mariculture planning purposes'.

The intent behind producing this research report and associated CD-ROM is to provide access to chlorophyll-*a* data, from a wide variety of sources, free of charge to interested parties. It is reasonable to cite data by referencing this report. Where major sections of data are to be extracted from the report it would be preferable to seek the approval of the original providers of the data (referenced in the research report and associated CD-ROM).

It is recommended that people read the **Terms and conditions of use** and the **Disclaimer of Warranty** incorporated on the CD-ROM before accessing the Helleren and Pearce 2000 file.

Adobe Acrobat Reader version 4.0 for Windows and Mac platforms is also supplied on the CD for users who do not have access to the Internet. For users who have access to the Internet, the latest version of Acrobat Reader is available from the Adobe website at *www.adobe.com* as a free download.