Water quality and seagrass biomass, productivity and epiphyte load in Princess Royal Harbour, Oyster Harbour and King George Sound

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Preface

This study was conducted by the Centre for Water Research, Murdoch University and forms part of the Albany Harbours Environmental Study (1988-1989). The appendices for this volume have been published separately (Centre for Water Research, Murdoch University, Aquatic Ecology Number 89-251), and are housed in the Environmental Protection Authority library.

A summary of the Albany Harbours Environmental Study (1988-1989) findings, and the recommendations of the Technical Advisory Group to the Environmental Protection Authority, can be found in Simpson and Masini (1990) Bulletin 412 of the Environmental Protection Authority.

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Acknowledgements

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Field work was carried out by officers of the Environmental Protection Authority, Centre for Water Research (CWR), Albany Town Council and Shire of Albany. Nutrient analyses were carried out in the nutrient analysis laboratory, CWR, at the University of Western Australia.

Global radiation data were provided by the Australian Bureau of Meteorology.

Abstract

Water and plant samples were collected from Princess Royal Harbour, Oyster Harbour and King George Sound between December 1987 and February 1989. Mean nutrient and chlorophyll *a* concentrations in the waters of Oyster Harbour were higher than either Princess Royal Harbour or King George Sound. In contrast, water clarity was lower.

The water quality of Princess Royal Harbour in 1988/89 had improved significantly since the survey conducted in 1978/79, and was similar to the water quality in King George Sound.

A high proportion of phosphorus entering Oyster Harbour is in a dissolved inorganic form. During floods a buoyant, nutrient-rich layer of freshwater flows over the top of the denser marine water of Oyster Harbour and out into King George Sound.

Seagrass leaf biomass reached a seasonal maximum in spring/summer at all sites. Seagrass biomass and shoot density was lower in the two harbours than in King George Sound. Stands of *P. sinuosa* in Princess Royal Harbour were particularly sparse.

Nutrient concentrations in seagrasses, epiphytes and periphyton indicated that Oyster Harbour was more nutrient enriched than Princess Royal Harbour and King George Sound.

Light was found to be the dominant factor affecting seagrass leaf growth in all three waterbodies. Maximum leaf production rates per shoot were highest in spring, but maximum rates per unit area of meadow occurred in summer. Production rates were less consistent in the harbours than in King George Sound indicating a reduced capacity to lay down below-ground storage reserves, creating an increased vulnerability to unfavourable conditions such as prolonged periods of low light levels.

Macroalgal smothering appears to be the major cause of seagrass decline in Princess Royal Harbour. In contrast, epiphytes are implicated as the main cause of seagrass decline in Oyster Harbour, apart from the south-east corner of the harbour where dense accumulations of macroalgae occur. This difference may be due to the better water clarity in Princess Royal Harbour favouring the proliferation of macroalgae, while the higher nutrient loading and relatively poor light conditions in Oyster Harbour may favour the growth of epiphytes.

1. Introduction

Concern about a decline in environmental quality in Princess Royal Harbour and Oyster Harbour near Albany, Western Australia, led to a series of investigations into the nature, extent and reasons for the environmental problems (Atkins *et al*, 1980; Bastyan, 1986; Jackson *et al*, 1986; Kirkman, 1987; Mills, 1987; Talbot *et al*, 1987). Two main problems were identified. Heavy metal contamination of biota was found in Princess Royal Harbour, and seagrass dieback had occurred in Princess Royal and Oyster Harbours. This report is concerned with the latter problem.

The extent of seagrass dieback was first documented by Bastyan (1986) who estimated that between 1962 and 1984, 45% of seagrass cover in Oyster Harbour had been lost and 66% in Princess Royal Harbour. Bastyan (1986) suggested that this loss was caused by increased nutrient loading to the harbours, which had resulted in the proliferation of macroalgae and epiphytes. These, he suggested, had smothered some of the seagrass and reduced their light supply, eventually causing death. This conclusion was supported by Kirkman (1987) in a recent review, and similar scenarios had been documented in other Western Australian bays and estuaries, notably Cockburn Sound (Cambridge, 1979; Cambridge and McComb, 1984; Silberstein *et al*, 1986) and the Peel-Harvey Estuarine System (Hodgkin *et al*, 1985).

In an overview, Mills (1984) emphasized the lack of detailed information about the cause of the problems, and the need for adequate documentation of the present state of the harbours to provide a reference base from which to assess responses to management. This report presents the results from a study of seasonal changes in the water quality and the primary production of seagrasses and epiphytes in the two harbours.

The three main aims of this study were:

1. To obtain data on seasonal changes in the physico-chemical characteristics of the water in the two harbours and in King George Sound. Seasonal data would be essential for understanding changes in water quality and for Princess Royal Harbour, would allow a direct comparison with data from an earlier survey (Atkins *et al*, 1980) to assess changes in the last nine years.
2. To record seasonal changes in the above-ground biomass, leaf productivity and epiphyte load of the two main species of seagrass in the two harbours, and in the nutrient concentrations of seagrass and epiphyte tissues. This information would determine whether epiphyte loads might significantly affect seagrass growth at particular times of the year, whilst comparisons with healthy seagrass stands in the nutrient-poor waters of King George Sound would indicate the environmental stress imposed on seagrass meadows in the two harbours. Statistical relationships between physical and biological parameters were also sought, to indicate the important factors which may control the growth of seagrass and epiphytes.
3. To measure seasonal changes in the periphyton loads on artificial seagrasses in the three water bodies, to estimate epiphyte productivity and to assess the use of periphyton as integrated indices of water quality.

2. Study area

Princess Royal Harbour and Oyster Harbour are two large (28.7 km^2 and 15.6 km^2 respectively) harbours located near the town of Albany (Figure 1). Both have narrow channels communicating with the marine waters of King George Sound.

The geomorphology of the two harbours is similar (Bastyan, 1986). Both are shallow with gently sloping sandy margins, which carry subtidal seagrass meadows. The dominant seagrass species are *Posidonia australis* Hook f., *Posidonia sinuosa* Cambridge et Kuo and *Amphibolis antarctica* (Labill.) Sonder ex Aschers.

Princess Royal Harbour has no river inflow. Freshwater is added by rainfall, seepage, and run-off from adjacent land, especially via the Elleker Road drain (Figure 2). This drain collects runoff from agricultural land in the Robinson Estate and Marbellup-Elleker region, and effluent from local industry. This area is largely developed (85% cleared) and the principal farming activities are beef farming and potato growing. Princess Royal Harbour is a significant port for the town of Albany and its hinterland.

Oyster Harbour is fed by two large rivers and several minor streams (Figure 3). Much of the catchment, especially that of the Kalgan River, has been cleared for agriculture (beef and sheep farming). The Kalgan River appears to be the most significant source of sediment (McKenzie, 1962). There are no industrial discharges into Oyster Harbour, and no major port facilities.

The average annual rainfall for Albany is 953 mm, and rain falls mainly from May to October. In Princess Royal Harbour mean salinities vary from 31‰ to 37‰ throughout the year and mean temperatures from 10°C to 21°C (Atkins *et al*, 1980). In Oyster Harbour the salinity of surface waters varies from less than 4‰ to 36‰, whilst bottom salinities vary from 9‰ to 36‰ (McKenzie, 1962).

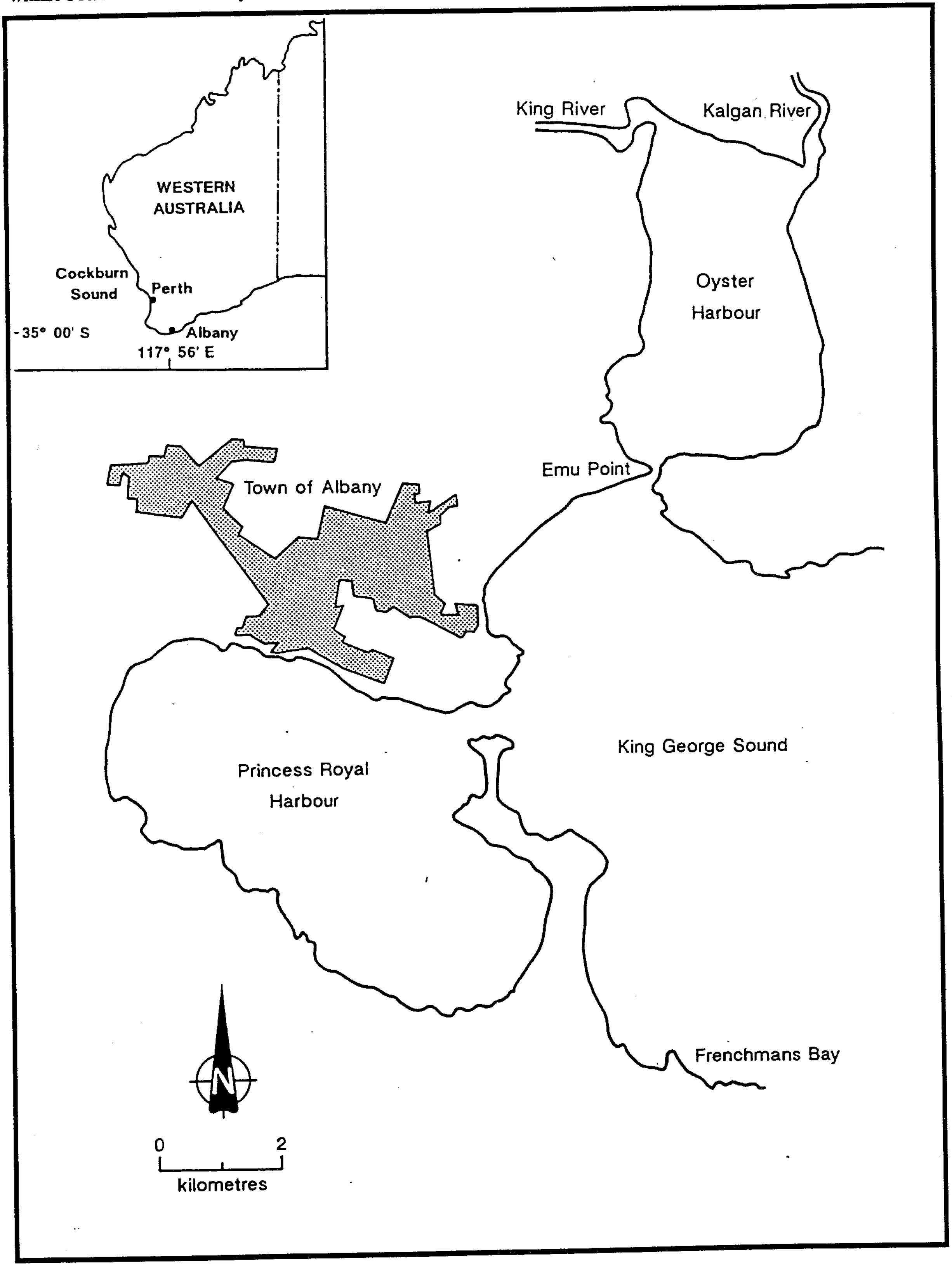


Figure 1. Princess Royal Harbour and Oyster Harbour study area

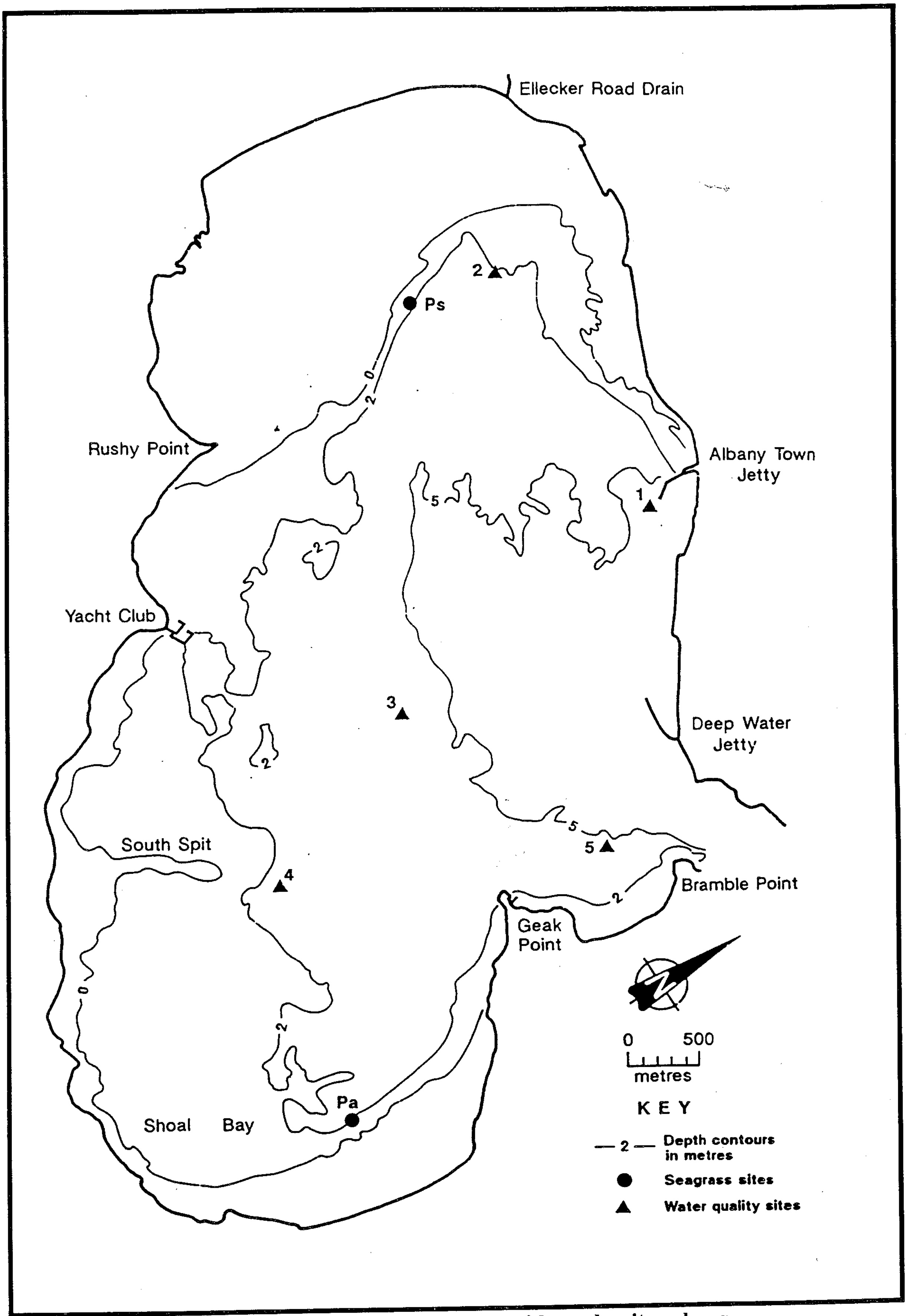


Figure 2. Bathymetry of Princess Royal Harbour with study sites shown

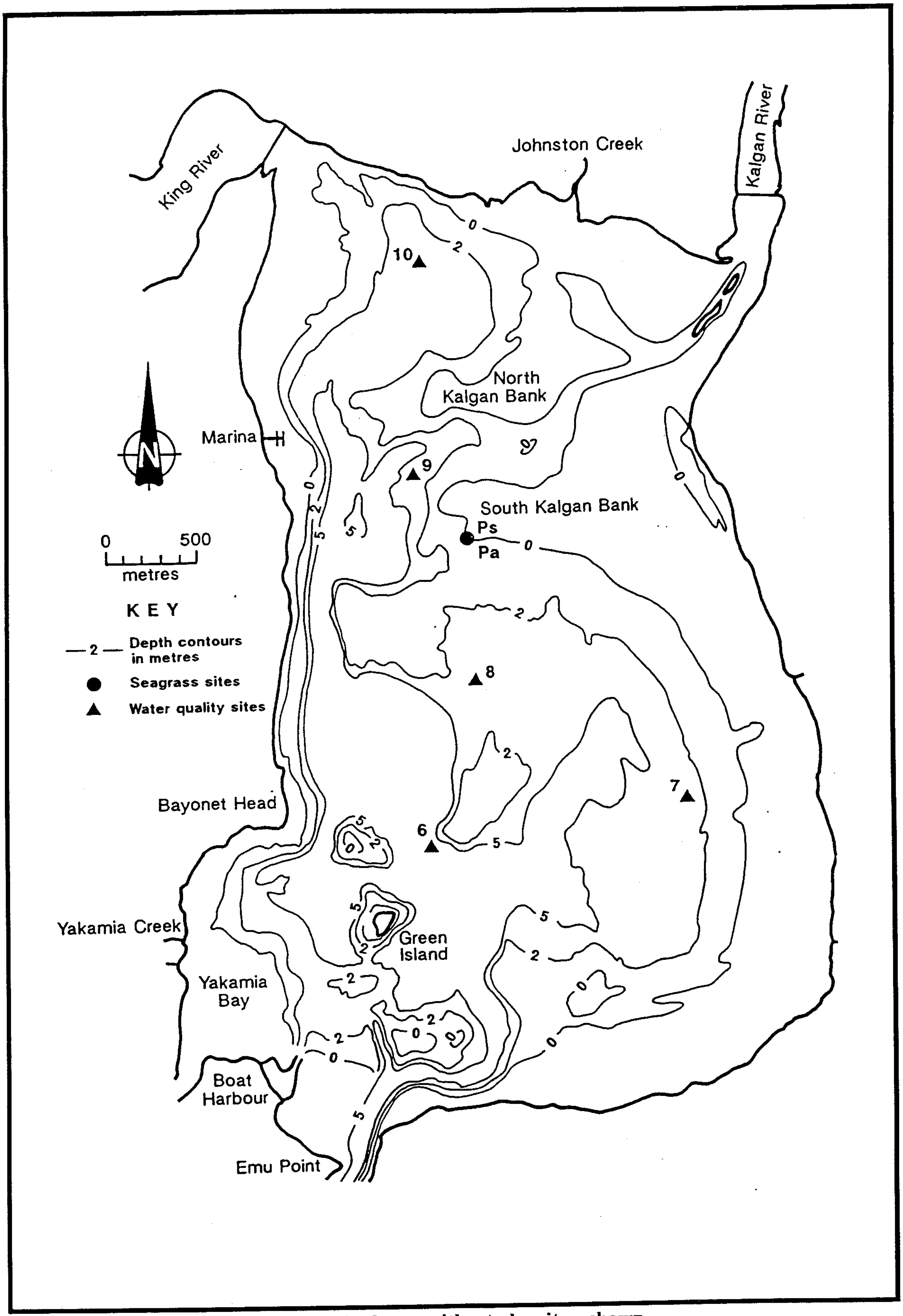


Figure 3. Bathymetry of Oyster Harbour with study sites shown

Tides are usually diurnal but may be semi-diurnal when the moon is near zero declination, particularly during spring and autumn (Hodgkin and Di Lollo, 1958). The maximum predicted tidal range at Princess Royal Harbour is 0.20 to 1.20 m, the mean variation being 0.40 m (Australian National Tide Tables 1981). Mills (1987) has estimated flushing times of the order of 14 days for both Princess Royal Harbour and Oyster Harbour.

3. Materials and methods

3.1 Water quality

Samples for nutrient analyses were collected at one site in King George Sound, and five sites in Princess Royal and Oyster harbours (Figures 2 and 3). The sampling frequency was monthly from December 1987 to April 1988 and fortnightly thereafter until November 1988, then monthly from December 1988 to February 1989. "Surface" water samples were collected approximately 0.3 m below the surface and "bottom" samples approximately 0.3 m above the sea-bottom, using 10 L Niskin bottles (General Oceanics). Surface and bottom water were mixed in equal proportions and subsampled for nutrient analysis unless significant (>3‰) salinity stratification was evident, when separate surface and bottom water samples were collected. Samples were immediately stored on ice, in 150 ml sealable polyethylene bags ("Whirlpak", Nasco, Kansas, USA) and immediately deep frozen upon return to the laboratory until analysed.

Salinity (±0.1‰), temperature (±0.1°C), dissolved oxygen (±0.1 mg l^{-1}), Secchi depths (±0.05 m) and light attenuation profiles were recorded at each site. Salinity, temperature and dissolved oxygen readings were taken at 1 m intervals through the water column, the first two using a portable salinity-temperature meter (Model 602, Yeo-Kal Electronics Pty Ltd, Australia) calibrated with standard seawater (Standard Seawater Service, Charlottenlund, Denmark), and the latter using an oxygen meter (Model 603, Yeo-Kal Electronics Pty Ltd, Australia). Percent oxygen saturation was calculated using temperature and salinity records for the site and an oxygen solubility nomograph (Strickland and Parsons, 1972).

Secchi disc readings were taken with a 0.2 m disc painted with black and white quadrants, and readings were always carried out on the unshaded side of the boat, as were data for light attenuation profiles. Light readings were taken using a Li-Cor Integrating Quantum/Radiometer/Photometer (Model LI-188B, Li-Cor Incorp., Nebraska, USA). Readings were taken at 0.2 m intervals down to a depth of 1 m, at 0.5 m intervals from 1-3 m and thereafter at 1 m intervals. The light attenuation coefficient was calculated as the slope of the regression of log light against depth, (Kirk, 1977). Total suspended solids were determined by filtering water through a pre-combusted (1 hour at 500°C) pre-weighed glass fibre filter (pore size 1.2 µm, Whatman Ltd, England); the filter was then weighed after oven drying at 80°C.

Ammonia-nitrogen (±5 µgl^{-1}) was measured using the isocyanurate method (Dal Pont *et al*, 1974). Nitrate-plus-nitrite (±2 µgl^{-1}) was determined after copper-cadmium reduction with a Technicon Autoanalyser II (Technicon Industrial Systems, Tarrytown, New York). Orthophosphate (±5 µgl^{-1}) was analysed by the single solution method (Major *et al*, 1972). Kjeldahl nitrogen (±200 µgl^{-1}) and total phosphorus (±10 µgl^{-1}) were determined after sulphuric and perchloric acid digests respectively (Anon, 1971), followed by the analyses for ammonia and orthophosphate given above. "Organic" nitrogen was determined by subtracting ammonia nitrogen from kjeldahl nitrogen, and "organic" phosphorus as the difference between orthophosphate and total phosphorus. Silicate silicon (±30 µgl^{-1}) was measured using the autoanalyser (Technicon Industrial Systems, Tarrytown, New York, Method 186 - 72 W/B). Samples were filtered through 1.2 µm filters (Whatman Ltd, England) in the field.

3.2 Plant material

Phytoplankton biomass was assessed as chlorophyll "a" concentrations. Water samples were filtered *in situ* using GFC filter papers (pore size 1.2 µm, Whatman Ltd, England), the filter papers were immediately stored on ice, and upon return to the laboratory deep frozen until analysed. The filters were ground in 90% acetone and the chlorophyll "a" concentration measured spectrophotometrically (Varian DMS 90 Spectrophotometer, Varian Techron Pty Ltd, Springvale, Australia) according to the method of Strickland and Parsons (1972).

Above-ground biomass of *Posidonia australis* and *P. sinuosa* was measured at a single site in each water body (Figures 2 and 3). Sites were chosen by locating the healthiest-appearing stand of each species of seagrass at a set depth in each water body (1 m deep for *P. australis* and 2 m deep for *P. sinuosa*). Sites near the inlets of the two water bodies were avoided, as water quality would have been influenced too much by oceanic exchange. Sampling was carried out every two months from December 1987 until October 1988. Sixteen replicate quadrats (0.01 m^2) were harvested at each site using SCUBA. preliminary trials in which forty quadrats were harvested established that 16 was the lowest statistically acceptable number of replicates. Seagrass material was scraped free of epiphytes using a razor blade and de-calcified in dilute hydrochloric acid (5% HCl). The numbers of leaves and shoots were recorded. Seagrass and epiphyte material was oven dried at 80°C, and the resulting dry weights converted to grams per square metre (g dw m^{-2}).

Samples of tissue were milled, and 200 mg subsamples assayed for total phosphorus following digestion in concentrated nitric and perchloric acids (Strickland and Parsons, 1972), and for total nitrogen using the autoanalyser after digestion in concentrated sulphuric acid in the presence of a mercury catalyst (Technicon Corp, Tarrytown, New York, Method 334-74 W/B). Five replicates were measured for both nitrogen and phosphorus. preliminary trials in which up to eight or ten replicates were analysed determined five as the lowest statistically-acceptable number of replicates for seagrass material.

Organic (ash-free) dry weight was determined by combusting pre-weighed subsamples (approximately 1 g) at 550°C for one hour, and the carbon content was calculated as 0.5 times the ash-free dry weight. The carbonate content of epiphyte material was estimated by combusting pre-weighed subsamples (approximately 100 mg) at 990°C for one hour.

Leaf productivity was determined at the biomass sites every two months from December 1987 until October 1988 using the marking technique of Kirkman and Reid (1979). Holes 1-2 mm in diameter were punched through the upper leaf sheath and enclosed leaf blades with surgical tongue forceps. Preliminary trials established that fifty shoots was the lowest statistically acceptable number that could be harvested to estimate leaf production. After five to 14 days the shoots were harvested, the length of new growth measured and the dry weight of new growth determined as described for biomass. The length of the longest intact leaf was also recorded. Mean leaf production per shoot per day was converted to leaf production per square metre per day (g dw m^{-2} day^{-1}) using shoot densities determined during biomass measurements. Specific leaf growth rate (% day^{-1}) was obtained by dividing leaf production by the above-ground biomass at the commencement of the marking period. The reciprocal of specific growth rate provided the "turnover time" or leaf replacement rate of the meadow in days.

3.3 Artificial seagrass

Quadrats of plastic seagrass (0.1 m^2) were assembled using a base of plastic-coated, woven-steel mesh (25 mm). Strips of plastic approximating a mean *P. australis* shoot size, with blade lengths of 60 mm, 300 mm and 385 mm and widths of 11 mm were attached to the grid (shoot density 1100 m^{-2}) using copper staples and plastic-coated wire. One quadrat was anchored at each site using steel pegs.

Quadrats were deployed from December 1987 until February 1989. Every two to four months the quadrats were replaced and the harvested quadrats placed in plastic bags on ice, and frozen immediately upon return to the laboratory. Twenty shoots were removed for chlorophyll "a" analysis, and the remainder randomly sorted into ten replicates (eight to ten shoots per replicate) for dry weight determination. Dry weights of periphyton ("epiphytes") were determined as described in Section 3.2. For chlorophyll "a" analysis epiphytes were scraped off with a razor blade, ground in 90% acetone, and the chlorophyll "a" concentration measured spectrophotometrically (Varian DMS 90 Spectrophotometer, Varian Techron Pty Ltd, Springvale, Australia) according to the method of Strickland and Parsons (1972). Chlorophyll "a" measurements were expressed as both per gram fresh weight of epiphytes and per square centimetre of plastic seagrass. Subsequent plots of mean chlorophyll "a" levels versus number of shoots indicated that only ten shoots needed to be sampled for statistically valid results. The amount of periphyton produced during each deployment interval was expressed as a production rate per day. Preliminary trials established that the accumulation of periphyton was linear with time.

3.4 Calculations

Independent linear correlations, students t-tests and stepwise linear multiple regressions were performed on physical and biological parameters using MASS (WESTAT, 1984) and STATVIEW programmes (Feldman *et al*, 1988). Global radiation data for Albany was supplied by the Australian Bureau of Meteorology, and the amount of photosynthetically active radiation (PAR) reaching the water surface calculated as 45% of total global radiation, and corrected for 15% scatter, according to the method of Hillman (1985). The amount of PAR reaching the seagrass beds was calculated using the attenuation coefficients and depths measured at each site, (Kirk, 1977). Daily lengths of periods of saturating irradiance for photosynthesis (H_{sat}) experienced by both species of seagrass were also calculated using functions for seasonal changes in day length and diurnal changes in light intensity (Hillman, 1985). The effective saturating light intensity for *P. australis* in the field was taken as 275 µE m^{-2} s^{-1} and for *P. sinuosa* as 170 µE m^{-2} s^{-1} (Masini *et al*, 1990).

4. Results and discussion

4.1 Water quality

In Princess Royal Harbour there was no significant difference between sites in the physical, chemical and biological characteristics of the water column. This was also true for Oyster Harbour, except for large river-flow events which are discussed separately. For this reason only mean data for each sampling occasion are discussed here.

Mean salinities (Figure 4) in Princess Royal (PRH) and Oyster Harbours (OH) were higher than in King George

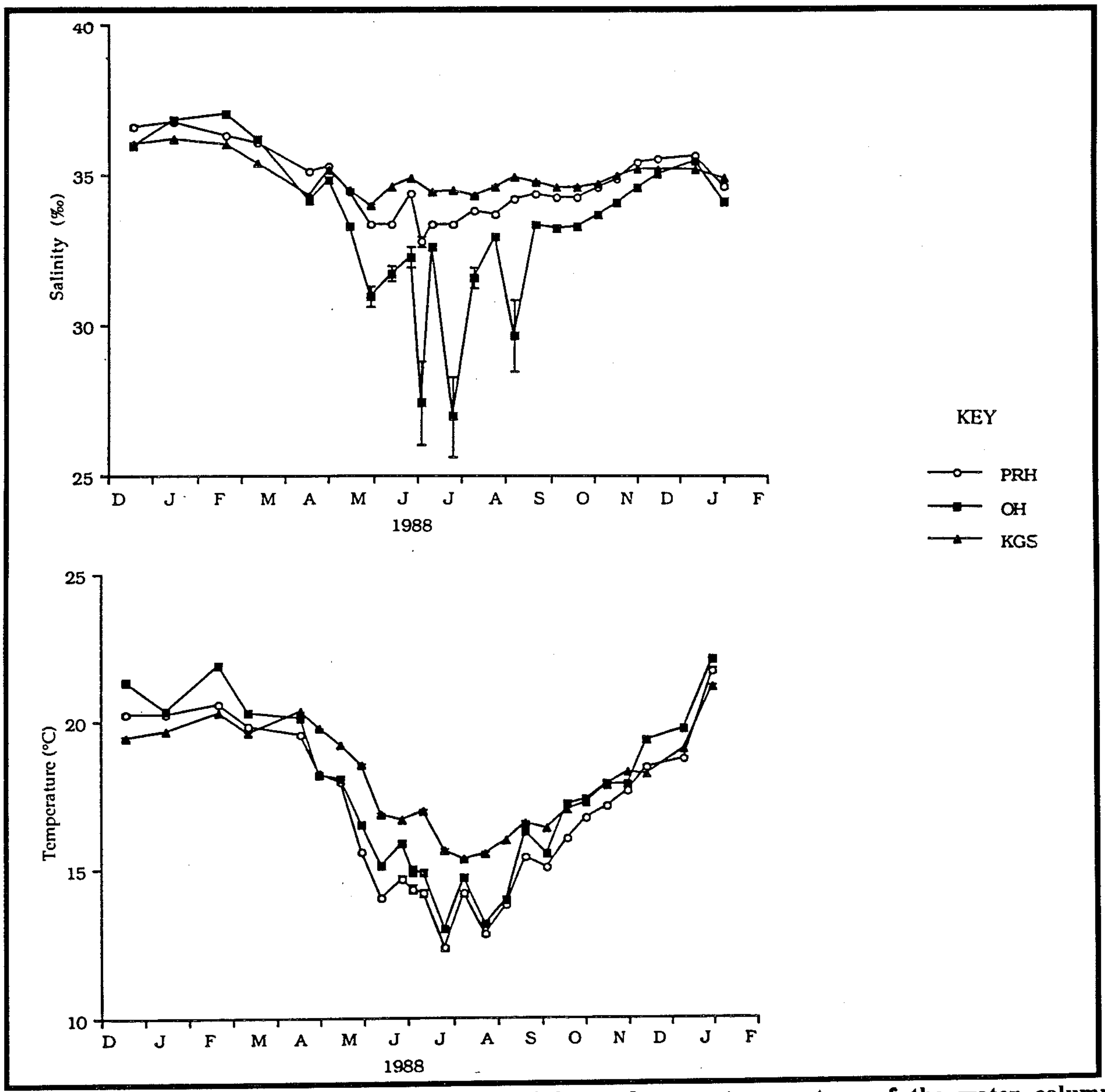


Figure 4. Seasonal changes in the mean salinity and mean temperature of the water column in King George Sound, Princess Royal Harbour and Oyster Harbour, December 1987 to February 1989. Standard error bars are included, but in most cases do not exceed the dimensions of the data point

Sound (KGS) from December to April, when as a result of river-flow (Oyster Harbour) and drainage (Princess Royal Harbour) they fell below those of King George Sound. Oyster Harbour had lower salinities in winter and spring than King George Sound and Princess Royal Harbour due to greater freshwater inflow. There was a general trend of decreasing salinity from summer to winter, due to a fall in evaporation rates from summer to winter (KGS, PRH and OH) and freshwater input in winter (PRH and OH). Salinities in Oyster Harbour fell sharply in mid-May, late June, late July and late August due to heavy rain in the catchment followed by large freshwater inflows. However salinities rapidly increased when river-flow subsided, indicating strong tidal flushing. Salinities in Princess Royal Harbour were less variable because of the absence of river flow. Minimum salinities reached in all three water bodies in were lower 1988/89 than in 1987/88, reflecting the much higher rainfall in winter 1988.

Maximum water temperatures (19-22°C) were recorded in February in both years (Figure 4) and the minimum (12-17°C) in late July/early August. Seasonal fluctuations in temperature were more extreme in Princess Royal and Oyster harbours than in the ocean, consistent with their shallower depth and smaller volume, coupled with restricted exchange with the ocean.

Mean dissolved oxygen (Figure 5) never fell below 70% saturation in the harbours or King George Sound during the daylight hours of the study. The oxygen concentration was more variable in the earlier part of the study (December 1987-August 1988) with relatively low concentrations in February and August 1988 and peaks in April and June 1988. These fluctuations do not appear to be attributable to biological factors (see below), and most likely result from physical processes such as wind mixing and thermal stratification. Between September 1988 and February 1989 dissolved oxygen concentrations remained similar within all three waterbodies, and between 90 to 110% saturation. During this period King George Sound generally had higher water column dissolved oxygen concentrations than the two harbours, while Princess Royal Harbour generally had lower dissolved oxygen concentrations.

Light attenuation (Figure 5) was similar in King George Sound and Princess Royal Harbour, varying between 0.1-0.2 m^{-1}, from December 1987 to August 1988. Between September 1988 and February 1989 light attenuation was generally lower in King George Sound. than the harbours. It was significantly ($p<0.01$) higher in Oyster Harbour than Princess Royal Harbour or King George Sound, especially in winter, because of the inflow of humic-stained river water and its associated sediment load. At other times the high light attenuation in Oyster Harbour is probably due to its higher suspended sediment load (see below).

Total suspended solids were significantly ($p<0.01$) higher in Oyster Harbour, especially during winter, and this is probably due to the sediment load associated with peak river-flow events (Figure 6). The higher concentrations in Oyster Harbour during "low flow" periods, when compared with the other two water bodies, may be due to sediment resuspension. There were no obvious seasonal trends in the particulate load of the water column in King George Sound or Princess Royal Harbour (Figure 6). King George Sound generally had a lower suspended solids concentration than Princess Royal Harbour except for the winter months June-September 1988, when the two were similar.

The organic content of the suspended solids varied between 40-60% in all three water bodies until late June 1988 (Figure 6). Until then, suspended solids concentrations were low and the relatively high organic content suggested a high proportion of new organic material (eg phytoplankton) compared to resuspended sediment, which typically has an organic content of <20%. The organic content fell dramatically in late June and remained low until mid August in all three waterbodies. This can be explained for Oyster Harbour as the initial fall was associated with a dramatic increase in the suspended solids concentration, and the low organic content would be due to the sediment load (largely inorganic) associated with river-flow. However, suspended solids in the other two water bodies showed a dramatic fall in organic content at the same time without concomitant increase in suspended solids; presumably there was nevertheless an increase in the proportion of sediment derived from inorganic sources even though it did not significantly affect the amount of total solids detected. The proportion of inorganic material fell again in all waterbodies in late August.

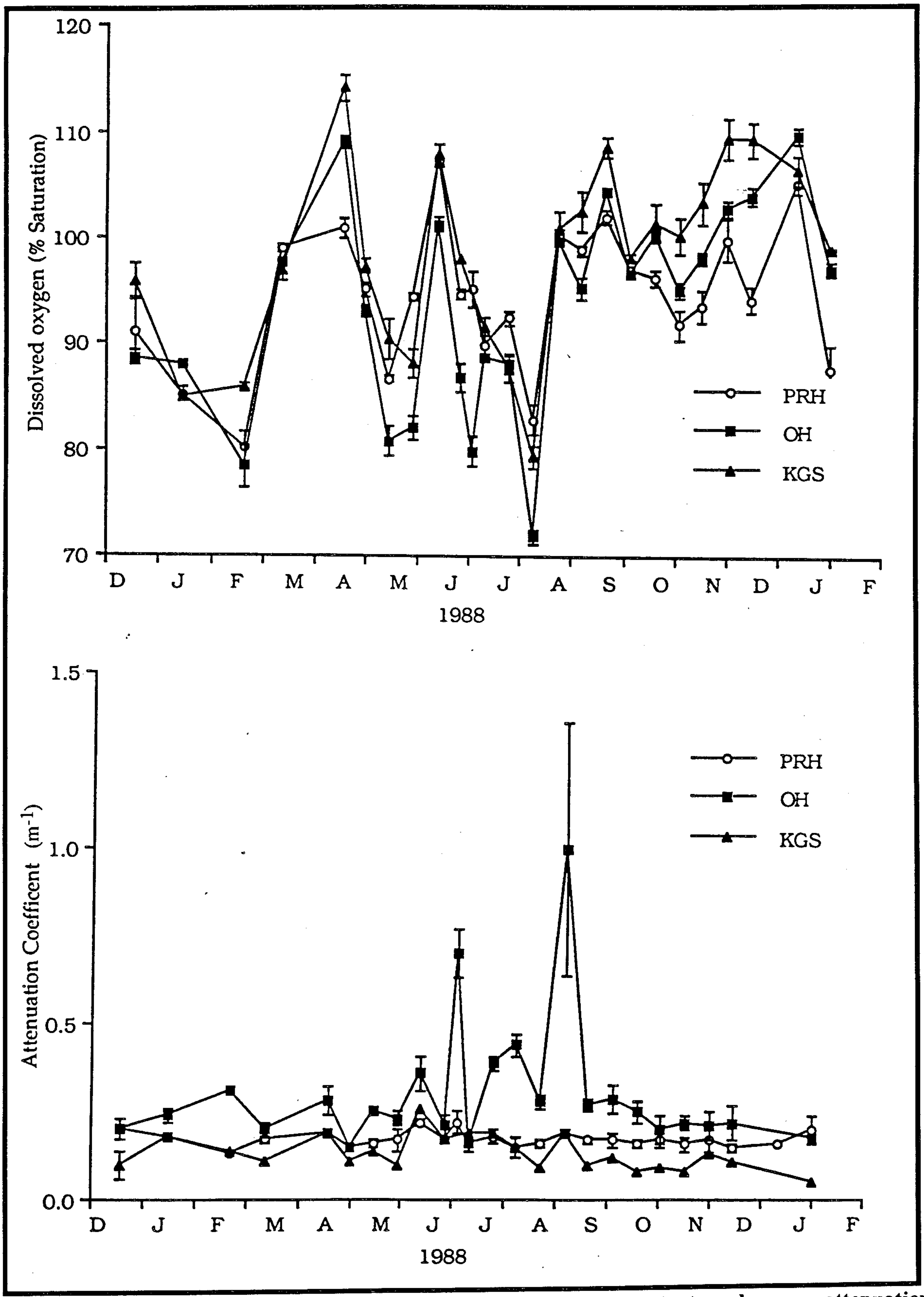


Figure 5. Seasonal changes in the mean dissolved oxygen content and mean attenuation coefficient of the water column in King George Sound, Princess Royal Harbour and Oyster Harbour. December 1987 to February 1989

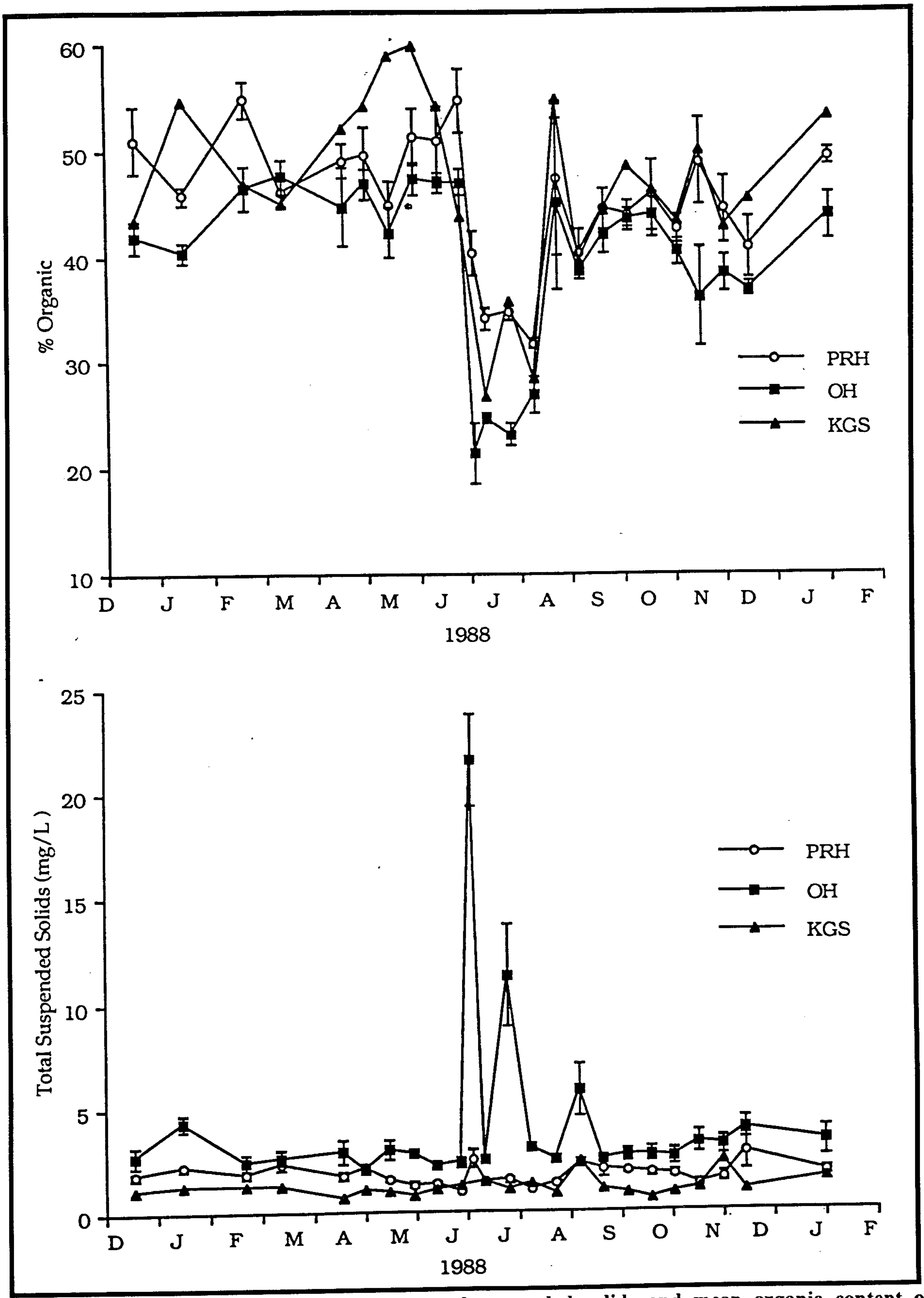


Figure 6. Seasonal changes in the mean total suspended solids and mean organic content of the suspended solids of the water column in King George Sound, Princess Royal Harbour and Oyster Harbour. December 1987 to February 1989

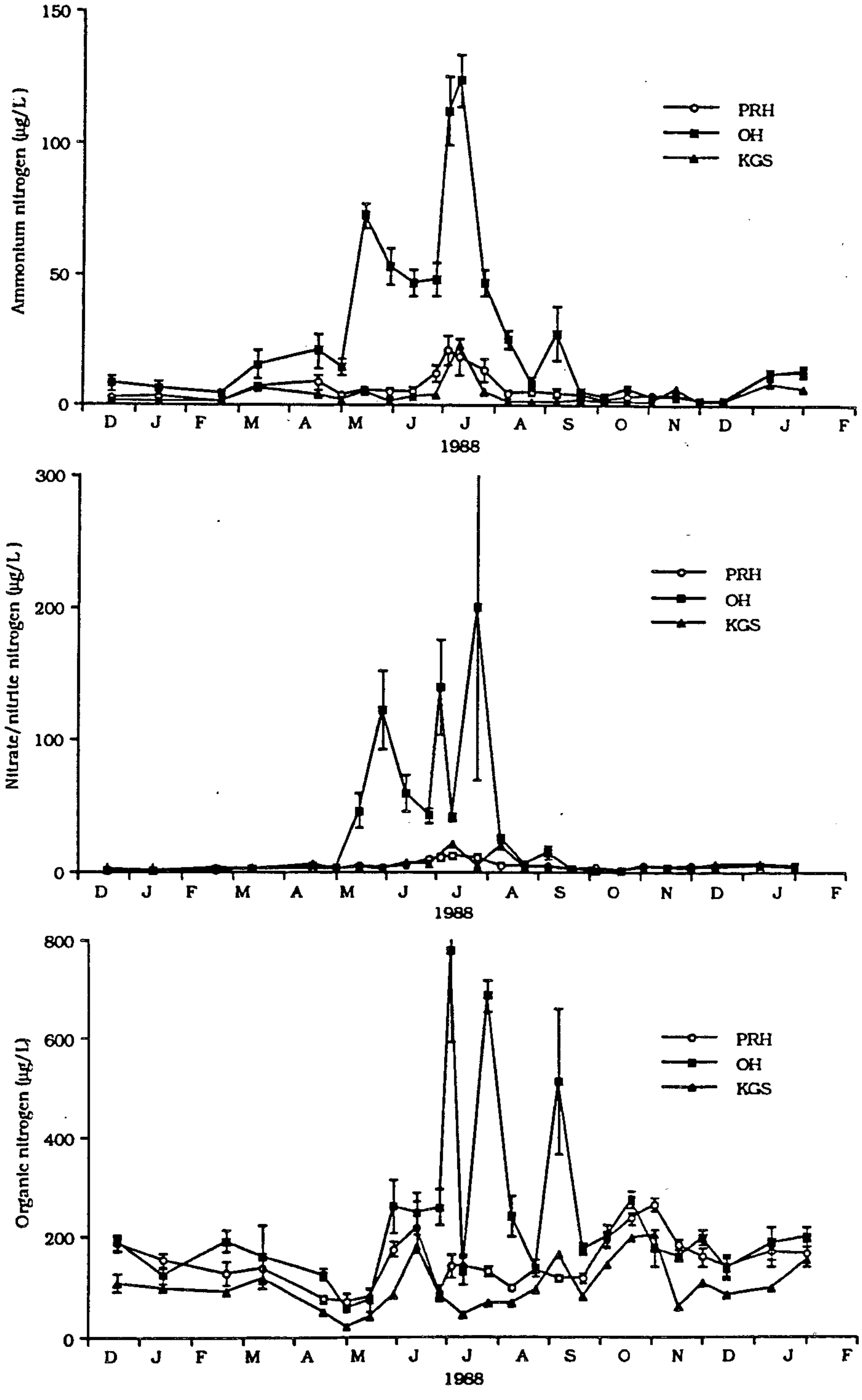


Figure 7. Seasonal changes in the inorganic (ammonia and nitrate-nitrite) and organic nitrogen concentrations of the water column in King George Sound, Princess Royal Harbour and Oyster Harbour. December 1987 to February 1989

Inorganic nitrogen concentrations (Figure 7) showed marked seasonal changes. Concentrations were similar in Princess Royal Harbour and King George Sound, which showed a slight increase in nitrate and ammonium concentrations in July, perhaps because of the remineralization of seagrass detritus following the decline in seagrass biomass at this time (see below). Initially the concentrations of inorganic nitrogen in Oyster Harbour were similar to those in the other waterbodies, but increased dramatically in May. By analogy with the Peel/Harvey system, river-flow would be the main source of nitrate, whereas the high ammonium concentrations are probably due to benthic recycling. Mean organic nitrogen concentrations (Figure 7) were below the reliable detection limit (~ 200 μg l^{-1}) in King George Sound and Princess Royal Harbour on most sampling occasions. Concentrations in Oyster Harbour were also low until June 1988 when concentrations increased. Oyster Harbour had significantly ($p<0.01$) higher total nitrogen concentrations than either King George Sound and Princess Royal Harbour, and Princess Royal Harbour had significantly ($p<0.05$) higher concentrations of ammonium nitrogen and organic nitrogen than King George Sound. Clearly, river loading dominates the nitrogen cycle of the water column in Oyster Harbour.

Phosphate phosphorus concentrations were low (below the reliable detection limit) at all sites until June when levels increased markedly in Oyster Harbour (Figure 8). There was evidence for a slight increase in phosphate concentration in Princess Royal Harbour and King George Sound in July. Organic phosphorus concentrations (Figure 8) were variable, generally ranging between 10-30 μg l^{-1} at all sites until June when concentrations increased in Oyster Harbour. Phosphorus concentrations were significantly ($p<0.05$) higher in Oyster Harbour compared to Princess Royal harbour and King George Sound. There was no significant ($p<0.05$) difference between the phosphorus concentration of the water column of Princess Royal Harbour and King George Sound. As for nitrogen, river inflow clearly dominates the phosphorus dynamics of the water column in Oyster Harbour.

There was no significant ($p<0.05$) difference between Princess Royal Harbour and King George Sound in mean soluble reactive silicate concentrations (Figure 9), but concentrations in Oyster Harbour were significantly ($p<0.01$) higher over the entire sampling period. The higher silicate concentrations in Oyster Harbour between December and April may be due to benthic regeneration, while the increase during winter would have been due to the input of dissolved silica in the inflowing river water.

Chlorophyll "a" concentrations were low; the maximum mean concentration measured during the study was 2.8 μg l^{-1} in Oyster Harbour on 25 May 1988 (Figure 9). Chlorophyll "a" concentrations in Oyster Harbour were significantly ($p<0.05$) higher than in either Princess Royal Harbour or King George Sound. The mean concentration in Princess Royal Harbour was significantly ($p<0.05$) higher than in King George Sound.

Chlorophyll concentrations in all three water bodies increased during the winter months, presumably in response to increased nutrient availability associated with freshwater inflow and decomposition of seagrass detritus. However the chlorophyll concentration in all three water bodies was generally less than 2 μgl^{-1} except on two occasions in Oyster Harbour. The low chlorophyll concentrations in Oyster Harbour are somewhat surprising given the relatively high nutrient concentrations, (especially nitrogen) during the winter months. A possible explanation is that there is little nutrient retention in Oyster Harbour and that the nutrient-rich freshwater simply flows over the more dense, saline water, with little opportunity for the uptake of plant nutrients (see below).

The ratios of inorganic nitrogen to phosphorus (by atom) were always below 30:1 in Princess Royal Harbour and King George Sound (Figure 10) indicating that of these two nutrients, nitrogen availability is more likely to be limiting plant growth than phosphorus. Nitrogen to phosphorus ratios were below 30:1 in Oyster Harbour except for the period March-May 1988 when ratios in excess of 200:1 were recorded. During this period phosphorus availability may have been limiting phytoplankton growth. The high inorganic nitrogen concentrations in the water column of Oyster Harbour during this period were due to high ammonium nitrogen concentrations and are therefore unlikely to be due to river flow, but maybe to the remineralization of seagrass detritus resulting from seagrass senescence at this time (see below). The increase in nitrogen levels relative to phosphorus suggests that while nitrogen is released to the water column phosphorus released during remineralization of seagrass detritus is probably being trapped by the sediments.

4.1.1 Comparison with 1978/79 survey

The water quality data collected during this study for Princess Royal Harbour, where possible, have been compared to data collected in 1978/79 by Atkins *et al* (1980) in order to detect any significant changes in water quality over this period. The 1978/79 data were the monthly means for the central basin sites, and can be compared to the data collected during this study.

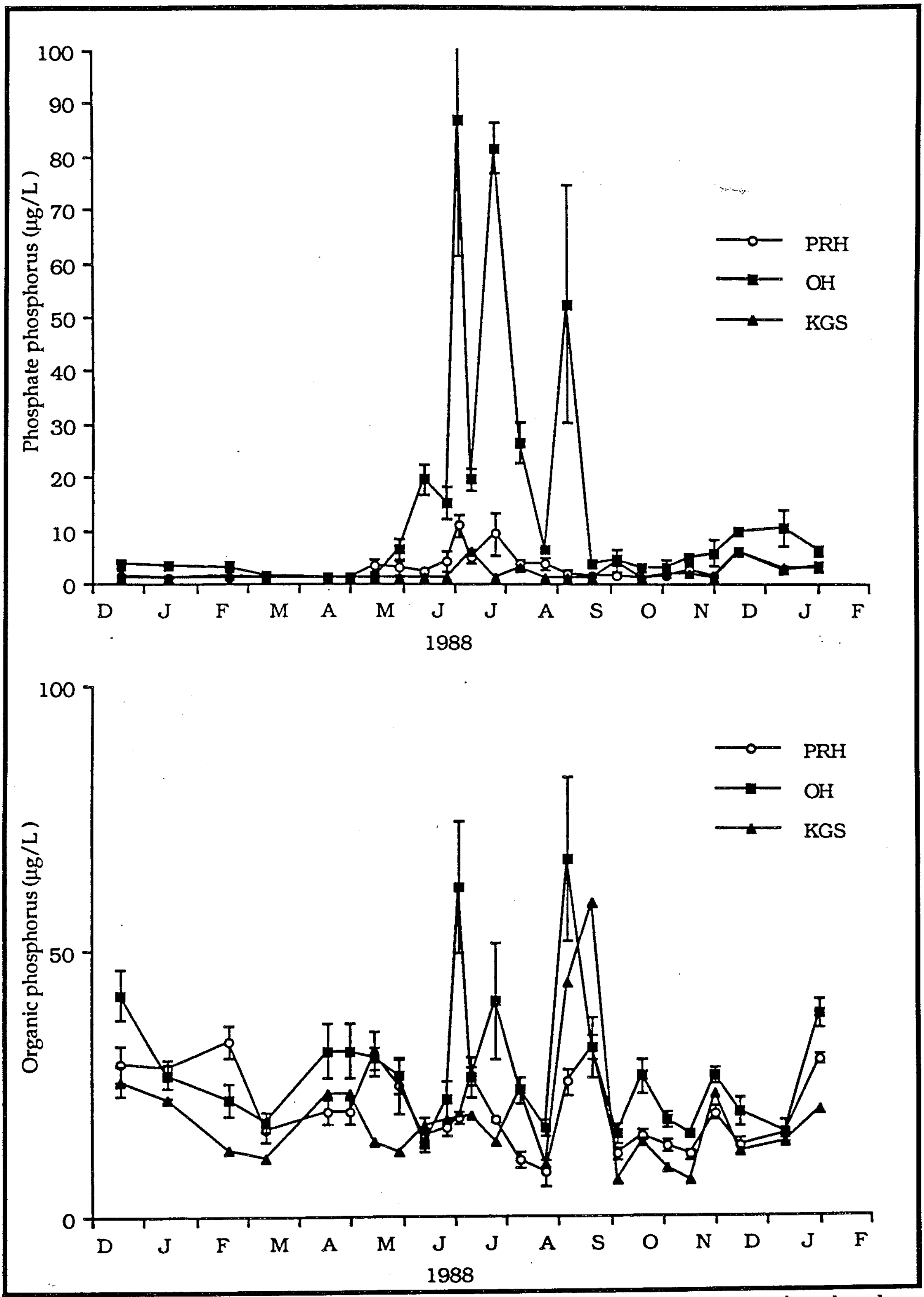


Figure 8. Seasonal changes in the phosphate phosphorus and organic phosphorus concentrations of the water column in King George Sound, Princess Royal Harbour and Oyster Harbour. December 1987 to February 1989

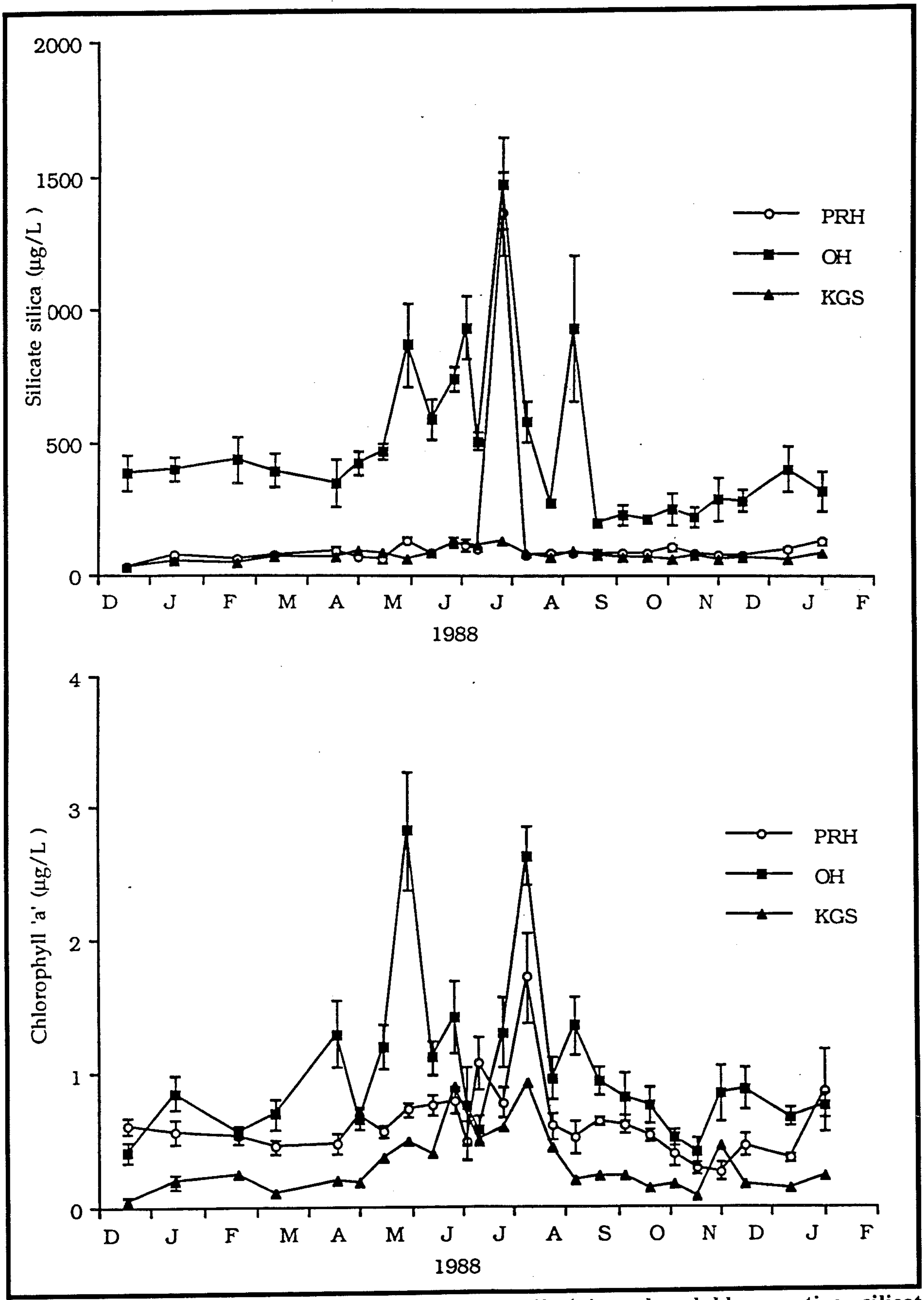


Figure 9. Seasonal changes in the chlorophyll 'a' and soluble reactive silicate concentrations of the water column in King George Sound, Princess Royal Harbour and Oyster Harbour. December 1987 to February 1989

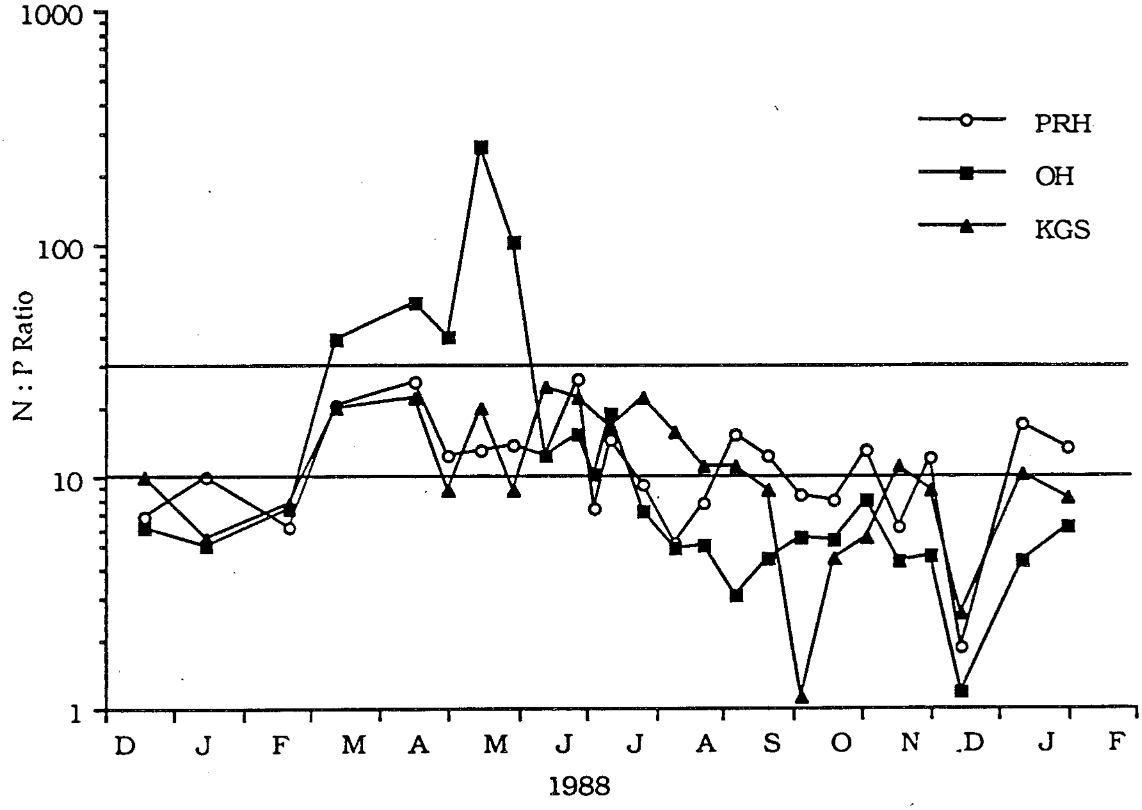


Figure 10. Seasonal changes in the inorganic N:P ratio of the water column in King George Sound, Princess Royal Harbour and Oyster Harbour. December 1987 to February 1989

Monthly mean salinities and temperatures were not significantly ($p<0.05$) different between the two surveys, suggesting that any significant differences between the two surveys in water column nutrient concentrations and chlorophyll "a" concentrations are not likely to be due to inter-annual variability in rainfall and runoff. This is concomitant with the similar mean annual salinities (35.5‰ ± 0.9‰ in 1978/79 and 34.9‰ ± 1.2‰ in 1987/88).

Monthly mean phosphate concentrations were significantly ($p<0.01$) higher (on average five times) in 1978/79 than for the corresponding months in 1987/88 (Figure 11). Organic phosphorus concentrations (Figure 11) were significantly higher most months in 1978/79 compared to 1987/88, though the mean for the year was not significantly ($p<0.05$) different between the two studies.

Monthly mean ammonium concentrations (Figure 12) were significantly ($p<0.01$) higher (on average four times) in 1978/79 compared to 1987/88. Monthly mean nitrate-nitrite concentrations in 1978/79 were higher in winter in 1987/88, and lower in summer (Figure 12), but there was no significant ($p<0.05$) difference in the mean for the year.

Monthly mean chlorophyll "a" concentrations (Figure 13) were significantly ($p<0.05$) higher in 1978/79 (on average 2.5x) compared to 1987/88.

The comparisons between the 1978/79 and 1987/88 surveys indicate that "water quality" (nutrient and chlorophyll concentrations) has improved considerably since the earlier survey. This is most likely due to a reduction in nutrient loading to the harbour from industry as a result of the findings of the study by Atkins *et al* (1980). These measures by industry have been successful in improving water quality and are most likely, directly responsible for the regeneration of seagrass in the central basin of Princess Royal Harbour (Hillman *et al* 1989), due to reduced phytoplankton biomass and consequent improvement in light penetration. However, the reductions in nutrient loading have not been sufficient to eliminate the macroalgal problem in Princess Royal Harbour, where significant losses of seagrass due to macroalgal smothering are still occurring. Nutrient loading needs to be reduced further, to a level limiting to macroalgal growth.

4.1.2 Flood event

Opportunistic sampling was carried out in Oyster Harbour on 29 June 1988 to determine the effects on water quality of a large flood event. Location of sampling sites and the sites used to draw the longitudinal and transverse sections are shown in Figure 14. Surface and bottom salinity contour plots are shown in Figure 15. Surface salinities ranged between 2‰ and 6‰, and the contour plot shows that most river-flow was from the Kalgan catchment; surface salinities were much higher in the mouth of the King River compared to the Kalgan River (Figure 15). The salinity contour plot of the bottom water (Figure 15) shows that water of marine origin covered most of the bottom of Oyster Harbour. The water column was strongly stratified, tidal flushing being sufficiently strong to resist erosion of the salt wedge by river-flow. The freshwater formed a thin layer less than 0.5 m thick overlying the dense marine water. A plume of freshwater extended well into King George Sound with a sharp halocline at all sites (Figure 15). Longitudinal and transverse depth profile contour plots of salinity (Figure 16) showed that only minimal mixing of fresh and marine water below 1 m. Longitudinal and transverse salinity differences were negligible, indicating even vertical mixing over the entire system.

Surface and bottom phosphate concentration contour plots are shown in Figure 17. Surface phosphate concentrations were between 100-180 $\mu g l^{-1} P$, the highest concentrations occurring around the mouth of the Kalgan River and most likely due to mixing of phosphate-rich freshwater with marine water by flow-induced shear mixing. Phosphate phosphorus accounted for approximately 50% of the total phosphorus concentration. Surface and bottom ammonium nitrogen concentrations contours (Figure 19) showed a markedly different pattern to phosphate and this is attributed to the dominant influence of sediment release on ammonium concentrations. River water generally has low concentrations of ammonium as does marine water, and most of the ammonium in the water column at this time would have originated from the remineralization of organic matter in the surface sediments, and subsequent mixing of ammonium into the water column. Surface nitrate nitrogen concentrations (150-300 $\mu g l^{-1} N$) were much higher than bottom water concentrations (20-80 $\mu g l^{-1} N$). The bottom nitrate concentration contours (Figure 18) showed a similar pattern to phosphate, with highest concentrations near the mouth of the Kalgan River. The highest surface nitrate concentrations were found in the south-eastern section of Oyster Harbour (Figure 18) and do not appear to be associated with river-flow which would normally be the dominant source of nitrate.

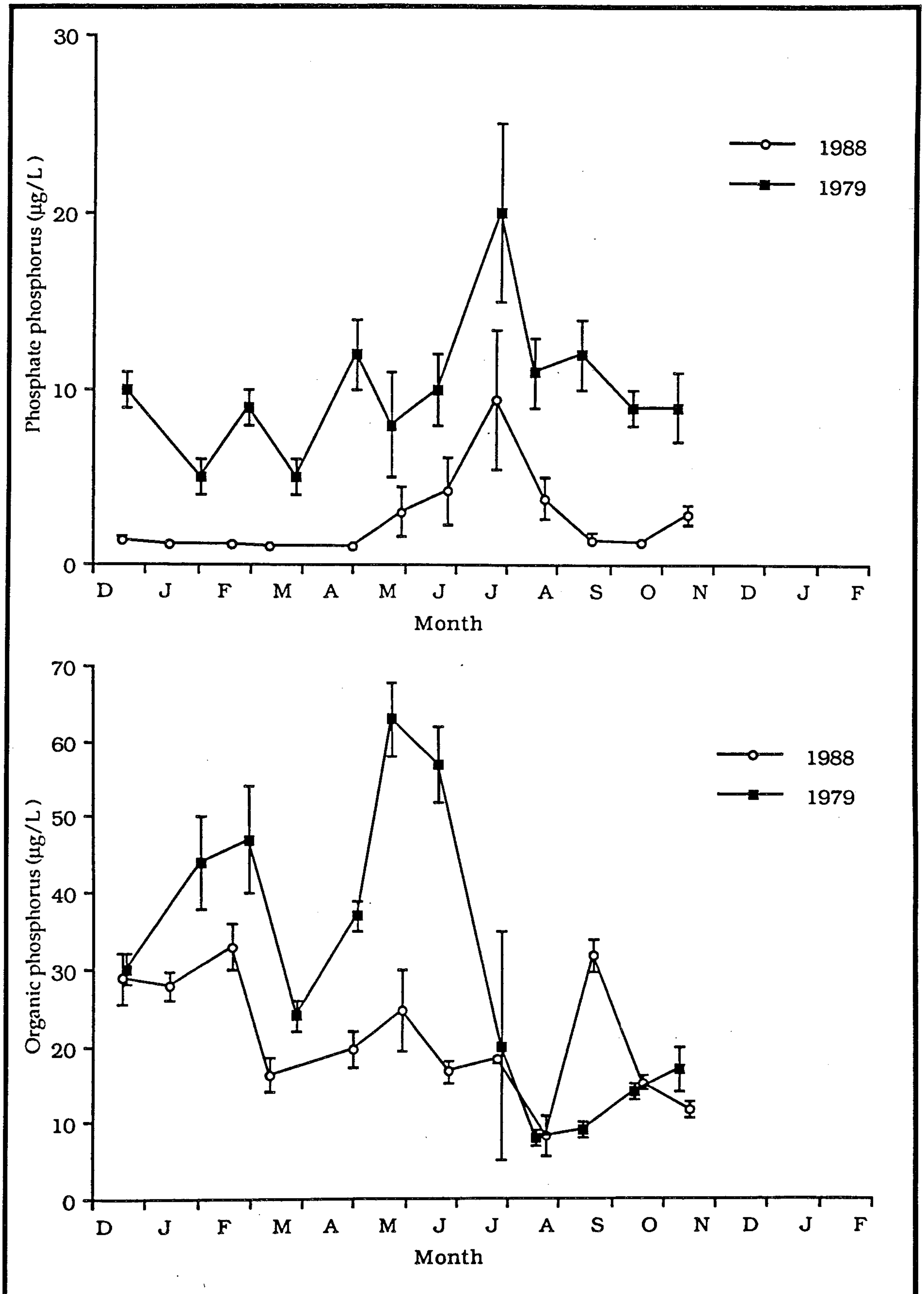


Figure 11. Seasonal changes in the phosphate phosphorus and organic phosphorus concentrations of the water column in Princess Royal Harbour in 1979 and 1988

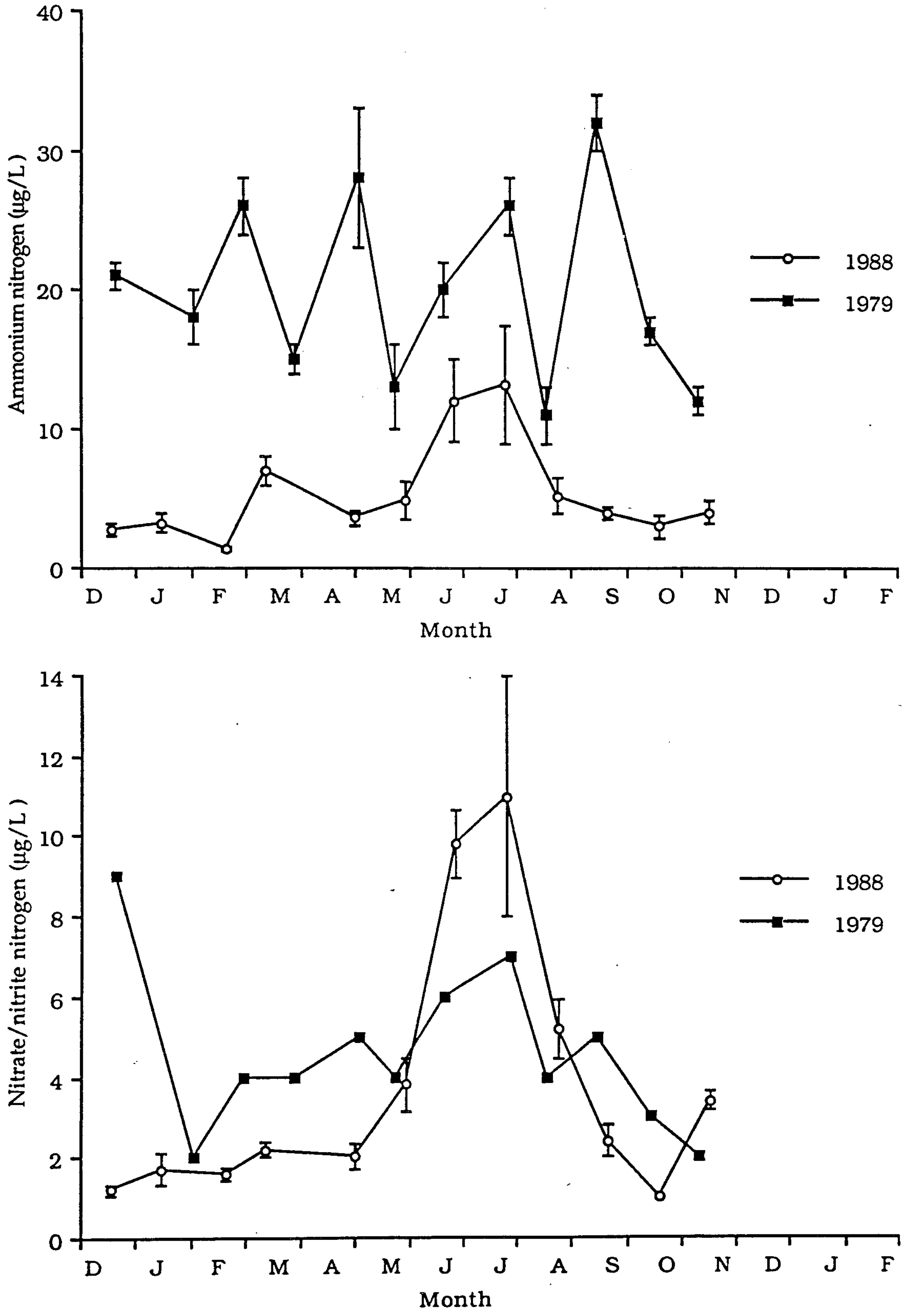


Figure 12. Seasonal changes in ammonium and nitrate-nitrite concentrations of the water column in Princess Royal Harbour in 1979 and 1988

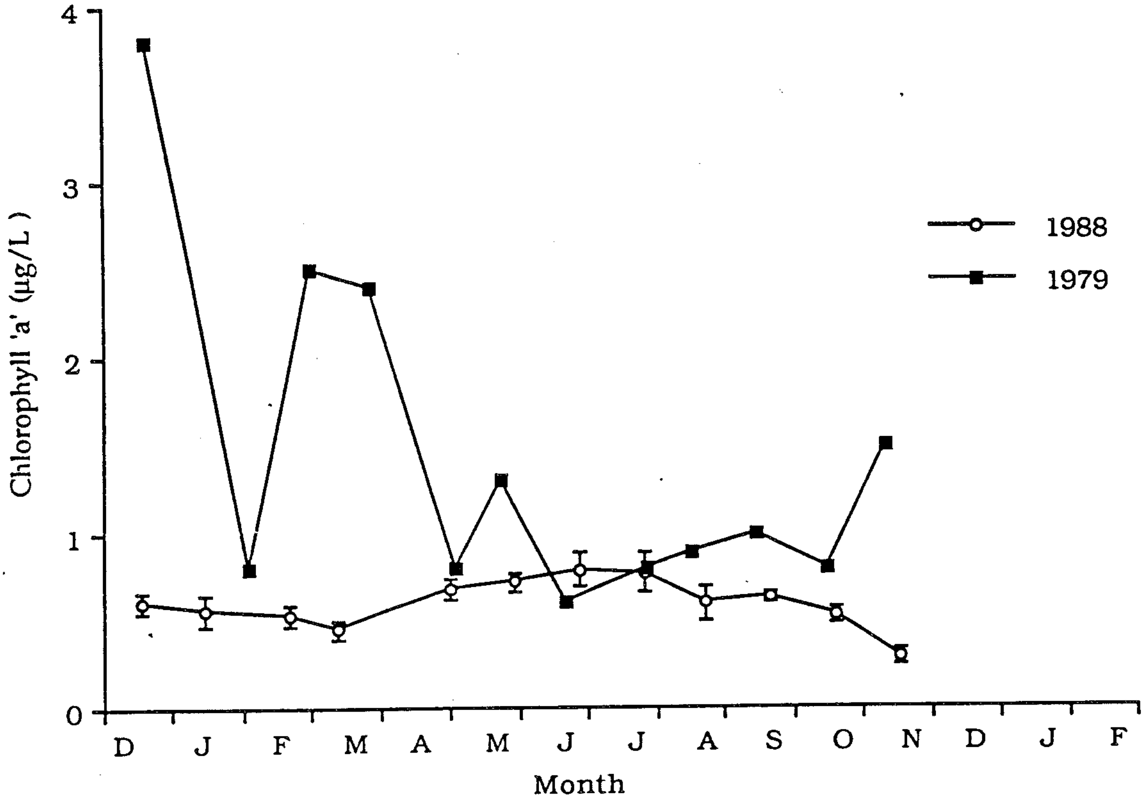


Figure 13. Seasonal changes in the chlorophyll 'a' concentrations of the water column in Princess Royal Harbour in 1979 and 1988

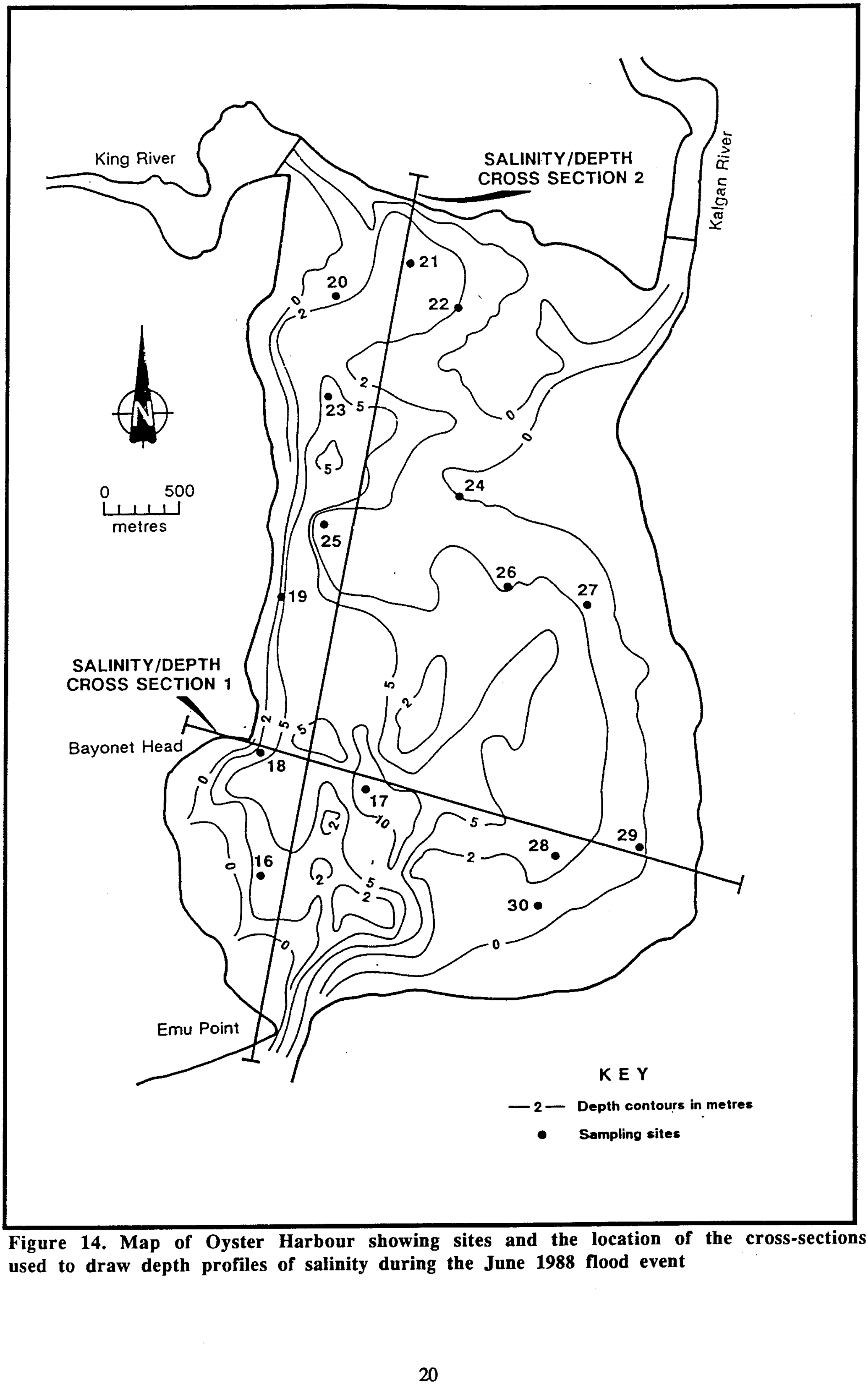
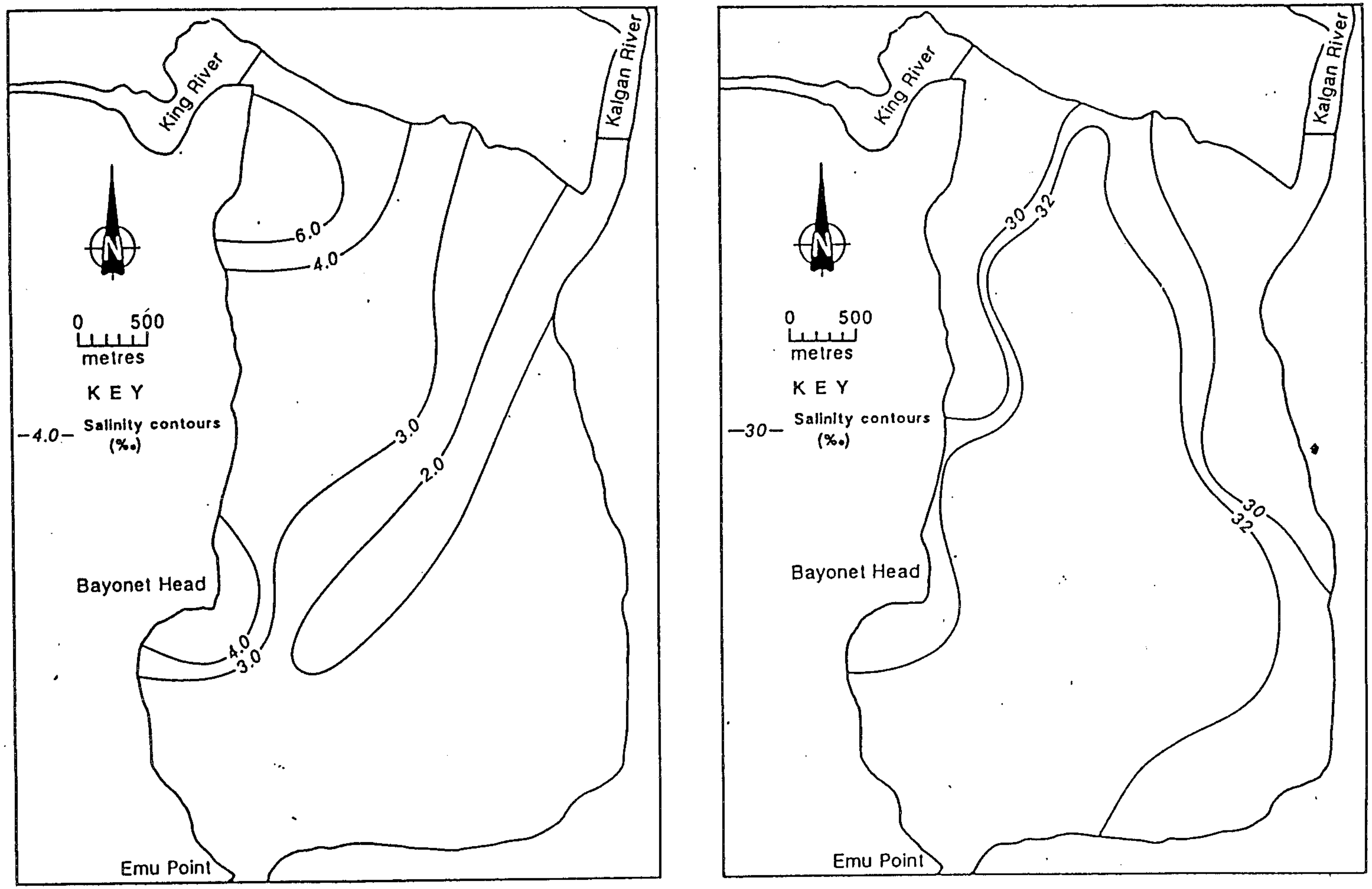


Figure 14. Map of Oyster Harbour showing sites and the location of the cross-sections used to draw depth profiles of salinity during the June 1988 flood event



SURFACE

BOTTOM

Figure 15 Map of Oyster Harbour showing the salinity contours of the surface and bottom of the water column during the June 1988 flood event.

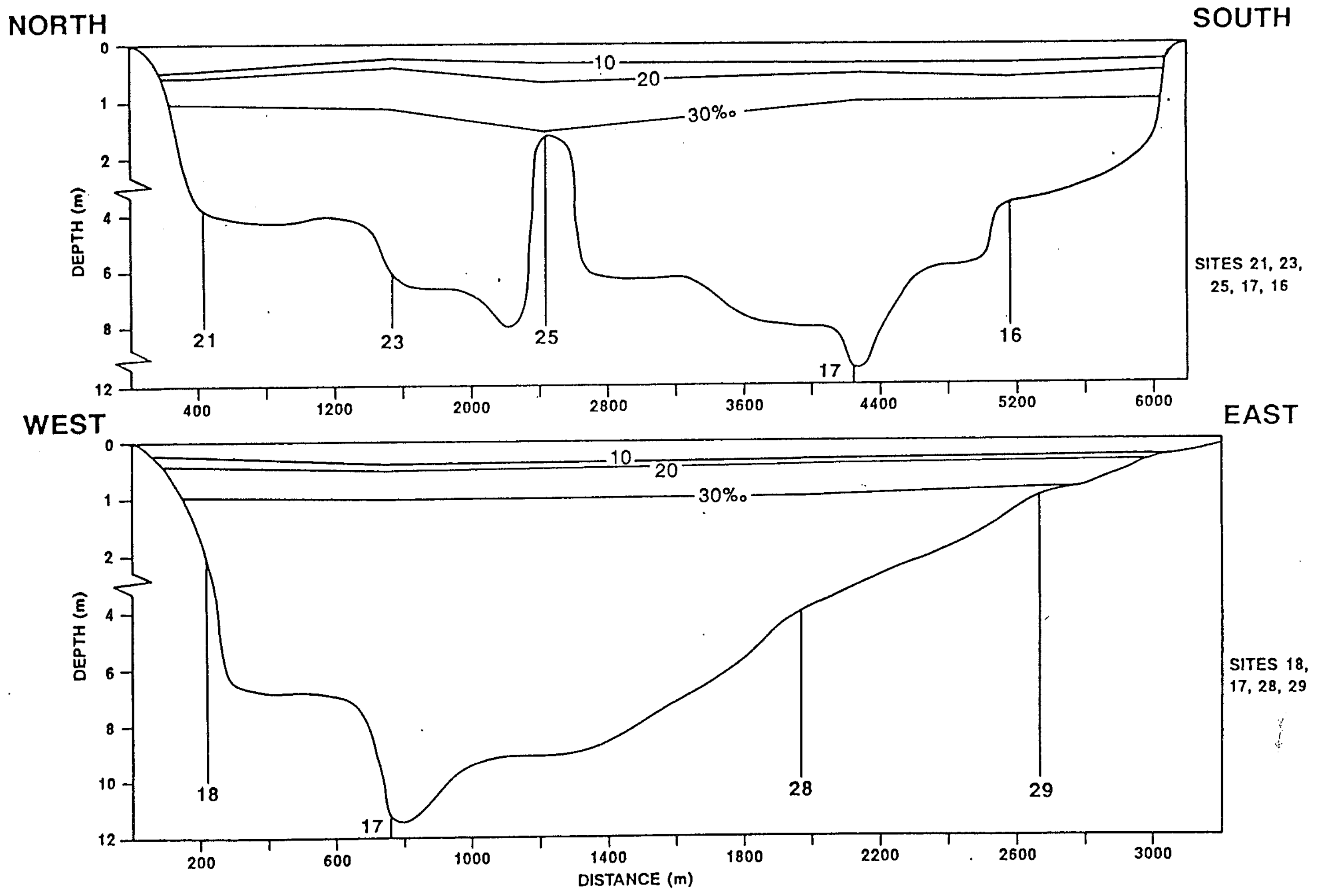
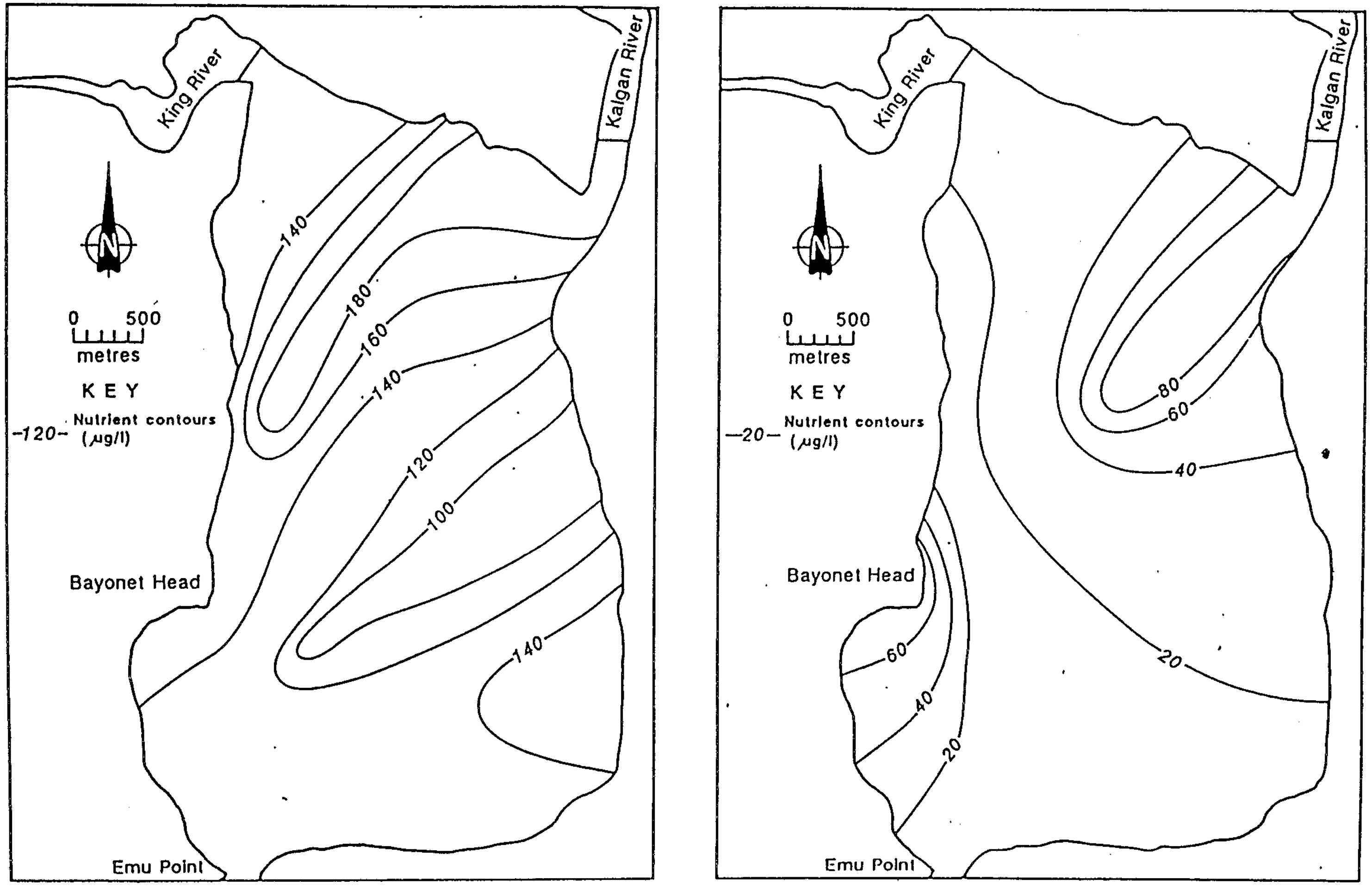


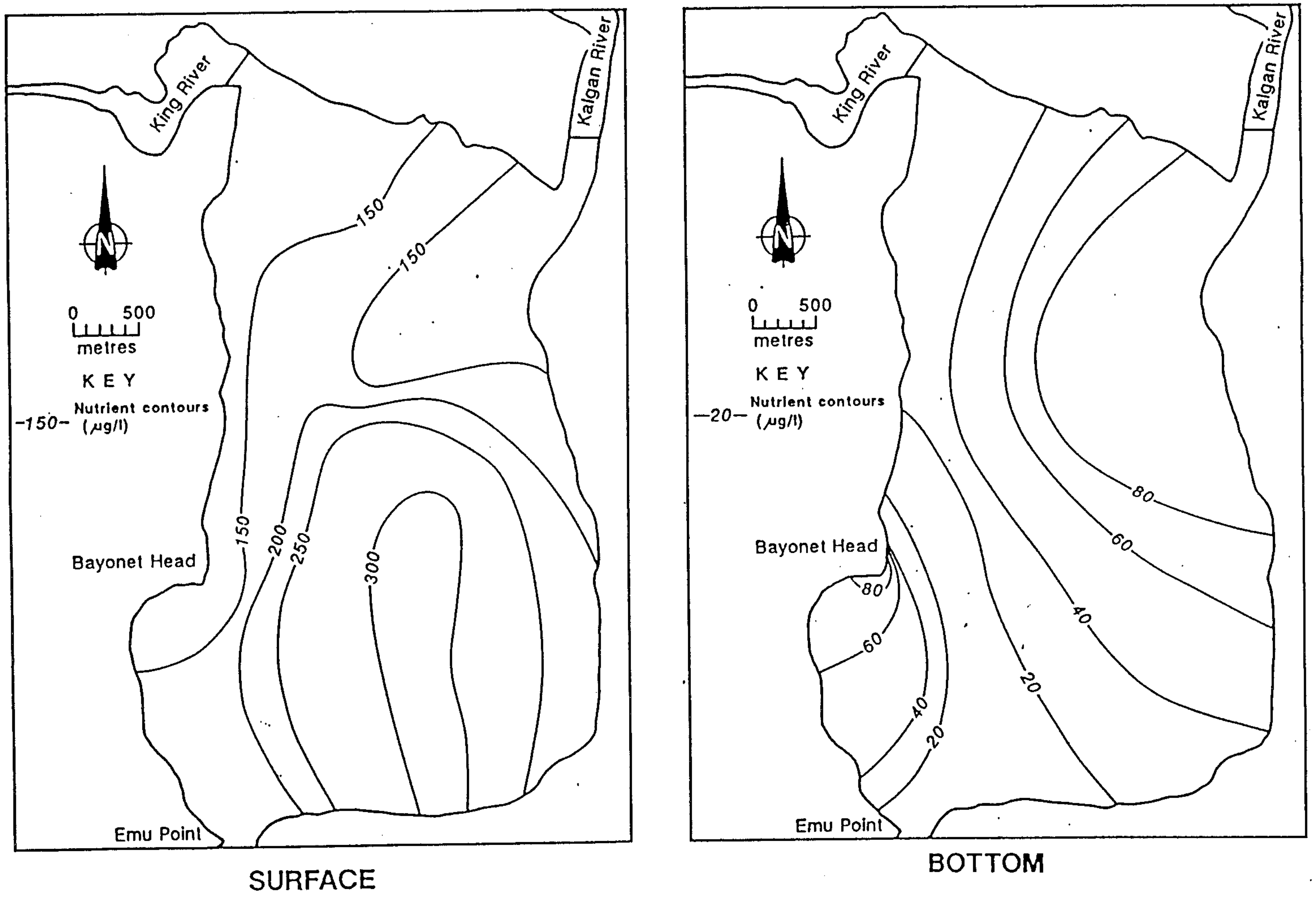
Figure 16 North-south and east-west cross-sectional depth profiles of Oyster Harbour showing the salinity stratification during the June 1988 flood event.



SURFACE

BOTTOM

Figure 17 Map of Oyster Harbour showing the contours of phosphate phosphorous concentrations in the surface and bottom of the water column during the June flood event.


SURFACE

BOTTOM

Figure 18 Map of Oyster Harbour showing the contours of nitrate-nitrite concentrations in the surface and bottom of the water column during the June flood event.

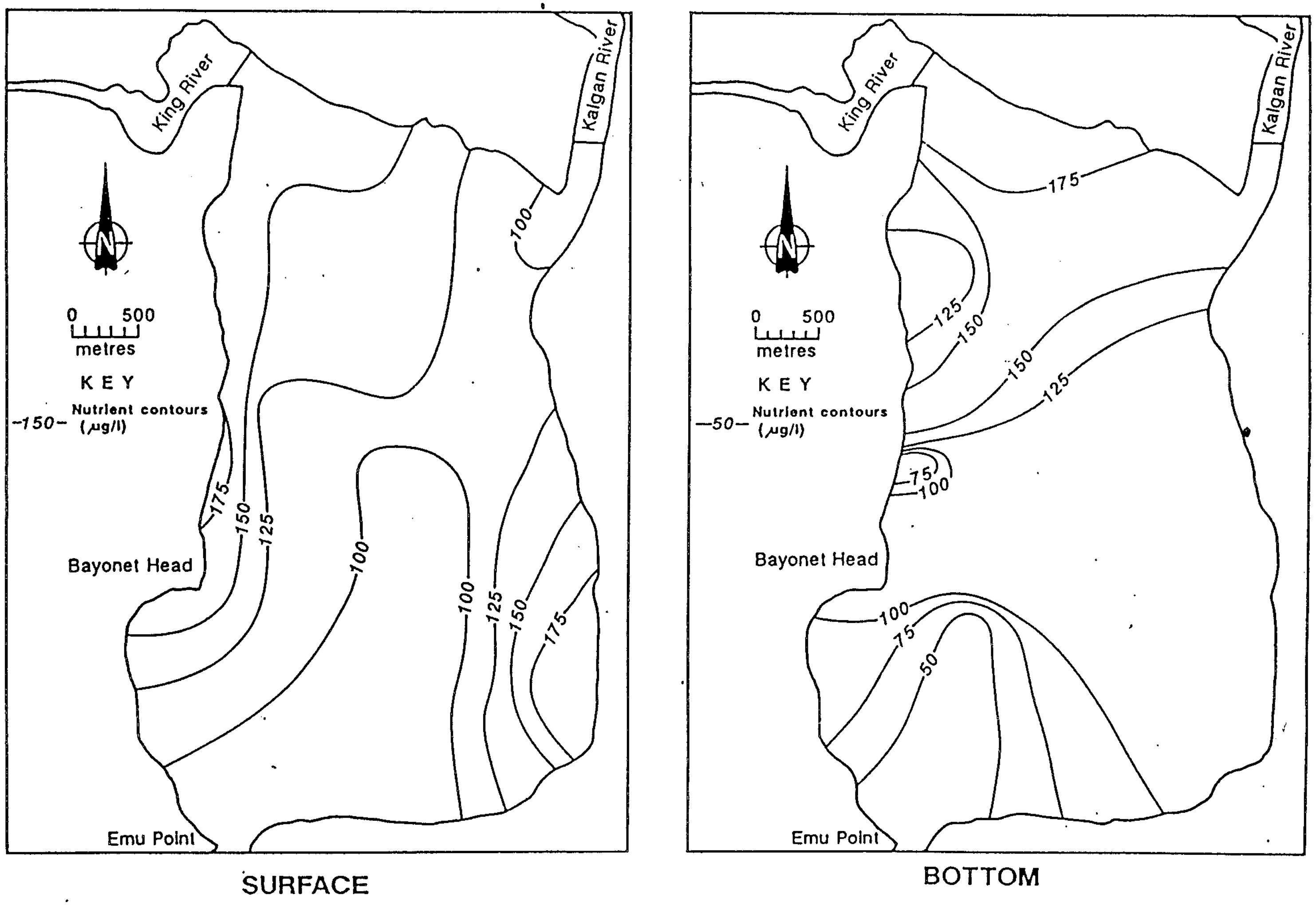


Figure 19 Map of Oyster Harbour showing the contours of ammonium concentrations in the surface and bottom of the water column during the June 1988 flood event.

Mechanisms of phosphorus retention in the system under the prevailing conditions could include sedimentation of particulate and colloidal compounds containing phosphorus, and biological fixation. Half of the phosphorus in the river water is free dissolved phosphate and direct sedimentation of the phosphate would be minimal. Biological fixation by phytoplankton is potentially important under stratified conditions as in the Harvey Estuary, but chlorophyll "a" concentrations in the surface layer were low indicating a low phytoplankton biomass. The buoyancy of the freshwater layer ensured that there was only minimal contact with benthic macrophytes. Thus, while extreme flow events such as this one, may carry a significant phosphorus load into the system, it appears that very little of this phosphorus is actually retained. The results of the water quality sampling carried out one week after the flood event (6 July 1988) indicate that most of the freshwater was flushed from the system within seven days. Phosphorus inputs under ambient flow conditions may be more biologically available because of the longer residence time of the freshwater, ensuring an increased possibility of vertical mixing and biological uptake by benthic macrophytes. The possible sedimentation of particulate phosphorus may also be important.

4.2 Seagrass and epiphyte biomass

Seasonal changes in the biomass of *P. australis* and *P. sinuosa* were similar in all three water bodies (Figure 20). The unimodal seasonal pattern, with maximum biomass in summer and minimum in winter, is typical of seagrasses growing in temperate waters, where reduced light and temperature in winter have significant effects on growth (Hillman *et al,* 1989b). The more robust species *P. australis* attained a significantly higher biomass (t-test, $p<0.05$) than did *P. sinuosa* in all three water bodies, and reached a maximum biomass approximately double that of the winter minimum. A halving of biomass from summer to winter also occurred for *P. sinuosa* in King George Sound, but in the two harbours the winter decline was far more pronounced, particularly in Oyster Harbour. The maximum biomass of *P. australis* and *P. sinuosa* in King George Sound was significantly higher ($p<0.05$) than in the two harbours. There was no significant difference between the two harbours in the maximum biomass reached by *P. australis*, but that reached by *P. sinuosa* in Oyster Harbour was significantly ($p<0.05$) higher than in Princess Royal Harbour.

Seasonal trends in shoot weight were similar to those of biomass for both species in all three water bodies with the exception of the shoot weights of *P. sinuosa* during December in King George Sound, which were very high (Figure 21). The data indicate that differences between the three water bodies in leaf biomass (Figure 20) were due to a combination of differences in shoot density and shoot weight. Seagrass stands in King George Sound were clearly more vigorous than in the two harbours, and the *P. sinuosa* meadow sampled in Princess Royal Harbour was particularly sparse.

Independent linear correlations were sought between seasonal changes in seagrass leaf biomass and seasonal changes in physico-chemical parameters (Appendix 3). In King George Sound, there were only two significant correlations; a negative relationship between the biomass of *P. australis* and % saturation of dissolved oxygen in the water column, and a positive relationship between the biomass of *P. sinuosa* and total phosphorus concentrations in the water column. In Princess Royal Harbour, the biomass of *P. australis* was significantly ($p<0.05$) positively correlated with salinity, temperature and total phosphorus in the water column, and significantly ($p<0.05$) negatively correlated with dissolved oxygen (% saturation), whilst the biomass of *P. sinuosa* was significantly ($p<0.05$) positively correlated with salinity and significantly ($p<0.05$) negatively correlated with dissolved oxygen (% saturation). In Oyster Harbour the biomass of *P. australis* was not significantly correlated with any physical or chemical aspect of the water column, but the biomass of *P. sinuosa* was significantly ($p<0.05$) positively correlated with global radiation, temperature, salinity and day length, and significantly ($p<0.05$) negatively correlated with dissolved oxygen (% saturation).

The correlations for the two harbours generally reflected the fact that low biomass occurred during winter, but did not indicate whether salinity, temperature or light was the most important factor affecting biomass. The significant negative correlations with dissolved oxygen levels in the water column were simply a result of seasonal changes in this parameter and not a causal relationship (see Section 4.1).

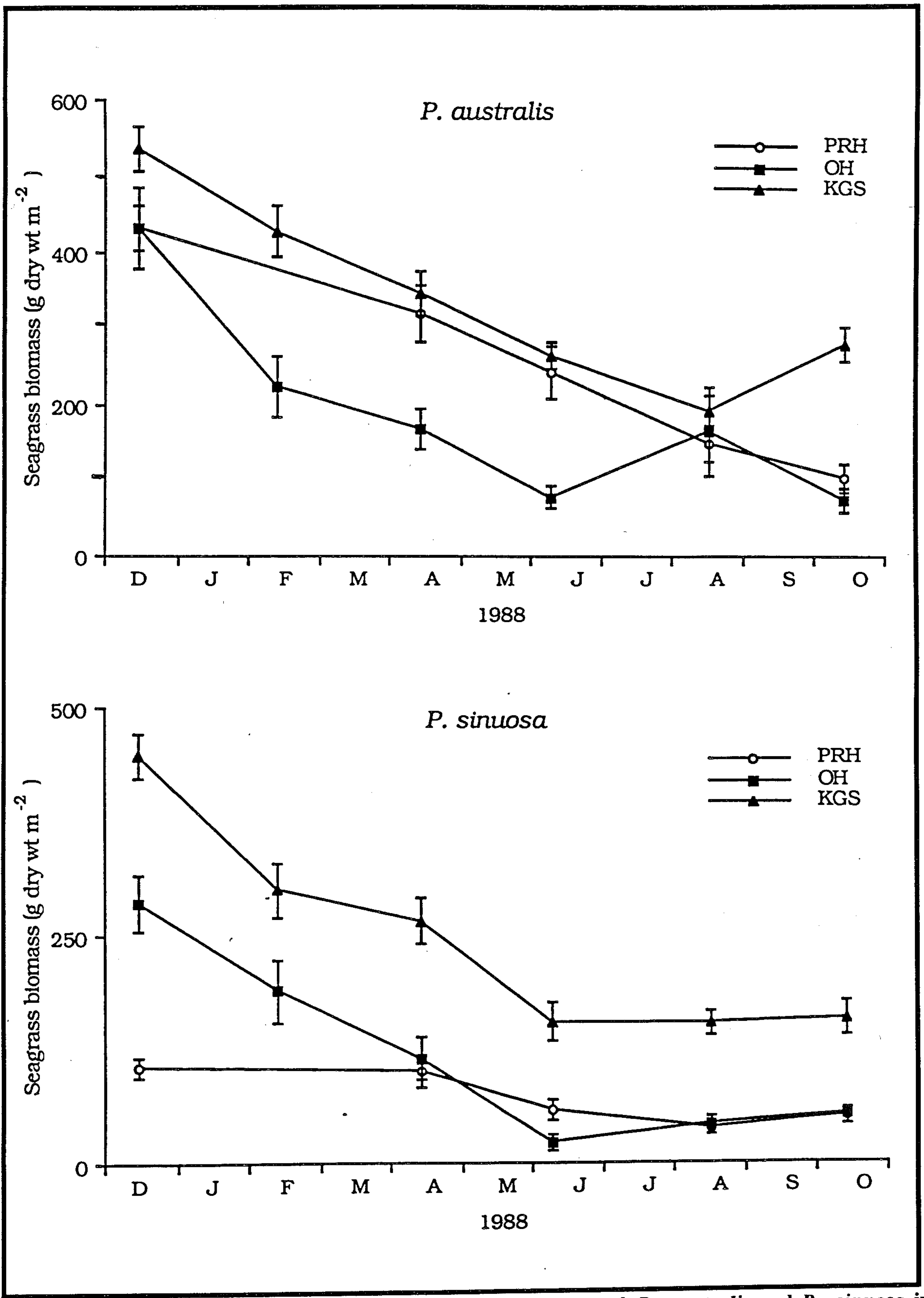


Figure 20. Seasonal changes in the above-ground biomass of *P. australis* and *P. sinuosa* in King George Sound, Princess Royal Harbour and Oyster Harbour from December 1987 to October 1988. Standard error bars are included

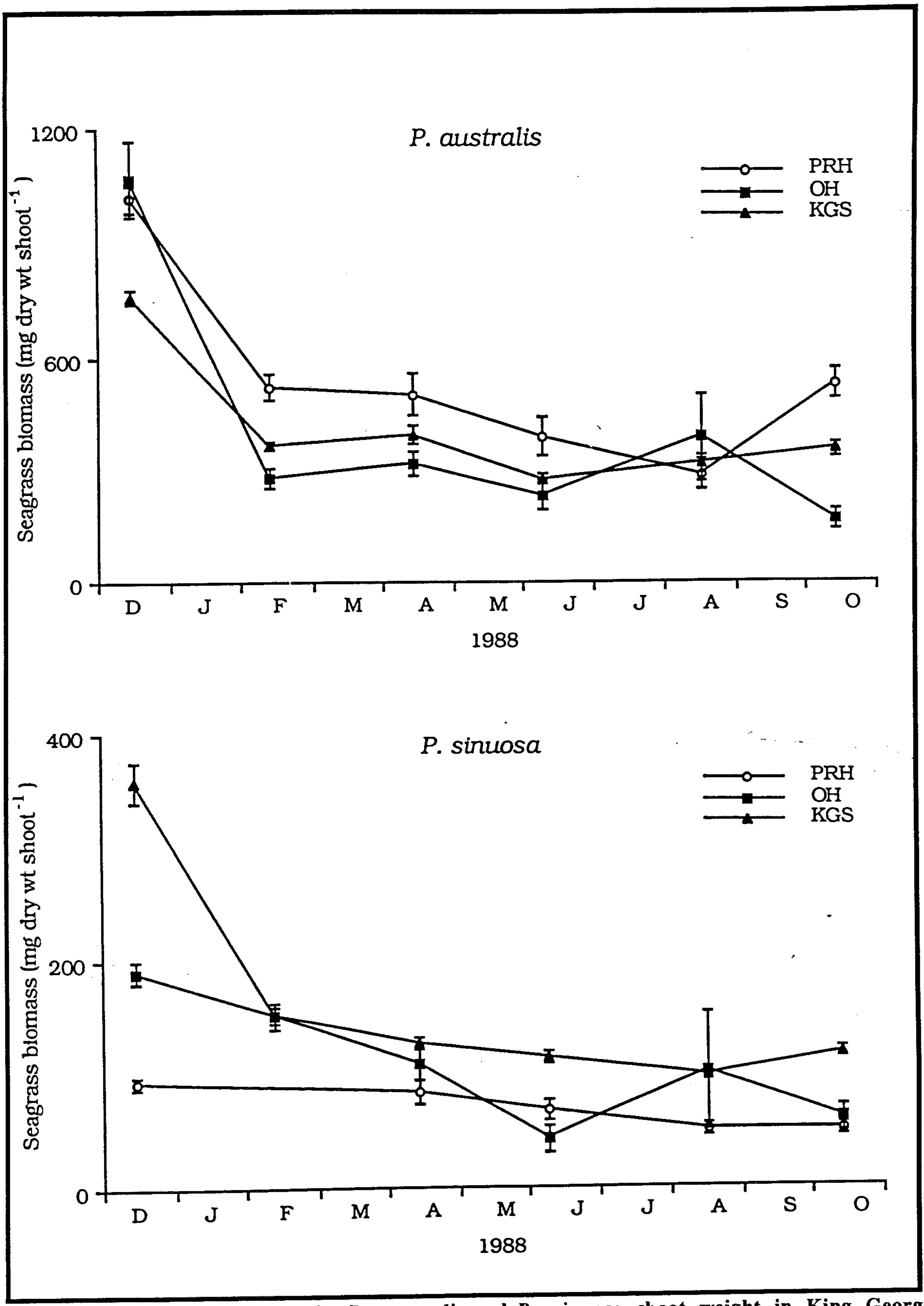


Figure 21. Seasonal changes in *P. australis* and *P. sinuosa* shoot weight in King George Sound, Princess Royal Harbour and Oyster Harbour from December 1987 to October 1988. Standard error bars are included

When correlations were sought using the combined data from all three water bodies, however, biomass was significantly ($p<0.05$) positively correlated with daylength, PAR (photosynthetically active radiation reaching the seagrass) and the H_{sat} period (the daily length of period of saturating irradiance for photosynthesis for a plant) for both *P. australis* and *P. sinuosa*, indicating that light availability was the most important factor affecting biomass.

Seasonal changes in the biomass of seagrass epiphytes in the three water bodies are shown as loads per unit area of shoot in Figure 22. Maximum epiphyte loads for *P. australis* occurred in either summer or late winter/early spring in all three water bodies, whilst for *P. sinuosa* there was a winter maximum in Princess Royal Harbour but little seasonal variation in the other two water bodies. Epiphyte loads on *P. sinuosa* shoots were generally similar to those on *P. australis* shoots, with the exception of *P. sinuosa* in Princess Royal Harbour, which had particularly high loads. With the exception of *P. sinuosa* in Princess Royal Harbour during winter, the E/L ratios (the ratio of epiphyte biomass to seagrass leaf biomass) did not exceed 0.25 for either species in all three water bodies, and this, according to the findings of Neverauskas (1987), is indicative of normal healthy *Posidonia* meadows (levels greater than 0.5 are indicative of excessive epiphyte growth due to nutrient enrichment).

The highest epiphyte load for *P. australis* was found in King George Sound during winter (mostly encrusting coralline algae), and for *P. sinuosa* in Princess Royal Harbour, also during winter (largely the brown algae *Asperoccus bullosus*, and red coralline algae). An E/L ratio of 1.01 was reached for *P. sinuosa* in Princess Royal Harbour during winter, which is indicative of eutrophic conditions. Epiphyte loads on *P. sinuosa* were significantly ($p<0.05$) higher in Princess Royal Harbour than in King George Sound or Oyster Harbour, but there was little difference between the latter two water bodies. There was little difference between the three water bodies in the epiphyte loads on *P. australis*.

For *P. sinuosa* the above trends were also reflected in the estimated epiphyte chlorophyll "a" loads per unit area of shoot, but for *P. australis*, levels in Oyster Harbour were significantly higher than in the other two water bodies (Figure 23). In Oyster Harbour the epiphyte loads on both species of seagrass were also underestimated, since a large proportion of the fine diatomaceous scum coating the seagrass leaves was lost when samples were collected.

Independent linear correlations were also sought between epiphyte weight per unit area of shoot and physico-chemical parameters, and between estimated epiphyte chlorophyll "a" loads per unit area of shoot and physico-chemical parameters (Appendix 4). There were, however, no consistent trends for either *P. australis* or *P. sinuosa* regardless of whether each water body was analysed separately or data for all three water bodies were combined. The lack of clear trends may be due to the different growth requirements of different species of epiphytes.

4.3 Seagrass and epiphyte nutrient concentrations

The nitrogen and phosphorus concentrations of leaves from *P. australis* and *P. sinuosa* are presented in Table 1. In all three water bodies nitrogen concentrations in *P. australis* tissues showed little seasonal variation, but for *P. sinuosa* there was a winter minimum. Phosphorus concentrations in both species of seagrass were lowest in summer in all three water bodies. Since seagrasses are capable of tapping sediment nutrient supplies (Hillman *et al*, 1989b) it is unlikely that seagrass growth was limited by phosphorus supply, and the winter maximum in phosphorus concentrations probably represents luxury uptake of phosphorus from the water column by the leaves, particularly in the two harbours, at a time of low growth rate (see below). The fact that nitrogen concentrations either varied little or reached a maximum when growth rates were highest (see Section 4.4) also suggests that seagrass growth was not limited by nitrogen supply.

When linear correlations between seasonal changes in seagrass nutrient concentrations and water column nutrient concentrations were sought for each water body, the only significant ($p<0.05$) positive relationship found was between *P. australis* leaf phosphorus and phosphate concentrations in Princess Royal Harbour (Appendix 5). When data for all sites were analysed, there were significant ($p<0.05$) positive correlations between leaf nitrogen concentrations and total nitrogen concentrations in the water column for both species of seagrass, and a significant positive correlation ($p<0.05$) between leaf phosphorus concentrations and phosphate concentrations in the water column for *P. sinuosa*. The reliance of seagrasses on sediment rather than water column nutrient supplies is not disproved by these correlations, which were probably due to luxury uptake of nutrients rather than the result of nutrient limitation of growth.

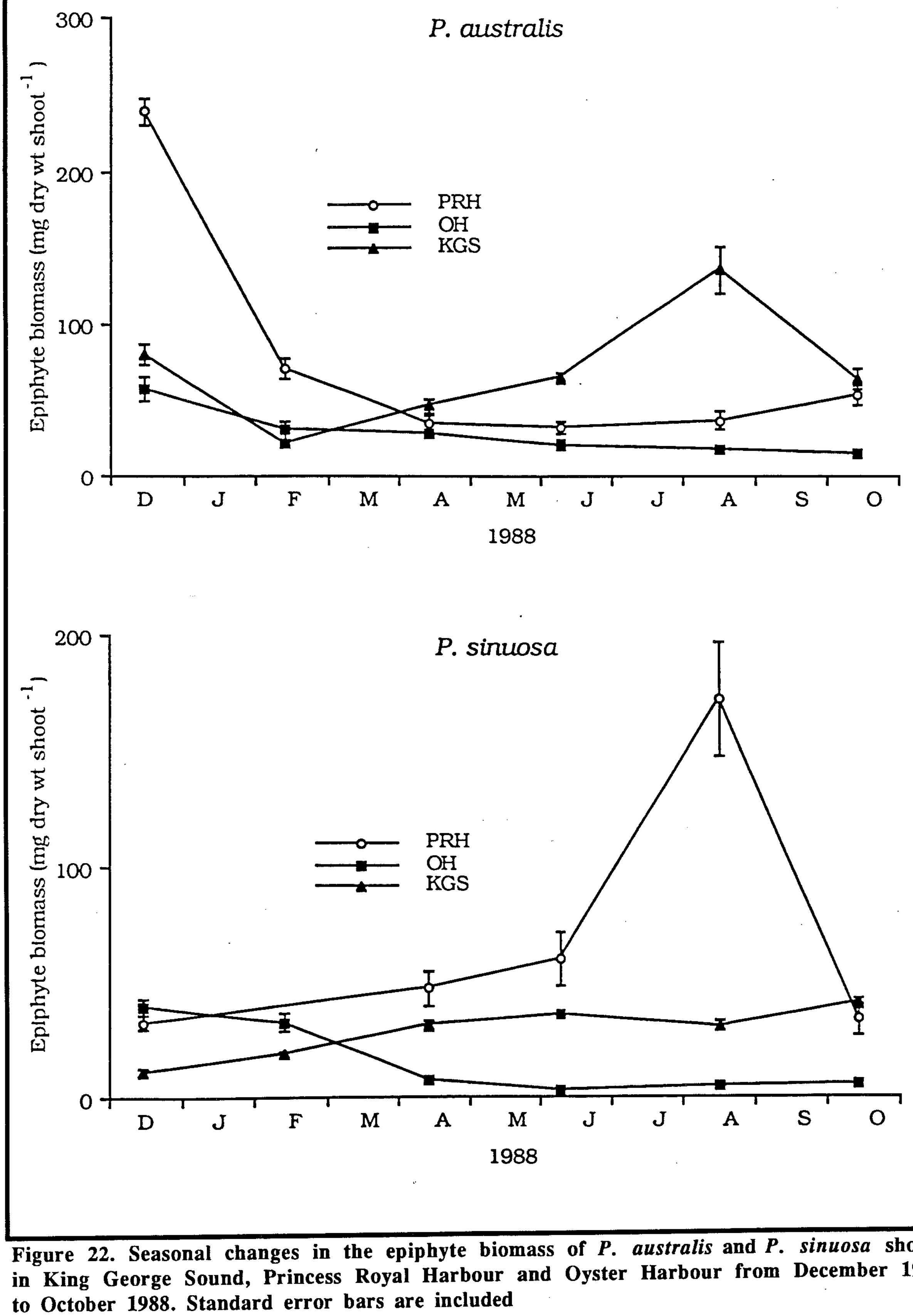


Figure 22. Seasonal changes in the epiphyte biomass of *P. australis* and *P. sinuosa* shoots in King George Sound, Princess Royal Harbour and Oyster Harbour from December 1987 to October 1988. Standard error bars are included

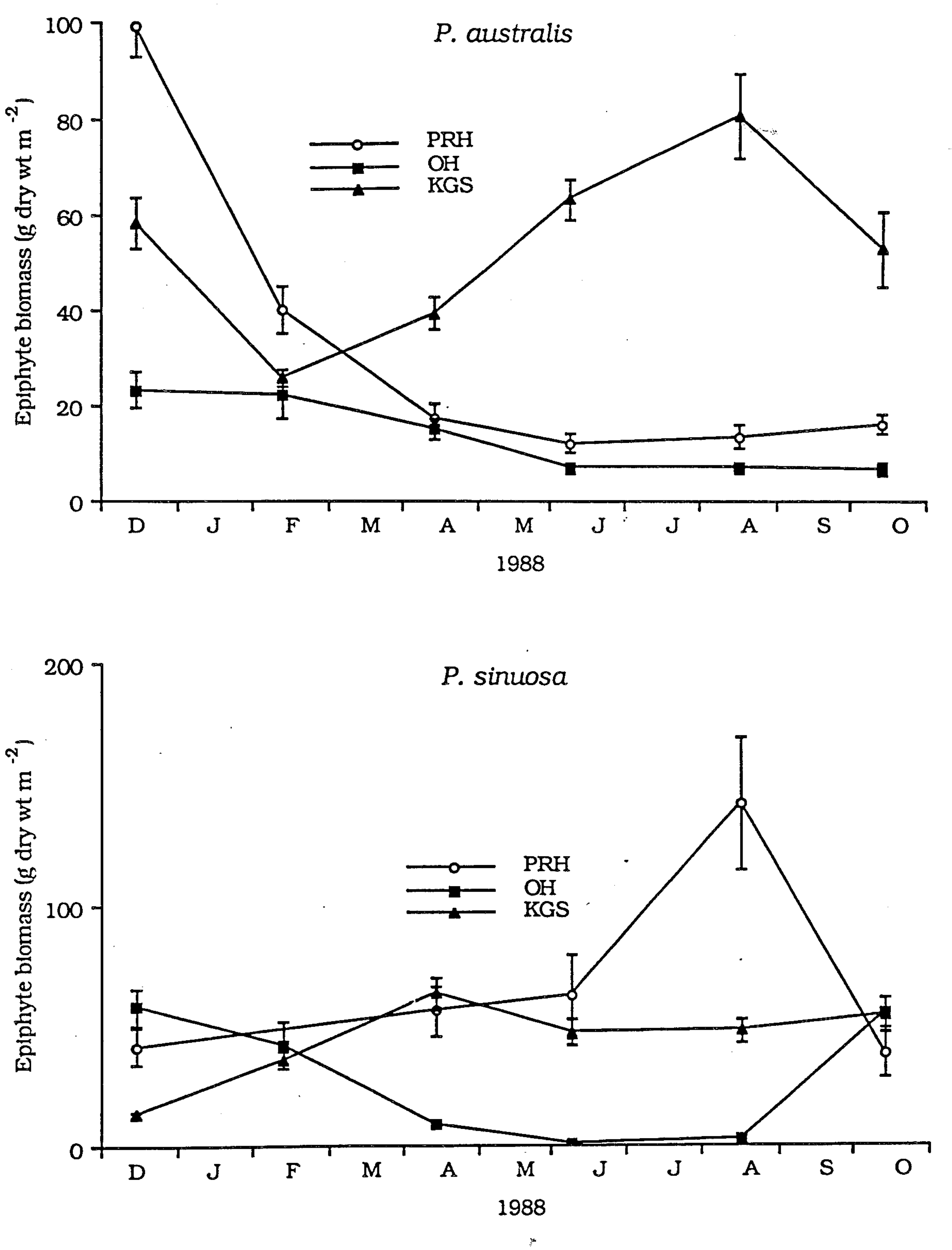


Figure 23. Seasonal changes in epiphyte biomass per unit area of *P. australis* meadow and *P. sinuosa* meadow in King George Sound, Princess Royal Harbour and Oyster Harbour from December 1987 to October 1988. Standard error bars are included

The concentrations of nitrogen and phosphorus in leaf tissue reported here are within the range reported for these species in Australia (Walker and McComb, 1987). As noted by Hillman *et al* (1989a), nutrient concentrations in *P. australis* were significantly higher ($p<0.05$) than in *P. sinuosa,* which may be due to different nutritional requirements of the two species, but no research has been carried out in this area. Nitrogen concentrations in both species of seagrass in Oyster Harbour were significantly ($p<0.05$) higher than in King George Sound or Princess Royal Harbour, but there was no significant difference between the latter two water bodies. There was no significant difference between the two harbours in the phosphorus concentrations in both species of seagrass, but values in King George Sound were significantly lower. The lowest nutrient concentrations in seagrass leaf tissues occurred in the most productive meadows (ie. in King George Sound, see Section 4.4), again emphasizing that the high nutrient concentrations in seagrasses in the two harbours were probably due to luxury uptake.

Table 1. Seagrass leaf tissue nitrogen and phosphorus concentrations in King George Sound (KGS), Princess Royal Harbour (PRH) and Oyster Harbour (OH). Data are mean ± standard error, and all values are in mg g^{-1} dry weight

Nitrogen						
Date	**KGS**		**PRH**		**OH**	
	Pa	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
16 February 88	9.4 ± 0.2	7.1 ± 0.1	9.2 ± 0.2	8.0 ± 0.1	12.3 ± 0.2	10.4 ± 0.1
14 April 88	-	5.4 ± 0.2	-	-	-	-
9 June 88	7.6 ± 0.7	5.8 ± 0.2	9.7 ± 0.3	7.1 ± 0.5	11.9 ± 0.5	8.2 ± 0.5
15 August 88	8.9 ± 0.4	6.8 ± 0.2	8.9 ± 0.2	6.4 ± 0.4	11.4 ± 0.2	8.3 ± 0.3
11 October 88	10.2 ± 0.6	7.2 ± 0.3	9.6 ± 0.3	8.8 ± 0.3	11.7 ± 0.3	8.6 ± 0.3
Phosphorus						
Date	**KGS**		**PRH**		**OH**	
	Pa	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
16 February 88	0.86 ± 0.02	0.71 ± 0.02	1.02 ± 0.01	0.88 ± 0.05	1.02 ± 0.04	0.75 ±0.02
14 April 88	0.88 ± 0.03	0.67 ± 0.02	1.34 ± 0.02	0.63 ± 0.01	-	-
9 June 88	0.94 ± 0.02	0.80 ± 0.03	1.36 ± 0.14	0.79 ± 0.09	1.30 ± 0.14	1.15 ± 0.12
15 August 88	1.27 ± 0.02	0.86 ± 0.04	1.65 ± 0.08	0.99 ± 0.14	1.44 ± 0.10	1.15 ± 0.07
11 October 88	0.78 ± 0.05	0.66 ± 0.03	1.16 ± 0.10	0.85 ± 0.12	1.59 ± 0.06	1.03 ± 0.05

Pa is *Posidonia australis*
Ps is *Posidonia sinuosa.*

The nitrogen and phosphorus concentrations in epiphytes on *P. australis* and *P. sinuosa* are presented in Table 2. In King George Sound seasonal changes in both nitrogen and phosphorus were the least pronounced, although nitrogen concentrations tended to be lowest in the spring. Nitrogen concentrations in epiphytes in Princess Royal Harbour tended to be highest in the spring whereas in Oyster Harbour values were highest in winter. Epiphyte phosphorus concentrations in the two harbours were very variable, but tended towards a summer minimum in Princess Royal Harbour and a summer maximum in Oyster Harbour.

Like the seagrass leaves themselves, nutrient concentrations in *P. australis* epiphytes were significantly ($p<0.05$) higher than in *P. sinuosa* epiphytes consistent with the view that epiphytes may derive part of their nutrient requirements directly from the seagrasses (Hillman *et al,* 1989b).

Table 2. Epiphyte tissue nitrogen and phosphorus concentrations in King George Sound, Princess Royal Harbour and Oyster Harbour. Data are the mean ± standard error, and all values are in mg g^{-1} dry weight

	Nitrogen					
	KGS		PRH		OH	
Date	***Pa***	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
16 Feb 88	7.29 ± 0.29	10.06 ± 0.84	12.72 ± 0.90	-	12.76 ± 0.25	18.19 ± 0.87
14 April 88	-	-	11.84 ± 1.78	5.50 ± 0.24	-	-
9 June 88	7.78 ± 0.47	8.44 ± 0.58	11.55 ± 0.56	7.97 ± 1.12	14.74 ± 0.71	22.41 (n=1)
15 Aug 88	8.18 ±0.51	8.73 ± 0.65	11.71 ± 1.24	8.11 ± 0.29	16.66 ± 0.32	15.16 ± 1.35
13 Oct 88	6.87 ± 0.54	6.00 ±0.13	15.68 ± 0.66	9.84 ± 0.76	11.49 ± 0.69	17.68 ± 1.80
	Phosphorus					
	KGS		PRH		OH	
Date	***Pa***	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
16 Feb 88	1.31 ± 0.29	1.24 ± 0.08	0.95 ± 0.05	-	2.62 ± 0.08	2.33 ± 0.15
14 April 88	1.33 ± 0.04	1.24 ± 0.05	1.70 ± 0.13	0.58 ±0.05	1.84 ±0.12	1.98 ± 0.05
9 June 88	1.38 ±0.06	1.28 ± 0.04	1.86 ± 0.10	0.99 ± 0.10	2.29 ±0.14	1.87 (n=1)
15 Aug 88	1.84 ± 0.23	1.58 ± 0.08	1.45 ± 0.13	1.00 ± 0.04	2.21 ± 0.16	1.67 ± 0.11
13 Oct 88	1.54 ± 0.09	1.26 ±0.03	1.84 ± 0.10	1.12 ± 0.13	1.64 ±0.08	2.17 ± 0.79

Pa is *Posidonia australis*

Ps is *Posidonia sinuosa.*

There were no significant positive correlations between epiphyte nutrient concentrations and water column nutrient concentrations when data for each of the three water bodies were analysed separately (Appendix 6). When data for all three water bodies were combined, only nitrogen concentrations in *P. sinuosa* epiphytes were significantly ($p<0.05$) positively correlated with ammonia and nitrate concentrations in the water column This may be partly attributable to the lack of marked seasonal changes of nutrient concentrations in the water column, and partly to the potential of epiphytes to derive part of their nutrient requirements directly from the seagrasses, as mentioned above.

Epiphyte nutrient concentrations in Oyster Harbour were significantly ($p<0.05$) higher than in the other two water bodies, and *P. australis* nitrogen concentrations in Princess Royal Harbour were significantly ($p<0.05$) higher than in King George Sound. However, nutrient concentrations in *P. sinuosa* epiphytes in Princess Royal Harbour were significantly lower than in the other two water bodies. A possible explanation for this may be that macroalgae accumulations near the *P. sinuosa* site may have been depleting nutrient supplies in the area. Macroalgae were observed to smother the seagrass beds in this area, particularly in spring.

Generally, the nutrient concentrations in both seagrass leaves and epiphytes indicated little difference between King George Sound and Princess Royal Harbour but there was evidence that Oyster Harbour was enriched compared to the other two water bodies. However epiphyte loads did not indicate serious eutrophication problems in any of the three water bodies.

The organic content and carbonate content of seagrass epiphytes are shown in Table 3, and also support the above conclusions. With the exception of *P. sinuosa* epiphytes in Princess Royal Harbour, the organic content of epiphytes in the two harbours was significantly ($p<0.05$) higher than in King George Sound, and the carbonate content was significantly lower. As discussed by Hillman *et al* (1989a), a high carbonate content and a low organic content is usually indicative of a high proportion of the encrusting coralline algae that are common in oligotrophic systems, whilst the reverse is true for nutrient-enriched systems, which usually have a greater proportion of green filamentous algae.

Table 3. Seasonal changes in epiphyte tissue organic content and carbonate content in King George Sound, Princess Royal Harbour and oyster Harbour. Data are the mean ± standard error, and all values are % of dry weight

Organic content						
Date	**KGS**		**PRH**		**OH**	
	Pa	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
16 February 88	32.3 ± 1.6	35.3 ± 0.2	37.2 ± 0.5	-	37.5 ± 2.0	40.4 ± 1.6
14 April 88	28.9 ± 0.8	36.5 ± 0.4	42.8 ± 1.4	30.5 ± 0.7	42.6 ± 1.5	49.8 ± 2.3
9 June 88	30.9 ± 2.0	32.5 ± 2.0	53.5 ± 2.0	29.1 ± 0.6	-	-
15 August 88	24.6 + 1.3	36.0 ±2.1	42.9 ± 2.3	30.4 ± 1.0	-	-
13 October 88	24.2 ± 0.5	32.2 ± 1.3	52.9 ± 0.8	35.6 ± 1.6	55.4 (n=1)	57.9 (n=1)
Carbonate						
Date	**KGS**		**PRH**		**OH**	
	Pa	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
16 February 88	42.0 ± 1.6	41.3 ± 1.2	33.4 ± 0.4	-	34.6 ± 3.2	37.3 ± 1.1
14 April 88	29.2 ± 1.2	22.1 ± 0.4	24.6 ± 0.4	27.9 ± 0.8	21.5 ± 1.0	16.2 ± 1.6
9 June 88	26.4 ± 1.0	25.7 ± 0.5	19.6 ± 0.8	27.5 ± 0.6	-	-
15 August 88	29.1 ± 1.1	24.2 ± 0.6	26.8 ± 1.8	25.5 ± 0.6	-	-
13 October 88	25.1 ± 0.8	22.1 ± 0.4	18.0 ± 0.2	18.7 ± 0.4	11.1 (n=1)	10.5 (n=1)

Pa is *Posidonia australis*
Ps is *Posidonia sinuosa.*

4.4 Seagrass productivity

Seasonal changes in the leaf production *P. australis* and *P. sinuosa* are shown in Figure 24. Seagrasses at all the sites showed the same unimodal seasonal pattern. With the exception of *P. sinuosa* in Princess Royal Harbour, maximum observed growth occurred in October (spring), but higher growth rates may have occurred in November. The decline in growth of *P. sinuosa* in Princess Royal Harbour in October coincided with the occurrence of a smothering accumulation of macroalgae (mainly *Cladophora*, *Lyngbya* and assorted brown algae). Opportunistic sampling of the macroalgae during October (using the method outlined in Hillman *et al*, 1989a) gave a mean biomass of 270 g m^{-2} (SE 44 g m^{-2}) over the entire area of seagrass from north of site 2 around to the Yacht Club (see Figure 2). There was also a sharp fall in the growth rate of *P. sinuosa* in Oyster Harbour in winter, which coincided with the inflow of turbid freshwater runoff from the two river catchments. There was little difference in the maximum growth rates reached by *P. australis* in the three water bodies, and between maximum growth rates reached by *P. sinuosa* in King George Sound and Oyster Harbour, however in Princess Royal Harbour *P. sinuosa* had significantly lower growth rates than in the other two water bodies. *P. australis* was clearly the more vigorous of the two species, with growth rates per shoot at least four times higher than those of *P. sinuosa.*

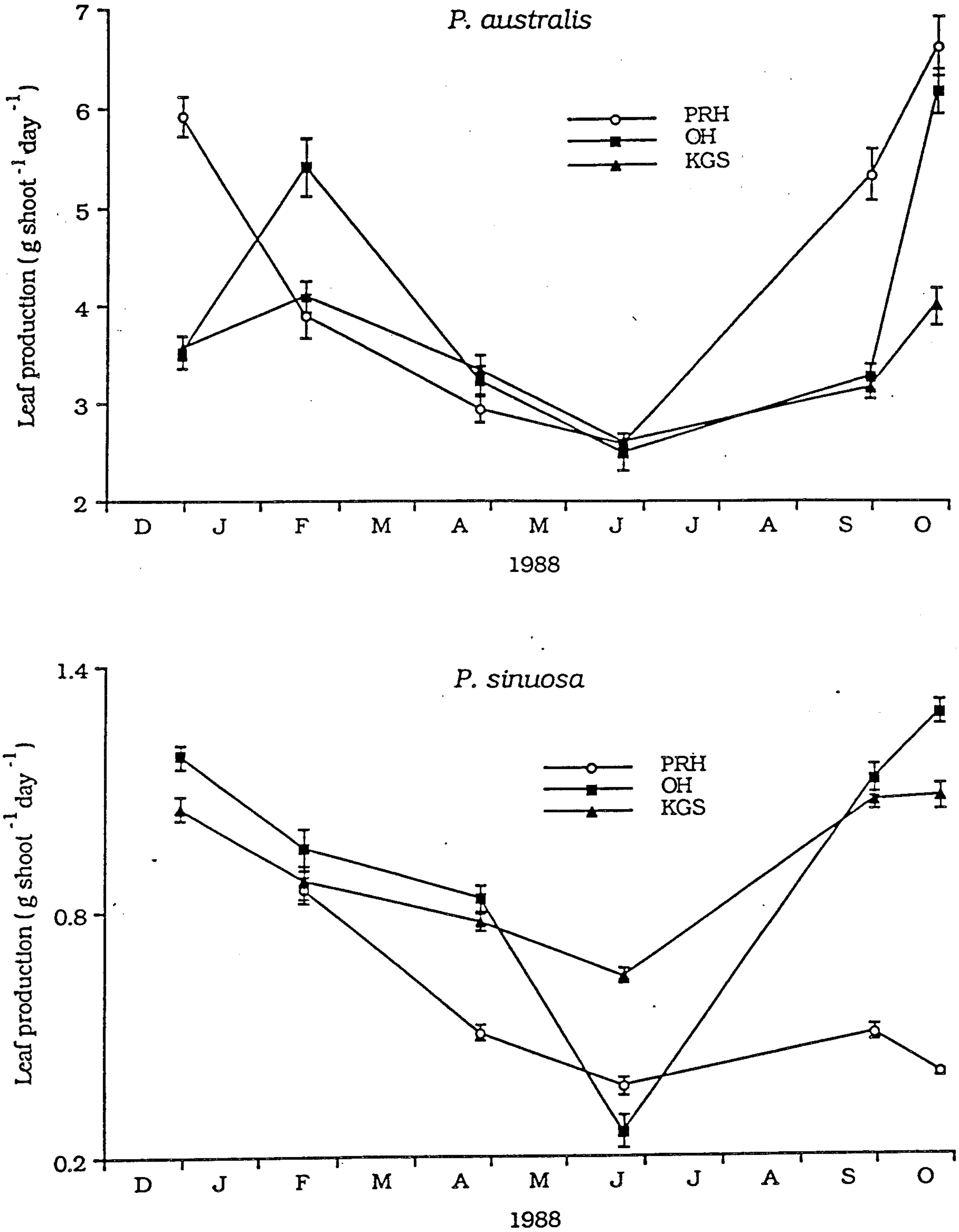


Figure 24. Seasonal changes in leaf production per shoot of *P. australis* meadow and *P. sinuosa* meadow in King George Sound, Princess Royal Harbour and Oyster Harbour from December 1987 to October 1988. Standard error bars are included

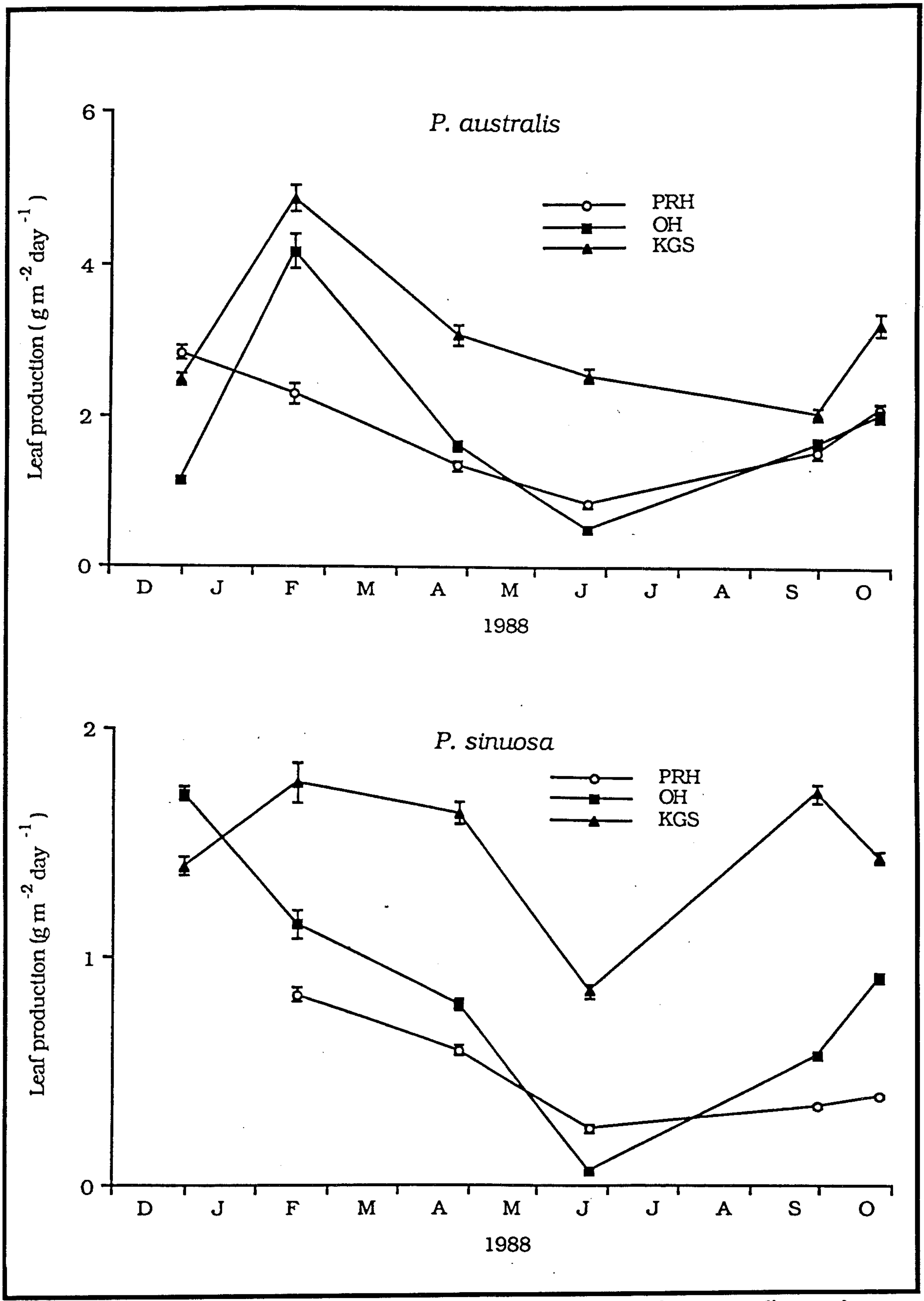


Figure 25. **Seasonal changes in leaf production per unit area of *P. australis* meadow and *P sinuosa* meadow in King George Sound, Princess Royal Harbour and Oyster Harbour from December 1987 to February 1988. Standard error bars are included**

Seasonal trends in leaf production per unit area of meadow (Figure 25) showed a summer maximum in all three water bodies. Unlike growth rates per shoot, production rates per unit area of meadow in King George Sound were significantly higher ($p<0.05$) than in the two harbours for both species, and seasonal fluctuations were less pronounced there. *P. australis* beds had an annual production of approximately 1100 g dw m^{-2} (330 g C m^{-2}), 670 g dw m^{-2} (200 g C m^{-2}) and 680 g dw m^{-2} (200 g C m^{-2}) in King George Sound, Princess Royal Harbour and Oyster Harbour respectively, whilst *P. sinuosa* beds had corresponding values of 535 g dw m^{-2} (160 g C m^{-2}), 210 g dw m^{-2} (65 g C m^{-2}) and 315 g dw m^{-2} (95 g C m^{-2}). The differences in production per unit area were caused by the greater shoot density in seagrass beds in King George Sound, and the extremely low production of *P. sinuosa* in Princess Royal Harbour was due to a combination of low production rates per shoot and low shoot densities.

The annual production data results in *P. australis* beds producing 2 crops per year in King George Sound, and 1.6 crops per year in Princess Royal and Oyster Harbours, with corresponding figures of 1.2, 2 and 1.1 crops per year for *P. sinuosa*. The significantly faster crop turnover of *P. sinuosa* in Princess Royal Harbour compared to the healthy meadow in King George Sound may indicate a stressed meadow, as has been demonstrated for tropical meadows (Hillman *et al*, 1989b) and Cockburn Sound (Silberstein *et al*, 1986). Leaf turnover times for *P. australis* varied seasonally from 90 to 200 days in King George Sound, 70 to 170 days in Princess Royal Harbour and 40 to 330 days in Oyster Harbour, with corresponding ranges of 90-330 days, 100-250 days and 60-330 days for *P. sinuosa*. Both species reached minimum times in spring in all three water bodies.

With the exception of *P. sinuosa* beds in Princess Royal Harbour and *P. australis* beds in Oyster Harbour, all the seagrass beds sampled showed a significant positive correlation with either the H_{sat} period and/or daylength (Appendix 7). When data for all sites were combined, the productivity of *P. australis* was significantly ($p<0.05$) correlated with the H_{sat} period and the productivity of *P. sinuosa* with H_{sat} period, daylength ($p<0.01$), PAR reaching the seagrass and incoming global radiation ($p<0.05$). There were no other consistent correlations with any other physico-chemical parameter. Extensive work by Dennison (1987) has indicated that seagrass growth is largely controlled by the length of the H_{sat} period, thus reinforcing the widely held belief that light is the most important factor controlling seagrass growth. The data obtained in this study support this conclusion. In Princess Royal Harbour the lack of a correlation between *P. sinuosa* growth and light reaching the meadow can be attributed to low growth rates in spring caused by light supply being blocked by overlying macroalgae. The lack of a relation for *P. australis* beds in Oyster Harbour may have been due to low growth rates caused by heavy epiphyte loads in summer, since as explained previously, epiphyte loads in Oyster Harbour were underestimated.

The emergence of light as an important factor controlling seagrass growth explains why the seasonal variation in leaf production per unit area of meadow is the least variable in King George Sound, since this water body has clearer water and less seasonal variation in water clarity, whilst the seagrasses are less affected by epiphyte loads or macroalgal accumulations. The more dense beds in King George Sound are also capable of harvesting more light than the sparser beds in the two harbours, and therefore achieve higher production rates per unit area. Furthermore, the fact that seagrass beds in the two harbours seasonally undergo significant periods of low production could result in less below-ground reserves being laid down in the rhizomes and roots and greater depletion of below-ground reserves. with reduced reserves they would more readily decline during periods of unfavourable environmental conditions. These conclusions are supported by data showing differences between the three water bodies in below-ground seagrass reserves, as discussed by Hillman *et al* (1989a).

4.5 Periphyton productivity

"Epiphyte" productivity expressed as ash free dry weight (AFDW) per day per unit area of artificial seagrass is shown in Figure 26, and as chlorophyll "a" per day per unit area of artificial seagrass in Figure 27. Seasonal trends and differences between the three water bodies were much easier to discern in Figure 27, since the data were a more accurate reflection of epiphyte productivity. Expressing epiphyte productivity as chlorophyll "a" effectively removed the confounding effects of carbonate and accumulated sediment, and deals only with the photosynthesising component of the plant. The data showed a bimodal seasonal variation in all three water bodies, with maxima in autumn and summer. Productivity at the *P. australis* sites was similar in King George Sound and Princess Royal Harbour, but in Oyster Harbour periphyton loads were at least double. At the *P. sinuosa* sites there were few differences except in summer when loads in King George Sound were significantly lower (Figure 27). The data show similar trends to those for loads on seagrass leaves, which are not expressed on a per day basis. Periphyton productivity at the *P. sinuosa* site was generally similar to the *P. australis* site in King George Sound, but in Princess Royal Harbour was significantly ($p<0.05$) higher at the *P. sinuosa* site than at the *P. australis* site, and in Oyster Harbour was significantly ($p<0.05$) higher at the *P. australis* site than at the *P. sinuosa* site. Since similar findings were made for epiphyte loads on real seagrasses in the three water bodies (see Section 4.2), it can be inferred that high epiphyte loads were due to physico-chemical factors rather than to differing interactions between seagrasses and epiphytes for different species of seagrass.

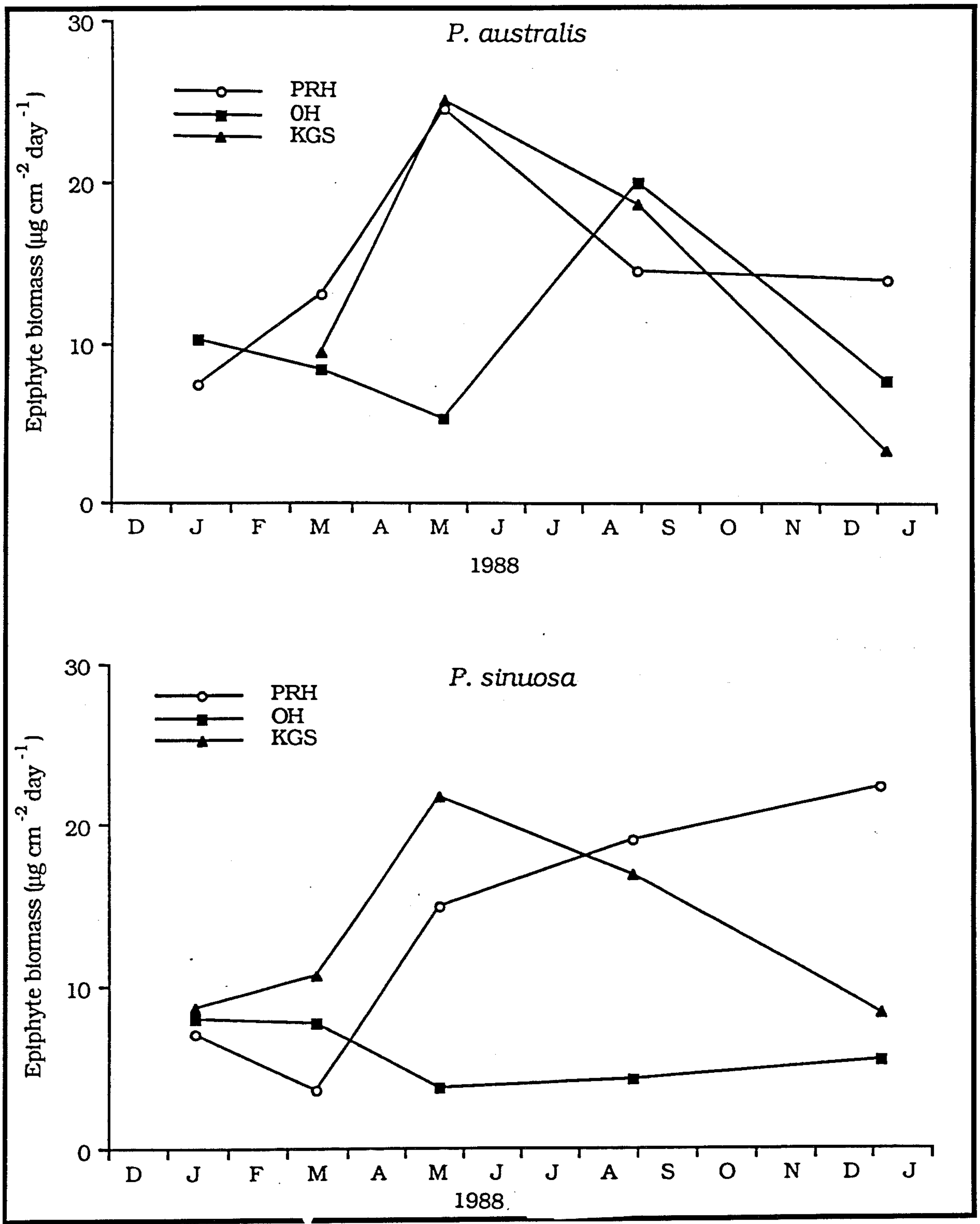


Figure 26. Seasonal changes in periphyton productivity expressed as AFDW per unit area of plastic seagrass at *P. australis* and *P. sinuosa* sites in King George Sound, Princess Royal Harbour and Oyster Harbour from December 1987 to February 1989. Standard error bars are included

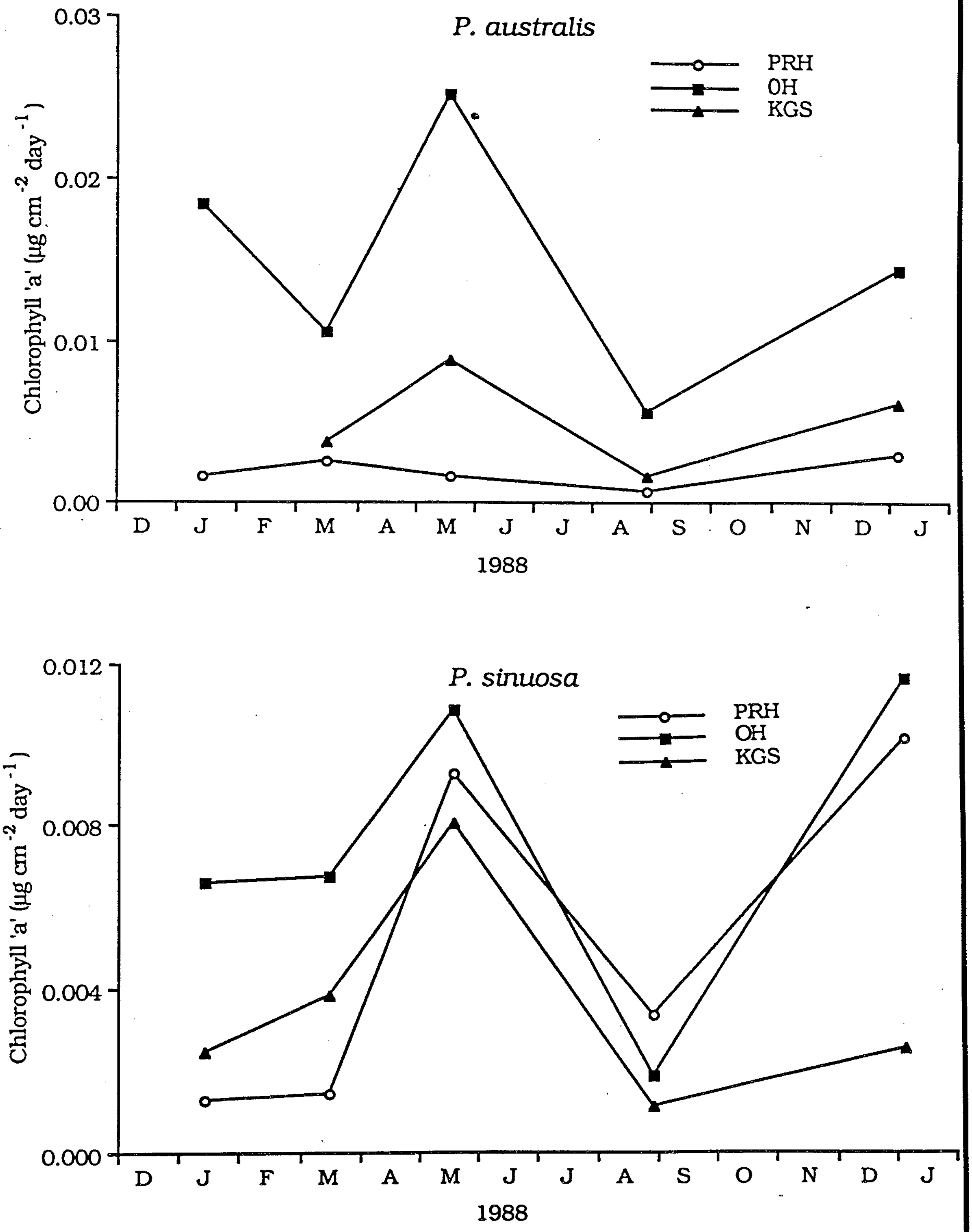


Figure 27. Seasonal changes in periphyton productivity expressed as chlorophyll "a" per unit area of plastic seagrass at *P. australis* and *P. sinuosa* sites in King George Sound, Princess Royal Harbour and Oyster Harbour from December 1987 to February 1989. Standard error bars are included

When compared with the data of Silberstein *et al* (1986), periphyton productivity at the *P. australis* sites in Princess Royal Harbour and King George Sound throughout the year, and at the *P. sinuosa* sites in all three water bodies for most of the year, were similar to those of an oligotrophic site in Cockburn Sound. However periphyton productivity in Oyster Harbour, and occasionally at the *P. sinuosa* site in Princess Royal Harbour (the western end), were similar to those of a site in Cockburn Sound where seagrass dieback due to nutrient enrichment has been well documented.

There was little difference in the nutrient concentrations in periphyton from artificial seagrass at *P. australis* and *P. sinuosa* sites within any water body (Table 4). The only consistent seasonal trend in the nutrient concentrations of periphyton was a distinct winter peak in phosphorus concentrations in Oyster Harbour (Table 4). Nutrient concentrations in periphyton were significantly lower than in real seagrass epiphytes. However, periphyton nutrient concentrations in Oyster Harbour were significantly ($p<0.05$) higher than in King George Sound or Princess Royal Harbour, and there were no significant differences between the latter two water bodies, similar to the findings for seagrass nutrient concentrations and epiphyte nutrient concentrations discussed previously. The organic content of periphyton in Oyster Harbour was also significantly ($p<0.05$) higher and the carbonate content significantly lower than in King George Sound or Princess Royal Harbour, with no significant differences between the latter two water bodies (Table 5), which again matches the findings for seagrass epiphytes.

There were no consistent trends apparent when correlations were sought between periphyton productivity and physico-chemical factors in each of the three water bodies, but when data for all sites were combined, chlorophyll "a" production at the *P. australis* sites was significantly ($p<0.05$) positively correlated with ammonia and nitrate concentrations in the water column, and chlorophyll "a" production at the *P. sinuosa* sites was significantly ($p<0.05$) positively correlated with phosphate concentrations in the water column (Appendix 8). Interestingly, when data for all sites were combined, periphyton nitrogen concentrations were significantly ($p<0.05$) positively correlated with phosphate concentrations in the water column and periphyton phosphorus concentrations were significantly ($p<0.05$) positively correlated with nitrate concentrations in the water column for both *P. australis* and *P. sinuosa* sites (Appendix 9). These results indicate that allowing for the confounding effects of seagrass-epiphyte nutrient transfer discussed previously, nutrient concentrations in the water column were affecting the growth of real seagrass epiphytes, and furthermore that there may be some kind of positive interaction between epiphyte nitrogen uptake and phosphorus uptake.

Table 4. The nitrogen and phosphorus concentrations of periphyton in King George Sound, Princess Royal Harbour and Oyster Harbour. Data are the mean ± standard error, and all values are in mg g^{-1}dry weight

Nitrogen						
Date	**KGS**		**PRH**		**OH**	
	Pa	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
14 January 88	-	2.9 ± 0.1	3.13 ± 0.1	3.0 ± 0.1	7.5 ± 0.2	8.7 ± 0.2
16 March 88	3.2 ± 0.1	3.3 ± 0.1	4.4 ± 0.2	5.8 ± 0.2	9.4 ± 0.3	7.8 ± 0.8
19 May 88	6.1 ± 0.2	4.7 ± 0.3	4.5 ± 0.1	6.6 ± 0.1	13.0 ± 1.1	11.6 ± 0.3
28 August 88	6.0 ± 0.2	7.1 ± 0.2	7.4 ± 2.0	4.5 ± 0.2	8.4 ± 2.5	13.9 ± 1.7
14 January 89	8.6 ± 0.5	7.2 ± 0.2	7.4 ± 0.1	6.8 ± 0.4	14.0 ± 0.8	15.7 ± 0.8

Phosphorus						
Date	**KGS**		**PRH**		**OH**	
	Pa	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
14 January 88	-	0.70 ± 0.02	0.60 ± 0.03	0.51 ± 0.02	1.21 ± 0.02	1.27 ± 0.04
16 March 88	0.84 ± 0.04	0.70 ± 0.01	0.48 ± 0.04	0.60 ± 0.02	1.00 ± 0.06	1.01 ± 0.04
19 May 88	0.70 ± 0.03	0.58 ± 0.02	0.34 ± 0.01	0.73 ± 0.02	2.06 ± 0.10	1.68 ± 0.04
28 August 88	0.64 ± 0.01	0.58 ± 0.03	0.44 ± 0.02	0.81 ± 0.02	1.21 ± 0.17	1.41 ± 0.01
14 January 89	1.02 ± 0.06	0.64 ± 0.10	0.69 ± 0.02	0.87 ± 0.02	1.28 ± 0.08	1.05 ± 0.07

Pa represents *Posidonia australis*
Ps represents *Posidonia sinuosa*

Table 5. The organic and carbonate contents of periphyton on plastic seagrass in King George Sound (KGS), Princess Royal Harbour(PRH) and Oyster Harbour(OH). Data are the mean ± standard error, and all values are % of dry weight

Organic content						
Date	**KGS**		**PRH**		**OH**	
	Pa	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
14 January 88	-	22.3 ± 0.3	24.1 ± 0.3	25.9 ± 0.5	44.4 ± 0.3	39.6 ± 0.1
16 March 88	27.4 ± 0.2	23.8 ± 0.2	23.2 ± 0.1	29.7 ± 0.7	39.3 ± 0.3	34.3 ± 0.6
19 May 88	22.5 ± 0.2	21.3 ± 0.2	20.8 ± 0.2	25.0 ± 0.3	41.6 ± 1.0	34.7 ± 0.2
28 August 88	18.6 ± 0.8	18.5 ± 0.3	23.5 ± 0.2	23.6 ± 0.2	46.4 ± 0.3	42.3 ± 0.4
14 January 89	36.8 ± 0.1	28.5 ± 0.4	23.0 ± 0.3	22.9 ± 0.3	51.4 ± 0.4	47.7 ± 1.9
Carbonate content						
Date	**KGS**		**PRH**		**OH**	
	Pa	***Ps***	***Pa***	***Ps***	***Pa***	***Ps***
14 January 88	-	28.3 ± 0.2	29.7 ± 0.6	29.8 ± 0.3	9.8 ± 0.4	9.2 ± 0.4
16 March 88	32.5 ± 0.2	32.4 ± 0.2	33.2 ± 0.2	31.6 ± 0.8	25.1 ± 0.3	28.5 ± 0.2
19 May 88	33.9 ± 0.2	33.6 ± 0.6	35.2 ± 0.2	31.1 ± 0.2	20.5 ± 0.5	22.3 ± 0.2
28 August 88	34.6 ± 0.2	36.1 ± 0.3	34.4 ± 0.2	33.4 ± 0.2	21.8 ± 0.3	17.8 ± 0.3
14 January 89	28.5 ± 0.5	33.4 ± 0.4	32.7 ± 0.2	32.1 ± 0.2	17.8 ± 1.2	17.5 ± 1.5

Pa represents *Posidonia australis*
Ps represents *Posidonia sinuosa*

In overview, although periphyton on artificial seagrass does not achieve the same biomass, nutrient concentrations, organic content or carbonate content as real seagrass epiphytes, they provide as accurate a measure of the relative degree of nutrient enrichment of different water bodies as real seagrass epiphytes, and furthermore appear to be a better means of determining the effect of water column nutrient concentrations on epiphyte growth. The chlorophyll "a" content of artificial epiphytes also appears to be a more useful measure of epiphyte productivity than dry weight.

The chlorophyll "a" content of periphyton may also be used to indicate the degree to which epiphytes affect seagrass productivity by blocking the incoming light supply. Silberstein *et al* (1986) have quantified the relationship between periphyton load (as chlorophyll "a" per unit area of "leaf" per day) and % light reduction to seagrasses by epiphytes. On the basis of this relationship the periphyton loads on *P. sinuosa* in King George Sound and on *P. australis* in King George Sound and Princess Royal Harbour never achieved levels sufficient to cause greater than a 25% reduction in light supply to the seagrasses, and usually the light reduction was less than 10%. *P. sinuosa* loads in Princess Royal Harbour and Oyster Harbour were mainly low, but in January 1989 were high enough to cause a light reduction of approximately 40%, whilst for *P. australis* in Oyster Harbour, although light reduction was usually less than 40% it occasionally reached 60-70%, which may explain the previously discussed lack of a significant positive correlation between *P. australis* productivity and light within this water body.

On the basis of the periphyton data obtained in this study it can be concluded that although nutrient enrichment in Oyster Harbour was not at a level to cause epiphyte loads that seriously affect seagrass productivity, the level is nonetheless sufficient for concern. To a lesser degree the results for the western end of Princess Royal Harbour (the *P. sinuosa* site) also indicate cause for concern.

5. Summary and conclusions

(i) Water quality in Oyster Harbour was significantly different to that in Princess Royal Harbour and King George Sound, in that nutrient and chlorophyll concentrations were higher, and light was more strongly attenuated.

(ii) Water quality in Princess Royal Harbour was generally similar to that over a healthy seagrass meadow in King George Sound.

(iii) A large flood event (29 June 1988) was monitored in Oyster Harbour and a freshwater layer 0.2-0.5 m thick was found throughout the system and extended into King George Sound. The halocline was very sharp at all sites indicating minimal vertical mixing. Inorganic nutrient levels were much higher in the surface freshwater layer, but chlorophyll concentrations were low.

Half of the phosphorus in the river water was dissolved phosphate and appears to have been advected over the top of the more dense estuarine water to King George Sound with minimal phosphorus retention in Oyster Harbour. Phosphorus entering Oyster Harbour during ambient river-flow conditions may be more important because of the greater potential for biological fixation.

(iv) Water quality in Princess Royal Harbour has improved significantly since the survey by Atkins *et al (1980)* in 1978/79.

(v) Seagrass leaf biomass reached the seasonal maximum in spring/summer at all sites. The biomass in typical beds of *P. australis* and *P. sinuosa* was higher in King George Sound than in the two harbours, and was a function of both sparser shoot densities and differences in shoot weights in the two harbours. Stands of *P. sinuosa* in Princess Royal Harbour were particularly sparse.

(vi) Nutrient concentrations in both seagrasses and epiphytes indicated that Oyster Harbour was more nutrient enriched than King George Sound or Princess Royal Harbour, but that there was little difference between the latter two water bodies.

(vii) In all three water bodies maximum seasonal leaf production rate per shoot was reached in spring, but maximum leaf production rate per unit area of meadow was reached in summer. The annual leaf production of *P. australis* was approximately 1100 g dw m^{-2} (330 g C m^{-2}), 670 g dw m^{-2} (200 g C m^{-2}) and 680 g dw m^{-2} (200 g C m^{-2}) in King George Sound, Princess Royal Harbour and Oyster Harbour respectively, whilst *P. sinuosa* beds had corresponding values of 535 g dw m^{-2} (160 g C m^{-2}), 210 g dw m^{-2} (65 g C m^{-2}) and 315 g dw m^{-2} (95 g C m^{-2}).

(viii) Light was found to be the most important factor affecting seagrass biomass and leaf growth in all three water bodies.

(ix) Seagrass leaf production in the two harbours underwent significant periods of low production compared to King George Sound, which could result in lowered below-ground reserves being laid down in the rhizomes and roots. Seagrass meadows in the two harbours would be more susceptible to decline during periods of unfavourable environmental conditions.

(x) Periphyton on artificial seagrass had lower loads and nutrient concentrations than real seagrass epiphytes. They indicated that Oyster Harbour was more nutrient enriched than King George Sound or Princess Royal Harbour, and that there was little difference between the latter two water bodies. Periphyton data also indicated that water column nutrient concentrations affect epiphyte growth, but that this effect is masked in real seagrass epiphytes due to seagrass-epiphyte nutrient transfer.

(xi) Chlorophyll "a" levels are a more accurate measure of artificial seagrass epiphyte productivity than dry weight, and therefore a more useful means of assessing the degree of nutrient enrichment of a water body.

(xii) The chlorophyll "a" levels on artificial seagrasses in Oyster Harbour indicated that periphyton loads were sufficiently high to cause a significant reduction in light supply to seagrasses, and therefore the degree of nutrient enrichment in the harbour is cause for concern. This was also evident, although to a lesser degree, at the western end of Princess Royal Harbour.

(xiii) Macroalgal smothering appears to be the main cause of present seagrass decline in Princess Royal Harbour, whereas epiphytes are implicated as being the main cause for seagrass decline in Oyster Harbour (excluding the south-east corner, where macroalgal smothering is clearly responsible). These differences are probably due to differences in nutrient loading and light penetration between the two harbours. The better light penetration in Princess Royal Harbour allows the proliferation of macroalgae, while the high nutrient loading and poor light penetration in Oyster Harbour favours the growth of epiphytes.

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