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**Distribution and biomass of seagrasses and algae, and
nutrient pools in water, sediments and plants in Princess Royal
Harbour and Oyster Harbour**

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**Distribution and biomass of seagrasses and algae, and nutrient
pools in water, sediments and plants in Princess Royal Harbour and
Oyster Harbour**

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Preface

This study was conducted by the Centre for Water Research, The University of Western Australia and forms part of the Albany Harbours Environmental Study (1988-1989). The appendices for this volume have been published separately (Centre for Water Research, UWA, Aquatic Ecology Number 88-201), 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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Aerial photographs used for the seagrass/macroalgae survey were taken in April 1987 by the Australian Survey Office, Canberra, ACT.

Abstract

Extensive sampling was conducted in February and March, 1988 to map the biomass and distribution of seagrass and macroalgae and to determine the size of nutrient pools in water, sediment and plants in Princess Royal Harbour and Oyster Harbour.

Water "quality" in Princess Royal Harbour in February 1988 was of a higher standard than that found by Atkins *et al* (1980) in February 1979, in that nutrient and chlorophyll concentrations were lower and light penetration through the water column was greater.

Sediment nutrient concentrations were generally highest in the deepest regions of both harbours due to sediment focusing. The sediments in the two harbours were the largest nutrient pool. Macroalgae were the largest plant nutrient pool, accounting for over 80% of plant biomass in Princess Royal Harbour and over 50% in Oyster Harbour. Macroalgae contained about 90% of the nitrogen and 70% of the phosphorus pool associated with aquatic plants in Princess Royal Harbour, and about 60% of nitrogen and 34% of the aquatic plant phosphorus pool in Oyster Harbour. The high mean areal macroalgal biomass (406 g m^{-2}) in Princess Royal Harbour was indicative of a highly eutrophic system. This was also supported by the characteristics of biomass, cover and carbonate content of algal epiphytes on seagrasses. The results of this study indicated that Princess Royal Harbour was more eutrophic than Oyster Harbour.

Dense macroalgal beds were found in the south-eastern corner of both harbours. Prevailing wind directions are such that these areas are the most sheltered and therefore are suitable for macroalgal growth and accumulation. Circulation patterns are also compatible with the accumulation of drift algae in this area of the harbours (Mills, 1987).

The rate of loss of seagrass area in the two harbours since 1984 was lower than that estimated between 1981 and 1984 by Bastyan (1986). Considerable losses of biomass are, however, continuing to occur, particularly in Princess Royal Harbour where 60% of above-ground seagrass biomass present in 1984 was lost by 1988. At present, major losses are occurring in the shallow dense seagrass beds, presumably due to macroalgal smothering. Present epiphyte loads were not considered to be high enough to cause significant losses of seagrass.

An increase in light supply is probably responsible for the seagrass regeneration recorded in some deeper areas of Oyster Harbour. This trend is expected to reverse if water quality deteriorates again. Macroalgal biomass in both harbours must be reduced to halt the loss of seagrass beds in shallow waters. The role of algal epiphytes in the decline of seagrass in both harbours may be more significant than implied from the results of this study due to the large interannual variation in nutrient loading to the harbours.

1. Introduction

Concern about a decline in environmental quality in Princess Royal Harbour and Oyster Harbour, near Albany, led to a series of studies being carried out to document the nature and extent of the environmental problems and identify their causes (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.

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

In an overview, Mills (1987) emphasized the lack of detailed information about the cause of the problem, and the need for adequate documentation of the present state of the harbours to provide a reference base from which to monitor responses to management. This report presents the results from one of a number of studies being carried out to provide information on seagrass distribution and water quality (physical, chemical and biological characteristics) in the harbours at the present time.

The primary objective of this study was to map the distribution of seagrass in Princess Royal Harbour and Oyster Harbour to ascertain whether the dieback was continuing, and to provide reference data against which the effects of management could be assessed. A number of permanent transects were also established in seagrass beds, so that future monitoring could detect more subtle changes in the status of the seagrass meadows than could be discerned from the distribution maps. A secondary objective was to carry out an intensive sampling survey (grid study) in February 1988 to estimate the size of the nutrient pools in the water, sediments and plants in both harbours. The grid study was also designed to provide information on spatial changes in seagrass biomass, epiphyte and macroalgae biomass, plant tissue nutrient concentrations, sediment nutrient concentrations and water quality in each harbour. Data on the relative size of the nutrient pools was collected to assess the degree of eutrophication of the two harbours, whilst documentation of the above-listed spatial changes was aimed at providing additional information to determine the cause of seagrass dieback.

Data on seagrass biomass, epiphyte biomass, plant tissue nutrient concentrations, sediment nutrient concentrations and water quality at two sites in the oligotrophic waters of King George Sound were also obtained for comparison with data from the two eutrophic harbours, to determine whether any parameters were useful indicators of eutrophication, and therefore valuable management tools for subsequent work. Statistical relationships between physical and biological parameters were also sought to provide a preliminary indication of important patterns and processes involved with eutrophication, although any relationships would require cautious interpretation since they would be based on data from one point in time.

2. Study area

Princess Royal Harbour and Oyster Harbour are two large (28.7 km² and 15.6 km² 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*. (Labrill.) Sonder ex Aschers.

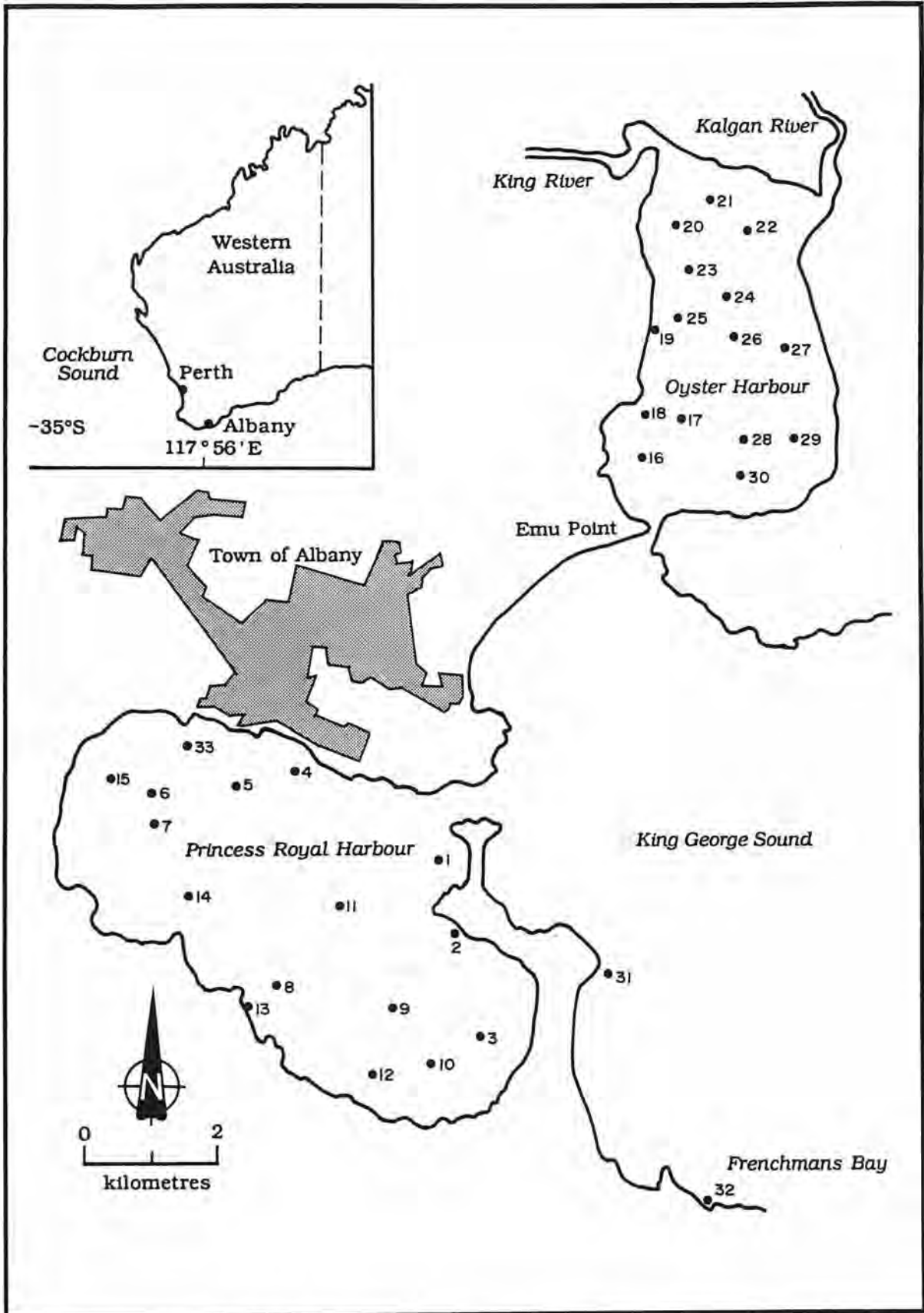


Figure 1. Princess Royal Harbour and Oyster Harbour study area with grid study sites shown

Princess Royal Harbour has no river inflow. Freshwater comes from 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, in addition to 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 also appears to be the most significant source of sediment (McKenzie, 1962). There are no industrial discharges into, or port facilities in, Oyster Harbour.

The average annual rainfall for Albany is 936 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 freshwater to 36‰, whilst bottom salinities vary from 9‰ to 36‰ (McKenzie, 1962).

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 m 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 samples

Samples for nutrient analyses were collected at two sites in King George Sound, sixteen sites in Princess Royal Harbour and 15 sites in Oyster Harbour (Figure 1) during the period 15-19 February 1988. Sites were chosen to give the maximum coverage of the range of biological and physical characteristics of each harbour, within budgetary constraints. "Surface" and "bottom" water samples were collected in order to detect any stratification of the water column, and to determine whether sediment release was a potential source of nutrients. "Surface" water samples were collected approximately 0.3 m below the surface and "bottom" samples approximately 0.3 m above the seabed, using 10 litre Niskin bottles (General Oceanics). Samples were immediately stored in 150 ml sealable polyethylene bags ("Whirlpak", Nasco, Kansas, USA) on ice, and upon return to the laboratory (within 12 hours) were deep frozen until analysed.

Salinity (accurate to $\pm 0.1\text{‰}$), temperature (accurate to $\pm 0.1^\circ\text{C}$), dissolved oxygen (accurate to $\pm 0.1\text{ mg l}^{-1}$), Secchi depths (accurate to $\pm 0.05\text{ m}$) and light attenuation profiles were recorded at each site. Salinity, temperature and dissolved oxygen readings were taken at 1m 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 diameter 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 line from a regression of \log^{10} light readings against depth, according to the method of 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.

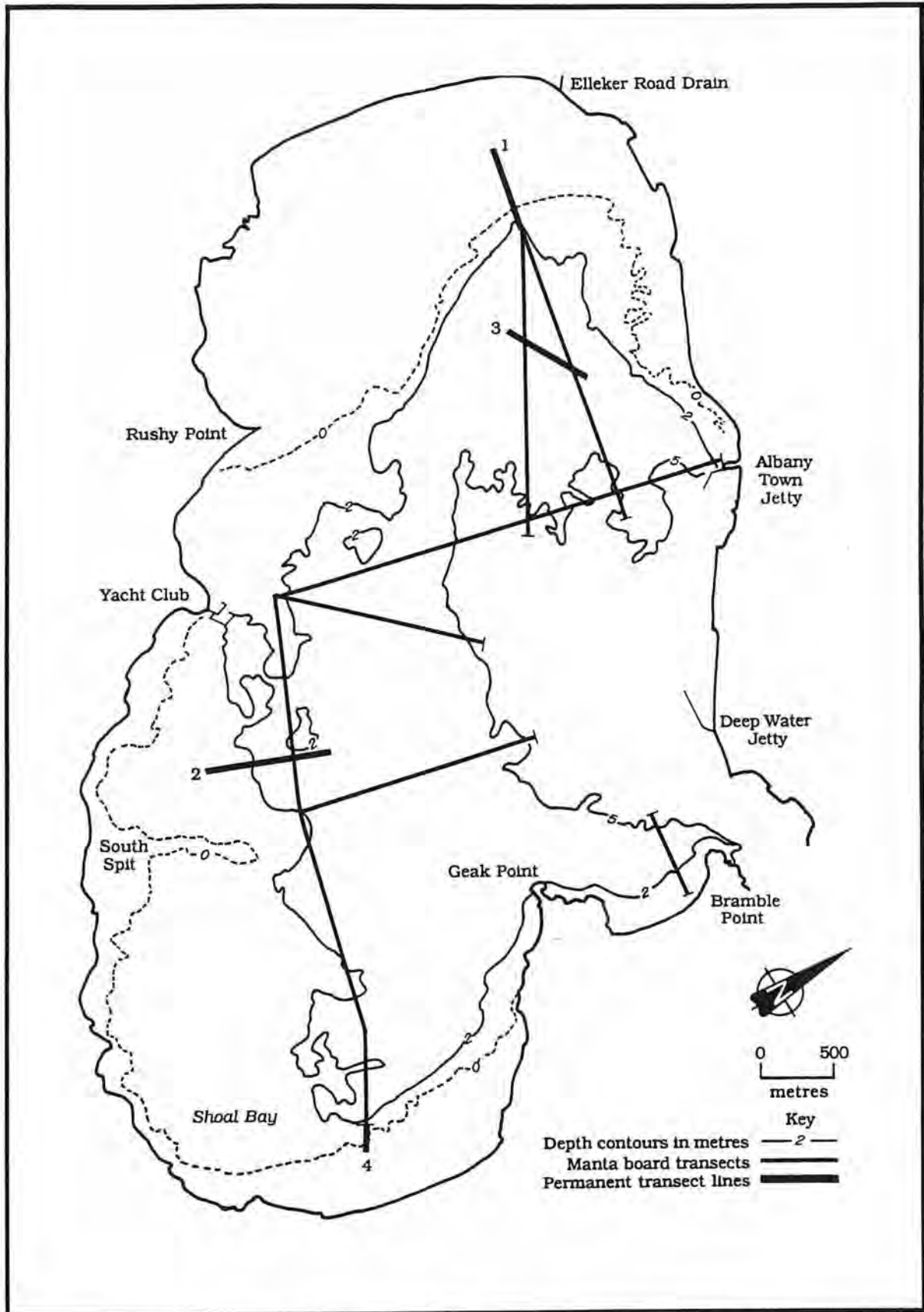


Figure 2. Bathymetry of Princess Royal Harbour with the location of field survey transects shown

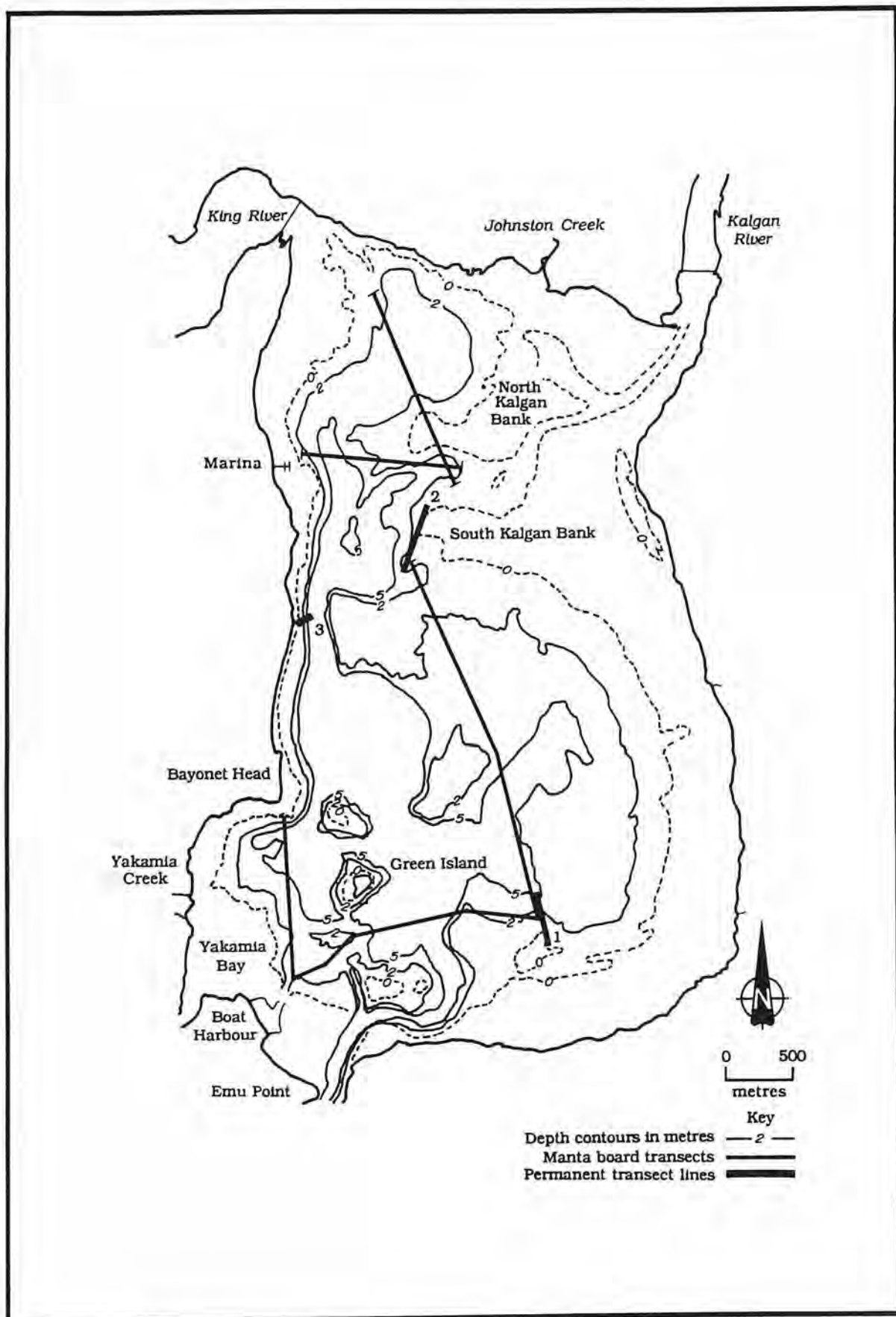


Figure 3. Bathymetry of Oyster Harbour with the location of field survey transects shown

Ammonia-nitrogen ($\pm 20 \mu\text{g l}^{-1}$) was measured using the isocyanurate method (Dal Pont *et al*, 1974). Nitrate - plus - nitrite ($\pm 2 \mu\text{g l}^{-1}$) was determined after copper-cadmium reduction with a Technicon Autoanalyser II (Technicon Industrial Systems, Tarrytown, New York). Orthophosphate ($\pm 10 \mu\text{g l}^{-1}$) was analysed by the single solution method (Major *et al*, 1972). Kjeldahl nitrogen ($\pm 200 \mu\text{g l}^{-1}$) and total phosphorus ($\pm 10 \mu\text{g l}^{-1}$) 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. Silica was measured using the autoanalyser (Technicon Industrial Systems, Tarrytown, New York, Method 186 - 72 W/B). Samples were filtered through $1.2 \mu\text{m}$ filters (Whatman Ltd, England) in the field.

3.2 Plant material

Phytoplankton biomass was assessed as chlorophyll "a" levels in the water column. Water samples for chlorophyll "a" analysis at each site were filtered *in situ* using GFC filter papers (pore size $1.2 \mu\text{m}$, Whatman Ltd, England). The filter papers were immediately stored on ice, and upon return to the laboratory were deep frozen until analysed. The filters were ground in 90% acetone and the chlorophyll "a" concentration measured spectrophotometrically (Varian DMS 90 Spectrophotometer, Varian Techtron Pty Ltd, Springvale, Australia) according to the method of Strickland and Parsons (1972).

Macroalgal biomass was estimated using methods currently in use in the Peel-Harvey estuarine system and Leschenault Inlet (Lukatelich pers comm). In areas of 100% macroalgal cover, macroalgal biomass was estimated by collecting five cores (each 0.0064 m^2). In areas of less than 100% cover, one core was taken for each 20% of macroalgal cover at the site: completely random sampling of, for example, an area of 60% cover may have resulted in five cores containing nothing instead of the two expected on statistical grounds, therefore it was considered more accurate to take three cores of macroalgae and adjust the biomass data for the visually determined percentage cover. Macroalgae samples were returned to the laboratory, washed of adhering sediments and different taxa separated. Above-ground seagrass biomass was estimated by harvesting 16 replicate quadrats (0.01 m^2) using SCUBA. A preliminary trial, in which 40 quadrats each of the two major species of seagrass (*Posidonia australis* and *P. sinuosa*) were harvested, was conducted at sites in King George Sound, Princess Royal Harbour and Oyster Harbour. This trial established that 16 quadrats were the minimum required to provide reproducible estimates of seagrass cover (Lukatelich *et al*, 1989). Upon return to the laboratory, above-ground seagrass material was separated into stems and leaves (in the case of *Amphibolis* spp), scraped free of epiphytes, decalcified in 5% hydrochloric acid and the number of leaves and shoots counted. Seagrass and macroalgal cover was determined by visual estimates (accurate to $\pm 10\%$) at each site and expressed as a percentage of the total visible area.

Below-ground seagrass biomass was estimated by the following method: five cores were taken by SCUBA divers using a stainless steel corer with a serrated edge (cross-sectional area of 0.0092 m^2). In the laboratory, samples were washed and sorted into roots, rhizomes and leaves.

All macroalgae, seagrass and epiphyte material was oven-dried at 80°C to a constant weight, and the resulting dry weights converted to grams per square metre (g m^{-2}). Samples for tissue nitrogen (four replicates) and phosphorus (five replicates) analysis were milled and 200 mg subsamples assayed for total tissue phosphorus following digestion in concentrated nitric and perchloric acids (Strickland and Parson, 1972). Total tissue nitrogen was determined by autoanalyser after digestion in concentrated sulphuric acid in the presence of a mercury catalyst (Technicon Corp, Tarrytown, New York, Method 334-74 W/B).

3.3 Sediments

Sediment samples were collected using a 0.0032 m^2 Perspex corer. The upper 2 cm from five replicate cores was bulked and subsampled. Samples were stored on ice in the field, and at 4°C before being analysed (within 12 hours).

Wet/dry ratio (W/D) was calculated from the weight loss after drying wet sediment to a constant weight at 105°C for 24 hours. Water content was calculated as $1 - (1 - (W/D))$. Organic matter was determined as loss on ignition at 550°C for one hour.

Extractable nitrogen and phosphorus were determined on aliquots of 2M NaCl extract (Lukatelich and McComb, 1985). Twenty grams of wet sediment was transferred into 250 ml graduated cylinders and brought to 220 ml

with 2M NaCl. The cylinder was then inverted ten times and the sediment allowed to settle for one hour. The supernatant was removed, centrifuged, filtered (0.45 μm Millipore filters), and analysed for orthophosphate, ammonia and nitrate-plus-nitrite nitrogen as outlined in Section 3.1. Total nitrogen and total phosphorus of the sediment was determined on oven-dried subsamples as outlined for plant material in section 3.2.

3.4 Mapping

Seagrass distributions in Princess Royal and Oyster Harbours were mapped directly from aerial photographs taken in April 1987 (scale 1:25,000). Distributions were recorded by manta-board surveys, SCUBA-diving and snorkel-diving (in February and March, 1988). In shallow clear water, observations were made from a dinghy using a glass-bottomed bucket. Accuracy for all visual observations was $\pm 10\%$, and the precision for the relocation of the manta-board surveys was ± 50 m. A tide datum was established for reference with the navigational charts used, and leadline soundings (accurate to ± 0.025 m) together with a hand-held compass were used for position fixing (± 50 m). All depths were corrected to chart datum.

The percentage cover of seagrass was assessed visually and recorded as follows: at points spaced approximately every 100 m along the shoreline, transects were run both along and at right angles to selected depth contours over the entire width of the meadow. In areas of uniform cover, percentage cover was assessed visually and recorded every 5 m unless an abrupt change ($>20\%$) occurred, when shorter intervals were used. Both depth and position were recorded whenever a significant change ($>20\%$) was observed in cover or species. Manta-board transects (precision of ± 20 m) were also carried out, the locations of which are shown in Figures 2 and 3, and percentage cover of seagrass and species composition were recorded every 5 m.

According to the recommendations of Orth and Moore (1983), percentage cover of seagrass was divided into four categories, numbered one to four, 100-75%, 75-45%, 45-15% and less than 15%. In some instances where distribution was not continuous, the term "patchy" was used. The presence of rhizome material was also noted. Areas were obtained using a digitizer (Model LD-2-20, Summagraphics Corp, Connecticut, USA, accuracy of $\pm 0.1\%$). The mapping exercise was initiated to assess large-scale (tens of metres) changes in area and per cent cover. However this technique is incapable of showing small-scale (metres) changes which may indicate early stages of recovery or deterioration in seagrass meadows. For example, between two sampling occasions a category two meadow could diminish from 70% cover to 50% cover and no difference would be indicated on the two maps. A series of permanent transects were therefore established in each harbour to provide more detailed information. Permanent transects of varying length were established in Princess Royal Harbour (four transects) and in Oyster Harbour (three transects) (Figures 2 and 3). Two metre long metal pegs were inserted in the sediment every 25 m for the length of each transect, and position fixes (± 0.1 m, Theodolite, Australian Survey Office) were taken to establish the location of the transects. Seagrass cover (accurate to $\pm 10\%$) for a 1 m wide belt along the transect line was recorded to an accuracy of ± 0.05 m; where seagrass cover was sparse ($<15\%$), the exact number of shoots was recorded.

3.5 Calculations

Independent linear correlations, students t-tests and stepwise linear multiple regressions were performed on physical and biological parameters using MASS programmes (WESTAT, 1984). Contour maps of water column, sediment and macroalgal parameters were made using the SYMAP programme (Dougenik and Seehan, 1977). Total water column nutrient and chlorophyll "a" load, macroalgal biomass, macroalgal nutrient load and sediment nutrient load were estimated from planimetry of computer drawn maps of the amount expressed per unit area. A digitizer (Model LD-2-20, Summagraphics, Connecticut USA) was used to measure the area of each size class interval. The amount in each size class was estimated by multiplying each size class area by the mean value for that class interval.

Total seagrass biomass and nutrient load were calculated using the seagrass distribution maps. The total area of each percentage cover category for each of the three main species (*Posidonia australis*, *P. sinuosa* and *Amphibolis antarctica*) was measured using the digitizer, and multiplied by the appropriate biomass or nutrient concentration for its location using the data obtained for the thirty one sites in the two harbours. For the purpose of the calculations, above-ground seagrass biomass data from an additional 12 sites had to be obtained (see Appendix 15 for site location and data) since the original 31 sites of the grid study did not cover all the categories of percent cover for each species in each harbour.

4. Results and discussion

4.1 Water quality

Mean nutrient, chlorophyll "a", and total suspended solid concentrations, and water clarity data for each harbour during the grid study are shown in Table 1. Oyster Harbour had significantly ($p < 0.05$) higher concentrations of phosphate phosphorus, ammonium nitrogen, nitrate-nitrite nitrogen, organic nitrogen and silicate. In most cases nutrient and chlorophyll "a" data were at the detection limits of the analytical methods used. The water quality of the harbours can be gauged to some extent by using Vollenweider's (1971) classification for the trophic levels of lakes: although this classification was developed for deep freshwater lakes in temperate climates, it is a means of assessing the relative trophic status of other water bodies in the absence of a similar classification for estuarine and coastal waters. Both harbours would be classified as meso-eutrophic on the basis of their total phosphorus levels in February 1988. The data obtained for nutrient and chlorophyll "a" levels in this study also indicated that water quality in the two harbours during February 1988 was better than in Wilson Inlet in 1982 (Lukatelich *et al.*, 1984) or in Cockburn Sound during the last ten years (Hillman and Bastyan, 1988) - the former being a meso-eutrophic embayment that has undergone some seagrass loss, and the latter a sheltered embayment where the loss of seagrass due to nutrient enrichment is well documented.

Table 1 also contains water quality data for February 1979 from the Atkins *et al.* (1980) study of Princess Royal Harbour, although analytical detection limits restrict comparisons to total phosphorus, ammonia and chlorophyll "a" levels and water clarity data. A considerable difference in water quality in Princess Royal Harbour between February 1979 and February 1988 is apparent. The limited data show a superior water quality in the latter survey, particularly in water clarity. The improvement in water clarity is of particular significance to seagrasses, since if these spot measures of water quality are indicative of the quality throughout the respective years, then seagrasses would have been able to survive at greater depths in 1988 than in 1979.

Table 1. Mean (\pm standard deviation) values of water quality parameters in Princess Royal Harbour and Oyster Harbour for the February 1988 grid study. Data from Atkins *et al.* (1980) study of Princess Royal Harbour for February 1979 are also presented. Nutrient values are in $\mu\text{g l}^{-1}$.

	Princess Royal Harbour		Oyster Harbour
	1979 $x \pm \text{SE}$ (n = 19)	1988 $x \pm \text{SD}$ (n = 16)	$x \pm \text{SD}$ (n = 15)
Orthophosphate phosphorus	9 ± 1	1 ± 0.4	2 ± 2
Organic - phosphorus	47 ± 7	28 ± 13	23 ± 11
Total phosphorus	56 ± 8	29 ± 13	25 ± 11
Ammonia - nitrogen	26 ± 2	2 ± 1	4 ± 6
Nitrate - nitrogen	$4 \pm (<1)$	2 ± 1	2 ± 1
Organic - nitrogen	~ 250	113 ± 61	185 ± 63
Total nitrogen	~ 280	117 ± 61	191 ± 66
Chlorophyll "a"	$2.5 (<1)$	0.4 ± 0.2	0.5 ± 0.2
Inorganic N:P ratio	7.4^1	6.9 ± 2.8	10.5 ± 12.4
Attenuation coefficient (m^{-1})	0.85^2	0.21 ± 0.09	0.25 ± 0.11
Secchi depth (m)	2.0	5.5 (n=2)	3.5 (n=2)

¹ Calculated from mean inorganic nitrogen and phosphorus values

² Calculated from the Secchi depth using Poole and Atkins (1927) equation relating Secchi depths to attenuation coefficients.

On the basis of available data it is not possible to say whether the improvement of water quality in Princess Royal Harbour is due to decreases in industrial nutrient inputs, reduced agricultural runoff due to successive dry years, a decrease in nutrient cycling in the biota, or a combination of all three. The distribution patterns of nutrients in the water column - with the exception of organic phosphorus (Figure 4) - did not offer any clues as to current major point sources of nutrients. Nor did the spatial maps of nutrient distribution show high nutrient concentrations corresponding to areas of past seagrass dieback, or present areas of stressed seagrass meadows or macroalgal accumulation (see sections 4.7 and 4.8). The pattern of organic phosphorus (Figure 4) under conditions of an incoming tide and strong easterly winds was, however, compatible with Atkins *et al* (1980) conclusion that the sewage treatment plant outfall (located just outside the harbour inlet channel) and the Metro Meats abattoir (formerly Borthwicks Abattoir, located just inside the harbour) are major point sources of nutrients.

Major nutrient point sources in Oyster Harbour are discernible, as shown in Figures 4 to 6. The King and Kalgan Rivers, and to a lesser extent Yakamia Creek, were clearly the major nutrient sources. Figures 4 to 6 support Mills (1987) suggestion that the King River is a greater source of phosphorus and the Kalgan River is a greater source of nitrogen. The Kalgan River also appeared to contribute the greater amount of total suspended solids (Figure 6). These characteristics are related to catchment size and major soil types; the King River catchment has sandier soils with low phosphorus retention characteristics, whereas the larger Kalgan River catchment has a greater proportion of heavier soils with higher phosphorus retention characteristics. It has been speculated that a large proportion of the nitrogen load from the Kalgan River is leaching losses from biologically fixed nitrogen, as well as fertilizer nitrogen (Mills, 1987).

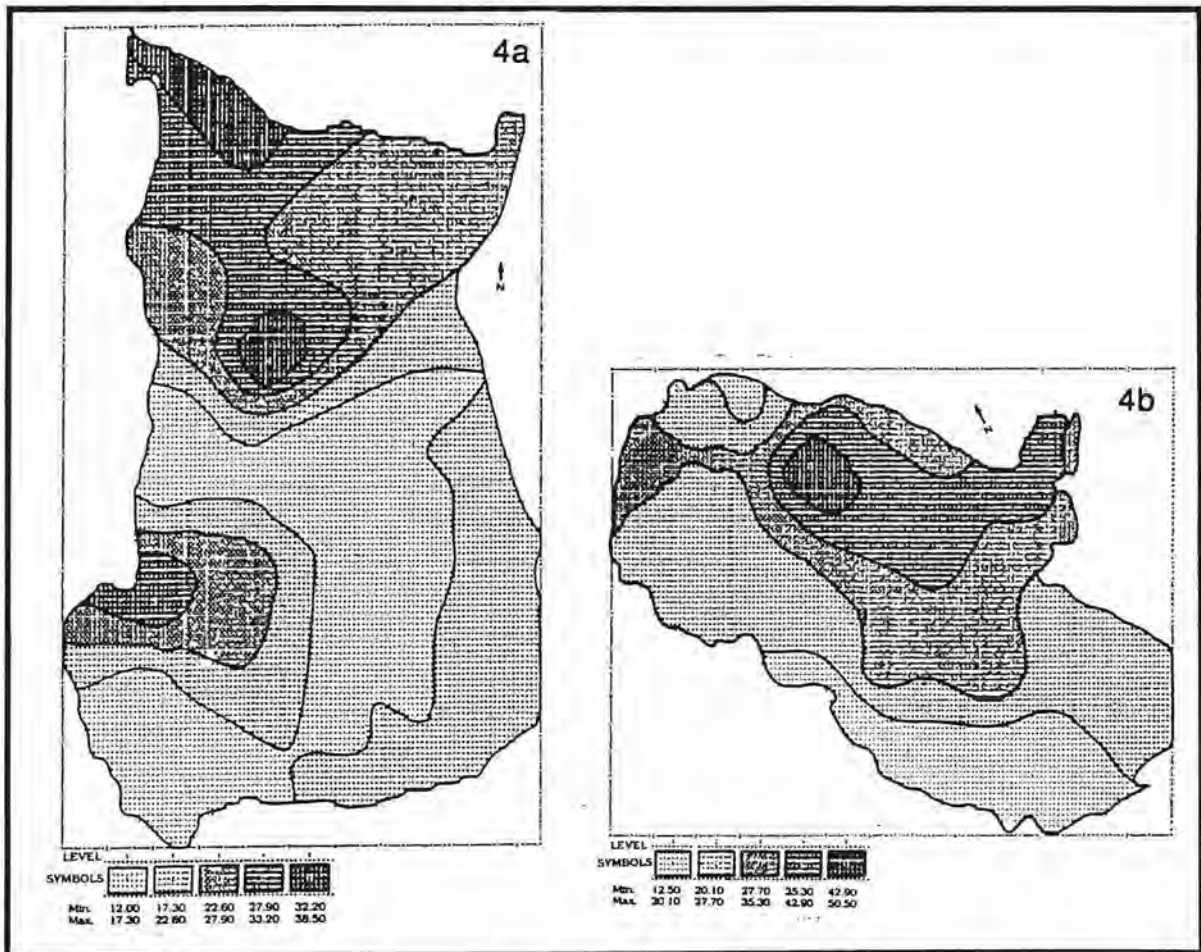


Figure 4a. Distribution of organic phosphorus in the waters of Princess Royal Harbour, February 1988. b. Distribution of organic phosphorus in the waters of Oyster Harbour, February 1988

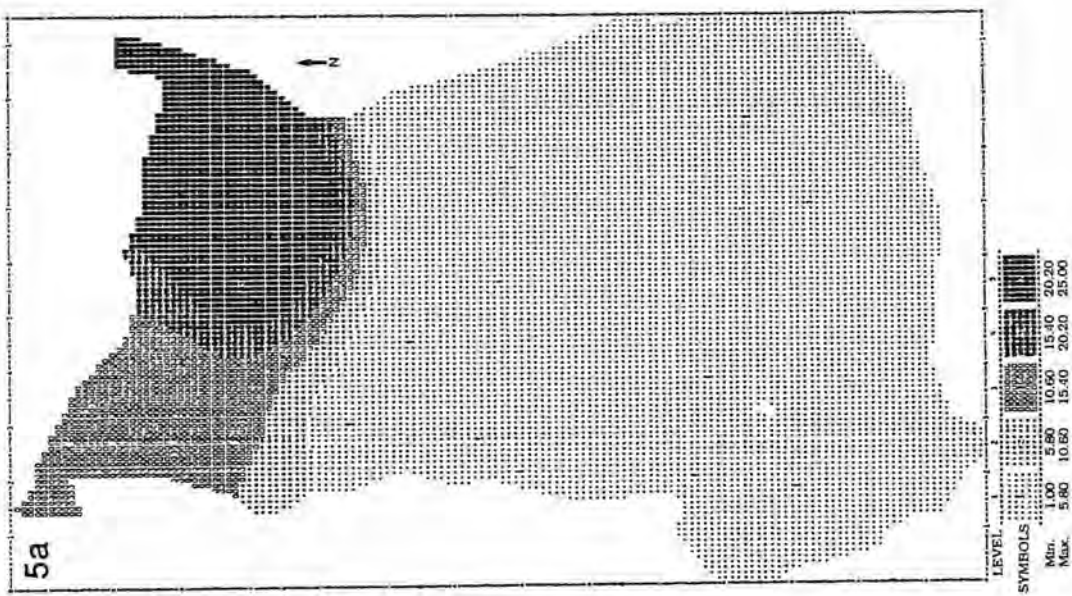
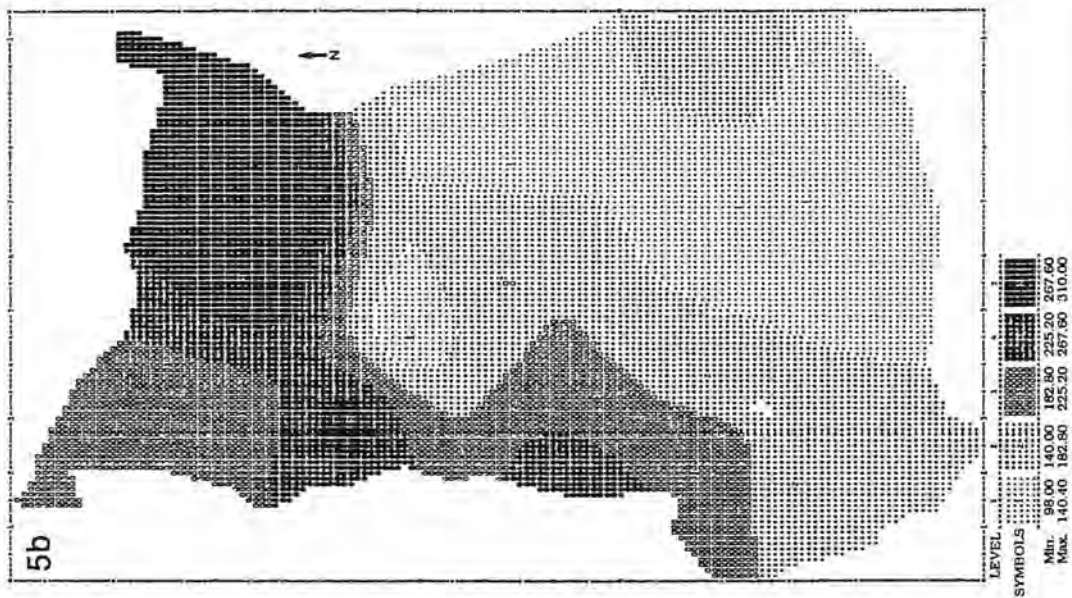


Figure 5a. Distribution of ammonia in the waters of Oyster Harbour, February 1988. b. Distribution of organic nitrogen in the waters of Oyster Harbour, February 1988

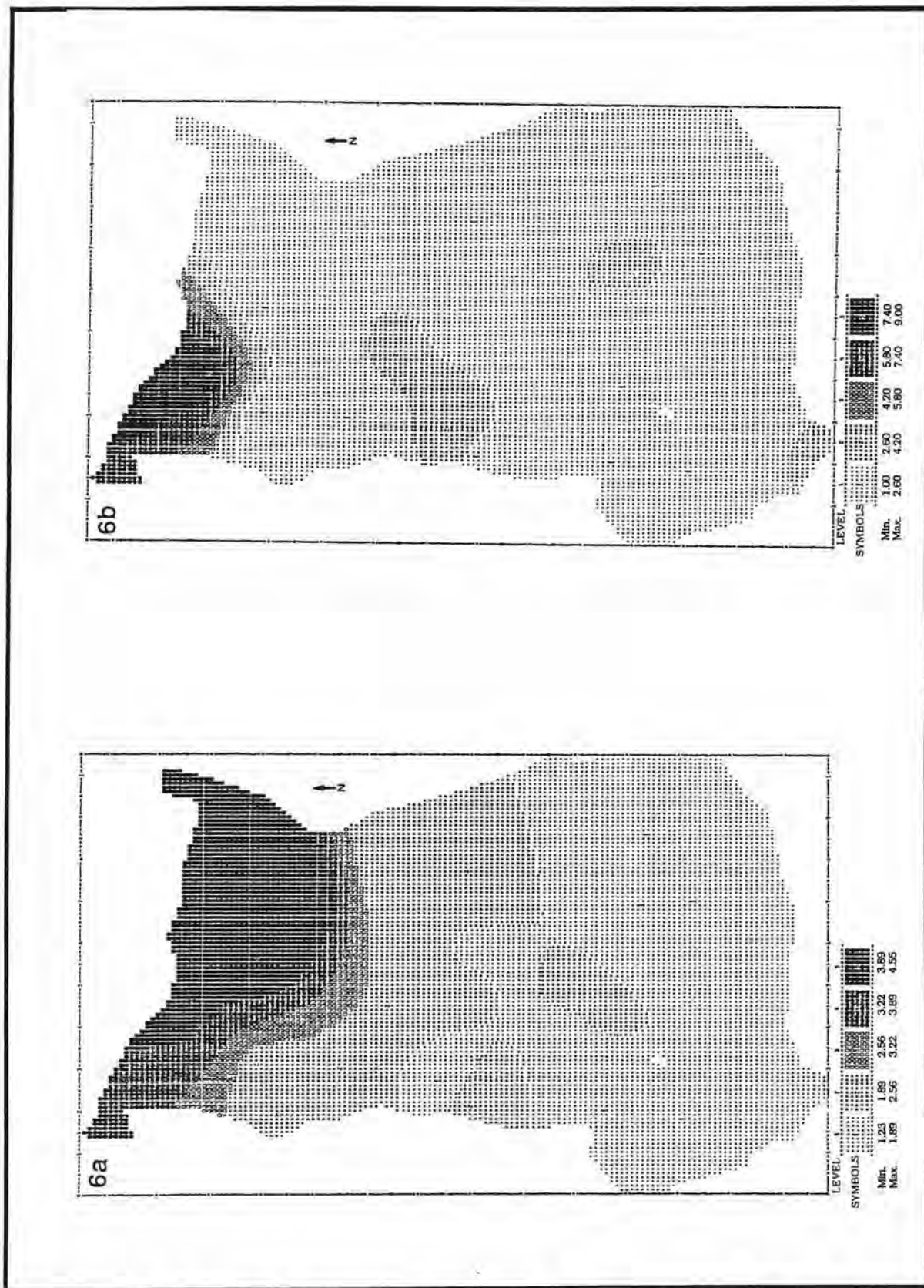


Figure 6a. Distribution of total suspended solids in the waters of Oyster Harbour, February 1988. b. Distribution of orthophosphate in the waters of Oyster Harbour, February 1988

The major input of total suspended solids and nutrients through the two rivers at the northern end of Oyster Harbour was the most likely cause of a marked spatial difference in water clarity. The mean attenuation coefficients of the two harbours were not significantly different (Table 1), however, whilst the water clarity of Princess Royal Harbour was relatively homogeneous, the northern end of Oyster Harbour was significantly more turbid (t-test, $p < 0.05$) than its southern end. Seagrasses would therefore be able to survive at greater depths in the southern end of Oyster Harbour than the northern end. The spatial maps of nutrient and suspended solids concentrations in Oyster Harbour also showed that high concentrations of these parameters corresponded to past and present areas of dieback of the deeper seagrass meadows in the northern end of the harbour, but not to current areas of loss of shallow seagrass meadows or macroalgal accumulation (see Sections 4.7 and 4.8).

4.2 Sediments

Princess Royal Harbour

In Princess Royal Harbour the distribution of areas of the highest concentrations of sediment nutrients did not equate significantly with past or present areas of seagrass decline. Highest concentrations of phosphorus and nitrogen (Figure 7) were found at site 4 in the dredged channel near the town jetty (see Figures 1 and 2) and at site 12, a shallow site, near South Spit (see Figures 1 and 2). The sediments in the central basin (the area greater than 2 m deep, see Figure 2) had the lowest concentrations (Figure 7). The shallow margins (<2 m deep) had intermediate concentrations of nitrogen and phosphorus.

The high concentrations of nitrogen and phosphorus in the sediments at site 4 are probably due to the accumulation of detrital material in the deep dredged channel. The sediment at site 4 also had a high water and organic content (Appendix 3). Many studies have found that sediment accumulation increases with depth - a phenomenon often referred to as sediment focussing (eg Evan and Rizler 1980, Davis and Ford 1982). Such sediment focusing results from the resuspension of sediments by wave action at shallow sites and subsequent sedimentation at deeper, less actively mixed, sites. Sediments are therefore usually coarser with low water, organic and nutrient contents in shallow high energy environments, and are usually fine and silty with high water, organic and nutrient contents in deeper waters. The high water, organic and nutrient content of the sediment at site 12 is also probably due to the accumulation of detrital material at this site which is relatively well protected from wave action by South Spit. The slightly higher water, organic and nutrient contents of the sediments of the shallow margins compared to the central basin sediments is probably due to the well known ability of seagrass meadows to trap organic detritus (Larkum *et al.*, 1989)

The mean organic content of the sediments in Princess Royal Harbour was not significantly different to Oyster Harbour sediments and is relatively high compared to sediments in the Wilson and Harvey estuaries (Table 2). The mean water content of Princess Royal Harbour sediments was not significantly different to that of Oyster Harbour and Harvey Estuary sediments (Table 2). Extractable nitrogen and phosphorus concentrations (Appendix 3) were not significantly different to those found in meso-eutrophic Wilson Inlet in 1982 (Lukatelich *et al.*, 1984). Mean concentrations of total nitrogen and total phosphorus were not significantly different to those of sediments in the highly eutrophic Harvey Estuary in February 1988 (Table 2).

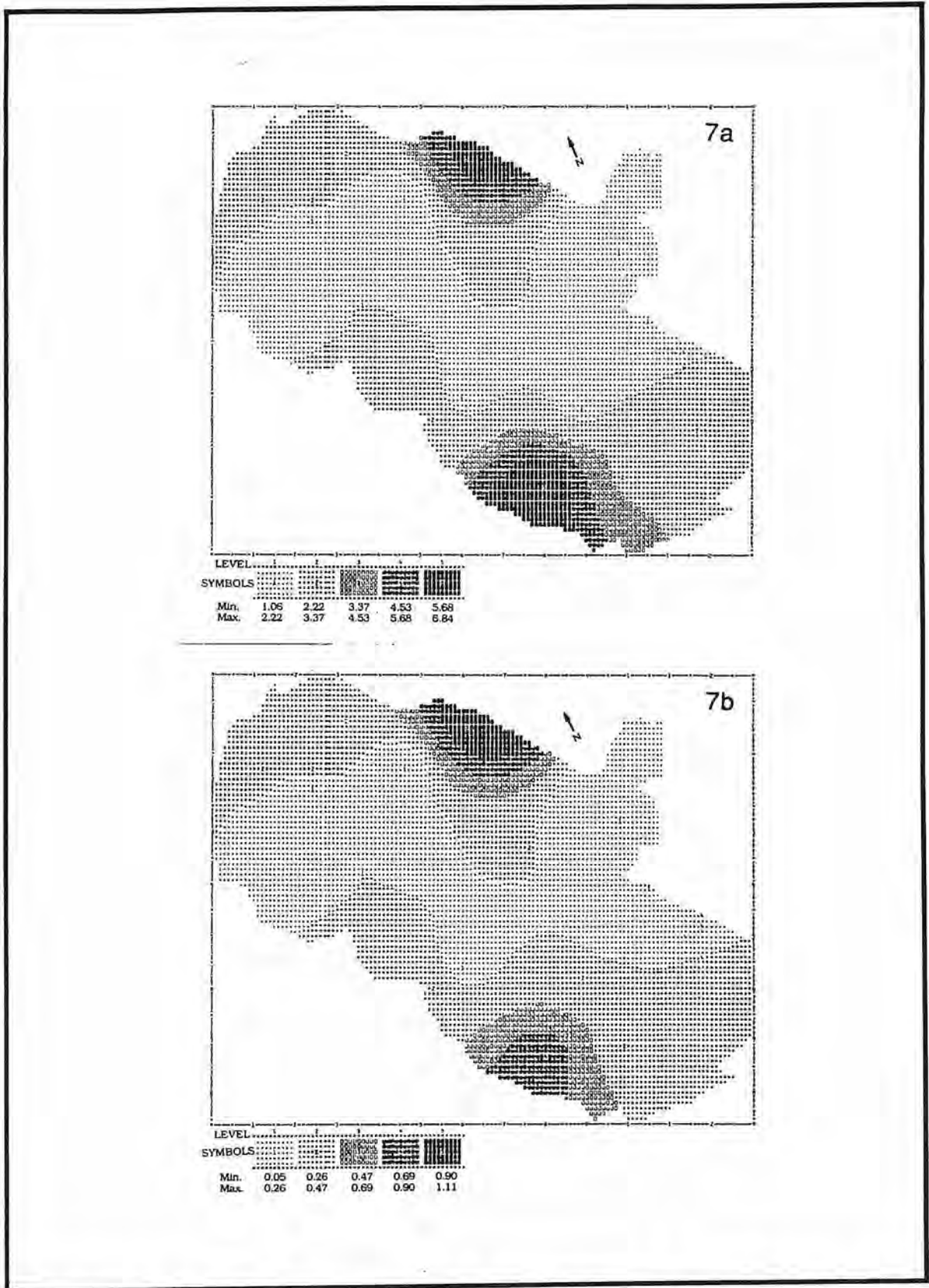


Figure 7a. Distribution of total nitrogen in the sediments of Princess Royal Harbour, February 1988. b. Distribution of total phosphorus in the sediments of Princess Royal Harbour, February 1988

The water, organic and nutrient contents of the shallow margin sediments within seagrass meadows in Princess Royal Harbour were higher than sediment collected from the control seagrass meadow in King George Sound (Appendix 3), but are similar to levels recorded within seagrass meadows in Shark Bay (D Walker, pers comm), a pristine subtropical embayment with extensive meadows of seagrass. These comparisons with the highly eutrophic Harvey Estuary and oligotrophic Shark Bay emphasized that data on the flux of nutrients from available (for plant growth) to unavailable forms in addition to data on the total nutrient levels in the sediments is necessary for an accurate assessment of the trophic status of water bodies. The importance of the decomposition of organic matter in sediment nutrient cycling was also suggested by the significant ($p < 0.05$) positive correlations of water content and organic content with extractable nitrogen and phosphorus concentrations. Princess Royal Harbour has possibly reached a state similar to that of Harvey Estuary, where the sediment nutrient bank is capable of maintaining eutrophic conditions even if other nutrient inputs cease, but this cannot be verified without data on the rate of nutrient fluxes.

Table 2. Sediment characteristics of the upper 2 cm of sediment in Princess Royal Harbour, Oyster Harbour, Wilson Inlet and Harvey Estuary. Data are the mean and range

	Organic Content (%)	Water Content (%)	Total Phosphorus ($\mu\text{g g}^{-1}$)	Total Nitrogen (mg g^{-1})
Princess Royal Harbour ¹ (n = 16)	10.5 1.0 - 32.1	57.0 25.3 - 86.3	337 53 - 1111	2.71 1.06 - 6.84
Oyster Harbour ¹ (n = 15)	11.4 3.9 - 37.5	56.6 39.8 - 72.6	316 147 - 739	2.01 1.36 - 3.03
Wilson Inlet ² (n = 16)	6.1 0.8 - 25.7	38.8 21.9 - 80.5	416 50 - 1750	1.73 0.34 - 7.39
Harvey Estuary ³ (n = 13)	9.2 1.3 - 19.6	58.8 36.7 - 79.2	376 133 - 713	2.94 1.44 - 4.96

- ¹ Princess Royal Harbour data This study
¹ Oyster Harbour data This study
² Wilson Inlet data Lukatelich *et al*, 1984
³ Harvey Estuary data February 88 Lukatelich, pers comm

Oyster Harbour

As in Princess Royal Harbour, the areas of highest concentrations of sediment nutrients in Oyster Harbour did not equate with past or present areas of seagrass decline. The highest concentrations of nitrogen and phosphorus in the sediments were found in the deeper portions of the harbour (Figure 8), and these sediments also had a high water and organic content (Appendix 3). The sediment collected near the mouth of the King River (Figure 1) also had a high water, organic and nutrient content, which may be due to the deposition of fine particulate material carried down by the King River.

Total nitrogen and phosphorus concentrations of the sediment in Oyster Harbour were not significantly different to that of Princess Royal Harbour and Harvey Estuary sediments (Table 2). Extractable nitrate and phosphate concentrations (Appendix 3) were not significantly different to those found in Princess Royal Harbour. Extractable ammonium concentrations in Oyster Harbour sediments were significantly ($p < 0.05$) lower than in Princess Royal Harbour sediments.

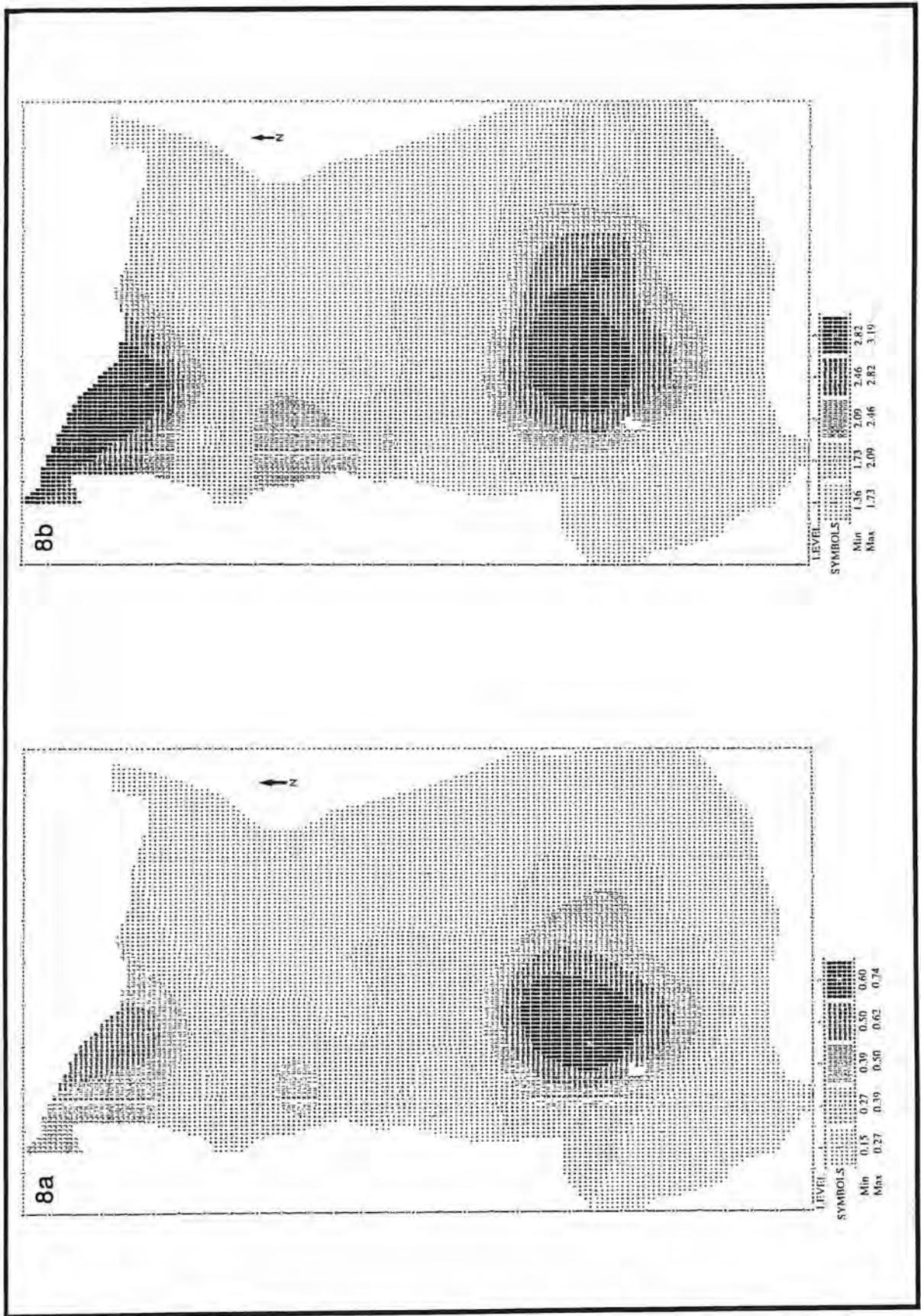


Figure 8a. Distribution of total phosphorus in the sediments of Oyster Harbour, February 1988. b. Distribution of total nitrogen in the sediments of Oyster Harbour, February 1988

The organic content, nitrogen and phosphorus (extractable and total) concentration of the sediment were significantly ($p < 0.05$) and positively correlated with water depth. Sediments in deeper waters generally have higher organic contents and nutrient levels as a result of sediment focusing (see above). The total nitrogen and phosphorus concentration of the sediment were significantly ($p < 0.05$) positively correlated with the water content and organic content of the sediment, which is a result of a large proportion of nutrients in the sediments being bound up in organic form. Sediments with a high organic content also generally have a high water content because the organic material increases the water holding capacity of the sediment, and the organics are generally rich in organic and inorganic nitrogen and phosphorus. As for Princess Royal Harbour, the available data indicate the potential importance of the decomposition of organic matter in sediment nutrient cycling, and therefore in contributing to the eutrophication of the harbour, but further studies would be needed to confirm this.

4.3 Seagrass and epiphyte biomass

Seagrass biomass and epiphyte biomass data for the grid study are presented in Appendices 4, 5 and 9. Seagrass biomass data for the most dense stands of seagrass in the two harbours in 1984 and 1988 are shown in Table 3, along with data for healthy stands in King George Sound in 1988. There were no significant differences ($p < 0.05$) between the two harbours in the leaf density, shoot density, leaf biomass, rhizome biomass or root biomass attained by the most dense stands of *P. australis* and *P. sinuosa* (Table 4). However the values of all these parameters for both species of seagrass in King George Sound were significantly higher ($p < 0.05$) than those achieved in either harbour (Table 4). The sites where *P. australis* biomass was measured in 1984 during Bastyan's (1986) study were identical to sites 3 and 24 during this study, and the data show a 30-60% reduction in the biomass of "dense stands" since 1984. This reduction in *P. australis* biomass, as well as the high biomass reached by *P. sinuosa* stands in the two harbours in 1984 compared to 1988 suggests that the inside- and outside-harbour differences are due to induced changes in the two harbours rather than to a natural variation between habitat types.

The ratio of above-ground to below-ground biomass achieved by *Posidonia* stands in King George Sound (1:1.6 for *P. australis* and 1:2.9 for *P. sinuosa*) was significantly lower than those of the most dense meadows in Oyster Harbour (1:0.6 for *P. australis* and 1:0.7 for *P. sinuosa*) or Princess Royal Harbour (1:1.1 for *P. australis* and 1:2 for *P. sinuosa*). There was no significant difference in ratios between the two harbours. The higher ratios in the two harbours were caused by proportionately lower root and rhizome biomass, particularly the latter (Table 3). The most dense stands of seagrass in the two harbours achieved approximately half the leaf biomass of stands in King George Sound, but less than a quarter of the root and rhizome biomass. This suggested that the below-ground reserves of meadows in the two harbours have been depleted during prolonged periods of adverse conditions, presumably when low light levels caused respiratory losses to exceed photosynthetic gains. The differences in leaf and shoot density between the two harbours and King George Sound support this conclusion, since previous studies have documented decreases in leaf and shoot density and increases in leaf length as a response by seagrasses to a reduction in light supply (Larkum *et al.*, 1989).

Epiphyte biomass data for the most dense stands of seagrass in the two harbours in 1988 are shown in Table 5 along with data for healthy stands in King George Sound. Mean epiphyte biomass (mg epiphyte g^{-1} seagrass) on *P. australis* and *P. sinuosa* in the two harbours was significantly higher ($p < 0.05$) than in King George Sound, but there was no significant difference between the two harbours (Table 4). Neverauskas (1987) suggests that the E/L ratio (ratio of epiphyte biomass to seagrass leaf biomass) is a useful indicator of excessive epiphytic growth due to nutrient enrichment, and that values of approximately 0.3 or less are typical of a normal healthy *Posidonia* meadow, whilst values of 0.5 or more indicate stressed meadows. The data of Silberstein (1980) yield an E/L ratio of approximately 0.05 for a healthy *P. australis* community in Cockburn Sound, and of > 0.50 for an unhealthy, nutrient enriched community. The E/L ratios for *P. australis* and *P. sinuosa* stands in the oceanic waters of King George Sound were 0.06 and 0.12 respectively, whilst the range of values for *Posidonia* spp in Oyster Harbour and Princess Royal Harbour were 0.09-0.34 and 0.09-0.23 respectively. The studies of Silberstein (1980) and Neverauskas (1987) indicate that the present epiphyte loads in the two harbours were sufficient to cause some light reduction and therefore reduced primary production of *Posidonia*, but were not indicative of severely stressed meadows.

Table 3. Biomass data for the most dense stands of seagrass in Princess Royal Harbour and Oyster Harbour in January 1984, and in Princess Royal Harbour, Oyster Harbour and King George Sound in February 1988

	1984				1988					
	Princess Royal Harbour		Oyster Harbour		Princess Royal Harbour		Oyster Harbour		King George Sound	
Species	<i>P aus</i>	<i>P sin</i>	<i>P aus</i>	<i>P sin</i>	<i>P aus</i>	<i>P sin</i>	<i>P aus</i>	<i>P sin</i>	<i>P aus</i>	<i>P sin</i>
Leaf density (no m ⁻²)	-	-	-	-	920 ±370	1370 ±920	1250 ±850	1660 ±1090	2000 ±700	2640 ±1030
Shoot density (no m ⁻²)	-	-	-	-	590 ±270	910 ±590	790 ±510	1200 ±790	1200 ±390	2060 ±136
Leaf biomass (g m ⁻²)	442 ±64	700 ±200	541 ±61	528 ±120	324 ±160	165 ±131	232 ±179	188 ±154	436 ±150	309 ±136
Leaf base biomass (g m ⁻²)	-	-	-	-	23 ±17	79 ±37	57 ±41	38 ±36	121 ±50	99 ±67
Rhizome biomass (g m ⁻²)	-	-	-	-	204 ±131	197 ±170	96 ±97	97 ±67	632 ±265	700 ±340
Root biomass (g m ⁻²)	-	-	-	-	155 ±96	130 ±109	72 ±40	71 ±37	282 ±200	471 ±222
Total biomass (g m ⁻²)	-	-	-	-	706 ±404	571 ±447	457 ±357	394 ±294	1471 ±665	1579 ±765

P aus = *Posidonia australis*

P sin = *Posidonia sinuosa*

Table 4. The probability of significant differences (students t-test, $p < 0.05$) in seagrass biomass and epiphyte biomass between Princess Royal Harbour (PRH), Oyster Harbour (OH) and King George Sound (KGS) in February 1988

	t-test between OH and PRH		t-test between PRH and KGS		t-test between OH and KGS	
	<i>P. australis</i>	<i>P. sinuosa</i>	<i>P. australis</i>	<i>P. sinuosa</i>	<i>P. australis</i>	<i>P. sinuosa</i>
leaf density	NS	NS	<0.001	<0.001	0.003	0.006
shoot density	NS	NS	<0.001	<0.001	0.004	0.003
leaf biomass	NS	NS	0.035	0.003	<0.001	0.012
leaf base biomass	NS	NS	<0.001	NS	NS	NS
rhizome biomass	NS	NS	0.012	0.018	<0.001	0.005
root biomass	NS	NS	0.008	0.015	0.005	0.004
epiphyte biomass	NS	NS	<0.001	0.003	0.005	0.001
epiphyte cover	0.018	NS	0.010	NS	NS	NS
epiphyte organic content	NS	<0.001	0.028	0.012	NS	0.016
epiphyte carbonate content	NS	<0.001	<0.001	<0.001	NS	0.045

NS = no significant difference

Table 5. Epiphyte biomass data for the most dense stands of seagrass in Princess Royal Harbour, Oyster Harbour and King George Sound in February 1988. Data are the mean \pm standard deviation

Parameter	Princess Royal Harbour		Oyster Harbour		King George Sound	
	<i>P. australis</i>	<i>P. sinuosa</i>	<i>P. australis</i>	<i>P. sinuosa</i>	<i>P. australis</i>	<i>P. sinuosa</i>
Epiphyte biomass (mg g ⁻¹ seagrass leaf)	122 \pm 39	201 \pm 94	103 \pm 60	213 \pm 95	61 \pm 11	126 \pm 39
Epiphyte cover (g m ⁻²)	40 \pm 21	35 \pm 30	22 \pm 23	42 \pm 45	26 \pm 8	35 \pm 16
Epiphyte organic content (%)	37 \pm 1	31 \pm 3	38 \pm 4	40 \pm 3	32 \pm 3	35 \pm 0.5
Epiphyte carbonate content (%)	33 \pm 1	29 \pm 1	35 \pm 6	37 \pm 2	42 \pm 3	41 \pm 2

The data in Table 5 in conjunction with the statistical comparisons in Table 4 show that epiphyte cover (g epiphyte m⁻² seagrass meadow) was significantly higher in Princess Royal Harbour than Oyster Harbour and significantly higher in Oyster Harbour than in King George Sound, whilst the reverse was true for the carbonate content of the epiphytes. A high carbonate content is usually indicative of a high proportion of encrusting coralline epiphytes and is common in oligotrophic ecosystems, whereas in eutrophic ecosystems there is a greater proportion of filamentous algae (eg *Cladophora*, *Enteromorpha*, *Chaetomorpha*, *Chondria*), therefore the carbonate content is less (May *et al.*, 1978). On the basis of data on epiphyte cover and epiphyte carbonate content, it could be argued that Princess Royal Harbour was more "eutrophic" than Oyster Harbour, and Oyster Harbour more eutrophic than King George Sound at the time of the present study.

There are no epiphyte data for the two harbours in 1981 and 1984, when the dieback was first documented (Bastyan, 1986). Bastyan's (1986) observations suggest, however, that epiphytic cover was heavier in Princess Royal Harbour in 1984 than during the present study, whilst in Oyster Harbour it has remained approximately the same. This in turn suggests that the reduction of light supply to seagrasses due to heavy epiphyte loads has been at least partly responsible for seagrass dieback in Princess Royal Harbour in the past, but the epiphyte loads have never been heavy enough to cause seagrass dieback in Oyster Harbour. Epiphyte loads measured during this study were not sufficient to be the main cause of seagrass dieback in either harbour, however the role of epiphytes in the decline of seagrass may be more significant than implied from the results of this study, due to the large interannual variation in nutrient loading to the harbours.

4.4 Seagrass and epiphyte nutrient concentrations

The mean values of seagrass and epiphyte nutrient concentrations for all seagrass sites in the two harbours are shown in Table 6 along with data for King George Sound (site 32). The raw data are presented in Appendices 6, 7 and 8. The tissue concentrations of nitrogen and phosphorus found in seagrasses in the three water bodies were within the range of values reported for these species in Australia (Walker and McComb, 1987). Values for *P. australis* tissues were consistently higher than those of *P. sinuosa* tissues, a fact also observed by Hocking *et al* (1988). This may be due to different nutritional requirements of the two species, since the more robust *P. australis* typically inhabits shallower (and therefore higher energy) environments than *P. sinuosa*, but as yet no studies have been carried out to determine the critical nutrient concentrations (for growth) of either species.

Table 6. Mean values of seagrass and epiphyte nutrient concentrations for all seagrass sites in Princess Royal Harbour and Oyster Harbour in February 1988, along with data for King George Sound (site 32). Data are the mean \pm standard deviation. All values are mg nutrient g⁻¹ tissue.

Parameter	Princess Royal Harbour		Oyster Harbour		King George Sound	
	<i>P. australis</i>	<i>P. sinuosa</i>	<i>P. australis</i>	<i>P. sinuosa</i>	<i>P. australis</i>	<i>P. sinuosa</i>
leaf nitrogen	9.10 \pm 1.00	5.80 \pm 3.70	11.60 \pm 1.60	8.90 \pm 2.90	9.40 \pm 0.90	7.10 \pm 0.60
leaf phosphorus	0.96 \pm 0.14	0.77 \pm 0.09	1.08 \pm 0.29	0.71 \pm 0.08	0.86 \pm 0.08	0.71 \pm 0.10
leaf base nitrogen	10.10 \pm 2.80	7.10 \pm 0.80	11.30 \pm 1.30	8.70 \pm 0.60	8.60 \pm 0.90	5.50 \pm 0.60
leaf base phosphorus	1.75 \pm 0.54	0.93 \pm 0.37	1.37 \pm 0.24	1.05 \pm 0.07	1.49 \pm 0.11	1.04 \pm 0.17
rhizome nitrogen	13.50 \pm 2.70	4.40 \pm 1.50	4.80 \pm 0.60	6.40 \pm 1.10	3.30 \pm 0.70	3.60 \pm 0.80
rhizome phosphorus	0.72 \pm 0.41	0.36 \pm 0.20	0.45 \pm 0.10	0.32 \pm 0.15	0.95 \pm 0.33	0.64 \pm 0.17
root nitrogen	6.80 \pm 0.50	4.90 \pm 0.80	6.30 \pm 0.50	4.40 \pm 0.40	4.70 \pm 0.30	4.60 \pm 0.70
root phosphorus	0.24 \pm 0.03	0.23 \pm 0.07	0.47 \pm 0.05	0.15 \pm 0.03	0.39 \pm 0.17	0.27 \pm 0.05
epiphyte nitrogen	12.70 \pm 1.60	10.80 \pm 3.40	13.60 \pm 2.20	26.50 \pm 13.70	7.30 \pm 0.50	10.10 \pm 1.50
epiphyte phosphorus	0.94 \pm 0.09	0.79 \pm 0.01	1.81 \pm 0.51	2.03 \pm 0.81	1.31 \pm 0.23	1.24 \pm 0.14

Statistically significant ($p < 0.05$) differences between the three water bodies in the nitrogen and phosphorus concentrations of seagrasses and epiphytes are summarized in Table 7. Seagrass research to date indicates that seagrasses obtain the larger part of their nutrient requirements from the sediments rather than the water column, and that seagrass rhizomes can act as a storage reservoir for carbohydrates and phosphorus that can be used when

external nutrient supplies and/or photosynthetic activity is insufficient for the plant's growth (Larkum *et al.*, 1989). Since sediment nutrient concentrations in King George Sound were significantly lower than in the two harbours, it could be expected that seagrass tissues from the two harbours - particularly the rhizomes - would show some sign of nutrient enrichment compared to seagrass tissues from King George Sound. There was evidence of this for rhizome and root nitrogen concentrations, particularly for *P. australis*, but conversely, rhizome phosphorus concentrations in King George Sound were generally higher than in the two harbours, whilst for above-ground tissues no consistent trends were apparent (Tables 6 and 7). The significantly lower phosphorus concentrations in rhizomes from the two harbours was unexpected, unless the depletion of below-ground reserves discussed previously (see Section 4.3) interferes in some way with the ability of the rhizomes to retain phosphorus. On an areal basis, seagrass meadows in King George Sound contained significantly higher amounts of nutrients (ie amounts of nitrogen and phosphorus per unit area) because of their higher biomass. Thus the effects of nutrient enrichment in the two harbours would have led to a loss of nutrients from the seagrass meadows into the water column and sediments as the initially healthy meadows declined. This nutrient release could have exacerbated the eutrophication problems.

Table 7. The probability of significant differences (students t-test, p=0.5) in seagrass and epiphyte nutrient concentrations between Princess Royal Harbour (PRH), Oyster Harbour (OH) and King George Sound (KGS) in February 1988

	t-test between OH and PRH		t-test between PRH and KGS		t-test between OH and KGS	
	<i>P. australis</i>	<i>P. sinuosa</i>	<i>P. australis</i>	<i>P. sinuosa</i>	<i>P. australis</i>	<i>P. sinuosa</i>
leaf nitrogen	<0.001	NS	NS	NS	<0.001	NS
leaf phosphorus	NS	NS	NS	NS	0.029	NS
leaf base nitrogen	NS	<0.001	NS	<0.001	0.004	<0.001
leaf base phosphorus	NS	NS	NS	NS	NS	NS
rhizome nitrogen	<0.001	0.010	<0.001	NS	0.009	0.002
rhizome phosphorus	NS	NS	NS	0.009	0.012	0.013
root nitrogen	NS	NS	<0.001	NS	<0.001	NS
root phosphorus	<0.001	0.030	NS	NS	NS	<0.001
epiphyte nitrogen	NS	0.012	<0.001	NS	<0.001	0.042
epiphyte phosphorus	0.003	0.003	0.026	<0.001	NS	NS

NS = Not statistically significant

Between-harbour differences in seagrass nutrient concentrations were also a mixture of expected and unexpected trends. Concentrations of nitrogen in *P. australis* rhizomes in Princess Royal Harbour were significantly higher than in Oyster Harbour, whilst the reverse was true for *P. sinuosa* rhizomes (Tables 6 and 7). These differences were probably linked to differences in extractable nitrogen levels in the sediments, as evidenced by the significant positive correlations between extractable nitrogen concentrations in the sediments and below-ground seagrass nitrogen concentrations for both *Posidonia* species (Tables 8 and 9). There is, however, no apparent explanation for the significantly higher nitrogen concentrations of *P. australis* leaves in Oyster Harbour compared to Princess Royal Harbour, particularly in view of the reverse case for rhizomes. There were significant positive correlations between leaf nitrogen and sediment nitrogen levels in Princess Royal Harbour (Table 8), but not in Oyster Harbour (Table 9), so the high nitrogen concentrations in Oyster Harbour seagrass leaves may have been due to

"luxury" uptake of nitrogen from the water column, as has been documented for other seagrasses in Western Australia (Hillman, unpublished data).

Phosphorus concentrations in *P. australis* roots were significantly higher in Oyster Harbour than in Princess Royal Harbour, whilst the reverse situation applied for *P. sinuosa* roots (Table 7). These trends did not appear to be linked to sediment phosphorus levels, nor were there any significant correlations between extractable phosphorus levels in the sediment and seagrass phosphorus levels, with the exception of a significant positive correlation between leaf base phosphorus and extractable phosphate in the sediment in Princess Royal Harbour (Table 8). This lack of discernible relationships for phosphorus may have been due to the ability of seagrass rhizomes to store phosphorus, and thus buffer the plant to some extent against changes in external nutrient supply. The importance of the rhizomes as a storage reservoir was suggested by the number of significant positive correlations in Princess Royal Harbour between rhizome nutrient levels and the nutrient levels in the leaves and leaf bases, and between rhizome nutrient levels and leaf biomass (Table 10). The lack of similar significant positive relationships in Oyster Harbour (Table 11) may be a consequence of luxury uptake of nutrients by seagrass leaves from the water column, as suggested previously. However all the above relationships are based on data from one point in time and further research is needed to confirm or refute these findings.

Epiphyte nitrogen levels in the two harbours were significantly higher than in King George Sound with the exception of *P. sinuosa* epiphytes in Princess Royal Harbour - which were higher than in King George Sound, but not significantly so (Tables 6 and 7). There was no significant difference in epiphyte phosphorus concentrations between King George Sound and Oyster Harbour, but epiphyte phosphorus concentrations in Princess Royal Harbour were significantly lower than in either of the other two water bodies. The significant differences in epiphyte nitrogen concentrations appeared to be linked to differences in sediment and seagrass rhizome nitrogen pools, but the corresponding case did not apply for epiphyte phosphorus levels. The mean N:P ratio of seagrass epiphytes was 9 in Oyster Harbour and 14 in Princess Royal Harbour, compared to values of 28 for macroalgae in the same water bodies. This difference was primarily caused by higher phosphorus concentrations in epiphyte tissues, and may indicate that the seagrass leaves were functioning in transferring sediment phosphorus to their epiphytes, as has been suggested in the literature for northern hemisphere species of seagrasses (Hillman *et al.*, 1988).

These data indicate that nitrogen concentrations in epiphyte and seagrass tissues may be useful indicators of nutrient enriched sediments, although further work is needed to verify this.

Table 8. Matrix of linear correlations between aspects of seagrass biomass and water quality, sediment characteristics, epiphyte cover and macroalgae biomass for *Posidonia* spp in Princess Royal Harbour, February 1988 (n=7).

	LIGHT ATT	DEPTH	WATER TP	WATER TN	CIL _a	SED WATER	SED ORG	EXT PO ₄	SED TP	EXT NO ₃	EXT NH ₄	SED TN	BPT BIO	BPT COV	EPI N	EPI P	EPI ORG	EPI CARB	MACRO BIO
Leaf No	-0.8163*	NS	NS	NS	NS	0.8366**	NS	0.7935*	NS	NS	NS	NS	NS	NS	-0.8164*	NS	-0.9829**	0.9334**	NS
Shoot No	-0.8519**	-NS	NS	NS	NS	0.8697**	0.7146*	0.8086*	NS	NS	NS	NS	NS	NS	-0.8266*	NS	-0.9718**	0.9237**	NS
Leaf Bio.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.8575**	NS	NS	NS	NS	NS	NS	0.8765**	NS
Leaf Base Bio.	NS	NS	-0.8300*	-0.7722*	NS	NS	NS	NS	NS	NS	NS	NS	0.8061*	NS	NS	NS	NS	NS	NS
Rhiz. Bio.	NS	NS	-0.7738*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.8709**	NS	NS	NS	0.9251**	0.7837*
Root Bio.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.8288*	NS
Total Bio.	NS	NS	-0.7600*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.9272**	NS	NS	NS	0.9729**	0.7914*
Leaf N	NS	NS	NS	NS	NS	NS	0.7264*	0.9045**	NS	0.8074*	0.8554**	NS	NS	NS	NS	NS	NS	NS	NS
Leaf P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Leaf Base N	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.8781**	0.8817**	NS	NS	NS	NS	NS	NS	NS	NS
Leaf Base P	NS	NS	NS	NS	NS	NS	NS	0.7612*	NS	NS	0.7905*	NS	NS	NS	NS	NS	NS	NS	NS
Rhizome N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.8345**	NS	NS	NS	NS	NS	NS	NS	NS
Rhizome P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.7153*	NS	NS	NS	NS	0.7838*	NS	NS	NS
Root N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Root P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.8281*	NS	NS	NS	NS	NS

* p < 0.05
 ** p < 0.01
 NS Not significant

Table 9. Matrix of linear correlations between aspects of seagrass biomass and water quality, sediment characteristics, epiphyte cover and macroalgae biomass for *Posidonia* spp in Oyster Harbour, February 1988 (n=9).

	LIGHT ATT	DEPTH	WATER TP	WATER TN	CHL a	SED WATER	SED ORG	EXT PO ₄	SED TP	EXT NO ₃	EXT NH ₄	SED TN	EPI BIO	EPI COV	EPI N	EPI P	EPI ORG	EPI CARB	MACRO BIO
Leaf No.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.7594	NS	NS	NS	NS	NS
Shoot No.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.7339*	NS	NS	NS	NS	NS
Leaf Bio.	NS	NS	NS	NS	NS	NS	0.6829*	NS	NS	NS	NS	NS	NS	0.8759**	NS	NS	NS	NS	NS
Leaf Base Bio.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.8175**	NS	NS	NS	NS	NS
Rhiz. Bio.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Root Bio.	NS	NS	NS	NS	NS	NS	NS	NS	0.6672*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Total Bio.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.8404**	NS	NS	NS	NS	NS
Leaf N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	-0.7343	NS	NS
Leaf P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Leaf Base N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Leaf Base P	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rhiz. N	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rhiz. P	NS	-0.8129**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Root N	NS	NS	NS	NS	NS	NS	NS	NS	NS	0.7509*	NS	NS	NS	NS	NS	0.7022*	NS	NS	NS
Root P	0.7330*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

* p < 0.05

** p < 0.01

NS Not significant

Table 10. Linear correlation matrix of seagrass biomass and nutrient concentrations for *Posidonia* spp in Princess Royal Harbour, February 1988 (n=7).

	LEAF NO.	SHOOT NO.	LEAF BIO	LEAF BASE BIO	RHIZ BIO	ROOT BIO	TOTAL BIO	LEAF N	LEAF P	LEAF BASE N	LEAF BASE P	RHIZ N	RHIZ P	ROOT N	ROOT P
Leaf No.	0.9946**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Shoot No		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Leaf Bio.			NS	NS	NS	0.8101*	0.8160*	NS	NS	NS	NS	0.9098*	0.7292*	NS	NS
Leaf Base Bio.				NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Rhiz. Bio.					0.8708**	0.9545**	NS	NS	NS	NS	NS	NS	NS	NS	NS
Root Bio.						0.8644**	NS	NS	NS	NS	NS	NS	NS	NS	0.7472*
Total Biol.							NS	NS	NS	NS	NS	NS	NS	NS	NS
Leaf N								NS	NS	0.8464*	NS	NS	NS	NS	NS
Leaf P									0.7920*	NS	NS	0.7843*	NS	0.7572*	NS
Leaf Base N										NS	NS	0.8429*	0.8921**	NS	NS
Leaf Base P											NS	0.8670**	0.8344*	NS	NS
Rhiz. N												NS	0.8859**	0.7897*	NS
Rhiz. P														NS	NS
Root N															NS
Root P															

* p < 0.05
 ** p < 0.01
 NS Not significant

Table 11. Linear correlation matrix of seagrass biomass and nutrient concentrations for *Posidonia* spp in Oyster Harbour, February 1988 (n=9).

	LEAF NO.	SHOOT NO.	LEAF BIO	LEAF BASE BIO	RHIZ BIO	ROOT BIO	TOTAL BIO	LEAF N	LEAF P	LEAF BASE N	LEAF BASE P	RHIZ N	RHIZ P	ROOT N	ROOT P
Leaf No.		0.9978**	0.9148**	0.8952**	NS	0.7998*	0.8297**	NS	NS	NS	NS	NS	NS	NS	NS
Shoot No			0.8987**	0.8739**	NS	0.7953*	0.8081**	NS	NS	-0.6688*	NS	NS	NS	NS	NS
Leaf Bio.				0.8978**	NS	0.7772*	0.8984**	NS	NS	NS	NS	NS	NS	NS	NS
Leaf Base Bio.					NS	0.7677*	0.9124**	NS	NS	NS	NS	NS	NS	NS	NS
Rhiz. Bio.						0.7299*	0.8231**	NS	NS	NS	NS	NS	NS	NS	NS
Root Bio.							0.9053**	NS	NS	NS	NS	NS	NS	NS	NS
Total Biol.								NS	NS	NS	NS	NS	NS	NS	NS
Leaf N									NS	0.7535*	0.7522*	NS	NS	NS	NS
Leaf P										NS	NS	NS	NS	NS	NS
Leaf Base N											NS	NS	NS	NS	NS
Leaf Base P												NS	NS	NS	NS
Rhiz. N													NS	-0.7873*	NS
Rhiz. P														NS	NS
Root N															NS
Root P															

* p < 0.05

** p < 0.01

NS Not significant

4.5 Biomass and nutrient concentrations in macroalgae

Macroalgal biomass in both harbours was dominated by *Cladophora* sp, which accounted for 86% (Princess Royal Harbour) and 92% (Oyster Harbour) of total biomass of macroalgae (Table 12). Of the other algae, *Enteromorpha* sp (Chlorophyta) was most prominent in Princess Royal Harbour (3.8% of total biomass) and *Lyngby* sp (Cyanophyta) was most prominent in Oyster Harbour (6.1% of total biomass).

Total macroalgal biomass was 11,650 tonnes dry weight and 1200 tonnes dry weight in Princess Royal Harbour and Oyster Harbour respectively (Table 12). Due to the difference in the size of the two harbours it is necessary to compare the estimates of total macroalgal biomass on an areal basis. Mean areal macroalgal biomass was 406 g m⁻² in Princess Royal Harbour and 77 g m⁻² in Oyster Harbour. Clearly, there was a significant difference in the biomass of macroalgae in the two harbours, indicating a greater nutrient input and/or greater nutrient retention in Princess Royal Harbour than Oyster Harbour. The one-off nature of the study means that this interpretation should be made with some caution however, since the biomass of macroalgae can vary by orders of magnitude from year to year, and nuisance levels of algae may develop within a month, as has been recorded in the Peel-Harvey estuarine system (Lukatelich and McComb, 1985).

Table 12. Biomass (tonnes) of macroalgae in Princess Royal Harbour and Oyster Harbour, February 1988.

	Princess Royal Harbour		Oyster Harbour	
	Biomass		Biomass	
Algal groups	tonnes	% of total	tonnes	% of total
Chlorophyta				
<i>Cladophora</i> sp	10064	86.4	1107	92.5
<i>Chaetomorpha</i> sp	400	3.4	13	1.1
<i>Enteromorpha</i> sp	448	3.8	0.5	0.04
Rhodophyta	390	3.3	3	0.2
Phaeophyta	364	3.1	0.5	0.04
Cyanophyta	6	0.05	73	6.1
Total	11649	100	1197	100

It is instructive to compare the estimates of macroalgal biomass for the two harbours with data from the Peel-Harvey system. Estimates of mean areal macroalgal biomass in the highly eutrophic Peel-Harvey system range from 45 to 710 g dry wt m⁻² (Lukatelich and McComb, 1985), and are typically less than 250 g dry wt m⁻² (93 g dry wt m⁻² in February 1988). The relatively high mean areal biomass recorded for Princess Royal Harbour is indicative of a highly eutrophic system. The biomass of macroalgae was much higher (13 times in PRH, 3.5 times in OH) than the biomass of above-ground seagrass in both harbours. It is also conservatively estimated that the biomass of *Cladophora* during the 1984 mapping survey was double that recorded in 1988.

The tissue concentrations of nitrogen and phosphorus (Appendices 11 and 12) found in the macroalgae were within the range of values recorded for similar species in the Peel-Harvey system, again emphasizing the eutrophic status of the two harbours. There were no significant correlations between macroalgae phosphorus concentrations and sediment nutrient concentrations, water content or organic content in either harbour. For macroalgae nitrogen concentrations, in Princess Royal Harbour the only significant relationship was a positive correlation between Rhodophyta nitrogen concentrations and extractable ammonia in the sediments, whilst in Oyster Harbour there were positive correlations between Cyanophyta nitrogen concentrations and the organic content and total nitrogen content of the sediments. The sediments are most likely a major source of nutrients for macroalgal growth.

4.6 Nutrient pools

The relative magnitude of the seagrasses, epiphytes, macroalgae, water column and sediments as nutrient pools in the two harbours is shown in Table 13.

Table 13. Nutrient loads (tonnes) in the water column, sediments, seagrass epiphytes and macroalgae in Princess Royal Harbour and Oyster Harbour, February 1988.

Princess Royal Harbour				
	Nitrogen		Phosphorus	
	tonnes	% of total	tonnes	% of total
Water Column	10	0.8	2.8	2.1
Sediments	1046	79	123	90.4
Seagrass:				
above-ground	6	0.5	0.5	0.4
below-ground	9	0.6	0.6	0.4
total	15	1.1	1.1	0.8
Epiphytes	2	0.2	0.2	0.2
Macroalgae	253	19.1	9.0	6.6
Total	1326	100	136.1	100
Oyster Harbour				
Water Column	10	2.4	1.2	2.2
Sediments	350	88.7	51	94.4
Seagrass:				
above-ground	3	0.8	0.3	0.6
below-ground	4	1.0	0.4	0.7
total	7	1.9	0.7	1.3
Epiphytes	1	0.2	0.1	0.2
Macroalgae	27	6.8	1.0	1.9
Total	395	100	54.0	100

In Princess Royal Harbour 79% of the nitrogen and 90% of the phosphorus was present in the sediments, with the corresponding figures of 89% of the nitrogen and 94% of the phosphorus in Oyster Harbour. The magnitude of the sediment pool is typical of south-western Australian estuaries and embayments (Lukatelich *et al*, 1984). In terms of the relative magnitude of the "biological" pools of nutrients (seagrass, epiphytes, macroalgae and the organic fraction of the water column), over 90% of the nitrogen and 69% of the phosphorus in Princess Royal Harbour was present in the macroalgae, followed by the seagrasses (5.2% N and 8.5% P), the organic fraction of the water column (3.4%N and 21%P) and epiphytes (0.8%N and 1.5%P). In Oyster Harbour macroalgae accounted for over 61% and 34% of the plant nitrogen and phosphorus respectively, followed by the organic fraction of the water column (20.6%N, 37.9%P), the seagrasses (16.5%N and 24.1%P) and epiphytes (1.8%N and 3.5%P). These data illustrate the effect of eutrophication in causing the decline of seagrasses and the accumulation of macroalgae, particularly in Princess Royal Harbour, since in oligotrophic ecosystems with seagrass meadows, epiphytes and macroalgae together are usually a smaller nutrient pool than the seagrasses.

4.7 Seagrass distribution

The seagrass distribution maps for 1981, 1984 and 1988 are presented in Figures 9, 10 and 11 for Princess Royal Harbour, and in Figures 12, 13 and 14 for Oyster Harbour. The 1981 and 1984 Oyster Harbour maps differ slightly from those contained in Bastyan (1986), as these maps were redrawn with a more accurate bathymetry chart.

The changes in area of seagrass canopy and density of cover since 1981 are summarized in Figure 15, which shows cumulative histograms of the areas of the four different categories of cover in each harbour for the three mapping exercises. The histograms indicate that since 1984, there has been an increase in seagrass area of approximately 60% (about 500 ha) in Princess Royal Harbour and a 9% decrease in seagrass area in Oyster Harbour. As the accuracy of the digitizer that measured the areas was less than $\pm 0.1\%$ (see Section 3.5), these changes are significant.

In Princess Royal Harbour the increase in area of "trace" (2-15% cover) meadow in 1988 corresponds to an area of *Amphibolis* and *P. sinuosa* in the central basin (the central area of the harbour that is >2 m deep) that was designated "very unhealthy seagrass (~2% cover)" in 1981 (Figure 9), and appeared to have deteriorated further in 1984 (Figure 10), but retained sufficient reserves in the stems and rhizomes to be able to re-shoot once water quality improved (Figure 11). The other major change to occur since 1984 was the loss of dense *Posidonia* canopy and reduced density of cover in shallow areas to the east of the yacht club and east of the south spit. These areas did not correspond to areas of heavy epiphyte biomass (Figure 16), but were observed to be overlain by a thick layer of macroalgae, predominantly brown algae.

In Oyster Harbour, the major change since 1984, apart from reduced density of cover in the North Kalgan Bank and the northern end of the South Kalgan Bank, was the continuing loss of dense *Posidonia* canopy in the shallows of the south-east sector of the harbour. As in Princess Royal Harbour, this area did not correspond to an area of heavy epiphyte biomass (Figure 17) but was overlain by a thick cover of macroalgae, principally of *Cladophora* sp. On the basis of the significant difference in water clarity between the northern and southern halves of Oyster Harbour noted in this study (Section 4.1), the reduced density of seagrass cover in the North Kalgan Bank and the northern end of the South Kalgan Bank since 1984 is likely to have been at least partly caused by a reduction in light supply due to increased water turbidity associated with the suspended sediment loads of the King and Kalgan Rivers: there was little difference in epiphyte biomass (or E/L ratio) between the northern half (mean and standard deviation of $200 \pm 60 \text{ mg g}^{-1}$) and southern half of Oyster Harbour ($231 \pm 65 \text{ mg g}^{-1}$). However, data on seasonal changes in epiphyte biomass are needed before this can be verified.

Several transects surveyed by Bastyan (1986) in 1981 and 1984 were re-surveyed in February 1988 to document more accurately (since the transects could be relocated exactly) the changes in seagrass distribution and biomass since 1984. In Oyster Harbour there has been a reduction in canopy density, and in some cases a complete loss of canopy, along all of the transects since 1984. (Figures 18 to 22). The most dramatic losses occurred along the Eastern Sector and Southern Sector (eastern side) transects (Figures 20 and 21). In these areas the sparse seagrass canopies present in 1984 have been completely replaced by dense banks of *Cladophora*. The loss of the seagrass canopy appeared to be due to the thick banks of *Cladophora* which overlay the meadows, presumably blocking all light from reaching the seagrass. Along the North and South Kalgan Bank transects (Figures 18 and 19) there has been a reduction of seagrass cover but the seagrass canopy was present in deeper waters than in 1984. This was most obvious along the South Kalgan Bank transect (Figure 19) where seagrass canopy was present at a depth of 2.2 m in 1988 compared to 1.7 m in 1984. This suggests that the light availability to seagrasses has increased sometime since 1984, although it was not possible to say whether the apparent extension of the seagrass meadows is due to re-shooting from below-ground reserves or active recolonization. The increase in light availability may have been due to a decrease in macroalgal smothering, a decrease in epiphyte loads, an improvement in water clarity or a combination of all three. Only slight reduction in canopy density of the *Posidonia sinuosa* meadow between 1.0 m - 2.0 m has occurred along the Southern Sector (western side) transect since 1984 (Figure 22). This transect is close to the entrance to King George Sound and the regular tidal flushing may be responsible for reasonable water quality in this region. Unfortunately there are no earlier data to ascertain whether water quality has changed since 1984.

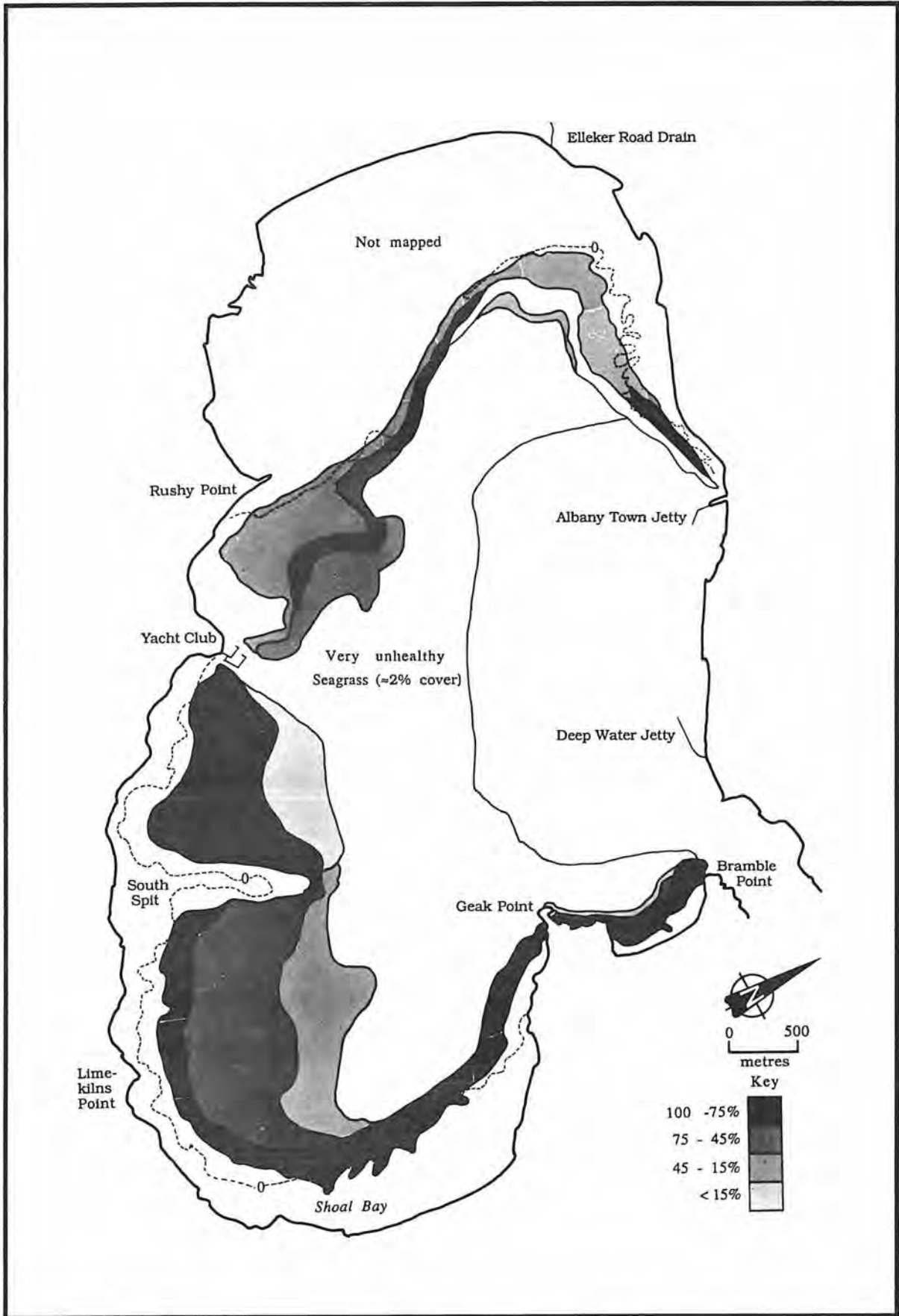


Figure 9. Distribution of seagrass in Princess Royal Harbour, 1981

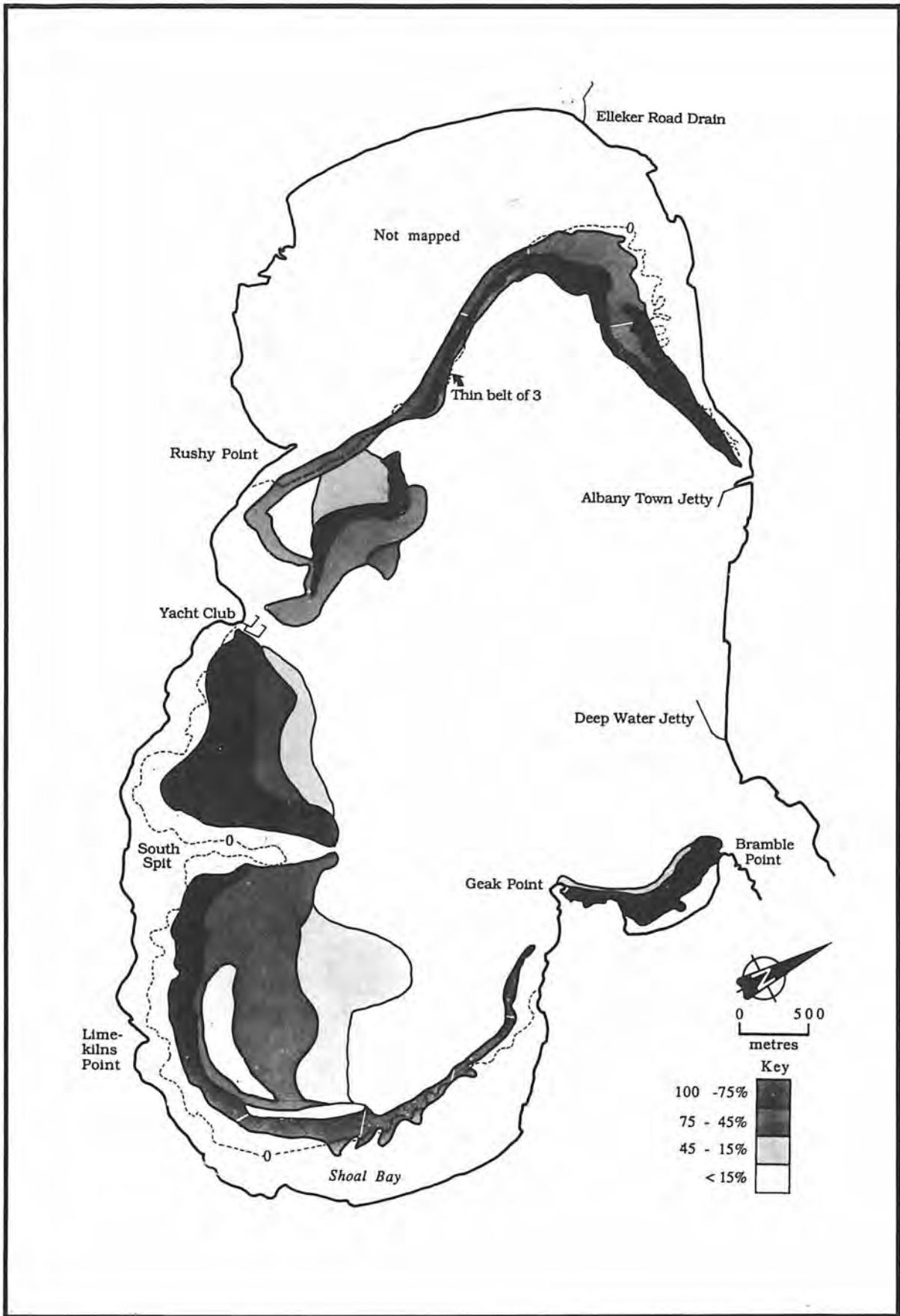


Figure 10. Distribution of seagrass in Princess Royal Harbour, 1984

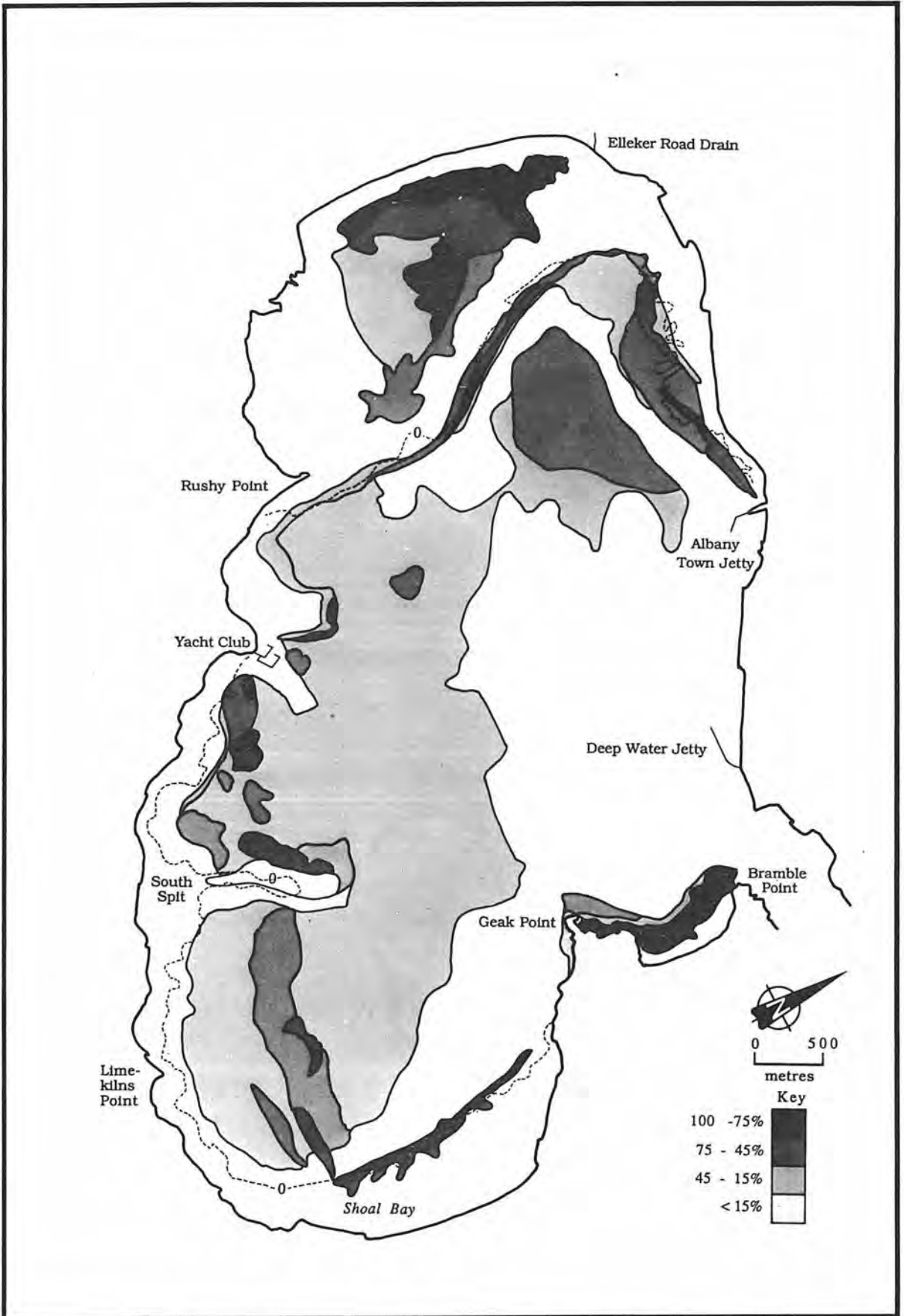


Figure 11. Distribution of seagrass in Princess Royal Harbour, 1988

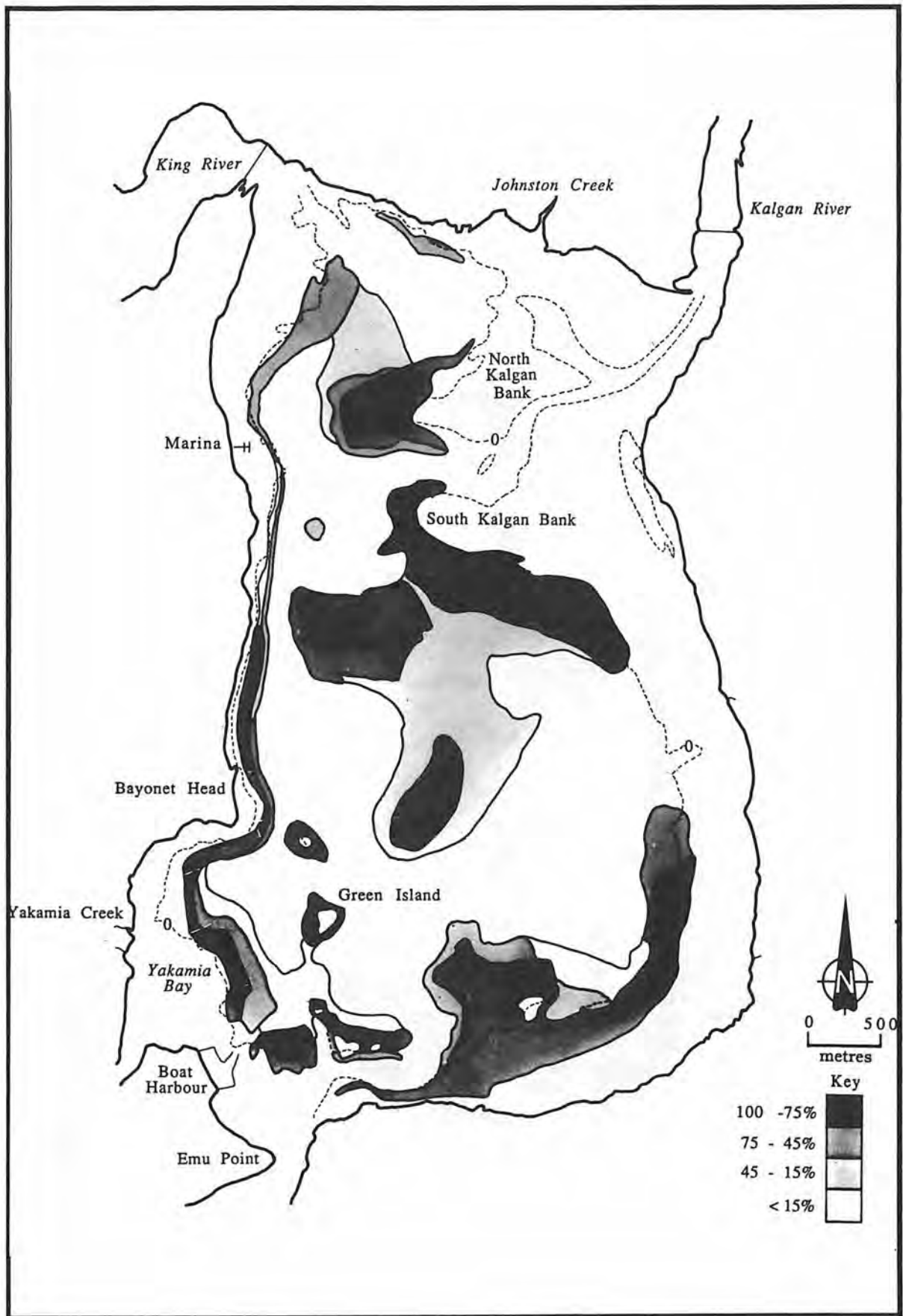


Figure 12. Distribution of seagrass in Oyster Harbour, 1981

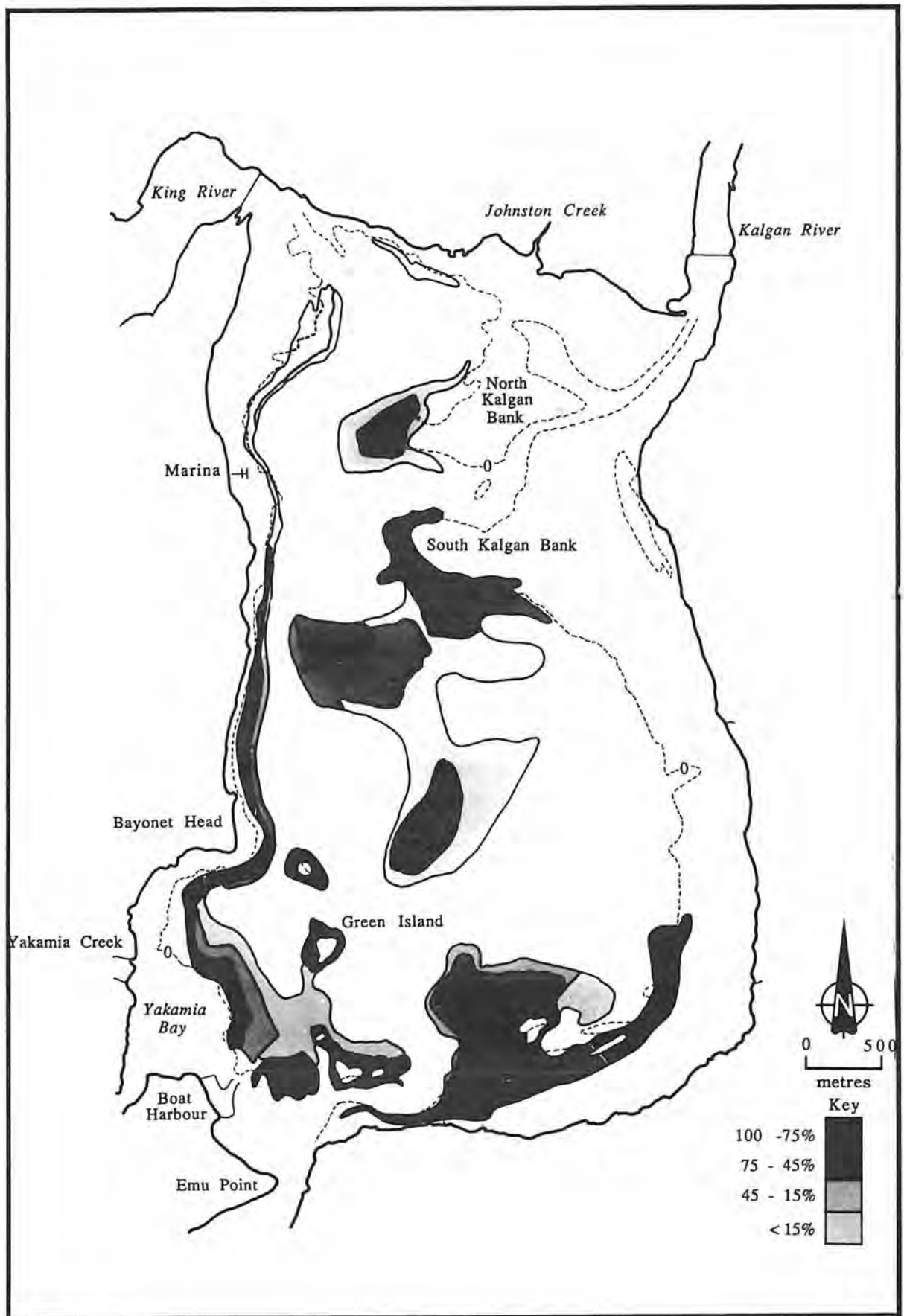


Figure 13. Distribution of seagrass in Oyster Harbour, 1984

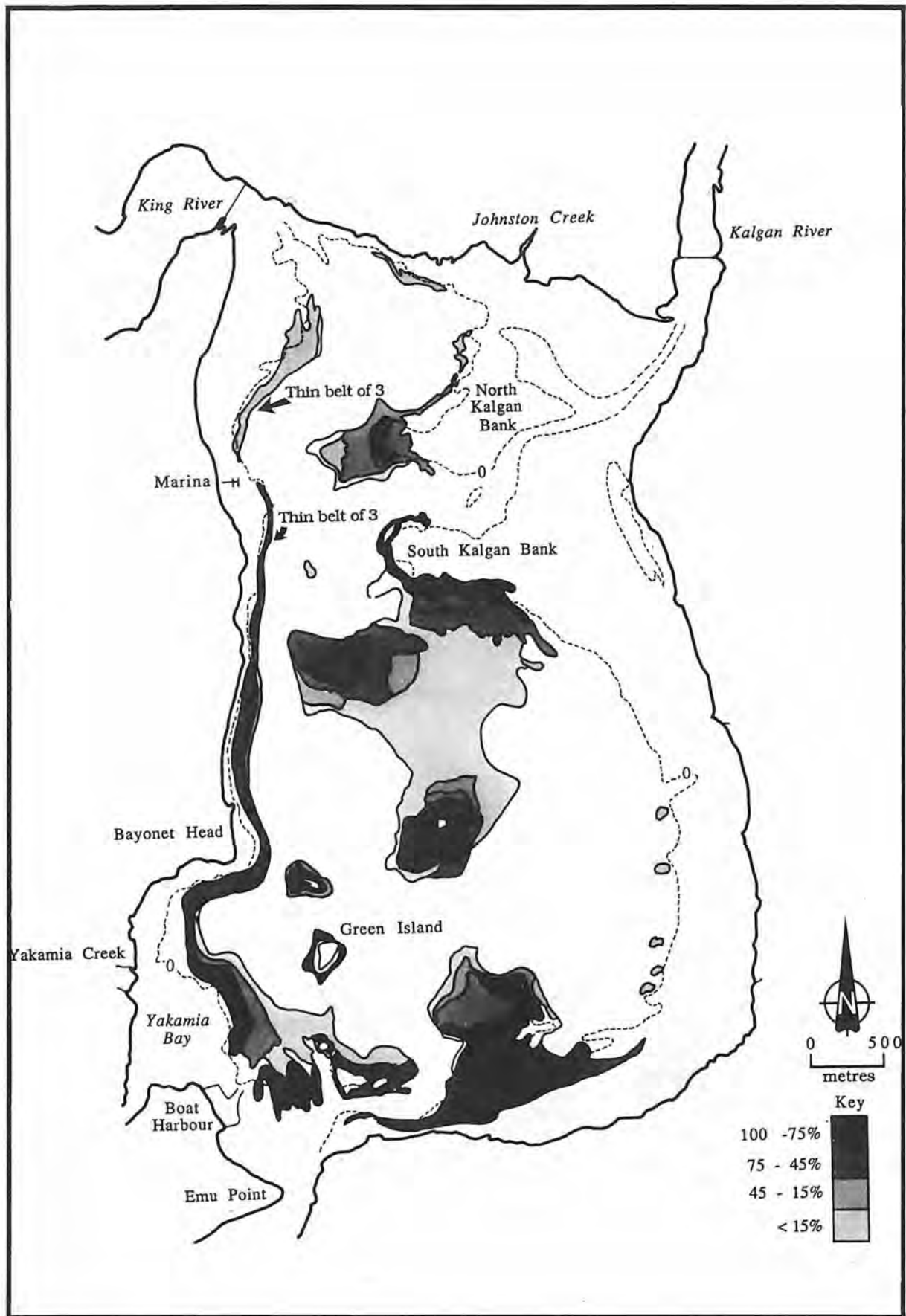


Figure 14. Distribution of seagrass in Oyster Harbour, 1988

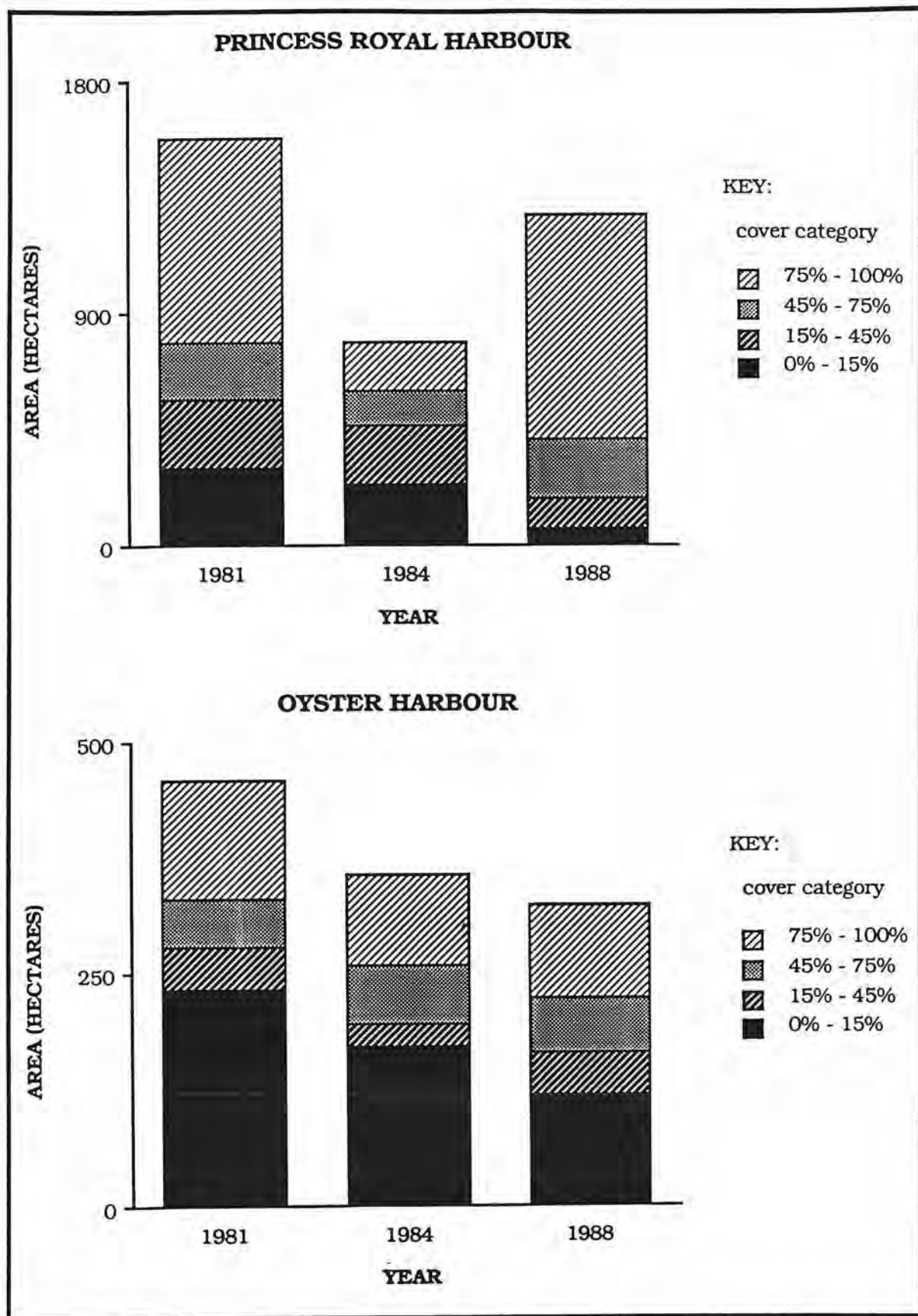


Figure 15. Cumulative histograms of the areas of the different categories of seagrass cover in Princess Royal Harbour and Oyster Harbour in 1981, 1984 and 1988

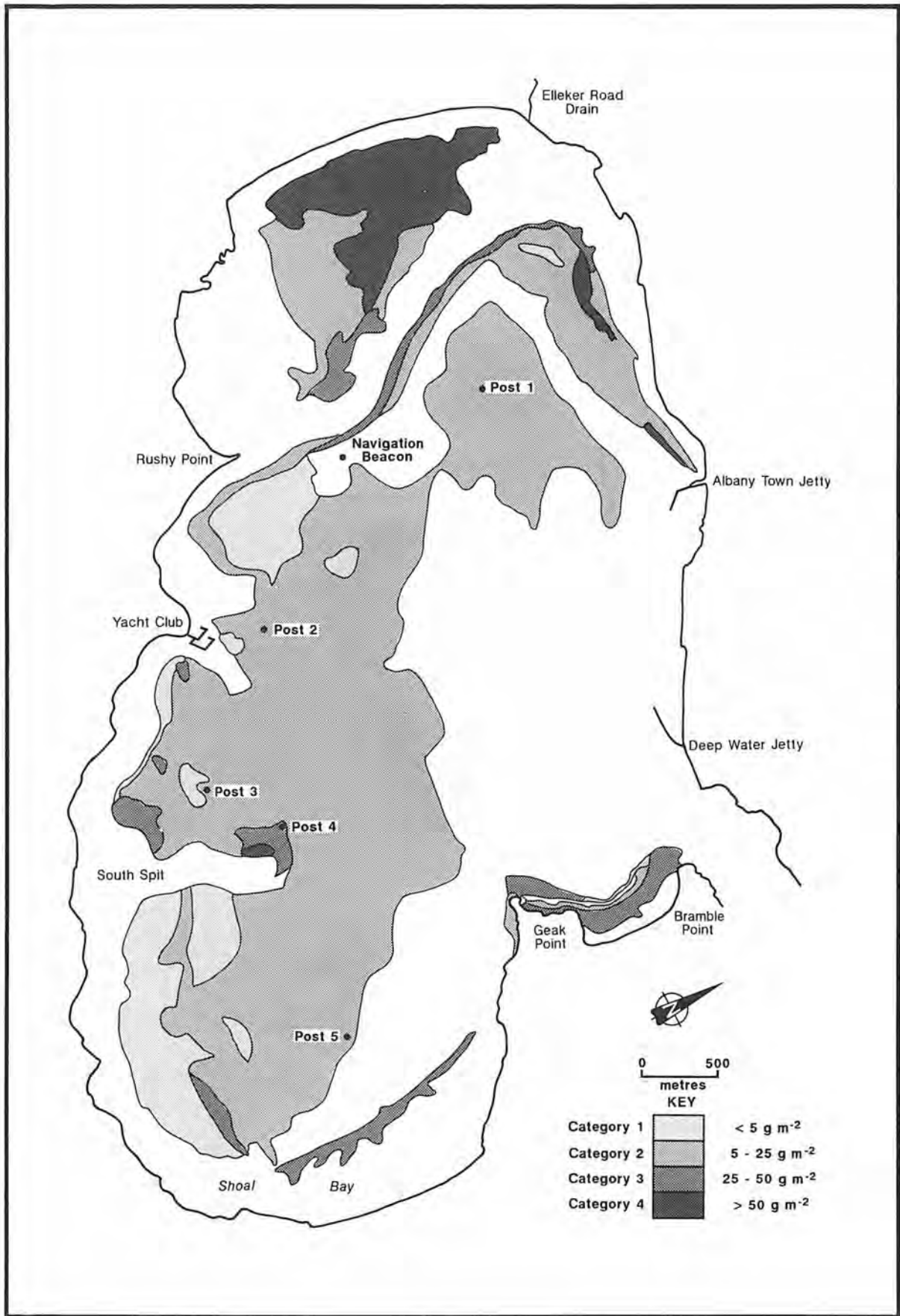


Figure 16. Distribution of epiphyte cover in Princess Royal Harbour, February 1988

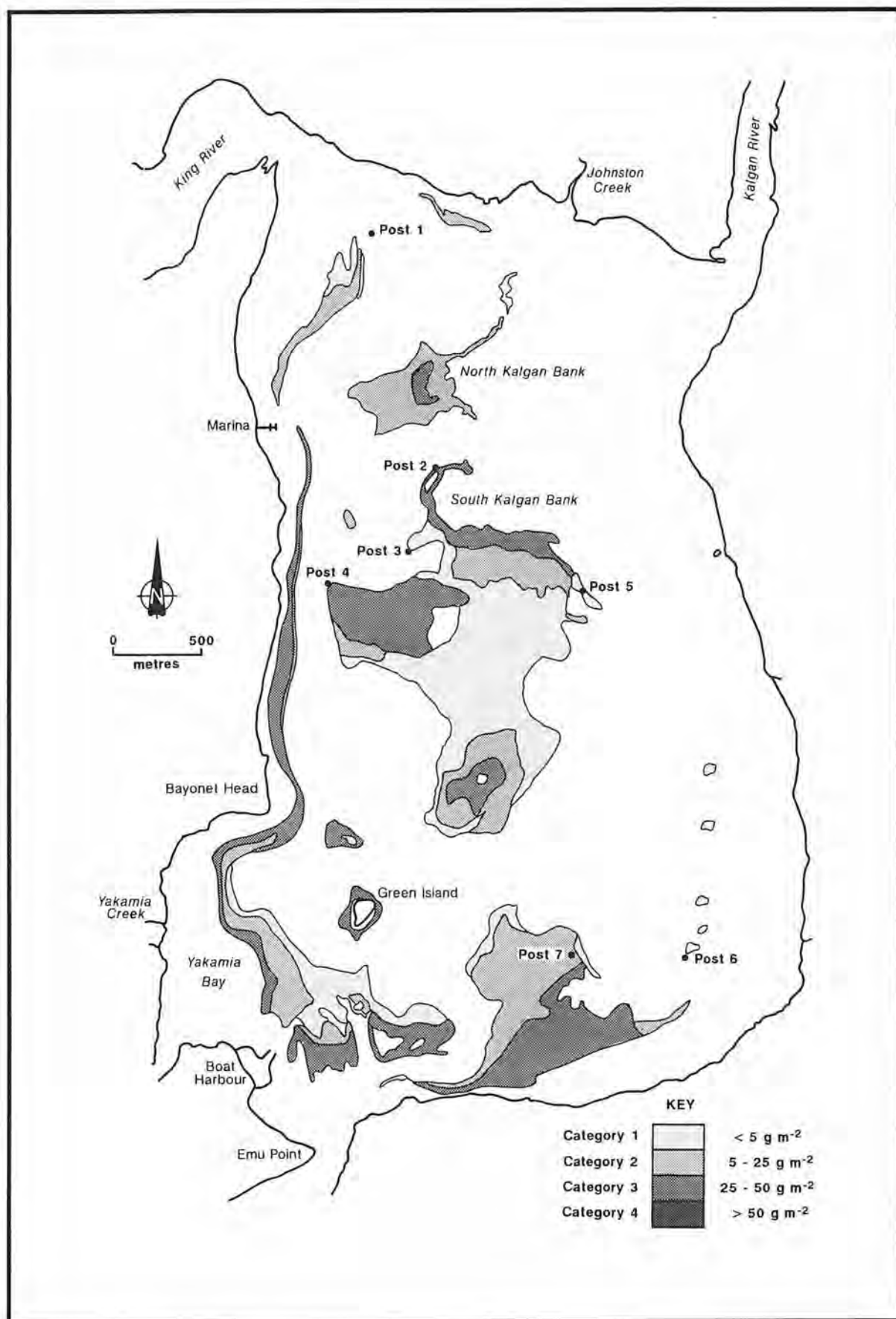
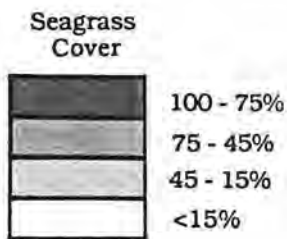













Figure 17. Distribution of epiphyte cover in Oyster Harbour, February 1988

Key



0.5m plant height

-  *Posidonia australis* (seagrass) - Pa
-  *Posidonia sinuosa* (seagrass) - Ps
-  *Hormosira banksii* (macroalgae) - H
-  *Cladophora* (macroalgae) - Clad
-  *Cystophyllum muricatum* (macroalgae) - Cm
-  Macroalgae - unidentified species - M
-  Epiphytes growing on *P. sinuosa* - Ps/Ep
-  Epiphytes growing on *P. sinuosa* and *A. antarctica* - Ps/Ep, Aa/Ep
-  *Amphibolis antarctica* (seagrass) - Aa
-  *Gracillaria* sp. (red algae) - Gs
-  Seagrass rhizomes

Key to figures 18 to 25 (pp 36 - 44)

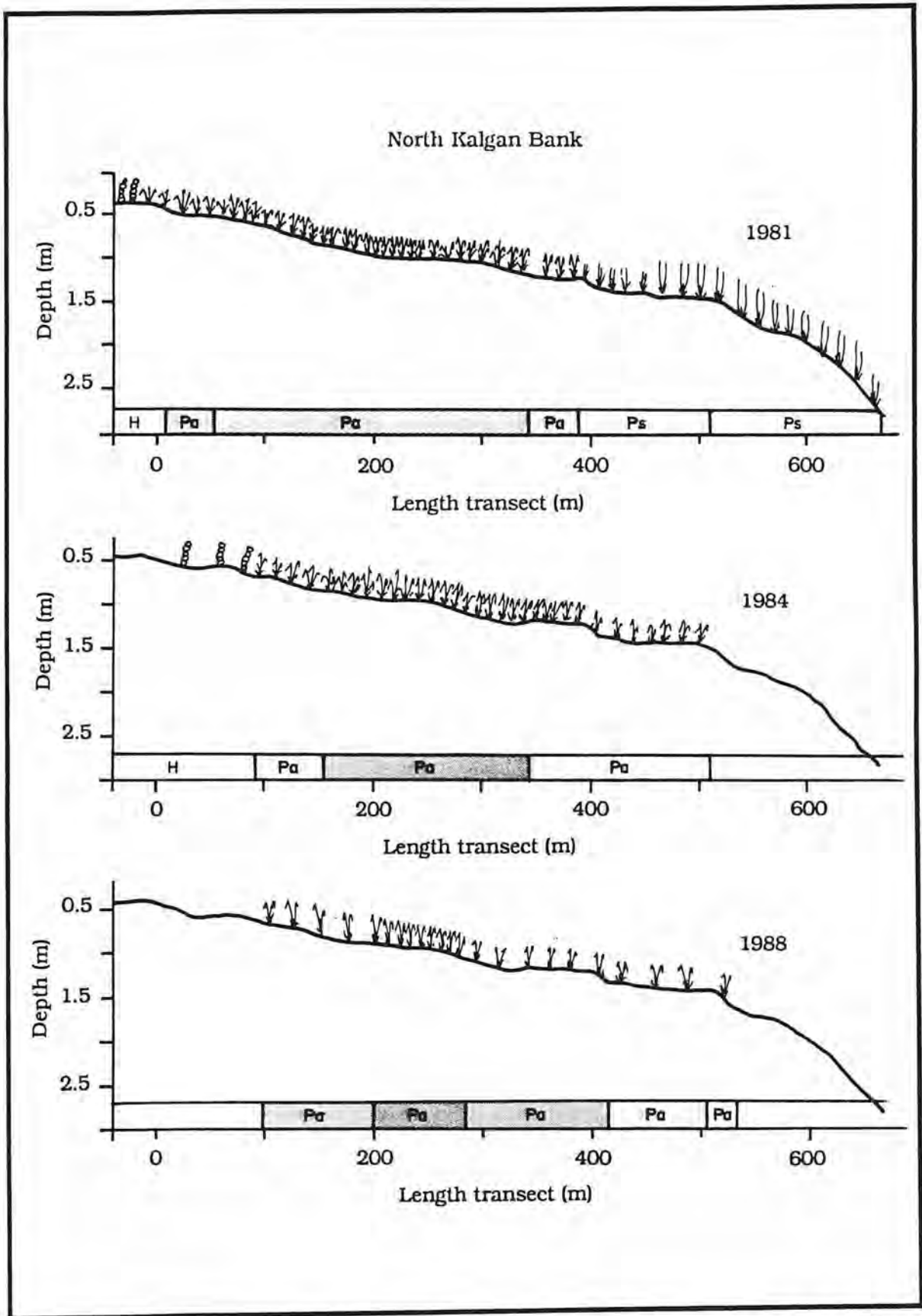


Figure 18. Transects of above-ground seagrass cover on the North Kalgan Bank, Oyster Harbour, in 1981, 1984 and 1988

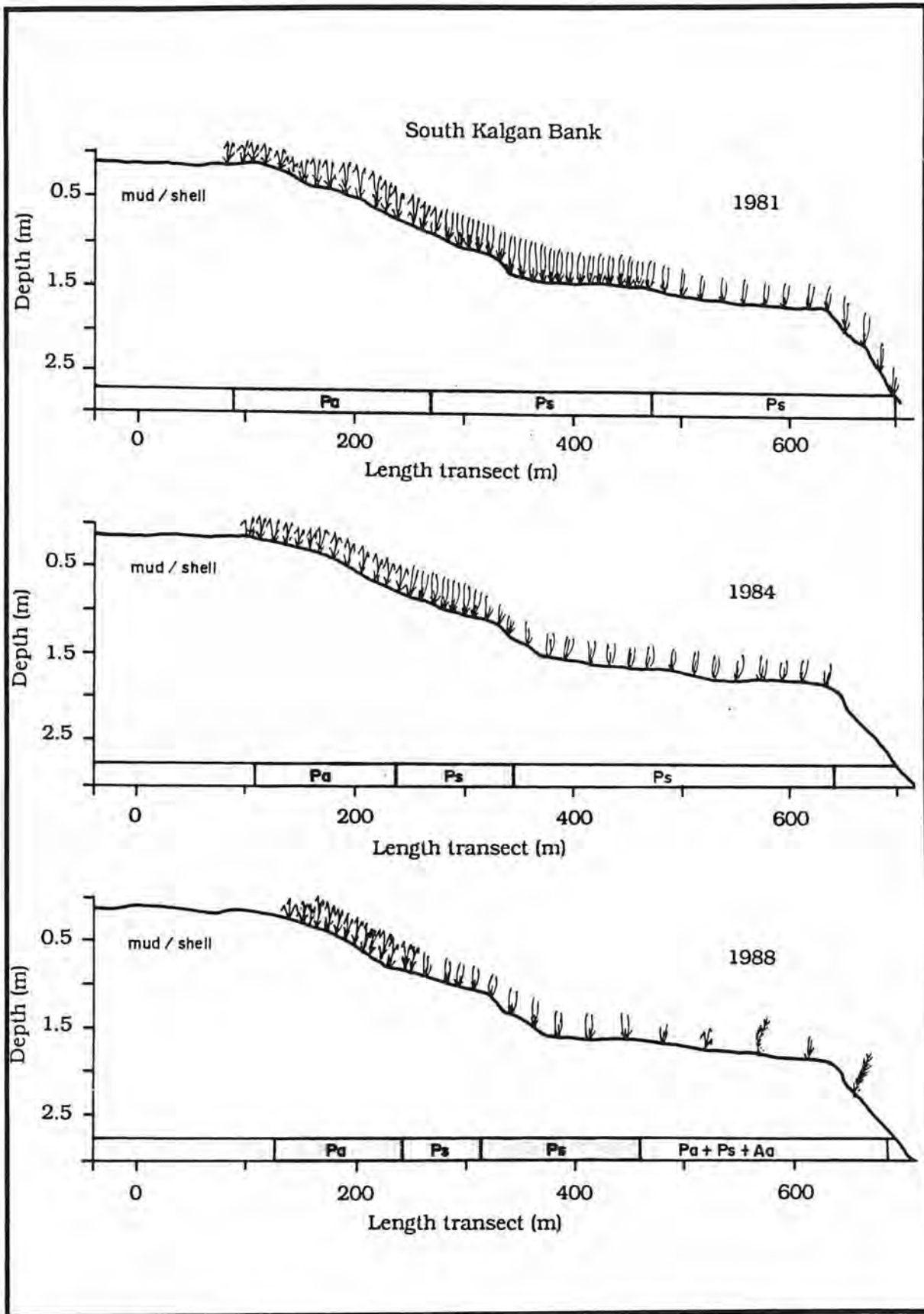


Figure 19. Transects of above-ground seagrass cover on the South Kalgan Bank, Oyster Harbour, in 1981, 1984 and 1988

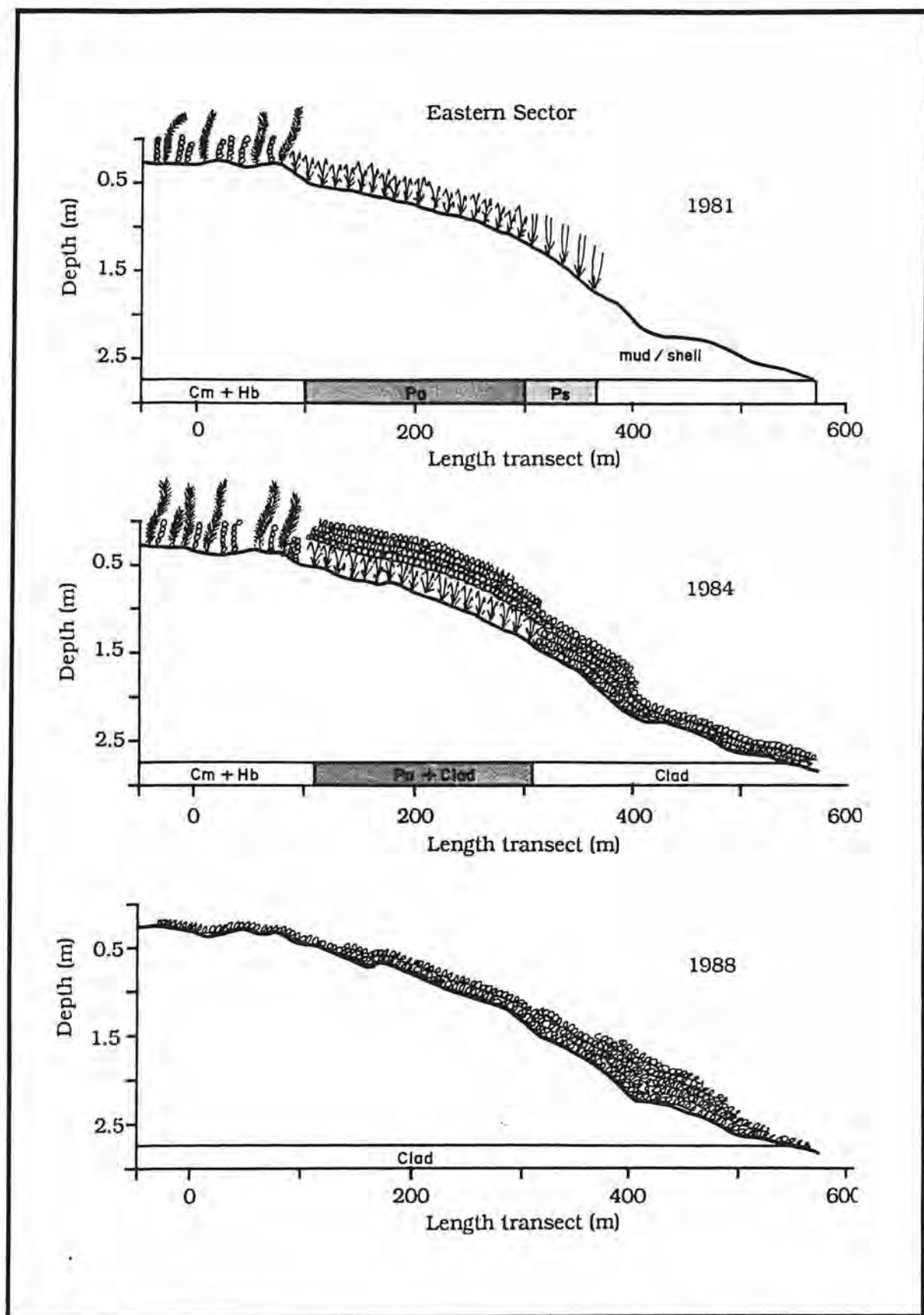


Figure 20. Transects of above-ground seagrass cover on the Eastern Sector, Oyster Harbour, in 1981, 1984 and 1988

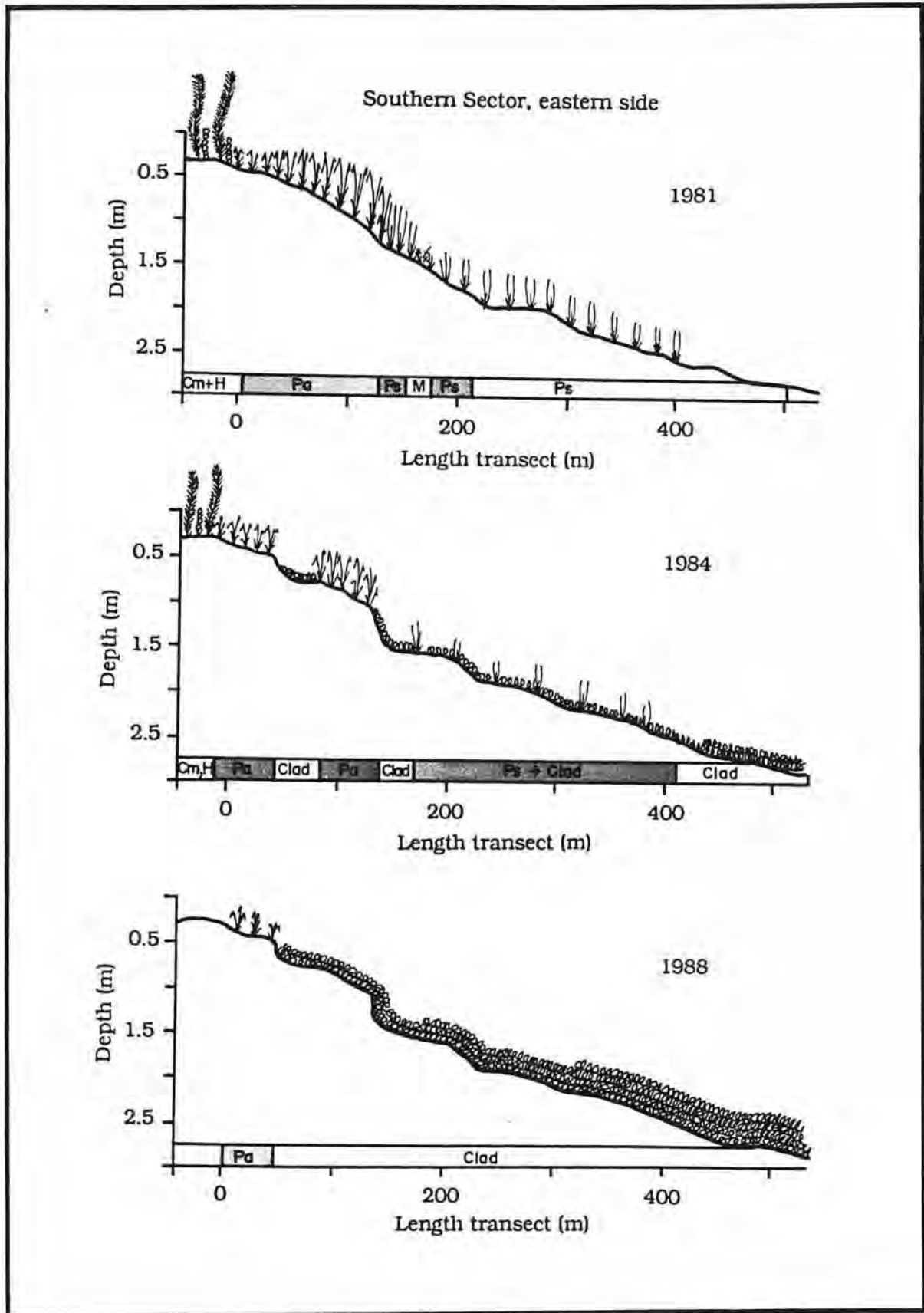


Figure 21. Transects of above-ground seagrass cover on the Southern Sector, eastern side, Oyster Harbour, in 1981, 1984 and 1988

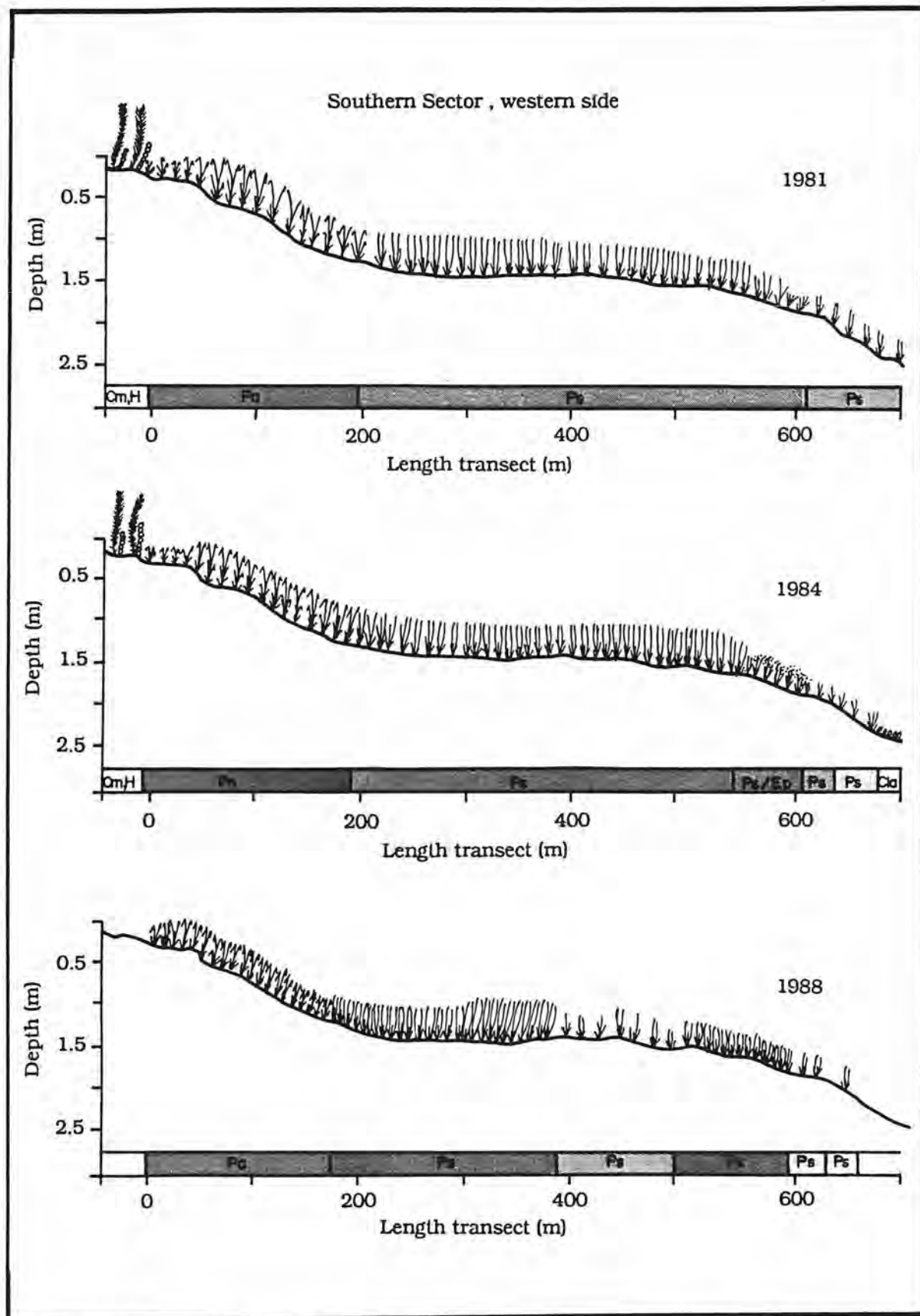


Figure 22. Transects of above-ground seagrass cover on the Southern Sector, western side, Oyster Harbour, in 1981, 1984 and 1988

Considerable loss of seagrass canopy since 1984 has occurred along the transects located at the western end of Princess Royal Harbour (Figures 23 and 24). The loss of the seagrass in the Shoal Bay region (Figure 25) has not been as extensive as the western end of Princess Royal Harbour. The depth limit of the *Posidonia australis* meadow has decreased from 1.6 m in 1984 to 1.0 m in 1988 in the Shoal Bay region. There are no data on below-ground seagrass biomass for the transects, so it cannot be determined whether the deeper areas are capable of re-establishing seagrass canopies if conditions become more favourable.

The mapping exercises indicated that seagrass losses have taken place up to the time of sampling, and it is therefore likely that they are occurring at present. The main losses are of dense stands in shallow waters, whilst the remaining dense stands are thinning in cover. However, the impression gained from the mapping exercises was that the rate of loss of seagrass area in the two harbours had slowed since 1984. The loss of biomass has nevertheless continued to be appreciable, because the denser beds are being affected. This can be seen in Figure 26, which depicts the changes in above-ground biomass since 1981 as cumulative histograms of the biomass of the areas occupied by the four different categories of cover in the two harbours. Although the area of seagrass increased in Princess Royal Harbour from 1984 to 1988 (Figure 15), the histograms in Figure 26 show that there was at least a 60% decrease in biomass. In Oyster Harbour although the loss in area from 1984 to 1988 was 9% (Figure 15), the loss in biomass was at least treble this (Figure 26). If the present rate of loss of seagrass is maintained, there will be no seagrass canopies of greater than 50% cover left in Princess Royal Harbour within three years, and in Oyster Harbour within six years. The longevity of the sparser beds (less than 50% cover) cannot be predicted accurately, but may be up to an order of magnitude greater.

4.8 Distribution of macroalgae

The distribution of macroalgae biomass, principally *Cladophora* (see above), in Princess Royal Harbour and Oyster Harbour is shown in Figures 27 and 28.

In Princess Royal Harbour dense accumulations ($>1000 \text{ g m}^{-2}$) of *Cladophora* were present at the western and south-eastern ends of the harbour (Figure 27). These beds have probably accumulated from wind-driven transport of *Cladophora* from other areas. No seagrass canopy was found under these dense *Cladophora* beds (Figure 11). Only trace amounts of macroalgae ($<1 \text{ g m}^{-2}$) were found below the 5 m contour (Figure 26). There was an extensive area of moderately dense accumulations of *Cladophora* ($200 - 1000 \text{ g m}^{-2}$) in the shallows from Rushy Point to Geak Point (Figure 27).

Macroalgae (*Cladophora*) were mainly confined to the middle (South Kalgan Bank to Green Island) and the south-eastern corner of Oyster Harbour (Figure 28). Dense *Cladophora* accumulations were found in the shallow waters of the south-east corner (Figure 28). These dense *Cladophora* accumulations appear to have been responsible for the loss of an extensive area of *Posidonia* meadow between 1981 and 1988 (Figures 12 to 14).

Dense macroalgal beds were present in the south-eastern corner of both harbours. The distribution of macroalgae did not appear to be linked to the distribution of sediment nutrient concentrations or water column nutrient concentrations. Prevailing wind directions are such that these areas are the most sheltered and therefore are suitable for macroalgal growth and accumulation. Circulation patterns are also compatible with the accumulation of drift algae in this area of the harbours (Mills, 1987).

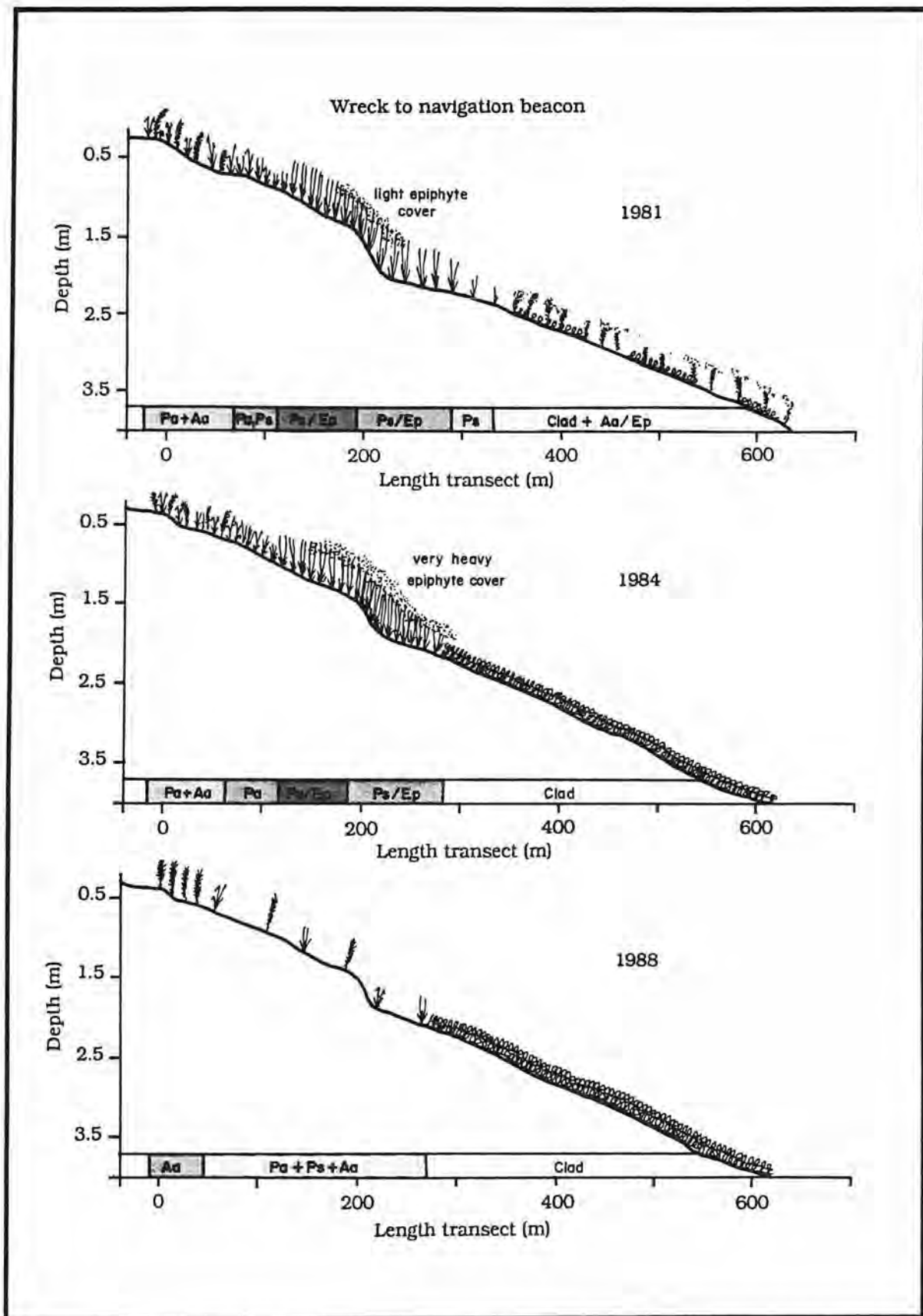


Figure 23. Transects of above-ground seagrass cover from the wreck to the navigation beacon, Princess Royal Harbour, in 1981, 1984 and 1988

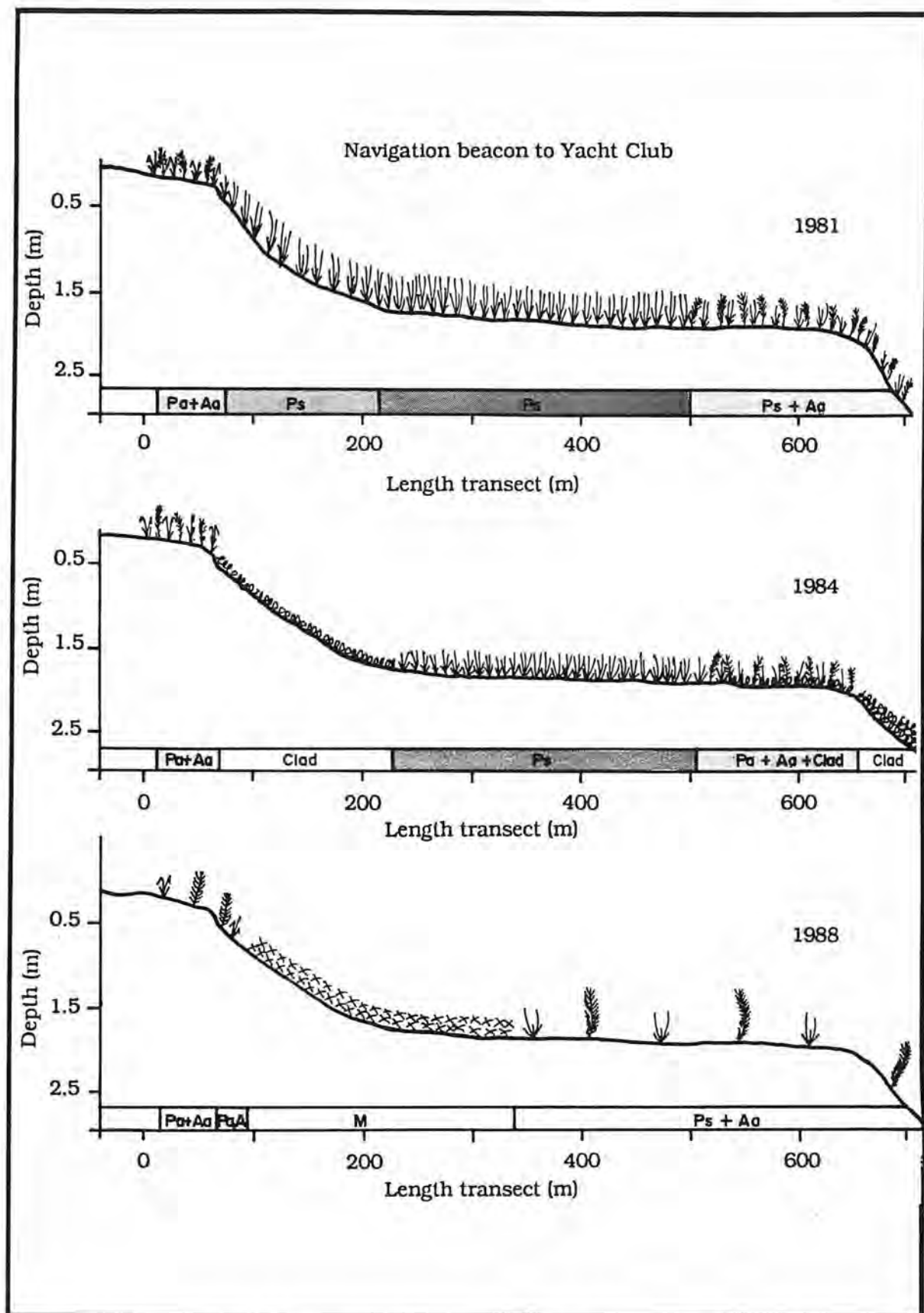


Figure 24. Transects of above-ground seagrass cover from the navigation beacon to the Yacht Club, Princess Royal Harbour, in 1981, 1984 and 1988

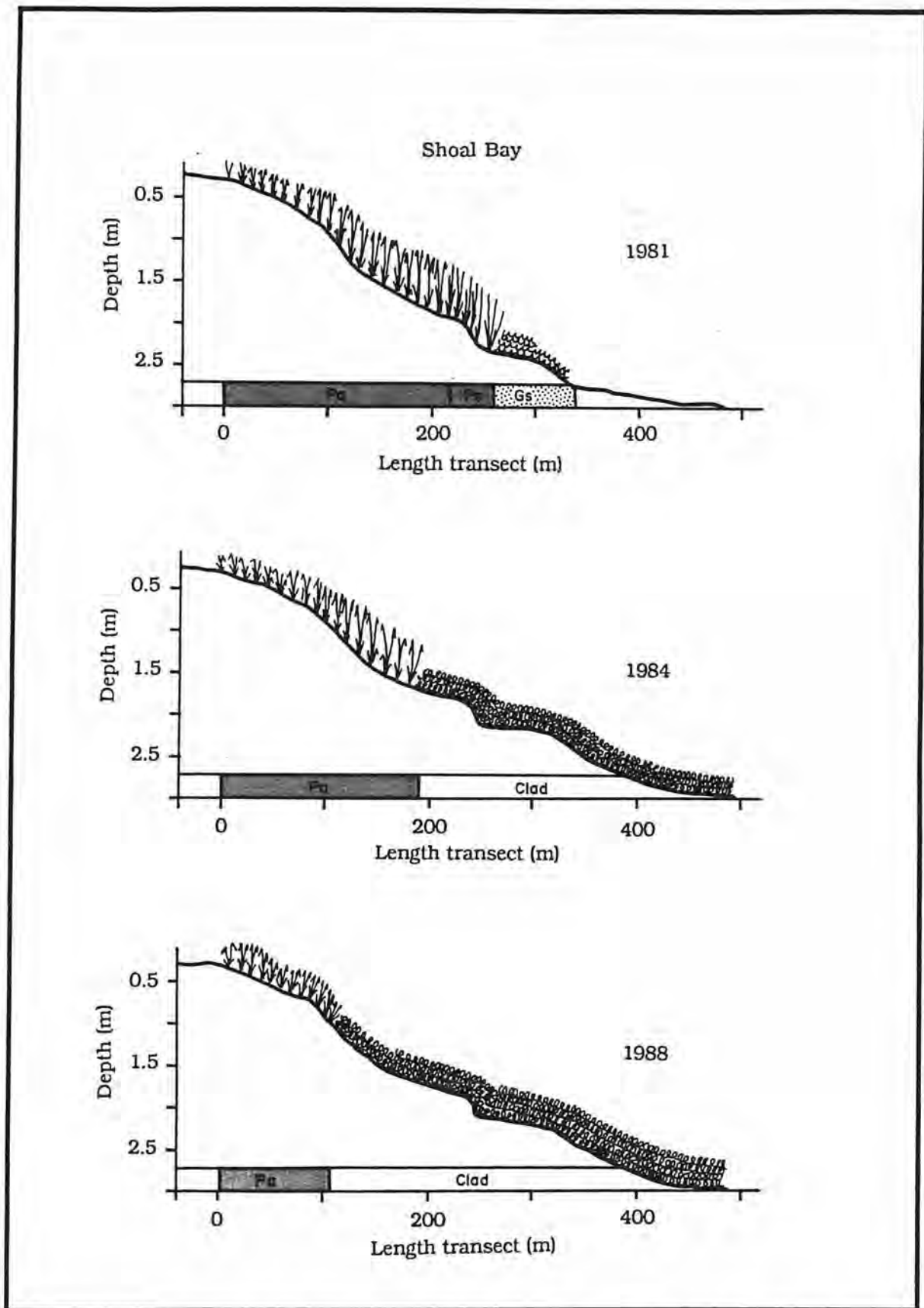


Figure 25. Transects of above-ground seagrass cover in Shoal Bay, Princess Royal Harbour, in 1981, 1984 and 1988

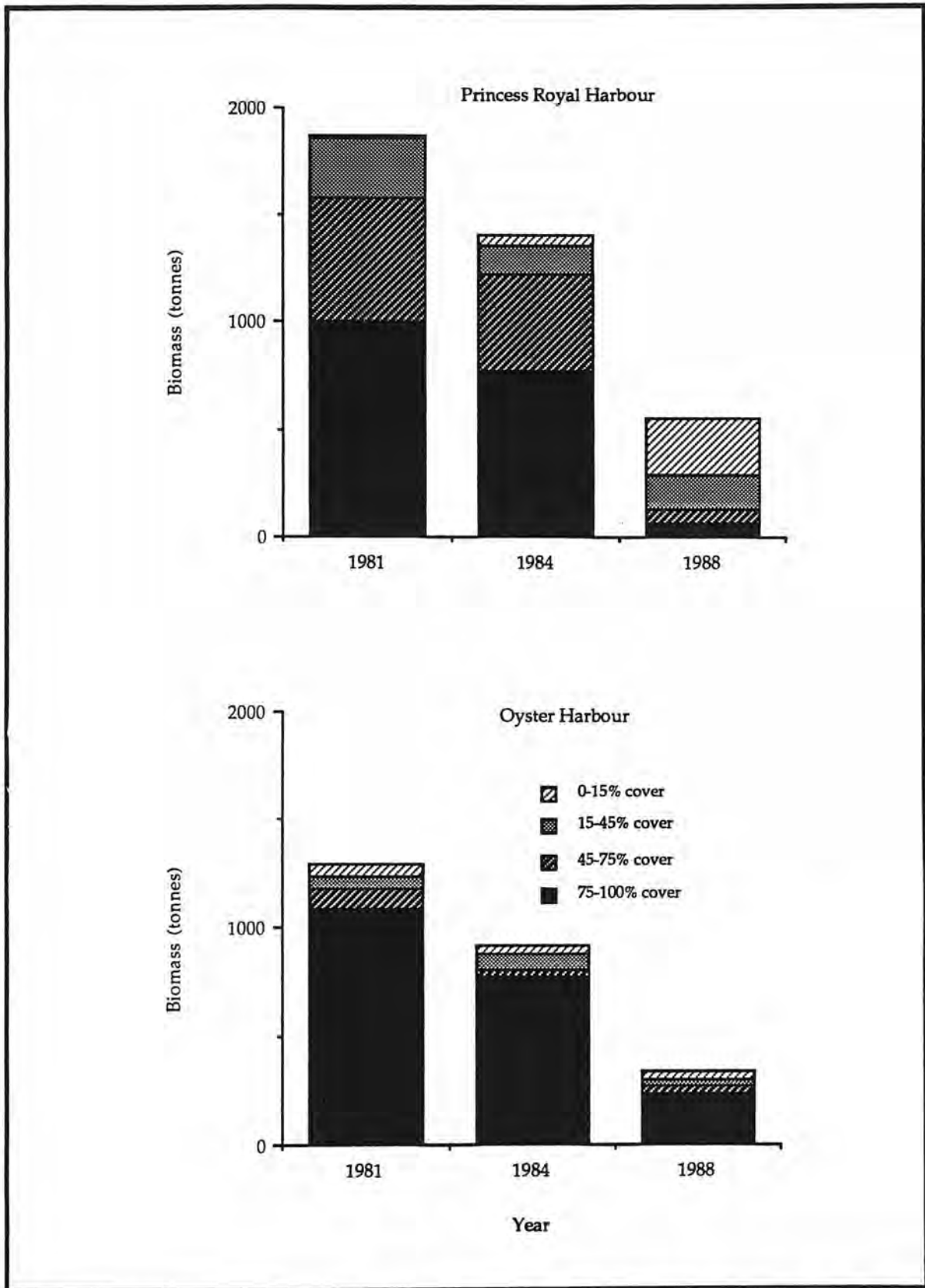


Figure 26. Cumulative histograms of the biomass of the areas occupied by the different categories of seagrass cover in Princess Royal Harbour and Oyster Harbour in 1981, 1984 and 1988

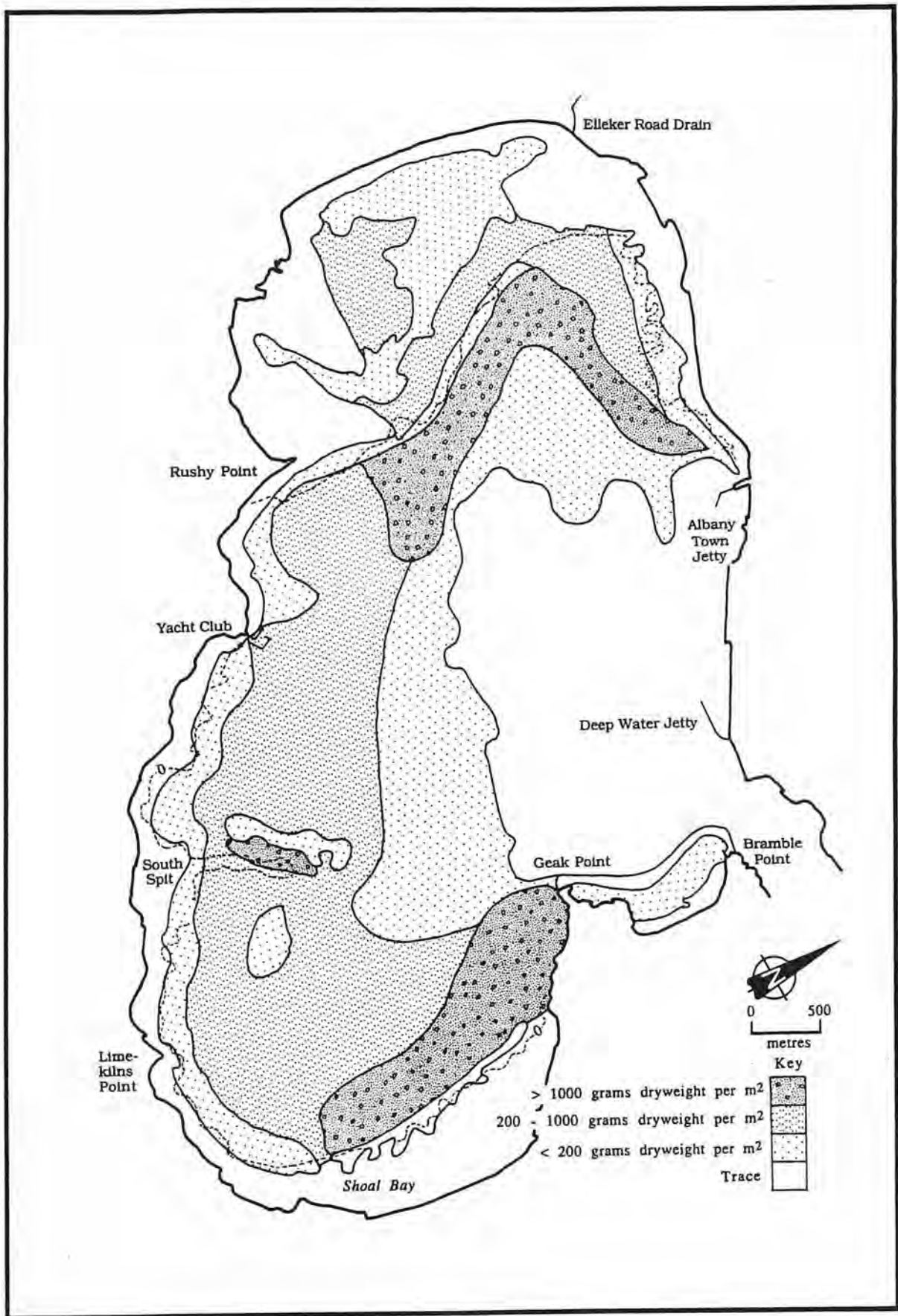


Figure 27. Distribution of macroalgae biomass in Princess Royal Harbour, February 1988

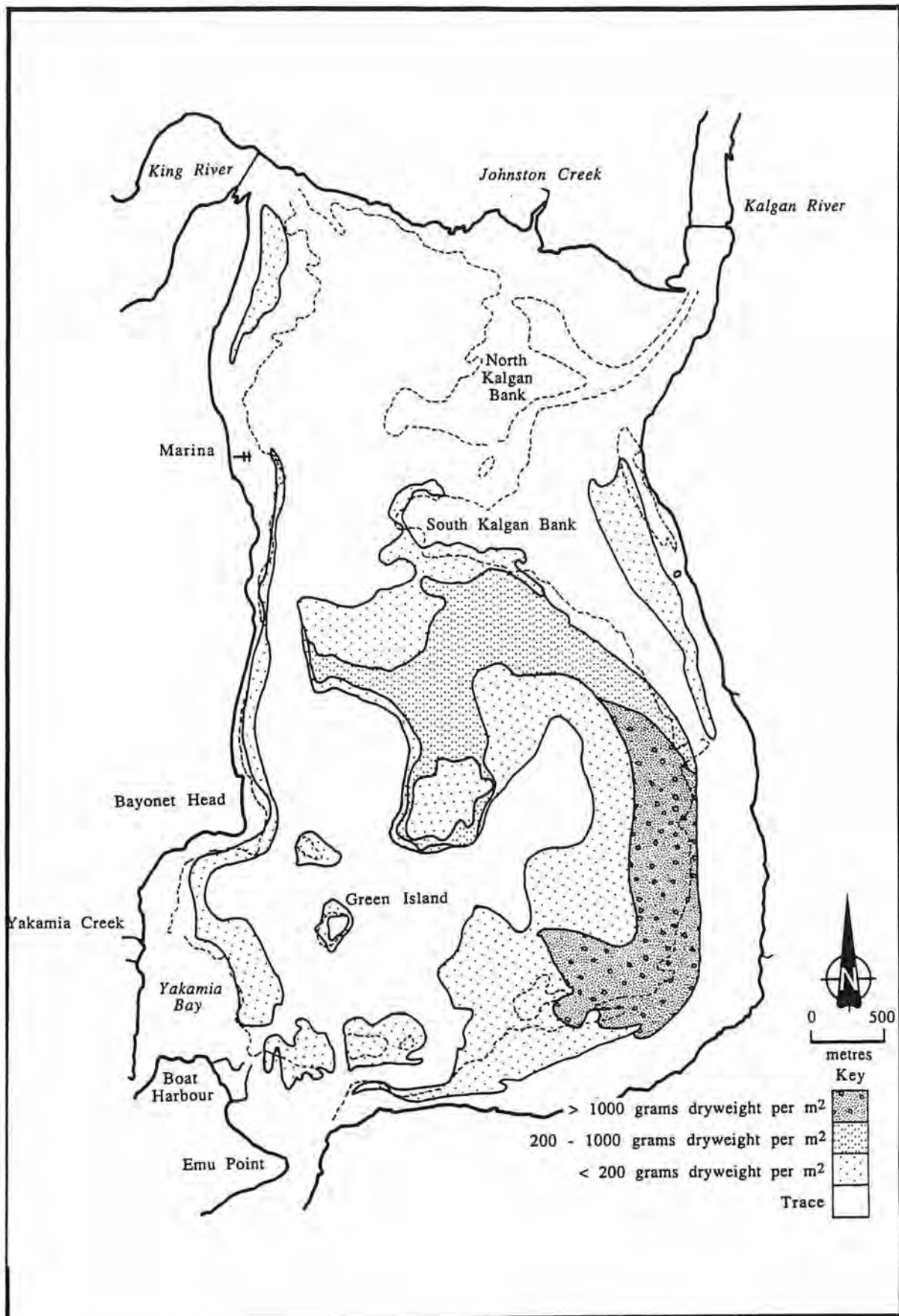


Figure 28. Distribution of macroalgae biomass in Oyster Harbour, February 1988

5. Summary and conclusions

1. Water quality in Princess Royal Harbour in February 1988 (this study) was better than in February 1979 (Atkins *et al.*, 1979), but no assessment can be made on whether water quality has improved as the data only represent one point in time. On the basis of Vollenweider's (1971) classification, both Princess Royal Harbour and Oyster Harbour are presently meso-eutrophic.
2. As is typical of south-western Australian estuaries and embayments, sediments in the two harbours were the largest nutrient pool, containing at least 80% of the total nitrogen and total phosphorus in both harbours.
3. The sediment nutrient concentrations in Princess Royal Harbour and Oyster Harbour were similar to those measured in other eutrophic estuaries in Western Australia, but data on the rate of nutrient flux from available forms for plant growth to unavailable forms is needed to better assess the extent of eutrophication in both harbours.
4. The distribution pattern of sediment nutrient concentrations did not appear to be linked to areas of seagrass dieback, areas of high epiphyte loads or areas of dense macroalgal accumulations.
5. The most dense beds of seagrass in the two harbours had significantly lower biomass than healthy beds in King George Sound. *P. australis* beds had a biomass of 324 g m⁻², 232 g m⁻² and 436 g m⁻² in Princess Royal Harbour, Oyster Harbour and King George Sound respectively, whilst the corresponding figures for *P. sinuosa* were 165 g m⁻², 188 g m⁻² and 309 g m⁻².
6. Epiphyte loads were sufficient to cause reduced primary production of seagrasses, but comparisons with other eutrophic coastal areas in Australia suggest these loads are not indicative of severely stressed meadows. However, the importance of epiphytes in causing the decline of the seagrass may have been underestimated in this study, due to the large interannual variation in nutrient loading to the harbours.
7. Data on epiphyte biomass, cover and carbonate content suggested that Princess Royal Harbour was more eutrophic than Oyster Harbour.
8. On the basis of the mapping exercises, the rate of loss of seagrass area in the two harbours has slowed since 1984, but the estimated rate of loss of seagrass biomass is still considerable, particularly in Princess Royal Harbour, as the losses that are occurring are mainly of the dense stands in shallow water.
9. Total macroalgal biomass was 11,650 tonnes dry weight and 1200 tonnes dry weight in Princess Royal Harbour and Oyster Harbour respectively. The biomass in both harbours was dominated by *Cladophora* sp. This species accounted for 86% of the total biomass in Princess Royal Harbour and 92% in Oyster Harbour.
10. Macroalgae were the largest plant nutrient pools in both harbours. The biomass of macroalgae was 13 times and 3.5 times that of above-ground seagrass in Princess Royal Harbour and Oyster Harbour respectively. Of the plant nutrient pools, macroalgae contained over 90% of the nitrogen and 69% of the phosphorus in Princess Royal Harbour and 61% of the nitrogen and 34% of the phosphorus in Oyster Harbour. Of the total nutrient pool associated with aquatic plants, macroalgae contained over 90% of the nitrogen and 69% of the phosphorus in the Princess Royal Harbour pool and 61% of the nitrogen and 34% of the phosphorus in the Oyster Harbour pool.
11. The relative magnitude of macroalgae as nutrient pools in ecosystems that were once dominated by extensive stands of seagrasses suggested that both harbours are eutrophic, Princess Royal Harbour more so than Oyster Harbour. When compared with data for other eutrophic ecosystems in Western Australia, the high mean areal biomass (406 g m⁻²) of macroalgae recorded for Princess Royal Harbour was also indicative of a highly eutrophic system.
12. Dense macroalgal accumulations (>1000 g m⁻²) were found in the south-eastern corner of both harbours, overlying areas where the most extensive seagrass dieback appeared to be occurring. Prevailing wind directions are such that these areas are the most sheltered and therefore are suitable for macroalgal growth and accumulation. Circulation patterns are also compatible with the accumulation of drift algae in this area of the harbours (Mills, 1987).

6. Hypotheses

1. The loss of seagrass in Princess Royal Harbour has been caused by the proliferation of seagrass epiphytes and macroalgae, caused in turn by an increase in nutrient loading from industrial, urban and rural sources in the last 25-30 years.
2. The present loss of shallow seagrass beds in the south-east sector of Princess Royal Harbour is being caused by macroalgal smothering: wind and water circulation patterns in the harbour cause macroalgae to accumulate in this area.
3. The lesser importance of seagrass epiphytes in Princess Royal Harbour found during this study compared to 1984, and the slowing of the rate of the areal extent of seagrass dieback since 1984, has been caused by several years of reduced nutrient loading. This has been the result of a reduction in nutrient input from industry, and reduced nutrient input from agricultural land in the catchment due to a succession of drier than average years. Data available at present does not allow the relative importance of these two sources to be assessed.
4. The loss of seagrass in Oyster Harbour has been caused by increased nutrient and sediment loads in the King and Kalgan Rivers in the last 25-30 years. This has been due to large-scale clearing and agricultural development of sandy duplex soils in the river catchments in the last 30 years. The increased turbidity of river inflow has resulted in a decrease in available light to the seagrasses in the northern half of the harbour which has caused the loss of seagrass from the deeper waters of this area. Nutrient enrichment has caused the proliferation of macroalgae, which wind and circulation patterns have caused to accumulate in the south-east sector, overlying and smothering shallow seagrass beds there.
5. The slowing of the rate of seagrass dieback in Oyster Harbour since 1984 has been caused by reduced sediment and nutrient loads from the King and Kalgan Rivers, due to a succession of drier than average years.
6. Pesticides, herbicides and other contaminants may have partially contributed to the seagrass dieback in both harbours, but the proliferation of macroalgae indicates that substances detrimental to aquatic plant physiology are unlikely to have been the major cause of the dieback. In the absence of hard data, the higher turnover rates and uptake rates of macroalgae compared to seagrass suggests that macroalgae would be, if anything, more sensitive to substances that interfere with their biochemistry.

7. Recommendations for further study

1. Studies should be carried out to examine the processes related to internal nutrient recycling in the harbours. The role of the sediments needs particular attention.
2. Investigations should be carried out on seagrass revegetation, especially using the smaller pioneer species such as *Halophila* and *Heterozostera*.
3. Epiphyte loads and macroalgae biomass should be assessed after a wet winter, as the results of the present study are only relevant for a dry winter.
4. The permanent transects should be re-surveyed annually, and if further significant losses of seagrass are indicated, seagrass mapping exercises should be carried out.

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