The Nutrient Status of Wilson Inlet 1982-1983

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The Nutrient Status of Wilson Inlet (1982-1983)

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FOREWORD

In any estuarine system it is quite normal for silt and nutrients to drain from river catchment areas and to accumulate in the slower moving estuary or inlet section. This is the process making estuaries so productive of plants, shellfish, fish, etc. Cycles of wetter or drier years may cause fluctuations in nutrient input, resulting in wide variations in plant growth within an estuary, but the general trend over the centuries is for our estuaries to shallow and for plant growth to increase.

Human settlement and activities can accelerate this process. The difficulty is to distinguish between natural oscillations which largely settle in time, and man-made effects which tend to cause a more permanent acceleration. To separate these two requires a great deal of data collected over a considerable time span.

The Denmark Shire Council wrote in January 1982 to the Minister for Conservation and the Environment expressing concern at the build up of weed in Wilson Inlet, and requesting that action be taken to monitor the condition of the Inlet. The first problem encountered was the paucity of historical data on the input of nutrients from river flow, and no measurements of the quantities of weed present. The first priority was to set up a pilot study to measure the nutrient input from rivers through a winter and the growth of weed through to the following summer. This was done under contract to the Department of Conservation and Environment during the winter of 1982 and the summer of 1982-83.

While one year's data are clearly insufficient to assess rates of change within Wilson Inlet, the greater experience gained from several years' study of the Peel-Harvey system enable the initial data from Wilson Inlet to be put into clearer perspective than would otherwise have been possible.

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SUMMARY

In response to the concern of local residents about the condition of Wilson Inlet, a study of the Inlet and its catchment was undertaken during the period 1982-1983. The aims of the study were to assess the current degree of eutrophication of the Inlet and to estimate the annual net retention or export of nutrients to or from the Inlet.

Streamflows and nutrient inputs from all the major streams and drains were measured during the winter months of 1982. During this period an estimated 5 tonnes of phosphorus and 42 tonnes of nitrogen entered the Inlet. However, the 1982 rainfall and runoff was well below the long-term means and in an average runoff year annual inputs would be of the order of 30 tonnes of phosphorus and 300 tonnes of nitrogen. The flow-weighted mean nutrient concentrations of streamflow for the catchment as a whole were 117 $\mu g\ l^{-1}$ phosphorus and 1070 $\mu g\ l^{-1}$ nitrogen.

One aim of the study was to identify areas within the Wilson Inlet catchment which are particularly prone to nutrient leaching. High nutrient losses to drainage were found to be associated with high rainfall and runoff, soils of low adsorption capacity, dense drainage and cleared agricultural land with a history of fertilizer application. The catchments possessing all these factors were the Sleeman, Cuppup and White Rivers and the southern extremity of the Hay River. The larger parts of the Denmark River and Hay River catchments (whose combined total areas comprise 89% of the Wilson Inlet catchment) lost very little nutrient to drainage due to their lower rainfall and runoff, small proportion of sandy soils and significant areas of uncleared land.

Wilson Inlet is showing one major symptom of eutrophication — the excessive amount of macrophyte growth. *Ruppia megacarpa* dominated ($>90\%$) plant biomass. Peak *Ruppia* biomass (~ 2200 g dry wt m^{-1}) was recorded in January. Peak total plant biomass in Wilson Inlet was estimated to be almost 16,000 tonnes dry weight.

Nitrogen concentrations in *Ruppia* tissue were relatively constant throughout the year, whereas tissue phosphorus concentration was inversely related to biomass. The data provide circumstantial evidence that phosphorus is more critical to the growth of *Ruppia* than nitrogen.

An assessment was made of the loss of nutrient due to bar opening and subsequent exchange with the ocean. Opening of the bar allowed the escape of estuary water to the ocean, and the amount of nutrient lost at the time of opening is governed by the height difference between the estuary and sea level. Subsequent exchange between the estuary and the ocean does not appear to be an important mechanism for nutrient loss, because the concentrations in the ocean are not very different to those in the estuary.

The amount of nitrogen and phosphorus lost from the system by bar opening and subsequent exchange are relatively small compared to the total amount of nutrient bound in plant material, especially in the summer months.

A nutrient budget was calculated for one cycle of bar opening and closing. Over this period there was a net retention of phosphorus in the Inlet but no gain of nitrogen.

INTRODUCTION

Aims of the Study

Residents in the Denmark area have expressed concern about the water quality of their estuary, some maintaining that this has deteriorated over the years. In particular, they draw attention to the large amount of 'weed' which grows in the shallows, where there are rotting accumulations in late summer when the water level falls. This suggests that there has been an increase in nutrient levels in the system, or eutrophication, which might be due to man's activities in the catchment or to alteration in the time of opening of the sand bar which, as discussed below, controls water and nutrient exchange between the estuarine basin and the ocean.

The aims of the study were to:

(i) Provide baseline data against which any future claims of major deterioration can be judged. Some caution is needed, because results of a short-term study will depend in part on the particular climatic conditions of the year under investigation. However, had similar monitoring information been available from 10 years or so ago, it would be much easier to assess the quality of the estuary at the present time.

(ii) Estimate nutrient input to the system from river flow.

(iii) Estimate the nutrient load of the water column, plant biomass, and surface sediments and compare this to the magnitude of nutrient inflow.

(iv) Estimate the total loss of nutrients from the system to the ocean during bar opening.

(v) Assess the degree of eutrophication of the Inlet at the present time.

The Study Area

Wilson Inlet lies on the south coast of Western Australia (Figure 1). The Inlet has an area of 48 km^2 and is 14 km long, east to west, and about 4 km wide (Figure 2). The Inlet is fed by two main rivers, the Denmark River and the Hay River, and three small rivers, the Sleeman River, Cuppup Creek and Little River. The western and northern margins of the Inlet are mainly rocky (granite) shores and the eastern and southern margins are sandy beaches.

No hydrographic chart is available for Wilson Inlet, and the only available data on the bathymetry of the Inlet is a map prepared by geography students from The University of Western Australia (Figure 2). The mouth of the Inlet is at the extreme western end and it is completely blocked by a massive sand bar for about seven months of the year (usually from January to July). Following closure of the bar, evaporation may reduce water levels considerably; the annual non-tidal variation in water level may exceed 2 m (Hodgkin, 1981), with up to 1.0 m being lost by evaporation.

The Inlet is, of course, tideless when the bar is closed. At this time changes in water level are caused by river runoff, direct rainfall on the Inlet, evaporation and wind. Lenanton (1974) states that wind waves produced by NE or SW winds blowing along the long axis of the Inlet may reach 1.2 m in height. After opening the bar, Wilson Inlet becomes tidal for 3–5 months each year, and marine water from the Southern Ocean intrudes and mixes with that of the estuary. Tidal influence is greatly affected by the position and dimensions of the channel through the bar. Marine astronomic tides have a small range (1.2 m maximum), and sea level changes due to longer-term forcing, such as changes in atmospheric pressure and shelf waves, often exceed the astronomic tide. The diurnal tides within the Inlet are severely attenuated by the bar, and are mostly very small ($<$10 cm).

Before the 1930's, the sand bar across the entrance to Wilson Inlet broke naturally when the accumulated winter runoff eventually ran over the top and scoured a channel to the sea. This always occurred on the western side of the bar, near the calcarenite cliffs. In the 1930's the Elleker-Nornalup railway was realigned close to the shoreline of Wilson Inlet. From this time until the removal of the railway line in 1958 it became necessary to artificially open the sand bar when the water level reached 1.015 m (A.H.D.), measured on a gauge at the town bridge, to avoid flooding the railway line. Later, potato farms were developed on the reclaimed land, providing another reason for restricting the water level in the Inlet. More recently, permanent roads and homes have been built close to the shores of the Inlet. It is therefore unlikely that the water level in the Inlet will ever be allowed to reach natural levels again.

The restriction placed on the water level in the Inlet has resulted in a reduced scouring action which has allowed the accumulation of a massive sand bank of marine origin behind the sea bar. In 1961 the Denmark River was dammed, and this reduced the flow of water into the Inlet, presumably contributing further towards reducing the scouring effect of water flow through the channel.

The position of the channel cut in the bar has been a subject of much discussion. Many advocate opening the bar at its western end where formerly the channel cut naturally. Lenanton (1974) advocates cutting the channel on the eastern side of the bar at the point which is the shortest distance between deep estuary water and the ocean, to allow for maximum exchange.

The dates, duration and position of the opening of the bar, from 1954 to the present, are given in Table 1.

The little that is known about the aquatic fauna and flora of the Inlet has been documented by Lenanton (1974), Hodgkin (1981) and Humphries *et al*. (1982).

Climate

The climate is typically mediterranean with mild, wet winters and warm to hot, dry summers. In moving inland from the coast there is a distinct gradient in meteorological variables. Mean annual rainfall decreases progressively from 1200 mm at Denmark in the south-west of the Wilson Inlet catchment to 700 mm in

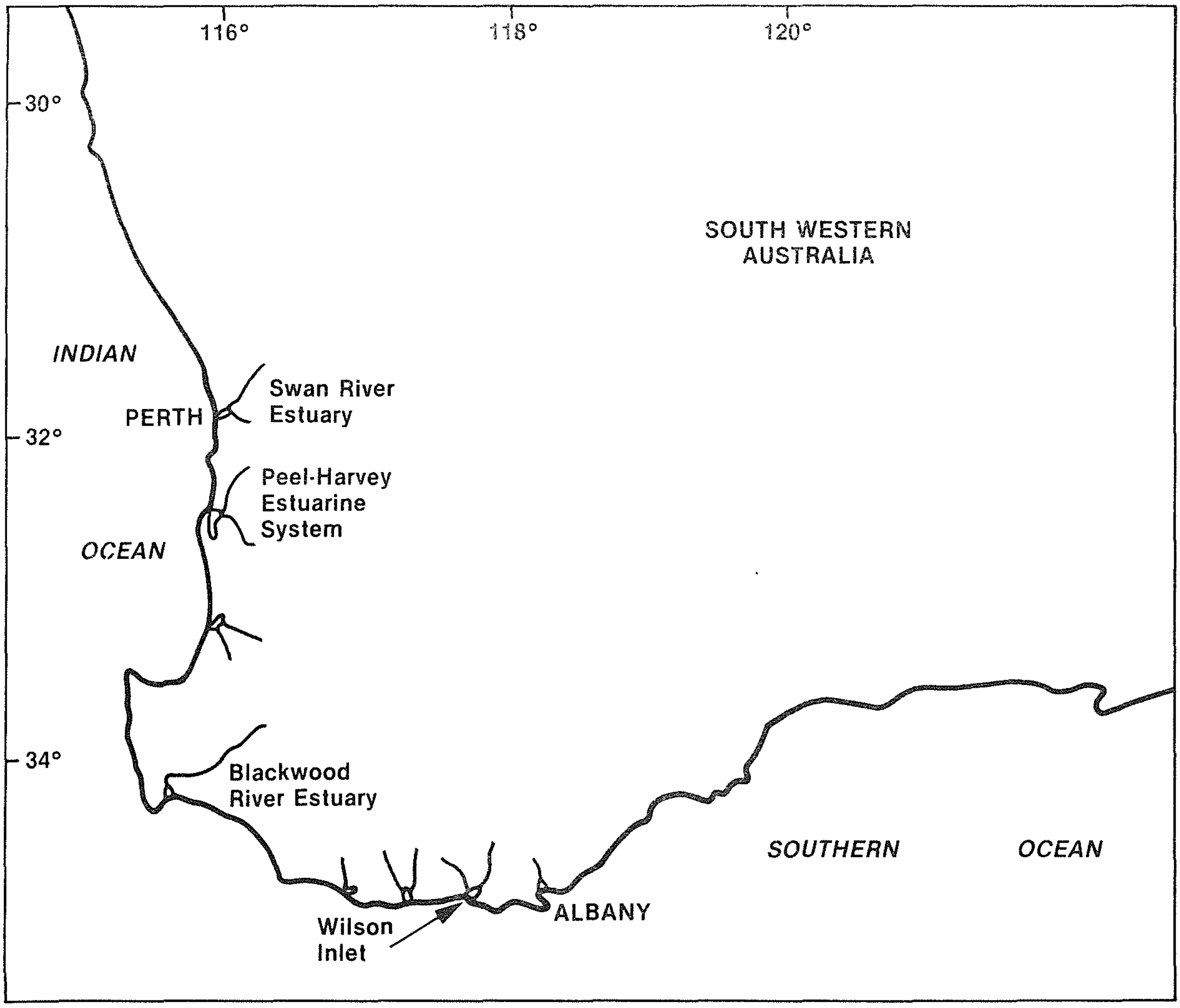


Figure 1. The location of Wilson Inlet in south-western Australia

the north of the catchment, in the region of Mount Barker (Figure 3). Conversely, mean annual class A pan evaporation increases from 1200 mm to 1500 mm across the same transect (Figure 4). Based on the figures for Albany (Figure 5), the closest long-term evaporation station, 74% of rain falls during the winter months of May to October and 69% of pan evaporation occurs during the summer months November to April. Average monthly rainfall exceeds average monthly pan evaporation for five months of the year, namely May to September (Figure 5).

Annual and seasonal climatic variations are primarily caused by fluctuations of the sub-tropical anti-cyclone belt. Most pressure patterns generate on-shore winds over the coastal zone which consequently enjoys a mild, humid climate. Further inland, however, the weather conditions become a little more severe and variable. The gradients of some climatical variables across the Denmark and Kent River basins are shown in Collins and Fowlie (1981; Table 1). The hydrometric network for the Wilson Inlet catchment is detailed in Humphries *et al.* (1982) and Collins and Fowlie (1981). Additional evaporimeters and pluviometers were located at Crusoe Island (in the Inlet) and at the Denmark Agricultural Research Station. A stage recorder was also installed and operated by the Public Works Department (Albany office) near the mouth of the Denmark River for the study.

Catchment and Drainage Characteristics

The Wilson Inlet catchment covers an area of some 2263 km^2. The boundaries of its principal subcatchments and their drainage networks are shown in Figure 3. The areas of the individual catchments and their drainage lengths and densities are given in Table 2. The catchments of the two major rivers, the Denmark and the Hay, comprise 89% of the total Wilson Inlet catchment area. The drainage densities are very similar for all the Wilson Inlet catchments.

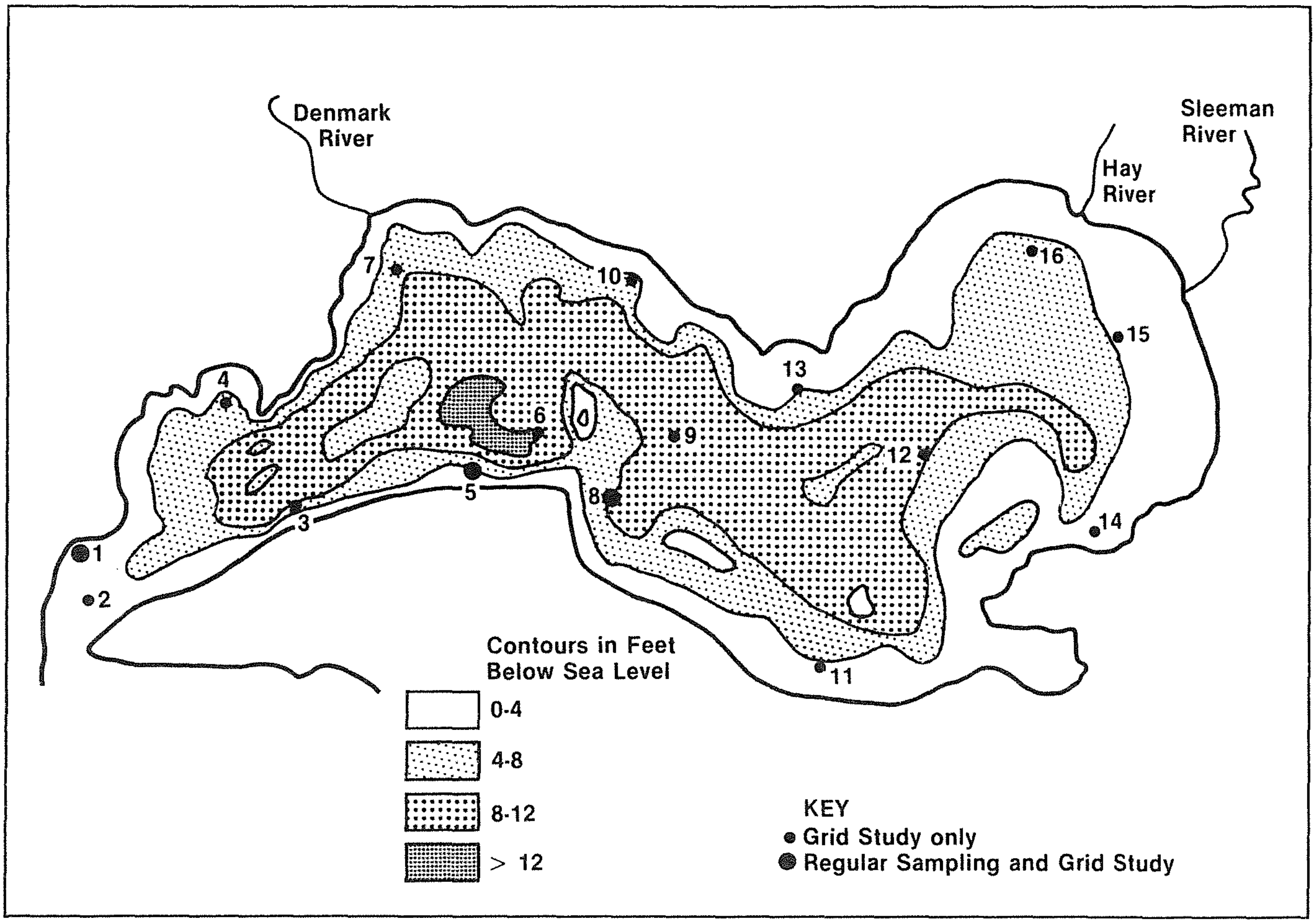


Figure 2. Bathymetry and location of sampling sites

Table 1. Channel through the Wilson Inlet sand bar: opening and closing dates, duration and position of opening[1]

Year	Opening Date	Closing Date	Period Open (Days)	Position of Opening
1954	N.A.[2]	N.A.	—	West Side
1955	15 June '55	N.A.	—	" "
1956	10 June '56	N.A.	—	" "
1957	8 August '57	N.A.	—	" "
1958	7 August '58	28 December '58	147	" "
1959	Bar Not Open	—	—	—
1960	12 July '60	5 January '61	177	" "
1961	4 July '61	24 December '61	173	" "
1962	17 August '62	24 January '63	160	Middle to East Side
1963	4 July '63	19 January '64	199	" "
1964	22 July '64	N.A.	—	" "
1965	24 August '65	N.A.	—	" "
1966	27 July '66	N.A.	—	" "
1967	18 July '67	April '68	277 ± 15	" "
1968	1 August '68	14 February '69	198	" "
1969	1 September '69	22 December '69	113	" "
1970	2 August '70	22 February '71	204	" "
1971	16 July '71	4 March '72	231	West Side
1972	10 August '72	10 December '72	122	" "
1973	13 August '73	14 February '74	185	" "
1974	5 August '74	N.A.	—	" "
1975	30 July '75	February '76	~199	" "
1976	6 July '76	February '77	~223	" "
1977	7 August '77	February '78	~191	" "
1978	30 June '78	2 March '79	246	" "
1979	16 July '79	February '80	~213	" "
1980	1 August '80	24 January '81	176	" "
1981	3 July '81	8 March '82	248	" "
1982	21 July '82	10 September '82	51	" "

[1] Sources of information: Public Works Department, Harbours and Rivers Section, Albany District Office; Department of Fisheries and Fauna File 142/51.

[2] N.A. = Not Available

Table 2. The areas, drainage lengths and drainage densities of the principal Wilson Inlet catchments

Catchment	Area km^2	Area %[1]	Drainage length (km)	Drainage density (km km^{-2})
Denmark River	708	31.3	229.0	0.32
Hay River	1301	57.5	450.8	0.44
Sleeman River	88	3.9	38.3	0.43
Cuppup River & White River	73	3.2	30.5	0.42
Lake Sadie Dr.	47	2.1	15.0	0.32
Little River	17	0.8	9.2	0.52
Nullaki	28	1.3	—	—
Wilson Inlet	2263	100		

[1] % of whole catchment for Wilson Inlet.

The Denmark and Hay Rivers progress through a sequence of valley forms, from their origin to the Inlet, which is characteristic of many of the rivers which drain the south-western marginal areas of the Great Plateau of Western Australia. Neither river extends so far inland as to connect with the salt lake chains of the interior, but rather they originate on the southern margin of the Great Plateau which slopes gently towards the Southern Ocean. The headwaters are broad, flat and swampy but the river valleys become increasingly incised downstream. Deeply incised, V-shaped valleys are evident close to where the rivers debouch onto the coastal plain. On the coastal plain itself, the stream gradients are small and flow is sluggish. In addition, the high water level of the Inlet (prior to the sand bar opening) causes water to back-up several hundred metres in rivers and as much as 5 km in Lake Sadie drain.

Landforms, Vegetation and Land Use

The area is underlain by a basement of pre-Cambrian gneissic and granitic rocks which have been intruded by younger porphyritic granite batholiths. These intrusions form massive granite outcrops which dominate the landscape. Near the coast they form headlands with embayments of lower country between them. The plateau itself is extensively laterized, showing typically a gravelly-sandy soil and/or duricrust overlying a deep pallid clay horizon and weathered parent material which form soil profiles as deep as 50 m.

As mentioned previously, the landforms exhibit a characteristic progression along the drainage lines from their inland divides to the coastal plain. Broad, flat, swampy headwaters progress to deeply incised, V-shaped valleys which have dissected the ancient lateritic landscape to expose various weathered and unweathered materials. As a result, the interfluves are extensively occupied by the laterite mantle whereas the valleys show morphology and soils dependent on the degree of stripping of the weathered profile, the geology of the bedrock, the amount of local relief and the colluvium on slopes.

The coastal plains are underlain by a thin sequence of sedimentary rocks which consist mainly of spongolite with some limestone. Climatic fluctuations in the quaternary led to changes in the sea level with periodic deposition of beach sands.

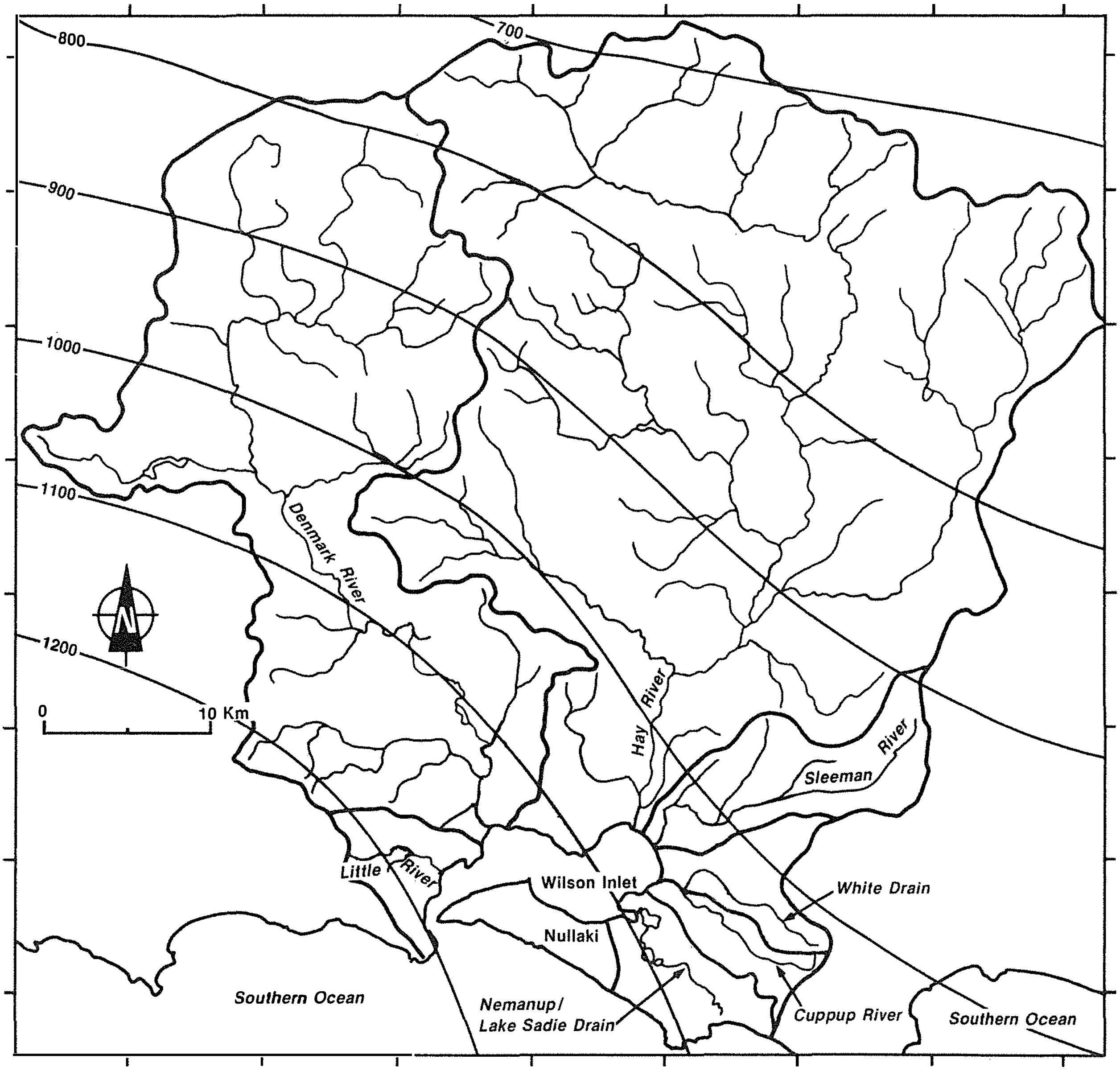
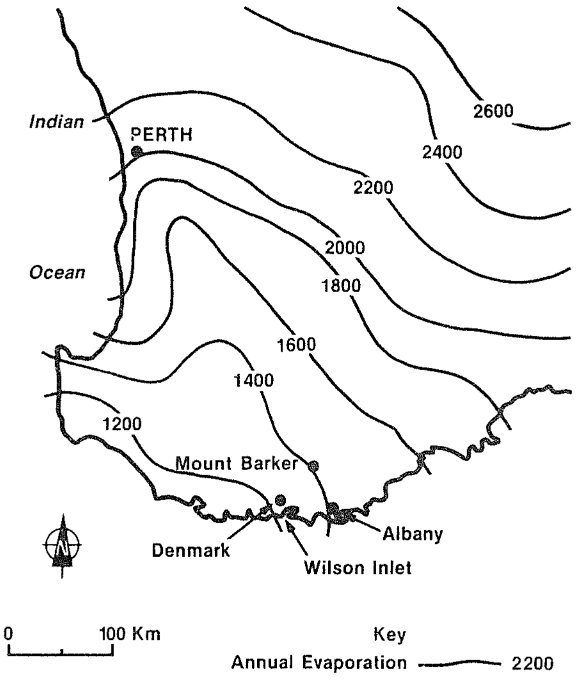


Figure 3. Rainfall isohyets, drainage and catchment boundaries for Wilson Inlet Catchment



Source: Department of Science
Bureau of Meteorology

Figure 4. Class A pan evaporation contours from south-west Western Australia

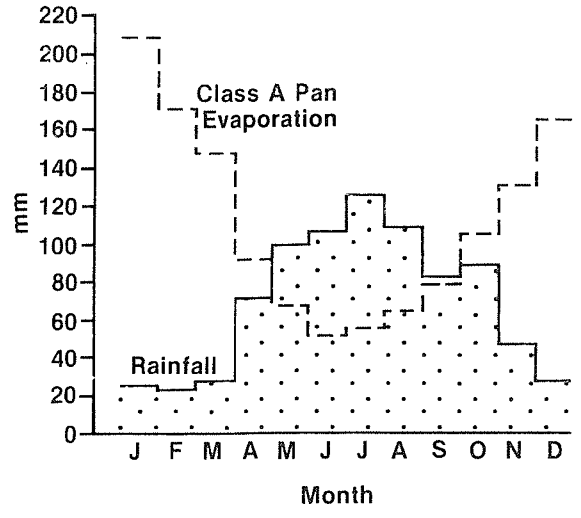


Figure 5. Long-term mean rainfall and evaporation at Albany

Dunes formed in low parts of the coastline and were blown inland. Most of the south coast is currently mantled with a belt of stabilized dunes which typically extend 2 to 3 km inland. The latest sands are calcareous (up to 67% $CaCO_3$, Enright, 1978) with little consolidation. The dunes frequently impede drainage, entrapping a belt of lakes and swamps behind them. Inland, the aeolian sands support heath vegetation. Under the high rainfall coastal conditions the sands often form duplex soils, with leached upper horizons and mottled clay B-horizons. In the broad valleys characterized by swampy depressions, the sandy soils show peaty horizons. These soils tend to be highly infertile.

A generalised set of landform units and land tenure classifications have been defined by Collins and Fowlie (1981) for the area. These are discussed in the following with respect to the principal Wilson Inlet catchments.

The Denmark River catchment is dominated by the upland lateritic formations of the Darling Range where jarrah forest (*Eucalyptus marginata*) predominates. Only 22% of the catchment has been cleared for agricultural use. The first order streams are characterized by sandy, swampy flats comprising leached sand or podzolic or solodic soils, vegetated by paperbark (*Melaleuca* spp) swamps, dense scrub and scattered trees. Further downstream the valleys become moderately incised and are characterized by gravelly yellow podzols and red earths. These alluvial valleys support jarrah - marri (*E. calophylla*) forest. Towards the south two landform units are evident. One comprises deeply incised valleys and steep slopes with podzolic soils upslope, red-earths mid-slope and alluvium in the valleys. Here karri (*E. diversicolor*)-marri forest predominates. (Karri forest is found on loamy soils derived from granite outcrops in the high rainfall zone where mean summer rain exceeds 300 mm). The second type is the rolling, dissected lateritic country characterised by gravelly ridges but mainly yellow podzolic soils. Jarrah occupies the ridges whilst wandoo (*Eucalyptus wandoo*) and swamp yates occur in the valleys. This area is used mostly for sheep and wool production with some oats and barley cropping.

The Hay River catchment is in many ways quite dissimilar to the Denmark River catchment. It is dominated by two landform types. The west is characterised by rolling, dissected lateritic country which eventually merges into the lateritic uplands. The eastern part of the catchment (and also the Sleeman River catchment) comprises lateritic sandplain swamps and plains with gravelly ridges. The lower relief results in swampy flats surrounding the stream channels. The soils are predominantly leached sands and yellow mottled soils which support jarrah scrub, yates and sandplain heaths. Fifty-three per cent of the Hay River catchment has been cleared for agricultural use.

The coastal plain is drained by Little River west of Wilson Inlet, and the Cuppup and White Rivers and Nemanup-Lake Sadie drain east of the Inlet. These catchments consist of swampy coastal plains with some dune formations. The soils support peppermint thickets, sand heaths and sedgelands. The sandy plains are used for beef production on improved pastures whilst the loamy red earths associated with granite outcrops support potato, fruit and vegetable growing, with some dairying on summer growing pastures.

Streamflow and Water Quality

Long-term annual rainfall and runoff are shown for the Denmark and Hay Rivers in Figures 6 and 7. In the case of the Hay River, the runoff values are estimated. Table 3 summarizes the mean annual runoff and rainfall values and the runoff:rainfall ratios for the two stations. Runoff is seen to be a small proportion of rainfall (7%) as is typical of forested catchments in the intermediate and low rainfall zones (1100–900 mm, 900–700 mm respectively) of the south-west region. A longitudinal profile of rainfall and runoff distribution for the Denmark River catchment (Figure 8) shows runoff peaking and then decreasing almost proportionately to rainfall with distance from the coast. The mean monthly distribution of streamflow (Figure 9) from the Denmark River shows that 80% of runoff occurs during the four winter months of July to October.

Table 3. Mean annual rainfall and runoff values for Denmark and Hay Rivers

Station	Denmark 603.136	Hay
Upstream % catchment area	83	97
Mean rainfall (mm)	960	830
Mean runoff (mm)	70	60
Runoff/rainfall	7.4%	7.2%

The Denmark River is the only significant water resource in the Wilson Inlet catchment and currently supplies the Denmark township from the Denmark pipehead dam. In order to protect this water resource, alienation of Crown land was curtailed in the Denmark catchment in 1956 and legislation to control clearing was enacted in 1978.

A surface water salinity assessment of the area was undertaken by the Public Works Department in 1978/79. From intensive subcatchment sampling, a map was composed of flow-weighted mean concentration of total soluble salts (Map 5, Collins and Fowlie, 1981). The high stream salinities in the north-eastern portion of the Wilson Inlet catchment indicate the presence of native forest clearing in intermediate and low rainfall zones with high soil salt storage.

Sediment concentrations in the streams are generally very low (Collins and Fowlie, 1981) and approach the limit of accurate determination (concentrations are frequently below 5 mgl^{-1} with only sporadic higher occurrences). Turbidity values are also generally low, but true colour values are high as most streams traverse reaches of swamp where they become discoloured with organic material. The pH values are generally neutral or slightly acidic.

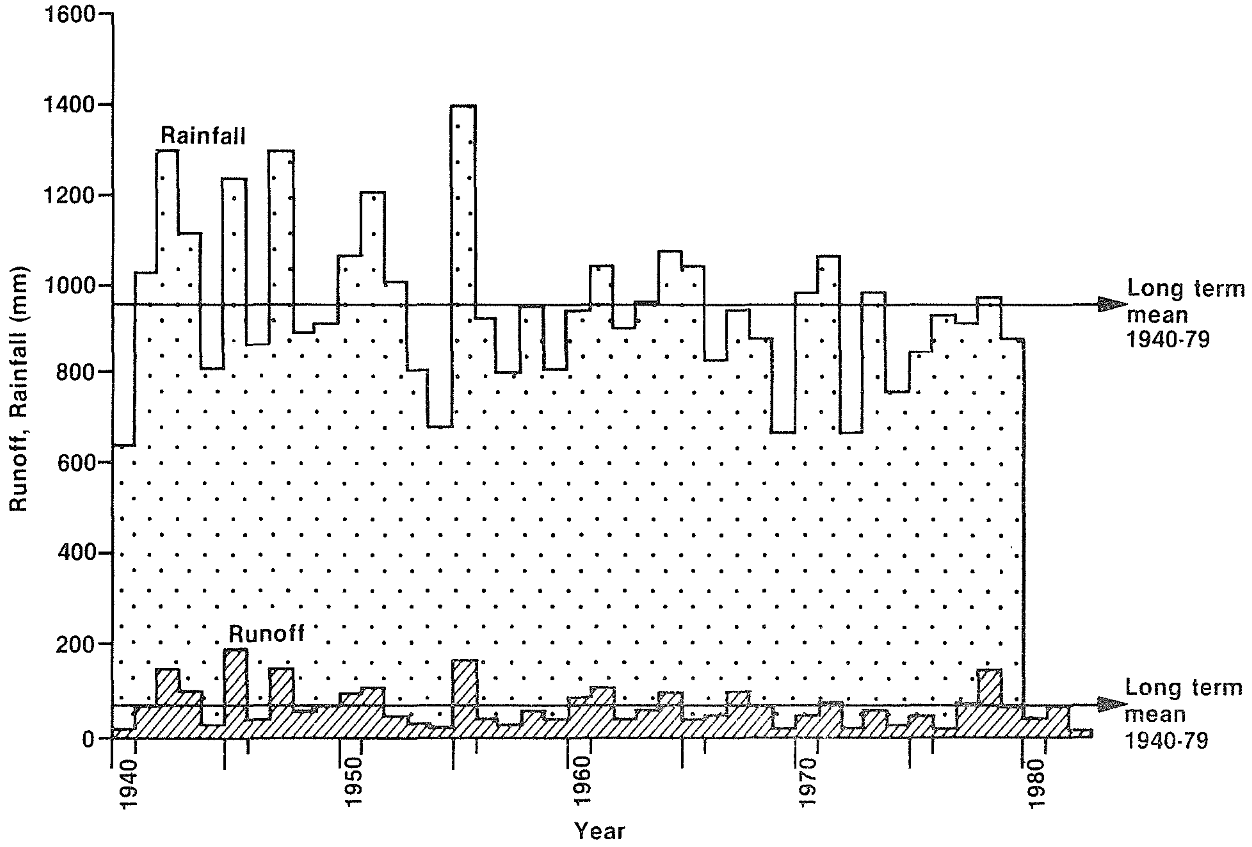


Figure 6. Denmark River long-term annual rainfall and runoff (adapted from Collins and Fowlie, 1981)

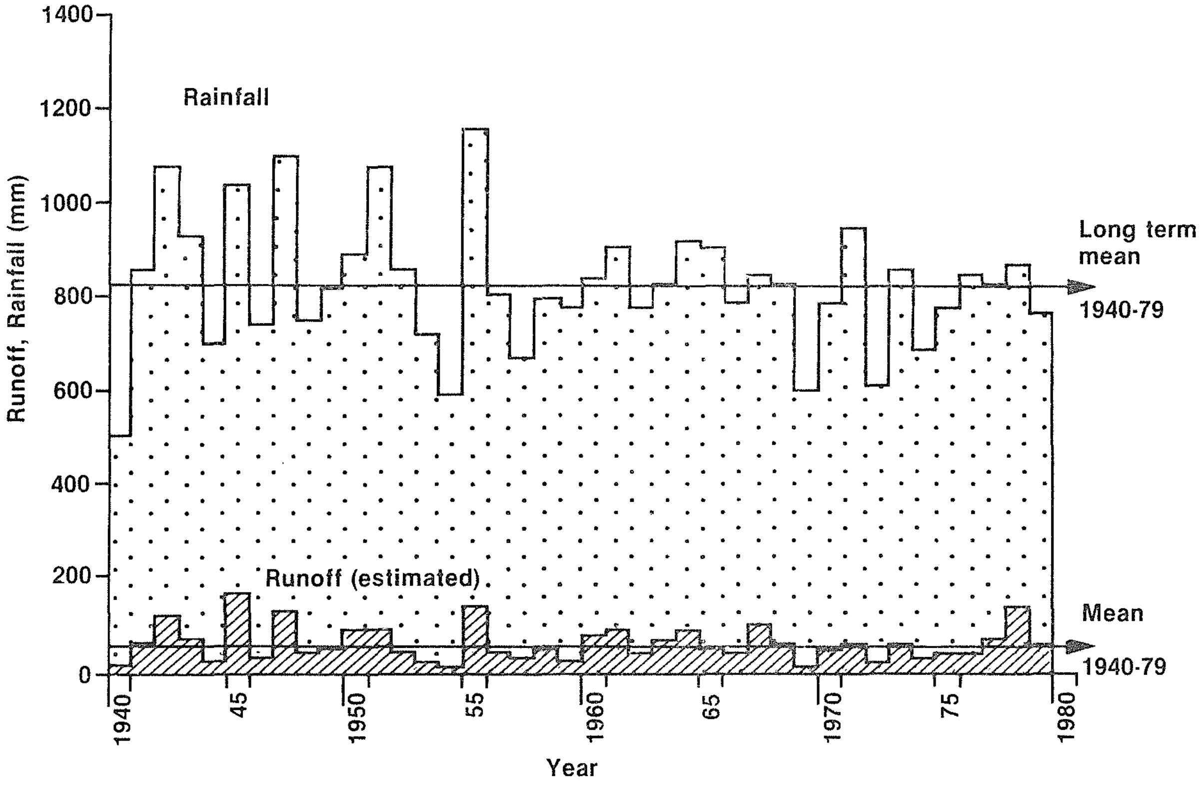


Figure 7. Hay River long-term annual rainfall and runoff (adapted from Collins and Fowlie, 1981)

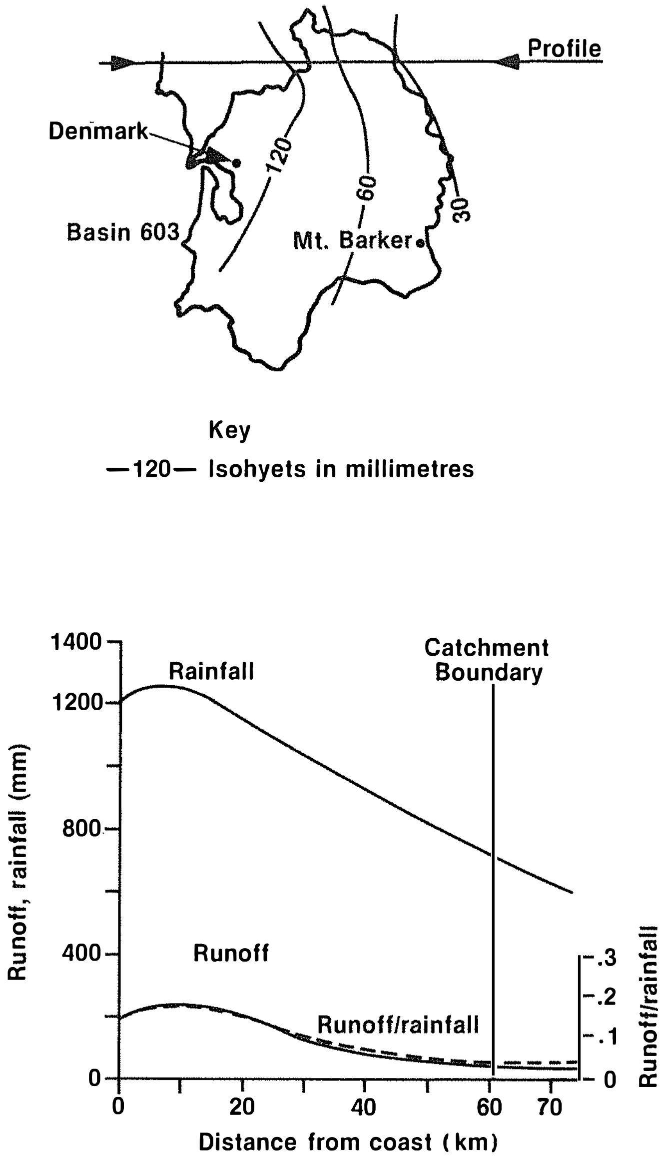


Figure 8. Longitudinal profile of rainfall and runoff across Wilson Inlet catchment (adapted from Collins and Fowlie, 1981)

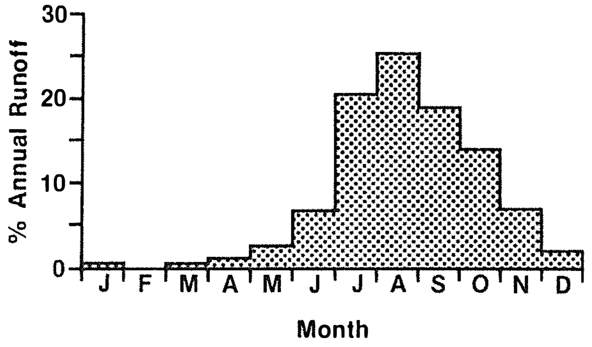


Figure 9. Denmark River monthly distribution of flow

MATERIALS AND METHODS

Water Samples

Samples were taken at three sites in the Inlet (Figure 2) at approximately 6 weekly intervals. The information from these regular sites was supplemented by three intensive sampling surveys (Grid studies) carried out at 16 sites on 14 July 1982, 1 December 1982 and 27 April 1983. 'Surface' water samples were collected approximately 10 cm below the surface using a one litre polyethylene bottle (Duranol Plastics Pty. Ltd., Melbourne, Aust.). 'Depth' samples were collected 10 cm from the bottom by diving. Samples were immediately placed in 150 ml sealable polyethylene bags (''Whirlpak'', NASCO, Kansas, U.S.A.), placed on ice, and frozen on return to the laboratory.

Temperature and salinity were recorded using an Auto-Lab portable Salinity-Temperature Meter (Model 602, Hamon, Autolab, Sydney) calibrated with standard seawater (Standard Seawater Service, Charlottenlund, Denmark). Dissolved oxygen was measured using a meter (Model 603, Yeo-Kal Electronics Pty Ltd, Australia). Per cent saturation was calculated using temperature-salinity records for the site and an oxygen solubility nomograph (Strickland and Parsons, 1972).

Secchi disc readings were taken with a 20 cm disc painted with black and white quadrants, and readings were always taken on the unshaded side of the boat.

Ammonia-nitrogen was measured on unfiltered water samples by the isocyanurate method (Dal Pont *et al.*, 1974). Nitrate plus nitrite-nitrogen was determined after copper-cadmium reduction with a Technicon Autoanalyser II (Technicon Industrial Systems, Terrytown, New York).

Organic nitrogen was determined by Kjeldahl digestion (concentrated sulphuric acid in the presence of a mercury catalyst, Anon. 1971), using a programmable block digester (Windrift Instruments, Welshpool, Australia). The resulting total ammonia was then determined using the autoanalyser (Technicon Industrial method 376-75 W/B, Technicon Industrial Systems, Terrytown, New York). The free ammonia concentration of the sample was then subtracted from the total ammonia concentration to give 'organic' nitrogen.

Orthophosphate was measured colorimetrically by the single solution molybdenum blue method (Major *et al.*, 1972). Total phosphorus was measured by digestion of water samples with a 1:1 mixture of concentrated nitric and perchloric acid and analysis of the resulting total orthophosphate using the single solution method (Anon. 1971; Major *et al.*, 1972; McGlynn, 1974). These samples were filtered in the field through 0.45 μm filters (Millipore Corp., Mass., U.S.A). 'Organic' phosphorus was calculated from the difference between total phosphorus and orthophosphate present in undigested samples.

Plant Material

Water samples for chlorophyll 'a' analysis were collected in one litre polyethylene bottles (Duranol), stored on ice, filtered through GFC-filter papers (pore size 1.2 m, Whatman Ltd., England) within 24 hours of collection and frozen. The filters were ground and chlorophyll measured spectrophotometrically (Varian 634S spectrophotometer, Varian Techron Pty. Ltd., Springvale, Australia) using the method for chorophyll 'a' of Strickland and Parsons (1972).

Samples for plankton identification were collected using a 20 μm plankton net, preserved with formalin (6‰), and stored in the dark.

Plant biomass was estimated by harvesting replicate (five at each regular site, two at each grid study site) quadrats (0.1 m^2) using SCUBA. Samples were returned to the laboratory, washed of adhering sediments, different taxa separated, and *Ruppia* sorted into above- and below-ground parts and oven-dried at 80°C. Resulting dry weights were converted to grams per square metre. Cover was assessed directly by diving at each site and expressing the area of plant cover as a percentage of the total visible area.

Samples for tissue N and P analysis were milled, replicates bulked, and 200 mg subsamples assayed for total tissue P (Strickland and Parsons, 1972) following digestion in concentrated nitric and perchloric acids. Total tissue N was measured using the autoanalyzer (Technicon Corp, Terrytown, N.Y., method 334-74 W/B) after digestion in concentrated sulphuric acid in the presence of a mercury catalyst.

Sediment

Sediment samples were collected using a 64 mm diameter Perspex corer. The top 4 cm from five replicate cores was bulked and subsampled. Samples were stored on ice in the field and at 4°C in the laboratory until analysed.

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

Extractable N and P were determined on aliquots of 2M NaCl extract. 20 g of wet sediment was transferred into 250 ml graduated cylinders and brought to 220 ml with 2M NaCl, inverted ten times and allowed to settle for one hour, centrifuged, filtered through 0.45 μm Millipore filters, and analysed for orthophosphate, ammonium and nitrate-nitrite nitrogen as outlined above.

Total phosphorus was determined as orthophosphate by the ascorbic acid-molybdate method (Strickland and Parson, 1972) after perchloric acid digestion. Total nitrogen samples were digested in concentrated sulphuric acid in the presence of mercury catalyst and analyzed by autoanalyser (Technicon methods No. 334-74W/B and No. 369-75A/B).

Two core samples were sub-sampled for sediment chlorophyll analysis by pushing the mouth of a No. 16 Duranol vial, which had a small hole drilled in the bottom, down into the sediment core. The vials were immediately placed on ice, and frozen on return to the laboratory.

Chlorophyll analysis was carried out on the top 10 mm of the frozen core. The sediment was ground in a mortar for 60 seconds and 50 ml of acetone was added. The sediment suspension was placed in a screw cap glass jar and left to extract in the dark for 24 hours at 4°C. A sub-sample (8 ml) was removed and centrifuged for eight minutes at 3500 r.p.m. to settle any particulate material. Chlorophyll 'a' determinations were made following methods outlined above, making adjustments where necessary in the calculations. The results are expressed as the amount of chlorophyll per unit area or gram dry weight of sediment.

Calculations

Linear correlations and stepwise multiple regressions were performed using SPSS programmes (Nie *et al.*, 1975). Mapping was done using a SYMAP programme (Dougenik and Seehan, 1977). Total water column nutrient and chlorophyll 'a' load, plant biomass, plant tissue nutrient load, and sediment nutrient and chlorophyll 'a' loads were estimated from planimetry of computer drawn maps of the amount expressed per unit area. A digitizer (Model 2000, Summagraphics Corp.) 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.

Estimates of Streamflow and Nutrient Input

A programme to quantify the inflow of nutrients to Wilson Inlet during the main runoff months of 1982 was undertaken on limited financial resources. Only one gauging station, located at Mount Lindsay gorge on the Denmark River (P.W.D. ref. no. 603 136), was in operation at the time of the study. Thus the establishment and running of a viable field programme was reliant on the enthusiastic help of the Denmark Shire Council and local volunteers.

Early in 1982 temporary gauging and sampling stations were installed on nine major streams, six of which flow directly into the Inlet. The properties of the upstream catchments defined by the sampling points are given in Table 4. The stations were located at some distance upstream from the Inlet (Figure 10) to avoid the problem of back-flooding as the Inlet water level rose prior to the sand bar opening. From the break of winter, staff gauges were read daily at each station. Rating curves were established for each station with manual current meterings.

Limited finance restricted the nutrient sampling frequency to once per week for each station. Sampling took place on the same day for most of the stations which involved a round trip of about 250 km. Samples were stored in sealable plastic bags and processed as described previously.

Table 4. Properties of study catchments (as defined by sampling stations)

Catchment	Area (ha)	Drainage density (km km^{-2})
Denmark River	53 090	0.32*
Scotsdale Brook	6 220	0.92
Hay River	121 924	0.44*
Hay Southern Tributary	3 408	0.63
Sleeman River	7 786	0.80
White River	2 727	0.51
Cuppup River	3 782	0.38
Nemanup/Lake Sadie Drain	3 932	0.36
Denmark Ag. Research Station	311	0.80

*whole catchment values

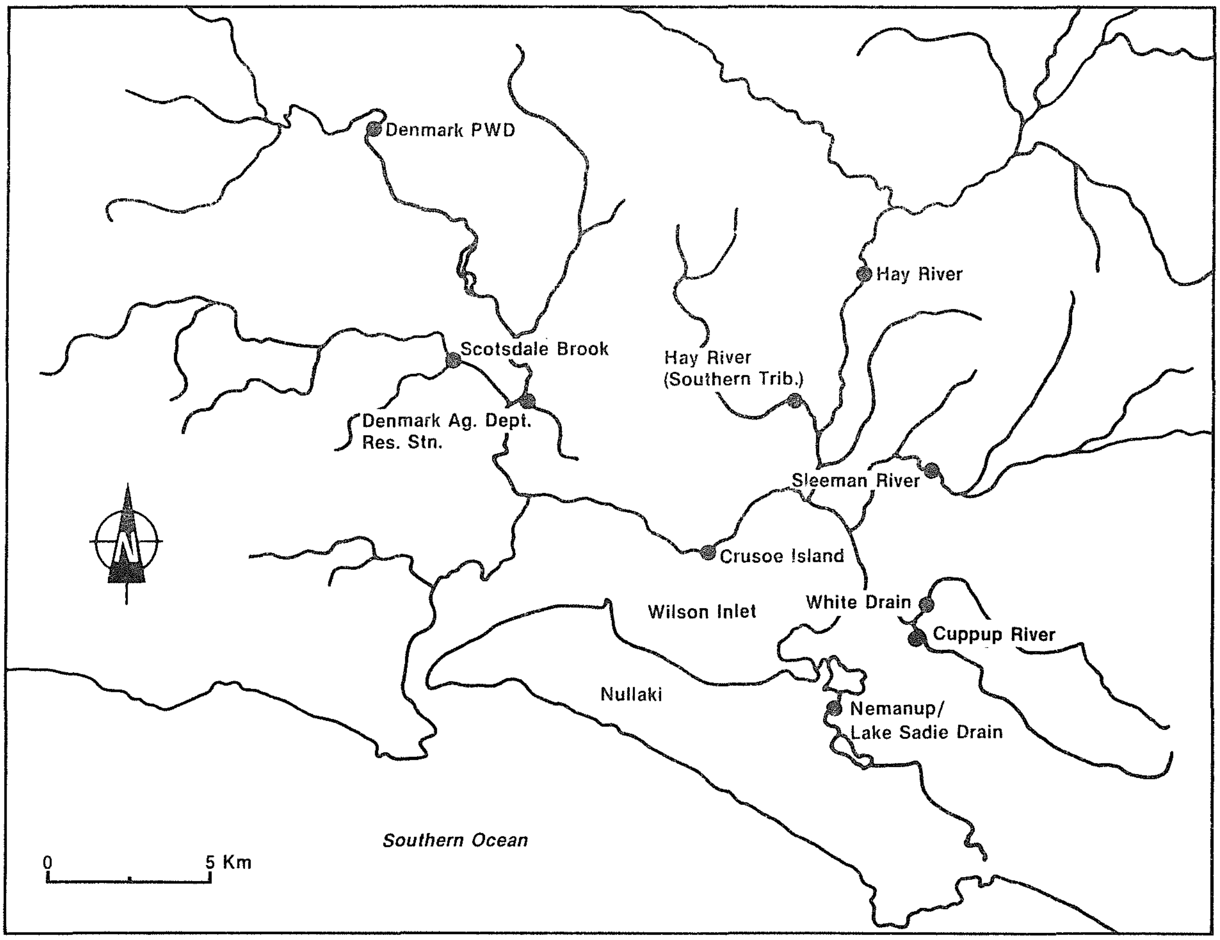


Figure 10. Gauging and sampling stations for the Wilson Inlet nutrient study (1982-1983)

RESULTS

Water Level

The water level in the estuary was dominated by the time of opening of the bar, which in the year of the study was opened for the shortest time on record (Table 1). It was broken artificially on 21 July when the estuary water level was approximately one metre above mean sea level, and closed naturally during the first week of September. During this time there was an abrupt fall in water level (of ca 70 cm) at the time of bar opening, and after the bar closed there was a slight rise, followed by a further reduction in water level because of evaporation. Water levels again began to rise at the end of the sampling period due to rainfall and riverflow (Figure 11).

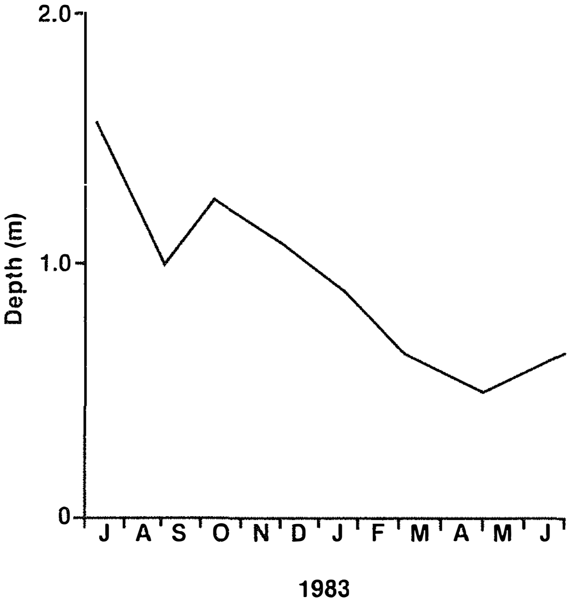


Figure 11. Seasonal variation in water depth at Site 1

Temperature

Water temperatures ranged between 12°C and 25°C, the latter being reached in January. There was little vertical stratification and little difference between the sites, although site 5 in the shallows generally had slightly higher temperatures (Figure 12A).

Salinity

Salinity was generally uniform, and ranged from 16-21°/oo (Figure 12B). When the bar was opened there was an increase in the salinity at site 1, which reached 26°/oo but this effect was not seen at other sites. Minimum salinity was reached in early October, after the bar had closed, because of further rainfall and consequent riverflow. Salinity then increased slowly until late April because of evaporation, with a fall in June when riverflow commenced. There was no significant (> 1°/oo) vertical salinity stratification in the estuary, except from one occasion in August at site 1, where the lens of marine water referred to above had penetrated while the bar was open.

Dissolved Oxygen

Dissolved oxygen levels (Figure 12C) remained close to or above 100 per cent saturation, i.e. at close to equilibrium with the air above. Higher levels are attributed largely to photosynthesis by *Ruppia*, as phytoplankton concentrations in the water were generally very low (see below). Even the minimum oxygen values observed during the study were at 75% saturation. Again there was negligible vertical stratification.

Light Penetration

Secchi disc readings were attempted throughout the study, but always exceeded the water depth, indicating good light penetration to the floor of the estuary.

Nutrients in Estuary Water

Phosphorus. Phosphate phosphorus levels were very low (Figure 13A), the maximum recorded level being only 6 μgl^{-1} which is close to acceptable detection limits. Average values from this survey are given in Table 5, along with information for other south western estuaries (see discussion). Organic phosphorus levels (Figure 13B) were also low compared to other estuarine systems (Table 5), and relatively stable apart from a rise in early March when rates of macrophyte decomposition were high (see below).

Nitrogen. Nitrate levels (Figure 14A) were generally low, with the greatest seasonal change at site 8 where there was a rise while the bar was open, and again an

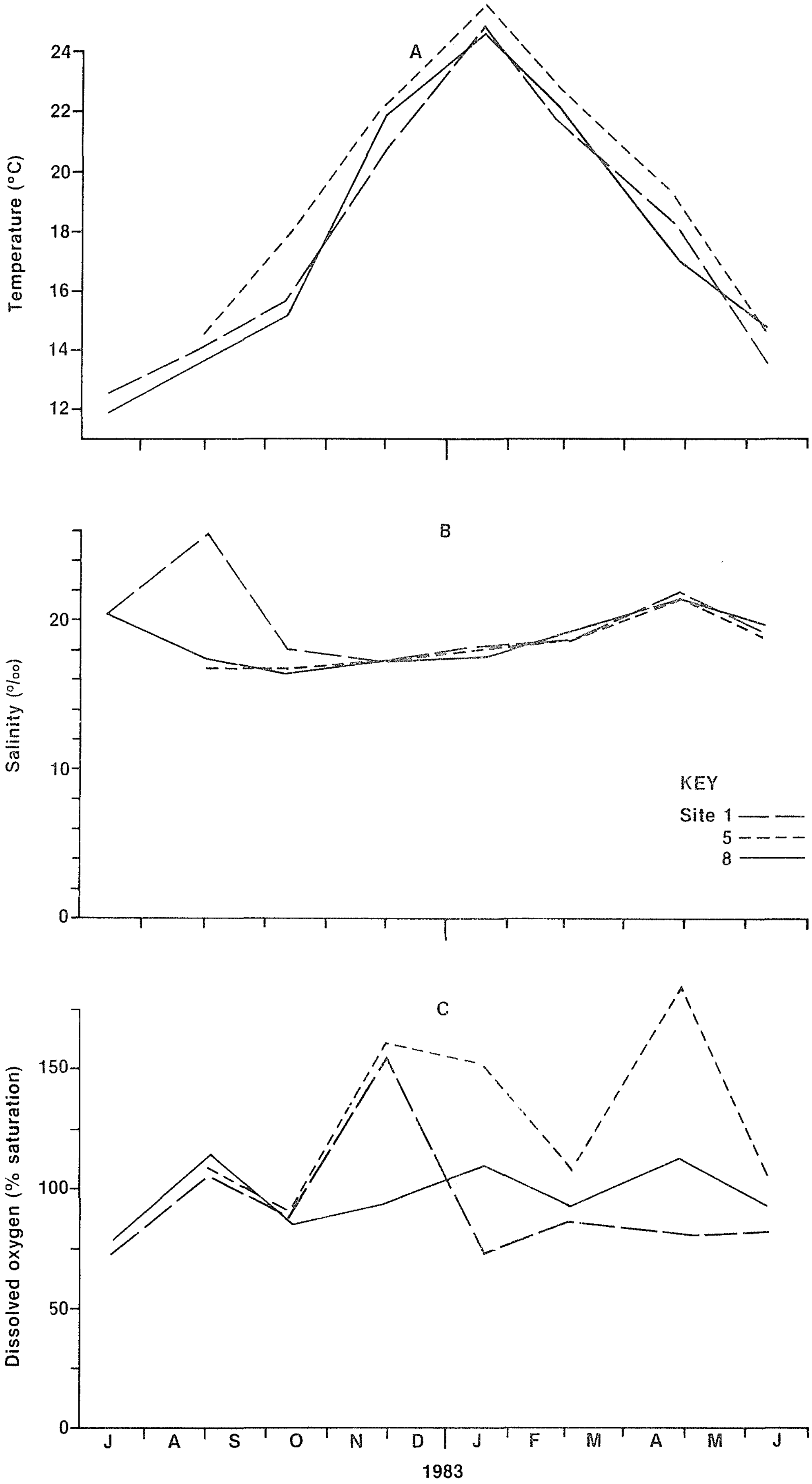


Figure 12. Season variation in (A) Temperature; (B) Salinity; (C) Dissolved oxygen in Wilson Inlet. Each point is the mean of surface and bottom readings.

upward trend between January and June. Ammonium levels (Figure 14B) were higher than nitrate levels but were still low when compared with other systems (Table 5). The highest concentration was observed at site 1 in April.

Organic nitrogen levels were also relatively constant during the year (Figure 14C) and high compared with the inorganic forms of nitrogen, suggesting that the available nitrogen had, for the most part, been incorporated into organic material through uptake by phytoplankton and other microscopic organisms, and by macrophytes. The highest concentrations were observed in July, prior to bar opening.

Phytoplankton

Surface chlorophyll concentrations are shown in Figure 15A. They were low compared to other systems (Table 5) and relatively constant. Although there may have been transient peaks not detected in the 6-weekly sampling, this appears unlikely because of the relatively low and constant levels. There was a minor peak at station 5 in April, but as there was no evidence of a bloom at the time of collection, this is attributed to contamination by microscopic epiphytic algae stirred up during the collection of the sample. Levels were on the whole higher at site 1 than at the other two sites; site 1 was a region of very high

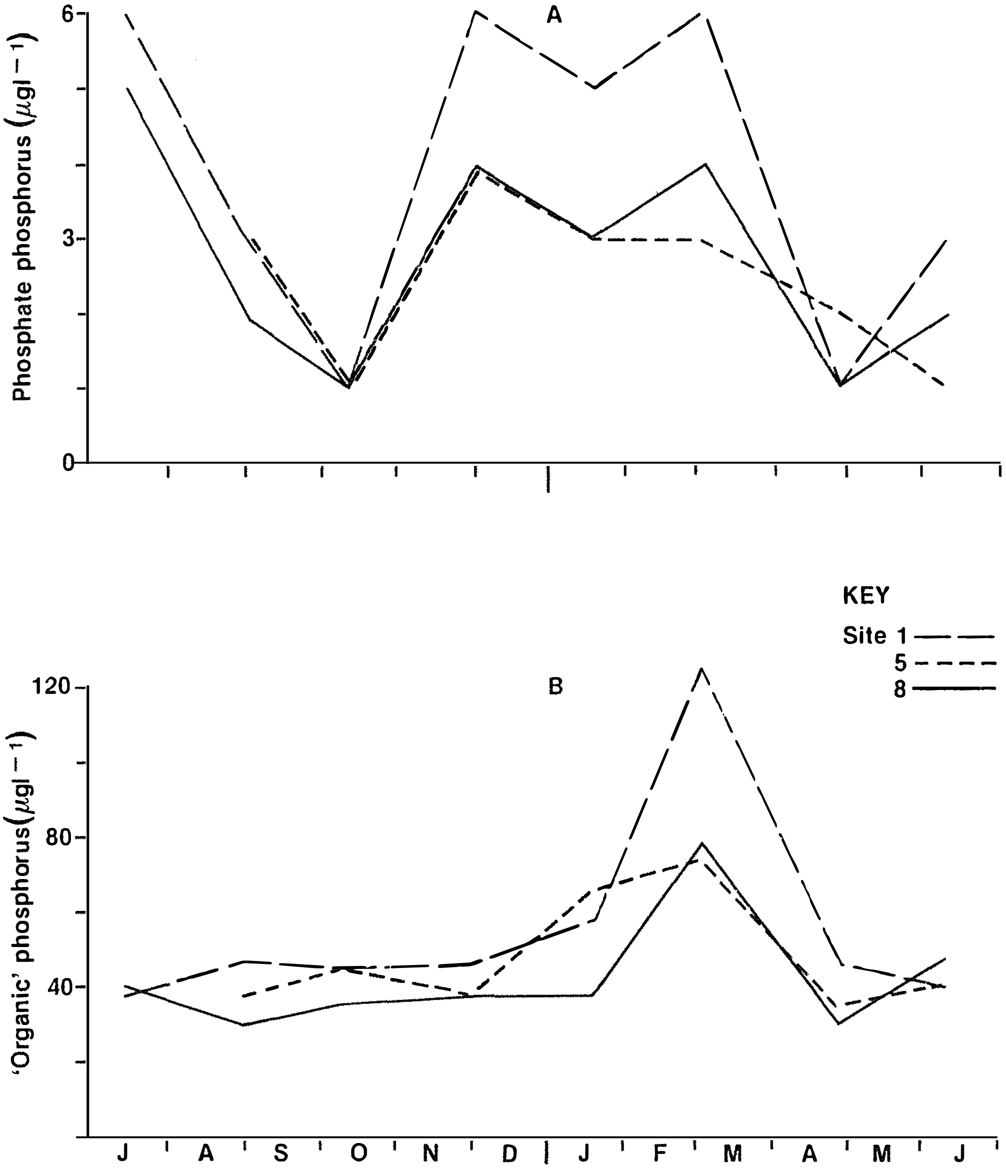


Figure 13. Season variation in phosphorus concentration of the water column in Wilson Inlet. (A) Phosphate phosphorus; (B) 'Organic' phosphorus. Each point is the mean of a surface and bottom sample

Table 5. Mean nutrient and chlorophyll 'a' values (μgl^{-1}) for the Peel-Harvey System, Swan River Estuary and Wilson Inlet

		'SUMMER'										'WINTER'									
						SWAN*										SWAN*					
		PEEL		HARVEY		ESTUARINE BASIN		UPPER ESTUARY		WILSON INLET		PEEL		HARVEY		ESTUARINE BASIN		UPPER ESTUARY		WILSON INLET	
		$\bar{X}$	MAX.	$\bar{X}$	MAX.	$\bar{X}$	MAX.	$\bar{X}$	MAX.	$\bar{X}$	MAX.	$\bar{X}$	MAX.	$\bar{X}$	MAX.	$\bar{X}$	MAX.	$\bar{X}$	MAX.	$\bar{X}$	MAX.
$PO_4 - P$	S	9	107	21	155	29	69	41	135	2	4	67	185	65	210	63	155	88	319	4	5
	B	8	34	20	128	33	76	48	186	3	6	29	95	56	212	49	115	88	323	3	5
ORG-P	S	107	266	174	495	46	84	70	180	50	88	84	127	100	154	60	124	71	195	37	41
	B	99	196	154	491	44	98	68	176	58	97	79	119	87	150	50	146	67	195	41	43
$NH_4 - N$	S	52	209	73	434	18	221	115	405	27	57	212	442	178	377	116	300	104	248	23	27
	B	108	750	258	846	34	301	158	509	34	69	211	438	261	694	165	837	118	587	21	27
$NO_3 - N$	S	54	575	38	217	18	345	87	325	5	9	584	1345	128	253	613	2000	798	2000	9	9
	B	65	952	40	207	17	295	83	283	6	10	392	728	135	283	327	1650	635	1750	8	8
ORG – N	S	1797	5715	3663	10132	523	1077	934	1661	916	1120	1019	1883	1223	1992	995	1151	1260	2221	934	1337
	B	1452	3831	2717	7054	490	1071	851	1573	926	1180	910	1627	1091	2092	705	1176	1219	2255	986	1382
CHLOROPHYLL 'A'	S	40.3	299.6	100.6	419.3	7.3	57.7	17.9	139.5	2.5	4.7	12.4	31.5	30.3	93.1	10.2	28.6	10.8	29.9	3.6	4.9
	B	27.1	90.2	68.1	259.5	5.3	52.9	8.1	55.5	8.6	16.8	11.9	41.1	21.8	61.9	4.3	19.6	10.5	29.9	8.1	10.8

'SUMMER' — September to May inclusive
'WINTER' — June to August inclusive
*Swan River data supplied by K. Hillman.

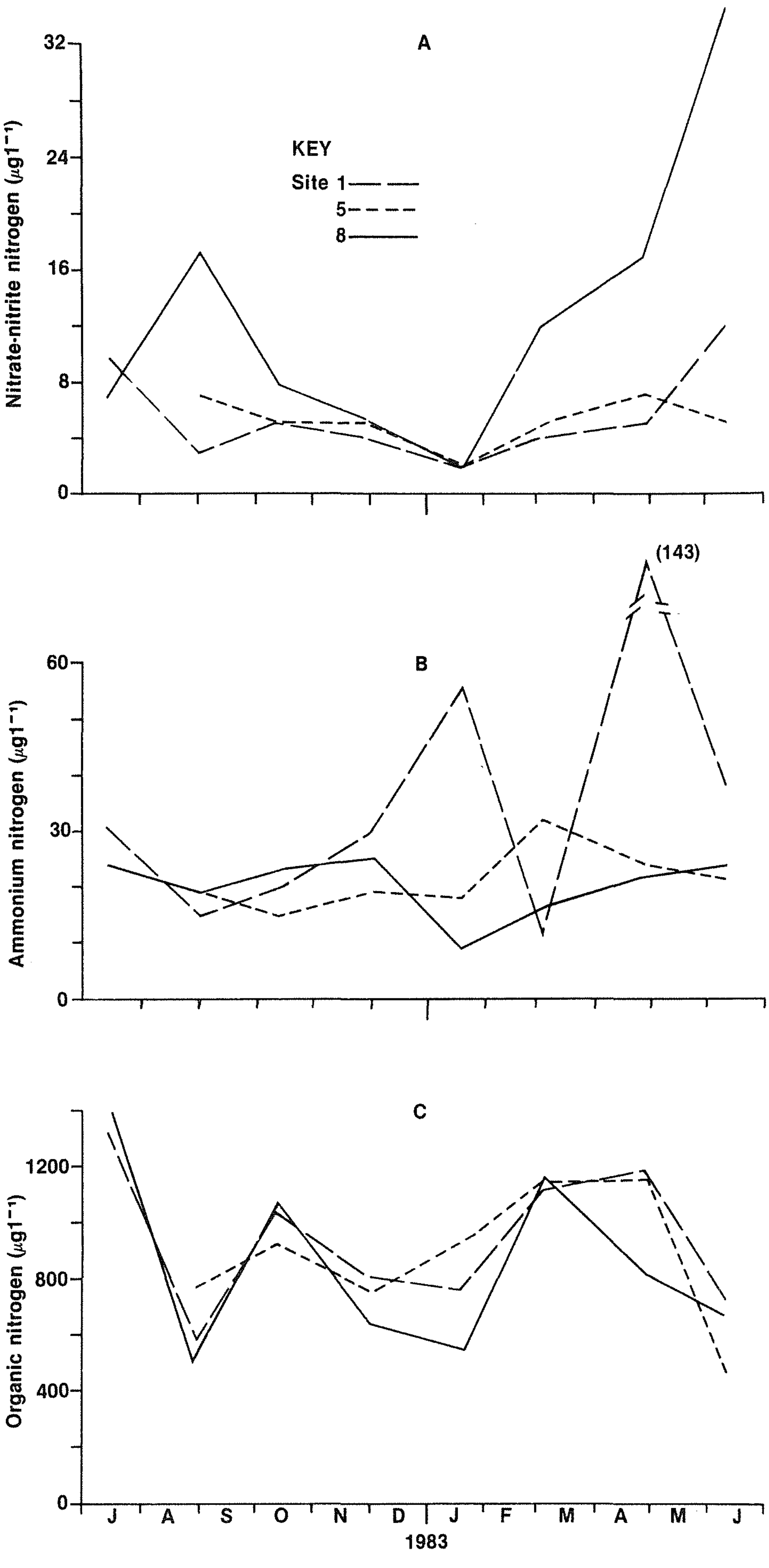


Figure 14. Seasonal variation in the nitrogen concentration of the water column in Wilson Inlet. (A) Nitrate + nitrite nitrogen; (B) Ammonium nitrogen; (C) Organic nitrogen. Each point is the mean of a surface and bottom sample

Ruppia biomass, and there was a suggestion of higher phosphorus levels at that site (Figures 13A, 13B). Figure 15B is the average of surface and bottom chlorophyll levels, which tend to be higher than surface levels. This is attributed to the stirring up of microscopic benthic and epiphytic algae at the time of sampling. Even so, the levels are relatively low when compared with those found in other systems (Table 5).

Preserved phytoplankton samples were examined to determine the main taxa present. The genera of microalgae observed are given in Table 6. On all occasions diatoms were the dominant microalgae. From July to January, *Chaetoceros* and *Cerataulina* were dominant. These diatoms also bloom in the Peel-Harvey estuarine system during winter in response to nutrient accession in river flow. From January to June the dominant genera were *Synedra* and *Amphora*, benthic and epiphytic diatoms which happened to be suspended in the water column. There was little true

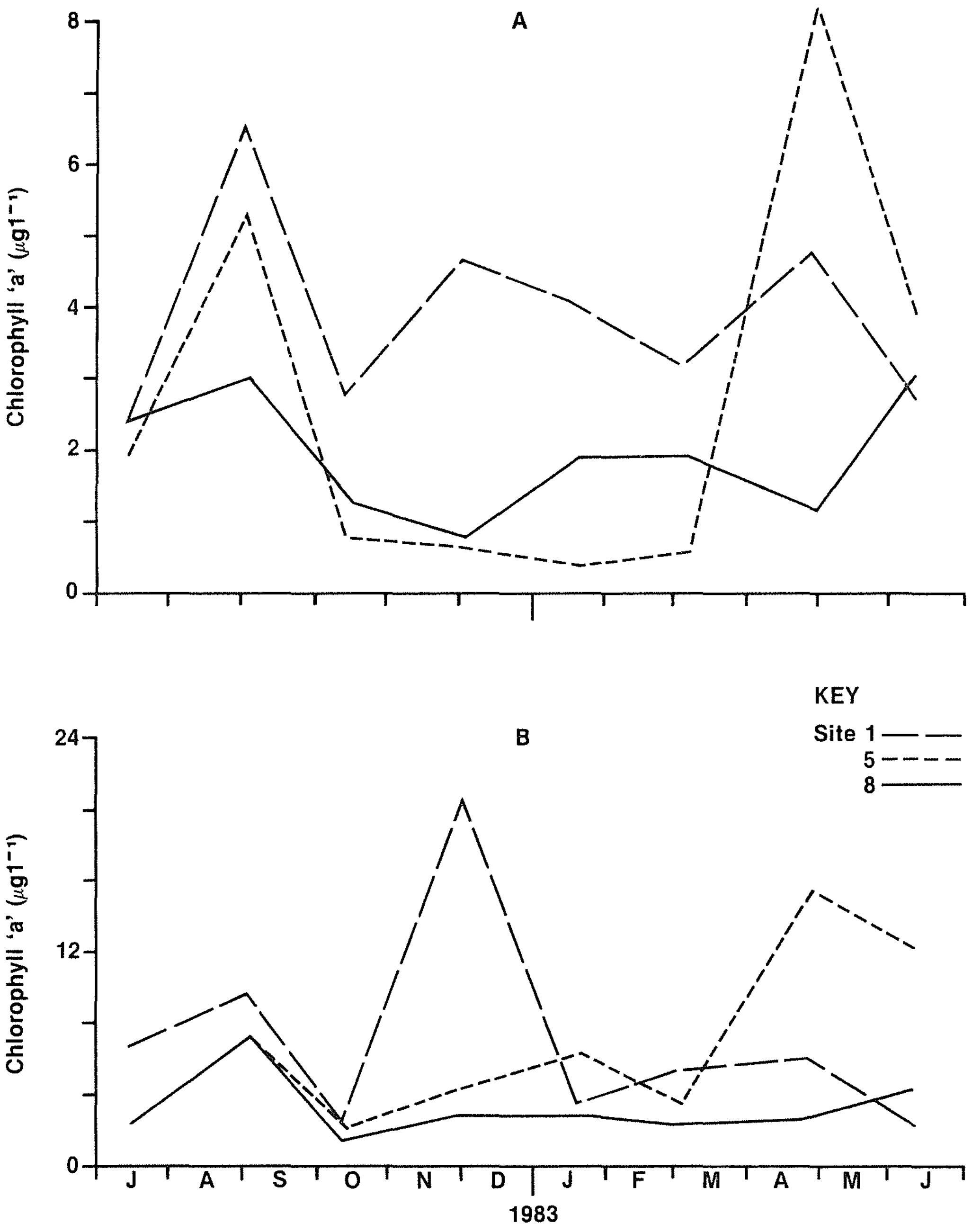


Figure 15. Seasonal variation in chlorophyll 'a' in Wilson Inlet. (A) Surface; (B) Mean concentration between a surface and bottom sample

phytoplankton observed during this period.

Overall, the diatom flora was similar to that observed in the Peel-Harvey system.

Zooplankton

Gladioferans was observed in large numbers in most samples and was present for the whole year. This organism also occurs in the Peel-Harvey system where it is generally only found in any quantity in winter and early spring.

Macrophyte Biomass

Table 7 lists the macroalgae and aquatic angiosperms found in the Inlet during the course of the present study.

Ruppia megacarpa dominated plant biomass (Figure 16A). *Ruppia* behaves as a perennial in the sytem, with above-ground biomass present throughout the year, although this fell to a low level at certain sites. The highest above-ground biomass and most obvious seasonal trends are seen in the data for site 1. Above-ground biomass was at a maximum in late January, at the time of highest water temperatures and maximum light intensities. After this there was rapid decomposition, with minimum biomass reached in June. Biomass at the other sites, although lower than at site 1, was nevertheless relatively high compared to other systems (Table 8). Above-ground biomass peaked at the same time as site 1, though seasonal trends are less obvious. Below-ground biomass (Figure 16B) again showed marked differences among sites. At site 1 there was very little below-ground material compared with that above (Figure 16A). At site 8 also, there was relatively little below-ground material, which was approximately one-tenth of that above until early December (Figure 16B). Site 5 is of comparable depth to site 1, but has a sandier sediment (Table 9) than the other two sites; its below-ground material was initially about half of that above, but fell to a much lower level in late autumn.

Ruppia is reported to form turions (bulbous storage organs), but in this situation the below-ground material was mainly slender rhizomes with thin roots penetrating to about 10–15 cm. Below-ground biomass was at a minimum in April, when above-ground material was also at a minimum; thus the depletion of below-ground material cannot be readily attributed to maintenance or growth of above-ground parts. Also, Figure 16C shows that the ratio of above-ground material to below-ground material was at a maximum somewhat later than peak above-ground biomass for all sites, suggesting more rapid net senescence of below-ground material at the time. There were no other obvious seasonal trends. Thus, based on these time course data, there is no strong evidence of an important role for the rhizomes in providing reserves for the maintenance of the shoot.

Figure 17A shows the biomass of macrophytes other than *Ruppia*. It is clear that total biomass (Figure 17B) is accounted for very largely by *Ruppia*. Sites 1 and 5 had virtually no macrophytes other than *Ruppia*, while at site 8 the contribution of the other macrophytes was significant, though still relatively small compared with *Ruppia*. Almost all of these other plants were red algae in the genus *Polysiphonia*. There were significant differences between sampling occasions, with peaks in mid-summer and early winter.

Table 6. Genera of microalgae observed in Wilson Inlet

Blue-Greens
- *Lyngbya*
- *Oscillatoria*

Dinoflagellates
- *Ceratium*
- *Gonyaulax*

Diatoms
- *Achnanthes*
- *Amphora*
- *Bacillaria*
- *Cerataulina*
- *Chaetoceros*
- *Cocconeis*
- *Cymbella*
- *Diploneis*
- *Gramatophora*
- *Gyrosigma*
- *Mastogloia*
- *Melosira*
- *Navicula*
- *Nitzschia*
- *Pleurosigma*
- *Striatella*
- *Synedra*

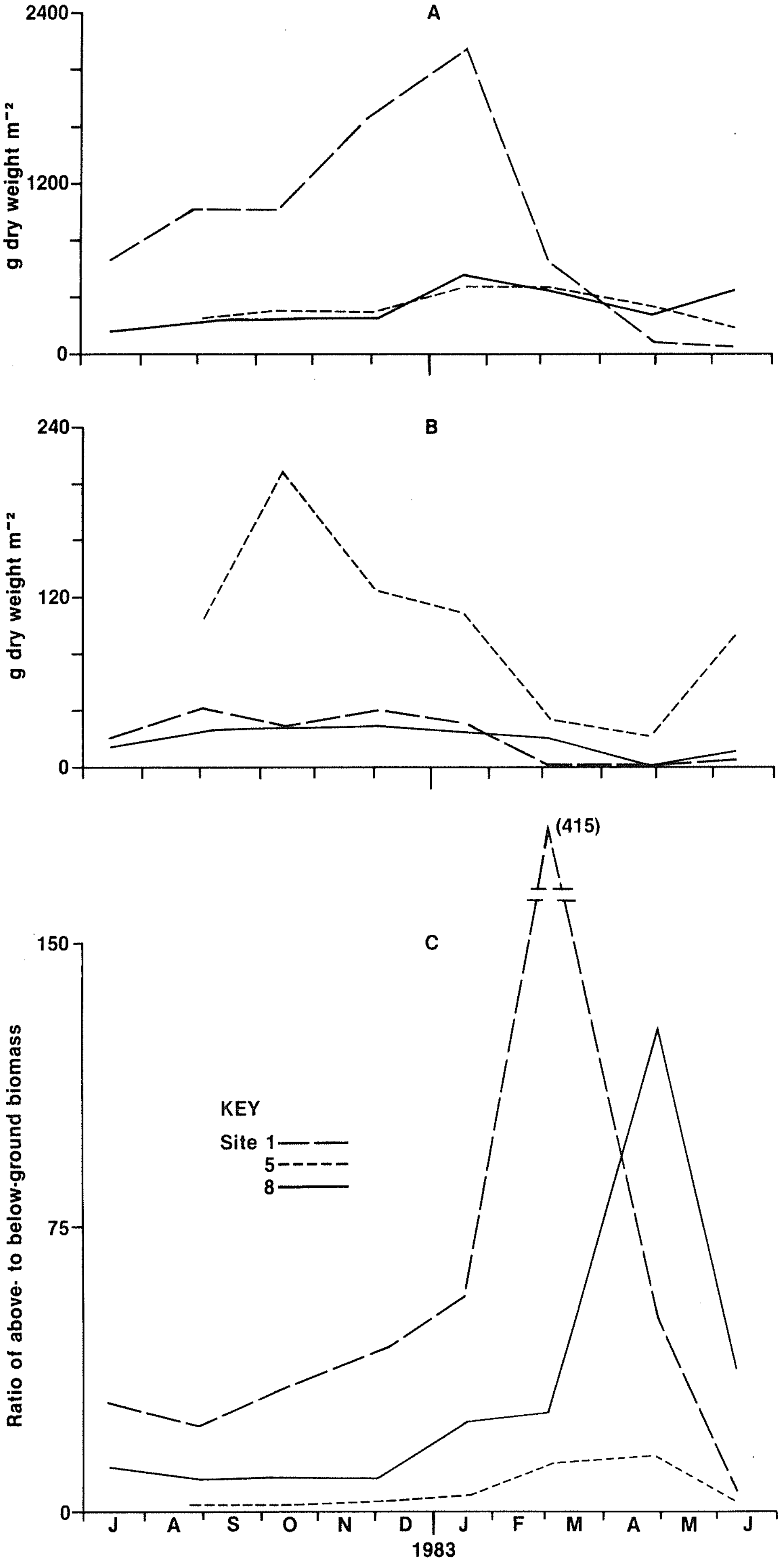


Figure 16. Seasonal changes in (A) *Ruppia* above-ground biomass; (B) *Ruppia* below-ground biomass; and (C) the ratio of above-ground to below-ground biomass in Wilson Inlet.

Table 7. Aquatic angiosperms and macroalgae observed in Wilson Inlet

AQUATIC ANGIOSPERMS:	*Ruppia megacarpa*
MACROALGAE:	
Chlorophyta	*Acetabularia (Polyphysa) peniculus* *Chaetomorpha linum* *Chaetomorpha aurea* *Cladophora* sp. *Enteromorpha intestinalis* (and other species) *Rhizoclonium* sp.
Charophyta	*Lamprothamnium papulosum*
Rhodophyta	*Ceramium* sp. *Polysiphonia* sp. *Chondria* sp. *Audouinella* sp. *Gracilaria verrucosa*
Phaeophyta	*Dictyotales* (one species)

Table 8. Peak *Ruppia* biomass in Wilson Inlet, Peel Inlet and the Blackwood River Estuary

Site and month of collection	Peak total *Ruppia* biomass (g dry weight m^{-2})
Wilson Inlet	
Poddy Shot Bay (Site 1) — January	2189
Two Trees (Site 5) — January	555
The Elbow (Site 8) — January	584
Blackwood River Estuary[1]	
Swan Lake — December	503
Blackwood Basin — September	180
North Bay — November	150
Thomas Island — February	100
Peel Inlet[2]	
Coodanup (shallow site) — March	340
Coodanup (deep site) — October	90

[1] Congdon and McComb 1979
[2] Carstairs 1978

Table 9. Sediment properties in Wilson Inlet

	Site 1	Site 5	Site 8
Wet/dry weight ratio	1.88[1]	1.32	1.42
Loss on Ignition (%)	4.3	1.3	1.8
% H_2O	45.9	24.5	28.9
Sediment Nutrient Concentration (mg g^{-2})			
Total phosphorus	0.33	0.09	0.13
Total nitrogen	1.86	0.47	0.70
Sediment Nutrient Load — top 2 cm (g m^{-2})			
Total phosphorus	5.40	2.64	2.94
Total nitrogen	31.92	12.90	17.19

[1] Each figure is the mean of two determinations.

Tissue Nitrogen and Phosphorus Content

Nutrient levels in above- and below-ground *Ruppia* tissue are shown in Figures 18 (total nitrogen) and 19 (total phosphorus). Nitrogen concentrations were relatively constant throughout the year, and somewhat higher in above-ground compared to below-ground material. There was no marked depletion of these levels even during periods of high growth in early summer. Again, there was no evidence for substantial reserves being accumulated in the rhizomes and redeployed some other time. There was no obvious difference between the sites. The concentration in the tissue was above the level of 13 mg g^{-1} given by Gerloff and Krombholz (1966) as critical for supporting maximum growth of a number of aquatic plants. The total amount of nitrogen contained by plant material at the sites would therefore be dominated by the changes in biomass, not by changes in concentration of nitrogen within the tissues.

In contrast, phosphorus shows more interesting trends (Figure 19). The phosphorus content of above-ground material rose at all sites to a maximum during August and remained high until November, with change in tissue concentration inversely related to biomass (Figure 16A). There was approximately the same trend in below-ground material, where the phosphorus concentration was similar to that in the above-ground material. At the time of major decomposition, there was no evidence of translocation of phosphorus to below-ground material, so that the loss from above-ground material must have been to the water column or the sediments. At site 1, one square metre of *Ruppia* would have lost 1.7 g of phosphorus to the water column or sediments. There was also a difference among sites, with site 5, having the coarser sediment, supporting plants with lower tissue phosphorus concentrations. Table 9 shows mean sediment nutrient data for these three sites. Site 5 had much lower sediment nutrient concentrations and loads than site 1, and though levels were more comparable with site 8, they were still somewhat lower.

There were marked seasonal trends inversely related to increases in biomass. Nitrogen to phosphorus ratios changed markedly with season (Figure 20), the changes being attributable to variations in phosphorus concentration, as nitrogen concentrations were relatively constant. The ratios were very high at times when phosphorus depletion had occurred in the tissues, and were about 10:1, a typical ratio for plant material, for only a few months of the year. During the late summer to autumn period (including the period of high biomass and decomposition) the phosphorus concentration in the tissue was below the level of 1.3 mg g^{-1}, which is critical for maintaining maximum growth of a number of aquatic plants (Gerloff and Krombholz 1966).

The data provide circumstantial evidence that phosphorus is more critical to the growth of *Ruppia* than nitrogen.

Sediments

Table 9 includes the physical and chemical characteristics of the sediments at the 3 regular sampling sites. The sediment at site 1 consisted of a silty sand with a relatively high water and organic content. The sediment at site 8 was much coarser than at site 1 and correspondingly had a much lower water and organic content. The sediment at site 5 was a coarse grey sand, and this had the lowest water and organic content.

The nutrient content of the sediments was generally well correlated with the type of sediment (see below), with fine silty sediments having the highest nutrient concentrations. Thus, the nutrient content of the sediment at site 1 was much

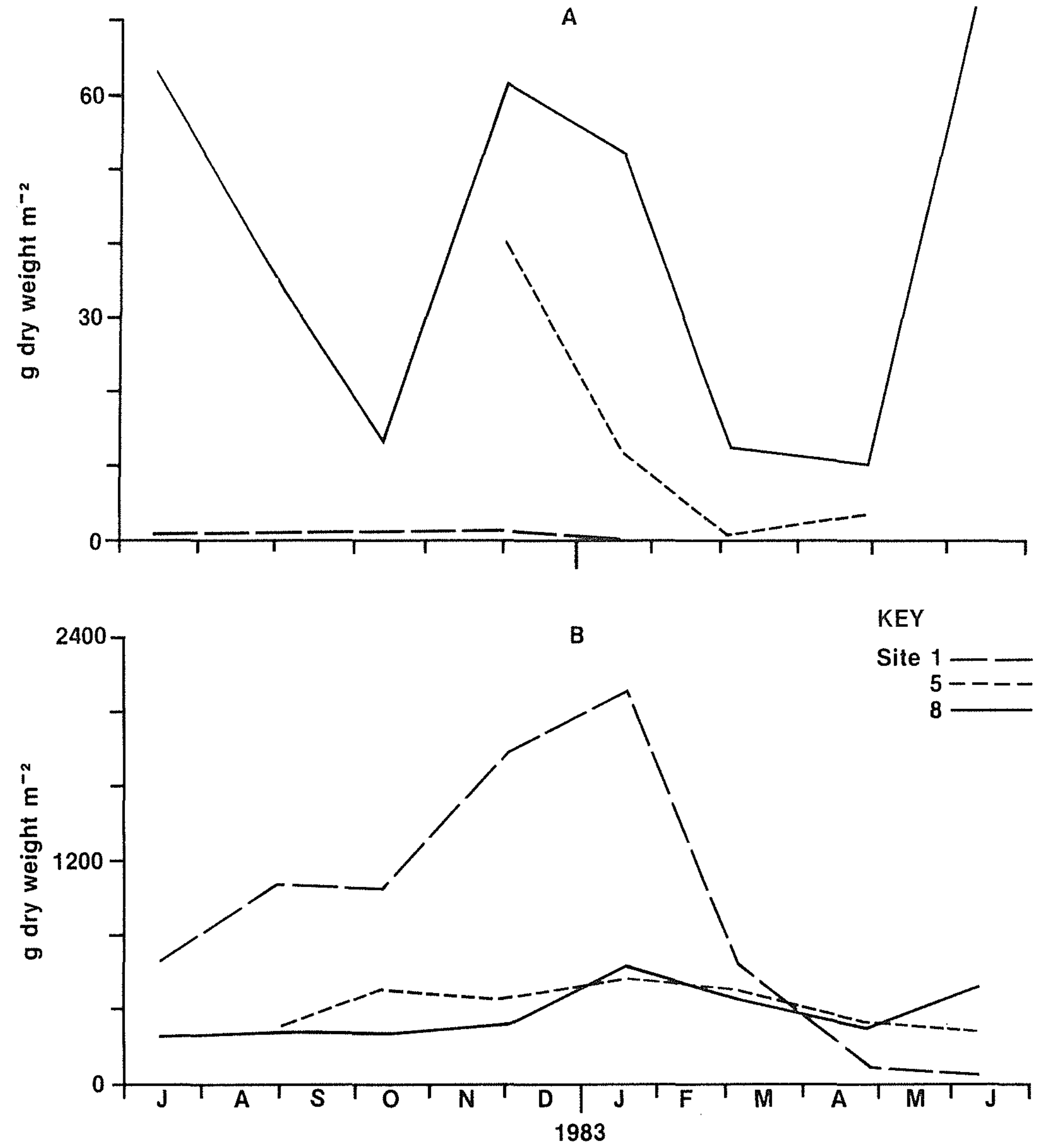


Figure 17. Season variation in (A) macrophyte biomass (excluding *Ruppia*) and (B) total plant biomass in Wilson Inlet

greater than that at site 8 and the sediment at site 5 had the lowest nutrient content.

Grid Surveys

The data from the three grid surveys (July and December 1982, April 1983) were first analysed separately, but as there was little difference between the surveys the data were combined for statistical analyses and only examples are presented here.

Water Column. The spatial distribution of nutrients in the water column was remarkably uniform on all occasions, and representative surface distributions are shown in Figures 21 and 22. The concentrations of phosphate and nitrate in the water column were significantly ($p<0.001$) and positively correlated with the concentrations of extractable phosphate and nitrate in the sediment below. This indicates that the concentrations in the water column are to some extent determined by exchange between water column and sediment.

There was an area of relatively high ammonium concentration in the Poddy Shot Bay area (Figure 21A) in April 1983, attributed to the decomposition of a dense *Ruppia* bed and subsequent release of ammonium.

Physical processes such as wind-driven circulation and vertical mixing probably account for much of the relatively small variance in the spatial distribution of the

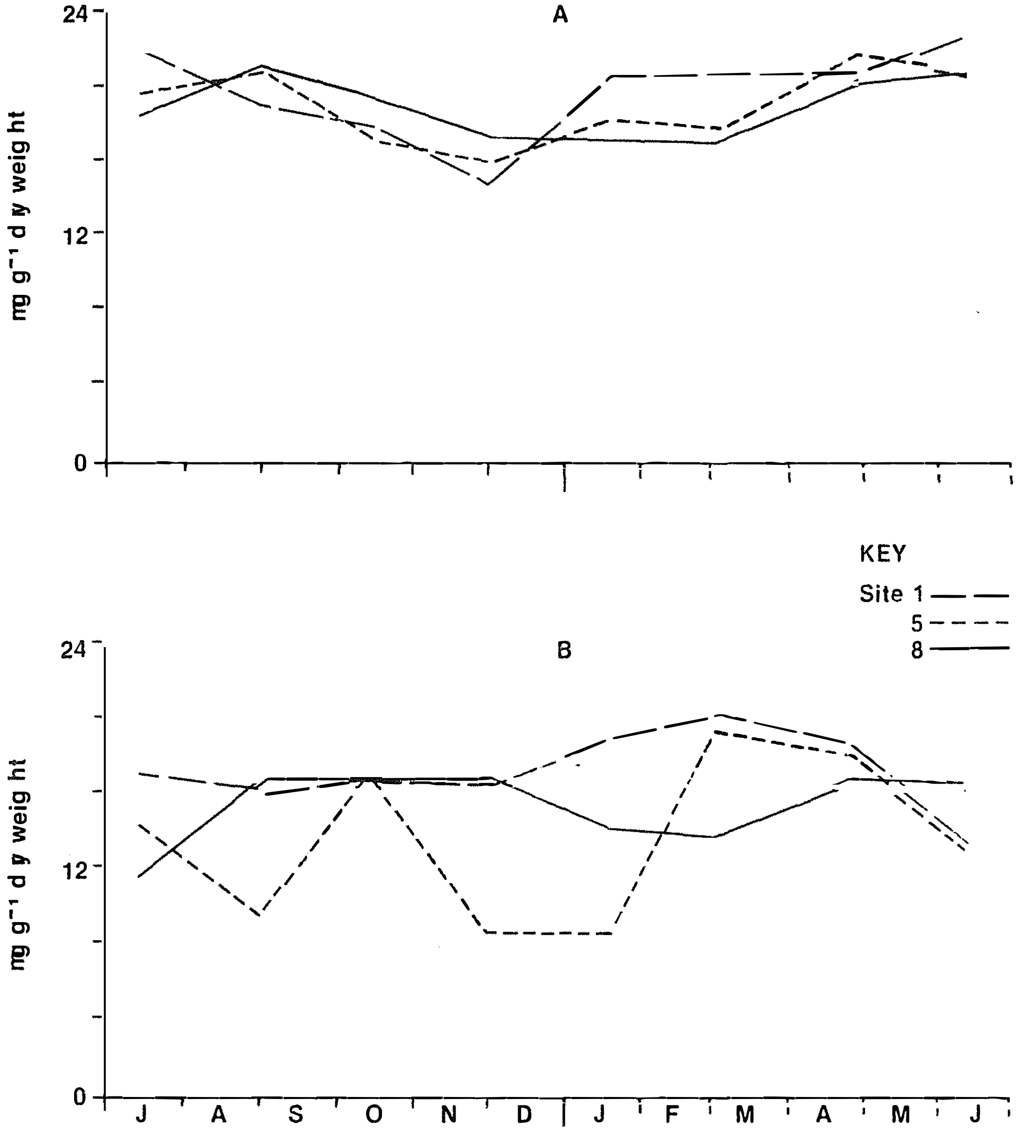


Figure 18 The nitrogen concentration in the tissues of *Ruppia* from Wilson Inlet: (A) above-ground material; and (B) below-ground material.

nutrients, especially of organic phosphorus and organic nitrogen. This suggestion is consistent with the small variation in salinity over the surface and depth of the estuary.

Chlorophyll levels were generally uniformly low. The spatial distribution (Figure 22C) was significantly positively correlated with the organic nitrogen content ($p<0.01$) of the water, and the *Ruppia* above-ground biomass ($p<0.05$). However, this latter correlation is attributed to contamination of water samples from dense *Ruppia* beds by epiphytic microalgae. The correlation between chlorophyll and organic nitrogen content of the water is probably explained by the fact that a high organic nitrogen content indicates areas of resuspension, where there would be a contribution of benthic microalgae to the chlorophyll concentration of the water.

Sediment. The fine silty sediments with high water and organic contents (Figure 23) occur in the deeper portions of the Inlet. The sediments in the shallower regions are a relatively coarse sand with a correspondingly low organic and water content. The deeper areas of the Inlet are probably sites of net accumulation (deposition), while the shallower regions are subject to erosion.

The wet/dry ratio, water content, and organic content of the sediments were significantly ($p<0.001$) positively correlated with water depth.

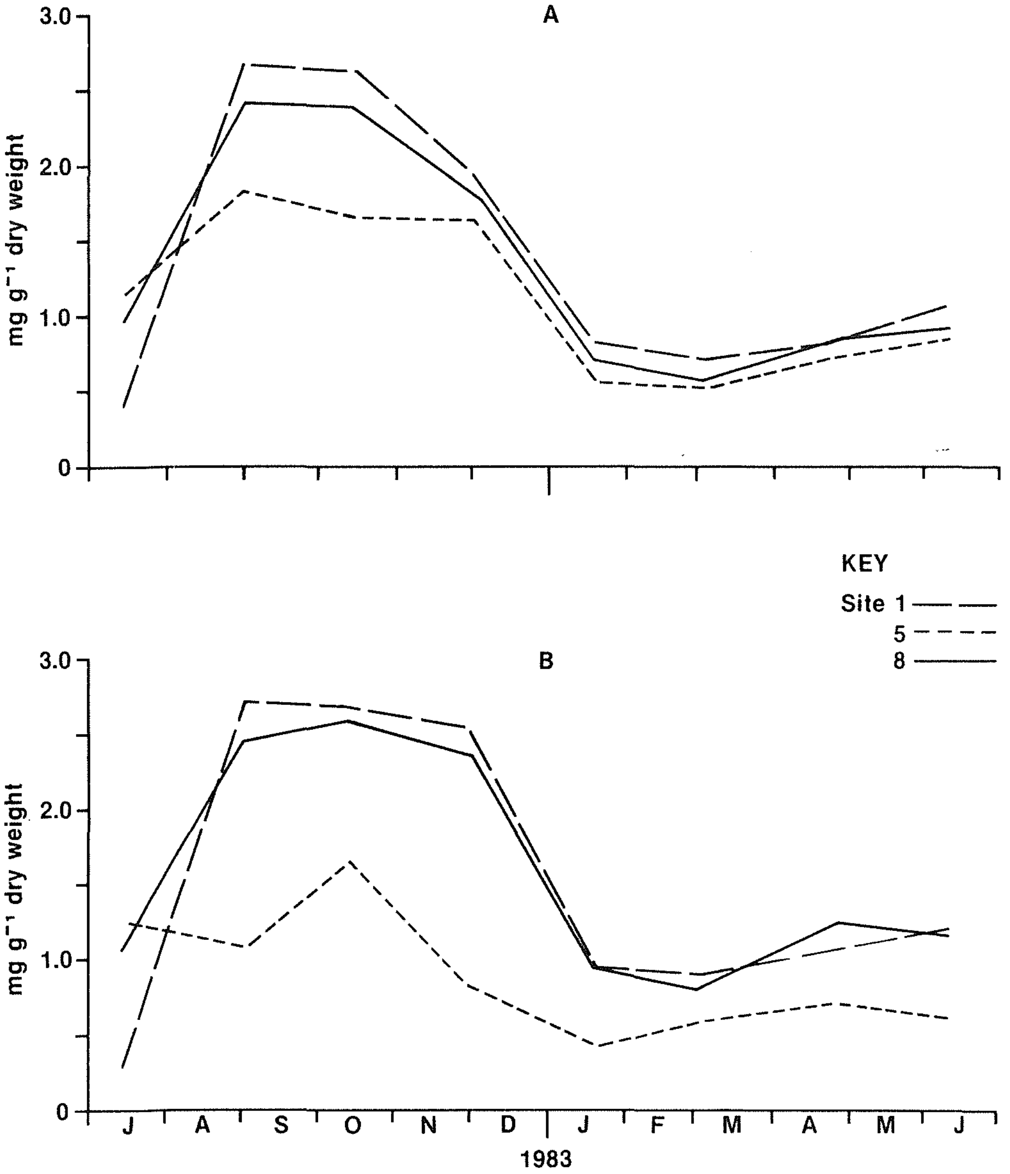


Figure 19 Concentrations of phsophorus in the tissues of *Ruppia* from Wilson Inlet: (A) above-ground material; (B) below-ground material.

The nitrogen and phosphorus (extractable and total) concentration of the sediment (Figures 24 and 25) was significantly ($p<0.01$) positively correlated with the wet/dry ratio, water content and organic content of the sediment; the fine, silty sediments in the deepest portions of the Inlet had the highest nutrient concentrations.

The sediment chlorophyll concentration (Figure 25C) was significantly ($p<0.01$) positively correlated with water depth, sediment type, and sediment nutrient concentration. The positive correlation between sediment chlorophyll and depth was somewhat surprising in view of possible light limitation, but the sediments in the deeper portions of the Inlet were covered with a thick *Oscillatoria* mat which suggests that, as indicated by the Secchi disc data, light penetration was adequate to support these algae.

Plant Material. The distribution of *Ruppia* is shown in Figure 26. Total biomass (above- and below-ground) was significantly ($p<0.01$) negatively correlated with water depth, suggesting that the distribution of *Ruppia* in Wilson Inlet is largely controlled by light. The depth limit for *Ruppia* in Wilson Inlet appears to be about 3.0 m; below this *Ruppia* is virtually absent. In this *Ruppia* is very different to the benthic microalgae, which are presumably able to function effectively at much lower light intensities.

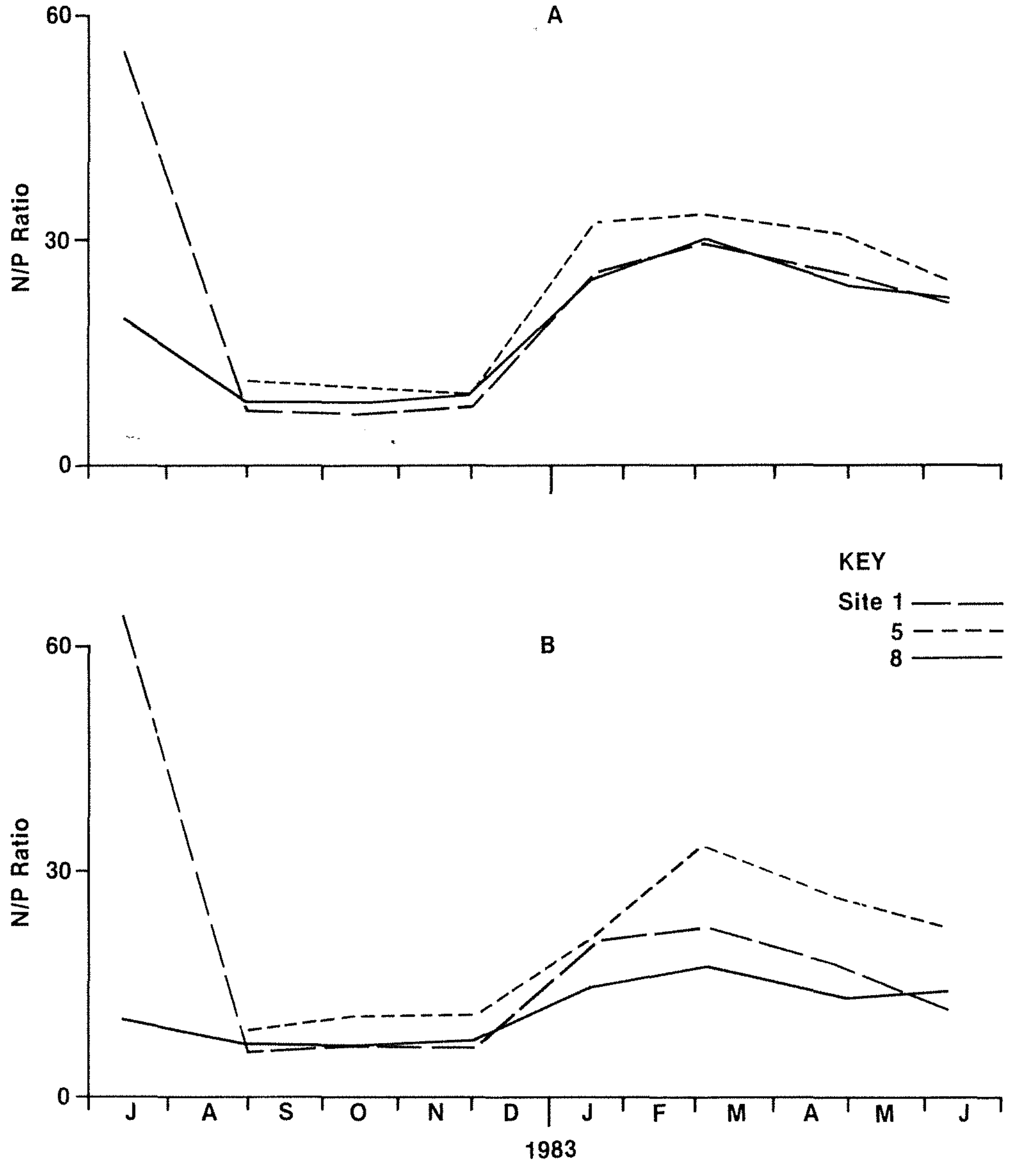


Figure 20 The ratio of nitrogen to phosphorus in the tissue of *Ruppia* from Wilson Inlet: (A) above-ground material; (B) below-ground material.

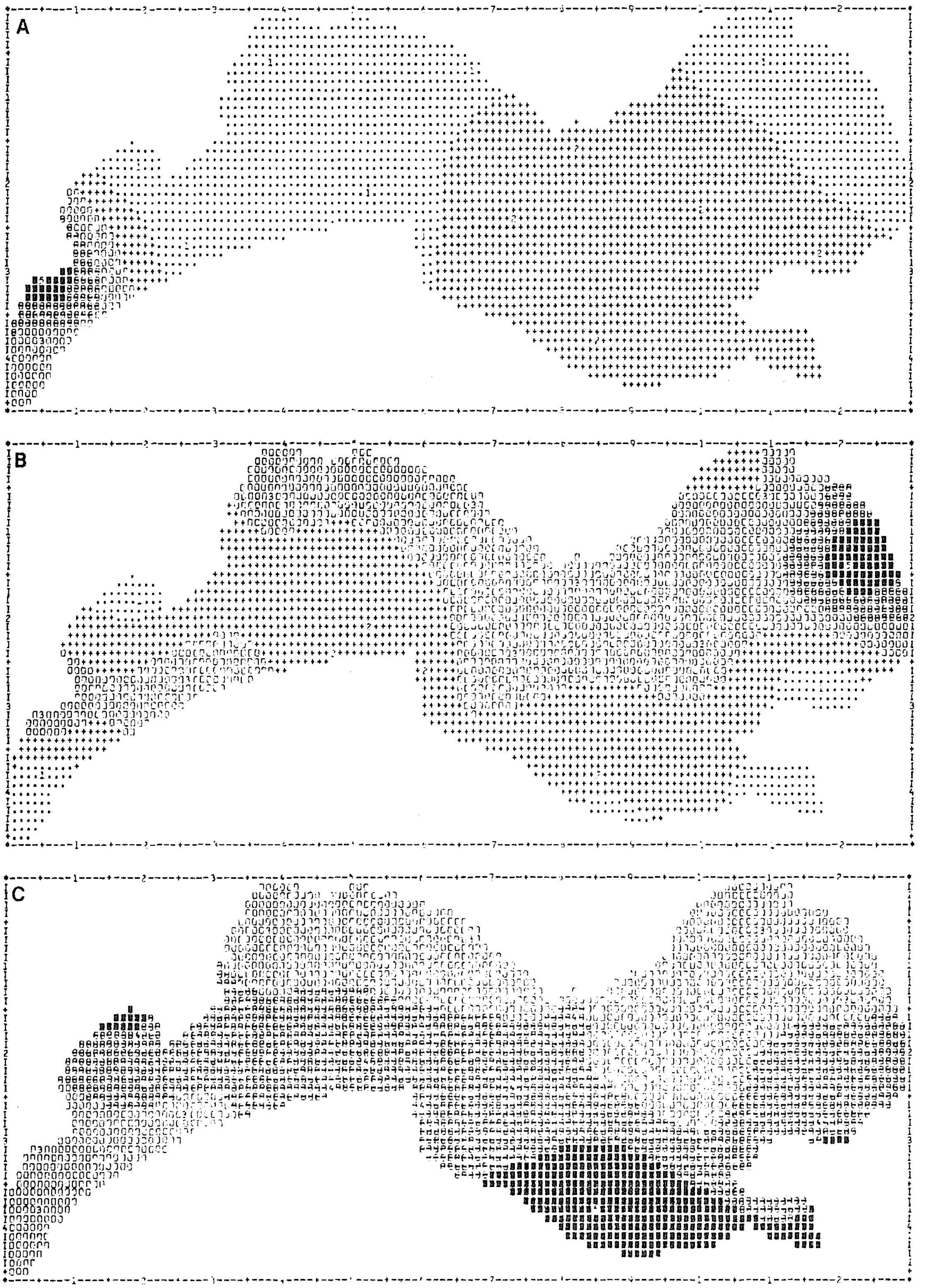


Figure 21. Distribution of nutrients in the surface waters of Wilson Inlet.
(A) Ammonium nitrogen, April, 1983; range 1 – 130$\mu g l^{-1}$.
(B) Nitrate-nitrite nitrogen, July 1982; range 1 – 20$\mu g l^{-1}$.
(C) Organic nitrogen, July 1982; range 1000 – 1500$\mu g l^{-1}$.
The data are divided into 5 equal size classes. Dark shading indicates highest relative concentration.

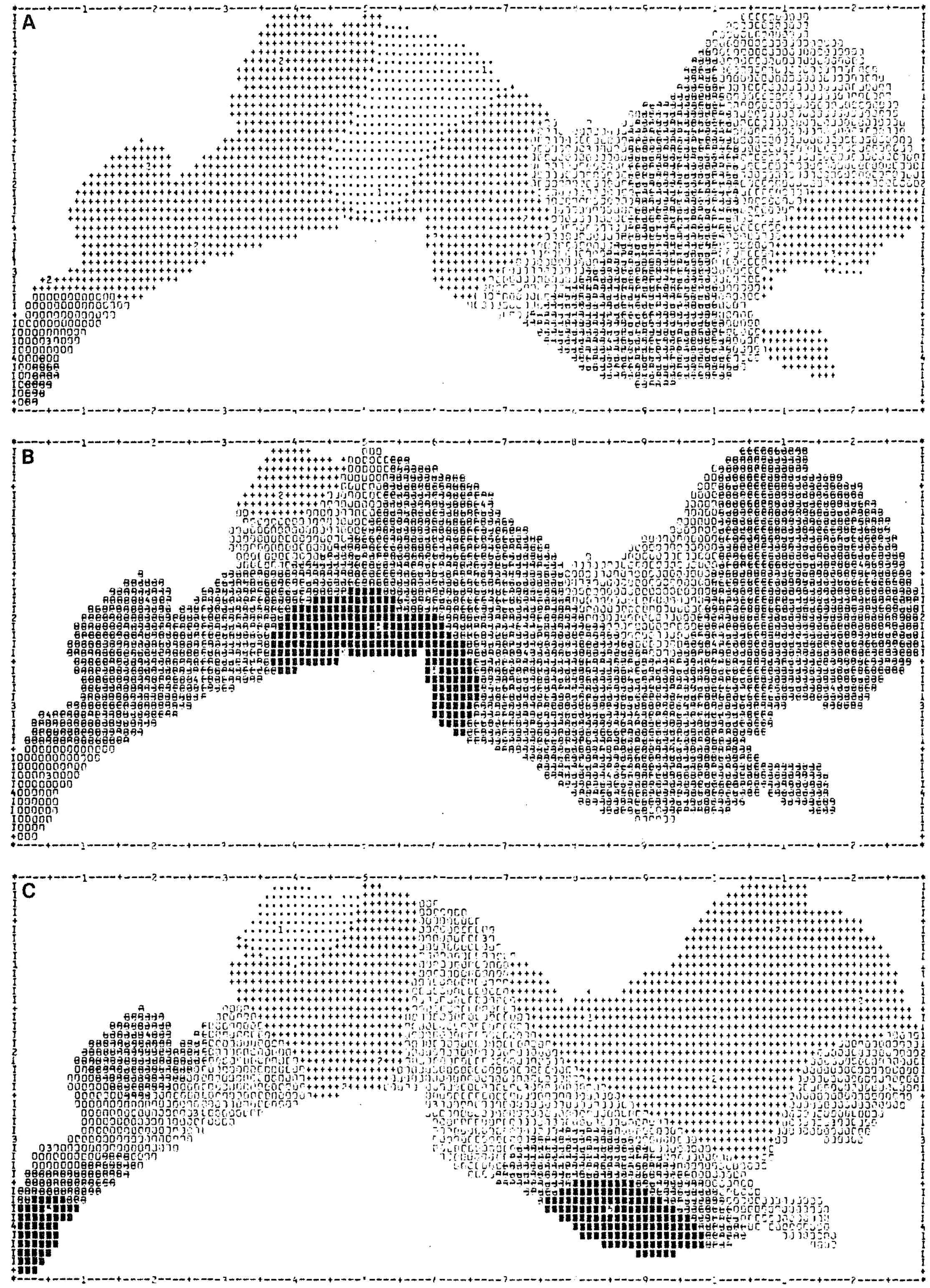


Figure 22. Distribution of nutrients and chlorophyll in the surface waters of Wilson Inlet.
(A) Phosphate phosphorus, July, 1982; range 1 – 15$\mu g l^{-1}$.
(B) 'Organic' phosphorus, July, 1982; range 1 – 50$\mu g l^{-1}$.
(C) Chlorophyll 'a', July, 1982; range 0 – 5$\mu g l^{-1}$.
The data are divided into 5 equal size classes. Dark shading indicates highest relative concentrations.

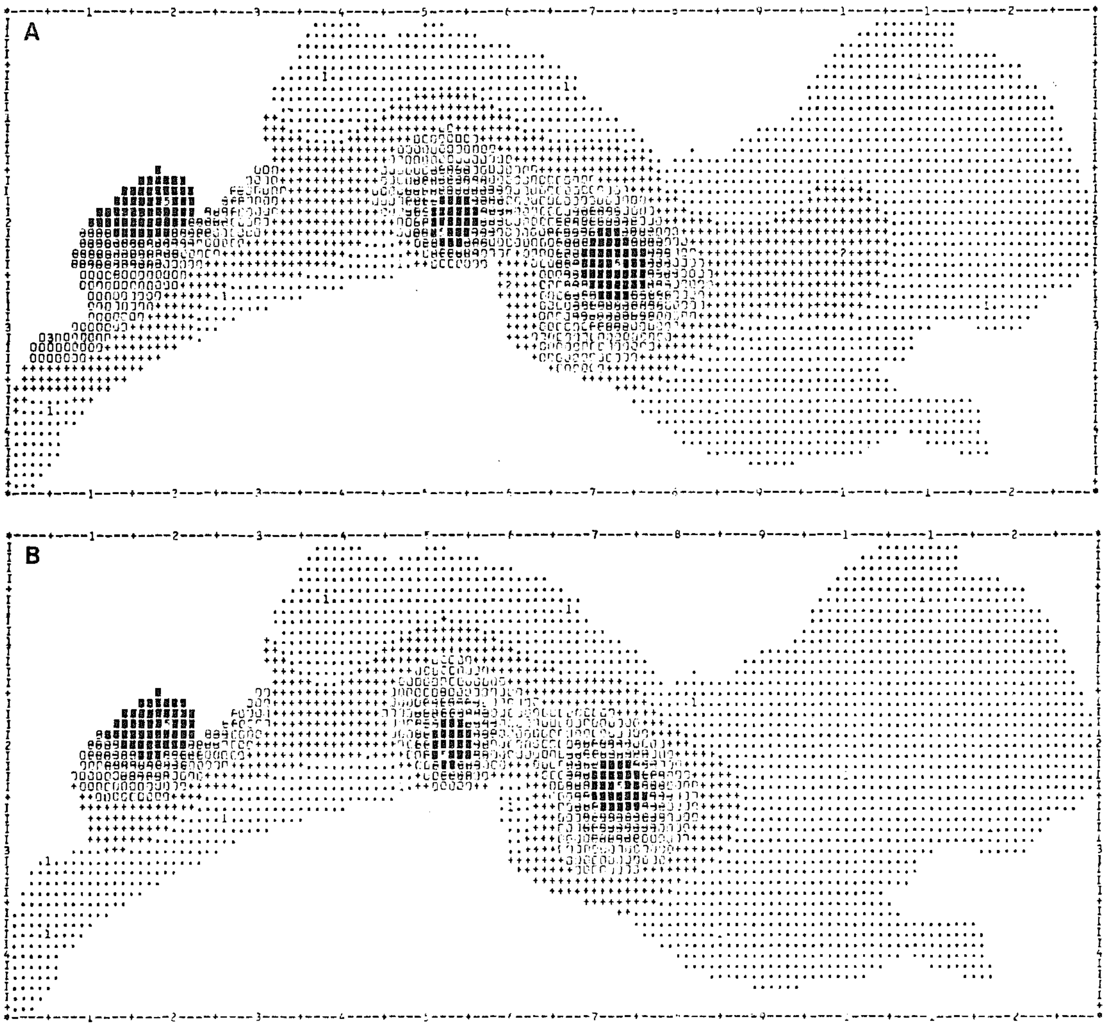


Figure 23. Distribution of sediment properties in Wilson Inlet in April 1983.
(A) Water content, April 1983; range 21 – 80%.
(B) Organic matter content, April, 1983; range 0.8 — 25.7%.
The data are divided into 5 equal size classes. Dark shading indicates highest relative percentage.

Ruppia above-ground biomass was significantly ($p<0.05$) positively correlated with the below-ground biomass.

The variance in the nitrogen concentration of above-ground material was small and not explained by any of the measured variables. The phosphorus concentration of *Ruppia* above-ground material was significantly ($p<0.01$) positively correlated with the phosphorus concentration of below-ground material.

The tissue nutrient concentration of *Ruppia* below-ground material was significantly ($p<0.05$) positively correlated with the sediment nutrient concentration. The nitrogen concentration of below-ground material was significantly ($p<0.01$) positively correlated with the phosphorus concentration.

Plant Biomass and Nutrient Loads

Planimetry of computer-drawn maps enabled the total water column nutrient content in Wilson Inlet to be computed (Table 10). The amounts in the top 2 cm of sediment were also measured in this way (Table 11). A comparison of these tables shows that considerably greater amounts of phosphorus and nitrogen are contained in the sediment as compared to the water column, a feature which is common to many water bodies including, from south-western Australia, the Blackwood River Estuary (Congdon and McComb , 1980), the Peel-Harvey System (Hodgkin *et al.*, 1981) and the Swan River Estuary (Hillman K, pers. comm.).

The total amount of extractable N and P in the sediment was considerably greater in

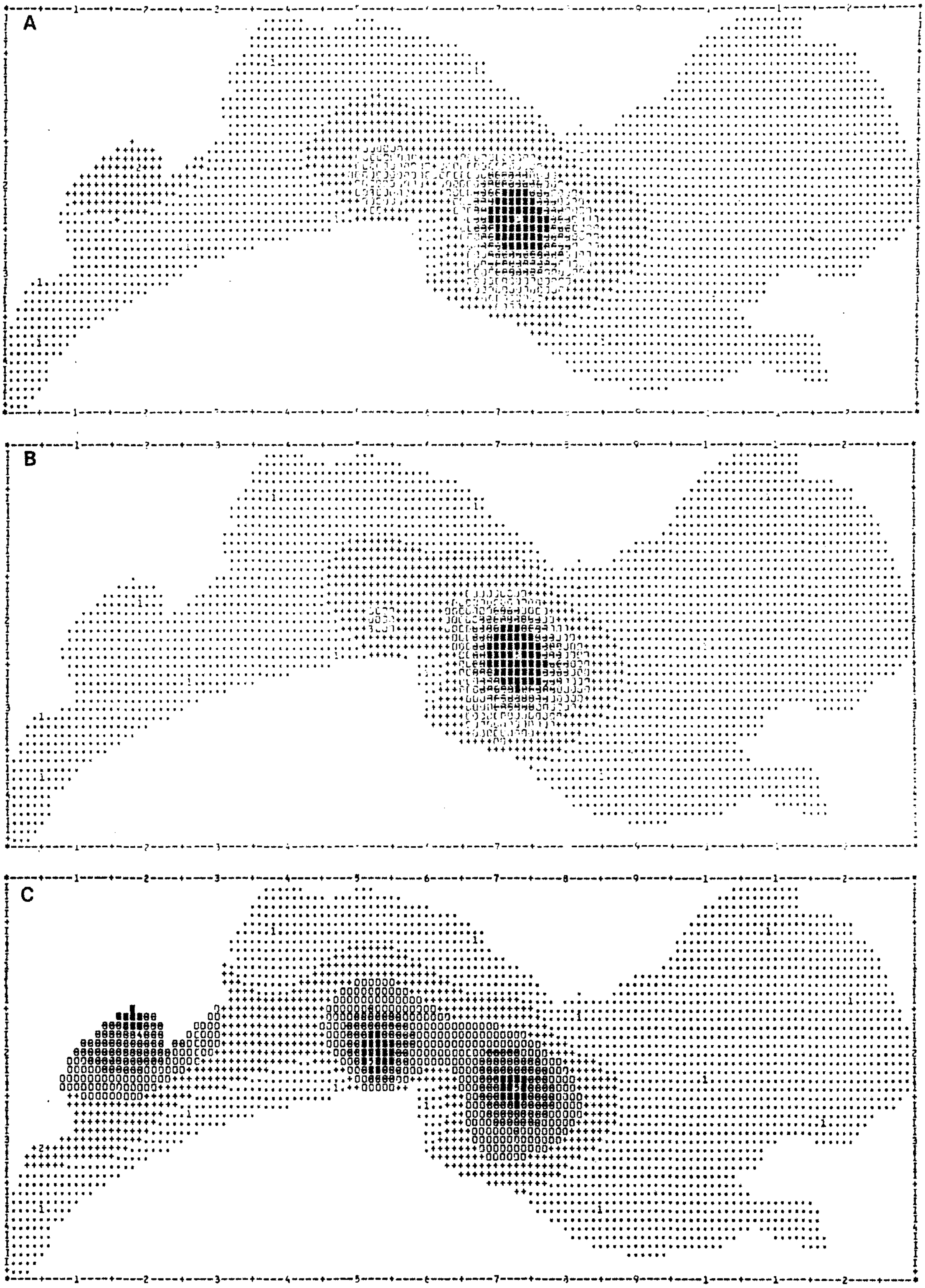


Figure 24. Distribution of sediment properties in Wilson Inlet.
(A) Extractable ammonium nitrogen, July 1982; range 9.0-123μgg^{-1}
(B) Extractable nitrate + nitrite nitrogen, April, 1983; range 0.16-2.76μgg^{-1}
(C) Total nitrogen, December, 1982, range 0.32 – 9.99 mg g^{-1}.
The data are divided into 5 equal size classes.
Dark shading indicates highest relative concentrations.

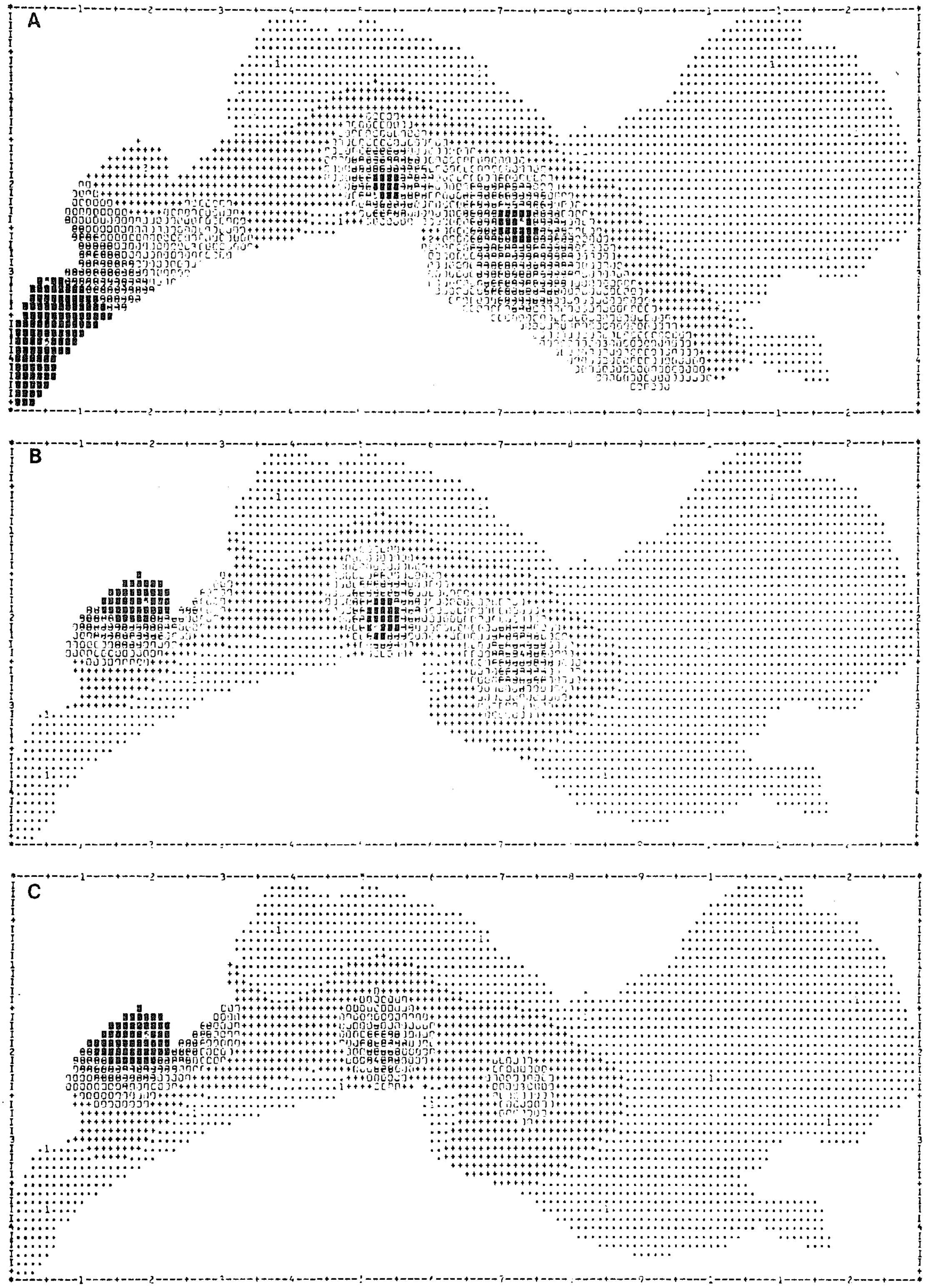


Figure 25. Distribution of sediment properties in Wilson Inlet.
(A) Extractable phosphate phosphorus, July 1982, range 0.40 – 12.50μg g^{-1}.
(B) Total phosphorus, April, 1983; range 0.05 – 1.75 mg g^{-1}.
(C) Chlorophyll 'a', April, 1983; range 2.8 – 45.8μg g^{-1}
The data are divided into 5 equal size classes. Dark shading indicates highest relative concentration.

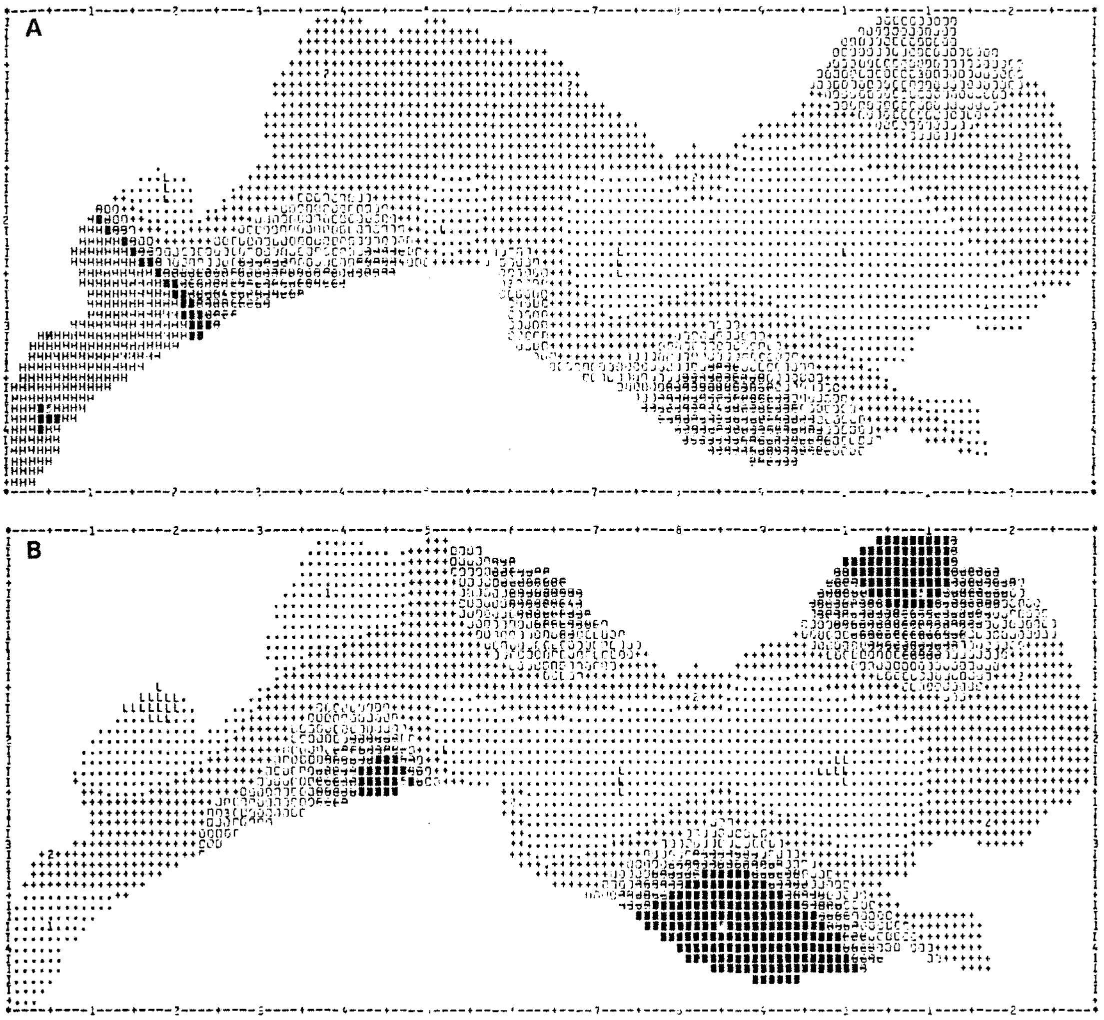


Figure 26. Distribution of *Ruppia* biomass in Wilson Inlet, December 1982.
(A) Above-ground biomass, range 0.0 – 1748.0 g dry wt m^{-2}. The data are divided into 7 size classes, below 2.0 g m^{-2} (L), 5 equal size classes between 2.0 – 400.0 g $m^{-2}$and above 400.0 g m^{-2} (H);
(B) Below-ground biomass, range 0.0 – 132 g dry weight m^{-2}
The date are divided into 6 size classes, below 1.0 g m^{-2} (L), and 5 equal size classes between 1.0 – 132 g m^{-2}.
Dark shading indicates highest relative biomass.

Table 10. Total nutrient content of the water of Wilson Inlet (tonnes)

	July	December	April
Phosphorus			
Phosphate	1.33	0.31	0.14
Organic phosphorus	4.09	5.11	3.48
Total phosphorus	5.42	5.42	3.62
Nitrogen			
Ammonium	5.13	2.07	2.81
Nitrate	1.30	0.57	1.52
Organic nitrogen	175.59	70.27	86.30
Total nitrogen	182.02	72.91	90.63

Table 11. Sediment nutrient content of Wilson Inlet (tonnes)[1]

	July	December	April
Phosphorus			
Extractable phosphate	3.50	1.43	0.57
Total phosphorus	84.65	167.00	196.82
Nitrogen			
Extractable nitrate	0.17	0.28	0.34
Extractable ammonium	20.27	3.68	2.68
Total nitrogen	713.82	1292.19	737.59

[1] Data are for the top 2 cm of sediment

the July study than in either the December or April studies. This was probably the result of trapping, by various processes, sedimentation and remineralisation of N and P from the current year's riverine inflow.

The amount of nutrient contained in plant material was computed by first assessing the total plant biomass (Table 12) and converting this, using the known tissue nutrient concentrations of N and P, to total nutrient content (Table 13). The amount of nutrient contained in plant material in December greatly exceeded the amount of nutrient in the water column at that time; at other times of the year it was comparable. The change from minimum to maximum biomass represents a large change in the amount of phosphorus and, to a lesser extent, nitrogen in this reservoir. It might also be borne in mind that the total biomass, here almost 16,000 tonnes in December, may well have reached 20,000 tonnes a little later in the year when peak *Ruppia* biomass was reached. Clearly the plant material, especially above-ground *Ruppia* biomass, represents a large reservoir of plant nutrients and, as it was largely absent from the estuary in earlier years, this reservoir represents a relatively recent accumulation of nutrients by the estuarine ecosystem.

Table 12. Plant biomass in Wilson Inlet (tonnes)

	July	December	April
Ruppia			
Above-ground	7,704	11,819	9,569
Below-ground	775	2,270	688
Total	8,479	14,089	10,257
Reds	466	1,505	236
Greens	47	8	13
Browns	60	13	35
Total	9,052	15,615	10,541

Table 13. Plant tissue nutrient content of Wilson Inlet (tonnes)

	July	December	April
Phosphorus			
Ruppia above-ground	6.86	22.42	6.28
Ruppia below-ground	0.66	2.74	0.44
Reds	0.23	0.91	1.04
Greens	0.05	0.01	0.004
Browns	0.04	0.03	0.011
Total	7.84	26.11	6.78
Nitrogen			
Ruppia above-ground	158.00	196.00	180.00
Ruppia below-ground	9.75	23.14	9.12
Reds	6.48	25.10	6.24
Greens	0.55	0.16	0.28
Browns	1.09	0.29	0.79
Total	175.87	244.69	196.43

The amount of chlorophyll contained in the water column and surface sediment is shown in Table 14. The amount in the surface sediment (top 1 cm) greatly exceeds that in the water column above it. The total amount of chlorophyll in the Inlet is relatively small compared with the Harvey Estuary, which is of comparable size, and contains approximately 10 tonnes of chlorophyll under non-bloom conditions and 40-50 tonnes of chlorophyll during phytoplankton blooms.

Table 14. Water column and sediment chlorophyll 'a' content of Wilson Inlet (tonnes)

	July	December	April
Water	0.33	0.22	0.23
Sediment	5.52	7.07	4.67
Total	5.85	7.29	4.90

Streamflows

In the absence of fully constructed gauging stations, the accurate determination of streamflow volumes is difficult owing to short time-scale variations in stream hydrographs and in some cases to unstable stream beds. Even daily stage readings proved difficult in some instances where large travel distances were involved. For the purpose of the study it was considered sufficient to estimate streamflow volume by multiplying instantaneous discharge by the appropriate time period (usually a day).

The 1982 winter streamflow at the Denmark River gauging station (603 136) is shown in Figure 27 along with rainfall for the same period. The winter of 1982 proved to be considerably drier than average with rainfall during the three month study period (July — September) being only 57% of the long-term mean rainfall. The drier-than-average winter was reflected even more dramatically in the stream runoff which was only 33.5% of the 22-year mean runoff for those months (Figure 28). The actual rainfall and runoff monthly figures of July, August and September 1982 and their relation to the long-term mean values for Denmark River are given in Table 15.

The temporal variation in rainfall and pan evaporation is shown for the Denmark Agricultural Research Station in Figure 29. For most weeks in June and July, rainfall exceeds pan evaporation and thereafter evaporation exceeds rainfall. During the early months of winter a substantial portion of the rainfall is taken up as soil moisture storage in the catchment. This may account for as much as 250–300 mm of rainfall in forested catchments in this region (Sharma, 1983). Since the maximum of the cumulative rainfall minus evaporation is 190 mm (Figure 29) it is apparent that, if the potential evaporation was attained, the moisture storage capacity of the catchment would not be exceeded and little runoff would be generated. This applies in particular to the central and northern portions of the Denmark and Hay catchments. The runoff that does occur in these areas probably derives from near-surface lateral flow adjacent to streams and by surface runoff from saturated areas occurring transiently in valley bottoms and convergent headwaters and from impermeable rocky outcrops. This surface runoff (and to a lesser extent direct rainfall on streams) will be the main contributor to stormflow. Since most of the streamflow from these catchments is derived from relatively small areas, the leaching of nutrients to drainage will generally be restricted to the same areas.

Small summer baseflows from the Denmark and Hay Rivers indicate that groundwater discharge is additionally contributing to streamflow.

Rainfall measurements and estimates of streamflow volumes of all the study catchments are given in Table 16. The low runoff coefficients of the Denmark and Hay catchments may be explained by reference to Figure 8 which shows the relation of runoff to rainfall with distance from the coast. It is not surprising that the runoff coefficients of these catchments are low, since much of their area lies inland. All the other study catchments lie in the high rainfall zone and their runoff coefficients are correspondingly higher (21 — 40%). The small catchment embodying the Denmark Agricultural Research Station has a particularly high runoff coefficient which may be due to its high percentage of cleared land (90%) and its relatively high drainage density (0.72 km km^{-2}).

Nutrient Concentrations in River Water

The samples collected weekly at the temporary gauging stations (Figure 10) were analysed for major nutrients as described previously. The range in concentration and the flow-weighted mean concentration of each nutrient and for each catchment is shown in Table 17.

Phosphorus is the most important nutrient as regards eutrophication of the Inlet, since algae in similar water bodies have been shown to be primarily phosphorus limited and also because the nitrogen input is less controllable due to fixation from the atmosphere by blue-green algae. The form of phosphorus most readily available to plants is phosphate. From Table 17 it is apparent that the stream concentrations of phosphate are generally low (in the context of eutrophication) with all the catchments, except Denmark Agricultural Research Station, having mean concentrations less than 200 μgl^{-1}. Of particular note is the very low mean phosphate concentrations in the Denmark and Hay River study catchments. In the other catchments the phosphate concentrations are higher indicating greater leaching of applied fertilizer.

Organic phosphorus is less readily available to plants, but may be released over a period of time. Organic phosphorus is seen to predominate in the Denmark River, Scotsdale Brook, Hay River and Lake Sadie Drain study catchments, whereas phosphate phosphorus predominates in the other catchments. As regards total phosphorus, the concentrations are all relatively low with the Denmark and Hay River catchments being significantly lower than the other catchments.

Nitrogen presents a similar picture to that of phosphorus. The forms of nitrogen most readily available to plants, i.e. ammonia,

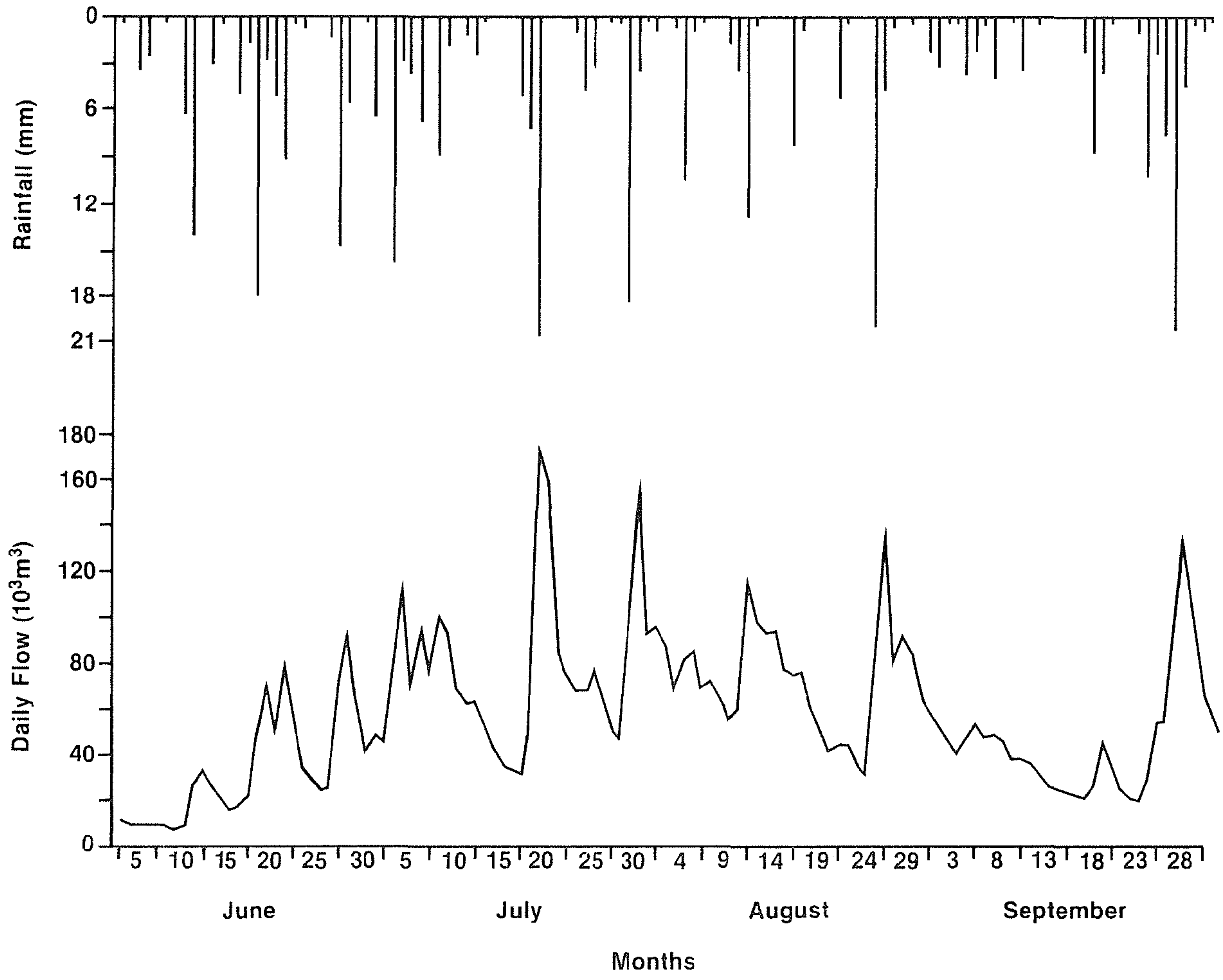


Figure 27. 1982 winter rainfall and runoff at Denmark River gauging station (603 136)

Table 15. Comparison of 1982 rainfall and runoff data to long-term means for Denmark River gauging station (603 136)

Month	mean rainfall (mm)	1982 rainfall (mm)	1982 rainfall / mean rainfall	mean flow (mm)	1982 flow (mm)	1982 flow / mean flow	mean flow / mean rain	1982 flow / 1982 rain
July	197	107	0.54	15.2	4.7	0.31	0.08	0.04
August	148	75.5	0.51	16.9	4.1	0.24	0.11	0.05
September	110	75.6	0.69	10.1	2.5	0.25	0.09	0.03
Total	455	258.1	0.57	42.2	11.3	0.27	0.09	0.04

nitrite and nitrate were found to have low concentrations. Their distribution amongst the study catchments is similar to that of phosphate phosphorus. The total nitrogen concentration was in all cases strongly dominated by organic nitrogen, but levels were again relatively low.

The weekly sampling frequency was naturally inadequate to define stormflow variations in concentration. The concentration time series (Figure 30, 31) at best show general seasonal tendencies but few trends are really identifiable.

Nutrient Loads from Streams

Nutrient loads were calculated by multiplying instantaneous nutrient concentration by weekly discharge. More sophisticated data analyses, for example using flow regressions with the gauged Denmark River streamflow, were not thought worthwhile in view of the associated probable errors. The computed loads for each stream and nutrient over the study period are given in Table 18. Since the sampling stations only represent upstream portions of catchments, the loads have been proportionately augmented to whole catchment areas in Table 19. These results reveal small nutrient inputs to the Inlet, with total phosphorus and nitrogen values of 4.6 tonnes and 42.3 tonnes respectively.

Mean Annual Nutrient Inputs

An over-riding factor in the measurement of baseline catchment runoff and nutrient inputs to the Inlet was low rainfall and runoff during the study period. The low runoff, which reached only one-third of the long-term mean runoff, resulted in the shortest period of inlet-ocean exchange on record.

Runoff is an important factor in determining the amount of nutrient leached from the landscape into the Inlet and it is therefore beneficial to obtain an estimate of nutrient input to the estuary in an average runoff year. To obtain this estimate, the nutrient loads measured during the study period have been proportionately multiplied by annual runoff and long-term mean runoff factors, as shown in Table 20. The proportionality between nutrient load and runoff in the above calculation is an assumption

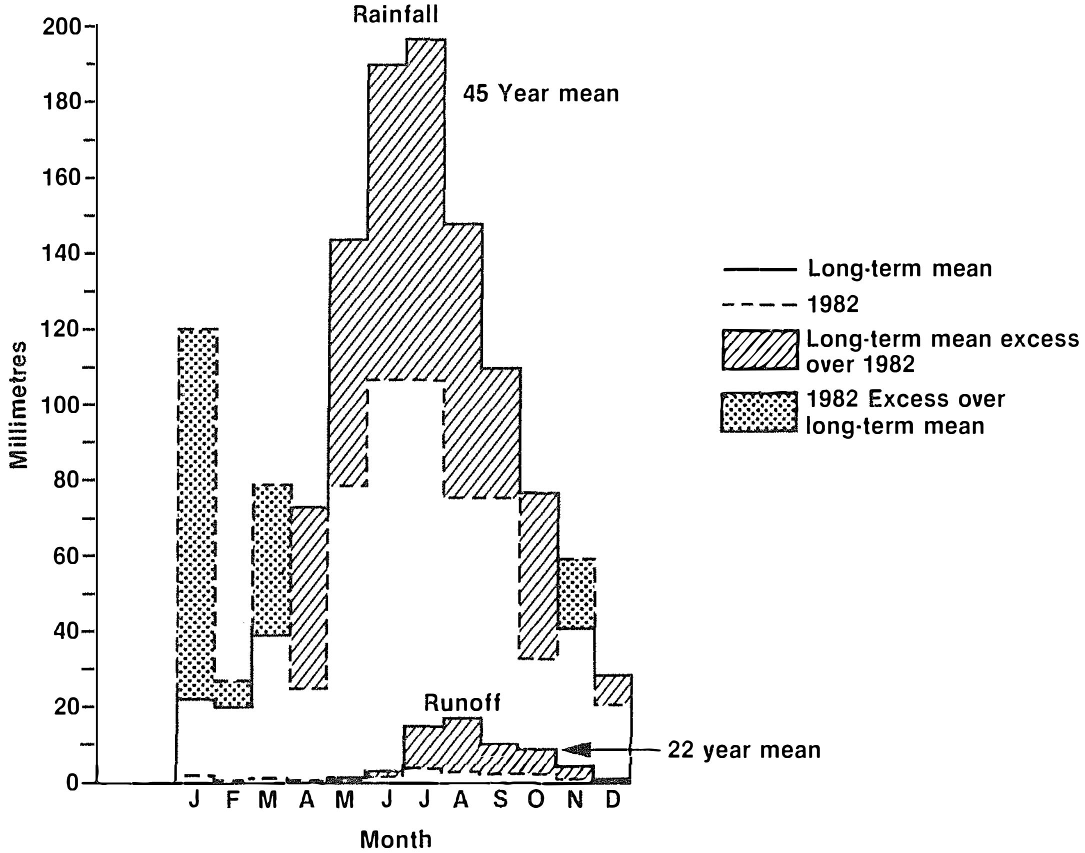


Figure 28. 1982 rainfall and runoff compared to long-term means for Denmark gauging station (603136)

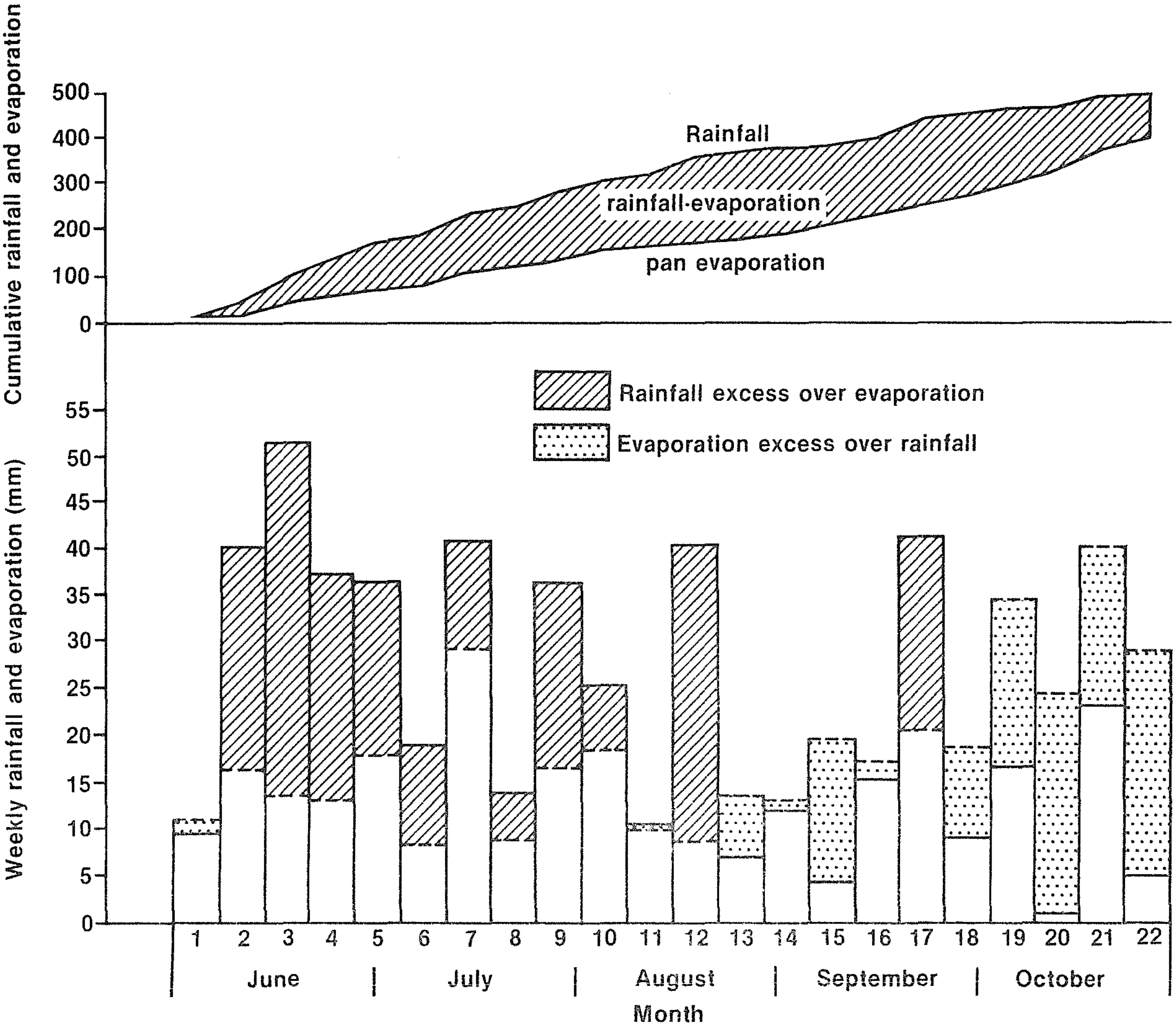


Figure 29. Rainfall and evaporation comparisons at Denmark Agricultural Research Station (June-Oct. 1982)

Table 16. 1982 winter rainfall and runoff values for the Wilson Inlet catchments (12.7.82-27.9.82)

Catchment	Rainfall Station	Rainfall mm	Runoff 10^6m^3	Runoff mm	Runoff/Rainfall
Denmark River	509 183	215	4.73	8.9	.04
Scotsdale Brook	009 647	291	4.84	77.8	.27
Hay River	WAIT2 + 009 581	209	11.72	9.6	.05
Hay Southern Tributary	509 183 WAIT1 + WAIT2	245	1.78	52.2	.21
Sleeman River	WAIT2 × .86	233	5.07	65.1	.28
White River	WAIT2 × .91	246	1.57	57.6	.23
Cuppup River	WAIT2 × .95	257	2.05	54.2	.21
Nemanup/Lake Sadie Drain	WAIT2	271	2.19	55.7	.21
Denmark Agricultural Research Station	WAIT1	249	0.31	99.7	.40

able 17. Nutrient concentration statistics for Wilson Inlet study catchments for the period 17.7.82-27.9.82 (units are $\mu g l^{-1}$)

Catchment	Ortho-phosphate		Organic phosphorus		Total phosphorus		Ammonia		Nitrite-Nitrate		Organic nitrogen		Total nitrogen	
	range	mean*	range	mean	range	mean	range	mean	range	mean	range	mean	range	mean
Denmark River	5-12	8	13-42	30	21-51	36	13-29	20	7-49	26	348-570	509	379-630	553
Scotsdale Brook	19-30	23	30-139	64	14-156	84	16-28	20	26-100	42	297-980	694	346-1036	758
Hay River	7-10	8	19-63	35	27-72	44	10-24	16	4-15	10	343-769	591	372-789	618
Hay Southern Tributary	73-213	116	45-202	85	125-298	202	22-45	34	13-21	17	1192-2743	1716	1271-2778	1561
Sleeman River	43-244	179	53-225	112	99-377	290	14-68	45	5-45	30	1153-3145	2161	1172-3243	2355
White River	21-197	89	47-113	89	92-310	176	14-83	44	3-100	34	1064-1787	1411	1085-1918	1478
Cuppup River	90-448	177	37-100	62	141-448	239	20-36	29	11-80	32	1096-1839	1585	1135-1883	1647
Nemanup/Lake Sadie Drain	14-66	34	31-77	52	55-110	87	18-61	32	3-46	18	667-1355	1157	719-1418	1207
Denmark Agricultural Research Station	193-689	457	1-159	65	290-822	490	32-140	65	22-129	98	1306-3711	2059	1430-3835	2222

Mean refers to flow-weighted mean concentration

Table 18. Total discharge and nutrient loads for proportions of catchments defined by sampling stations for the period 12.7.82-27.9.82

Catchment	Discharge ($10^6 m^3$)	Ortho-P (tonne)	Organic-P (tonne)	Total P (tonne)	Ammonia (tonne)	Nitrate-Nitrite (tonne)	Organic-N (tonne)	Total-N (tonne)
Denmark River	4.73	0.04	0.14	0.17	0.10	0.12	2.39	2.60
Scotsdale Brook	4.84	0.09	0.31	0.41	0.10	0.21	3.36	3.67
Hay River	11.72	0.10	0.41	0.51	0.19	0.12	6.92	7.23
Hay Southern Tributary	1.78	0.21	0.15	0.36	0.06	0.03	3.06	3.14
Sleeman River	5.07	0.91	0.57	1.47	0.23	0.15	10.96	11.33
White River	1.57	0.14	0.14	0.28	0.07	0.05	2.22	2.32
Cuppup River	2.05	0.35	1.10	0.45	0.05	0.07	2.93	3.05
Nemanup/Lake Sadie Drain	2.19	0.08	0.11	0.19	0.07	0.04	2.53	2.64
Denmark Agricultural Research Station	0.31	0.14	0.02	0.15	0.02	0.03	0.63	0.68
Totals	34.3	2.1	2.0	4.0	0.9	0.8	35.0	36.7

Table 19. Discharge and nutrient loads augmented to whole catchment areas*

Catchment	Area factor	Discharge ($10^6 m^3$)	Total P (tonne)	Total N (tonne)
Denmark River	1.21	5.72	0.21	3.15
Scotsdale Brook	1.07	5.18	0.44	3.93
Hay River	1.03	12.07	0.53	7.45
Hay Southern Tributary	1.48	2.63	0.53	4.65
Sleeman River	1.16	5.88	1.71	13.14
White River Cuppup River	1.12	4.05	0.82	6.01
Nemanup/Lake Sadie Drain	1.21	2.65	0.23	3.19
Denmark Agricultural Research Station	1.12	0.35	0.17	0.76
Totals		38.51	4.64	42.28

*For period from 12.7.82 to 27.9.82.

although it is valid for the Harvey catchment. Thus, in conclusion, the nutrient loads to Wilson Inlet in an average runoff year would be of the order of 30 tonnes of phosphorus and 300 tonnes of nitrogen.

Table 20. Augmenting total nutrient inputs to the 1982 year and to an average runoff year

	Phosphorus (tonnes)	Nitrogen (tonnes)
Study period (12.7.82-27.9.82)	4.6	42.3
1982 year (factor = 1.93)*	8.8	81.6
Average runoff year (factor = 3.45)*	30.6	281.7

*these factors are based solely on the Denmark Gauging Station (603 136)

Nutrient Losses to Drainage in Relation to Fertilizer Applied

The artificial fertilizer application statistics for Wilson Inlet catchment over the 1981-82 period are summarised in Table 21. Unfortunately it has not been possible to divide application rates between individual catchments. A total of 16 555 tonnes of superphosphate was applied which corresponds to a mean application rate of 146.8 kg ha^{-1} over the whole catchment. In terms of phosphorus application these figures convert to 1500 tonnes of phosphorus or 13.4 kg ha^{-1}. Against this relatively high input only 0.03kg ha^{-1} of total phosphorus or less than 0.6% of that applied was estimated to be leached to drainage in 1982. This loss is only likely to increase to 2% in an average runoff year.

Table 21. Artificial fertilizer use in Wilson Inlet catchment for 1981-82 (Australian Bureau of Statistics, W.A. office)

	Total no. of holdings Total area of holdings No. of holdings fertilized Area fertilized	523 168,350 ha 450 112,789 ha
Superphosphate	No. of holdings fertilized Total amount applied Mean application rate (assuming whole area fertilized)	397 16,555 tonnes 146.8 kg/ha
Urea	No. of holdings fertilized Total amount applied	12 32 tonnes
Other straight nitrogenous fertilizers	No. of holdings fertilized Total amount applied	28 153 tonnes
Other nitrogenous fertilizers	No. of holdings fertilized Total amount applied	41 392 tonnes
Potash compounds and mixtures not containing N	No. of holdings fertilized Total amount applied	136 2529 tonnes

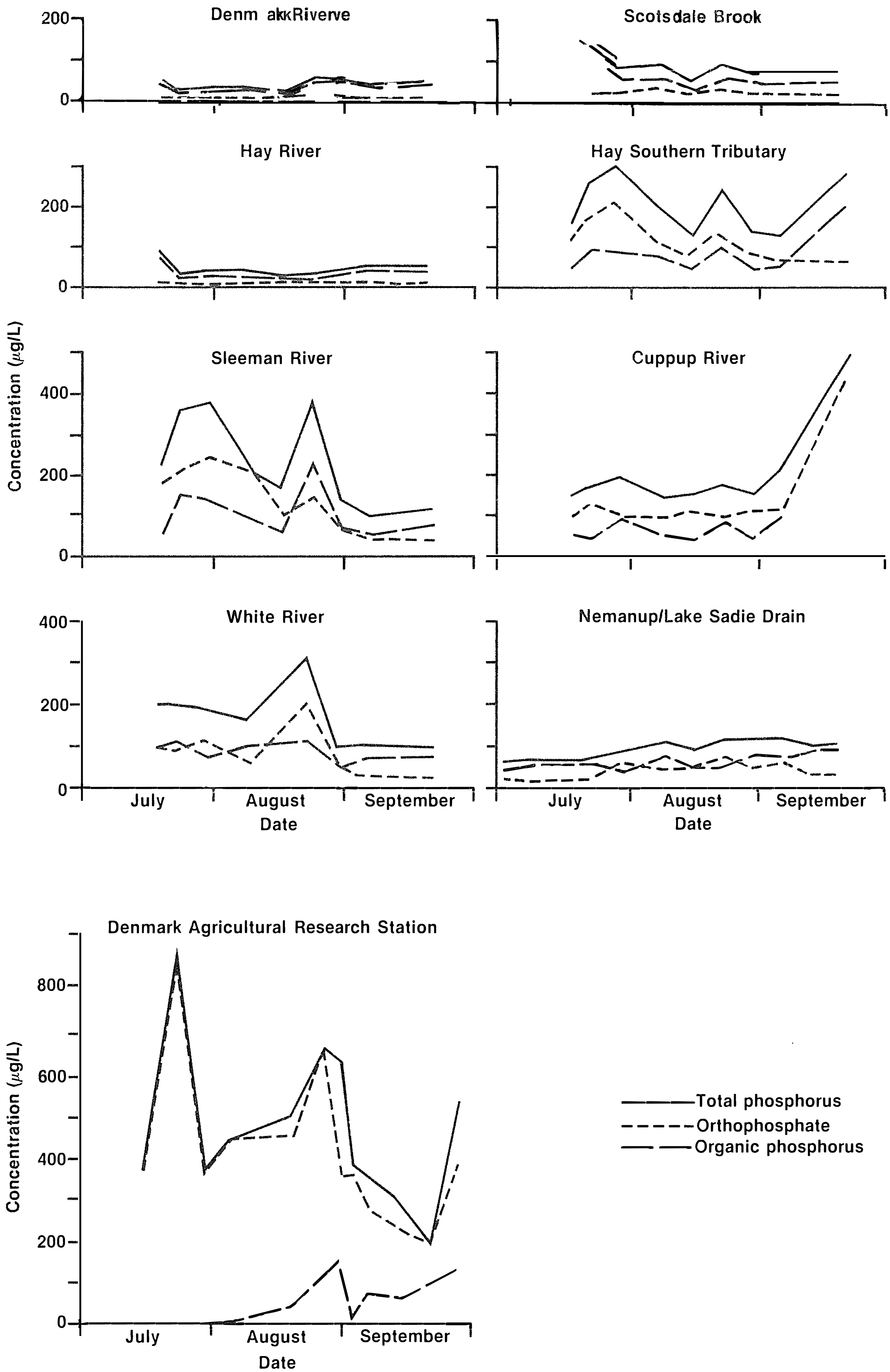


Figure 30. Phosphorus concentrations in Wilson Inlet drainage (July-Sept. 1982)

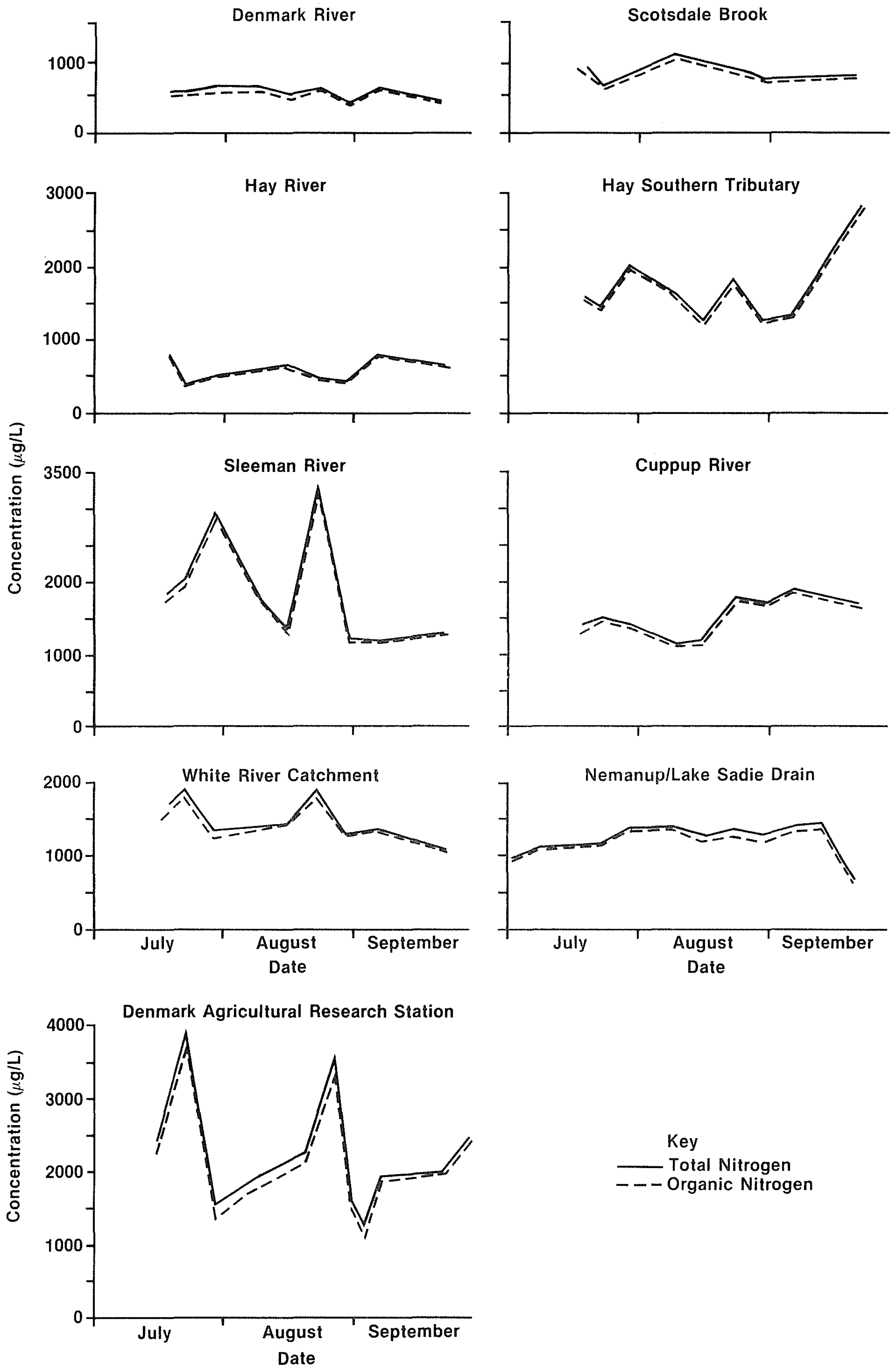


Figure 31. Nitrogen concentrations in Wilson Inlet drainage (July-Sept. 1982)

DISCUSSION

Comparison with Historical Data

Between 1945-52 analyses of the chemical properties of certain south-western Australian estuaries were carried out by CSIRO, and some data were collected from Wilson Inlet (Spencer, 1952). Nitrate and phosphate concentrations in the water from the CSIRO study are compared with the results of the present survey in Table 22, for sites with similar locations and sampling depths. From these limited data, there is no evidence of an increase in concentration at the time of the present study.

Concentrations of total phosphorus and total nitrogen in the surface sediments are compared, for similar sites, in Table 23. Again, there is no evidence of a change in nutrient concentration.

Table 22. Comparison of water quality data for Wilson Inlet collected by CSIRO 1945-52 (Spencer, 1952) and the present study. (Only sites with similar locations and sampling depths are compared).

	CSIRO		Present Study	
PO_4-P (μgl^{-1})	$\bar{X}$[1]	7	$\bar{X}$	5
	range	0-31	range	1-28
	n	13	n	3
NO_3-N (μgl^{-1})	$\bar{X}$	17	$\bar{X}$	8
	range	0-450	range	3-28
	n	13	n	3

[1](Water column mean — surface and bottom)

Table 23. Comparison of surface sediment analyses for Wilson Inlet by CSIRO 1946-50, (Spencer, 1952) and the present study. (Only sites with similar locations and sampling depths were compared)

	CSIRO		Present Study	
Total phosphorus (μg g^{-1})	$\bar{X}$	564	$\bar{X}$	335
	range	160-945	range	80-1340
	n	4	n	3
Total nitrogen (μg g^{-1})	$\bar{X}$	4.4	$\bar{X}$	3.2
	range	1.8-6.7	range	0.8-8.7
	n	4	n	3

There are no firm data for plant biomass in earlier years, but R. Spencer (pers. comm.) does not recall prominent stands of *Ruppia* in the 1945-52 survey. This is in keeping with reports from local residents who, as mentioned in the Introduction, have noticed excessive growths of *Ruppia* only in recent years.

Comparisons with other Systems

Table 5 compares mean nutrient and chlorophyll 'a' levels in the waters of Wilson Inlet with those of the Swan River Estuary and the Peel-Harvey Estuarine System. The data are divided into 'summer' and 'winter' phases, since in these systems river flows may be expected to bring high nutrient concentrations into the estuary. Of the inorganic ions, phosphate and nitrate concentrations are strikingly lower in Wilson than in the other systems, while ammonia is considerably lower than the others, apart from the Swan estuarine basin in summer. Organic phosphorus is also generally lower in Wilson, though comparable with the Swan basin in summer; organic nitrogen is much lower than Peel and Harvey, but higher than the Swan basin in summer.

Chlorophyll 'a' concentrations are again very low when compared with those of other systems (Table 5).

Thus the properties of the open water — nutrient concentration and chlorophyll levels — along with good aeration and light penetration, enable the conclusion to be drawn that the water quality in Wilson Inlet is of a high standard, and better than that of the other systems tabulated.

The surface sediments of Wilson Inlet, Peel Inlet and Harvey Estuary are compared in Table 24 for several occasions. Total phosphorus and total nitrogen are comparable in each. Extractable phosphorus and nitrogen concentrations are more erratic, tending to rise to high levels after dense phytoplankton blooms in Peel Inlet and Harvey Estuary (August 1978). Apart from the peaks, there is some evidence to suggest that extractable phosphorus levels are somewhat higher in Wilson, while

Table 24. Mean Nitrogen and Phosphorus content of the top 2 cm of sediment in Wilson Inlet, Peel Inlet and Harvey Estuary

	Ext. P (mg m^{-2})	Total P (g m^{-2})	Ext. N (mg m^{-2})	Total N (g m^{-2})
Wilson Inlet				
July 1982	83.4 ± 20.6[2]	2.1 ± 0.4	404 ± 30	15.2 ± 2.5
December 1982	32.5 ± 4.3	3.7 ± 0.6	84 ± 7	28.1 ± 3.2
April 1983	12.9 ± 1.6	4.2 ± 0.5	65 ± 9	16.4 ± 2.3
Peel Inlet[1]				
March 1978	10.8 ± 3.7	2.0 ± 0.2	144 ± 32	22.6 ± 1.7
August 1978	88.6 ± 32.9	2.2 ± 0.3	1147 ± 285	21.7 ± 2.1
March 1979	6.6 ± 1.4	2.3 ± 0.2	200 ± 25	18.1 ± 3.1
September 1979	11.9 ± 1.8	2.4 ± 0.2	108 ± 12	18.1 ± 3.1
Harvey Estuary[1]				
March 1978	18.1 ± 5.3	2.1 ± 0.2	170 ± 23	23.9 ± 1.0
August 1978	100.2 ± 20.2	2.5 ± 0.2	1117 ± 175	23.6 ± 2.5
March 1979	6.3 ± 1.0	2.3 ± 0.2	311 ± 29	19.2 ± 5.0
September 1979	15.8 ± 3.2	2.1 ± 0.2	143 ± 16	15.5 ± 1.7

[1] Gabrielson, 1981

[2] ± standard error

extractable nitrogen levels are comparable. Overall, however, the picture is one of general comparability in the sediments of the three systems.

As noted elsewhere, however, it is the biomass of *Ruppia* which is such a striking feature of Wilson Inlet. It is difficult to compare plant biomass for different systems, but peak biomass of *Ruppia* is given in Table 8 for sites in Wilson Inlet, Peel Inlet, and the Blackwood River Estuary; the high biomass at Wilson Inlet is clear.

More generally, there are no real guidelines for the trophic status of water bodies in Australia. Sawyer (1952) suggested that nuisance algal growth could be expected when the concentration of inorganic P and N equalled or exceeded 10 μgl^{-1} and 300 μgl^{-1} respectively. The levels of inorganic N and P in Wilson Inlet were well below these levels all year.

Vollenweider's (1971) table for trophic levels in lakes is widely used for classifying water bodies.

	Total P (μgl^{-1})	Inorganic N (μgl^{-1})
ultra — oligotrophic	<5	<200
oligo — mesotrophic	5-10	200-400
meso — eutrophic	10-30	300-650
eu — polytrophic	30-100	500-1500
polytrophic	>100	>1500

The yearly average total phosphorus level is 42 μgl^{-1} which places Wilson Inlet in the eu-polytrophic class. Total inorganic nitrogen, however, has a yearly average of 32 μgl^{-1} which places the Inlet in the ultra-oligotrophic class.

Vollenweider quotes a classification based on chlorophyll from Sakamoto (1966) —

oligotrophic	0.3 — 2.5 μgl^{-1}
mesotrophic	1 — 15 μgl^{-1}
eutrophic	5 — 149 μgl^{-1}

The yearly surface average for Wilson Inlet is 3.0 μgl^{-1} which places it in the mesotrophic class. Overall Wilson Inlet could be classified as a mesotrophic water body in comparison with these fresh water data. Wilson Inlet is very similar in terms of nutrient levels and trophic status to Princess Royal Harbour, Albany (Atkins *et al.*, 1980).

Catchment Runoff and Nutrient Levels

Evaluation of Hydrologic and Physiographic Factors Controlling Nutrient Loss to Drainage

To assess the importance of different hydrologic and physiographic factors, Table 25 summarises the nutrient drainage losses and compares them to some key catchment indices. Excessive leaching of phosphorus to drainage has been associated in the Peel-Harvey catchment with a number of these factors, namely:

(i) clearing of native land for agriculture and the subsequent application of superphosphate fertilizer;

(ii) high rainfall and high runoff;

(iii) surficial sands of low phosphorus adsorption capacity;

(iv) high drainage densities.

The significance of the above factors has been borne out in the Wilson Inlet catchment. With the exception of their southern extremities, the Denmark River and Hay River catchments contribute by far the lowest nutrient losses in terms of g ha^{-1}, an important finding because these two catchments comprise 89% of Wilson Inlet catchment. The main factors contributing to their low nutrient losses are their low runoff coefficients (.07), their proportion of sand (2-24%) and significant areas of uncleared land (Denmark 22%, Hay 54% private land cleared).

Scotsdale Brook, which is actually a tributary of the Denmark River, makes a significant contribution to the total nutrient load because of its high runoff coefficient, high rainfall location, high drainage density and large proportion of deeply incised valleys. The very low concentrtion of phosphate in this stream reflects the virtual absence of sandy soils and a 50% proportion of uncleared land.

Markedly higher mean nutrient concentrations, particularly phosphate phosphorus, are evident in the Hay Southern Tributary, and the Sleeman, White and Cuppup Rivers. In each case it appears that the high proportion of cleared sandy soils and high runoff coefficients have resulted in widespread leaching of applied fertilizer into drainage.

The comparatively low mean nutrient concentrations of the Nemanup — Lake Sadie Drain must reflect the high proportion (96%) of uncleared land in this catchment. In contrast, the Denmark Agricultural Research Station stream had the highest mean nutrient concentrations which is probably due to the high degree of clearing (90%), the high runoff coefficient (0.4), the high drainage density (0.72 km km^{-1}) and the fertilizer history of this catchment.

Comparison to the Peel-Harvey Estuarine System

The Peel-Harvey estuarine system is a eutrophic water body exhibiting serious environmental problems. The cause of eutrophication has been identified as large-scale nutrient leaching of artificial fertilizers from the coastal plain catchment of the system. Table 26 compares the estimated annual phosphorus inputs to Wilson Inlet with four years of data from the Peel-Harvey system (Birch pers. comm.). A most important factor as regards eutrophication is the total phosphorus load to a water body. A comparison of the two data sets shows that the total phosphorus input to Wilson Inlet is less than 25% of the Peel-Harvey input. This proportion is likely to be an upper estimate because in all but one year of the Peel-Harvey data set runoff was well below average. As regards mean phosphorus concentration, that of the Wilson Inlet is significantly lower. Also of interest is the difference in nutrient concentration between plateau landforms and the coastal plain in both systems. On this basis it can be concluded that the Peel-Harvey system is much more disposed to eutrophication due to its relatively large coastal plain component which contains significant areas of low phosphorus adsorbing, well-drained sands under high rainfall which have been cleared for agricultural use.

Loss of Nutrients due to Bar Opening and Subsequent Exchange with the Ocean

The total volume of Wilson Inlet was calculated using the data presented in Figure 2 and interpolating contours. The total volume at mean sea level was calculated to be 85 x $10^6 m^3$. Before the bar was opened the estuary exceeded mean sea level by approximately 1.0 m, so the volume lost when the bar was breached was estimated to be 48 x $10^6 m^3$. Because of strong long-shore currents at the mouth of the estuary it is assumed that this water was totally lost to the system. The phosphorus and nitrogen loads lost to the sea were computed by multiplying the estimated water loss by the concentration in estuary water which, as shown earlier, was relatively uniform over large areas. The losses are included in Table 27. It is useful to recall, for comparative purposes, the total amounts in the water column and plant material at the time (Tables 10 and 13).

It is more difficult to estimate closely the effect of water exchange between the Inlet and ocean after the bar had been breached, as direct experimentation of

Table 25. **Nutrient leaching in relation to catchment hydrologic and physiographic factors**

Catchment	Area (ha)	Drainage Density (km km^{-2})	P^{+} loss to drainage		N loss to^{+} drainage		Rainfall^{+} (mm)	$\frac{\text{Runoff}^{+}}{\text{Rainfall}}$	Land Tenure (%)					Landform Units (%)								
			g ha^{-1}	μgl^{-1*}	g ha^{-1}	μgl^{-1*}			1	2	3	4	5	1	2	3	4	5	6	7	8	9
Denmark River	70339	0.32	3	36	49	550	215	.04	21.5	11.9	65.3	0	1.3	0	6.8	64.4	6.3	5.6	13.8	1.8	1.3	0
Scotsdale Brook	6685	0.90	66	85	590	758	291	.27	48.9	43.6	6.5	0	1.0	0	0	8.4	24.8	0	66.8	0	0	0
Hay River	130143	0.44	4	44	59	617	209	.05	53.6	17.7	26.8	1.9	0	24.4	8.2	13.1	39.7	12.2	0	1.7	0.7	0
Hay Southern Tributary	5033	0.63	106	202	921	1764	245	.21	37.0	31.5	31.5	0	0	0	12.2	0	51.3	0	0	36.5	0	0
Sleeman River	9058	0.43	189	290	1455	2234	233	.28	75.4	22.3	2.3	0	0	75.9	1.9	0	0	0	0	5.1	0	0
White River	2727	0.51	103	178	851	1478	246	.23	61.9	33.8	4.3	0	0	0	0	0	0	0	2.4	86.9	0	10.7
Cuppup River	3782	0.38	119	220	807	1488	257	.21	84.1	15.9	0	0	0	60.2	0	0	0	0	10.3	29.5	0	0
Nemanup-Lake Sadie Drain	4739	0.32	48	87	671	1205	271	.21	4.3	36.5	59.2	0	0	0	0	0	0	0	0	30.7	0	69.3
Denmark Agricultural Research Station	347	0.72	432	484	2186	2194	249	.40	89.7	10.3	0	0	0	0	0	0	64.1	0	7.6	28.3	0	0

*flow-weighted mean concentration over study period

$^{+}$data refer specifically to study catchments and period

Land Tenure

1. Private land — cleared
2. Private land — uncleared
3. Forest reserves and Crown lands
4. National parks and conservation reserves
5. Townships

Generalised Landform Units

1. Lateritic sandplain swamp and plains with gravelly ridges, leached sands and yellow mottled soils, scrub Jarrah, Yates and sandplain — 'heaths'.
2. Sandy/swampy flats and drainage lines:— Leached sands and podzolic or solodic soils: paperbark swamps, dense scrub and scattered trees.
3. Laterite plateau and uplands:— Duricrust on ridges. Gravels and sands in depression over kaolinitic clays: Jarrah forest formation.
4. Rolling dissected lateritic country:— Gravelly ridges, but mainly yellow podzolic soils:— Jarrah on ridges, Wandoo and swamp Yates in valleys.
5. Moderately incised valleys, or gentle slopes:— Gravelly yellow podzols and red earths. Alluvium valleys: Jarrah-Marri forest.
6. Deeply incised valleys or steep slopes:— Podzolic soils up-slope, red earths mid-slope, alluvium in valleys: Karri-Marri forest.
7. Coastal dunes and swampy coastal plains, calcareous or leached sands, humus podzols, gravelly knolls, Peppermint thickets, sand heaths and sedgelands.
8. Granitic ranges and outcrops and shallow colluvial soils.
9. Coastal sand dune.

Table 26. Comparison of phosphorus inputs to the Peel-Harvey Estuary and Wilson Inlet systems

	Phosphorus load (tonnes)	Flow-weighted mean phosphorus concentration ($\mu g l^{-1}$)	Predominant land form
Peel-Harvey system (1978-82 averages)			
Harvey River and drains	89	380	Coastal Plain
Serpentine River	39	360	Coastal Plain
Murray River	18	90	Plateau
	Total 146	Mean 260	
Wilson Inlet (estimated annual average)			
Denmark River	4.3	60	Plateau
Hay River	7.1	70	Lateritic dissected
Sleeman River	11.4	290	Lateritic sand plain
Cuppup River White River	4.9	202	Lateritic sand plain & coastal dunes
Nemanup drain	1.5	87	Coastal dunes
Denmark Agricultural Research Station	1.1	484	Lateritic dissected
	Total 30	Mean 117	

Table 27. Estimated mass of nutrient lost to the ocean in 1982 due to bar opening (tonnes)[1]

PO_4-P	- 0.31
Org. P	- 1.66
Total P	- 1.97
NO_3-N.	- 0.40
NH_4-N	- 1.47
Org. N	-63.22
Total N	-65.09
Chlorophyll 'a'	- 0.11

[1] This assumes a water loss to the sea of 48 × $10^6 m^3$

such exchange is fraught with difficulties (Black *et al.*, 1980). Nevertheless some estimates can be made, and for this purpose the nutrient concentrations in ocean water were assumed to be the same as those beyond Garden Island (Sepia Depression) for which yearly average concentration data were obtained for the Cockburn Sound Study (Chiffings, 1979). As a simplistic calculation, we may ignore exchange processes within the estuary itself and imagine a complete replacement of estuarine water by fresh marine water, shown as 100% exchange in Table 28. In fact the exchange would rarely, if ever, be this extreme. In the present study marine water appeared only to penetrate to the site closest to the entrance, suggesting an exchange of less than 10%. Perhaps a 50% exchange might be approached in the years when the bar has remained open for a long period and the salinity of the Inlet water approaches 25‰. Despite the inaccuracy of these figures, however, several conclusions may be drawn from the data. First, losses due simply to bar opening and, in this case, the loss to the ocean of the head of approximately 1.0 metre of water above mean sea level, are responsible for removing more nutrient than subsequent exchange, even when one assumes a considerable replacement of estuary water by marine water. This is largely because the concentration of nutrient in the marine water is not very different from that of the estuary. In years of high rainfall and riverflow the nutrient concentrations in the estuary water may be somewhat higher than those measured in the present study, in which well below average rainfall and runoff were recorded. Under those conditions exchange with the ocean may be more significant. It is also useful to note that the amounts of nitrogen and phosphorus lost from the system by bar opening and subsequent exchange are relatively small compared to the total amount of nutrient bound in plant material, especially in the summer months.

It must also be borne in mind that in addition to the volume of water lost on bar opening, and nutrients lost due to subsequent exchange, water brought into the estuary by subsequent river flow is also lost to the ocean while the bar is open.

Estimated Nutrient Budget for Wilson Inlet

From knowledge of stream inputs and ocean outputs it is possible to calculate water and nutrient balances for one cycle of the sand bar opening and closing. From this analysis the net retention or export of nutrients from Wilson Inlet can be estimated.

The results of the water and nutrient budget calculations are shown in Table 29. Here the nutrient inputs have been computed from flow-weighted mean concentrations of 117 μgl^{-1} phosphorus and 1070 μgl^{-1} nitrogen. Rainfall minus evaporation for the Inlet was based on Denmark Post Office rainfall data and Albany evaporation data. Streamflows were estimated from Denmark gauging station records and the other streamflow values obtained during the study period.

Following closure of the bar on 8th March 1982, the major water input to the Inlet was streamflow since direct rainfall and evaporation loss almost cancelled each other. On 21st July the bar was artificially opened and over the following week the water level in the Inlet fell by 0.76 m (P.W.D. pers. comm.). Taking into account the water inputs during this week, the water components at 28th July almost exactly balanced, although this agreement must be regarded as fortuitous in view of the likely errors in the flow estimates. For the subsequent period of bar opening (until bar closure on 10th September) it is assumed that stream input equals output to the ocean so that there is no net change in the water storage in the Inlet over the bar opening and closing cycle. This assumption allows an estimate of water and nutrient loss to the ocean during the latter period.

The nutrient balances are computed from stream flow-weighted mean concentrations and the Inlet mean concentrations just prior to bar opening. On this basis it is seen that a net retention of 3.8 tonnes of phosphorus occurred in the Inlet. On the other hand, there appeared to be a net loss of 8.9 tonnes of nitrogen from the Inlet. This was brought about by the high organic nitrogen concentrations — the highest recorded — measured in July,

Table 28. Calculated nutrient loss under different flushing regimes (tonnes)

	10% flushing	50% flushing	100% flushing	Water column nutrient content	Plant tissue nutrient content	Sediment nutrient content
Phosphorus	− 0.1	− 0.7	− 1.3	5.4	26.1	167.0
Nitrogen	− 3	− 16	− 32	73	245	1292

Table 29. Estimated nutrient budget for Wilson Inlet (1982-1983)

Sand-bar function	Water Budget				Nutrient Budget					
	Stream-flow Input (10^{6}m^{3})	Rainfall-Evap. on Inlet	Ocean Loss (10^{6}m^{3})	Change in Inlet water storage	P input stream-flow (tonne)	P output ocean (tonne)	P change in Inlet (tonne)	N input stream-flow (tonne)	N output ocean (tonne)	N change in Inlet (tonne)
Closed 8.3.82-21.7.82	26.6	+ 3.6	0	30.2	3.1	0	+ 3.1	28.5	0	+ 28.5
Open 21.7.82-28.7.82	5.1	+ 1.0	− 36.5	− 30.4	0.6	− 1.5	− 0.9	5.4	− 49.5	− 44.1
Open 29.7.82-10.9.82	22.6	+ 2.2	− 24.6*	+ 0.2	2.6	− 1.0	+ 1.6	24.2	− 17.7	+ 6.5
Totals	54.3	6.8	− 61.1	0.0	6.3	− 2.5	+ 3.8	58.1	− 67.2	− 8.9

* value not measured but used to close water balance

prior to bar opening. The high levels may have been the result of wind-induced sediment stirring and the actual levels at the time of bar opening may have been lower which would have resulted in a net retention of nitrogen.

Points to be Considered for Management

Wilson Inlet is showing one major symptom of eutrophication, the large amount of macrophyte growth, and especially *Ruppia*. There is some evidence that this has increased in recent years. On the other hand, water quality is generally good, as indicated by low ambient nutrient levels, low levels of phytoplankton in the water, lack of oxygen depletion, and comparison with other south-western estuaries.

The sediments do not appear to be nutrient enriched (based on limited historical data), but there is a large nutrient bank in the plant biomass. It follows that the prolific growth of *Ruppia* is both a consequence of nutrient enrichment, and the mechanism by which ambient nutrient levels are kept low. The plant material forms a major bank of nutrient in the system, and its removal would greatly reduce the amount of nutrient present. It would also remove the main sink for nutrients trapped in the system, so that if it were practicable to totally remove *Ruppia*, it is possible that undesirable blooms of phytoplankton (including blue-greens) might occur. Care must therefore be exercised in using harvesting as a mechanism for eutrophication control. Nevertheless, harvesting of part of the biomass, which could be carried out in the shallows and near boat ramps, would remove a significant portion of the nutrient bank without eliminating the plant from the estuary.

Opening of the bar allows the escape of estuary water to the ocean, and the amount of nutrient lost at the time of opening is a simple reflection of the height difference between the estuary and sea level. Simple exchange between the estuary and the ocean does not appear to be an important mechanism for nutrient loss, because the concentrations in the ocean are not very different to those in the estuary.

An important effect of having the bar channel open is to allow the loss of river water to the ocean, rather than its ponding and evaporation within the estuary itself. Even in years of weak river flow, significant losses to the ocean may occur. If it were feasible for the bar to be opened earlier (June) and for it to be kept open, significantly greater losses of nutrient may occur because this would greatly reduce the residence time of nutrient-rich river water in the Inlet. This would result in less time for nutrient uptake by plants, and so reduce nutrient retention.

An assessment of the importance of bar opening on the fishery was outside the scope of this study. However, the importance of the timing of the bar opening and length of opening needs hardly to be emphasised as this would greatly influence the recruitment of juvenile fish to the system. This supports the suggestion that the bar should be opened in years of low rainfall when the water level in the Inlet does not reach flood levels.

The major factors governing nutrient inputs to Wilson Inlet have been listed on pages 42-43. On this basis, future land use changes which are likely to increase nutrient input to the estuary are:

- Clearing of native vegetation for agricultural use and the conventional application of fertilizers. This applies particularly to areas of sandy soils under high rainfall.
- Increasing the drainage network.

The most susceptible areas in the above respects are the catchments of the Sleeman, White and Cuppup Rivers, Nemanup-Lake Sadie Drain and the southern extremity of the Hay River catchment. These catchments are all under relatively high rainfall, have 20-40% uncleared private land and 40-100% sandy soils.

Two land use practices which decrease nutrient input to the Inlet have arisen from the Peel-Harvey study, namely the use of less super-phosphate (while still maintaining full agricultural production) and the use of slow-release fertilizers. These methods are still under investigation but, if proven successful, are known to be applicable to the sandy soils of the Albany-Denmark region.

Further Work

Although the overall quality of the Wilson Inlet system is generally good, the large *Ruppia* biomass is indicative of gradual nutrient enrichment. Increased nutrient enrichment will favour the growth of epiphytes on the *Ruppia*, already noticeable in some areas, and this will lead to its eventual demise. *Ruppia* could possibly be replaced by either phytoplankton and/or macroalgae which may lead to a far greater nuisance than the *Ruppia* is at present. Continued low frequency monitoring should be carried out to assess any gradual deterioration. Possibly two grid surveys a year is all that is required, one preferably carried out in winter and the other some time in January at the time of peak *Ruppia* biomass.

An assessment should also be made of the possible application in the Wilson Inlet catchment of any modifications to agricultural practice devised to reduce nutrient inflow into the Peel-Harvey system.

If practicable, experimental harvesting of *Ruppia* should be undertaken in parts of the estuary as a control measure, and the effects of harvesting known amounts of biomass assessed by subsequent monitoring.

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