NUTRIENT LOADING AND PHYTOPLANKTON BLOOMS IN LAKE JOONDALUP, WANNEROO, WESTERN AUSTRALIA

Department of Conservation and Environment
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NUTRIENT LOADING AND PHYTOPLANKTON BLOOMS IN LAKE JOONDALUP, WANNEROO, WESTERN AUSTRALIA

by

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APPENDICES

1. INTRODUCTION

Lake Joondalup is the focus for extensive urban development with the growth of the 'north-west corridor', and the establishment of the Joondalup Regional Centre on the lake's western shore (Stephenson 1977). The lake itself is the dominant feature of the landscape and careful management will be needed if the value of the lake is to be maintained.

The lake is an important waterfowl refuge, and feeding and breeding area (Bekle 1980). In a study of the fauna of the lakes of the northern Swan Coastal Plain, the Western Australian Museum (1978) found that Lake Joondalup produced the greatest number of organisms per sample, and contained all major habitat divisions.

1.1 EUTROPHICATION

Urbanization has long been recognized as a significant factor affecting the water quality of aquatic ecosystems. It generally increases hydrologic and nutrient loading to receiving waters by increasing the amount of impervious area (and thus run-off), raising the water-table due to clearing and watering of lawns and gardens, and increasing the concentration of nutrients in run-off water (Watson, Loucks and Wojner 1981).

Lake Joondalup is already subject to eutrophication (Congdon and McComb 1976; Congdon 1979; Gordon, Finlayson and McComb 1981). Eutrophication is the nutrient enrichment of natural waters, and is manifested as increased algal biomass. The increase in algal biomass, and changes in phytoplankton species composition, can greatly degrade water quality. An increase in the concentration of phosphorus relative to nitrogen (N:P>8) results in a shift to noxious blue-green algae (Schindler 1977), and this ratio can be as important as the absolute level of loading of either nutrient.

For the management of eutrophication, it is important to have base-line data on the seasonal and spatial distributions of nutrients within a lake. Significant sources of nutrients need to be identified so that they can be monitored, and assessed in the light of further development.

Some blue-green algae, such as Anabaena spiroides which already produces blooms in Lake Joondalup (Congdon 1979), cause odour problems and are toxic to waterfowl and other animals. Algal blooms decrease the biological and aesthetic value of a lake, and so careful management is required to reduce eutrophication.

This study was undertaken to determine nutrient loadings to Lake Joondalup, to identify the major sources of nutrient, and to examine the relationship between nutrient concentrations and phytoplankton blooms.

1.2 LAKE MORPHOMETRY AND HYDROLOGY

Lake Joondalup is one of the largest permanent lakes of the Swan Coastal Plain. However, the lake is shallow (Table 1.1), and undergoes large seasonal changes in volume in response to seasonal variation in rainfall and evaporation (Figs. 1.2 and 1.3; Congdon 1985). Since the Metropolitan Water Board first started taking records of water level at the lake, the maximum depth has varied from 2.5 m (September 1980) to 3.3 m (August 1970). At the lowest water level the lake's area had decreased by some 15%. The largest seasonal change on record is for 1970, when the maximum depth varied by 1.5m from March to August, representing a volume change of $6.9 \times 10^6 m^3$ and an area increase of 25%.

Surface water flows into the lake from the Wallubuenup/Beenyup Swamp system to the south, and from stormwater sumps. In 1980 88% of surface discharge into the lake came from the southern swamps (Congdon 1985).

1.3 SAMPLING SITES AND DATA BASE

Most of the water quality data collected during this study has been stored on computer tape and punched cards to form a data base for future analysis and reference. Site numbers recorded in the computer data are based on the order and frequency of sampling of the sites, with distinctive numbers used for sites other than those in the lake (Appendix 1). For simplicity, in this report sites have been renumbered consecutively from north to south (Figs. 2.3 and 2.4).

2. SEASONAL AND SPATIAL CHANGES IN PHYSICAL AND CHEMICAL ASPECTS

2.1 INTRODUCTION

Previous studies have examined seasonal changes in Lake Joondalup on a monthly or two monthly basis (Congdon and McComb1976; Gordon, Finlayson and McComb 1981). The earlier study was based on the mean concentrations from 6 sites (details for individual sites given in Congdon 1973), and the latter on bulked water samples from 9 sites, from within the main waterbody of the lake.

To further our understanding of the nutrient dynamics and inputs to the lake, it was necessary to examine short-term temporal variation, and spatial variation in more detail. In particular, possible sources of nutrients to the lake had to be monitored regularly to quantify their significance in the nutrient budget of the lake. These included stormwater and water flowing from the Wallubuenup/Beenyup Swamp system to the south.

Other nutrient pools which can influence the lake nutrient budgets are the lake sediments and vegetation, and the study also briefly examined the nutrient stocks held within these components.

2.2 MATERIALS AND METHODS

2.2.1 SAMPLING PROGRAMME

Several sites were sampled regularly from September 1978 to December 1980 to monitor seasonal and spatial changes in nutrient concentrations. Early samples were collected at 2 to 4 week intervals, but from November 1978 samples were collected at least weekly from sites 19, 34, 36, 37, 46 and 47 (Table 2.1).

Sites 19 and 34 were located on the western shore of the main lake basin, and site 37 on the eastern shore (Fig. 2.1). When site 37 was inaccessible due to falling water levels and the build up of decaying algae aided by the prevailing south-westerly winds, water samples were taken from nearby site 35.

Samples were collected twice weekly from site 57 when water began flowing into Lake Joondalup from the south in May 1980. Twice-weekly samples were also taken from site 46 when water began flowing through the culvert under Ocean Reef Road in June 1980, and from site 36 in the stormwater sump at the end of Ariti Avenue in July 1980.

Samples were collected when water was flowing into the stormwater sumps on Edgewater Drive and Ariti Avenue, in order to characterise the nutrient status of storm water. Such samples were only collected after heavy rains when water was flowing from stormwater drains.

Water samples were collected from Beenyup Swamp (site 59) and Lake Goollelal (site 73) monthly (Fig. 2.2). Wallubuenup Swamp was sampled when water was present at accessible sites after winter rain. Samples were collected from the northern section at sites 65 to 69, on either side of Woodvale Drive. Site 70 was located at a culvert under Whitfords Avenue, at the southern end of the swamp. Since very high nutrient concentrations were found at this site, and these were much higher than concentrations in Lake Goollelal, sites 71 and 72 were sampled between Hocking Road and Whitfords Avenue. Site 72 was located in a drainage channel which runs between these two roads. Very little surface water was seen in the channel during the period of the study and sample were very turbid and so were filtered through a Whatman's GF/C glass filter paper prior to analysis. Site 71 was situated in a swamp draining into the culvert, and lying a few hundred metres west of market gardens and a caravan park.

For comparisons between sites, site 46 has been grouped with sites 47 and 54, in the southernmost basin of Lake Joondalup, since it is affected principally by the flow of water from this basin.

2.2.1.1 Grid Studies

Grid studies, in which a large number of sites was sampled within a few hours, were done to quantify the total nutrient loading within the lake, and to examine spatial patterns. The number of grid studies undertaken was limited by low water levels, especially between January and June (Table 2.2). Sampling sites are shown in Figures 2.3 and 2.4.

Sediment samples were only collected during the December 1978 and July 1979 grid studies. A small grid study, of sites in the southern basin of Lake Joondalup only, was done in November 1979 during a blue-green algal bloom. Sites in Beenyup Swamp, other than site 59, were only sampled during the July 1979 grid study.

2.2.2 PHYSICOCHEMISTRY OF THE WATER COLUMN

2.2.2.1 Sample Collection and Handling

Water samples were collected from just below the surface at each site. Samples for nutrient analysis were dispensed into150 ml sealable, sterilized polyethylene bags (Whirl-paks, NASCO, Kansas, U.S.A.). All samples were put on ice immediately after collection for transport to the laboratory. Nutrient samples were then frozen until analysed (MacDonald and McLaughlin 1982).

2.2.2.2 Phosphorus

Reactive phosphorus (PO_4 -P - often referred to as orthophosphate) was determined by the single solution method (Major, Dal Pont, Klye and Newell 1972). Total phosphorus (TP) was determined by the same method after perchloric acid digestion to mineralize organic phosphorus. The digestion was carried out in 25 x 200 mm test tubes heated in a block digester (American Public Health Association 1971; McGlynn 1974).

2.2.2.3 Nitrogen

Ammonium-nitrogen (NH_4 -N) was determined by the indophenol method (Dal Pont, Hogan and Newell 1974). An autoanalyzer (Technicon Autoanalyzer II, Technicon Industrial Systems, Tarrytown, New York) was used in the determination of nitrate plus nitrite (Technicon Method No. 158-71W, 1972). In natural waters, nitrite concentrations are typically 10% or less of the nitrate concentration. Elsewhere in this report the "nitrate plus nitrite" fraction will be referred to as "nitrate" (NO_3 -N) for convenience.

Total nitrogen (TN) was obtained by summing nitrate plus nitrite and Kjeldahl nitrogen. Kjeldahl digestion was used to reduce organic nitrogen to ammonium-nitrogen (APHA 1971), and this was determined using an autoanalyzer method (Technicon Method No 329-74W/B, 1977).

2.2.2.4 Dissolved and Particulate Phosphorus and Nitrogen

Occasional samples were analysed to gain some idea of the amount of particulate phosphorus and nitrogen that they contained. Samples were filtered through 0.45 mm membrane filters (Millipore HAWP 04700) and then analysed for total dissolved nitrogen and phosphorus as described above. The particulate fraction was then calculated by subtracting these values from the total nitrogen and phosphorus values.

These samples were collected between 2 May and 29 November 1979, between 22 May and 12 June 1980, and on 24 January 1980.

2.2.2.5 Alkalinity and pH

Alkalinity was determined by titration against dilute acid to pH 8.3 for phenolphthalein alkalinity, and pH 4.8 for total alkalinity (American Public Health Association 1971), using an automatic titrator (W G Pye & Co Ltd, Cambridge). pH readings were taken as soon as possible, on return to the laboratory (Model E488, Metrohm Ltd, Herisau, Switzerland or W G Pye & Co Ltd, Cambridge).

2.2.2.6 Optical Densities and Humic Substances

Various methods were used to trace the distribution of humic acids or yellow substance in the lake and southern swamps. Optical densities were measured at 370, 430, 530 and 630 nm using a spectrophotometer (Varian UV/Visible Model 634S, Varian Techtron Pty Ltd, Mulgrave, Victoria) (Golterman 1975), and at 440 nm for yellow substance (Kirk 1976). On one occasion humic substances were determined semi-quantitatively by the trichromatic method of Lawrence (1980), using wavelengths of 280, 300 and 370 nm.

2.2.3 PHYSICOCHEMISTRY OF THE SEDIMENTS

2.2.3.1 Sample Collection and Handling

Samples were collected with sediment corers made of PVC pipe 4.5 cm in diameter, placed in 50 ml plastic (Duranol) vials and frozen for storage. Samples were taken from each core at 0 - 5 cm and 20 - 25 cm during the July 1979 grid study. Deeper samples were taken early in July 1979 from two sites. Three samples were taken to 37 cm at site 12 and four samples were taken at 57 cm at site 16. These were the deepest cores obtainable at these sites with the corer used.

2.2.3.2 Sediment Density

The volume and weight of each sediment sample was determined, after thawing, so that the density and nutrient content per unit of sediment surface area could be calculated.

2.2.3.3 Water Content

Porcelain crucibles (50 ml) were dried in an oven at 110°C, cooled in a desiccator for 2 hours and weighed. Each vial of thawed sediment was mixed well, and 5 to 10 g of sediment weighed into the crucibles. These samples were dried at 110°C overnight and weighed. The water content was then calculated as a percentage of the fresh sediment weight.

2.2.3.4 Organic Matter and Carbonate Content

Organic matter was estimated by loss on ignition in a muffle furnace at 550°C for 1 hour, and carbonate by subsequent loss on ignition at 950°C for 1 hour (Dean 1974). After each ashing distilled water was added, the sample dried at 110°C overnight, cooled in a desiccator and then weighed, to correct for lattice water loss during the ignition step (Marchant and Williams 1977).

2.2.3.5 Soluble Nitrogen and Phosphorus

Several solvents have been used to determine extractable or available nutrients in soils and sediments (Cottenie and Kiekens 1981); however, the meaning of the results in terms of natural processes is not always clear. Luscombe, Syers and Gregg (1979) have found that water extracts of soil phosphorus give a better relationship with plant productivity than conventional extraction techniques. To gain some estimate of the potential availability of nitrogen and phosphorus in Lake Joondalup sediments, samples were extracted in deionized distilled water and analyzed for soluble forms of nitrogen and phosphorus.

Five grams of each sediment sample were dispensed into a 500 ml erlenmeyer flask, 350 ml of deionised distilled water added and the flasks shaken vigorously. The flasks were left standing for 3 hours, with occasional shaking. The sediment suspensions were then filtered through a 0.45 µm membrane filter (Millipore HAWP 04700) and the filtrate bagged in Whirlpaks and frozen for later analysis. Each extraction was duplicated, and analyzed for soluble reactive phosphorus (SRP), total soluble phosphorus (TSP), nitrate + nitrite (SNOX), ammonium-nitrogen (SNH) and total dissolved nitrogen (TDN). Soluble organic phosphorus (SOP) and soluble organic nitrogen (SON) were calculated by subtraction of the inorganic forms from the totals. Methods of analysis were as described in section 2.2.2.

2.2.3.6 Total Nitrogen and Phosphorus

Total nitrogen was determined after Kjeldahl digestion (H_2SO_4 and Hg catalyst) of 2 g of sediment, by an autoanalyzer method (Technicon methods No 334-74 W/B and No 369-75 A/B, 1977).

Total phosphorus was determined by the single solution method (Major et al 1972) after digestion with perchloric and nitric acids.

2.3 RESULTS

2.3.1 PHYSICOCHEMISTRY OF THE WATER COLUMN

2.3.1.1 Phosphorus

- Differences between sites

Mean reactive phosphorus concentrations in the main waterbody of the lake were 40 to 54 μg P l^{-1} with a range of individual observations from 4 to 402 μg P l^{-1} (Table 2.3). Sites in the southernmost basin of the lake had mean concentrations of 217 to 412 μg P l^{-1} with a range of 20 to 1102 μg P l^{-1} (Table 2.4). High concentrations were found to the south of the lake where site 57 had a mean of 283 μg P l^{-1} (range 4 to 622 μg P l^{-1}) and Beenyup Swamp (site 59) had a mean of 373 μg P l^{-1} (range of 106 to 1036 μg P l^{-1}) (Table 2.5). The same trend of increasing concentration towards the south also applies for organic phosphorus (Tables 2.3 to 2.6).

Very high concentrations of reactive phosphorus were found in samples of water taken from sites in Wallubuenup Swamp (Table 2.6). The mean concentration recorded for site 70, at the culvert under Whitfords Avenue, was 545 μg P l^{-1} (range of 268 to 771 μg P l^{-1}) and at site 71 the mean was 1037 μg P l^{-1} (range of 481 to 1362 μg P l^{-1}).

Reactive and organic phosphorus concentrations were higher in Lake Goollelal than in the main waterbody of Lake Joondalup, but lower than at the southern sites (Table 2.5). Comparatively low levels of phosphorus were found in stormwater samples taken from the sumps (Table 2.7). Reactive phosphorus gave mean concentrations of 14 to 26 μg P l^{-1} and organic phosphorus 11 to 52 μg P l^{-1}.

Using the criteria for total phosphorus concentrations and lake trophic status, all of the lake sites would be classified as eutrophic using the systems of Sakamoto (1966) and Cullen Rosich and Bek (1978), and eu-polytrophic to polytrophic using Vollenweider's (1971) system (Table 2.8).

- Seasonal changes

  - Main waterbody

Sites in the main waterbody of Lake Joondalup showed the general trend of the highest concentrations of phosphorus occurring from late summer to early winter, when the water levels were lowest (Table 2.9, Figs. 2.5 and 2.10). Overall, much higher reactive phosphorus concentrations were found in 1980 than 1979, and this may be related to the lower water level attained in 1980.

Samples from site 19 showed a general increase in reactive phosphorus concentrations and decrease in organic phosphorus concentrations through 1979. There was a large decrease in concentrations in autumn 1980, as the water level increased due to increasing rainfall (Figs. 2.5c and 2.10c).

Water samples could not be collected from site 37 during late summer and autumn 1980 due to falling water levels and the build-up of decomposing algae, so samples were taken from nearby site 35. These samples showed low levels of reactive phosphorus compared to sites 19 and 34 at this time (Fig. 2.5b), and may indicate seepage of phosphate-deficient groundwater at this site.

- Southernmost basin

Phosphorus levels were usually much higher in the southernmost basin than in the main waterbody. Samples from site 47 had particularly high concentrations of reactive phosphorus from late spring to early autumn, but concentrations were still of the order of 200 to 300 μg P l^{-1} during winter (Fig. 2.6). High reactive phosphorus concentrations often coincided with low organic phosphorus concentrations (Fig. 2.11).

Samples of water flowing through the culvert under Ocean Reef Road (site 46) contained high concentrations in winter which decreased into spring, and this may be related directly to flow (Fig. 2.8a). Generally organic phosphorus concentrations were much lower than reactive phosphorus concentrations (Fig. 2.11a).

- Site 57 and Beenyup Swamp

Site 57 showed high concentrations of reactive phosphorus during winter and spring, and much lower levels in summer and autumn when there was no surface flow from Beenyup Swamp (Fig. 2.8b). Samples taken in summer and autumn were of groundwater seepage and contained 4 to 91 μg reactive P l^{-1}, with a modal value of about 50 μg P l^{-1}. A concentration of 622 μg reactive P l^{-1} was recorded in late winter 1980. Organic phosphorus concentrations showed the same trend but were more variable in winter and spring (Fig. 2.12a).

Water samples from Beenyup Swamp showed high concentrations of reactive phosphorus throughout the year. Peak concentrations of both reactive and organic phosphorus were recorded in autumn 1979 and 1980 when water levels were lowest (Figs. 2.9 and 2.13). Concentrations in excess of 400 μg reactive P l^{-1} were recorded in winter and spring.

- Wallubuenup Swamp

The few water samples collected from Wallubuenup Swamp showed peak phosphorus levels in late winter to early spring, although reactive phosphorus concentrations were always high. Site 72 had relatively low phosphorus concentrations when compared with sites 70 and 71 (Fig. 2.14).

- Stormwater sumps

Water samples from the stormwater sump adjacent to Lake Joondalup's eastern shore (site 36) contained comparatively low levels of phosphorus. Highest concentrations of reactive phosphorus were recorded in late spring and early summer (43 to 47 μg P l^{-1}) but peaks of 25 to 43 μg P l^{-1} occurred at other times (Fig. 2.9c). Organic phosphorus concentrations rarely exceeded 50 μg P l^{-1} except for a large peak (151 μg P l^{-1}) in summer 1979 (Fig. 2.13c).

- Lake Goollelal

The Lake Goollelal site showed peaks of 780 μg reactive P l^{-1} and 287 μg organic P l^{-1} in February 1979, but concentrations did not exceed 200 μg P l^{-1} during 1980 (Figs. 2.9 and 2.13). Organic phosphorus peaked in summer and autumn, and was lowest in winter and spring.

2.3.1.2 Nitrogen

- Differences between sites

Sites in the main waterbody gave mean ammonium-nitrogen concentrations of 37 to 102 μg N l^{-1}(range of 5 to 1024 μg N l^{-1}), although site 35 had higher concentrations (x = 335 μg N l^{-1}, range of 11 to 1684 μg N l^{-1}) which is probably attributable to seepage of ammonium-rich groundwater or to high rates of denitrification as this site was generally only sampled when water levels were low and the sediments very active (Table 2.3).

Higher concentrations were recorded in the southernmost basin where the means were 96 to 173 μg NH_4-N l^{-1} and the range 1 to 1864 μg NH_4-N l^{-1} (Table 2.4). Lower values were found in samples collected to the south of Lake Joondalup (Tables 2.5 and 2.6).

Sites 57 and 59 (Beenyup Swamp) had mean concentrations of 50 and 71 μg NH_4-N l^{-1} with an overall range of 1 to 597 μg NH_4-N l^{-1}; sites in Wallubuenup Swamp had means between 22 and 58 μg N l^{-1} with a range of 18 to 288 μg N l^{-1}; and Lake Goollelal had a mean of 81 μg NH_4-N l^{-1} with a range of 7 to 529 μg N l^{-1} .

Low levels of ammonium-nitrogen were found in the stormwater sumps where the means ranged from 19 to 41 μg N l^{-1} and the range was 1 to 166 μg N l^{-1} (Table 2.7).

Nitrate concentrations were low in the main waterbody of the lake; the means covered the range 2.5 to 9.7 μg l^{-1}(total range was 1 to 76 μg N l^{-1}) (Table 2.3). Concentrations were higher in the southern basin where the means ranged from 14.8 to 26.5 μg N l^{-1} and the total range from 1 to 383 μg N l^{-1} (Table 2.4).

Concentrations as high as 850 μg NO_3-N l^{-1} were recorded at site 57 at times of surface flow (mean = 32.4 μg N l^{-1}, range of 1 to 850 μg N l^{-1}) although the highest concentration recorded in samples from Beenyup Swamp (site 59) was only 32 μg N l^{-1} (Table 2.5). This may be due to a lower frequency of sampling of Beenyup Swamp.

Very high nitrate concentrations were recorded in samples taken from sites 70 and 71, at the southern end of Wallubuenup Swamp (Table 2.6). Site 70 gave a mean of 2382 μg N l^{-1} and a range of 1 to 7000 μg N l^{-1}, and site 71 a mean of 1320 μg N l^{-1} with a range of 37 to 3075 μg N l^{-1}.

Higher nitrate concentrations were found in Lake Goollelal than in Lake Joondalup (Table 2.5), where the mean was 40 μg N l^{-1} and the range 1 to 173 μg N l^{-1}. Stormwater samples from the sumps also contained high concentrations. Means ranged from 36 to 78 μg NO_3-N l^{-1} and the overall range was 1 to 360 μg N l^{-1} (Table 2.7).

Trends for organic nitrogen are less clear but the highest concentrations were found at the southern sites (sites 47 and 54) and the lowest in the stormwater sumps (Tables 2.4 and 2.7).

- Seasonal changes

  - Main waterbody

Nitrogen concentrations in the main waterbody of Lake Joondalup tended to peak in summer-autumn, with high levels being recorded in 1980 (Figs. 2.15, 2.19, and 2.24, Table 2.9). Concentrations in excess of 100 μg NH_4-N l^{-1} were present in summer and autumn and they exceeded 300 μg NH_4-N l^{-1} in 1980, suggesting that high ammonium-nitrogen concentrations are related to low water levels. Comparatively low NH_4-N concentrations were recorded in winter and springs of 1979 and 1980, although high peaks (>200 μg NH_4-N l^{-1}) were present in spring 1978. Peak NH_4-N concentrations were much higher at sites 35 and 37 than at sites 19 and 34 (Fig. 2.19), as discussed above.

Nitrate concentrations peaked in summer 1979 at all sites and there were peaks in summer 1980 at site 34 and early spring at site 19 (Fig. 2.19). Higher peaks were recorded at site 37 (and 35) in late autumn of 1979 and 1980, where concentrations exceeded 60 µg NO_3-N l^{-1}. Concentrations at all sites were generally less than 10 µg NO_3-N l^{-1}.

Organic nitrogen concentrations peaked in autumn with very high concentrations being recorded in autumn 1980 at sites 19 and 34 (Fig. 2.24).

. Southernmost basin

Ammonium-nitrogen concentrations in the southernmost basin of Lake Joondalup (site 47) peaked in late spring - early summer, with levels higher than 1,000 µg NH_4-N l^{-1} at those times (Fig. 2.16). These peaks followed blooms of the nitrogen-fixing blue-green alga Anabaena spiroides (see Chapter 4), and probably represent nitrogen released on collapse of the blooms, some of which may have been derived from nitrogen fixation. Concentrations were generally less than 200 µg NH_4-N l^{-1} at other times.

Concentrations of NH_4-N in water flowing through the Ocean Reef Road causeway culvert (site 46) were usually less than 200 µg NH_4-N l^{-1} at times of high flow, with a peak of 205 µg l^{-1} in August 1979, when there was also a minor peak (179 µg l^{-1}) at site 47. Concentrations higher than 200 µg NH_4-N l^{-1} were recorded at site 46 when there was little flow through the culvert, reaching 820 µg l^{-1} in December 1979, and again, these high peaks occurred after blooms of Anabaena spiroides.

A high peak in nitrate concentration was recorded in early summer 1979 at site 47 (383 µg NO_3-N l^{-1}), and minor peaks in early spring of 1979 (51 µg l^{-1}) and 1980 (42 µg l^{-1}) (Fig. 2.20b). Site 46 also had a peak in early spring 1979 (59 µg l^{-1}), spring 1980 (58 µg l^{-1}) and in late winter 1980 (98 µg l^{-1}) (Fig. 2.20a), at times when water was flowing through the culvert. High concentrations were recorded in early autumn (80 µg l^{-1}) and early winter 1979 (120 µg l^{-1}) when there was no flow.

High concentrations of organic nitrogen were found at site 47 in December 1978 (early summer), November 1979 (late spring) and March 1980 (late summer), following blooms of Anabaena spiroides (Fig. 2.25). High organic nitrogen concentrations were also associated with blue-green algal blooms at site 46, in autumn 1979 when there was no flow through the culvert and in spring 1979 as flow was decreasing (Fig. 2.25).

. Site 57 and Beenyup Swamp

To the south of Lake Joondalup, a high NH_4-N peak (597 µg NH_4-N l^{-1}) occurred at site 57 in autumn 1980 (Fig. 2.17b), at the time of a nitrate peak and following an algal bloom. Concentrations rarely exceeded 100 µg NH_4-N l^{-1} at other times. In Beenyup Swamp (site 59) NH_4-N peaked in early winter (210 µg l^{-1}) and late spring 1979 (140 µg l^{-1}), and in spring 1980 (150 µg l^{-1}), while concentrations were low over summer; less than 30 µg l^{-1} (Fig. 2.17c).

Peaks in the nitrate concentrations were recorded at site 57 in late winter 1979 (850 µg NO_3-N l^{-1}), and autumn and winter 1980 (to 440 µg l^{-1}) (Fig. 2.21b). The autumn peak followed an algal bloom (see Fig. 4.3), otherwise levels were low when there was no surface flow from Beenyup Swamp (less than 20 µg l^{-1}). Nitrate concentrations recorded for Beenyup Swamp were much lower, 32 µg l^{-1} being the maximum (Fig. 2.22a). Maxima were recorded in late winter - early spring and these peaks did not follow peaks in chlorophyll a, so it appears that the high concentrations recorded at site 57 were derived from in situ nitrogen-fixation in autumn and local seepage of nitrate at other times.

Organic nitrogen concentrations at site 57 did not show the same amount of variation as the inorganic forms, but a peak (2410 μg N l^{-1}) was recorded in April 1980, towards the end of the algal bloom (Fig. 2.25d). Organic nitrogen levels peaked in early autumn (4400 μg l^{-1} in 1979 and 23396 μg l^{-1} in 1980) in Beenyup Swamp, at the time of low water levels and high chlorophyll a concentrations (Fig. 2.26).

. Wallubuenup Swamp

Samples from the Wallubuenup Swamp sites contained relatively low concentrations of ammonium-nitrogen, the only level in excess of 100 μg NH_4-N l^{-1} was a peak of 288 μg l^{-1} recorded at site 70 following a high peak in nitrate concentration (Fig. 2.28). High levels of nitrate were recorded at the culvert under Whitfords Avenue (site 70) in late winter 1979 (7000 μg NO_3-N l^{-1}), mid-spring 1979 (5000 μg l^{-1}) and winter and spring 1980 (several readings above 2000 μg l^{-1}) (Fig. 2.28). Few seasonal samples were taken from the other sites in Wallubuenup Swamp but a peak of 3075 μg l^{-1} was recorded at site 71 in late winter. Samples from the other sites contained low nitrate levels (11 out of 14 samples contained less than 8 μg NO_3-N l^{-1}, the others being site 69 - 118 μg l^{-1} in April 1980, and site 72 - 90 and 313 μg l^{-1} in August and September 1980).

Like ammonium-nitrogen, organic nitrogen levels showed little seasonal variation, except for a peak of 23,294 μg N l^{-1} recorded at site 69 in April 1980. As this site was adjacent to a paddock, animal waste may have been responsible for this high level.

. Stormwater sumps

Ammonium-nitrogen concentrations in water samples from the sump on the eastern shore of Lake Joondalup (site 36) showed no distinct seasonal trends. Concentrations were usually less than 50 μg NH_4-N l^{-1}, but peak concentrations of 166 μg l^{-1} and 66 μg l^{-1} were recorded in late winter 1979 and summer 1980 (Fig. 2.18).

There was, however, a marked seasonality in the concentration of nitrate (Fig. 2.23). Concentrations peaked in late winter - early spring indicating a large nitrate input in stormwater (up to 233 μg NO_3-N l^{-1} in 1979 and 360 μg l^{-1} in 1980), as concentrations were generally less than 20 μg l^{-1} when stormwater runoff was not significant.

. Lake Goollelal

Samples from Lake Goollelal showed NH_4-N peaks in late summer 1979 (529 μg l^{-1}) with smaller peaks in winter 1979 (171 μg l^{-1}), winter 1980 (129 μg l^{-1}) and spring 1980 (149 μg l^{-1}) (Fig. 2.17).

Nitrate peaked in late summer 1979 (145 μg NO_3-N l^{-1}), and in winter 1979 (173 μg l^{-1}) and 1980 (160 μg l^{-1}) (Fig. 2.22).

Organic nitrogen peaked in autumn of both years (1724 μg N l^{-1} in 1979 and 2914 μg l^{-1} in 1980), following peaks in chlorophyll a concentration (Fig. 2.26).

2.3.1.3 Inorganic Nitrogen to Phosphorus Ratio

In the main waterbody of Lake Joondalup, the ratio of inorganic nitrogen to phosphorus was highest in spring 1978 (N:P = 117:1 at site 19), and to a lesser extent in summer 1980 at sites 19 and 34 (Fig. 2.30). A ratio of N:P = 57:1 was recorded at site 37 in autumn 1979. These peaks coincided with high ammonium-nitrogen levels. However, at other times the N:P ratio did not exceed 15:1, indicating that inorganic nitrogen may generally be limiting algal production at these sites (Redfield 1958).

In the southernmost basin of the lake the highest inorganic N:P ratio recorded was only 16.7:1, at site 47 in August 1979 (Fig. 2.31). Peaks in the N:P ratio occurred at times when ammonium-nitrogen concentrations were high, such as in November1978 and December 1979 at sites 46 and 47. Overall, the N:P ratio was very low (less than 2:1) so that inorganic phosphorus was relatively more plentiful than inorganic nitrogen.

Samples collected from site 57, Beenyup Swamp (site 59) and Lake Goollelal (site 73) usually contained low inorganic N:P ratios. A peak of 32.6:1 at site 57 in autumn 1980 was associated with high nitrate and ammonium-nitrogen levels at a time when there was no surface flow (Fig. 2.31). Minor peaks of 3.3:1 to 6.5:1 at other times were associated with high nitrate levels. A peak of inorganic N:P of 11.0:1 in September 1980 in Lake Goollelal was associated with a high level of ammonium-nitrogen. These data suggest that inorganic nitrogen would be more limiting to algal production than inorganic phosphorus in these waters.

High inorganic N:P ratios were recorded in the stormwater sump at site 36, during winter and early spring (88:1 in 1979 and 137:1 in 1980) due to the high concentrations of nitrate present (Fig. 2.32). At other times the ratio was less than 15:1, suggesting that nitrogen would be more limiting than phosphorus during the warmer months.

2.3.1.4 Dissolved and Particulate Phosphorus and Nitrogen

At the sites in the main waterbody, the mean dissolved phosphorus concentrations were 31 to 40% of the mean total phosphorus concentrations at the times of sampling (Table 2.10). Dissolved phosphorus made up a larger proportion of the total in southern sites - 58 to 76% in the southernmost basin of the lake, 67% at site 57, 74% in Beenyup Swamp (site 59), and 81% in Lake Goollelal (site 73) (Tables 2.11 and 2.12). Stormwater from sumps off Ariti Avenue contained 59 to 60% dissolved phosphorus (Table 2.12). So, on average, the particulate fraction was only larger than the dissolved phosphorus fraction in the main waterbody of the lake.

The mean reactive phosphorus concentrations exceeded the mean dissolved phosphorus concentrations at all sites except site 54, where only five samples were taken, and the stormwater sumps off Ariti Avenue. This supports the contention that the molybdenum blue analysis for phosphate also includes some larger molecular fractions (Stainton 1980), although some ortho-phosphate may be adsorbed onto clay or silt particles and included in the particulate fraction. Filtration artifacts are also possible (Tarapchak, Bigelow and Rubitschun 1982).

Total dissolved phosphorus (TDP) comprised 60 to 68% of the mean reactive phosphorus for sites in the main waterbody, 82 and 87% for sites 46 and 47 in the southernmost basin, 81% for sites 57 and 59 (Beenyup Swamp), and 90% for Lake Goollelal. Reactive phosphorus was 96% of the mean total dissolved phosphorus at site 54 and 68 to 71% in the stormwater from the sumps. Hence, about 30% of the dissolved phosphorus in stormwater is organic phosphorus.

Most of the nitrogen was found in the dissolved fraction. In the main waterbody mean total dissolved nitrogen (TDN) concentrations were about 75% of the mean total nitrogen concentrations, except for site 35 where it was 83% (Table 2.14). TDN was 64 to 79% of the total for sites in the southern basin (Table 2.15), 90% at site 57, 83% in Beenyup Swamp (site 59) and 64% in Lake Goollelal (site 73) (Table 2.16), and 70% at site 36, and 83% in the Ariti Avenue sump (Table 2.17).

Most of the dissolved nitrogen was organic; only 2 to 11% was inorganic in the main waterbody, 5 to 8% in the southern basin, 7% at site 57, 8% in Beenyup Swamp, 15% in Lake Goollelal, 13% at site 36, and 24% in the sump on Ariti Avenue. This reflects the high proportion of nitrate and low organic nitrogen in stormwater over winter.

2.3.1.5 pH and Alkalinity

Lowest pH and alkalinity levels were generally recorded in winter, and the pH of samples decreased with distance south in the lake (Table 2.18 and Appendix 2). This suggests the flow of humic substances from Wallubuenup Swamp into Lake Joondalup during winter. pH readings of 6.8 for sites 57 and 68 in July 1979 are particularly low.

The data suggest an increase in total alkalinity with distance south, but there is insufficient data to substantiate this trend.

High pH readings in the southernmost basin of Lake Joondalup in November 1979 were associated with a blue-green algal bloom (Appendix 2), indicating the production of CO_2 in respiration of the bloom and its decomposition.

2.3.1.6 Optical Densities and Humic Substances

Optical densities increased with decreasing wavelength (from 530 to 250 nm), and also with distance south in the Lake Joondalup/Beenyup Swamp/Wallubuenup Swamp system (Appendix 2, Fig. 2.33). Optical densities of water samples from the Ariti Avenue sump (site 36) and Lake Goollelal (site 73) were comparatively low.

High optical densities in the blue-ultraviolet region of the spectrum indicate the presence of yellow substance (gilvin) or humic acids (Kirk 1976; Larsen and Rockwell 1980; Lawrence 1980). The data show that the water flowing from Wallubuenup Swamp to Lake Joondalup is coloured by these substances.

Fulvic acid concentrations usually fall within the range1 - 10 $\mu g\ l^{-1}$ in natural waters (Lawrence 1980). Concentrations determined in the current study all exceeded 37 $\mu g\ l^{-1}$ (Table 2.19), with a peak reading of 351 $\mu g\ l^{-1}$ for site 71 which lies south of Whitfords Avenue.

Rose (1979) used gel (Sephadex) permeation chromatography to investigate the humic substances in Lake Joondalup waters and their possible origins. He found that these substances appeared to be the same throughout the lake with molecular weights ranging from 500 to 50,000, and that they gave the same scans as various plant leachates.

Alderdice, Craven, Creswick and Johnson (1978) investigated humic substances in swamps in the Myall Lakes region of NSW and found humic acids of MW 28,000 to 42,000 and fulvic acids of MW 3,600 to 6,600.

2.3.2 PHYSICOCHEMISTRY OF THE SEDIMENTS

2.3.2.1 Density, Loss on Ignition and Carbonate

- Differences between sites

Sediment density was inversely related to loss on ignition, since organic matter is less dense than sand (Tables 2.20 and 2.21). The densest sediments (>1.3 g fresh weight cm^{-3}) were located at site 37, where a very sandy bottom suggests a possible area of groundwater seepage, and some northern sites (sites 5 and 11) (Fig. 2.34).

Highest organic matter contents (>65% dry weight), as indicated by loss on ignition, were recorded in the small northern basin (site 1) and the southern section of the lake, north of the Ocean Reef Road causeway (sites 38, 40-42), where decomposing Baumea articulata sedge was relatively abundant (Fig. 2.35). There was a significant correlation between loss on ignition and water content (Tables 2.20 and 2.21), showing that more organic sediments hold more water, as would be expected.

Carbonate content was inversely related to loss on ignition (Tables 2.20 and 2.21), showing that there is decreasing carbonate with increasing organic matter content of the sediments. Low carbonate levels (<11%) were found at site 1 and the southern sites, while high carbonate levels (>44%) were found at sites 5 and 14 (Appendix 3).

Changes with depth

Sediment profiles examined in July 1979 showed decreasing organic matter (loss on ignition) with depth to 57 cm (Table 2.22). This is consistent with the presence of a metaphyton layer at the surface. This trend was confirmed over a larger area during the grid study of 42 sites conducted in July 1979 also (Table 2.23). Mean sediment density and carbonate content showed little difference between the two depths sampled during the grid study, although carbonate showed some variation in the deeper core.

Seasonal differences

Sediment density, loss on ignition and carbonate content showed no appreciable difference between the December 1978 and July 1979 grid studies (Table 2.23).

2.3.2.2 Phosphorus

Differences between sites

Sediment phosphorus concentrations varied considerably over the lake (0.002 to 8.25 mg TP g^{-1} dry weight) (Table 2.23). Total phosphorus concentrations were significantly correlated with sediment density, water content, loss on ignition and carbonate content during the December 1978 grid study, although the more extensive data collected during the July 1979 grid study only yielded a significant correlation between total phosphorus concentrations in the surface sediments and loss on ignition (Tables 2.20 and 2.21). Highly significant correlations were found between TP, TSP and SRP in surface sediment samples collected during the December 1978 and July 1979 grid studies (Tables 2.20 and 2.21). Deeper samples, taken in July 1979, only showed a significant correlation between the TSP and SRP fractions (Table 2.21).

Highest sediment phosphorus concentrations were found in the southern regions of the lake, north of the Ocean Reef Road causeway (Appendix 3). In July 1979, high phosphorus concentrations (>1.5 μg TP g^{-1} dry weight, >150 μg TSP g^{-1} , and >175 μg SRP g^{-1}) were also found at northern sites (sites 5, 10, 12); sites not sampled in December 1978.

In the deeper sediments (20 to 25 cm) sampled in July 1979, the highest total phosphorus concentration (1.13 mg P g^{-1} dry weight) was recorded at site 54, in the southernmost basin, south of Ocean Reef Road (Appendix 3). Relatively high levels of total soluble and soluble reactive phosphorus fractions were again found at sites 5, 10 and 12, although TSP only exceeded 150 μg g^{-1} dry weight at sites 4 and 20, and SRP did not exceed 34 μg g^{-1} dry weight.

Changes with depth

Sediment cores taken in early July show a large decrease in total phosphorus concentration with increasing depth (Table 2.22). This corresponds to a decrease in organic matter (as loss on ignition) with increasing depth. The mean concentrations of TP, SRP and TSP were also significantly lower in the deeper samples collected during the grid study than in the surface samples (Table 2.23).

Seasonal changes

Few seasonal data were collected but the mean total phosphorus concentration of surface sediment samples collected in December 1978 was less than that of similar samples collected in July 1979 (Table 2.23). This may indicate a loss of phosphorus to the water column during summer due to turbulence from wind at low water levels or to increased biological activity and mineralization of organic phosphorus at higher temperatures. Soluble reactive phosphorus and TSP showed no appreciable difference between the two grid studies.

2.3.2.3 Nitrogen

- Differences between sites

Sediment nitrogen concentrations varied considerably over the lake (Table 2.23), with the highest concentrations being found in the southern region of the lake, north of Ocean Reef Road (Appendix 3). The highest concentrations of soluble nitrogen were found at site 5 in the northern basin during July 1979.

The concentrations of all nitrogen fractions were positively correlated with loss on ignition, except for SNH and SNOX in the surface samples taken in July (Tables 2.20 and 2.21). Particularly significant correlations were found for the deeper sediments. Nitrogen fractions were also generally well correlated with water content and again most significantly for the deeper samples taken in July 1979, suggesting that soluble (organic) compounds in the interstitial water contain much of the nitrogen.

- Changes with depth

Nitrogen, like phosphorus and loss on ignition, showed a decrease in concentration with increasing depth in cores taken in early July 1979 (Table 2.22). Deep samples (20 to 25 cm) taken during the July 1979 grid study also contained lower mean concentrations of all nitrogen fractions, except soluble nitrate, than the surface samples (Table 2.23).

- Seasonal changes

The few seasonal sediment data collected indicate lower concentrations of soluble ammonium, soluble organic nitrogen and total nitrogen in December 1978 than in July 1979, as was the case with total phosphorus (Table 2.23). Soluble nitrate showed no appreciable difference between the two grid studies.

2.3.2.4 General

Soluble phosphorus forms (SRP and TSP) were correlated with soluble ammonium (SNH) and soluble nitrate (SNOX) in the surface sediments (Tables 2.20 and 2.21). Total nitrogen (TN) was correlated with total phosphorus (TP) and TSP. The December 1978 data also produced significant correlations between TP and SNH and soluble organic nitrogen (SON), and the July 1979 surface sediment data between TN and SRP, and between SNOX and SRP and TSP.

Deeper samples taken during the July 1979 grid study gave significant correlations between SNOX and TP and SRP, and between SON and TP, SRP and TSP (Table 2.21).

2.4 DISCUSSION

2.4.1 SPATIAL PATTERNS

Within the main waterbody of Lake Joondalup, sites 35 and 37 on the eastern shore gave significantly higher organic phosphorus, NH_4-N, NO_3-N and lower chloride concentrations than the other regularly sampled sites (Table 2.3). The lower chloride concentrations and the presence of dense, sandy sediments (Fig. 2.34b) suggest that the higher levels of nutrients may originate from groundwater seepage. The direct influence of the sediments cannot be ignored as site 35 was usually only sampled when water levels were low and temperatures high over summer. Methane bubbles indicated that the sediment was very active at this time and high rates of denitrification are possible.

In Wallubuenup Swamp high reactive phosphorus and NO_3-N concentrations were recorded and these decreased with distance north, to Lake Joondalup. Lower concentrations were found in Lake Goollelal so the data suggest a large input of phosphate and nitrate into Wallubuenup Swamp at the southern end. Highest concentrations were found at sites 70 and 71, near Whitfords Avenue. Mean concentrations were lower at site 72, in the channel which would connect Lake Goollelal with Wallubuenup Swamp at times of very high water levels. Possible sources of nutrients near sites 70 and 71 are market gardens and a caravan park, although market gardens also occur north of Whitfords Avenue (Fig. 1.1).

The proportion of dissolved phosphorus also increased with distance south, from Lake Joondalup to Lake Goollelal. The dissolved fraction was 30 to 40% of the total in the main waterbody of Lake Joondalup, 74% in Beenyup Swamp and 80% in Lake Goollelal. However, mean reactive phosphorus concentrations exceeded TDP concentrations, so this does not confirm a hypothesis that the southern swamps are contributing a large load of dissolved organic phosphorus to the lake. If decomposing swamp vegetation was yielding a significant phosphorus load to the lake, one would expect a large organic fraction.

Highest concentrations of organic phosphorus, NH_4-N and organic N were recorded in the southern basin, during late spring/early summer or autumn when blue-green algal blooms had reached peak levels. Much lower concentrations of nitrogen were recorded at site 57 at these times and it is likely that some of the high nitrogen concentrations result from in situ nitrogen fixation by Anabaena blooms. High nitrogen concentrations in autumn 1980 may have also been due to evaporation, as the water level was very low. A high organic phosphorus concentration (1218 $\mu g\ P\ l^{-1}$) was recorded at site 54 in mid autumn 1980 when water had just begun flowing from Beenyup Swamp and the total phosphorus concentration at site 57 was less than 200 $\mu g\ P\ l^{-1}$. This implies that the sediments may have contributed phosphorus or that the high concentration resulted from evaporation, as reflected by the low water level.

Stormwater samples contained high concentrations of NO_3-N and low concentrations of phosphorus, relative to concentrations within the lake. Approximately 30% of the TDP and 76 to 87% of the TDN in stormwater were in the organic fraction.

The ratio of inorganic N to P was usually less than 15:1 in Lake Joondalup and decreased with distance to the south where phosphorus loadings were high. This suggests that inorganic nitrogen is more likely to limit algal production than inorganic phosphorus. High inorganic N:P ratios were recorded in stormwater in winter and early spring when concentrations of NO_3 were high.

Schindler (1977) suggests that nutrient loadings with a nitrogen to phosphorus ratio of 8:1 or less result in a shift in phytoplankton populations to noxious blue-green algae. Inorganic nitrogen to phosphorus ratios of less than 8:1 were often found at sites in Lake Joondalup, Beenyup Swamp and Lake Goollelal, and seldom exceeded 8:1 at sites in the southernmost basin of the lake, where blooms of Anabaena spiroides occurred.

Optical densities and pH decreased with distance south, from Lake Joondalup to Wallubuenup Swamp. This suggests a flow of humic substances from the swamp into the lake in winter. High nutrient concentrations could be associated with these substances. Jackson and Hecky (1980), in their study of waterbodies in boreal forest, found that most of the dissolved phosphorus was associated with humic-iron-phosphate complexes.

The nutrient content of the sediments varied considerably over the lake. Highest nitrogen and phosphorus concentrations were found in the southern region, to the north of the Ocean Reef Road causeway.

2.4.2 TEMPORAL PATTERNS

Phosphorus and nitrogen concentrations in the main waterbody peaked in summer/autumn. Gordon, Finlayson and McComb (1981) also found that nitrogen peaked in summer/autumn 1975. In 1973, NH_4-N and organic N also peaked in summer/autumn, with a second peak in organic nitrogen in spring. Reactive phosphorus peaked in autumn and spring, and organic phosphorus in summer (Congdon and McComb 1976). In the current study, higher concentrations of nitrogen and phosphorus were recorded in 1980, when the water level was lowest, than in 1979. This suggests that nitrogen and phosphorus concentrations are inversely related to water-level, and that evaporation increases concentrations in the water column.

Highest phosphorus concentrations were recorded at the southern sites in winter and spring when water flow was greatest, indicating the input of phosphorus from Wallubuenup Swamp. Highest concentrations of NH_4-N and organic nitrogen, however, were recorded in the southernmost basin in late spring/summer, during blue-green algal blooms.

Nitrate concentrations in stormwater reached their peak in late winter/early spring.

A comparison of the nutrient data collected over different years for Lake Joondalup shows an increase in the mean concentrations of phosphorus, ammonium-nitrogen and organic nitrogen from 1973/1975 to 1979/1980 (Table 2.24). High values recorded for NH_4-N in 1973 and NO_3-N in 1975 were obtained using quite different methods from those used subsequently, and so it is possible that this accounts for the different results. In 1973 NH_4-N was assayed by distillation and nesslerization (Congdon 1973), and subsequently by the more sensitive cyanurate and indo-phenol methods (Finlayson 1975, current study). In 1975, NO_3-N was estimated by the ultra-violet method (Finlayson 1975).

Although recovery of added nitrate was checked, the method is not recommended for waters containing high levels of organic matter (American Public Health Association 1971). The current study used copper-cadmium reduction in an autoanalyzer.

The apparent increase in nutrient levels over the years is related to decreasing water levels. The minimum water level in Lake Joondalup was 16.62 m AHD in 1973, 16.99 m AHD in 1975, 16.51 m AHD in 1978, 16.63 m AHD in 1979 and 16.38 m AHD in 1980. The higher mean nutrient concentrations recorded in 1980 corresponded to the lowest recorded water level for at least 12 years. The increase in mean chloride concentrations over the years is also a reflection of decreasing water level. The increase in nutrient concentration with increasing chloride concentration (or decreasing water level) is shown in Fig. 2.36 for the available data.

There will be difficulty in discerning long-term trends in nutrient concentrations of lakes of the Swan Coastal Plain due to the large seasonal and year-to-year variation in rainfall and evaporation and their effects on lake volume. Given sufficient data to establish the regression line between nutrient concentration and chloride concentration (or water level), any increase in the slope of the line should indicate an increase in nutrient loadings to the lake.However the sensitivity of this method depends on the collection of data from sufficient sites, and years of different rainfall, so as to encompass any natural variation due to spatial and seasonal variation within the system.

2.4.3 HUMIC SUBSTANCES

Humic substances can have a significant effect on aquatic productivity (Jackson and Hecky 1980). Humic matter has been shown to stimulate algal and bacterial growth (Prakash and Rashid 1968; Nechutova and Tichy 1970; Milanovich, Wilson and Yeh 1975; Cheng and Tyler 1976; Giesy 1976), but it may also inhibit growth by fixation of trace metals or phosphorus (Saunders 1957; Sakamoto 1971; Golterman 1973; Goodman and Cheshire 1973; Francko and Heath 1979), by inhibition of enzymes (Butler and Ladd 1971), or by lowering of the pH or the absorption of light (Shapiro 1957). Wilson (1978) found that at concentrations of the order of 15 $\mu g\ l^{-1}$ of humic acid, metal ion complexation was substantial and could control the availability of micronutrients in freshwaters.

In a study of two Tasmanian lakes, Cheng and Tyler (1976) showed that tripton (non-living particulate organic matter) stimulated algal productivity and could be substituted with micronutrients and chelators. They concluded that the nutritive role of tripton was through the maintenance of micronutrients in available form through chelation.

Whether humic substances stimulate or inhibit biological activity seems to depend on their nature (eg average molecular weight) and abundance (Jackson and Hecky 1980). Toxic substances, such as phenols, may also be present in dissolved organic material, and these would also inhibit productivity.

The plant decomposition products, fulvic acid (molecular weight (MW <10,000), humic acids (MW 10,000 300,000), tannins and lignins are the major forms of naturally-occurring dissolved organic compounds. Humic and fulvic acids are amorphous, yellow-brown or black, hydrophilic and acidic, and result in the yellow brown colouration of many lakes and rivers. Humic acid is soluble at pH 9 but insoluble at pH 2, while fulvic acid is soluble at both pH 9 and pH 2. Tannins and lignins are high molecular weight, polycyclic aromatic compounds which are highly resistant to chemical and biological degradation. Lignin is built up of methoxy- and hydroxy-phenylpropane units, while tannins are either polymers of gallic acid linked to carbohydrate residues (hydrolyzable tannins) or polymeric flavanoid compounds (condensed tannins) (Lawrence 1980).

Low phytoplankton standing crops occur in Beenyup Swamp and at site 57, to the south of Lake Joondalup, despite the presence of high nutrient concentrations. The water at these sites is more highly coloured with dissolved material and has a lower pH than water from sites to the north. As this water meets the more alkaline water of the lake basins, algal blooms may occur and it is hypothesized that humic substances in the water from the south inhibit primary production in some manner, and that this inhibition is removed as the water flows north and mixes with the more alkaline lake water.

There is some support for this hypothesis from liming experiments. Hillbricht-Ilkowska, Rybak, Kajak, Dusoge, Ijsmont-Karabin, Spodniewska, Weglenska and Godlweska-Lipowa (1979) investigated the effect of adding lime to a humic lake in Poland and found a mobilization of reserves of organic matter with an increase in the number and diversity of zooplankton, rapid changes in inorganic nitrogen and phosphorus concentrations, and increased bacterial decomposition. However, they did not find a significant increase in the phytoplankton biomass. This contrasts with the findings of Waters and Ball (1957) who found an increase in algal biomass and a bloom of blue-green algae in a lake in North Michigan following liming.

2.5 SUMMARY

1. Nutrient concentrations showed a negative relationship with water-level, generally peaking in summer/autumn.

2. Phosphorus concentrations in the water column showed an increasing gradient with distance south, with very high concentrations in Wallubuenup and Beenyup Swamps.

3. Comparatively low concentrations of phosphorus were found in water samples from stormwater sumps.

4. Phosphorus concentrations in the main waterbody were inversely related to water levels - highest concentrations occurred in late summer to early winter. Overall, higher concentrations were recorded in 1980 than in earlier years

5. Water flowing into Lake Joondalup from the south (at site 57) contained high concentrations of phosphorus in winter and spring. This site contained much lower concentrations in summer and autumn when there was no surface flow from Beenyup Swamp.

6. The highest phosphorus concentrations were recorded in the southern end of Wallubuenup Swamp and these peaked in late winter to early spring.

7. The highest ammonium-nitrogen concentrations (to 1864 $\mu g\ N\ l^{-1}$) were recorded in the southernmost basin of Lake Joondalup, with lower values to the south - in Beenyup and Wallubuenup Swamps.

8. The highest values for nitrate-nitrogen in Lake Joondalup were also recorded in the southernmost basin, but very high concentrations were found at sites in the southern end of Wallubuenup Swamp.

9. There were marked seasonal peaks in the nitrate plus nitrite content of stormwater; comparatively high concentrations were present in late winter to early spring.

10. Nitrogen concentrations, in the main waterbody of Lake Joondalup, peaked in summer/autumn, suggesting a negative relationship with decreasing water levels. Highest concentrations were recorded in 1980 when water levels were lowest.

11. Like ammonium, the highest organic nitrogen concentrations were recorded in the southernmost basin of Lake Joondalup, and these peaked in late spring to summer, usually following blooms of Anabaena.

12. An algal bloom at site 57 in autumn 1980 (a rare occurrence) was followed by peaks in concentrations of NH_4-N, NO_3-N and organic N.

13. Nitrate plus nitrite concentrations in Beenyup Swamp were relatively low (<32 μg N l^{-1}).

14. Samples from the southern end of Wallubuenup Swamp contained comparatively low concentrations of NH_4-N and high concentrations of NO_3-N.

15. Water samples from Lake Joondalup contained ratios of inorganic N:P of less than 15:1, except on a few occasions in spring and summer when NH_4-N concentrations were high, suggesting that inorganic nitrogen is more likely to limit algal production than inorganic phosphorus. This ratio was particularly low in samples from the southernmost basin and Beenyup Swamp where phosphorus loadings were high.

16. High inorganic N:P ratios were recorded in stormwater (site 36) in winter and early spring when concentrations of NO_3 were high.

17. The proportion of phosphorus which was dissolved increased with distance south, being 31 to 40% of the total in the main waterbody, 58 to 76% in the southern basin, 67% at site 57 and 74% in Beenyup Swamp. 81% of the phosphorus in Lake Goollelal was dissolved, while stormwater contained 59 to 60%.

18. Mean reactive phosphorus concentrations exceeded mean TDP concentrations at most sites. However, about 30% of the TDP in stormwater was found in the organic fraction.

19. Most of the nitrogen was found in the dissolved fraction - 64 to 90% of the mean total nitrogen concentration was in the TDN fraction. 76 to 98% of the dissolved nitrogen was organic; the highest proportion of inorganic nitrogen in TDN being found in stormwater where organic nitrogen concentrations were comparatively low and NO_3-N concentrations comparatively high.

20. The lowest pH and alkalinity readings were usually recorded in winter, and pH and optical densities decreased with distance south of the lake, suggesting a flow of humic substances from Wallubuenup Swamp into Lake Joondalup in winter. Fulvic and humic acid concentrations were found to be quite high in several samples from sites south of the lake.

21. The densest sediments were found near site 37, on the eastern shore of Lake Joondalup - an area of suspected groundwater seepage.

22. The nutrient content of the sediments varied considerably over the lake. The highest nitrogen and phosphorus concentrations were found in the southern region of the lake - north of Ocean Reef Road

23. The total phosphorus concentration in surface sediment was significantly correlated with loss on ignition (organic matter content) and soluble phosphorus fractions.

24. Organic matter content (as loss on ignition) decreased with sediment depth. There was also a large decrease in phosphorus and nitrogen content with increasing depth.

25. Soluble nitrogen fractions in deeper sediment (20 to 25 cm) were well correlated with loss on ignition and water content.

3. THE PHOSPHORUS AND NITROGEN BUDGETS FOR LAKE JOONDALUP

3.1 INTRODUCTION

Phosphorus and nitrogen are generally considered to be the most important nutrients affecting aquatic productivity and the potential for phytoplankton blooms. The other major macro-nutrients (carbon, hydrogen, oxygen and sulphur) are rarely limiting to aquatic production since they are readily available to an ecosystem from atmospheric sources, and have higher concentrations in the hydrosphere than nitrogen and phosphorus (Deevey 1970).

Phosphorus undergoes a sedimentary biogeochemical cycle, which is effectively one-way since the element has no natural gaseous forms. Phosphorus is only returned to the terrestrial environment by the process of mountain-building over long periods of geological time. The mining of phosphorus deposits in guano for fertilizers has accelerated the phosphorus cycle, and significantly added to the eutrophication of waterways, but this man-made reversion of the one-way phosphorus cycle may be temporary as the world resources of guano are being rapidly depleted.

Since it has naturally-occurring gaseous forms, nitrogen undergoes an atmospheric biogeochemical cycle. Exchanges of nitrogen between the biosphere and the atmosphere occur through the bacterial-mediated processes of nitrogen-fixation and denitrification.

The nutrient mass-balances of Australian lakes has been little studied (Wood 1975; Cullen et al 1978; Bales, Curtin, Campbell and Hart 1980). In this study, the mass balance approach was used to quantify the nitrogen and phosphorus budgets of Lake Joondalup.

3.1.1 NUTRIENT LOADINGS

The formulation of nutrient budgets includes the calculation of 'loadings'. The concept of permissible loadings has been used in the formulation of models to guide the management of lakes subject to eutrophication (eg Vollenweider 1976). The loading gives the rate of supply of nutrients to the phytoplankton community of a lake.

'Specific surface loadings' or 'areal nutrient loadings' are calculated by dividing the nutrient load entering a lake by its area (Cullen et al 1978). De Groot (1981) differentiates between 'net external loading' which takes account of outputs as well as inputs, 'gross external loading' which only includes inputs, and 'internal loading' which is the residual in the mass balance calculation representing sediment/water column exchange.

3.1.2 THE PHOSPHORUS BUDGET

Since there is no outflow of surface water from Lake Joondalup, the phosphorus budget can be represented by:

$$DP = P_i + P_p + P_s$$

where DP = the change in phosphorus content of the water column;
P_i = the phosphorus input in surface water;
P_p = the phosphorus input in precipitation and dry fallout; and
P_s = the net phosphorus exchange through the lake's sediments.

Phosphorus exchange through the lake's sediments could take place through groundwater inflow or outflow, sedimentation or suspension of particulate phosphorus, diffusion of dissolved phosphorus, or through the uptake or release of phosphorus by the metaphyton or macrophytes. The sediment exchange is the most difficult parameter to measure, but can be estimated as the unknown in the mass-balance equation. Hence:

$$+P_s = DP - P_i - P_p$$

3.1.3 THE NITROGEN BUDGET

The nitrogen budget can be represented by the equation:

$$DN = N_i + N_p + N_f + N_s - N_d$$

where DN = the change in nitrogen content of the water column;
N_i = the nitrogen input in surface water;
N_p = the nitrogen input in precipitation and dry fallout;
N_f = biological nitrogen fixation;
N_s = the net nitrogen exchange through the lake's sediments; and
N_d = the nitrogen lost by denitrification.

The measurement of the contributions to the nitrogen budget of transformations between gaseous and dissolved forms, due to N_2-fixation and denitrification, is difficult. They can be determined by ^{15}N labelling techniques (Madsen 1979), or N_2 fixation can be determined by the acetylene reduction method (Hardy, Holsten, Jackson and Burns 1968) and denitrification by the acetylene inhibition technique (Burton and Beauchamp 1984). Each of these methods is used to measure rates over relatively short incubation times. For annual mass-balance purposes, one would need to incubate samples from several sites to encompass spatial variation, and at several times through the year with occasional diurnal incubations to determine seasonal variation. Such a labour-intensive survey was not feasible for the present study.

Nitrogen fixation by blue-green algae can make a significant contribution to nitrogen loadings (Ashton 1981). The acetylene reduction technique has been used to investigate N_2-fixation by the blue-green alga Anabaena spiroides in Lake Joondalup (Congdon 1979). Extrapolations based on these data suggest a contribution of less than 0.10 kg N ha^{-1} yr^{-1} (total of 52 kg N yr^{-1}) from this source. N_2-fixation can also occur in the sediments and the rhizospheres of aquatic plants due to bacterial activity. Finlayson and McComb (1978) found maximum rates of sediment fixation of 0.002 nm C_2H_2 $g^{-1}min^{-1}$, and rhizosphere fixation of 0.06 nm C_2H_2 $g^{-1}min^{-1}$.

Extrapolation suggests that these sources may contribute a maximum fixation of less than 2.52 kg N_2yr^{-1} (4.8 g $ha^{-1}yr^{-1}$) and 22 g N_2yr^{-1} (0.8 g ha^{-1} of swamp vegetation yr^{-1}) respectively (Congdon 1979). These extrapolations suggest that nitrogen fixation does not contribute significantly to the total nitrogen mass-balance of the lake. It may be locally significant however, such as in the southern basin of the lake during blooms of Anabaena.

Denitrification is an anaerobic process in which nitrate or nitrite is reduced to N_2 and a small amount of N_2O. Rigorous anoxia is not necessary, but a significantly lowered oxygen tension is (Payne 1983). Although denitrification can occur in anaerobic micro-environments in the water column, in a shallow lake such as Lake Joondalup, the bulk of it is associated with the accumulation of nitrate in the oxidized surface layers of the sediments (below 1 cm) and in oxidized patches introduced by burrowing animals (Sorensen 1978).

Net denitrification can be estimated from the N:P ratio of the sediments, assuming that all of the phosphorus entering a lake is lost to the sediments, and that N_2-fixation or groundwater exchange is not significant (Andersen 1974).

If we assume that N_2-fixation and denitrification in the water column does not make a significant contribution to the nitrogen budget, then the net effects of any N_2-fixation and denitrification can be included in the sediment exchange term, so:

$$+N_s = DN - N_i - N_p$$

3.2 MATERIALS AND METHODS

3.2.1 PHOSPHORUS AND NITROGEN WITHIN THE LAKE WATER COLUMN

Phosphorus and nitrogen in the water column were determined from the nutrient data collected during the grid studies (see Chapter 2). The mass of each nutrient was calculated for each site by multiplying the concentration in mg m^{-3} by the depth in metres, and then mapped using the SYMAP computer mapping package (Dougenik and Seehan 1977).

A digitizer (Model ID RS232, Summagraphics Corp, Fairfield, Connecticut) was used to determine the areas of map in each size class. These areas were multiplied by the mean mass for each size class and summed to obtain the total masses of phosphorus and nitrogen in the lake waterbody during each grid study, corrected for changes in lake area by a factor derived from the hypsographic curve.

3.2.2 PHOSPHORUS AND NITROGEN INPUTS IN SURFACE FLOW

Phosphorus and nitrogen loadings were calculated for inflowing water from sites 36, 46 and 57. The discharge at each site (Congdon 1985) was multiplied by the measured nutrient concentration for each sampling time. Daily loadings between sampling days were then estimated by interpolation. These were then summed to find the total phosphorus and nitrogen inputs for each study period.

3.2.3 PHOSPHORUS AND NITROGEN INPUTS IN ATMOSPHERIC FALLOUT

Phosphorus and nitrogen concentrations were determined for rainwater samples taken from the rain gauge at Edgewater (Congdon 1985), and a rain collector at the University of Western Australia campus at Crawley. The rain collector consisted of a heavy 750 ml Erlenmeyer flask with a large funnel (maximum diameter of approximately 20 cm).

Both rainfall collectors were rinsed with 50% HCl and deionised distilled water from time to time, to minimize contamination. Snails and insects sometimes collected in the rain gauge at Edgewater and these samples were discarded.

Samples were collected from Edgewater on each sampling day, whilst they were taken on the university campus as soon as a sufficient volume had collected. The number of nutrient analyses performed on each occasion was determined by the volume of rainfall collected. The methods described in Chapter 2 were used for the phosphorus and nitrogen analyses.

The phosphorus and nitrogen inputs to the lake, from rainfall, were calculated by multiplying the overall mean concentrations found in rainfall at Edgewater by the total rainfall and the mean area of the lake for each study period.

The nutrients in rainwater samples may include nutrients from dry fallout as well as wet fallout, and this can be quite significant (McColl, Monete and Bush 1982). Elsewhere in this report the nutrient input in rainwater will be referred to as atmospheric fallout.

3.2.4 PHOSPHORUS AND NITROGEN POOLS IN THE LAKE SEDIMENTS

The total phosphorus and total nitrogen data collected during the July 1979 grid study were given the same treatment as the water data, to determine the total masses of phosphorus and nitrogen in the lake sediments to 10 cm depth.

3.2.5 NUTRIENT EXCHANGE BETWEEN THE SEDIMENTS AND THE WATER COLUMN

In March 1979 two simple experiments were conducted to investigate the exchange of nutrients between the sediments and the water column, to get some indication of the possible role of the sediments in the nutrient budget of the lake.

An in situ experiment was conducted at site 22 (Fig. 2.3), in which sediment was stirred up into the water column with an oar. Water samples were taken from above the sediments before and after stirring, filtered, and analyzed for reactive phosphorus, ammonium nitrogen, nitrate (plus nitrite) nitrogen, and total phosphorus.

The exchange of reactive phosphorus between sediments and solutions of different phosphate concentration was investigated in the laboratory. Solutions containing 0, 25, 50 and 100 µg PO_4-P l^{-1}, and surface (0 - 5 cm) and deeper sediments (25 - 30 cm) were used. Three grams of fresh sediment were added to100 ml of each solution, shaken for 2 minutes, filtered through a glass fibre filter paper (Whatman's GF/C), and then analysed for reactive phosphorus.

3.2.6 NUTRIENT POOLS IN THE VEGETATION

Samples of submerged macrophytes were collected in July 1980 for nutrient analysis. Replicate samples were collected with an Ekman grab in November and December 1980 for standing crop determination. Samples of emergent macrophytes were collected in September 1980.

The sedges Lepidosperma longitudinale and Baumea juncea were harvested from 25 by 25 cm quadrats, and belowground material collected down to 30 cm, for standing crop determination.

Plant material was hand-sorted, dried at 80°C, and weighed for standing crop determinations. Subsamples were ground in a hammer mill (Glen Creston model c.580, Stanmore, England) with a 1 mm screen. Ash content was determined after ashing in a muffle oven at 650°C for 3 hours. Phosphorus was determined by the single solution method (Major et al 1972), after digestion of duplicated 0.2 g subsamples with 3 ml of concentrated HNO_3, followed by 2 ml of 1:1 HNO_3 and $HClO_4$. Nitrogen was determined on 0.1 g subsamples using Kjeldahl digestion, distillation in a Markham still, collection of ammonia in boric acid/indicator solution, and titration against dilute HCl.

3.3 RESULTS

3.3.1 PHOSPHORUS AND NITROGEN WITHIN THE LAKE WATER COLUMN

3.3.1.1 Phosphorus

No consistent seasonal trends are apparent, probably because the quantities are dependent on the lake volume, which varies not only seasonally, but yearly with rainfall (Table 3.1). 'Reactive' phosphorus was usually the dominant fraction, although 'organic' phosphorus was more abundant in January 1979.

3.3.1.2 Nitrogen

Ammonium-nitrogen was the most abundant inorganic nitrogen fraction, while organic nitrogen was always abundant (Table 3.1). Nitrate appeared to be most abundant in winter months, although a particularly high quantity was recorded in December 1978.

3.3.2 NUTRIENT INPUTS IN SURFACE FLOW

3.3.2.1 Phosphorus

Total phosphorus input was well correlated with flow ($r = 0.951$, $P < 0.001$ for site 46, $r = 0.778$, $P < 0.05$ for site 36) with the greatest inputs occurring in winter (Tables 3.2 to 3.4). The reactive fraction was always most abundant at sites 46 and 57 (Figs. 3.1 and 3.2), while organic phosphorus was more abundant at site 36 in winter (Fig. 3.3). The phosphorus input from site 36 amounted to less than 2% of that from the culvert under Ocean Reef Road at site 46.

From 19 July to 22 December 1980, the phosphorus input at site 46 amounted to only 64% of that at site 57, so 36% of the phosphorus was trapped in the southernmost basin of the lake, south of Ocean Reef Road. This comprised 50% of the 'organic' phosphorus and 31% of the 'inorganic' (reactive) phosphorus.

3.3.2.2 Nitrogen

The total nitrogen inputs of the surface waters flowing into the lake were also well correlated with flow ($r = 0.980$, $P < 0.001$ for site 46, $r = 0.917$, $P < 0.01$ for site 36). The inorganic fraction comprised less than 10% of the total nitrogen loads flowing through sites 46 and 57 (Tables 3.2 and 3.3), and nitrate was generally as abundant as ammonium nitrogen (Figs. 3.4 and 3.5). Nitrate amounted to 26% of the total nitrogen flowing from the stormwater sump at site 36, and was 30% of the total during winter months (Table 3.4). Ammonium-nitrogen was less than 15% of the inorganic fraction during winter but became proportionately more abundant than nitrate as rainfall decreased (Fig. 3.6). The total nitrogen input from the sump was about 5% of that from site 46.

Between 19 July and 22 December 1980, the nitrogen input at site 46 amounted to 92% of that at site 57. There was a small increase in the inorganic nitrogen input between sites 57 and 46, mainly in August when there was no blue green algal bloom in the southern basin of the lake, so the addition of inorganic nitrogen in the basin would be through the mineralization of organic nitrogen or release of inorganic nitrogen from the sediments. The mass of organic nitrogen decreased by 9% between sites 57 and 46, due to sedimentation and/or mineralization.

3.3.2.3 The Source of Nutrients in Surface Flow From Wallubuenup Swamp

Nitrogen and, especially, phosphorus loadings of surface water flowing through the Ocean Reef Road culvert are quite significant, and for management purposes it is important to determine the source(s) of these nutrients. Few data could be collected from the environs of Wallubuenup Swamp because of the ephemeral nature of the surface water and the lack of accessibility due to the dense swamp vegetation. However, very high concentrations of phosphorus and nitrate were recorded in the southern end of the swamp (see Chapter 2), and a few flow data were collected at site 70, the culvert under Whitfords Avenue (Table 3.5).

It is difficult to directly compare the flows and nutrient loadings at site 70 with those entering Lake Joondalup, at sites 46 or 57, because there are approximately 3 km of swamps between these sites and the rate of flow through them is not known. Nevertheless, some indication of the importance of nutrient sources south of Ocean Reef Road can be gained by comparing flows at these sites over the same general period.

The flows at site 70 for 21 August and 1 September 1980 amount to only 0.1 to 6% of the flows recorded at site 57 from 28 August to 4 September (Table 3.5). Chloride loadings at site 70 for September 1st amount to only 0.7 to 2% of those recorded at site 57 from 28 August to 4 September. Nutrient loads, other than nitrate, were only 0.8 to 4.6% of those at site 57 over the same period. Nitrate loadings were high at site 70, being 64 to 187% of those at site 57 and suggesting that NO_3 (and NO_2) may be assimilated or denitrified by the swamps.

Overall, these data indicate that there is a large input of water containing nitrogen, phosphorus and chloride from the swamps, including those north of Whitfords Avenue. The nutrient contributions of the various forms of land-use in the area require close investigation. These include nutrients from the fertilizing of market gardens, from poultry farm waste, and from the sewage disposal systems of caravan parks.

3.3.3 NUTRIENT INPUTS IN ATMOSPHERIC FALLOUT

3.3.3.1 Phosphorus

No significant differences were recorded in mean concentrations of phosphorus fractions between the two sites (using t tests), although reactive phosphorus concentrations tended to be higher on the Crawley campus (Table 3.6, Fig. 3.7). Phosphorus concentrations varied considerably, with some suggestion of lower concentrations in late July August. At times the reactive phosphorus fraction accounted for less than 50% of the total phosphorus, indicating that wind-borne particulate material may be a significant atmospheric input.

For the purposes of the phosphorus budget, the mean concentration of 28 µg TP l^{-1} recorded for the Edgewater site was used.

3.3.3.2 Nitrogen

Concentrations of nitrogen fractions in the rainwater samples showed greater variation than phosphorus concentrations, and again t tests discerned no significant differences between the two sites (Table 3.7). Like phosphorus, lower concentrations were again indicated in late July August (Fig. 3.8). Organic nitrogen was the dominant fraction, supporting the hypothesis that wind-borne particulate material is important.

The mean total nitrogen concentration of 570 µg N l^{-1} recorded at Edgewater was used in the nitrogen budget.

3.3.4 NUTRIENT POOLS WITHIN THE LAKE ECOSYSTEM

The major nutrient pools within the lake ecosystem include the water column, the sediments and the vegetation. Nutrient concentrations found in the emergent macrophytes are listed in Tables 3.8 and 3.9. The actual concentrations found in each component of the biomass, and the nutrient standing stocks will vary with changes in phenology of each species through the seasons. However these data provide "an order of magnitude" figure for comparison with other nutrient pools in the lake. Typha contained the highest concentrations of nitrogen and phosphorus in live culms at the time of sampling, these concentrations being some three times higher than those recorded for the native sedge Baumea articulata.

In general, nutrient concentrations of dead culms are significantly lower than in live culms, suggesting retranslocation of nutrients to the rhizomes on senescence of the shoots. It is interesting to note that rhizomes of Typha contain 72% of the phosphorus found in live culms, but only 21% of the nitrogen (Table 3.8). Less nitrogen was also found in the rhizomes of Baumea juncea and Lepidosperma longitudinale than in the live culms, relative to the distribution of phosphorus. This may suggest nitrogen limitation.

Submerged macrophytes are mainly found in the deeper northern basin and the central basin of Lake Joondalup (Fig. 3.9), and are dominated by the charophytes Chara fibrosa and Nitella congesta, and the angiosperm Najas marina. The distribution of these species is patchy, with considerable variation in standing crops (Table 3.10). The ash content of the charophytes varies considerably with age, as calcium carbonate deposits build up as a result of carbon uptake for photosynthesis. The submerged macrophytes contained higher concentrations of nitrogen than the emergent macrophytes, especially on an ash-free dry weight (AFDW)basis (Table 3.11). Phosphorus concentrations were similar for the two life-forms. The new growth of the charophytes contained higher phosphorus concentrations than the older plants.

Considering the nutrient pools on a per unit area basis, the sediments contain the highest proportion of nitrogen and phosphorus. Assuming an average water depth of 1 m and an active sediment depth of 10 cm, the water column contained less than 1% of the nitrogen and phosphorus that the sediment contained in July1979 (Tables 3.12 and 3.13).

The emergent macrophytes contained more nitrogen and phosphorus per unit area than the water column. Schoenoplectus validus possessed 32% of the nitrogen and 7% of the phosphorus, found in the sediments. Swamp vegetation covers some 84 ha of the lake and is dominated by the sedge Baumea articulata, with Typha orientalis being the next most abundant emergent macrophyte. Using the estimated nutrient content of Baumea articulata (Table 3.12), the swamp vegetation would contain some 252 kg of nitrogen and 14 kg of phosphorus, which is considerably less than the nutrient pool found in the water column in July 1979 (Table 3.13).

Since they are sparse and have comparatively low standing crops, the submerged macrophytes contain low stocks of nitrogen and phosphorus (Table 3.12), and contribute little to the total nutrient pool of the lake ecosystem.

3.3.5 NUTRIENT EXCHANGE BETWEEN THE SEDIMENTS AND THE WATER COLUMN

Two simple experiments were conducted to examine the role of sediment/water column exchange in the nutrient budgets. The in situ stirring of the sediments resulted in a decrease in the concentrations of reactive phosphate, organic phosphorus and ammonium-nitrogen in the water column (Table 3.14). Metaphyton is well distributed over the lake and it is likely that the suspended sediment consisted largely of metaphyton. Suspending the metaphyton would result in it receiving more light and probably stimulate assimilation of nutrients.

The shaking of surface sediment in solutions of phosphate resulted in a small increase in the reactive phosphorus concentration at concentrations below 50 $\mu g\ l^{-1}$, and a small decrease above 50 $\mu g\ l^{-1}$, suggesting an equilibrium concentration of between 25 and 50 μg P l^{-1}. Shaking the deeper sediments resulted in an increase in reactive phosphate concentration, which decreased with increasing phosphate concentration of the solution (Table 3.15).

3.4 DISCUSSION

3.4.1 THE PHOSPHORUS BUDGET

The data collected suggest that the mass of phosphorus in the water column of the lake, increased in January through to September 1980 and decreased in October and November, when water levels were highest, perhaps because resuspension of sedimenting phosphorus is less likely since wind stirring has less effect on deeper water. The data for the period January to July 1979 show a large net decrease in the mass of phosphorus in the water column (Table 3.16).

In the period 14 January to 20 November 1980, flow through the culvert under Ocean Reef Road (site 46) contributed 73% of the external phosphorus inputs, atmospheric fallout contributed 26% and stormwater from site 36 contributed only some 1% (Table 3.16).

Phosphorus exchange through the sediments within the lake resulted in a net loss of phosphorus from the water column, amounting to 78% of the external inputs. This loss could be due to sedimentation of organic phosphorus in dead phytoplankton and other particulate matter, uptake by metaphyton and macrophytes, and diffusion into the sediments.

Schaffner and Oglesby (1978) consider that lakes with a hydraulic residence time of years retain 75 to 95% of the phosphorus input, while those with residence times of a few months retain 30 to 40% of the input. Further, Lee, Rast and Jones (1978) conclude that lakes with a hydraulic residence time of more than a few months incorporate 80 to 90% of phosphorus into their sediments.

The hydraulic residence time (or turnover time) for Lake Joondalup is given by:

$$\frac{\text{maximum lake volume}}{\text{lake inputs (outputs)/yr}}$$

$$= \frac{5.08 \times 10^6 m^3}{5.54 \times 10^6 m^3\ yr^{-1}} = 0.92 \text{ yr for 1980}$$

Since Lake Joondalup only loses water through evaporation and groundwater significant phosphorus loss can only occur through groundwater flow. This is unlikely because the calcareous soils in the region would readily absorb phosphate. Consequently, all of the phosphorus entering the lake ends up in the sediments. This is reflected in the high phosphorus contents of the sediments of the southern end of the lake - closest to the largest input of phosphorus, through the culvert under the Ocean Reef Road causeway (see Appendix 3).

3.4.2 THE NITROGEN BUDGET

In contrast to the phosphorus budget, there was a net decrease in the mass of nitrogen in the water column over the period 14 January to 20 November 1980 (Table 3.17). Over this period, the main input of nitrogen was from atmospheric fallout which contributed some 69% of the lake's external inputs. The culvert under Ocean Reef Road (site 46) supplied 30% of the nitrogen inputs and stormwater from site 36 contributed about 1%.

Nitrogen loss to the sediments, estimated as the residual, amounted to some 4.5 tonnes. External inputs to the lake would only account for 63% of this loss, so the data indicate a net loss from the water column of 1.7 tonnes over the study period. The loss of nitrogen could be due to denitrification, sedimentation of particulate material such as dead phytoplankton, or uptake by metaphyton and macrophytes.

Assuming that all the phosphorus loss is to the sediments, equivalent amounts of nitrogen lost through sedimentation can be estimated from the mean N:P ratio of the surface sediments (Andersen 1974). The mean N:P ratio of the surface sediments (by weight) was 47.06:1 for July 1979 (Table 2.23), and the phosphorus loss for the study period was 288 kg. The estimated loss of nitrogen by sedimentation would therefore be 13553 kg which is three times higher than the net loss given by the mass balance calculation. This may indicate that the top 5 cm of sediment does not represent the current state of sedimentation, or that the mean N:P ratio of the sediments does not represent the true picture of sediment composition over the lake as a whole. The total nitrogen and phosphorus contents of the sediments varied considerably, although they were correlated with each other at the 1% level (Table 2.21).

The literature suggests that denitrification in aquatic sediments is of the order of 1.5 g N $m^{-2}yr^{-1}$ (15 kg $ha^{-1}yr^{-1}$) (Table 3.18). This would represent a loss of 6480 kg of nitrogen from an area the mean size of Lake Joondalup in 1980. This figure is of the same order of magnitude as the computed loss of nitrogen from the water column, disregarding any sedimentation and retention of nitrogen in the sediments.

3.4.3 SPECIFIC SURFACE LOADINGS

For the period 14 January to 11 November 1980, Lake Joondalup had a gross (and 'net' since there is no surface outflow) external phosphorus loading of 86 mg P m^{-2} and an internal phosphorus loading of -67 mg P m^{-2} (Table 3.19). The gross (and net) external nitrogen loading was 655 mg N m^{-2} and the internal nitrogen loading was -1,050 mg N m^{-2}. These would approximate the annual loadings very closely since there was negligible surface flow and rainfall in those weeks of 1980 which were not sampled by grid studies. 88% of the annual phosphorus load, and 75% of the nitrogen were contributed in the four months from June to October. 61% of the phosphorus and 55% of the nitrogen came in 70 days from June to August.

In his study of northern hemisphere lakes, Vollenweider (1971) concluded that 70 mg P $m^{-2}yr^{-1}$ and 1000 mg N $m^{-2}yr^{-1}$ were permissible loadings for lakes up to 5 m mean depth, with dangerous loadings being in excess of 130 mg P $m^{-2}yr^{-1}$ and 2000 mg N $m^{-2}yr^{-1}$. On this basis, in 1980 Lake Joondalup exceeded the permissible loading of phosphorus only, although it was not in the dangerous category. However, the specific surface loadings were calculated for the whole area of Lake Joondalup. Considering the southernmost basin alone, the area was110 x 10^3m^2 in August 1975 (from the Metropolitan Water Board's contour map). Using the nitrogen and phosphorus loadings from sites 46 and 57, the southernmost basin of Lake Joondalup would have gross specific surface loadings of more than 4200 mg P $m^{-2}yr^{-1}$ and 10280 mg N $m^{-2}yr^{-1}$, and net specific surface loadings of more than 1760 mg P $m^{-2}yr^{-1}$ and 2660 mg N $m^{-2}yr^{-1}$ for 1980. These include estimated loadings in rainfall of 23 mg P m^{-2} yr^{-1} and 473 mg N $m^{-2}yr^{-1}$, and are minimum loadings since the mean area of the basin was much smaller in 1980 than in August 1975 (the depth had not been as great since 1975), and the loadings only cover the period to 22 December1980. These loadings are well within Vollenweider's dangerous category, especially for phosphorus, and explain the occurrence of blue-green algal blooms in the southernmost basin.

The gross external phosphorus loadings to the southernmost basin of Lake Joondalup, are higher than those reported previously for Australia. Cullen et al (1978) recorded areal phosphorus loadings to Lake Burley Griffin of 3.48 and 3.72 g P $m^{-2}yr^{-1}$ for normal and drought years respectively. A total phosphorus loading of 2.8 g P $m^{-2}yr^{-1}$ has been estimated for Lake Daylesford in Victoria (Bales et al 1980). This lake receives agricultural run-off, waste material from a former potato-processing factory, and run-off and seepage from an unsewered community.

In his study of Lake Westeinder, near Amsterdam, De Groot (1981) recorded a gross external loading of 2.3 g P $m^{-2}yr^{-1}$ (6.3 mg P m^{-2} d^{-1}) and internal loadings of -20 to + 13 mg P m^{-2} d^{-1}. These are much higher than the daily loadings estimated for the whole of Lake Joondalup, where the highest external daily loading was 0.8 mg P $m^{-2}d^{-1}$ and internal daily loadings ranged from -0.9 to +0.5 mg P $m^{-2}d^{-1}$ (Table 3.19).

The nutrient loadings from atmospheric fallout are within the range of loadings recorded elsewhere (Table 3.20). The atmospheric phosphorus loading was 27% of the total external loading, and the atmospheric nitrogen loading was 72% of the total. Previous studies have found that atmospheric fallout accounts for 17% (Columbia Lake, Connecticut - Rich and Pallotti 1977), 25% (Dunham Pond, Connecticut - Kortmann 1980), and 50% (Lake Warniak, Poland - Kowalczewski and Rybak 1981; Rawson Lake, Canada - Schindler et al 1976) of total phosphorus inputs. Rainfall contributes 15% of the total nitrogen input to hypereutrophic Lake Sallie, Minnesota (Brakke 1977), and wet and dry fallout contribute 10% of the dissolved nitrogen to Dunham Pond, Connecticut (Kortmann 1980) and 31% of total nitrogen to Lake Okeechobee, Florida (Messer and Brezonik 1983). Hence the atmospheric nitrogen loadings to Lake Joondalup are quite significant.

3.5 SUMMARY

1. In the period 14 January to 20 November 1980, surface discharge from the culvert under Ocean Reef Road contributed73% of the external phosphorus inputs, atmospheric fallout contributed 26% and stormwater (site 36) contributed only 1%.

2. More than 98% of the phosphorus input in surface discharge to Lake Joondalup comes from the southern swamps, and is dominated by reactive phosphorus.

3. The inputs of total phosphorus and nitrogen are correlated with flow rate, with the greatest inputs occurring in winter.

4. Sedimentation resulted in the loss of 78% of the external input of phosphorus from the water column.

5. Between January 14 and November 20 1980 there was a net increase of 81 kg of phosphorus in the water column of the lake.

6. Atmospheric fallout contributed 69% of the external nitrogen inputs, surface discharge from the culvert under Ocean Reef Road contributed 39%, and stormwater (site 36) contributed about 1%.

7. Nitrate amounted to 26% of the total nitrogen flowing from the stormwater sump (site 36), and was 30% of the total during winter months.

8. Nitrogen loss to the sediments amounted to some 4.5 t, indicating a net loss of 1.7 t from the water column over the budget period.

9. Concentrations of phosphorus and nitrogen in atmospheric fallout varied considerably, with mean concentrations of 28 μg P l^{-1} and 570 μg N l^{-1}.

10. The sediments contain a large nutrient pool. The surface 10 cm of sediment contains more than 100 times the nitrogen and phosphorus found in the water column.

11. Preliminary experiments suggest that stirring up of surface sediments may not release significant quantities of inorganic phosphorus.

12. The vegetation of the lake contains less than 10% of the nitrogen and phosphorus found in the water column.

13. For the period 14 January to 20 November 1980, the gross external nutrient loadings were 86 mg P m^{-2} and 655 mg N m^{-2}. The phosphorus loading exceeds that considered to be permissible for shallow lakes (Vollenweider 1971).

14. The nutrient loadings from atmospheric fallout are within the range recorded elsewhere, and account for 27% of the external phosphorus loading and 72% of the external nitrogen loading.

4. CHANGES IN PHYTOPLANKTON STANDING CROP

4.1 INTRODUCTION

The eutrophication of a lake leads to a build-up in phytoplankton populations with a change in species composition. Generally, blooms of blue-green algae (Cyanobacteria) become more common and these often produce unpleasant odours and are toxic to waterfowl and other animals. Phytoplankton standing crop estimated as the concentration of the pigment chlorophyll a, is therefore a useful measure of eutrophication and is sometimes used as a criterion for determining lake trophic status (Table 1.2). Chlorophyll a is a good indicator of nutrient conditions and shows a strong positive correlation with phytoplankton production (Brylinsky and Mann 1973).

Chlorophyll pigments are degraded by the loss of phytol groups and ions, and the degradation products tend to decrease in solubility and become more stable. These physiologically-inactive green pigments (phaeophytins, phaeophorbides and chlorophyllides) have absorption peaks in the same region of the spectrum as the chlorophylls, and may result in an overestimate of chlorophyll concentration. Chlorophyllase, which occurs in the chloroplasts, removes the phytol group. Acidification, even with very weak acids, releases the Mg from the porphyrin head and replaces it with 2 H atoms. Subsequently, the blue absorption band is shifted towards the UV region and intensified, and also the red absorption is shifted toward the longer wavelengths and is decreased by about 50% (Yentsch 1967). A correction for phaeophytin, using acidification, is thought to correct most of this error.

Spatial and temporal variation in phytoplankton standing crops were monitored by the chlorophyll a technique at the same times as the nutrients, to further the understanding of phytoplankton population dynamics in Lake Joondalup.

Several environmental factors influence phytoplankton production, the principal ones being nutrient availability, light, temperature, and water turbulence. The management of algal blooms, in a particular system, relies on the identification of the particular factors leading to high standing crops, and on the understanding of how these factors interact.

There are two basic approaches to disentangling the effects of several variables on algal growth. One is to examine the effects in laboratory culture, where all but one variable can be held constant. With this approach there are difficulties in extrapolating from the microcosm, back to the more complex interactions in the natural system. The other approach is to identify principal factors by statistical analysis of environmental data. The ideal approach is to use a combination of both of these.

Data from the present study were analysed using correlation and multiple regression analysis.

4.2 MATERIALS AND METHODS

4.2.1 CHLOROPHYLL a AND PHAEOPHYTIN ANALYSES

Samples for chlorophyll a and phaeophytin analysis were collected at the same times and sites as the samples for nutrient analysis, including grid studies. Samples were taken from the surface in 1L polypropylene bottles and stored under cool and dark conditions. On return to the laboratory, a known volume of water was filtered through a 47 mm glass fibre filter paper (Whatman GF/C, mean retention size 1.7 mm). These filter papers were then frozen until the chlorophyll extraction could be done, usually within 2 weeks.

The filter and filtrate containing the phytoplankton was ground with a tissue grinder on a stirring motor, and the chlorophyll extracted in 90% acetone at 4°C for 24 hours. The extract was then centrifuged at 3500 rpm for 7 min and the optical densities at 665 nm and 750 nm determined with a spectrophotometer (Varian 634S UV Visible Spectrophotometer, Varian Techtron Pty Ltd, Springvale, Victoria). To correct for phaeophytin, 1 drop of 1 N HCl was added to the extract and the OD readings repeated. Chlorophyll a and phaeophytin concentrations were then calculated (Strickland and Parsons 1972).

4.2.2 RECORDS OF PHYTOPLANKTON TAXA PRESENT

Regular collections of phytoplankton for counts or taxonomic identification could not be made, as these are very time-consuming and labour-intensive activities. However on several occasions observations were made on the taxa present and these are listed in Table 4.7. Prescott's (1978) key was used for identifications.

4.2.3 STATISTICAL ANALYSES

The relationship between phytoplankton standing crop (as chlorophyll a) and nutrient concentrations was investigated using regression analysis using the SPSS programmes of Nie et al (1975).

4.3 RESULTS

4.3.1 DIFFERENCES BETWEEN SITES

On average, sites in the southernmost basin of Lake Joondalup showed higher chlorophyll a and phaeophytin concentrations than sites in the main waterbody (Tables 4.1 and 4.2). The overall mean for sites in the southernmost basin was 116.9 mg chlorophyll a l^{-1} (range of 0.1 to 1425.8 µg l^{-1}), compared with 27.5 µg l^{-1} (range of 0.6 to 439.8 µg l^{-1}) for sites in the main waterbody.

Site 46, in the culvert under Ocean Reef Road, had the lowest mean chlorophyll concentration of the southern sites, as it was not connected to the southernmost basin at times of lowest water levels and no flow (Table 4.2). Highest concentrations were recorded at site 54 as this site was the last to dry up in summer/autumn, and it could be sampled further into the period of low water levels. Phaeophytin concentrations show the same general trends as they depend directly on chlorophyll concentrations.

Samples from sites to the south of Lake Joondalup showed comparatively lower chlorophyll and phaeophytin concentrations than sites within the lake (Table 4.3). Site 57, in the channel between the lake and Beenyup Swamp, gave a mean concentration of only 12.7 µg chlorophyll a l^{-1}.

Samples from Lake Goollelal had quite low chlorophyll concentrations, with a mean of 8.9 µg l^{-1} and a maximum of only 37.2 µg l^{-1}. This may reflect the lower sampling frequency of Beenyup Swamp and Lake Goollelal. Low chlorophyll and phaeophytin concentrations were also found in the stormwater sumps (Table 4.4).

The data for phaeophytin concentrations do not suggest a significant input of chlorophyll degradation products from Beenyup and Wallubuenup Swamps. Mean phaeophytin concentrations were equivalent to 26% of the mean chlorophyll a concentrations in the main waterbody, 29% in the southernmost basin, and 29% in Beenyup Swamp. The mean phaeophytin concentration was 49% of the mean chlorophyll a concentration found in Lake Goollelal, and this may indicate an input of chlorophyll degradation products from decomposing Eichornia or other macrophytes, or a different phytoplankton flora.

4.3.2 TEMPORAL VARIATION

4.3.2.1 The Main Waterbody

Sites in the main waterbody of Lake Joondalup showed peaks in chlorophyll a concentrations in late summer to early autumn (Fig. 4.1, Table 4.5). Highest concentrations were 10 to 18 times greater at sites 19 and 34 in 1980 than in 1979, and mean concentrations for the main waterbody were 3 times greater in 1980 than in 1979 (Table 4.6). This suggests a negative relationship with water level and a positive relationship with nutrient concentrations, especially ammonium-nitrogen. Chlorophyll a concentrations were of the order of 50% lower in late winter/early spring 1980 than in 1979.

Anabaena was observed at southern sites in the lake in October to December, whilst Microcystis and Aphanothece (from the metaphyton) were observed from October to April

(Table 4.7). Masses of Spirogyra build up sometimes in the spring and these accumulate at site 37 in the summer, probably due to the prevailing south-westerly winds.

4.3.2.2 The Southernmost Basin

Peaks in chlorophyll a concentrations were recorded in late spring/summer and mid-autumn to mid-winter, for sites in the southernmost basin of Lake Joondalup (Fig. 4.2). Higher concentrations were recorded in 1979/1980 than in 1978/1979, with the highest being recorded in mid-autumn 1980 at site 54, when the other sites had dried up. Relatively low concentrations were recorded from winter to early spring, when water flow from the south was greatest.

High chlorophyll a concentrations were attributable to blooms of the blue-green alga (Cyanobacteria) Anabaena spiroides (Table 4.7). Other species such as Microcystis, Nannochloris(?) and Heterogloea(?) were present when the Anabaena blooms collapsed.

4.3.2.3 Site 57 and Beenyup Swamp

Samples from site 57, in the channel between Lake Joondalup and Beenyup Swamp, contained very low chlorophyll a concentrations except in summer/autumn when there was no flow of water from Beenyup Swamp (Fig. 4.3). Similarly, chlorophyll a concentrations at site 59, in Beenyup Swamp, only exceeded 2 μg l^{-1} in summer and autumn.

4.3.2.4 Lake Goollelal

During this study, chlorophyll a concentrations in samples from site 73 in Lake Goollelal never exceeded 40 μg l^{-1}, and they peaked in autumn 1979 and 1980, and spring 1980 (Fig. 4.3). A filamentous blue-green alga was present in March 1979, and a green alga (Quadrichloris(?)) and the blue-green Microcystis aeruginosa were present in May 1980.

4.3.2.5 Site 36

Low chlorophyll a concentrations were also recorded for site 36, the stormwater sump on the eastern shore of Lake Joondalup, with a peak concentration of 26 μg l^{-1}. Peaks occurred in spring 1978/summer 1979, spring 1979 and autumn 1980 (Fig. 4.3).

4.3.2.6 General

Contour maps of chlorophyll a distribution within Lake Joondalup show areas of highest concentration along the eastern shore in January 1979 and March 1979, when there was no water flow from the south, and in August 1980 and September 1980 (see Appendix 3). Higher standing crops on the eastern shore may be related to the inflow of nutrients in groundwater.

In June 1980, highest phytoplankton standing crops were found in the south of Lake Joondalup, just north of Ocean Reef Road - at the time when water had begun to flow through the culvert. This suggests that phosphorus in the inflowing water may have triggered an increase in phytoplankton standing crop.

Highest chlorophyll a levels were found in the southernmost basin in October 1980, and just north of the culvert in November 1980. This also suggests the movement of a productive, nutrient-rich body of water northwards into the lake with time. Increased populations of Anabaena spiroides were evident in the southern areas of the lake in October and November (Table 4.7).

4.3.3 FACTORS INFLUENCING VARIATION IN PHYTOPLANKTON STANDING CROP

4.3.3.1 Correlation Analysis of Chlorophyll a Against Nutrient Concentrations

The correlation of mean chlorophyll a concentrations with mean nutrient concentrations, on a whole lake basis, was investigated with simple linear regression analysis of the grid studies' data (Table 4.8). Mean chlorophyll a concentration was only significantly correlated with mean organic nitrogen concentration, whilst mean reactive phosphorus concentration was correlated with organic phosphorus concentration.

A simple correlation with inorganic nutrient concentrations was not found, and is unlikely for this time scale because of the seasonal changes in several factors affecting phytoplankton production, which do not vary together. For example, although phytoplankton standing crop may be correlated with phosphate levels in the spring or summer, it may not be on a whole year basis, since high phosphorus concentrations are found in winter when light, temperature and turbulence may limit production.

The correlation between chlorophyll and organic nitrogen suggests that most of the organic nitrogen in the water column is associated with phytoplankton.

4.3.3.2 Correlation Analysis of Chlorophyll a Against Nutrient Concentrations For Single Sites Over Time

Correlations between chlorophyll a concentrations and nutrient concentrations were investigated for site 47, where Anabaena blooms occurred (Table 4.9). Chlorophyll was significantly correlated with organic phosphorus, ammonium-nitrogen and organic nitrogen. The close positive correlation with the organic fractions suggests that most organic nutrient in the water column is tied up within phytoplankton cells, and it is notable that the most significant correlation was with organic nitrogen. The correlation with organic phosphorus was not as significant, suggesting that luxury consumption of phosphorus from the phosphorus-rich waters may occur.

Chlorophyll a was (only just significantly) negatively correlated with NH_4-N, suggesting that NH_4-N is taken up as the phytoplankton standing crop increases so that it becomes limiting. This is supported by the low inorganic nitrogen to phosphorus ratios found at this site (Fig. 2.31). Chlorophyll a was not correlated with reactive phosphorus, reflecting the high concentrations of inorganic phosphorus available in the waters flowing from the southern swamps.

Among the nutrient fractions, reactive phosphorus was significantly correlated with organic nitrogen ($r = 0.389$, $n = 66$, $P = 0.00063$) and NH_4-N ($r = 0.333$, $n = 66$, $P = 0.00312$), and organic phosphorus was significantly correlated with organic nitrogen ($r = 0.218$, $n = 65$, $P = 0.04086$).

4.3.3.3 Correlation Analysis of Chlorophyll a Against Nutrient Concentrations and Other Parameters For the Southernmost Basin During an Anabaena Bloom

A grid study was made of the southernmost basin of Lake Joondalup during a bloom of Anabaena spiroides on November 29, 1979. A maximum chlorophyll a concentration of 5261 μg l^{-1} was recorded at site 53.

Other chlorophyll concentrations ranged from1.5 μg l^{-1} at site 57 to 329 μg l^{-1} at site 50. A negative relationship was found between chlorophyll and Secchi transparency, and absorbance of the water at 440 nm (when the high reading from site 53 was excluded) (Table 4.10). The absorbance at 440 nm is a measure of the amount of gilvins (including humic acids) in the water (Kirk 1976). Chlorophyll was positively correlated with pH, suggesting that there was less algal growth at low pH, which would result from the acidic nature of the gilvins.

Chlorophyll a concentration was again most significantly correlated with the organic nitrogen concentration, and to a lesser extent, with PO_4-P concentrations (Table 4.11). This indicates that nitrogen is important under these conditions of high PO_4-P concentrations, and may reflect some N_2-fixation.

4.3.3.4 Patterns of Chlorophyll a and Nutrient Distributions During Grid Studies

Some indication of possible causal relationships can be gained by examining patterns of chlorophyll a and nutrient distributions within the lake at each grid study (see contour maps in Appendix 3).

During January 1979 the highest chlorophyll concentration recorded was 33 $\mu g\ l^{-1}$ at site 29. At this time the highest concentrations of nitrogen and phosphorus were in the southern end of the lake. In March 1979 the highest chlorophyll level was 65 $\mu g\ l^{-1}$ at site 37, and the highest concentrations of phosphorus, NH_4 and total nitrogen were again to the south. However, the highest NO_3 concentration was found at site 37. This was a time of low water levels and seepage of groundwater of comparatively high nitrate concentration may have favoured phytoplankton growth at this site.

In July 1979 the highest chlorophyll concentrations were recorded in the southernmost basin (34 $\mu g\ l^{-1}$) where PO_4 concentrations were very high. NH_4 and NO_3 concentrations were comparatively high at site 57 but low in the basin. This suggests that very high PO_4 levels may have favoured phytoplankton production which caused inorganic nitrogen concentrations to fall, and perhaps become limiting.

During the January 1980 grid study, when the southernmost basin was separated from the main waterbody, very high chlorophyll concentrations were found at sites 21 (175 $\mu g\ l^{-1}$), 24 (100 $\mu g\ l^{-1}$) and 37 (154 $\mu g\ l^{-1}$) on the eastern side of the lake. No direct relationship with nutrient concentrations was apparent.

In June 1980, when water had not begun to flow into the lake through the Ocean Reef Road culvert, the highest chlorophyll concentrations (to 144 $\mu g\ l^{-1}$) were found in the south of the lake but north of Ocean Reef Road. The highest phosphorus and organic nitrogen concentrations were also found in this region, while inorganic nitrogen concentrations were comparatively low. This suggests that phytoplankton production was favoured by high PO_4 concentrations, resulting in the depletion of inorganic nitrogen.

In July 1980, high chlorophyll concentrations were found at sites 24, 37, 39, 40, 43, and 44 in the south-east of the lake, where high PO_4 concentrations were also found. Higher PO_4 concentrations were present in the southernmost basin of the lake but chlorophyll concentrations were less than 5 $\mu g\ l^{-1}$, suggesting that light availability, temperature or humic acid concentrations was limiting phytoplankton growth.

Chlorophyll concentrations were low (less than 9 $\mu g\ l^{-1}$) during the grid studies in August and September 1980, although concentrations of phosphorus and nitrogen were relatively high in the south of the lake. This also suggests that something other than nutrient availability was limiting production.

Chlorophyll concentrations greater than 11 $\mu g\ l^{-1}$ were not found north of Ocean Reef Road in October 1980, although 70 $\mu g\ l^{-1}$ chlorophyll a was recorded at site 47 in the southernmost basin. The highest organic and reactive phosphorus and lowest inorganic nitrogen concentrations were associated with this bloom.

In November 1980, chlorophyll concentrations were low in the southernmost basin (less than 7 $\mu g\ l^{-1}$), whereas they reached 66 $\mu g\ l^{-1}$ just north of the Ocean Reef Road causeway. High phosphorus and organic nitrogen, and low inorganic nitrogen concentrations were associated with this bloom.

4.3.3.5 Patterns of Chlorophyll a and Nutrient Distributions at Particular Sites

Chlorophyll concentrations in the main waterbody peaked in mid-autumn (Fig. 4.1), at the same time as PO_4, organic P and organic N (Figs. 2.5, 2.10, 2.24). Inorganic N peaked before, and following these chlorophyll peaks (Figs. 2.15 and 2.19).

This is also largely true of sites in the southernmost basin, except peaks in inorganic nitrogen tended to follow peaks in chlorophyll (Figs. 4.2, 2.17, 2.20, 2.21). This is also reflected in increased inorganic N:P ratios following blooms (Fig. 2.31).

Peak chlorophyll concentrations occurred at site 57 in summer to mid-autumn when there was no flow of water from Beenyup Swamp, and nutrient concentrations were low when compared to those found at times of flow (Figs. 4.3a, 2.8, 2.21). This implies that there is something inhibitory to phytoplankton in water flowing from the southern swamps.

Site 59, in Beenyup Swamp, had peak chlorophyll concentrations in early autumn as water levels reached their lowest levels (Fig. 4.3b). This coincided with very high concentrations of reactive and organic phosphorus, and organic nitrogen (Figs. 2.9, 2.12, 2.26). Highest inorganic nitrogen concentrations followed peaks in chlorophyll.

Highest concentrations of chlorophyll in Lake Goollelal, at site 73, coincided with peaks in the concentrations of organic nutrients, and low concentrations of inorganic nutrients (Figs. 4.3c, 2.9, 2.13, 2.17, 2.22 and 2.26).

4.4 DISCUSSION

The highest concentrations of chlorophyll a and phaeophytin were found in the southernmost basin of the lake, and were related to blooms of the cyanobacteria Anabaena spiroides. Sites further south of the lake, in Beenyup Swamp and between the swamp and Lake Joondalup (site 57), had quite low concentrations, often lower than those found at sites within the main waterbody of the lake. Chlorophyll concentrations were also quite low in the stormwater sump draining into Lake Joondalup (site 36), and in Lake Goollelal (site 73).

The overall pattern suggests that phytoplankton blooms in the southern end of Lake Joondalup are triggered by high phosphorus concentrations entering the lake from Beenyup and Wallubuenup Swamps. The low nitrogen to phosphorus ratio of the water results in depletion of nitrogen, which favours the N_2-fixing blue-green alga Anabaena spiroides. There is another limiting factor, since chlorophyll concentrations are very low at site 57 and in Beenyup Swamp at times of blooms in the southernmost basin, and this appeared to spread to this basin in November 1980. It is likely to be associated with humic substances. This could be through the production of an unfavourably low pH (Shapiro 1957), complexation and the consequential unavailability of a trace element (micronutrient) (Saunders 1957), or the inhibition of enzymes (Butler and Ladd 1971).

Peak chlorophyll a concentrations occurred in the main waterbody of Lake Joondalup in late summer to early autumn, and in the southernmost basin in late spring and summer, and mid-autumn to mid-winter. Lowest chlorophyll a concentrations were recorded in late winter to early spring when light, temperature and water turbulence would be least favourable.

Since Lake Joondalup is very shallow and thus dominated by ambient atmospheric conditions, light and temperature changes were not monitored during this study. Temperature and secchi disk transparency changes have been monitored in previous studies (Congdon and McComb 1976; Gordon et al 1981). Gordon et al (1981) found that phytoplankton numbers were not significantly correlated with temperature or sunlight hours.

The yearly data suggest an increase in chlorophyll a concentrations, and hence phytoplankton standing crops, with time (Table 4.6). Gordon's (1975) data show particularly low concentrations, but are based on only 11 samples. Also his analytical method was different and may have given a lower yield of chlorophyll. Similarly, only 28 samples were collected in 1978 and these were restricted to the months of September and December. Hence the apparent increase in chlorophyll concentrations over the years may only reflect the frequency of sampling.

Chlorophyll a levels have been used to delimit lake trophic status (Table 2.8). According to the criteria of Sakamoto (1966) and Cullen et al (1978), the mean chlorophyll concentrations at all sites sampled in Lake Joondalup indicate eutrophic conditions. Site 36, in the stormwater sump, site 57, in the channel south of the lake, and site 73, in Lake Goollelal, also fall into the mesotrophic category.

4.5 SUMMARY

1. Mean concentrations of chlorophyll *a* and phaeophytin were higher in the southernmost basin of Lake Joondalup than in the main waterbody.

2. Much lower chlorophyll *a* and phaeophytin concentrations were found in Beenyup Swamp and the channel connecting it to Lake Joondalup, than in the lake itself.

3. Chlorophyll *a* concentrations in the main waterbody were highest in late summer to early autumn, and were higher in1980 than 1979.

4. In the southernmost basin of the lake, chlorophyll *a* peaked in late spring to summer and mid-autumn to mid-winter. Relatively low concentrations were recorded from winter to early spring, when water flow from the south was greatest. High chlorophyll *a* concentrations were attributable to the blue-green alga (Cyanobacteria) *Anabaena spiroides*.

5. In January 1979, March 1979, August 1980 and September 1980 the highest concentrations of chlorophyll *a*, within Lake Joondalup, were found near the eastern shore. This may reflect the inflow of nutrients in groundwater.

6. Chlorophyll *a* concentrations were best correlated with organic nitrogen concentrations, suggesting that nitrogen is the limiting nutrient.

7. During an *Anabaena* bloom in the southernmost basin of Lake Joondalup, chlorophyll *a* was negatively correlated with the absorbance at 440 nm (a measure of yellow substances or gilvin in the water) and positively correlated with pH. This suggests that humic acids inhibit phytoplankton growth in Beenyup Swamp water, and this inhibition is removed as the water mixes with Lake Joondalup.

8. Phytoplankton blooms appear to be caused by the high phosphorus loads in water flowing from Wallubuenup and Beenyup Swamps. The low nitrogen to phosphorus ratio of the water favours the N_2-fixing blue green alga *Anabaena spiroides*.

9. The mean chlorophyll concentrations indicate that Lake Joondalup is eutrophic.

5. GENERAL DISCUSSION AND RECOMMENDATIONS

5.1 THE WATER BALANCE

The water level of Lake Joondalup fluctuates seasonally and from year to year due to variation in rainfall. Evaporation has the greatest effect on the water balance, followed by precipitation (Table 5.1).

Surface discharge from the Wallubuenup/Beenyup Swamp system accounted for 88% of the surface water inflow to the lake in 1980, and stormwater contributed the remaining 12%. Surface discharge was equivalent to some 25% of the precipitation input. The contribution of the two sources of surface discharge will be affected by alterations to land-use and land-form in the lake's catchment, and stormwater discharge can be expected to increase as the catchment is increasingly urbanized.

The net groundwater seepage into the lake, calculated as the residual in the water balance, was similar to the discharge from the swamps (Table 5.1). Groundwater abstraction would tend to decrease groundwater seepage, whilst application of imported MWB water to lawns and gardens, and through septic tanks, would add to groundwater seepage. The net effect of these processes cannot be predicted from the present study.

Public opinion will probably consider that the aesthetic value of the lake to the regional sub-centre would be enhanced if the water level is maintained so that little of the lake bed is exposed in summer and autumn (eg at 17.5 m AHD). At low water levels much of the lake bed is exposed (25% in May 1980), algal blooms are promoted, and sediments and decomposing algae release unpleasant odours such as hydrogen sulphide and methane. It is unlikely that wildlife would be disadvantaged by slightly higher water levels in late summer and autumn, although attention should be given to maintaining the feeding grounds of wading birds. For these reasons it is important that future management of the lake includes some consideration of the potential effects of particular developments on the water balance.

5.2 THE PHOSPHORUS AND NITROGEN BUDGET

In 1980 surface discharge from the swamps contributed 73% of the phosphorus input to the lake, stormwater 1%, and atmospheric fallout 26%. Discharge from the swamps contributed some 30% of the nitrogen, stormwater 1% and atmospheric fallout 69%. Hence the discharge from the swamps is a very significant phosphorus source, whilst atmospheric fallout is the most significant nitrogen source (Table 5.1).

The mass balance indicates that 78% of the phosphorus entering the lake in 1980 was lost to the sediments, and there was a net gain of 81 kg to the water column. The nitrogen mass balance suggests a loss of 4.5 tonnes of nitrogen from the water column, including inputs in 1980, resulting in a net loss of some 1.7 tonnes from the water column. Assuming that the mass of phosphorus sedimented in 1980 multiplied by the average N:P ratio of the surface sediments, approximates the mass of nitrogen lost through sedimentation (Andersen 1974), a net loss of some 17.4 tonnes is indicated. This is nearly four times the sedimentation estimate from the mass balance, and if correct, would imply a large amount of N_2-fixation was taking place, equivalent to 14.5 tonnes. It is more likely that the average N:P ratio of the surface sediments, taken down to 5 cm depth, does not reflect the current N:P ratio of sedimenting material.

If the 1980 data are indicative of year-to-year trends then the N:P ratio would be decreasing and the phosphorus content of the water column increasing. The loss of nitrogen from the water column and the high N:P ratio of the sediments suggest that denitrification is not significant - or at least that it is far less significant than N_2-fixation.

5.3 PHYTOPLANKTON BLOOMS

The eutrophication of Lake Joondalup is clearly most affected by the large input of phosphorus from the south, resulting in intense blooms of blue-green algae. In the absence of water flow from the south, phytoplankton blooms still occur in the main waterbody of the lake in late summer and autumn (Fig. 4.1), at the time of low water levels and high nutrient concentrations.

The available data suggest that chlorophyll a concentrations increased in Lake Joondalup from 1975 to 1980, and that over the same period water levels decreased and phosphorus concentrations increased (Table 5.2). The concentration of PO_4-P may have simply increased due to decreasing lake volume and this would then determine chlorophyll concentrations. The large seasonal and year-to-year variations mean that data covering a longer time span are required, to prove or dismiss the hypothesis that there has been a significant increase in nutrient loadings to Lake Joondalup, with a resultant increase in phytoplankton blooms.

Blooms of Anabaena, Microcystis and Spirogyra result in masses of decomposing algae accumulating on the lake's surface. These collect on the windward (eastern) shore at times of high winds and release hydrogen sulphide and methane as they decompose. Some blue-green algae, including Anabaena spiroides, produce an odour resembling an insecticide - the gamma isomer of benzene hexachloride (Aplin 1979).

Chlorophyll a concentrations indicate that Lake Joondalup is eutrophic. The value of the lake, both as a landscape feature and a wildlife habitat, will be enhanced if eutrophication is reduced and algal blooms minimized.

5.4 MANAGEMENT OF EUTROPHICATION

Several methods have been proposed for reducing lake eutrophication (Table 5.3), although practice exceeds understanding in some instances (Welch 1984). Phosphorus is well accepted as the long-term controlling nutrient in most freshwater systems, and it is also the nutrient most amenable to manipulation.

The external loading of phosphorus can be reduced by waste-water treatment and/or diversion, and treatment of the inflow. One possible source of nutrients is septic tank effluent. Whelan and Barrow (1984) have shown that within a few years after installation, most of the phosphate discharged from septic tanks moves into the groundwater.

This possible phosphorus input can be diverted by connecting all houses to the sewerage system. Although a small area of houses on the lake's eastern shore were still using septic tanks at the time of this study, most of the houses in the lake's catchment are connected to the metropolitan sewerage system.

The inflow of nutrients from the southern swamps could be treated by increasing the retention time of the water within the swamps. Dense emergent macrophytic vegetation will retard phytoplankton blooms due to shading and will aid the sedimentation of particulate phosphorus. This hypothesis requires testing as some swamps export nutrients and wetlands are generally better at filtering nitrate than phosphate (Yates and Sheridan 1983).

Simple diversion of the water input from the swamps may not be satisfactory as this is a significant source of water for the lake. Its diversion would reduce the lake's water levels, increasing nutrient concentrations and possibly phytoplankton blooms.

A decrease in the external phosphorus loading could be compensated for by increased internal loading from the sediments (Ryding and Forsberg 1976). Lean et al (1975) present evidence that sediments can exchange up to 18 mg P $m^{-2}d^{-1}$ even under aerobic conditions. However, on present evidence this seems unlikely for Lake Joondalup, as the lake showed a large negative internal loading and the ubiquitous metaphyton (north of the Ocean Reef Road causeway) appears to buffer any nutrient release from the sediments. In the southernmost basin, where there is no metaphyton and the greatest external phosphorus loadings, increased internal loading from the sediment could occur. As this basin is small and dries out over summer it is amenable to dredging.

Possible sources of phosphorus in the region of the Wallubuenup and Beenyup Swamps include the caravan park near Whitfords Avenue, and agricultural land used for market gardening, grazing, poultry farms and viticulture. These possible sources require further investigation. If the sources are point sources then they are amenable to diversion or waste treatment. If non-point sources are responsible then changes in land management are favoured.

Many of the methods of disrupting internal nutrient cycles are not applicable to Lake Joondalup because of its shallow nature and hence the absence of stratification. Dredging is costly ($1.25 to $60 US per cubic metre, Welch 1984) and may further degrade the lake through increased turbidity. The inactivation or precipitation of phosphorus with alum, zirconium chloride or fly ash has a short-lived effect in shallow unstratified lakes. Bottom sealing with alum floc or plastic sheeting is not a popular method and would not be practical for a lake as large as Lake Joondalup.

In some lakes the water level has been reduced to allow the shallow sediments to dry, compact and consolidate. Phosphorus release may increase following lake refilling but long-term release may be less. Significant areas of the lake bed of Lake Joondalup are exposed at the end of dry summers and there is no evidence to suggest that further draining of the lake would significantly reduce phosphorus concentrations. It is possible that if the lake bed was exposed less, the metaphyton might further restrict internal cycling of phosphorus from the sediments.

Biotic harvesting, of vegetation or fish, has not been demonstrated to have any effect on the phosphorus content of any lake (Welch 1984).

Nutrient concentrations within the lake could be reduced by dilution with water containing lower nutrient concentrations. Although it is not practical to add large volumes of fresh water to the lake, increased stormwater discharge would have the same effect. This study found relatively low phosphorus concentrations in stormwater compared to discharge from the southern swamps. Some monitoring of stormwater is recommended, however, because it could contain toxic substances such as heavy metals (eg lead) and aromatic hydrocarbons (MacKenzie and Hunter 1979), and phosphate concentrations in stormwater can become significant (Cordery 1977). The addition of borewater could be useful in some areas, such as the southernmost basin in summer.

5.5 RECOMMENDATIONS

The immediate management of eutrophication in Lake Joondalup would be most effective if the actual sources of high phosphorus concentrations for the southern swamps could be determined. This would determine whether diversion or some other form of land management would be most practical. If this phosphorus source could not be eliminated, then some form of waste-water treatment would be required. Simple diversion of all water flowing from the southern swamps would have a significant effect on the lake's water budget resulting in lower lake levels, particularly in summer, which may detract from the lake's aesthetic value.

The simplest and cheapest form of waste-water treatment may be to retard water flow from the southern swamps for a period, provided the swamp vegetation will remove phosphorus from the water. The efficacy of this method would require testing.

Eutrophication of the southernmost basin of the lake could be reduced by dredging it, and pumping in bore-water during summer. This option would be favoured if housing or public facilities were to be established close to this basin.

Phytoplankton blooms still occur in the main waterbody of Lake Joondalup, during late summer and autumn, in the absence of nutrient-rich water flowing from the south. These peaks in phytoplankton standing crop are associated with low water levels and high nutrient concentrations, resulting from high summer evaporation rates and low rainfall. Such blooms would be reduced if low water-levels were avoided. The cheapest option for adding more surface water to the lake, would be the diversion of more stormwater into the lake. Occasional monitoring of stormwater quality is recommended, and pretreatment by ponding in sumps or filtration through sand or a vegetation buffer to remove particulates would be beneficial. Restrictions on the use of bores tapping groundwater on the eastern shore of the lake is another option which could be examined, to see if it can have a significant effect on the water levels of the lake in summer.

There are not many management options available to reduce eutrophication of Lake Joondalup as the lake has a large area, shallow depth and undergoes large seasonal changes in volume. The main contributors to the water budget of the lake are evaporation and rainfall, and these are not amenable to manipulation. The effective management of the eutrophication of Lake Joondalup is probably best achieved with an holistic approach to the management of the whole catchment.

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Figures 1.1 to 4.3
and
Tables 1.1 to 5.3

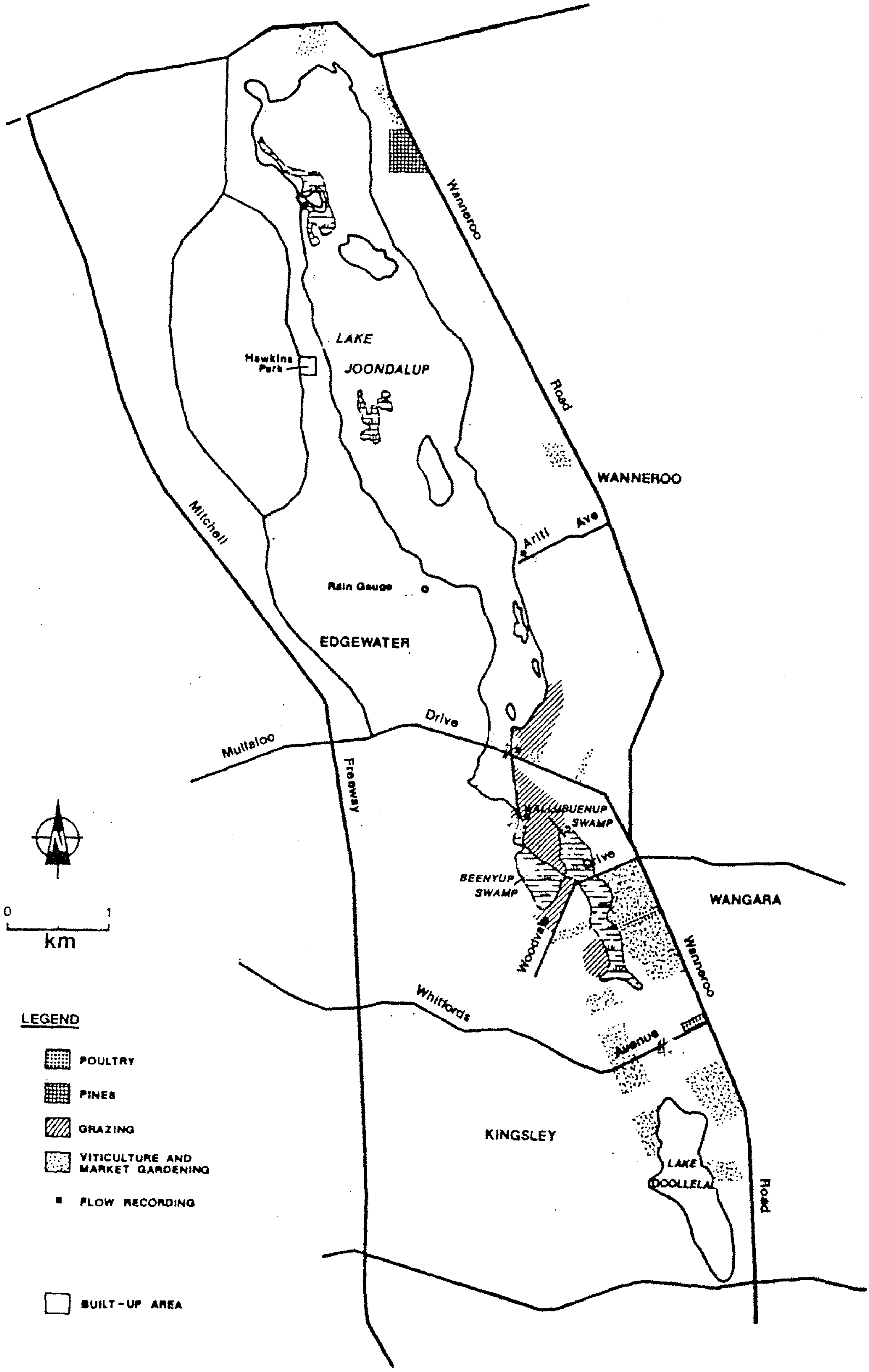


Fig 1.1 Lake Joondalup and its catchments, showing land-use.

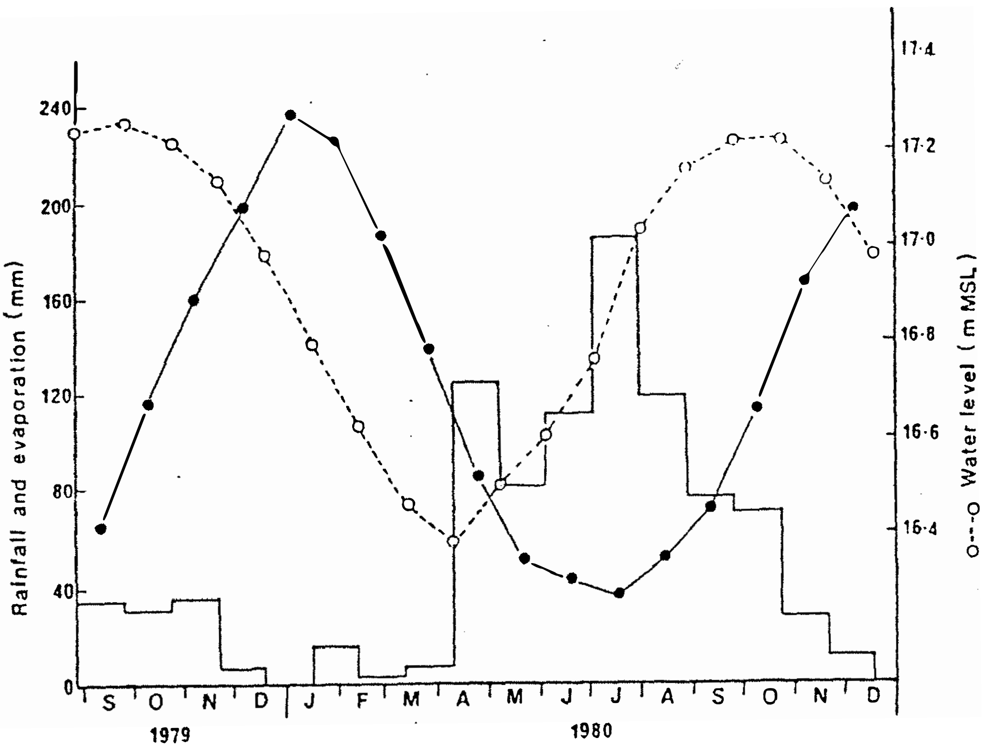


Fig 1.2 Seasonal changes in rainfall (bars), evaporation (.) and water level (o) in Lake Joondalup.

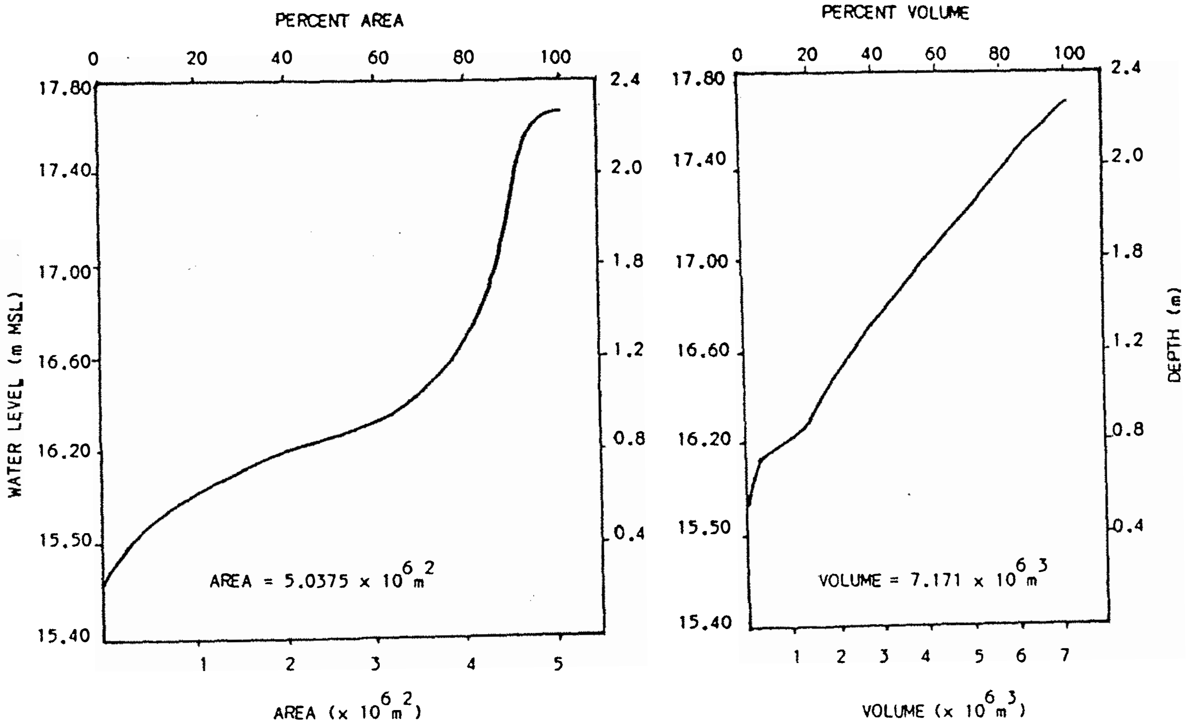


Fig 1.3 The (a) hypsographic and (b) direct volume curves for Lake Joondalup (based on the MWB bathymetry map for August 1, 1-75).

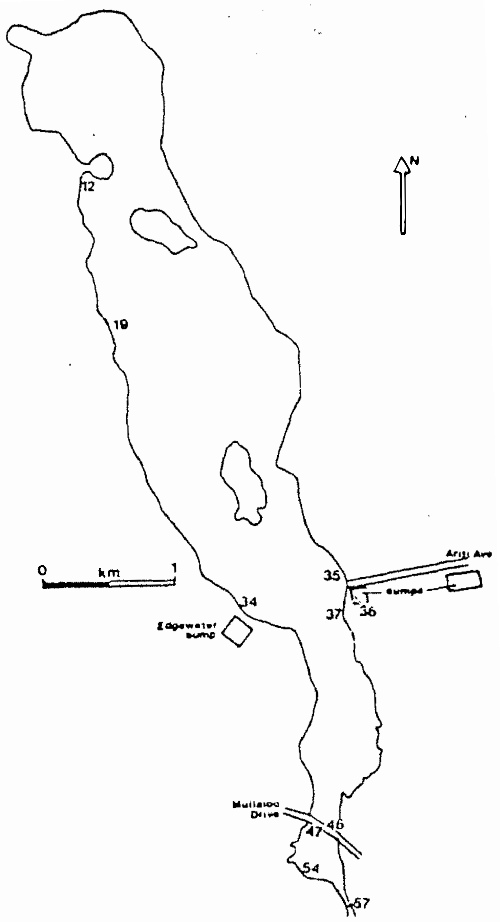


Fig 2.1 Sites in Lake Joondalup which were sampled regularly for nutrients and chlorophyll*a*.

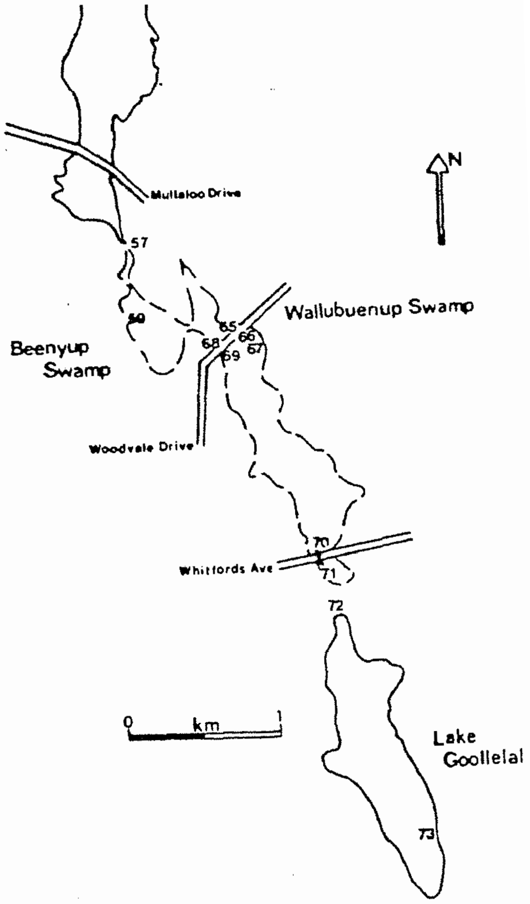


Fig 2.2 Sampling sites in Beenyup Swamp, Wallubuenup Swamp and Lake Goollelal.

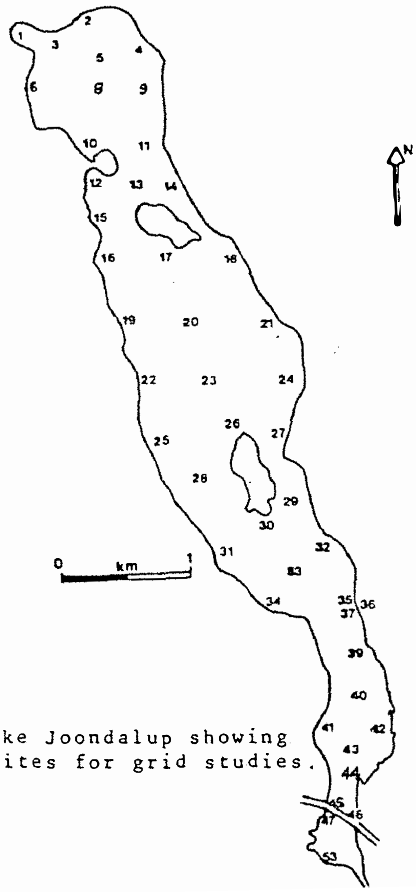


Fig 2.3 Lake Joondalup showing sampling sites for grid studies.

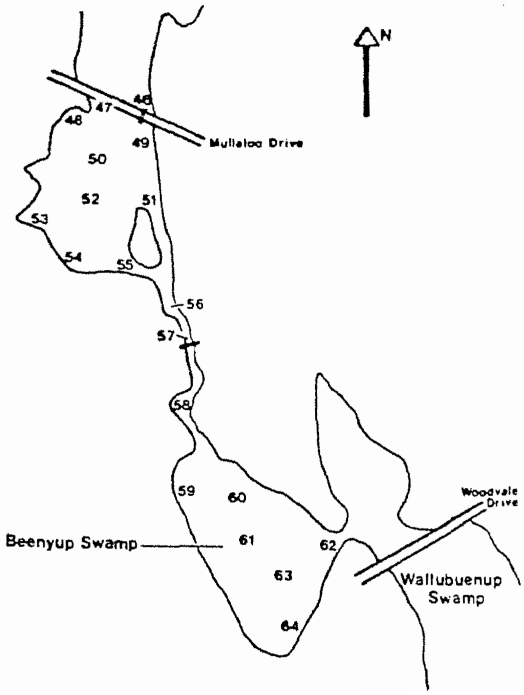


Fig 2.4 Sites in the southern basin of Lake Joondalup and in Beenyup Swamp, which were sampled during some grid studies.

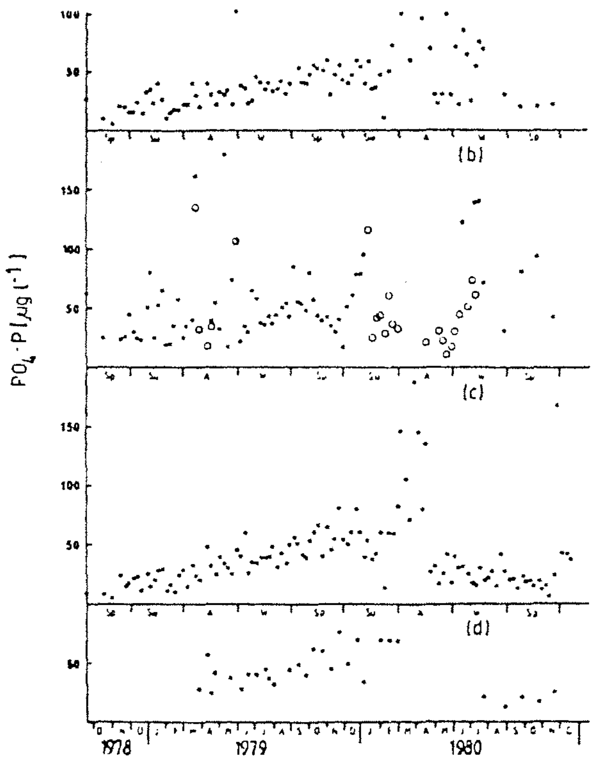


Fig 2.5 Seasonal changes in reactive phosphorus concentrations at (a) site 34, (b) sites 35(o) and 37(.), (c) site 19, and (d) site 12, in the main water body of Lake Joondalup.

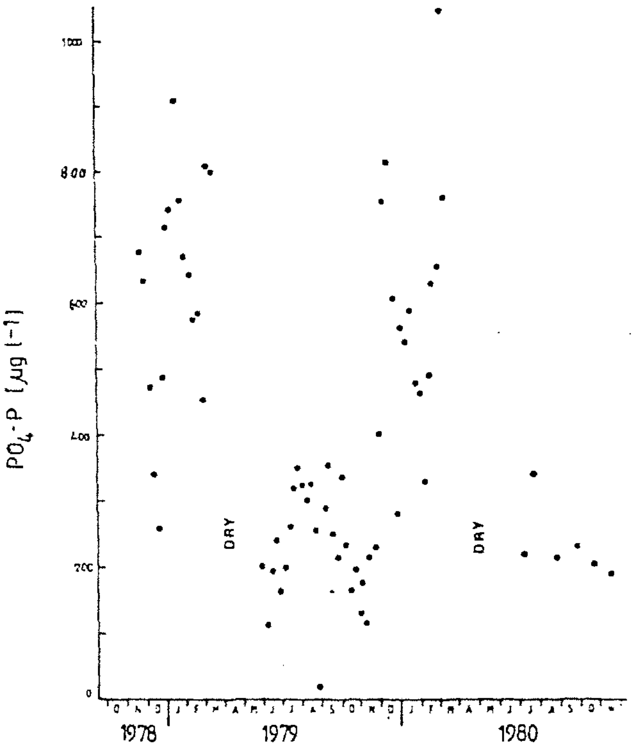


Fig 2.6 Seasonal changes in reactive phosphorus concentrations at site 47 in the southernmost basin of Lake Joondalup.

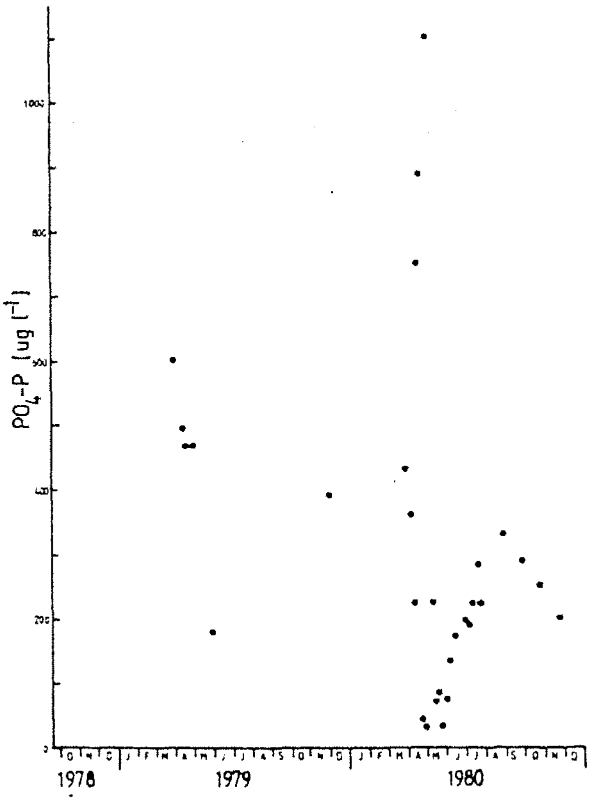


Fig 2.7 Seasonal changes in reactive phosphorus concentrations at(a)site 46, the culvert under Ocean Reef Road, and(b)site 57, in the channel connecting Beenyup Swamp to Lake Joondalup.

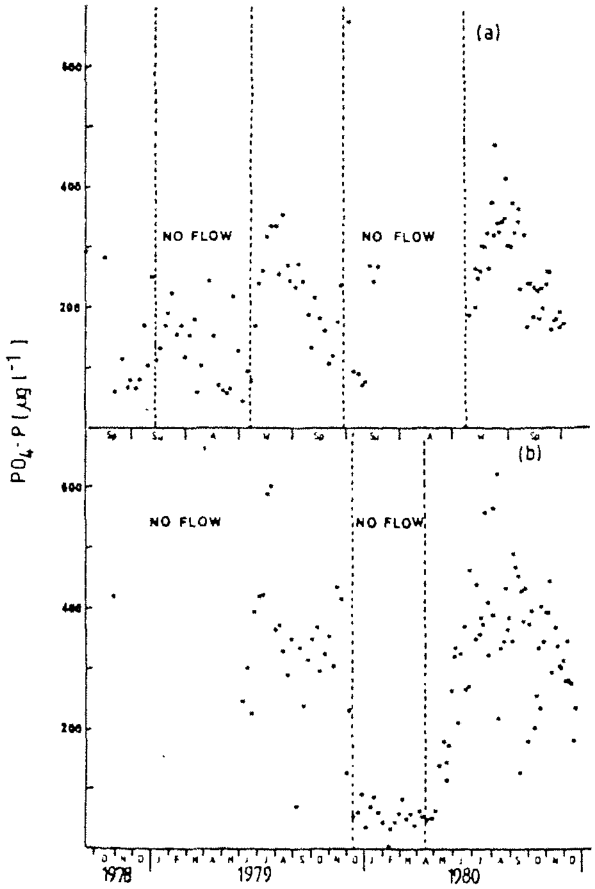


Fig 2.8 Seasonal changes in reactive phosphorus concentrations at(a)site 46 the culvert under Ocean Reef Road,and (b)site 57, in the channel connecting Beenyup Swamp to Lake Joondalup.

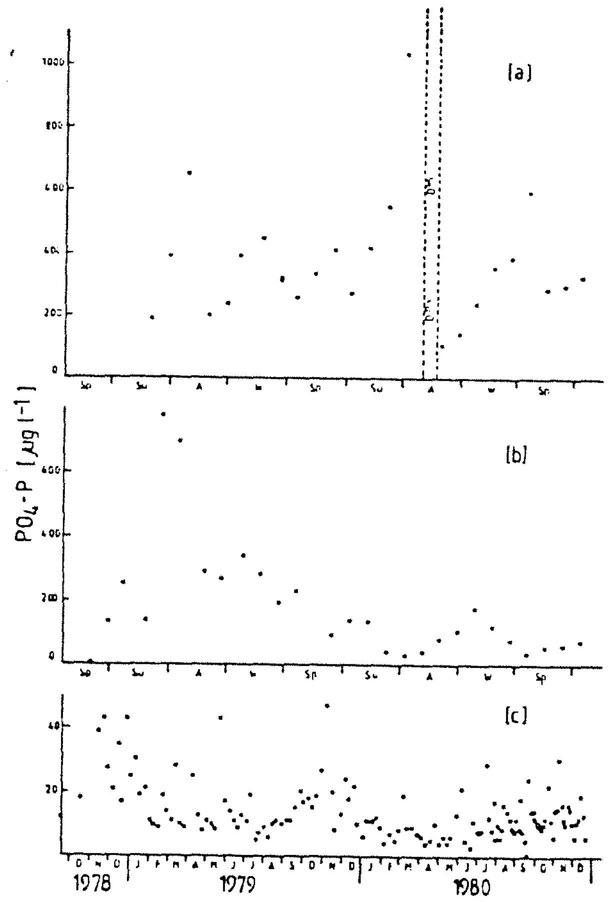


Fig 2.9 Seasonal changes in reactive phosphorus concentrations at(a)site 59, in Beenyup Swamp,(b)site 73,in Lake Goollelal, and(c)site 36, the stormwater sump on the eastern shore of Lake Joondalup.

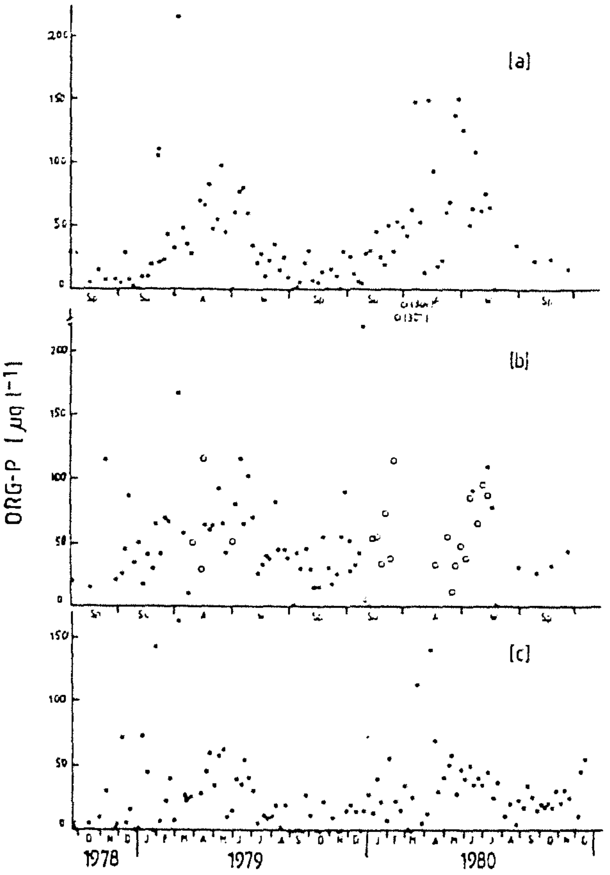


Fig 2.10 Seasonal changes in organic phosphorus concentrations at(a)site 34,(b)sites 37(.)and 35(o),and(c)site in the main waterbody of Lake Joondalup.

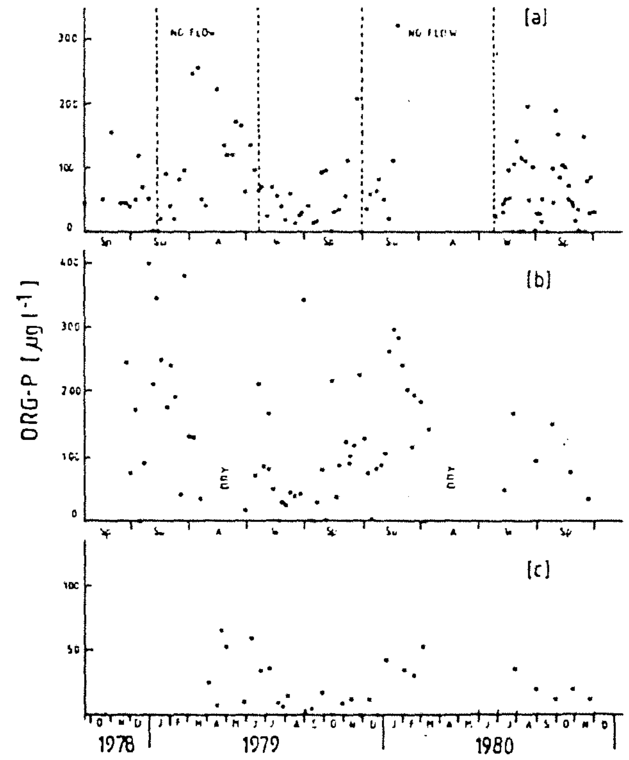


Fig 2.11 Seasonal changes in organic phosphorus concentrations at(a)site 46, the culvert under Ocean Reef Road, (b) site 47 in the southernmost basin, and(c)site 12 in the main waterbody.

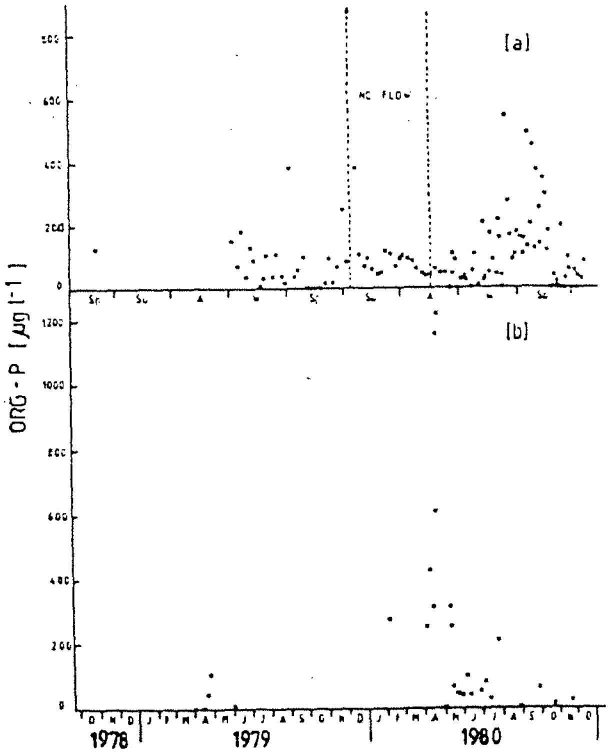


Fig 2.12 Seasonal changes in organic phosphorus concentrations at(a)site 57, in the channel connecting Beenyup Swamp to the southernmost basin of Lake Joondalup, and(b)site 54, in the southernmost basin.

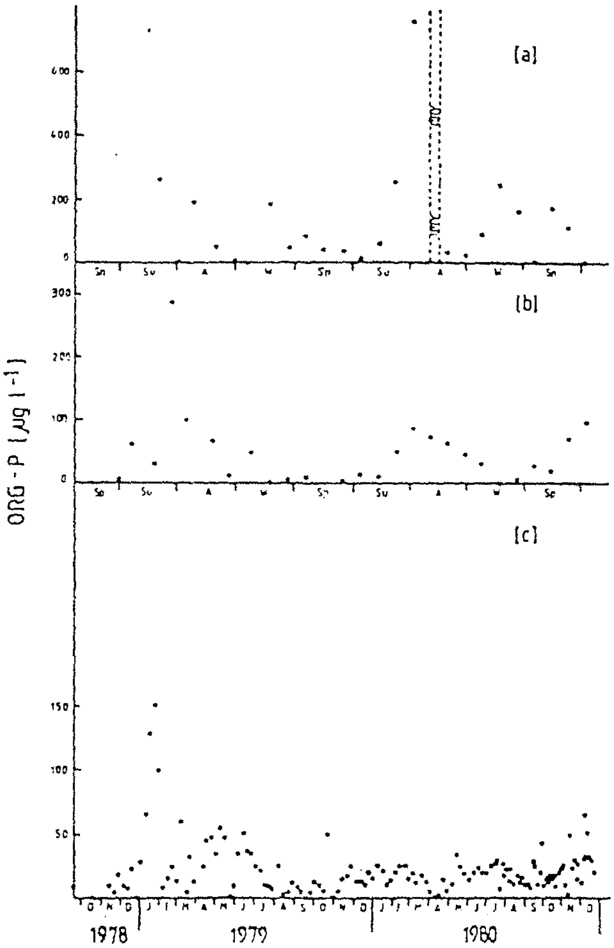


Fig 2.13 Seasonal changes in organic phosphorus concentrations at(a)site 59, in Beenyup Swamp,(b)site 73 in Lake Goollelal, and(c)site 36,in the stormwater sump on the eastern shore of Lake Joondalup.

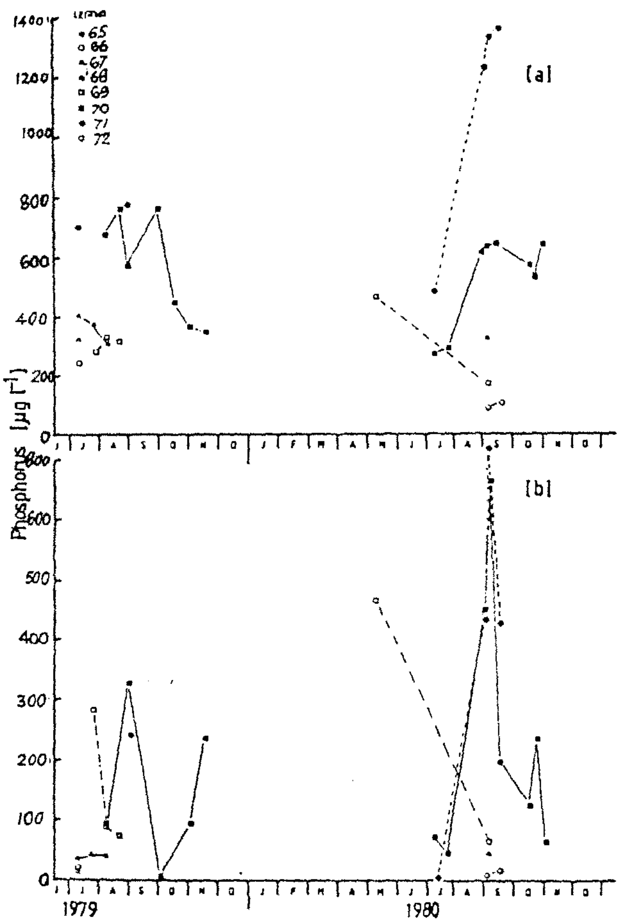


Fig 2.14 Seasonal changes in(a)reactive phosphorus and(b)organic phosphorus concentrations at sites in Wallubuenup Swamp.

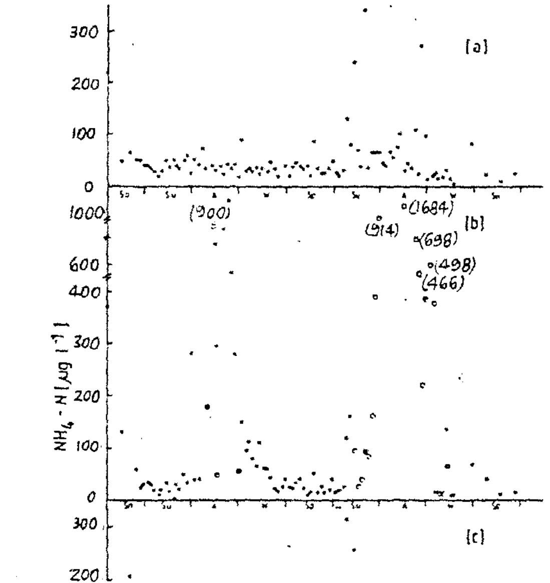


Fig 2.15 Seasonal changes in ammonium-nitrogen concentrations at(a)site 34, (b)sites 37(.)and 35(o),(c)site 19, and(d) site in the main waterbody of Lake Joondalup.

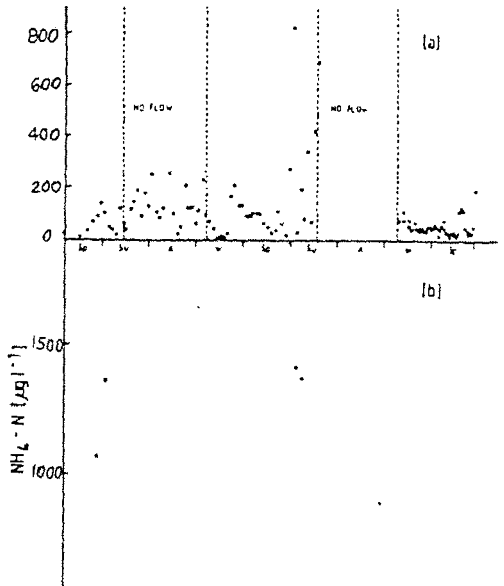


Fig 2.16 Seasonal changes in ammonium-nitrogen concentrations at(a)site 46, in the culvert under Mullaloo Drive, and (b)site 47, in the southernmost basin of Lake Joondalup.

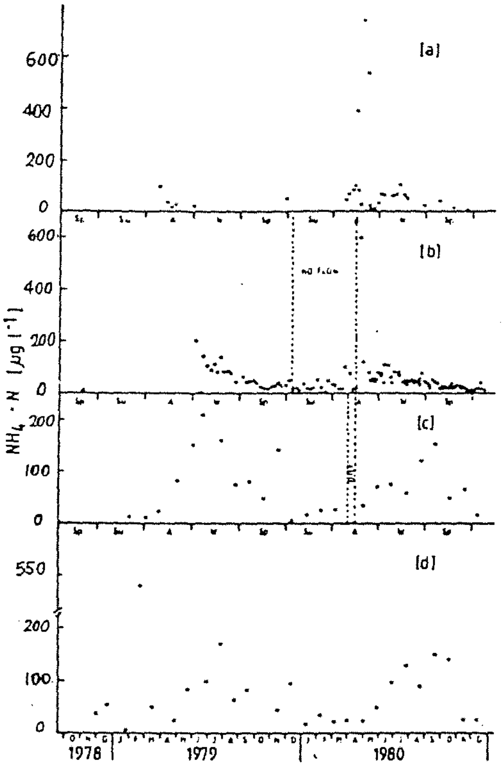


Fig 2.17 Seasonal changes in ammonium-nitrogen concentrations at(a)site 54, in the southernmost basin(b)site 57, in the channel between Beenyup Swamp and the southernmost basin,(c)site 59, in Beenyup Swamp, and(d) site 73 in Lake Goollelal.

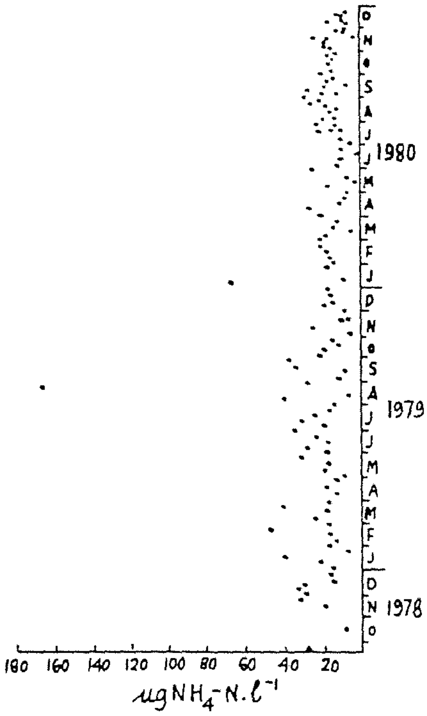


Fig 2.18 Seasonal changes in ammonium-nitrogen concentrations at site 36, the stormwater sump on the eastern shore of Lake Joondalup.

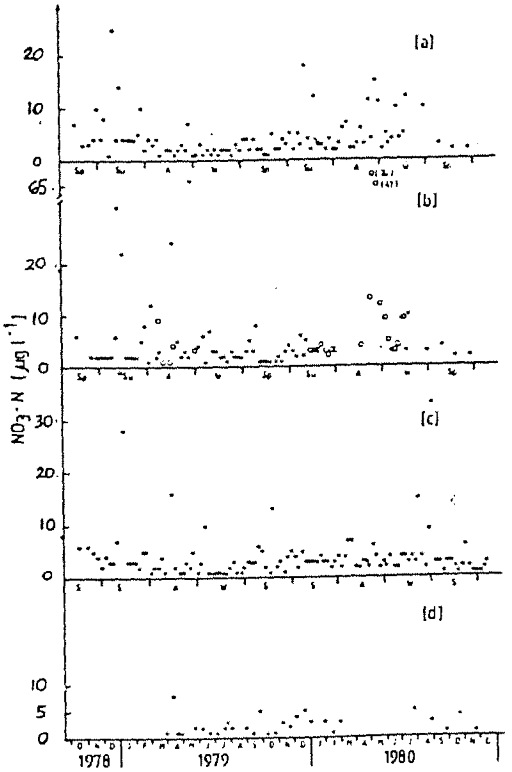


Fig 2.19 Seasonal changes in nitrate nitrogen concentrations at(a)site 34,(b) sites 37(.)and 35(o),(c)site 19, and(d) site 12, in the main waterbody of Lake Joondalup.

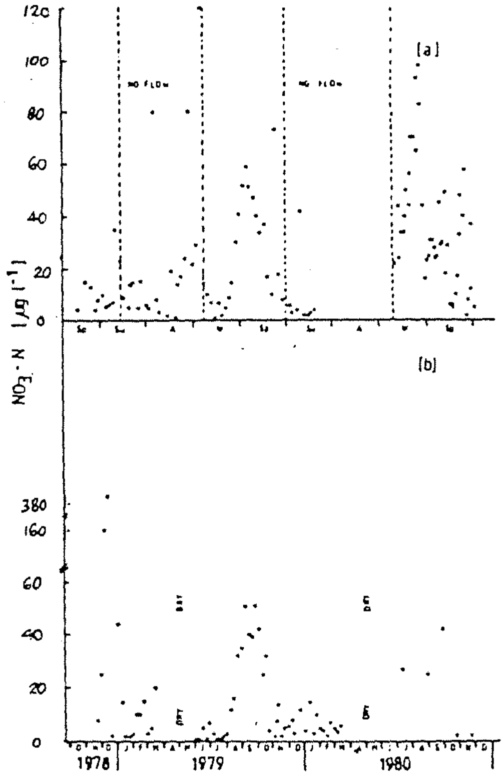


Fig2.20 Seasonal changes in nitrate nitrogen concentrations at(a)site 46, in the culvert under Mullaloo Drive, and(b)site 47, in the southernmost basin of Lake Joondalup.

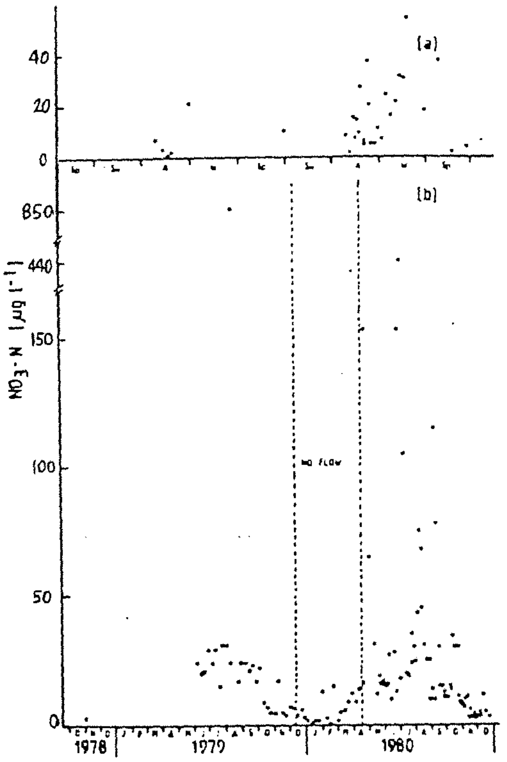


Fig 2.21 Seasonal changes in nitrate nitrogen concentrations at(a)site 54, in the southernmost basin of Lake Joondalup, and(b)site 57, in the channel connecting the basin to Beenyup Swamp.

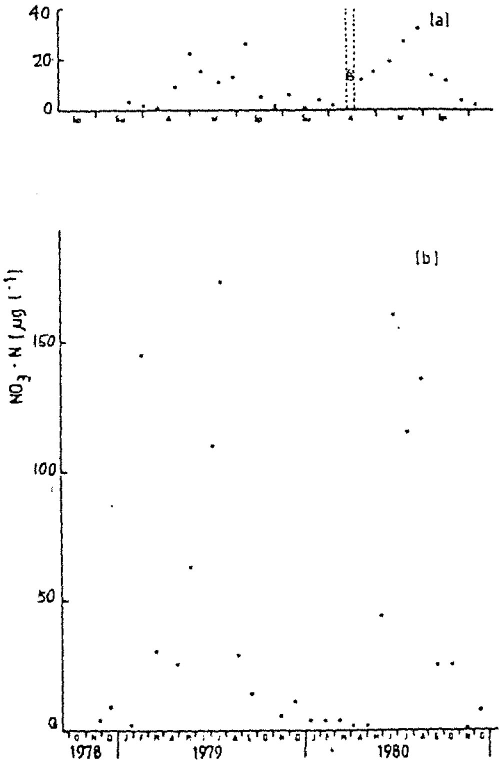


Fig 2.22 Seasonal changes in nitrate nitrogen concentrations at(a)site 59, in Beenyup Swamp, and(b)site 73 in Lake Goollelal.

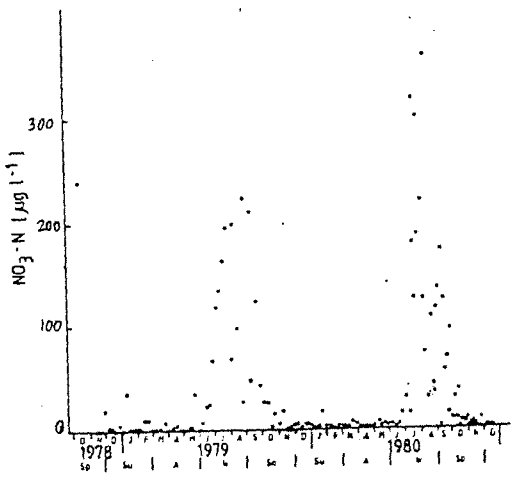


Fig 2.23 Seasonal changes in nitrate nitrogen concentrations at site 36, in the stormwater sump on the eastern shore of Lake Joondalup.

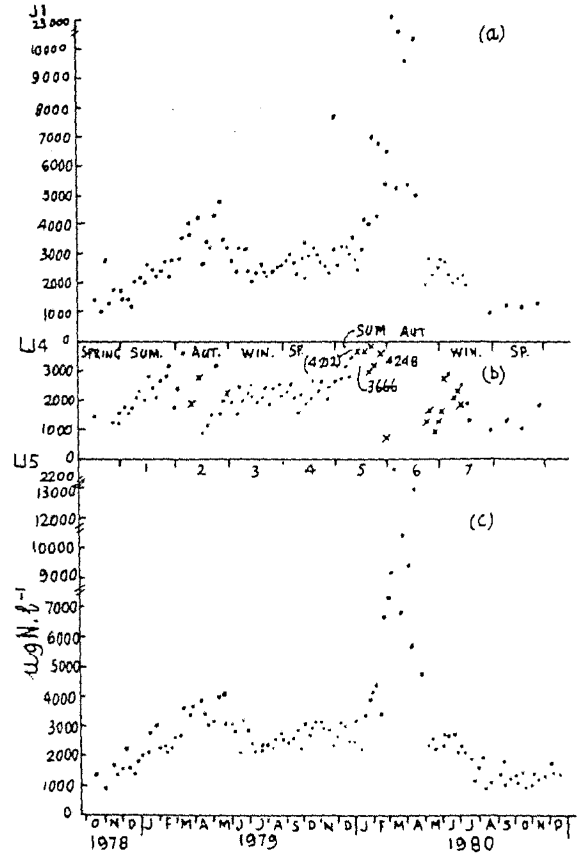


Fig 2.24 Seasonal changes in organic nitrogen concentrations at(a)site 34(b) sites 37(.)and 35(x),and(c)site 19, in the main waterbody of Lake Joondalup.

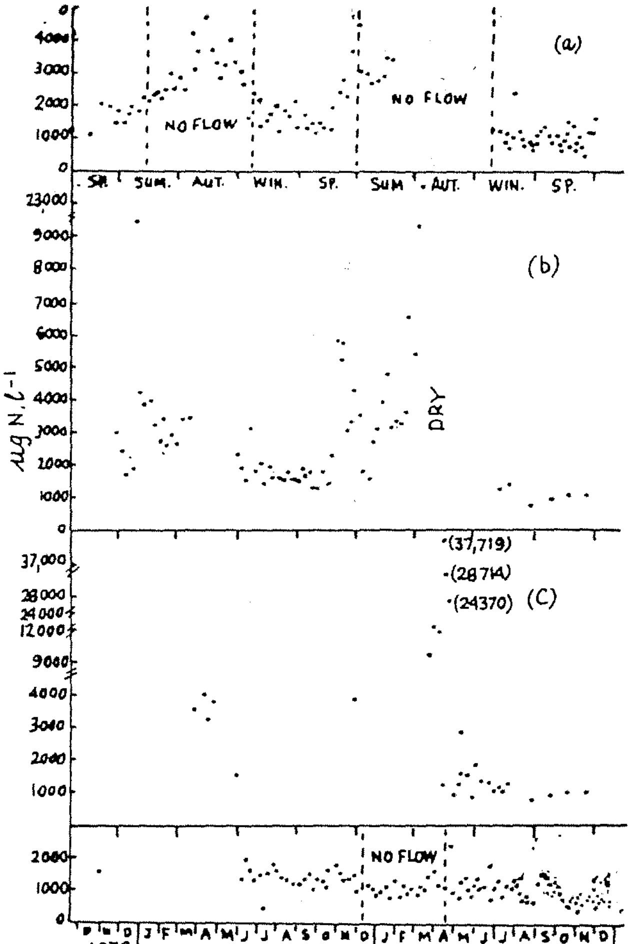


Fig 2.25 Seasonal changes in organic nitrogen concentrations at(a)site 46,in the culvert under Mullaloo Drive,(b)site 47 and(c)site 54 in the southernmost basin of Lake Joondalup,and(d)site 57,in the channel connecting the basin to Beenyup Swamp.

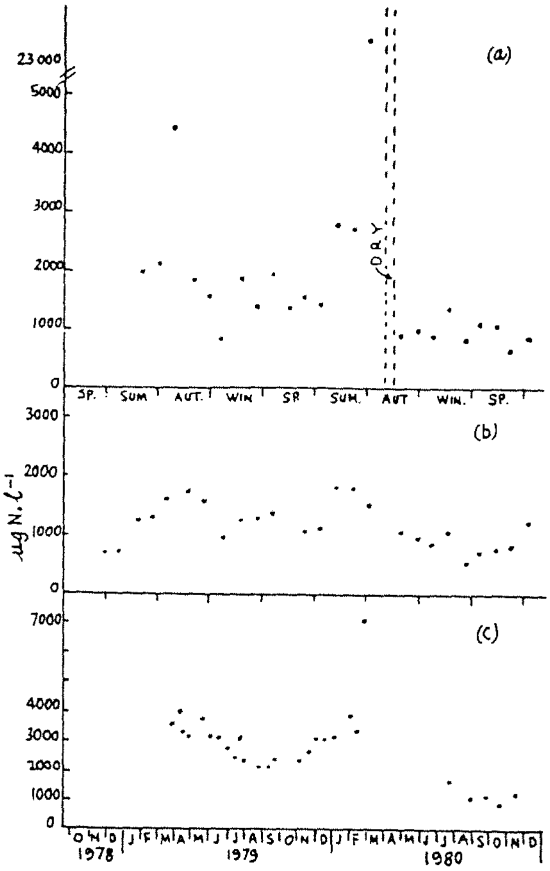


Fig 2.26 Seasonal changes in organic nitrogen concentrations at(a)site 59,in Beenyup Swamp,(b)site 73,in Lake Goollelal,and(c)site 12 in the main waterbody of Lake Joondalup.

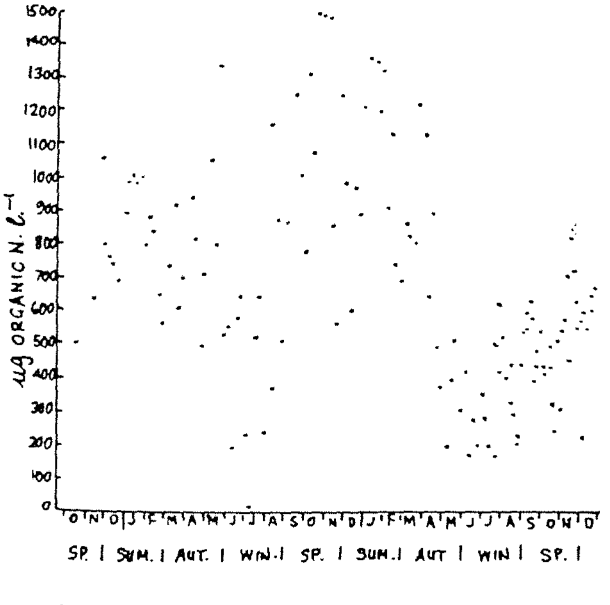


Fig 2.27 Seasonal changes in organic nitrogen concentrations at site 36, in the stormwater sump on the eastern shore of Lake Joondalup.

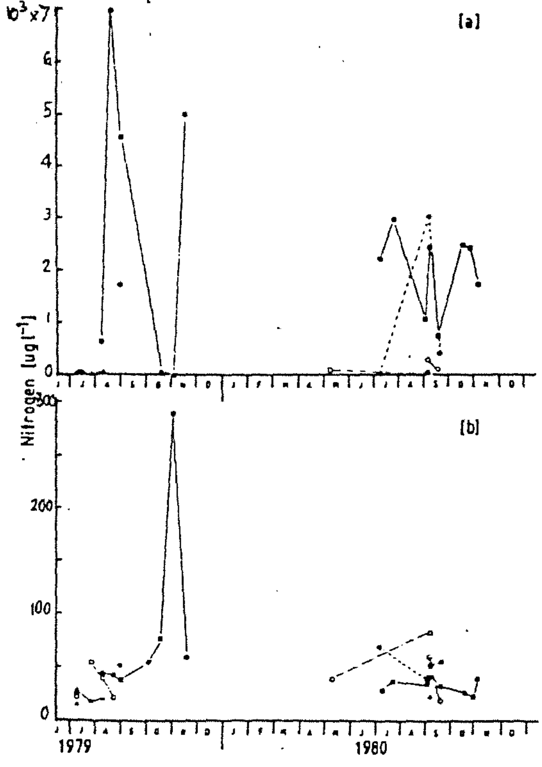


Fig 2.28 Seasonal changes in(a) ammonium and(b)nitrate nitrogen concentrations at sites in Wallubuenup Swamp. See Fig 2.14 for legend.

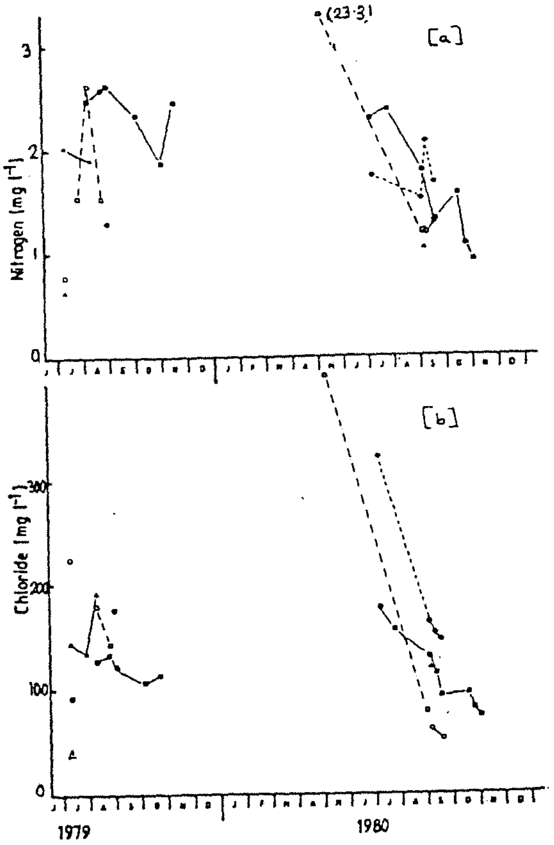


Fig 2.29 Seasonal changes in(a) organic nitrogen and(b)chloride concentrations at sites in Wallubuenup Swamp. See Fig 2.14 for legend.

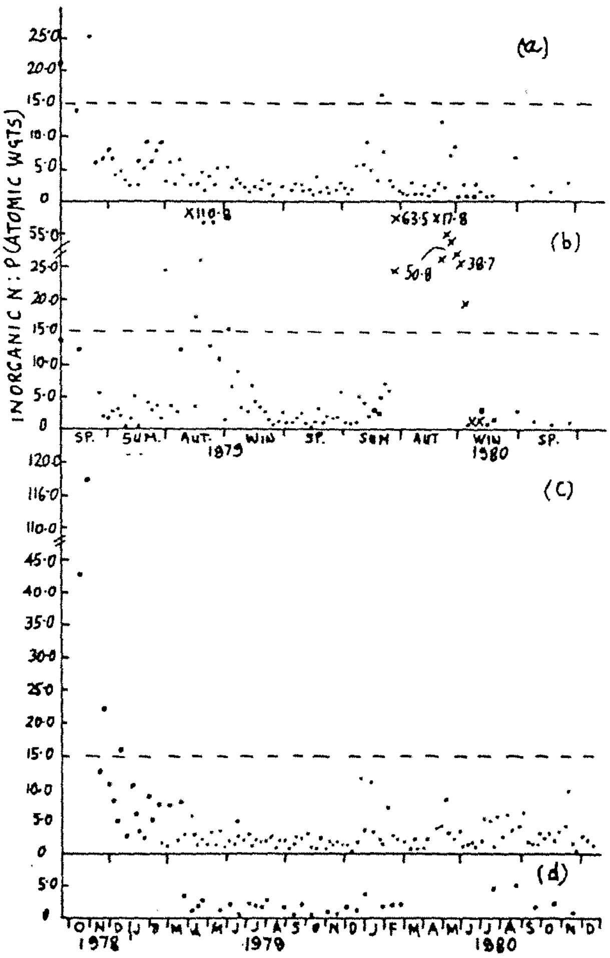


Fig 2.30 Seasonal changes in the ratio of inorganic nitrogen to phosphorus at(a)site 34,(b)sites 37(.)and 36(x),(c)site 19, and (d)site 12, in the main waterbody of Lake Joondalup.

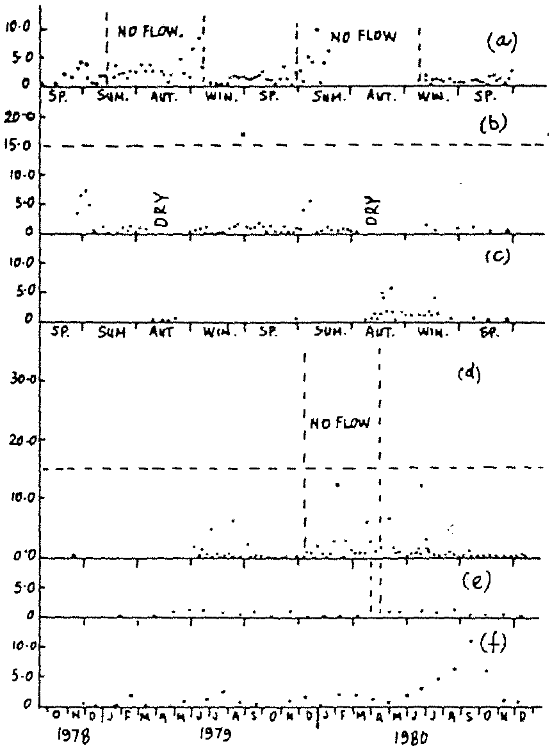


Fig 2.31 Seasonal changes in the ratio of inorganic nitrogen to phosphorus at(a)site 46,in the culvert under Mullaloo Drive,(b)site 47 and(c) site 54,in the southernmost basin of Lake Joondalup,(d)site 57,in the channel between the basin and Beenyup Swamo,(e)site 69,in Beenyup Swamp,and(f)site 73 in Lake Goollelal.

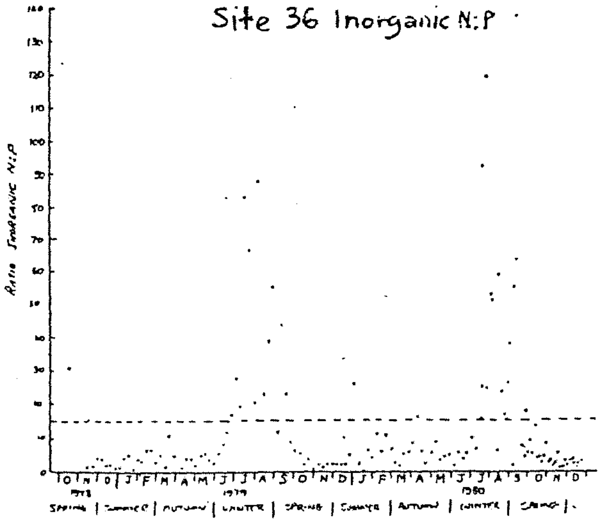


Fig 2.32 Seasonal changes in the ratio of inorganic nitrogen to phosphorus at site 36,in the stormwater sump on the eastern shore of Lake Joondalup.

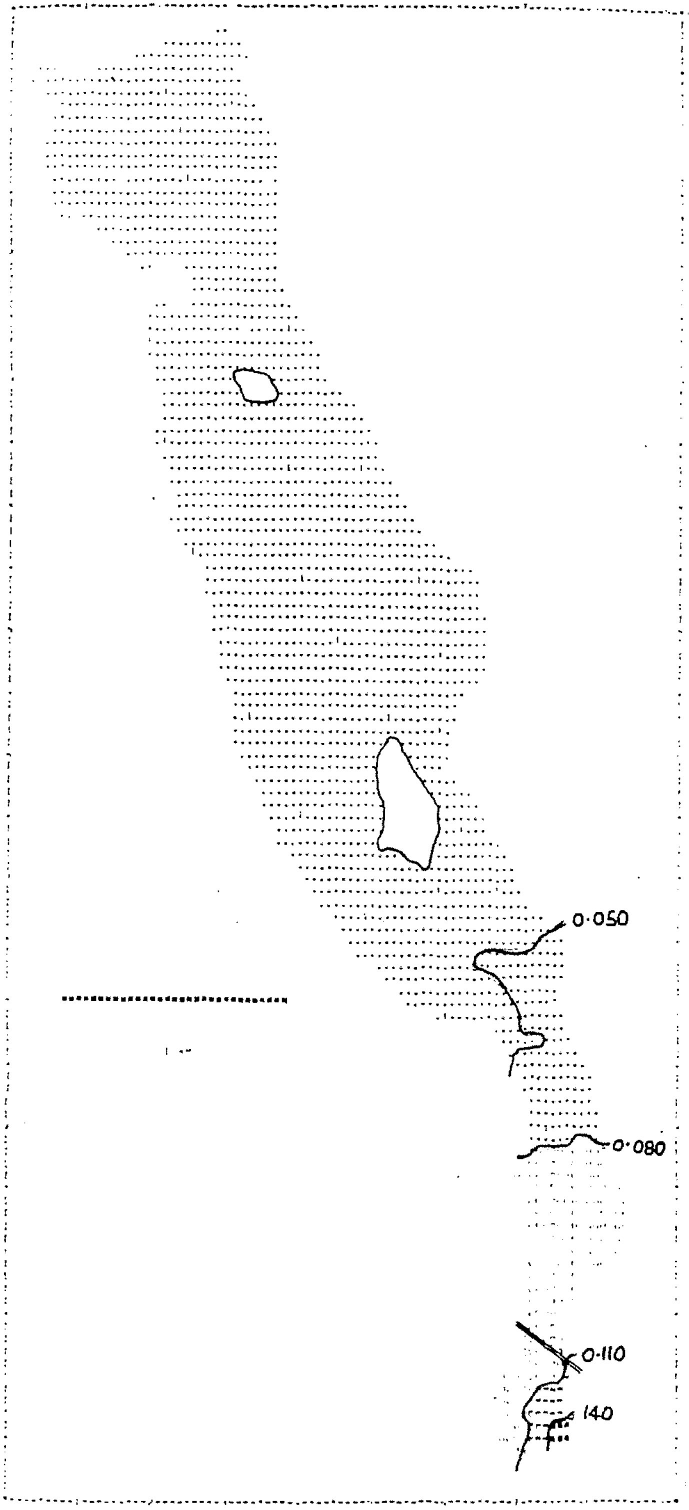


Fig 2.33 The distribution of the optical densities, at 440nm, of water in Lake Joondalup during the July 1980 grid study.

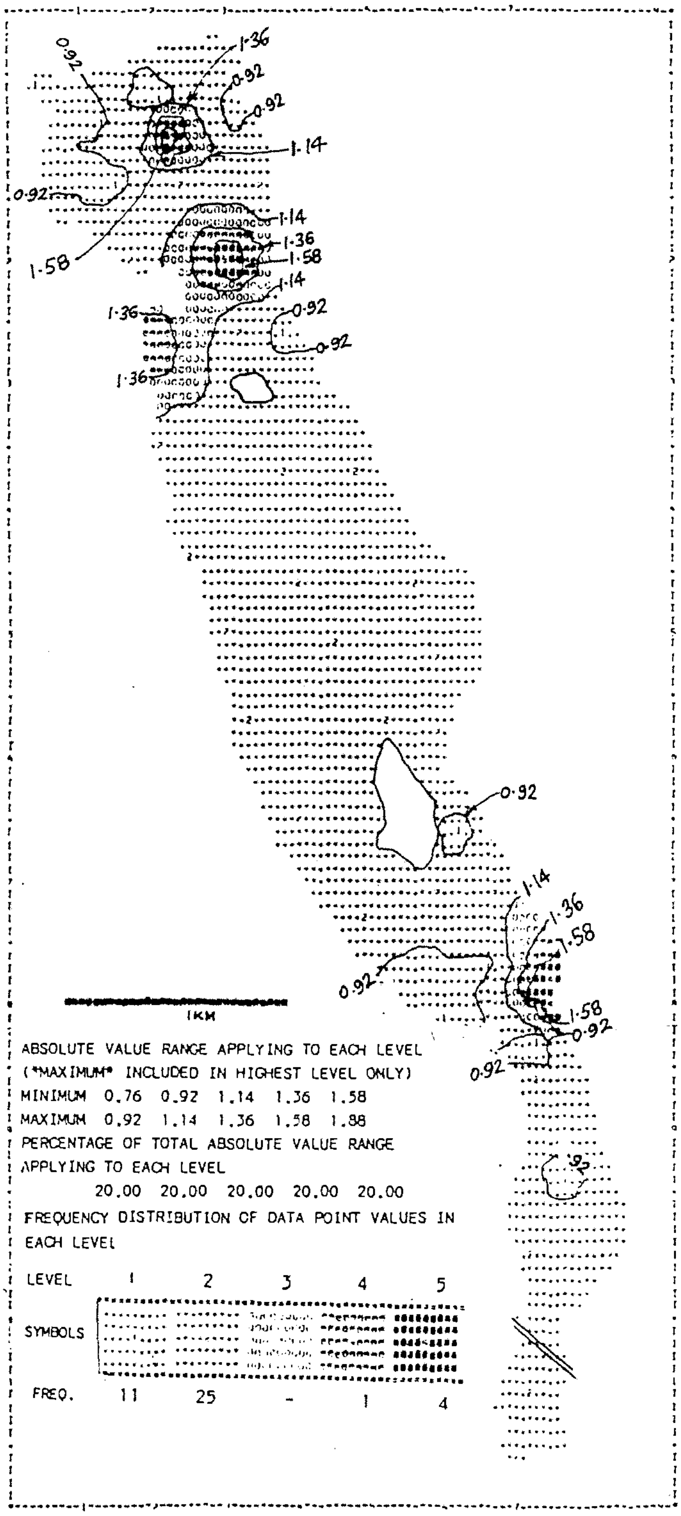


Fig 2.34(a) Densities of surface sediments(g fresh weight.cm^3) during the July 1979 grid study.

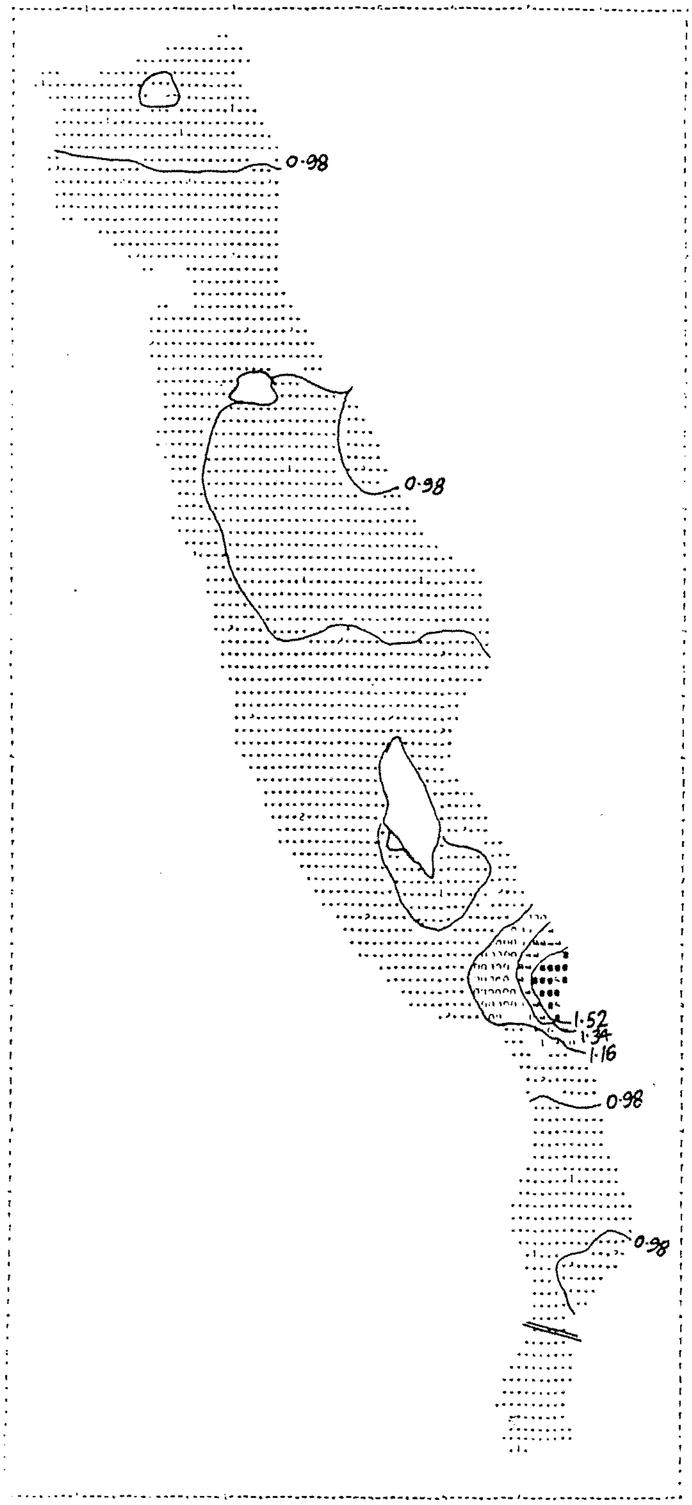
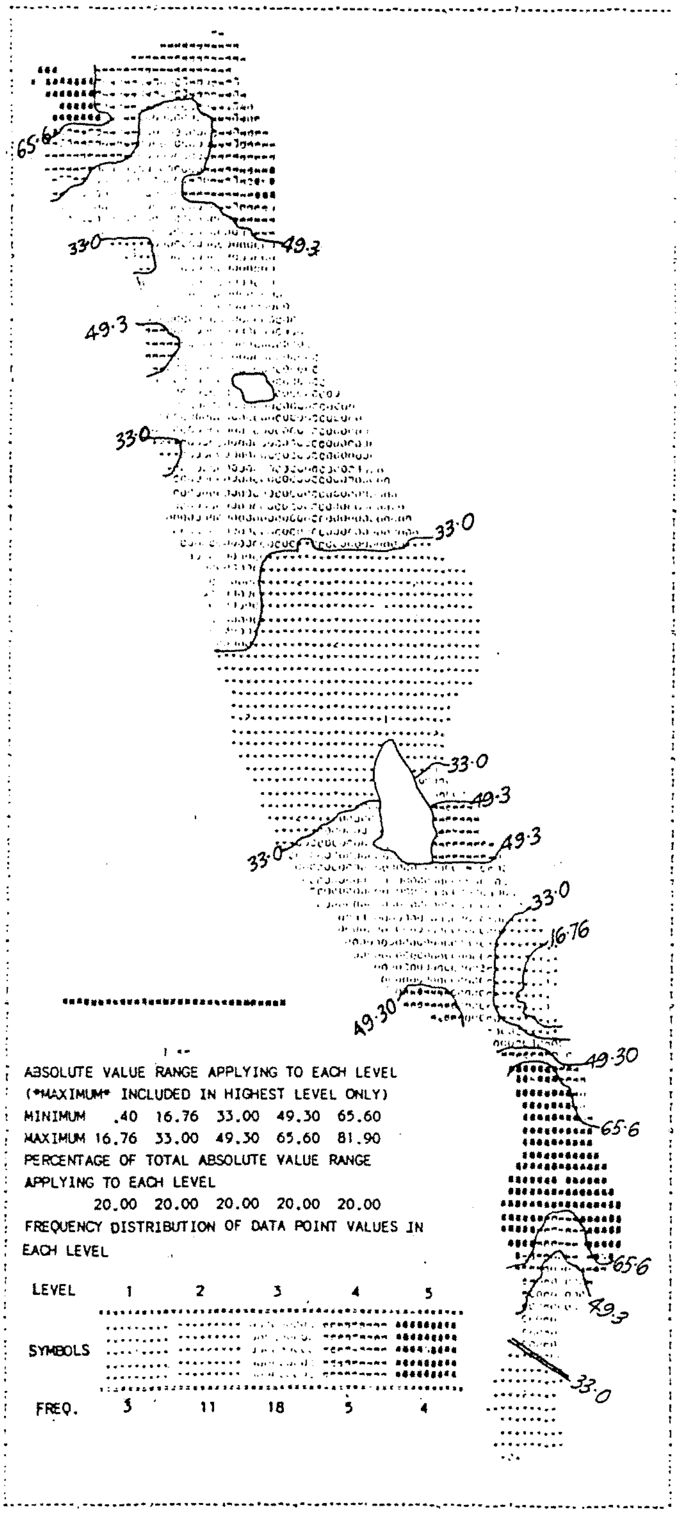


Fig 2.34(b) Densities of sediments (g fresh weight.cm^3)at 20 to 25cm depth, during the July 1979 grid study.



```
ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
(*MAXIMUM* INCLUDED IN HIGHEST LEVEL ONLY)
MINIMUM   .40  16.76  33.00  49.30  65.60
MAXIMUM 16.76  33.00  49.30  65.60  81.90
PERCENTAGE OF TOTAL ABSOLUTE VALUE RANGE
APPLYING TO EACH LEVEL
        20.00  20.00  20.00  20.00  20.00
FREQUENCY DISTRIBUTION OF DATA POINT VALUES IN
EACH LEVEL

 LEVEL     1        2        3        4        5

 SYMBOLS

 FREQ.     3        11       18       5        4
```

Fig 2.35 Percentage loss on ignition (dry weight) of surface sediments from the July 1979 grid study.

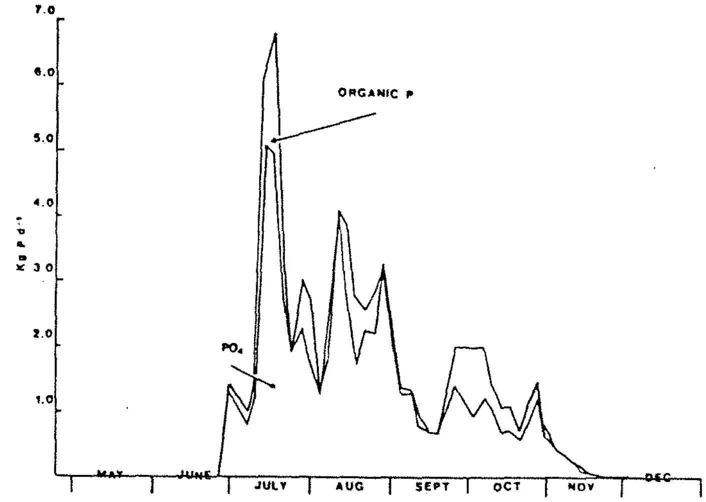


Fig 3.1 Variation in daily phosphorus loads at site 46

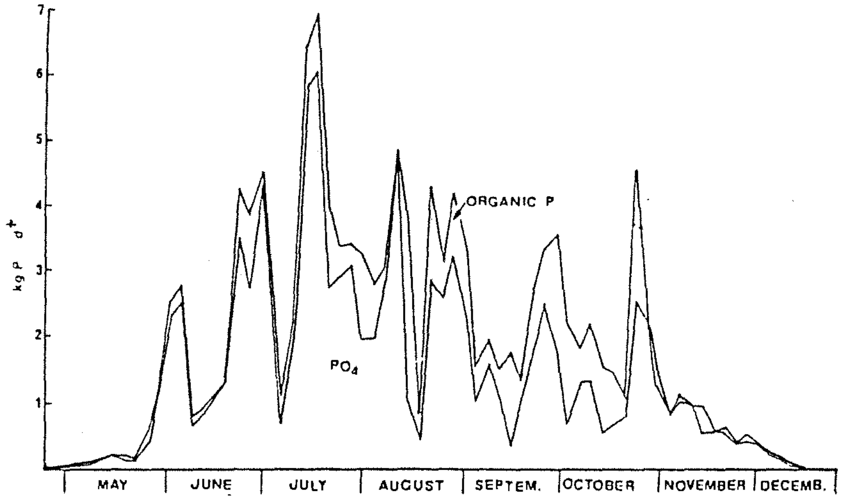


Fig 3.2 Variation in daily phosphorus loads at site 57.

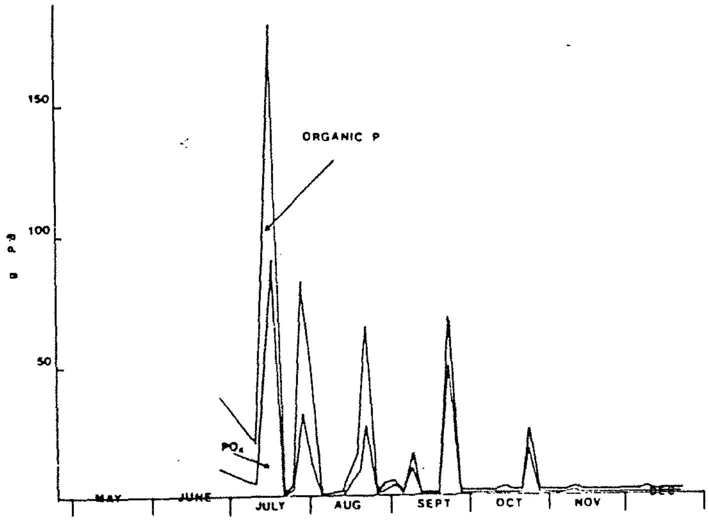


Fig 3.3 Variation in daily phosphorus loads at site 36.

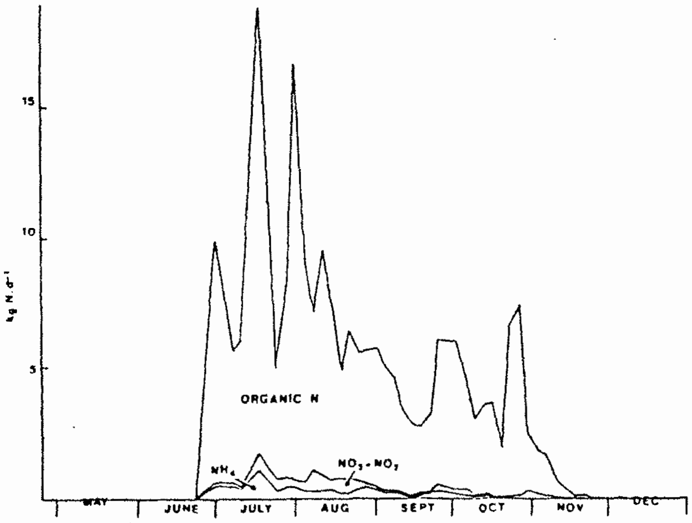


Fig 3.4 Variation in daily nitrogen loads at site 46.

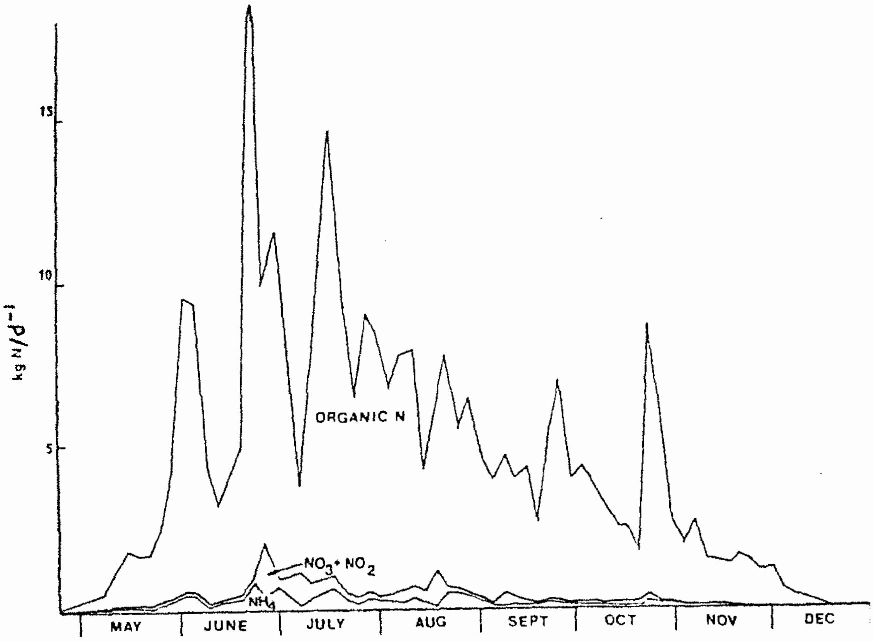


Fig 3.5 Variation in daily nitrogen loads at site 57.

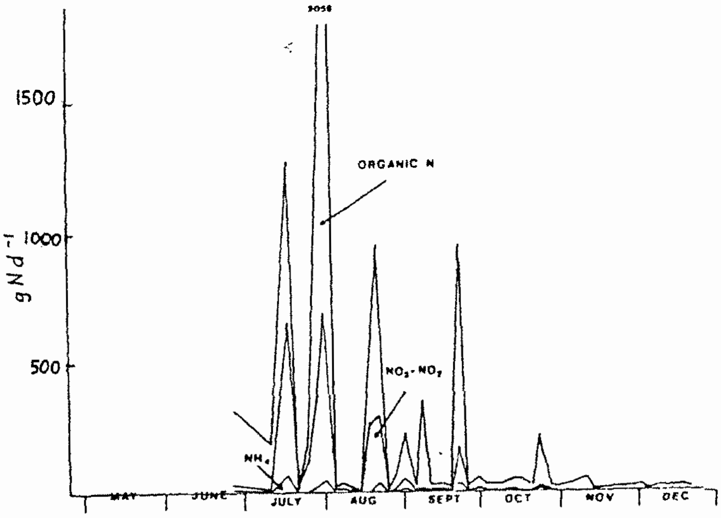


Fig 3.6 Variation in daily nitrogen loads at site 36.

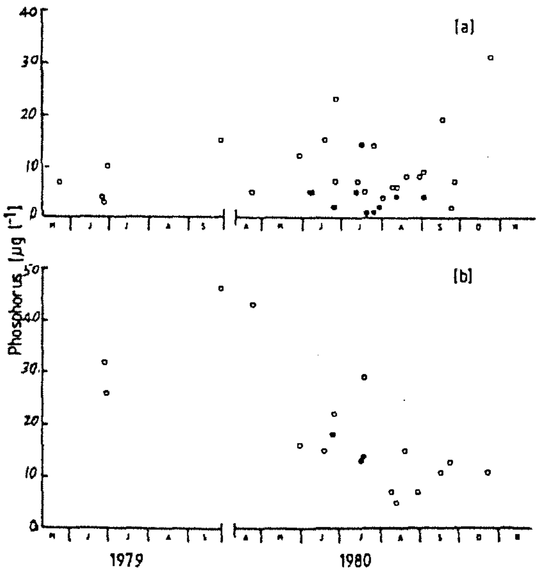


Fig 3.7 Changes in(a)the reactive phosphorus and(b)the organic phosphorus concentration of rainwater collected at Edgewater (.)and the University of WA campus(o).

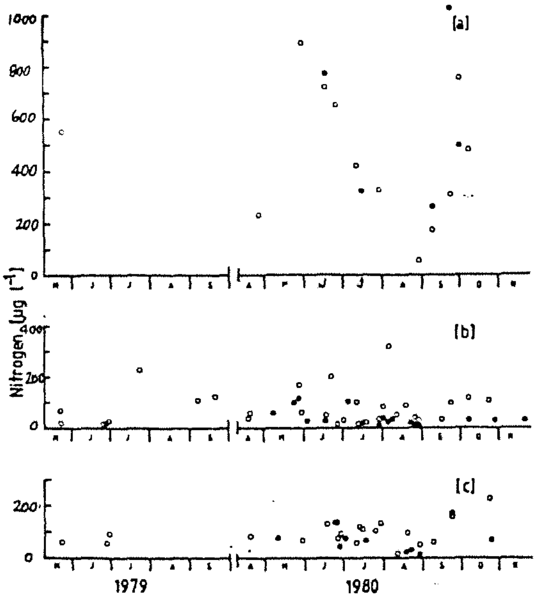


Fig 3.8 Changes in(a)the kjeldahl nitrogen,(b)the nitrate nitrogen and (c)the ammonium nitrogen concentrations of rainwater collected at Edgewater(.) and the University of WA campus(o).

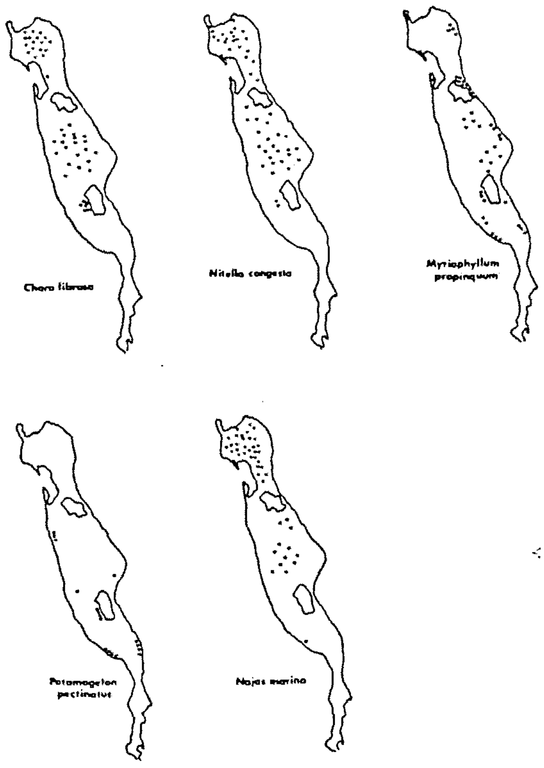


Fig 3.9 The distribution of benthic macrophytes in Lake Joondalup (at December 1980).

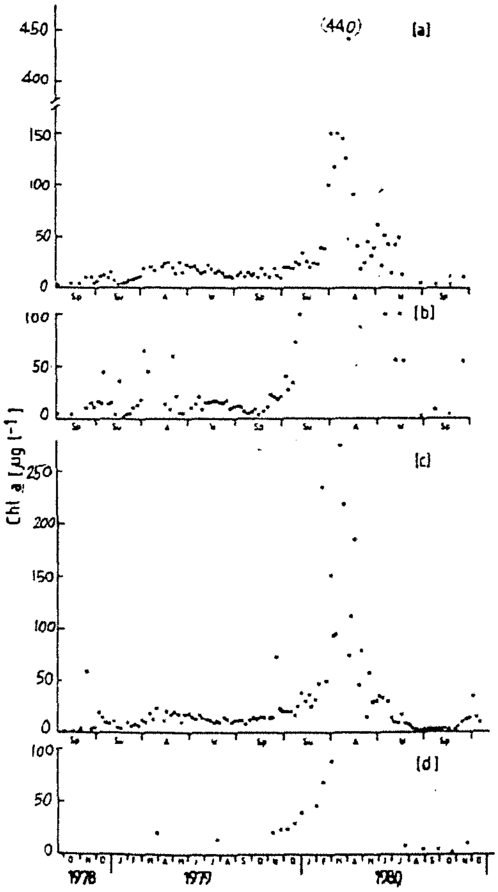


Fig 4.1 Seasonal changes in chlorophyll a concentrations at(a)site 34,(b)site 37,(c)site 19,and(d)site 12,in the main waterbody of Lake Joondalup.

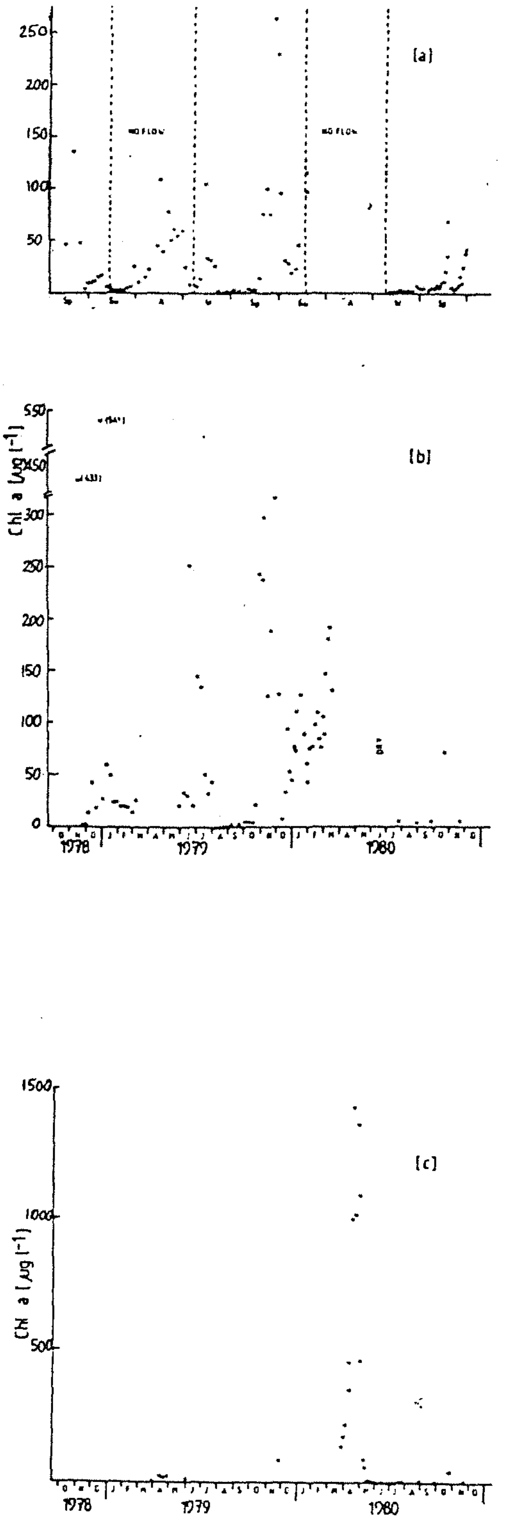


Fig 4.2 Seasonal changes in chlorophyll a concentrations at (a) site 46, in the culvert under Mullaloo Drive, and sites (b) 47 and (c) 54, in the southernmost basin of Lake Joondalup.

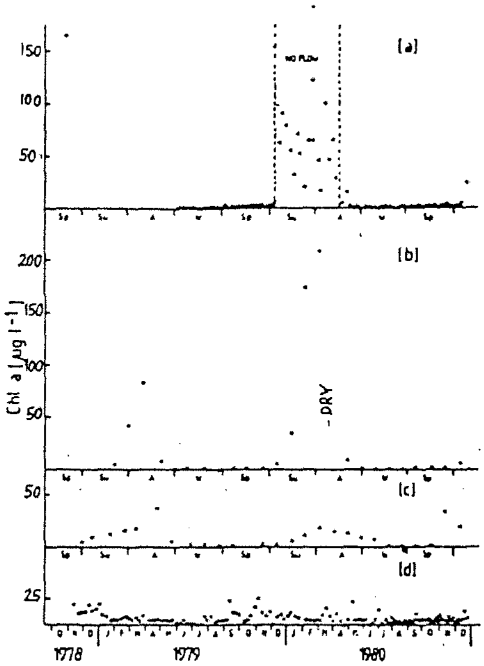


Fig 4.3 Seasonal changes in chlorophyll a concentrations at (a) site 57, in the channel between Beenyup Swamp and Lake Joondalup, (b) site 59, in Beenyup Swamp (c) site 73, in Lake Goollelal, and (d) site 36, in the stormwater sump on the eastern shore of Lake Joondalup.

Table 1.1: Lake Joondalup morphometry based on M.W.B. contour map for August 1, 1975

Parameter	Abbreviation	Value	Derivation
Length	L	7 km	
Breadth	B	1.3 km	
Maximal depth	D_m	2.17 m	
Shoreline	S	15.46 km	Grid method (Wood 1975)
Area	A	503.8 ha	Grid method (Wood 1975)
		549 ha	Weighing method
Volume	V	6.395×10^6 m^3 (kl)	Grid method (Wood 1975)
Mean depth	$\bar{d}$	1.27 m	V/A
Shore development	SD	1.94	$S/2\sqrt{\pi A}$
Catchment area		37.4 km^2	Weighing method

Table 2.1: Frequency of collection of water samples from regularly sampled sites.

Site Number	Twice weekly	Weekly	Monthly	Fortnightly
12			24.7.80 - 20.11.80	28.3.79 - 28.2.80
19		14.11.78 - 18.12.80		
34		14.11.78 - 24.7.80	24.7.80 - 20.11.80	
36	17.7.80 - 22.12.80	14.11.78 - 17.7.80		
37		14.11.78 - 24.7.80	24.7.80 - 20.11.80	
46	30.6.80 - 1.12.80	14.11.78 - 30.6.80		
47		14.11.78 - 24.7.80	24.7.80 - 20.11.80	
54	27.3.80 - 24.7.80		24.7.80 - 20.11.80	
57	15.5.80 - 22.12.80	6.6.79 - 15.5.80		
59			31.1.79 - 11.12.80	
73			1.11.78 - 11.12.80	

Table 2.2: Details of grid studies.

Month	Date	Number of sites sampled	Comments
December	6.12.78	9	Predominantly northern sites
December	13.12.78	11	Predominantly southern sites
January	31.1.79	12	
March	7.3.79	11	
July	25.7.79	45	
November	29.11.79	11	Only southern basin of Lake Joondalup sampled intensely.
January	14.1.80	30	
June	19.6.80	21	
July	24.7.80	40	
August	26.8.80	40	
September	25.9.80	40	
October	23.10.80	40	
November	20.11.80	40	

Table 2.3: Comparison of nutrient and chloride data collected from sites in the main waterbody of Lake Joondalup - September 1978 to December 1980.
(Chloride as mg l^{-1}, others as µg. l^{-1})

Site		PO_4-P	Organic P	NH_4-N	NO_3-N	Organic N	Chloride
12	$\bar{x}$ ± S.E.	43 ± 3	22 ± 3	37 ± 3	2.5 ± 0.3	2853 ± 232	611 ± 85
	n	29	29	28	29	27	14
	range	13-77	1 - 65	11-74	1.0 - 8.0	946-7106	288-1254
19	$\bar{x}$ ± S.E.	40 ± 3	28 ± 3	46 ± 4	4.2 ± 0.5	3004 ± 252	593 ± 33
	n	112	111	111	112	111	112
	range	4-187	1-163	6-314	1-39	425-22147	91-1696
34	$\bar{x}$ ± S.E.	48 ± 4	41 ± 4	52 ± 5	4.6 ± 0.5	3243 ± 279	629 ± 37
	n	95	94	94	95	94	93
	range	6-402	1-215	7-340	1-29	449-23011	100-1736
35	$\bar{x}$ ± S.E.	46 ± 7	83 ± 19	335 ± 88	9.7 ± 3.6	2644 ± 408	330 ± 37
	n	23	22	22	23	19	28
	range	11-134	11-369	11-1684	1.0 -76.0	723-8666	164-807
37	$\bar{x}$ ± S.E.	54 ± 4	55 ± 6	102 ± 23	5.5 ± 1.2	2115 ± 74	364 ± 18
	n	66	65	65	66	65	64
	range	17-179	1-246	5-1074	1-66	845-3597	147-862

Table 2.4: Comparison of nutrient and chloride data collected from sites in the southernmost basin of Lake Joondalup - September 1978 to December 1980.
(Chloride as mg l^{-1}, others as µg l^{-1})

Site		PO_4-P	Organic P	NH_4-N	NO_3-N	Organic N	Chloride
46	$\bar{x}$ ± S.E.	217 ± 10	73 ± 7	96 ± 11	27 ± 2	1845 ± 92	327 ± 27
	n	108	106	108	109	108	109
	range	45-675	1-369	6-820	1-120	499-4739	78-1278
47	$\bar{x}$ ± S.E.	417 ± 29	128 ± 13	173 ± 45	21 ± 6	3142 ± 379	239 ± 16
	n	66	65	67	64	66	69
	range	20-1049	1-400	1-1864	1-383	456-23457	81-730
54	$\bar{x}$ ± S.E.	314 ± 46	204 ± 60	99 ± 30	15 ± 2	5549 ± 1646	383 ± 37
	n	30	28	30	31	30	33
	range	33-1102	1-1218	5-745	1-54	853-37719	104-797

Table 2.5: Comparison of nutrient and chloride data collected from sites south of Lake Joondalup - November 1978 to December 1980.
(Chloride as mg l^{-1}, others in µg l^{-1})

Site		PO_4-P	Organic P	NH_4-N	NO_3-N	Organic N	Chloride
57	$\bar{x}$ ± S.E.	283 ± 14	110 ± 12	50 ± 6	32 ± 9	1146 ± 33	147 ± 5
	n	112	111	110	111	110	111
	range	4-622	1-872	1-597	1-850	544-2410	77-327
59 Beenyup Swamp	$\bar{x}$ ± S.E.	373 ± 39	117 ± 33	71 ± 12	11 ± 2	2479 ± 925	267 ± 36
	n	24	24	24	24	24	24
	range	106-1036	1-758	5-210	1-32	643-23396	80-746
73 Lake Goollelal	$\bar{x}$ ± S.E.	169 ± 34	45 ± 10	81 ± 18	40 ± 10	1194 ± 89	205 ± 16
	n	29	29	29	29	29	29
	range	7-780	1-287	7-529	1-173	530-2914	55-423

Table 2.6: Comparison of nutrient and chloride data for water samples taken from Wallubuenup Swamp.
(Chloride as mg.l^{-1}, others as µg l^{-1})

Site		PO_4-P	Organic P	NH_4-N	NO_3-N	Organic N	Chloride
65	x̄ ± SE	699	-	25	5	-	92
	n	1	-	1	1	-	1
	range	-	-	-	-	-	-
66	x̄ ± SE	244	17	23	3	766	225
	n	1	1	1	1	1	1
	range	-	-	-	-	-	-
67	x̄ ± SE	325	14	15	2	621	43
	n	1	1	1	1	1	1
	range	-	-	-	-	-	-
68	x̄ ± SE	353 ± 20	39 ± 3	22 ± 2	5.5 ± 0.7	1647 ± 313	146 ± 15
	n	4	4	4	4	3	4
	range	306 - 400	31 - 46	18 - 26	4 - 7	1024 - 2016	119 - 189
69	x̄ ± SE	312 ± 48	83 ± 31	47 ± 10	28.0 ± 22.5	6036 ± 4321	212 ± 83
	n	5	5	5	5	5	4
	range	170 - 468	1 - 192	22 - 82	4 - 118	1195 - 23294	76 - 450
70	x̄ ± SE	545 ± 43	216 ± 50	59 ± 17	2381.8 ± 536.7	1963 ± 166	116 ± 8
	n	15	13	15	14	13	13
	range	268 - 771	1 - 669	28 - 288	5 - 7000	909 - 2610	74 - 173
71	x̄ ± SE	1037 ± 174	368 ± 121	53 ± 11	1320.0 ± 686.7	1659 ± 131	192 ± 33
	n	5	5	5	4	5	5
	range	461 - 1362	1 - 729	24 - 70	37 - 3075	1297 - 2085	147 - 324
72[1]	x̄ ± SE	95 ± 8	14 ± 3	39 ± 20	201.5 ± 111.5	1239 ± 65	58 ± 5
	n	2	2	2	2	2	2
	range	87 - 103	1 - 16	19 - 58	90 - 313	1174 - 1304	53 - 63

[1] Samples filtered through Whatman GF/C glass fibre filter due to high turbidity.

Table 2.7: Comparison of nutrient and chloride data collected from stormwater sumps near Lake Joondalup (September 1978 to December 1980)
(Chloride as mg l^{-1}, others as µg l^{-1})

Site		PO_4-P	Organic P	NH_4-N	NO_3-N	Organic N	Chloride
36	x̄ ± S.E.	14 ± 1	22 ± 2	19 ± 1	42 ± 6	674 ± 28	119 ± 6
	n	134	132	132	133	132	133
	range	1-47	1-151	1-166	1-360	13-1497	12-355
Ariti Avenue Sump	x̄ ± S.E.	26 ± 8	52 ± 21	41 ± 9	78 ± 13	410 ± 139	20 ± 3
	n	10	9	10	9	9	9
	range	5-85	7-223	2-85	19-140	126-1465	10-36
Edge-water Sump	x̄ ± S.E.	21 ± 2	11 ± 4	27 ± 6	36 ± 7	221 ± 69	9 ± 2
	n	5	4	5	4	3	2
	range	15-26	1-20	6-40	17-49	109-348	7-10

Table 2.8: Criteria delimiting lake trophic status.

(a) Sakamoto (1966, cited by Vollenweider, 1971)

Trophic status	Total P (	Total bound N $\mu g\ l^{-1}$	Chlorophyll a)
oligotrophic	2 - 20	2 - 20	0.3 - 2.5
mesotrophic	10 - 30	100 - 700	1 - 15
eutrophic	10 - 90	500 - 1300	5 - 140

(b) Vollenweider (1971)

Trophic status	Total P ($\mu g\ l^{-1}$	Inorganic N)
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

(c) Cullen *et al*. (1978)

Lake trophic status	Mean productivity (mg $C/m^2/d$)	Chlorophyll a (mg/m^3)	Max. algal cell volume (cm^3/m^3)	Total P (mg/m^3)	Total N (mg/m^3)	Dominant phytoplankton classes
oligotrophic	50 - 300	0.3 - 3.0	1	5	250	Bacillariophyceae Chrysophyceae Cryptophyceae
mesotrophic	250 - 1000	2 - 15	3 - 5	5 - 30	250 - 1000	Variable
eutrophic	1000	10 - 500	10	30 - 1000	1000 - 10000	Bacillariophyceae Cyanophyceae Chlorophyceae

Table 2.9: Nutrient concentrations ($\mu g\ l^{-1}$) detected during grid studies.

Date		PO_4-P	Organic P	NH_4-N	NO_3+NO_2-N	Organic N
6.12.78	$\bar{x}$ ± S.E.	67 ± 43	44 ± 16	188 ± 124	19 ± 15	1633 ± 114
	n	10	9	10	10	10
	range	10 - 472	1 - 171	34 - 1360	2 - 160	1321 - 2342
13.12.78	$\bar{x}$ ± S.E.	56 ± 25	43 ± 12	64 ± 25	35 ± 30	1580 ± 27
	n	12	12	12	12	12
	range	15 - 342	1 - 117	21 - 344	1 - 383	1436 - 1741
31. 1.79	$\bar{x}$ ± S.E.	77 ± 49	117 ± 22	42 ± 9	3 ± 1	2376 ± 44
	n	13	13	13	13	13
	range	9 - 672	6 - 257	15 - 143	2 - 14	2088 - 3120
7. 3.79	$\bar{x}$ ± S.E.	112 ± 74	133 ± 21	94 ± 25	4 ± 1	2683 ± 107
	n	10	10	10	10	11
	range	13 - 808	34 - 246	40 - 254	2 - 12	2315 - 3383
25. 7.79	$\bar{x}$ ± S.E.	90 ± 19	18 ± 3	29 ± 3	2 ± 1	2370 ± 42
	n	46	46	46	46	45
	range	22 - 602	1 - 70	8 - 138	1 - 31	1624 - 3122
14. 1.80	$\bar{x}$ ± S.E.	36 ± 1	36 ± 3	59 ± 1	3 ± 0	3392 ± 149
	n	30	30	30	30	31
	range	28 - 61	1 - 77	47 - 80	2 - 4	1069 - 4306
19. 6.80	$\bar{x}$ ± S.E.	121 ± 28	89 ± 18	29 ± 4	5 ± 1	2621 ± 136
	n	21	21	21	21	21
	range	16 - 513	1 - 268	16 - 110	2 - 28	1235 - 4050
24. 7.80	$\bar{x}$ ± S.E.	67 ± 17	40 ± 7.	20 ± 2	11 ± 2	1536 ± 48
	n	40	40	41	39	39
	range	12 - 559	1 - 209	5 - 52	3 - 54	686 - 2017
28. 8.80	$\bar{x}$ ± S.E.	59 ± 15	25 ± 3	54 ± 12	7 ± 1	946 ± 16
	n	42	41	41	41	41
	range	12 - 416	1 - 107	16 - 357	3 - 30	657 - 1227
25. 9. 80	$\bar{x}$ ± S.E.	60 ± 13	28 ± 5	33 ± 7	6 ± 2	1190 ± 27
	n	41	41	41	41	41
	range	18 - 379	3 - 151	9 - 179	1 - 45	806 - 1448
23.10.80	$\bar{x}$ ± S.E.	42 ± 9	33 ± 4	16 ± 1	3 ± 0	1158 ± 31
	n	41	41	41	41	41
	range	15 - 248	5 - 181	10 - 43	1 - 11	738 - 1552
20.11.80	$\bar{x}$ ± S.E.	60 ± 10	22 ± 3	12 ± 1	3 ± 1	1626 ± 42
	n	41	41	41	41	41
	range	15 - 336	1 - 79	6 - 26	1 - 49	883 - 2381

Table 2.10: Phosphorus fractions in water samples collected from the main waterbody of Lake Joondalup.

Site		TDP	PP	PO$_4$-P	Organic P
19	$\bar{x}$ ± S.E.	28 ± 3	37 ± 3	44 ± 2	21 ± 3
	n	32	32	35	35
	range	7 - 66	1 - 71	18 - 80	1 - 63
34	$\bar{x}$ ± S.E.	34 ± 5	50 ± 5	53 ± 11	39 ± 7
	n	33	33	35	35
	range	7 - 146	20 - 165	22 - 402	1 - 149
35	$\bar{x}$ ± S.E.	33 ± 2	74 ± 23	55 ± 17	52 ± 12
	n	4	4	4	4
	range	28 - 37	29 - 129	29 - 106	33 - 85
37	$\bar{x}$ ± S.E.	34 ± 4	66 ± 7	50 ± 6	50 ± 5
	n	27	27	29	29
	range	9 - 77	31 - 214	17 - 179	2 - 116

Table 2.11: Phosphorus fractions in water samples collected from the southernmost basin of Lake Joondalup.

Site		TDP	PP	PO$_4$-P	Organic P
46	$\bar{x}$ ± S.E.	175 ± 16	104 ± 11	201 ± 19	76 ± 13
	n	28	27	30	29
	range	62 - 353	23 - 246	45 - 483	1 - 318
47	$\bar{x}$ ± S.E.	198 ± 13	141 ± 26	242 ± 19	97 ± 18
	n	26	25	27	26
	range	38 - 338	22 - 647	20 - 480	1 - 343
54	$\bar{x}$ ± S.E.	125 ± 26	40 ± 9	120 ± 28	46 ± 14
	n	5	5	5	5
	range	43 - 187	13 - 68	34 - 180	10 - 95

Table 2.12: Phosphorus fractions in water samples collected from site 57, Beenyup Swamp and Lake Goollelal.

Site		TDP	PP	PO_4-P	Organic P
57	$\bar{x}$ ± S.E.	253 ± 16	125 ± 11	311 ± 20	74 ± 15
	n	28	28	30	30
	range	23 - 457	25 - 235	60 - 589	1 - 382
59	$\bar{x}$ ± S.E.	222 ± 26	80 ± 7	273 ± 30	35 ± 11
	n	7	7	7	7
	range	134 - 306	54 - 112	172 - 393	5 - 26
73	$\bar{x}$ ± S.E.	206 ± 33	47 ± 12	229 ± 38	24 ± 9
	n	5	5	5	5
	range	98 - 299	14 - 87	109 - 338	6 - 48

Table 2.13: Phosphorus fractions in water samples collected from stormwater sumps at the time of flow.

Site		TDP	PP	PO_4-P	Organic P
36	$\bar{x}$ ± S.E.	21 ± 3	14 ± 2	15 ± 1	19 ± 3
	n	35	35	36	36
	range	4 - 72	1 - 50	5 - 47	1 - 55
Ariti Ave	$\bar{x}$ ± S.E.	22 ± 2	15 ± 5	15 ± 2	23 ± 2
sump	n	2	2	2	2
	range	20 - 24	10 - 20	13 - 16	21 - 24
Edgewater	$\bar{x}$ ± S.E.	19	7	25	1
sump	n	1	1	1	1

Table 2.14: Nitrogen fractions in water samples collected from the main waterbody of Lake Joondalup.

Site		TDN	PN	NH_4-N	NO_3-N	Organic N
19	$\bar{x}$ ± S.E.	2173 ± 96	698 ± 76	33 ± 2	3 ± 0	2817 ± 84
	n	34	34	35	35	35
	range	1147 - 4233	1 - 1726	17 - 65	1 - 13	2093 - 4069
34	$\bar{x}$ ± S.E.	2085 ± 85	736 ± 78	44 ± 8	3 ± 1	2815 ± 102
	n	33	33	34	35	35
	range	562 - 3160	1 - 2046	14 - 272	1 - 15	2083 - 4731
35	$\bar{x}$ ± S.E.	2331 ± 278	470 ± 103	241 ± 115	5 ± 1	2554 ± 430
	n	4	4	4	4	4
	range	1760 - 3051	225 - 655	37 - 498	3 - 9	1625 - 3666
37	$\bar{x}$ ± S.E.	1721 ± 57	587 ± 86	128 ± 44	5 ± 2	2167 ± 72
	n	28	28	29	29	29
	range	1021 - 2548	50 - 2432	9 - 1024	1 - 66	1450 - 3158

Table 2.15: Nitrogen fractions in water samples collected from the southernmost basin of Lake Joondalup.

Site		TDN	PN	NH_4-N	NO_3-N	Organic N
46	$\bar{x}$ ± S.E.	1884 ± 130	511 ± 117	115 ± 23	29 ± 5	2235 ± 167
	n	28	28	30	30	30
	range	771 - 3908	1 - 2285	6 - 691	1 - 120	1206 - 4491
47	$\bar{x}$ ± S.E.	1535 ± 81	871 ± 193	60 ± 10	16 ± 3	2309 ± 227
	n	27	27	27	27	27
	range	829 - 2890	1 - 4149	10 - 179	1 - 51	1282 - 5819
54	$\bar{x}$ ± S.E.	1058 ± 155	488 ± 112	39 ± 11	14 ± 4	1494 ± 150
	n	5	5	5	5	5
	range	511 - 1385	210 - 778	14 - 66	5 - 24	957 - 1871

Table 2.16: **Nitrogen fractions in water samples collected from site 57, Beenyup Swamp and Lake Goollelal.**

Site		TDN	PN	NH_4-N	NO_3-N	Organic N
57	$\bar{x}$ ± S.E.	1405 ± 59	161 ± 38	61 ± 8	44 ± 28	1385 ± 53
	n	30	30	29	30	29
	range	564 - 2401	1 - 799	1 - 198	2 - 850	544 - 198
59	$\bar{x}$ ± S.E.	1375 ± 203	277 ± 121	101 ± 7	15 ± 3	1407 ± 154
	n	7	7	7	7	7
	range	295 - 1844	1 - 761	47 - 210	5 - 26	827 - 1929
73	$\bar{x}$ ± S.E.	874 ± 156	487 ± 97	76 ± 9	52 ± 17	1233 ± 119
	n	5	5	5	5	5
	range	578 - 1463	262 - 728	50 - 100	14 - 110	957 - 1579

Table 2.17: Nitrogen fractions in water samples collected from stormwater sumps at time of flow.

Site		TDN	PN	NH_4-N	NO_3-N	Organic N
36	$\bar{x}$ ± S.E.	612 ± 60	268 ± 41	23 ± 4	58 ± 14	764 ± 71
	n	35	33	36	36	35
	range	19 - 1224	1 - 977	5 - 166	1 - 360	13 - 1497
Ariti	$\bar{x}$ ± S.E.	372 ± 12	77 ± 76	57 ± 28	33 ± 14	342 ± 147
Avenue	n	2	2	2	2	2
sump	range	360 - 384	1 - 152	29 - 85	19 - 46	195 - 488

Table 2.18: Physicochemical data from grid studies.

Date	Parameter	pH	Alkalinity (mg CaCO$_3$ l^{-1})		Optical Density			
			Total	Phenolph	300 nm	370 nm	430 nm	440 nm
25.7.79	$\bar{x}$ ± S.E.	8.14 ± 0.06	112.8 ± 2.56	-	0.333 ± 0.026	-	-	0.048 ± 0.003
	n	44	44	-	44	-	-	44
	range	6.8 - 8.8	98 - 208	-	0.229 - 0.972	-	-	0.034 - 0.153
14.1.80	$\bar{x}$ ± S.E.	9.23 ± 0.03	127.5 ± 2.87	27.1 ± 1.17	0.257 ± 0.006	0.089 ± 0.003	0.047 ± 0.003	0.044 ± 0.002
	n	32	32	24	31	31	31	31
	range	8.7 - 9.4	108 - 180	10 - 40	0.214 - 0.340	0.070 - 0.135	0.035 - 0.087	0.032 - 0.083
19.6.80	$\bar{x}$ ± S.E.	8.65 ± 0.08	-	-	-	0.115 ± 0.017	-	0.062 ± 0.008
	n	21	-	-	-	21	-	21
	range	7.50 - 9.00	-	-	-	0.038 - 0.303	-	0.016 - 0.146
24.7.80	$\bar{x}$ ± S.E.	8.32 ± 0.03	-	-	0.201 ± 0.022[1]	0.103 ± 0.012	0.024 ± 0.002[2]	0.042 ± 0.005
	n	41	-	-	41	41	41	41
	range	7.8 - 8.7	-	-	0.106 - 0.742	0.048 - 0.414	0.010 - 0.076	0.017 - 0.165

[1] Measurement done at 320 nm

[2] Measurement done at 530 nm

Table 2.19: Concentrations of dissolved organic compounds in water samples taken on 21 August, 1980.[1] (mg l^{-1})

Site	Fulvic + humic acids	Tannic acid	Lignosulfonic acid
19	39.9	0	6.1
46	169.4	0	0
57	231.0	0	0
59 Beenyup Swamp	234.2	0	0
68	316.7	0	0
69	186.8	0	0
70	274.3	0	0
71	350.7	0	0
72[2]	214.1	0	0
73 Lake Goollelal	37.4	0	0

[1] Determined by the method of Lawrence (1980) using wavelengths of 280 nm, 300 nm and 370 nm.

[2] Sample 72 was filtered due to a high particulate matter concentration.

Table 2.20: Correlation matrix for sediment parameters from the December 1978 grid studies. (n = 12).

	Dens.	Water	% LOI	% Carb.	TN	TP	SRP	TSP	SNH	SNOX	SON
Density		r =-0.471 sig = 0.0618 N.S.	-0.6565 0.0102 *	0.681 0.0074 **	-0.621 0.0155 *	-0.7147 0.0045 **	-0.7057 0.0052 **	-0.703 0.0054 **	-0.602 0.0191 *	-0.214 0.2522 N.S.	-0.588 0.0067 **
Water content			0.761 0.0020 **	-0.700 0.0056 **	0.827 0.0005 ***	0.518 0.0422 *	0.377 0.1136 N.S.	0.385 0.1084 N.S.	0.617 0.0163 *	0.915 0.00001 *****	0.539 0.0351 *
% LOI				-0.954 0.00000 *****	0.829 0.00043 ***	0.498 0.04987 *	0.372 0.1168 N.S.	0.375 0.1147 N.S.	0.522 0.041 *	0.720 0.0041 **	0.5245 0.0400 *
% Carbonate					-0.8696 0.00012 ***	-0.578 0.0244 *	-0.368 0.11976 N.S.	-0.411 0.0919 N.S.	-0.4899 0.05298 N.S.	-0.642 0.01223 *	-0.6000 0.0196 *
TN						0.699 0.0057 **	0.471 0.0613 N.S.	0.509 0.0455 *	0.600 0.0197 *	0.725 0.0038 **	0.664 0.0093 **
TP							0.900 0.00003 ****	0.946 0.00000 *****	0.860 0.00017 ***	0.281 0.1882 N.S.	0.969 0.00000 *****
SRP								0.988 0.00000 *****	0.910 0.00002 ****	0.132 0.3408 N.S.	0.903 0.00003 ****
TSP									0.900 0.00003 ****	0.138 0.3347 N.S.	0.948 0.00000 *****
SNH										0.409 0.0935 N.S.	0.888 0.00006 ****
SNOX											0.326 0.1505 N.S.
SON											

P <0.00001 ***** P <0.0001 **** P <0.001 *** P <0.01 ** P <0.05 *

Table 2.21: Correlation matrix for sediment parameters from the July 1979 grid study (including Beenyup Swamp).

Surface sediment (0-5 cm)

Deep Sediment (20-25 cm)

	Density	Water content	Chlorophyll	Phaeophytin	Metaphyton	% LOI	% Carbonate	TN	TP	SRP	TSP	SNH	SNOX	SON
Density		r= -0.499 n= 46 s= 0.0002 ***	-0.047 45 0.378	-0.006 45 0.483	0.092 40 0.285	-0.424 46 0.0016 **	0.010 46 0.472	-0.035 46 0.409	-0.013 46 0.464	0.235 45 0.060	0.234 45 0.061	0.293 45 0.025 *	0.256 44 0.040 *	0.190 45 0.106
Water content	-0.712 46 0.00000 *****		0.034 45 0.413	-0.259 45 0.043 *	0.283 40 0.038 *	0.678 46 0.00000 *****	0.156 46 0.151	0.289 46 0.026 *	0.218 46 0.072	0.287 45 0.028 *	0.310 45 0.019 *	0.248 45 0.051	0.309 44 0.021 *	0.433 45 0.0015 **
Chlorophyll	-	-		0.181 46 0.115	0.217 41 0.087	0.236 45 0.059	-0.137 45 0.185	0.182 45 0.116	0.197 45 0.099	0.217 44 0.079	0.214 44 0.081	-0.040 44 0.398	-0.136 43 0.192	0.020 44 0.449
Phaeophytin	-	-	-		-0.238 41 0.067	-0.061 45 0.346	-0.341 45 0.011 *	0.017 45 0.456	0.170 45 0.132	0.017 44 0.457	-0.036 44 0.408	-0.116 44 0.226	-0.055 43 0.362	-0.266 44 0.040 *
Metaphyton	-	-	-			0.348 40 0.014 *	-0.277 40 0.042 *	0.192 40 0.117	0.136 40 0.201	0.215 39 0.095	0.256 39 0.058	0.152 39 0.177	0.155 39 0.173	0.464 39 0.0015 **
% LOI	-0.433 46 0.0013 **	-0.704 46 0.00000 *****	-	-	-		-0.209 46 0.082	0.508 46 0.00016 ***	0.426 46 0.0016 **	0.307 45 0.020 *	0.295 45 0.025 *	0.042 45 0.392	0.110 44 0.239	0.362 45 0.0073 **
% Carbonate	-0.308 46 0.0186 *	0.212 46 0.079	-	-	-	-0.289 46 0.026 *		-0.072 46 0.316	-0.210 46 0.081	-0.005 45 0.486	-0.052 45 0.362	0.521 45 0.00012 ***	0.411 44 0.0028 **	0.252 45 0.047 *
TN	-0.317 46 0.016 *	0.610 46 0.00000 *****	-	-	-	0.761 46 0.00000 *****	-0.122 46 0.209		0.889 46 0.00000 *****	0.640 45 0.00000 *****	0.544 45 0.00006 ****	0.173 45 0.127	0.151 44 0.164	0.293 45 0.0299 *
TP	-0.176 46 0.121	0.131 46 0.192	-	-	-	0.148 46 0.152	-0.218 46 0.073	0.218 46 0.073		0.717 45 0.0000 *****	0.649 45 0.00000 *****	0.044 45 0.387	0.038 44 0.403	0.146 45 0.170
SRP	-0.222 42 0.079	0.265 42 0.0446 *	-	-	-	0.458 42 0.0011 **	-0.117 42 0.231	0.236 42 0.067	0.140 42 0.188		0.972 45 0.00000 *****	0.403 45 0.0030 **	0.351 44 0.0097 **	0.362 45 0.0072 **
TSP	-0.128 43 0.207	0.108 43 0.245	-	-	-	0.147 43 0.174	0.045 43 0.387	0.197 43 0.103	-0.049 43 0.377	0.323 42 0.018 *		0.308 45 0.0197 *	0.300 44 0.024 *	0.379 45 0.0051 **
SNH	-0.199 44 0.097	0.504 44 0.00001 *****	-	-	-	0.616 44 0.00000 *****	-0.001 44 0.497	0.739 44 0.00000 *****	0.167 44 0.139	0.163 42 0.151	0.141 43 0.183		0.886 44 0.00000 *****	0.679 45 0.00000 *****
SNOX	-0.129 44 0.203	0.509 44 0.0002 ***	-	-	-	0.687 44 0.00000 *****	-0.273 44 0.036 *	0.627 44 0.00000 *****	0.274 44 0.036 *	0.546 42 0.0009 ****	0.146 43 0.175	0.663 44 0.00000 *****		0.773 44 0.00000 *****
SON	-0.239 44 0.055	0.481 44 0.00048 ***	-	-	-	0.541 44 0.00008 ****	-0.125 44 0.209	0.520 44 0.00015 ***	0.257 44 0.046 *	0.425 42 0.0025 **	0.480 43 0.00056 ***	0.434 44 0.00164 **	0.591 44 0.00001 *****	

P≤ 0.00001 *****   P≤ 0.0001 ****   P≤ 0.001 ***   P≤ 0.01 **   P≤ 0.05 *

Table 2.22: Lake Joondalup sediment cores (4 July, 1979).

Site	Depth (cm)	Description	Density (g wet wt. cm^{-3})	Water content (%)	Lattice water (% dry wt.)	Organic matter (% dry wt.)	Carbonate (% dry wt.)	Total nitrogen ($mg\ g^{-1}$ dry wt.)	Total nitrogen ($mg\ cm^{-3}$)	Total phosphorus ($\mu g\ g^{-1}$ dry wt.)	Total phosphorus ($\mu g\ cm^{-3}$)
12	0 - 5	Top metaphyton	0.91	92.5	0.5	82.0	3.0	41.1	2.81	1573	107
	15 - 20	Juncture of metaphyton and peat	0.95	90.[illegible]	0.3	85.8	2.8	28.7	2.73	856	81
	32 - 37	Coarse peat	0.95	78.3	0.2	43.6	2.0	12.4	2.56	171	35
16	0 - 5	Top metaphyton	0.95	90.1	3.0	60.0	6.0	30.7	2.89	899	95
	30 - 35	Lower metaphyton	0.96	90.2	0.1	68.7	2.7	34.8	3.27	816	77
	40 - 45	Dark red gelatinous sediment	0.97	87.9	0.3	31.[illegible]	3.2	41.5	5.02	388	47
	52 - 57	Light red/pink rubbery sediment	0.95	84.5	1.4	45.1	11.3	15.0	2.15	212	30

Table 2.23: Physico-chemical data for sediment samples collected during grid studies.

Date	Samples	Meta-phyton (cm)	Density (g fwt cm^{-3})	% LOI	% carbonate	TN (mg g^{-1} dry wt)	TP (mg g^{-1} dry wt)	SNH (μg g^{-1} dry weight)	SNOX (μg g^{-1} dry weight)	SON (μg g^{-1} dry weight)	SRP (μg g^{-1} dry weight)	TSP (μg g^{-1} dry weight)
6 & 13.12.'78	L.Joondalup 0-5 cm	-	1.07±0.05	42.7± 5.3	9.8± 2.1	13.1± 1.5	0.38±0.10	108± 27	1.1±0.1	299± 62	40± 21	46± 23
		-	10	10	10	10	10	10	10	10	10	10
		-	0.8 -1.4	18.5-65.7	1.2-19.2	6.5-21.5	0.15-0.97	7-305	0.6-1.8	95-695	2-206	1-212
25.7.1979	L.Joondalup 0-5 cm	10.6± 1.8^1	1.06±0.04	41.5± 2.9	12.2± 1.9	32.0± 8.0	0.68±0.20	265±105	1.2±0.4	1349±322	41± 11	53±13
		41)^2	42	42	42	42	42	41	40	41	41	41
		0.1-55.4^3	0.7 -1.8	0.4-81.9	0.1-55.7	0.1-341.9	0.00-8.25	1-4375	0.1-14.0	29-9999	1-294	1-375
25.7.1979	L.Joondalup 20-25 cm	-	1.01±0.03	34.3± 2.6	13.3± 1.5	12.8± 1.2	0.15±0.03	83± 11	2.9±0.2	193± 24	5 ± 1	26±11
		-	42	42	42	42	42	44	44	44	42	43
		-	0.8 -1.7	0.2-78.8	0.1-30.9	0.1-41.3	0.00-1.13	1-316	1.0-6.0	10-520	1-34	1-435
25.7.1979	Beenyup Swamp 0-5 cm	0	0.95±0.49	34.7± 1.9	2.6± 1.4	15.3± 3.2	0.97±0.44	45± 8	2.3±0.8	232± 39	17± 7	21± 7
		4	4	4	4	4	4	4	4	4	4	4
		0	0.7- 1.1	30.0-39.5	0.6- 6.7	9.2-24.0	0.34-2.28	26-63	1.0-4.0	150-310	6-38	7-39
25.7.1979	Beenyup Swamp 20-25 cm	-	0.98±0.10	24.6± 6.1	1.3± 0.3	7.6± 2.0	0.09±0.03	29± 5	2.8±0.5	123± 15	2 ± 0	3 ± 1
		-	4	4	4	4	4	4	4	4	4	4
		-	0.9 -1.1	11.2-38.0	0.4- 1.8	1.9-10.6	0.02-0.16	13-37	2.0-4.0	90-154	2 - 3	2 - 4
14.1.1980	L.Joondalup	25.1± 2.7	-	-	-	-	-	-	-	-	-	-
		31	-	-	-	-	-	-	-	-	-	-
		7.3-86.7	-	-	-	-	-	-	-	-	-	-

$^1\bar{x}$±S.E. ^{2}Number of samples ^{3}Range of samples

Table 2.24: Comparison of phosphorus, nitrogen and chloride data on a year-to-year basis for the main waterbody of Lake Joondalup (Chloride as mg l^{-1}, others as μg l^{-1}).

Year		PO_4-P	Organic P	NH_4-N	NO_3-N	Organic N	Chloride	Source
	x̄ ± S.E.	22 ± 4	42 ± 5	312 ± 48	-	1980 ± 124	386 ± 29	
1973	n	41	40	38	-	40	41	Congdon (1973)
	range	2 - 130	1 - 166	8 - 1250	-	852 - 4276	155 - 726	
	x̄ ± S.E.	19 ± 4	25 ± 5	20 ± 7	880 ± 165	1726 ± 147	-	Gordon (1975)
1975	n	11	11	10	11	8	-	Finlayson (1975)
	range	1 - 35	1 - 51	5 - 74	190 - 1896	1260 - 2475	-	
	x̄ ± S.E.	23 ± 2	24 ± 5	79 ± 15	6.3 ± 1.3	1538 ± 56	283 ± 22	Current study
1978	N	28	26	28	28	28	25	- sites 19, 34 and 37
	range	4 - 63	1 - 114	11 - 371	1 - 29	933 - 2272	91 - 619	from 19 September only.
	x̄ ± S.E.	45 ± 3	37 ± 3	66 ± 10	4.1 ± 0.5	2671 ± 46	507 ± 17	Current study
1979	n	175	174	171	175	170	157	- sites 12, 19, 34, 35
	range	11 - 402	1 - 246	5 - 1024	1 - 66	845 - 4731	147 - 1068	and 37.
	x̄ ± S.E.	52 ± 4	49 ± 5	95 ± 18	5.4 ± 0.8	3456 ± 329	617 ± 38	
1980	n	121	120	120	121	117	128	As above.
	range	7 - 187	1 - 369	6 - 1684	1 - 76	425 -23011	164 - 1736	

Table 3.1 : The mass of phosphorus and nitrogen (Kg) in Lake Joondalup at the times of grid studies

Month	Date	PO_4-P	Organic P	Total P	NH_4-N	NO_3-N	Organic N	Total N
December	6&13.12.1978	179	114	293	230	87	6446	6763
January	31.01.1979	128	260	388	97	6	6238	6341
July[1]	25.07.1979	203	45	248	101	8	8758	8867
January	14.01.1980	79	66	145	139	6	7750	7895
June	19.06.1980	86	73	159	45	7	3373	3425
July	24.07.1980	147	115	262	65	29	5070	5164
August	28.08.1980	221	92	313	188	26	3984	4198
September	25.09.1980	234	102	336	118	17	4397	4532
October	23.10.1980	138	140	278	67	11	5443	5521
November	20.11.1980	159	67	226	48	8	6143	6199

[1] At the July 1979 grid study the sediment contained 29.4 x 10^3 kg P and 1262 x 10^3 kg N to 10 cm depth.

Table 3.2 : Phosphorus and nitrogen inputs (Kg) at site 46 between studies

Period	Days	PO_4-P	Organic P	Total P	NH_4-N	NO_3-N	Organic N	Total N
14.01.80 - 19.06.80	157	0	0	0	0	0	0	0
19.06.80 - 24.07.80	35	61	14	75	15	9	235	258
24.07.80 - 28.08.80	35	79	18	97	11	15	254	280
28.08.80 - 25.09.80	28	37	3	40	5	3	98	106
25.09.80 - 23.10.80	28	27	15	42	4	4	117	125
23.10.80 - 20.11.80	28	12	3	15	3	1	64	68
20.11.80 - 22.12.80	28	0	0	0	0	0	1	1
Total	339	216	53	269	38	32	769	838

Table 3.3 : Phosphorus and nitrogen inputs (Kg) at site 57 between grid studies

Period	Days	PO_4-P	Organic P	Total P	NH_4-N	NO_3-N	Organic N	Total N
20.12.79 - 24.04.80	156	0	0	0	0	0	0	0
24.04.80 - 22.05.80	28	3	1	4	1	1	24	26
22.05.80 - 19.06.80	28	32	3	35	2	8	130	140
19.06.80 - 24.07.80	35	114	21	135	16	17	336	369
24.07.80 - 28.08.80	35	86	31	117	10	8	206	224
28.08.80 - 25.09.80	28	41	19	60	4	3	112	119
25.09.80 - 23.10.80	28	34	27	61	3	2	94	99
23.10.80 - 20.11.80	28	33	7	40	2	1	79	82
20.11.80 - 22.12.80	28	7	1	8	0	0	20	20
Total		350	110	460	38	40	1001	1079

Table 3.4 Phosphorus and nitrogen inputs (g) at site 36 between grid studies

Period	Days	PO_4-P	Organic P	Total P	NH_4-N	N_3-N	Organic N	Total N
19.06.80 - 24.07.80	35	741	933	1674	613	3637	8437	12687
24.07.80 - 28.08.80	35	306	510	816	473	5568	11577	17618
28.08.80 - 25.09.80	28	242	113	355	218	738	5022	5978
25.09.80 - 23.10.80	28	74	35	109	52	73	1058	1183
23.10.80 - 20.11.80	28	74	43	117	61	30	1082	1173
20.11.80 - 22.12.80	28	33	35	68	33	4	504	541
Total for period 19.06.80 - 22.12.80		1470	1669	3139	1450	10050	27680	39180

Table 3.5 Comparison of flows and nutrient loadings at sites 70 and 57.

Site	Date	Flow cm^3 s^{-1}	PO_4-P	Organic P	Total P g d^{-1}	NH_4-N	NO_3-N	Organic N	Total N	Chloride kg d^{-1}
70	21.08.1980	1976								
	1.09.1980	880	49	15	64	3	56	98	157	
57	28.08.1980	102075	3228	944	4172	397	88	5865	6350	997
	1.09.1980	68660	2296	1056	3352	231	83	4164	4478	641
	4.09.1980	35160	1057	492	1549	100	30	3688	3818	349

Table 3.6 : Phosphorus concentrations (µg l^{-1}) in rainwater collected at Edgewater[1] and on the University of Western Australia campus at Crawley.

Site	Parameter	SRP	Organic P	Total P
Edgewater	$\bar{x}$ ± S.E.	4 ± 1	15 ± 2	28 ± 6
	n	9	3	7
	range	1 - 14	13 - 18	13 - 60
Crawley	$\bar{x}$ ± S.E.	10 ± 1	20 ± 3	31 ± 3
	n	24	15	20
	range	2 - 31	5 - 46	11 - 61

[1] The sampling location at Edgewater is shown in Fig 1.1

concentrations (μg l^{-1}) in rainwater collected at Edgewater[1] and on the University of Western Australia campus at Crawley.

Site	Parameter	NH_4-N	NO_3-N	Organic N	Kjeldahl N[2]	T
Edgewater	$\bar{x}$ ± S.E.	67 ± 14	42 ± 8	857	577 ± 144	570
	n	12	18	1	5	
	range	4 - 175	5 - 118		264 - 1032	341
Crawley	$\bar{x}$ ± S.E.	98 ± 10	130 ± 41[3]	349 ± 82	463 ± 74	547
	n	20	33	10	12	9
	range	17 - 226	3 - 1275	1 - 819	54 - 889	83 -

[1] The sampling location at Edgewater is shown in Fig. 1.1

[2] Kjeldahl nitrogen is equivalent to organic plus NH_4-N.

[3] Without two high flyers $\bar{x}$ ± S E = 78 ± 13, n = 31, range = 3 - 203.

Table 3.8: Ash, nitrogen and phosphorus contents of emergent macrophytes collected in the vicinity of Lake Joondalup, Wanneroo.

Species	Component	Ash (% dry wt)	Nitrogen (mg g^{-1} AFDW)	Phosphorus (μg g^{-1} AFDW)	Site of collection
Baumea articulata	Live culms	7.2	7.8	487	Off Cockman Rd,
	Dead culms	17.6	3.6	118	Wallubuenup Swamp.
Schoenoplectus validus	Live culms	19.8	18.5	1348	Site 37
	Dead culms	16.0	10.2	352	
Typha orientalis	Live culms	14.7	21.7	1436	Site 37
	Dead culms	4.2	4.0	709	
	Rhizomes	16.0	4.6	1034	
	Major roots	22.8	7.3	168	
Baumea juncea	Live culms	11.1	4.3	174	South-east shore
	Dead culms	12.0	4.4	183	near site 6.
	Rhizomes	3.7	2.2	204	
	Roots	11.5	6.8	215	
Lepidosperma longitudinale	Live culms	11.8	11.2	463	South-east shore
	Dead culms	6.3	4.0	158	near site 6.
	Leaf litter	10.6	11.5	387	
	Rhizomes	9.9	6.2	485	
	Roots	8.4	8.9	158	

Table 3.9 : Standing crops and nutrient stocks of emergent macrophytes collected from Lake Joondalup

Species	Component	Standing Crop (g dry wt m^{-2})	Nitrogen (g N m^{-2})	Phosphorus (mg P m^{-2})
Baumea juncea	Live culms	2730	10.4	423
	Dead culms	415	1.6	67
	Rhizomes	1297	2.8	256
	Roots	93	0.6	18
Lepidosperma longitudinale	Live culms	844	8.3	344
	Dead culms	175	0.6	26
	Leaf litter	426	4.4	147
	Rhizomes	1263	7.0	552
	Roots	204	1.7	30

Table 3.10: Standing crops and ash content of aquatic macrophytes sampled with an Ekman grab on November 20 and December 18, 1980.

		Standing crop (g dry wt m^{-2}) Total	Ash-free	% Ash
Chara baueri	x̄ ± S.E.	37.75 ± 10.34	13.62 ± 1.17	57.4 ± 1.4
(mixed *Chara/Najas* community)	n	11	10	10
	range	3.28 - 103.50	1.57 - 47.02	50.67-62.98
Najas marina	x̄ ± S.E.	1.11 ± 0.26	0.79 ± 0.18	21.41 ± 1.01
(mixed *Chara/Najas* community)	n	9	9	5
	range	0.02 - 2.63	0.02 - 1.77	18.56 - 24.53
Najas marina	x̄ ± S.E.	2.74 ± 0.61	2.12 ± 0.47	22.40 ± 0.29
(dense *Najas* community)	n	6	6	4
	range	1.53 - 5.68	1.20 - 4.41	21.59 - 22.93
Najas marina	x̄ ± S.E.	0.37	-	-
(mixed *Nitella/Najas* community)	n	1	-	-
	range	-	-	-
Nitella congesta	x̄ ± S.E.	28.37	14.04	50.52
	n	1	1	1
	range	-	-	-

Table 3.11: Ash, nitrogen and phosphorus contents of submerged aquatic plants collected from Lake Joondalup (24 July, 1980).

Species	Ash (% DW)	Nitrogen (mg g^{-1}) DW	AFDW	Phosphorus (µg g^{-1}) DW	AFDW	Comments
Nitella congesta	56.8	12.6	29.1	300	694	Old calcified growth
	20.3	22.4	28.1	870	1091	New growth
Najas marina	-	26.0	-	1539	-	
Chara baueri	57.8) 58.0	16.2) 15.3	38.4) 36.4	193) 187	457) 444	Old calcified growth
	58.2)	14.4)	34.4)	181)	433)	Old calcified growth
	34.4) 34.2	22.2) 21.7 ±1.0	33.8) 33.0 ±1.4	757) 731 ±42	1154) 1112 ±62	New growth, site 3
	33.9)	22.4)	33.8)	754)	1140)	New growth, site 7
	-	20.5)	31.1)	683)	1041)	New growth, site 7

Table 3.12 : Nutrient contents per unit area of components of the Lake Joondalup ecosystem.

	Nitrogen ($g\ N\ m^{-2}$)	Phosphorus ($mg\ P\ m^{-2}$)	Comments
Water column	1.27 ± 0.08[1]	87 ± 24	From July 1979 grid study, to 1 m depth.
Sediment	216 ± 46 $_{-3}$	50110 ± 1285	From July 1979 grid study, to 10 cm depth
Schoenoplectus validus[2]	69	3610	Aboveground biomass only
Baumea articulata[3]	30	1658	Aboveground biomass only
Baumea juncea	15	764	
Lepidosperma longitudinale	18	952	
Chara baueri	0.6	7	For mean standing crop of 36 g dry weight m^{-2}
Nitella congesta	0.4	13	For standing crop of 28 g dry weight m^{-2}
Najas marina	0.04	3	For mean standing crop of 1.7 g dry weight m^{-2}

[1] x̄ ± S E

[2] Based on standing crop measured at Loch McNess, March 1978. Live culms = 2.14 kg m^{-2}, dead culms = 4.38 kg m^{-2}.

[3] Based on standing crop measured at Bennett Rd Swamp, Bremer Bay, August 1974. Live culms = 3.12 kg m^{-2}, dead culms = 2.55 kg m^{-2}.

Table 3.13: Comparison of nitrogen and phosphorus pools in Lake Joondalup for July 25, 1979. (All values given in kg)

	Total phosphorus	Total nitrogen	Comments
Water column	248	8,867	
Sediment	29,350	1,262,000	To 10 cm depth
Swamp vegetation	14	252	

Table 3.14: The effect of stirring sediments *in situ* on nutrient concentrations in the water column at site 22 (March 1979).

	PO_4-P	Organic P	Total P (µg l^{-1})	NH_4-N	NO_3-N
Before stirring	34	29	63	42	3
After stirring	11	24	35	25	3

Table 3.15: The effect of shaking sediments in phosphate solutions of various concentrations.

Concentration of solution (µg PO_4-P l^{-1})	Reactive phosphorus concentration after shaking	
	Surface sediment (0-5 cm)	Deep sediment (25-30 cm)
0	3.3	17.3
25	27.7[1]	39.8
50	49.3[1]	61.0
100	90.7[1]	103.8

[1] Mean of three replicates, otherwise two.

Table 3.16 : The phosphorus mass-balance for Lake Joondalup (kg P)

Period	Lake P mass	Net change	Inputs				Residual
			Site 46	Site 36	Rainfall	Total	
13.12.1978	293	-	-	-	-	-	-
13.12.78 - 31. 1.79	388	+95	0	0	3	3	+ 92
31. 1.79 - 25. 7.79	248	-140	-	-	48	≥48	≤-188
25. 7.79 - 14. 1.80	145	-103	-	-	28	≥28	≤-131
14. 1.80 - 19. 6.80	159	+14	0	-	28	≥28	≤-14
19. 6.80 - 24. 7.80	262	+103	75	2	27	104	- 1
24. 7.80 - 28. 8.80	313	+51	97	1	20	118	- 67
28. 8.80 - 25. 9.80	336	+23	40	0	10	50	- 27
25. 9.80 - 23.10.80	278	-58	42	0	9	51	-109
23.10.80 - 20.11.80	226	-52	15	0	3	18	- 70
20.11.80 - 22.12.80	-	-	0	0	1	1	
14. 1.80 - 22.12.80	-	+81	269	3	97	369	-288

Table 3.17 : The nitrogen mass-balance for Lake Joondalup (kg N)

Period	Lake N mass	Net change	Measured inputs				Residual
			Site 46	Site 36	Rainfall	Total	
13.12.1978	6763	-	-	-	-	-	-
13.12.78 - 31. 1.79	6341	-422	0	0	55	55	-477
31. 1.79 - 25. 7.79	8867	+2526	-	-	971	≥971	≤+1555
25. 7.79 - 14. 1.80	7895	-972	-	-	567	≥567	≤-1539
14. 1.80 - 19. 6.80	3425	-4470	0	-	572	≥572	≤-5042
19. 6.80 - 24. 7.80	5164	+1739	258	13	542	813	+926
24. 7.80 - 28. 8. 80	4198	-966	280	18	400	698	-1664
28. 8.80 - 25. 9.80	4532	+334	106	6	194	306	+28
25. 9.80 - 23.10.80	5521	+989	125	1	177	303	+686
23.10.80 - 20.11.80	6199	+678	68	1	68	137	+541
20.11.80 - 22.12.80	-	-	1	1	29	31	
14. 1.80 - 20.11.80	-	-1696	837	39	1953	2829	-4525

Table 3.18: Denitrification rates found in aquatic sediments.

Waterbody	Denitrification rate ($g\ N\ m^{-2}\ yr^{-1}$)	Analytical technique	Source
Lake Okeechobee, Florida	0.5 - 1.3 $^{-5}$	Acetylene blockage and mass balance.	Messer & Brezonik (1983)
Lake Arresø, Denmark	1.3	^{15}N	Madsen (1979)
Delaware Inlet, N.Z.	0 - 6.1 ($\bar{x}$ = 1.5)	Acetylene blockage	Kaspar (1982)
6 shallow lakes, Denmark	0 - 47	Mass balance and sediment analysis, assuming no N_2-fixation.	Andersen (1974)
6 lakes, Switzerland	1 - 20	As above	Vollenweider (1968)
Freshwater sediments	2.3 - 3.7	Acetylene blockage	Chan & Knowles (1979)
Several sources	0 - 1.5[1]		Kamp-Nielson and Andersen (1977)

[1] $g\ N\ m^{-2}\ d^{-1}$

Table 3.19: External and internal specific surface loadings of phosphorus and nitrogen to Lake Joondalup.

Period	Days	Mean area ($\times 10^6$ m^2)	Total loading ($mg\ m^{-2}$) Phosphorus External	Total loading Phosphorus Internal	Total loading Nitrogen External	Total loading Nitrogen Internal	Daily loading ($\mu g\ m^{-2}\ d^{-1}$) Phosphorus External	Daily loading Phosphorus Internal	Daily loading Nitrogen External	Daily loading Nitrogen Internal
13.12.1978 - 31.1.79	39	4.349	0.7	21.2	13	-110	18	542	324	-2812
14.1.1980 - 19.6.80	157	3.995	7.0	-3.5	143	-1262	45	-22	911	-8038
19.6.1980 - 24.7.80	35	4.072	25.5	-0.3	200	227	730	-7	5706	6486
24.7.1980 - 28.8.80	35	4.387	26.9	-15.3	159	-379	769	-436	4546	-10829
28.8.1980 - 25.9.80	28	4.484	11.2	-6.0	68	6	400	-215	2437	223
25.9.1980 - 23.10.80	28	4.505	11.3	-24.2	67	152	404	-864	2402	5439
23.10.1980 - 20.11.80	28	4.478	4.0	-15.6	31	121	144	-557	1093	4314
14.1.1980 - 20.11.80	311	4.318	85.5	-66.7	655	-1050				

Table 3.20: Nutrient loadings recorded in atmospheric fall-out.

Study site	Atmospheric nutrient loadings ($mg\ m^{-2}\ yr^{-1}$) Phosphorus	Nitrogen	Source
Lake Joondalup, W.A.	23	473	This study
Jarrah forest, Dwellingup, W.A.	30	355	Bell and Barry (1981)
Onkaparinga R., South Australia.	49	701	Buckney (1979)
South Australia	12 - 14	319 - 369	Wood (1979)
Victoria	10 - 48 0($\bar{x}$=40)	-	Greenhill *et al.* (1983)
Queensland	10 - 30	-	Probert (1976)
Dwellingup, W.A.	15	70	O'Connell (unpublished)
Denmark	10	1230	Andersen (1974)
Durban, South Africa	50	2300	Simpson and Hemens (1978)
Northern California	-	80 - 305[1]	McColl *et al.* (1982)
	-	54 - 438[2]	" " "
General	5 - 45	560 - 10000	Loehr (1974)
General	8 - 800	170 - 3000	Uttormark *et al.* (1974 - cited in Wood 1979).

[1] NH_4 and NO_3-N only, wet fall-out.

[2] NH_4 and NO_3-N only, dry fall-out.

Table 4.1 : Comparison of chlorophyll a and phaeophytin data collected from sites in the main waterbody of Lake Joondalup - Sept. 1978 to Dec. 1980. ($\mu g\ l^{-1}$)

Site		Chlorophyll a	Phaeophytin
12	$\bar{x}$ ± S.E.	27.1 ± 6.4	4.3 ± 0.7
	n	15	15
	range	2.1 - 88.6	0.1 - 9.1
19	$\bar{x}$ ± S.E.	28.5 ± 4.3	7.9 ± 1.2
	n	111	111
	range	0.6 - 273.7	0.1 - 86.9
34	$\bar{x}$ ± S.E.	30.9 ± 5.4	9.0 ± 1.3
	n	94	94
	range	3.8 - 439.8	0.1 - 93.1
35	$\bar{x}$ ± S.E.	28.1 ± 3.7	6.6 ± 0.9
	n	12	11
	range	8.0 - 47.6	3.6 - 12.8
37	$\bar{x}$ ± S.E.	22.6 ± 2.9	7.6 ± 0.9
	n	n	65
	range	1.9 - 100.2	1.3 - 49.5

Table 4.2 : Comparison of chlorophyll a and phaeophytin data collected from sites in the southermost basin of Lake Joondalup - Sept. 1978 to Dec. 1980. ($\mu g\ l^{-1}$)

Site		Chlorophyll a	Phaeophytin
46	$\bar{x}$ ± S.E.	25.9 ± 4.1	7.4 ± 1.0
	n	106	106
	range	0.9-263.1	0.1 - 68.6
47	$\bar{x}$ ± S.E.	80.2 ± 11.7	26.1 ± 4.0
	n	74	74
	range	0.1 - 541.1	0.6 - 215.0
54	$\bar{x}$ ± S.E.	244.5 ± 74.0	67.1 ± 19.8
	n	33	33
	range	0.7 - 1425.8	0.1 - 492.3

Table 4.3 : Comparison of chlorophyll *a* and phaeophytin data collected from sites south of Lake Joondalup - Nov. 1978 to Dec 1980.

($\mu g\ l^{-1}$)

Site		Chlorophyll *a*	Phaeophytin
57	$\bar{x} \pm$ SE	12.7 ± 2.7	4.3 ± 0.8
	n	107	107
	range	0.1 - 164.0	0.1 - 39.3
59	$\bar{x} \pm$ SE	24.2 ± 11.2	7.1 ± 3.6
Beenyup Swamp	n	24	23
	range	0.1 - 207.7	0.1 - 77.5
73	$\bar{x} \pm$ SE	8.9 ± 1.7	4.4 ± 0.7
Lake	n	29	29
Goollelal	range	0.4 - 37.2	0.5 - 13.2

Table 4.4 : Comparison of chlorophyll *a* and phaeophytin data collected from stormwater sumps near Lake Joondalup - Sept. 1978 to Dec. 1980.

($\mu g\ l^{-1}$)

Site		Chlorophyll *a*	Phaeophytin
36	$\bar{x} \pm$ SE	6.7 ± 0.4	3.0 ± 0.2
	n	131	131
		0.1 - 26.3	0.1 - 16.7
Ariti	$\bar{x} \pm$ SE	8.5 ± 5.0	3.0 ± 1.2
Avenue	n	5	5
sump	range	1.6 - 27.8	1.2 - 7.8

Table 4.5 Chlorophyll a and phaeophytin concentrations ($\mu g\ l^{-1}$) detected during grid studies

Date		Chlorophyll a	Phaeophytin
6.12.1978	$\bar{x}$ ± SE	10.4 ± 1.5	3.9 ± 0.7
	n	10	10
	range	4.5 - 19.2	1.4 - 8.7
13.12.1978	$\bar{x}$ ± SE	14.2 ± 2.7	4.3 ± 0.8
	n	12	12
	range	6.5 - 42.5	1.5 - 12.4
31. 1.1979	$\bar{x}$ ± SE	9.3 ± 2.4	3.0 ± 0.6
	n	13	13
	range	1.5 - 33.3	0.8 - 7.7
7. 3.1979	$\bar{x}$ ± SE	19.0 ± 5.1	8.9 ± 2.7
	n	10	10
	range	9.0 - 64.7	2.5 - 31.0
25. 7.1979	$\bar{x}$ ± SE	15.5 ± 0.9	6.5 ± 0.8
	n	47	47
	range	0.6 - 34.2	1.0 - 36.6
14. 1.1980	$\bar{x}$ ± SE	33.9 ± 6.6	8.7 ± 2.4
	n	32	32
	range	5.7 - 175.2	0.1 - 75.5
19. 6.1980	$\bar{x}$ ± SE	56.4 ± 8.7	13.6 ± 3.2
	n	20	20
	range	1.1 - 144.2	0.7 - 49.5
24. 7.1980	$\bar{x}$ ± SE	11.7 ± 1.8	4.0 ± 0.5
	n	41	41
	range	0.4 - 54.1	0.5 - 16.9
28. 8.1980	$\bar{x}$ ± SE	4.3 ± 0.2	1.8 ± 0.1
	n	41	41
	range	0.9 - 8.6	0.1 - 3.8
25. 9.1980	$\bar{x}$ ± SE	4.4 ± 0.3	1.7 ± 0.1
	n	41	41
	range	1.4 - 8.4	0.5 - 2.8
23.10.1980	$\bar{x}$ ± SE	7.6 ± 2.4	2.6 ± 0.3
	n	41	41
	range	0.1 - 70.0	0.4 - 9.1
20.11.1980	$\bar{x}$ ± SE	17.5 ± 2.4	6.9 ± 0.5
	n	41	41
	range	0.4 - 66.4	1.4 - 13.9

Table 4.6 : Comparison of chlorophyll a and phaeophytin data on a year-to-year basis for the main waterbody of Lake Joondalup

Year		Chlorophyll a	Phaeophytin	Source
1975	$\bar{x}$ ± SE	4.3 ± 0.8	-	Gordon (1975)
	n	11	-	
	range	1.2 - 8.5	-	
1978	$\bar{x}$ ± SE	12.2 ± 2.3	4.0 ± 0.5	
	n	28	28	This study
	range	1.5 - 58.5	0.5 - 12.9	
1979	$\bar{x}$ ± SE	16.7 ± 0.9	6.2 ± 0.4	
	n	155	154	This study
	range	1.9 - 72.6	0.1 - 36.6	
1980	$\bar{x}$ ± SE	47.4 ± 5.9	11.4 ± 1.5	
	n	113	113	This study
	range	2.1 - 439.8	0.1 - 93.1	

Table 4.7: Phytoplankton taxa and their occurrence at the study sites.

Site 19:

01.11.1978) 26.02.1979) 15.03.1979) 11.04.1979) 15.11.1979) 03.01.1980)	*Microcystis aeruginosa* (?)
23.10.1980 (16.11.1980 (	*Spirogyra* sp.
14.11.1978	*Merismopedia* (?), *Scenedesmus*

Site 34:

17.10.1978	*Spirogyra* sp.
14.11.1978	*Anabaena* sp.
20.11.1978	*Anabaena spiroides*

Site 36:

25.07.1979) 01.08.1979) 15.08.1979) 22.08.1979) 06.09.1979) 12.09.1979) 19.09.1979)	*Spirogyra* sp.

Site 37:

28.12.1978	*Anabaena* (?) bloom
20.11.1980	*Anabaena spiroides*
20.12.1978 (17.01.1979 (15.11.1979 (13.12.1979 (27.12.1979 (03.01.1980 (23.10.1980 (	*Microcystis aeruginosa*
03.01.1979) 17.01.1979) 14.02.1979) 21.02.1979) 07.03.1979) 15.03.1979) 01.11.1979)	*Spirogyra* sp.

Site 46:

17.10.1978 (01.11.1978 (23.10.1978 (	*Anabaena spiroides*
03.10.1979	Green colonial alga (spherical)

Site 47:

20.12.1978) 28.12.1976) 10.01.1979) 01.11.1979) 10.01.1980) 17.01.1980) 23.10.1980)	*Anabaena spiroides*
28.12.1978 (20.07.1979 (24.12.1979 (10.01.1980 (	*Microcystis aeruginosa*
14.02.1980) 21.02.1980)	*Nannochloris* (?)
20.12.1978 (28.12.1978 (10.01.1979 (12.09.1979 (03.10.1979 (13.12.1979 (27.12.1979 (	Green spherical colonial alga

Site 54:

27.03.1980	*Heterogloea* (?)
28.08.1980	*Microcystis aeruginosa*

Site 57:

01.11.1978	*Spirogyra* sp.

Site 59:

28.03.1979	*Anabaena*, diatoms, euglenophytes
06.03.1980	*Oscillatoria princeps*

General:

19.06.1980	*Spirogyra* sp. present at sites 30 and 33.
23.10.1980	*Anabaena spiroides* common south of site 38; *Microcystis* present at sites 29, 32, 37; *Microcystis* and *Aphanothece* common at sites 20 and 23; abundant *Spirogyra* at sites 19, 22 and 23.
29.11.1980	*Anabaena spiroides* abundant at sites 30, 32, 33, 39 and 43.

Table 4.8 : Correlation matrix for mean concentrations determined during grid studies (n=12)

	Chlorophyll a	Phaeophytin	PO_4-P	Organic P	NH_4-N	NO_3-N	Organic N
Chlorophyll a		r = 0.939 *** P>99.9%	r = 0.476 N.S.	r = 0.295 N.S.	r = -0.104 N.S.	r = -0.157 N.S.	r = 0.683 * P>95%
PO_4-P				r = 0.669 * P>95%	r = 0.094 N.S.	r = -0.163 N.S.	r = 0.387 N.S.
Organic P					r = 0.196 N.S.	r = -0.128 N.S.	r = 0.497 N.S.
NH_4-N						r = 0.425 N.S.	r = 0.089 N.S.
NO_3-N							r = -0.285 N.S.

Table 4.9 : Correlations between chlorophyll a concentrations and environmental variables for site 47.

Variable	r	n	P
Phaeophytin	0.618	74	0.00001
Organic N	0.526	63	0.00001
Organic P	0.296	62	0.0098
NH_4-N	-0.211	64	0.0470
----------	----------	----------	---------- 5% level of significance
NO_3-N	-0.161	61	0.1077
Chloride	0.154	66	0.1085
PO_4-P	-0.008	63	0.4747

Table 4.10 : Correlation matrix for physico-chemical parameters measured during the November 1979 grid study in the southernmost basin of Lake Joondalup.

	Chlorophyll a	Secchi Transparency	Absorbance at 440 nm	pH	Phenolphthalein alkalinity	Total alkalinity
Chlorophyll a[1]		r =-0.68 * P>90%	r = 0.94 **** P>99.9%	r = 0.24 N.S.	r = 0.19 N.S.	r = 0.01 N.S.
Secchi Transparency	r = -0.68 * P>90%		r = 0.66 * P>90%	r = -0.86 *** P>99%	r = -0.80 *** P>99%	r = 0.24 N.S.
Absorbance at 440 nm	r = -0.63 ** P>95%	r = 0.66 * P>90%		r = 0.06 N.S.	r = -0.01 N.S.	r = 0.08 N.S.
pH	r = 0.75 ** P>95%	r = -0.86 ** P>95%	r = -0.40 N.S.		r = 0.86 **** P>99.9%	r = 0.06 N.S.
Phenolphthalein alkalinity	r = 0.68 ** P>95%	r =-0.80 ** P>95%	r = -0.49 N.S.	r = 0.85 *** P>99%		r = -0.72 ** P>95%
Total alkalinity	r = -0.61 * P>90%	r = 0.24 N.S.	r = 0.09 N.S.	r = 0.08 N.S.	r = -0.73 ** P>95%	

[1] Not including site 53 where chlorophyll a exceeded 5,260 μg l^{-1} and absorbance at 440 nm was 0.207 (maximum of 330 μg chlorophyll a l^{-1} and 0.095 absorbance at other sites).

Table 4.11 : Correlations between chlorophyll a concentrations and nutrient concentrations for the November 1979 grid study of the southernmost basin of Lake Joondalup (site 53 has been omitted from the analysis as it had a particularly high chlorophyll a concentration).

Variable	r	n	P
Organic N	0.81	10	>99%
PO_4-P	0.60	10	>90%
NH_4-N	0.33	10	N.S.
Organic P	-0.26	9	N.S.
Chloride	-0.20	10	N.S.
NO_3-N	-0.07	10	N.S.

Table 5.1: Estimated annual (a) water and (b) nutrient balances for Lake Joondalup

(a)		Comments
Precipitation (10^6 m^3)	3.37	Based on period from 20/12/1979 to 18/12/1980
Evaporation	5.04	
Swamp discharge	0.79	
Sump discharge	0.10	
Total discharge	0.90	
Groundwater seepage	0.77	

(b)	Phosphorus	Nitrogen	
Swamp discharge (kg)	269	838	Based on period from 14/1/1980 to 22/12/1980
Sump discharge	3	39	
Total discharge	272	877	
Atmospheric fallout	97	1953	
Total input	369	2830	
External loadings (kg ha^{-1} y^{-1})			
Discharge	0.63	2.03	Based on a mean area of 432 ha
Atmospheric fallout	0.22	4.52	
Total	0.85	6.55	
Sedimentation by mass balance			
(kg)	288	4525	
(kg ha^{-1} yr^{-1})	0.67	10.48	
Input N:P (weight)	7.67		
N:P in surface sediment	47.06		
Estimated N sedimentation			
(kg)		17365	
(kg ha^{-1} yr^{-1})		31.37	
Estimated N_2 fixation			
(kg)		14535	
(kg ha^{-1} yr^{-1})		24.82	

Table 5.2: Comparison of water level, chlorophyll a and nutrient concentrations on a year-to-year basis for the main waterbody of Lake Joondalup

Year		Water level	Chlorophyll a	PO_4-P	Organic P	NH_4-N	NH_3-N	Organic N
1973[1]	$\bar{x}$ ± S.E.	-	-	22 ± 4	42 ± 5	312 ± 48	-	1980 ± 124
	n	-	-	41	40	38	-	40
	range	16.62-17.53	-	2 - 130	1 - 166	8 - 1250	-	852 - 4276
1975[2]	$\bar{x}$ ± S.E.	-	4.3 ± 0.8	19 ± 4	25 ± 5	20 ± 7	880 ± 165	1726 ± 147
	n	-	11	11	11	10	11	8
	range	16.99-17.76	1.2 - 8.5	1 - 35	1 - 51	5 - 74	190 - 1896	1260 - 2475
1978[3]	$\bar{x}$ ± S.E.	-	12.2 ± 2.3	23 ± 2	24 ± 5	79 ± 5	6.3 ± 1.3	1538 ± 56
	n	-	28	28	26	28	28	28
	range	16.51-17.47	1.5 - 58.5	4 - 63	1 - 114	11 - 371	1 - 29	933 - 2272
1979[4]	$\bar{x}$ ± S.E.	-	16.7 ± 0.9	45 ± 3	37 ± 3	66 ± 10	4.1 ± 0.5	2671 ± 46
	n	-	155	175	174	171	175	170
	range	16.63-17.26	1.9 - 72.6	11 - 402	1 - 246	5 - 1024	1 - 66	845 - 4731
1980[5]	$\bar{x}$ ± S.E.	-	47.4 ± 5.9	52 ± 4	49 ± 5	95 ± 18	5.4 ± 0.8	3456 ± 329
	n	-	113	121	120	120	121	117
	range	16.38-17.22	2.1 - 439.8	7 - 187	1 - 369	6 - 1684	1 - 76	425 - 23011

[1] Date from Congdon (1973).

[2] Data from Gordon (1975) and Finlayson (1975).

[3] Current study data for sites 19, 34 and 37 from 19th September only.

[4] Current study data for sites 12, 19, 34, 35 and 37.

Table 5.3: Methods of reducing lake eutrophication (Welch 1984)

A. REDUCTION IN NUTRIENT INFLOW
   1. Waste-water treatment
   2. Waste-water/stormwater diversion
   3. Land treatments
   4. Treatment of inflow
   5. Product modification (eg. detergents)

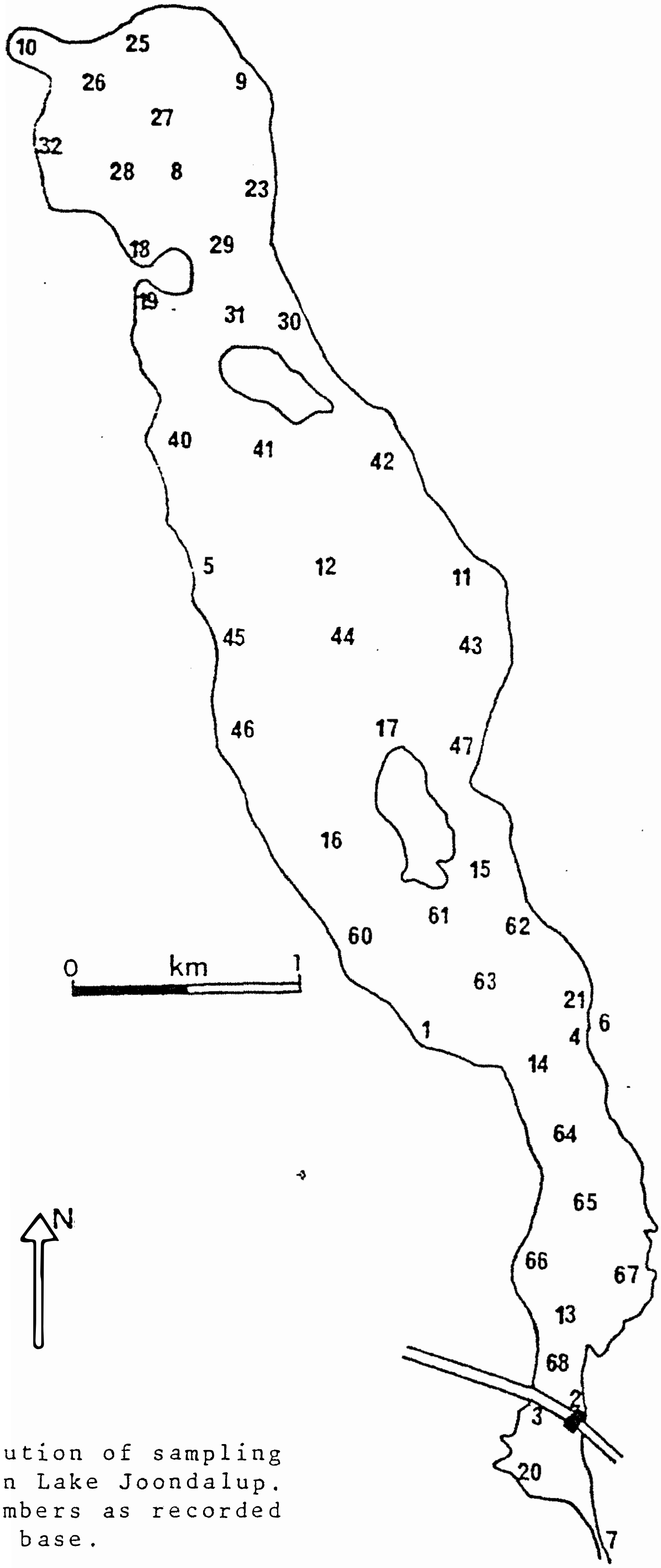
B. DISRUPTION OF INTERNAL NUTRIENT CYCLES
   1. Dredging
   2. Destratification/aeration
   3. Hypolimnetic aeration
   4. Nutrient inactivation/precipitation
   5. Bottom sealing
   6. Lake-level manipulation
   7. Biological cycling to higher trophic levels

C. ACCELERATION OF NUTRIENT OUTFLOW
   1. Biotic harvesting
   2. Selective (hypolimnetic) discharge
   3. Dilution/flushing

APPENDIX 1

Site Numbers Used In The Data Base

(Figure 1 & Table 1)



Appendix 1.

Fig 1: Distribution of sampling sites in Lake Joondalup. Site numbers as recorded in data base.

Appendix 1.

Table 1. Site numbers used in this report and corresponding original site numbers used in the computer-based data bank.

Site Numbers Used in this report	Original site numbers	Site Numbers Used in this Report	Original site numbers
1	10	37	4
2	25	38	14
3	26	39	64
4	9	40	65
5	27	41	66
6	32	42	67
7	28	43	13
8	8	44	68
9	23	45	24
10	18	46	2
11	29	47	3
12	19	48	84
13	31	49	85
14	30	50	81
15	33	51	86
16	40	52	87
17	41	53	83
18	42	54	20
19	5	55	82
20	12	56	88
21	11	57	7
22	45	58	89
23	44	59	99
24	43	60	98
25	46	61	97
26	17	62	94
27	47	63	96
28	16	64	95
29	15	65	W1
30	61	66	W2
31	60	67	W3
32	62	68	W4
33	63	69	W5
34	1	70	W6
35	21	71	W7
36	6	72	W8
		73	93

APPENDIX 2

pH Alkalinity and Optical Density Data

(Tables 1 to 10)

APPENDIX 2

Table 1: pH and alkalinity records for sites within the main waterbody of Lake Joondalup

Site	Date	ph	Total alkalinity	Phenolphthalein alkalinity
			(mg $CaCO_3$ l^{-1})	
19	25. 7.79	8.4	106	
	29.11.79	8.9	142	22
	14. 1.80	9.2	115	22
	19. 6.80	8.7		
	24. 7.80	8.3		
	21. 8.80	8.0		
34	25. 7.79	8.4	104	
	29.11.79	9.0	140	16
	14. 1.80	9.2	116	25
	19. 6.80	8.9		
	24. 7.80	8.2		
37	25. 7.79	7.5	116	
	29.11.79	8.6	174	6
	14. 1.80	9.3	132	30
	19. 6.80	8.6		
	24. 7.80	8.3		
	$\bar{x}$ ± S.E.	8.6 ± 0.12	127 ± 7.4	20 ± 3.4

Table 2: pH and alkalinity records for sites in the southernmost basin of Lake Joondalup

Site	Date	pH	Total alkalinity	Phenolphthalein alkalinity
			(mg $CaCO_3$ l^{-1})	
46	25. 7.79	7.6	124	
	29.11.79	8.5	170	4
	24. 7.80	8.0		
	21. 8.80	7.8		
47	25. 7.79	7.5	125	
	29.11.79	9.2	158	42
	24. 7.80	7.9		
54	29.11.79	9.0	162	36
	19. 6.80	7.7		
	24. 7.80	7.9		
	$\bar{x}$ ± S.E.	8.1 ± 0.19	148 ± 9.7	27.3 ± 11.8

Table 3: pH and alkalinity records for site 57, Beenyup Swamp and Lake Goollelal

Site	Date	pH	Total alkalinity	Phenolphthalein alkalinity
			(mg $CaCO_3$ l^{-1})	
57	25. 7.79	6.8	123	
	29.11.79	7.4	184	0
	19. 6.80	7.5		
	24. 7.80	7.8		
	21. 8.80	7.6		
59	25. 7.79	7.3	127	
	24. 7.80	7.8		
	21. 8.80	7.6		
(Beenyup swamp)	$\bar{x}$ ± S.E.	7.5 ± 0.11	145 ± 19.7	0
73	25. 7.79	7.3		
	24. 7.80	7.9		
	21. 8.80	7.7		
(Lake Goollelal).	$\bar{x}$ ± S.E.	7.6 ± 0.18		

Table 4: pH and alkalinity records for sites within Wallubuenup Swamp

Site	Date	pH	Total alkalinity	Phenolphthalein alkalinity
			(mg $CaCO_3$ l^{-1})	
68	25. 7.79	6.8	169	-
	21. 8.80	7.6	-	-
69	25. 7.79	7.3	244	-
	21. 8.80	7.6	-	-
70	25. 7.79	7.1	46	-
	21. 8.80	7.2	-	-
71	21. 8.80	7.1	-	-
72	21. 8.80	7.4	-	-
	$\bar{x}$ ± S.E.	7.3 ± 0.09	153 ± 57.7	-

Table 5: pH and alkalinity records for the stormwater sump on the eastern shore of Lake Joondalup

Site	Date	pH	Total alkalinity	Phenolphthalein alkalinity
			(mg $CaCO_3$ l^{-1})	
36	25. 7.79	8.4	96	-
	29.11.79	7.7	110	0
	19. 6.80	7.5	-	-
	24. 7.80	7.9	-	-
	$\bar{x}$ ± S.E.	7.9 ± 0.19	103	

Table 6: Optical density readings for sites within the main waterbody of Lake Joondalup

Site	Date	250	280	Wavelength (nm) 300	320	370	440	530
19	25. 7.79	-	-	0.261	-	-	0.044	-
	29.11.79[1]	-	-	-	-	-	0.017	0.004
	14. 1.80	-	-	0.231	-	0.074	0.035	-
	19. 6.80	-	-	-	-	0.057	0.030	-
	24. 7.80	-	-	-	0.131	0.061	0.026	0.017
	21. 8.80	0.498	0.344	0.234	-	0.071	0.029	0.016
	11.12.80[1]	-	-	-	0.139	0.055	0.016	0.005
34	25. 7.79	-	-	0.229	-	-	0.038	-
	29.11.79[1]	-	-	-	-	-	0.028	0.006
	19. 6.80	-	-	-	-	0.081	0.044	-
	24. 7.80	-	-	-	0.159	0.124	0.017	0.035
37	25. 7.79	-	-	0.279	-	-	0.042	-
	29.11.79[1]	-	-	-	-	-	0.022	0.006
	14. 1.80	-	-	0.287	-	0.098	0.048	-
	19. 6.80	-	-	-	-	0.124	0.075	-
	24. 7.80	-	-	-	0.209	0.111	0.055	0.040
	$\bar{x}$	-	-	0.254	0.160	0.086	0.035	0.016
	S.E.	-	-	0.011	0.018	0.008	0.004	0.005

Table 7: Optical density readings for sites in the southernmost basin of Lake Joondalup

				Wavelength (nm)				
Site	Date	250	280	300	320	370	440	530
46	25. 7.79	-	-	0.552	-	-	0.068	-
	29.11.79[1]	-	-	-	-	-	0.045	0.013
	24. 7.80	-	-	-	0.473	0.255	0.094	0.042
	21. 8.80	1.077	0.821	0.639	-	0.254	0.088	0.035
47	25. 7.79	-	-	0.922	-	-	0.153	-
	29.11.79[1]	-	-	-	-	-	0.048	0.014
	24. 7.80	-	-	-	0.492	0.260	0.095	0.043
	8.12.80	-	-	-	0.307	0.159	0.069	0.042
	11.12.80	-	-	-	0.296	0.129	0.038	0.011
54	25. 7.79	-	-	0.568	-	-	0.070	-
	29.11.79[1]	-	-	-	-	-	0.060	0.022
	19. 6.80	-	-	-	-	0.206	0.067	-
	24. 7.80	-	-	-	0.500	0.264	0.098	0.044
	8.12.80	-	-	-	0.305	0.148	0.056	0.028
	11.12.80[1]	-	-	-	0.278	0.121	0.035	0.011
	$\bar{x}$	-	-	0.670	0.379	0.200	0.072	0.028
	S.E.	-	-	0.086	0.039	0.020	0.008	0.004

Table 8: Optical density readings for site 57, Beenyup Swamp and Lake Goollelal

				Wavelength (nm)				
Site	Date	250	280	300	320	370	440	530
57	25. 7.79	-	-	0.972	-	-	0.121	-
	29.11.79[1]	-	-	-	-	-	0.072	0.022
	19. 6.80	-	-	-	-	0.303	0.103	-
	24. 7.80	-	-	-	0.742	0.414	0.165	0.076
	21. 8.80	1.350	1.046	0.835	-	0.340	0.124	0.054
	8.12.80	-	-	-	0.524	0.276	0.099	0.043
	11.12.80	-	-	-	0.535	0.274	0.097	0.039
	11.12.80[1]	-	-	-	0.465	0.226	0.074	0.027
59 (Beenyup Swamp)	25. 7.79	-	-	0.798	-	-	0.100	-
	24. 7.80	-	-	-	0.755	0.423	0.168	0.078
	21. 8.80	1.443	1.119	0.894	-	0.358	0.124	0.051
	11.12.80[1]	-	-	-	0.531	0.260	0.086	0.031
	$\bar{x}$	1.397	1.083	0.875	0.592	0.319	0.111	0.047
	S.E.	0.047	0.037	0.038	0.051	0.023	0.009	0.007
93 (Lake Goollelal)	25. 7.79	-	-	0.208	-	-	0.018	-
	24. 7.80	-	-	-	0.134	0.062	0.021	0.008
	21. 8.80	0.347	0.247	0.177	-	0.061	0.021	0.009
	$\bar{x}$	-	-	0.193	-	0.062	0.020	0.009
	S.E.	-	-	0.016	-	0.000	0.001	0.000

Table 9: Optical density readings for sites within Wallubuenup Swamp

Site	Date	Wavelength (nm) 250	280	300	370	440	530
68	25. 7.79	-	-	1.050	-	0.288	-
	21. 8.80	1.472	1.161	0.954	0.455	0.193	0.089
69	25. 7.79	-	-	1.100	-	0.311	-
	21. 8.80	0.901	0.717	0.575	0.272	0.124	0.064
70	25. 7.79	-	-	0.682	-	0.103	-
	21. 8.80	1.487	1.161	0.945	0.398	0.159	0.071
71	21. 8.80	1.752	1.388	1.154	0.502	0.216	0.105
72	21. 8.80	1.381	1.061	0.837	0.319	0.109	0.039
	$\bar{x}$	1.399	1.098	0.912	0.389	0.188	0.074
	S.E.	0.139	0.109	0.072	0.042	0.028	0.011

Table 10: Optical density readings for the stormwater sump on the eastern shore of Lake Joondalup

Site	Date	Wavelength (nm) 300	320	370	440	530
36	25. 7.79	0.085	-	-	0.008	-
	29.11.79[1]	-	-	-	0.023	0.001
	19. 6.80	-	-	0.017	0.007	-
	24. 7.80	-	0.065	0.033	0.014	0.008
	8.12.80	-	0.062	0.038	0.018	0.012
	11.12.80[1]	-	0.070	0.032	0.011	0.004
	$\bar{x}$	-	0.066	0.030	0.014	0.006
	S.E.	-	0.002	0.005	0.003	0.002

[1] These samples were filtered through a Whatman's GF/C filter before analysis

APPENDIX 3

Selected Isograms From Grid Studies

(Microfiche)