HYDROLOGY, NUTRIENT LOADING & PHYTOPLANKTON IN

LAKE JOONDALUP

by
R.A. Congdon

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HYDROLOGY, NUTRIENT LOADING AND PHYTOPLANKTON IN LAKE JOONDALUP : A FEASIBILITY STUDY

by : R. A. Congdon, Ph. D.,
Department of Botany,
University of Western Australia,
NEDLANDS W.A 6009

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Preface

Lake Joondalup is the focus for increasing urban development, with the establishment of the Joondalup Regional Centre of the Northwest Corridor, on the western shore of the lake (Stephenson, 1977). As development proceeds, the lake itself will be subjected to many changes which will affect the lake's catchment, the composition of its waters and bottom sediments, its fringing vegetation, its aquatic plants, and its birdlife and other fauna.

The lake will be required to serve diverse functions: to provide an attractive landscape, to provide recreation, to serve as a fauna reserve and to absorb catchment run-off. Unless correctly managed, nuisances such as insect pests, aquatic weeds and noxious odours may develop within the lake system.

In order to manage the area it is necessary to have information about the nature and sources of water in the lake, the levels of nutrients (particularly nitrogen and phosphorus) in the water, and the relationships between these nutrients and aquatic plants.

This information should ideally be obtained from a long-term monitoring programme carried out during development, so that changes can be observed as they occur. Before such a programme is undertaken, however, it is advisable to examine, in the short term, the feasibility of carrying out an ongoing study.

This report presents the results of a feasibility study, commenced on a part-time basis in September 1978 and expanded to a full-time study in January 1979.

1. Introduction

1.1 *General*

A sampling programme was commenced in September 1978 to obtain contemporary data to generate specific hypotheses (see below). This data, together with data collected by Congdon in 1973 and Finlayson and Gordon in 1975, has been punched onto computer cards. This facilitates statistical analysis of the data (correlations, regressions, etc.) and provides a data base for further work (e.g. modelling).

Discussions have been held with Mr D. Everall and Mr J. Singleton of the Metropolitan and Regional Planning Authority regarding proposed development in the area of the lake, Dr R. Black of W.A.I.T. regarding methods of measuring drain flow and evaporation, Dr P. Newman of Murdoch University regarding his proposed studies of the lake, and Dr F. Honey of CSIRO regarding the possibility of using LANDSAT satellite imagery to document changes in the lake.

Preliminary investigations have been made to determine the ease of sampling benthic macrophytes, to collect sediment nutrient data, to collect groundwater from beneath the lake, to measure blue-green algal N_2-fixation, to examine the feasibility of using laboratory nutrient enrichment culture techniques to examine phytoplankton-nutrient relationships, and to examine the feasibility of using aerial photographs to document the spread of *Typha orientalis* in the fringing plant communities.

Lake morphometrics have been determined from a depth contour map prepared by the Metropolitan Water Board on August 1, 1975 (Table 1.1; Figures 1.1, 1.2). These estimates have been used in nutrient and water budget calculations.

Shore development is the ratio of actual shoreline length to the length of circumference of a circle of equal area to the lake (Welch, 1948). It indicates increasing irregularity from circular form as it exceeds 1.0.

The direct volume curve exhibits certain structural relations of the lake basin (Figure 1.1). Shallow depths (less than 1 m) represent less than 20% of the lake volume, while more than 80% of the lake's volume is contributed by depths between 1.2 and 2 m.

The hypsographic curve also represents certain elements in the form of the lake basin (Welch, 1948) (Figure 1.2). It shows depth plotted against subsurface horizontal area. The extent of shallow water in a lake is a determining factor in the interrelationship between the zones of photosynthetic production and decomposition, as well as in determining the area available for

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

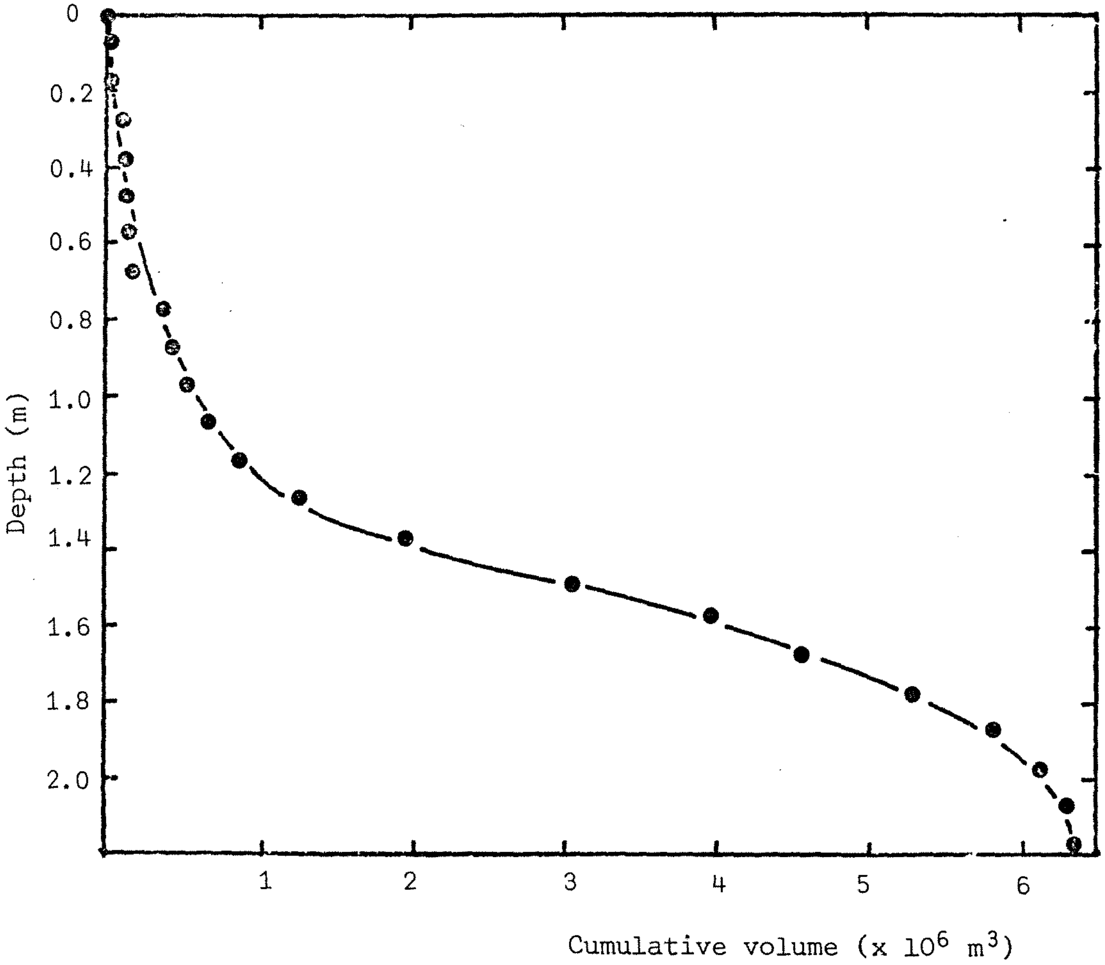


Fig. 1.1. The direct volume curve for Lake Joondalup

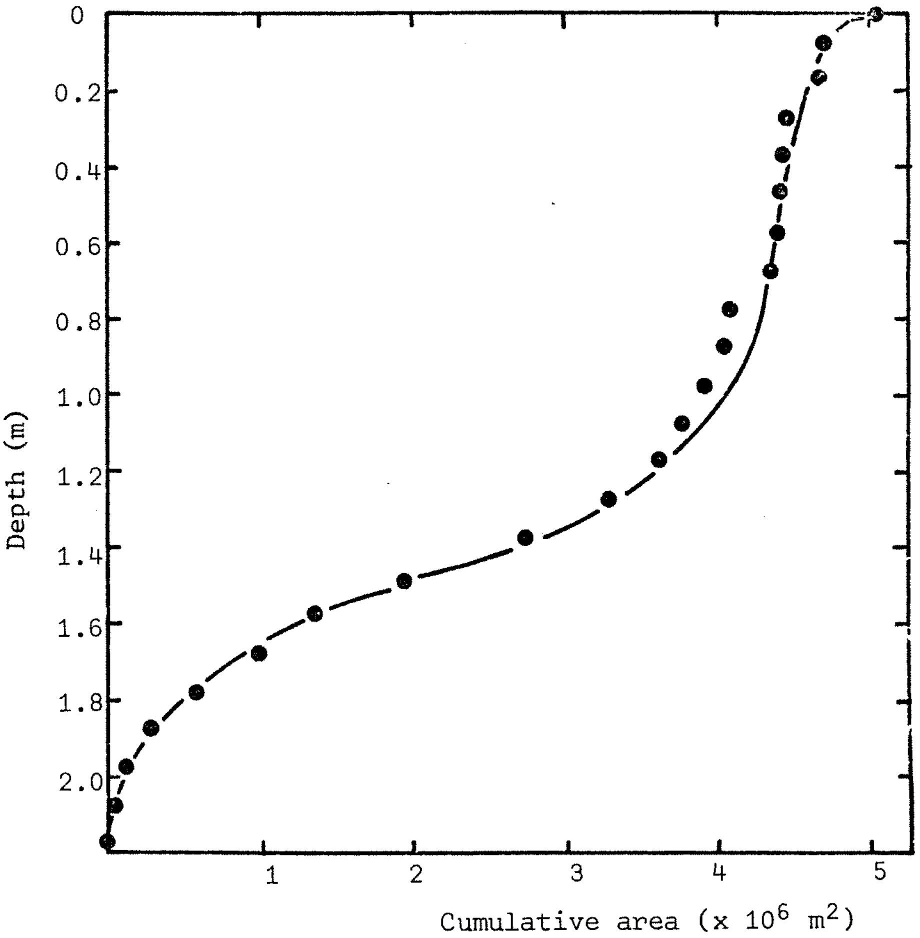


Fig. 1.2. The hypsographic curve for Lake Joondalup.

growth of rooted aquatic plants and associated littoral communities (Wetzel, 1975). The hysographic curve also allows the estimation of the area of lake bed exposed for a given fall in water level. The water level changed by about 1 m in 1973, and this represents some 20% of the area of the lake.

By international standards, Lake Joondalup is rich in nutrients and according to a number of criteria, it can be classed as eutrophic (Table 1.2).

Table 1.2

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) Lake Joondalup (Sept 1978 - Feb 1979)

	Total P	Inorganic N	Organic N	Chlorophyll
Range	12 - 1158	7 - 1889	1036 - 9422	1 - 541
Mean	226	133	2220	26

1.2 *Sampling programme*

Five sampling sites on the lake margin have been selected on the basis of their accessibility and likely interest. They have been sampled each week since mid-November 1978, but were also sampled in mid-September, mid-October and then fortnightly until mid-November.

Chlorophyll a and phaeophytin are determined to estimate the phytoplankton standing crop. Soluble reactive phosphorus, total phosphorus, ammonium-nitrogen, nitrate + nitrite nitrogen and organic nitrogen are measured to determine the nutrient status of the water. Chloride is determined to estimate the concentration of total dissolved salts, as a marker of lake evaporation and water sources (i.e. runoff and drainage contain lower chloride levels).

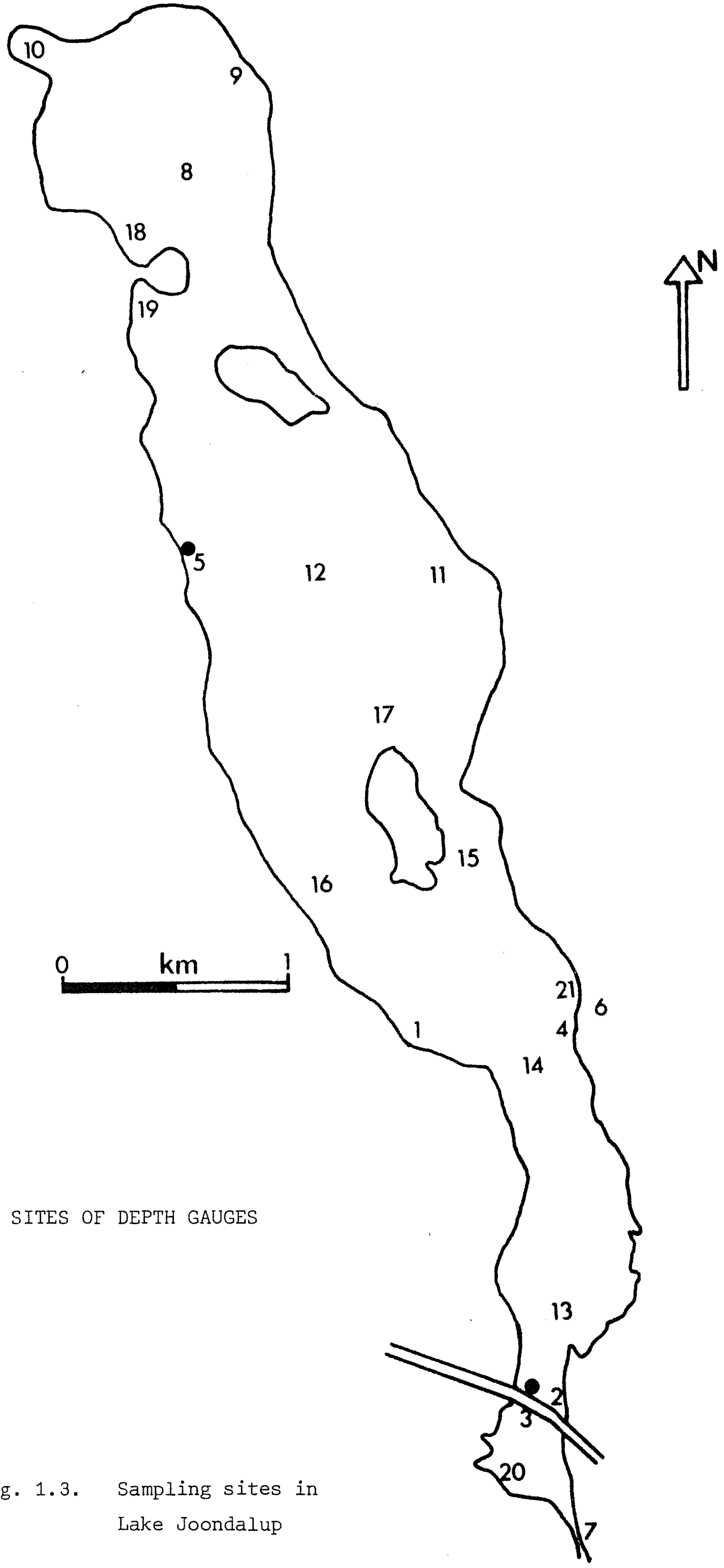
The five sites are shown in Figure 1.3 and described below. Site 1 is situated near Picnic Cove at Edgewater, in the proximity of recent urban development. A stormwater sump is located close by; this sump will be replaced by a stormwater drain discharging directly into the lake. The site will therefore also be convenient for sampling this drain. The site is situated beneath paperbark trees (*Melaleuca rhaphiophylla*), and decomposing litter and shading could produce effects different to those in more exposed positions (e.g. high nutrient levels, but perhaps with low phytoplankton), so it may be representative of the paperbark woodland fringing much of the lake.

Site 2 is situated on the northern side of the culvert running under Mullaloo Road. It is therefore convenient for documenting water flow and nutrient contributions from the south. At present the depth of the water in the culvert is determined each week (Figure 2.2) and it is hoped that the flows can be calculated from a discharge rating curve prepared at a later date (see section 2.1(b)). A depth gauge is located near site 2 and is read weekly.

Site 3 is located south of Mullaloo Road. This site has given some interesting readings of nutrient and phytoplankton levels (see below) and provides a useful gauge of inputs from the south.

Site 4 is at the end of Central Rd, on the eastern shore. It is an exposed site, prone to the build-up of algae on the shore due to the prevailing south-westerly winds. Nearby is site 6, a stormwater sump which discharges into the lake through a sandy channel. Samples taken here indicate the composition of stormwater entering the lake.

Site 5 is located on the western shore of the lake, and is approached by Quinlan Rd. It is an exposed site, and a depth gauge located there is read weekly.



● SITES OF DEPTH GAUGES

Fig. 1.3. Sampling sites in Lake Joondalup

A further 10 sites in Lake Joondalup have been sampled on a monthly basis since December 1978 where there has been sufficient water depth to approach them by boat. The marginal sites may not give a true indication of conditions in the centre of the lake, and the additional sites will allow this possibility to be examined. These sites were also chosen to include those used in 1973 (Congdon and McComb, 1976), to allow further comparison. Such a spread of sites provides for the possibility of using the Symap computer programme to examine the general distribution of factors within the lake, and how they differ seasonally (see Appendix 2).

Since January 1979, a water sample has been collected from Beenyup Swamp each month (Figure 1.4). As there seems to be a large nutrient input from this area, it is intended to sample it in great detail during the coming winter, when water flows are high and depth allows boating access. From this work it is hoped to establish the nutrient source and to document the input of water and nutrients into Lake Joondalup.

Three sites in Lake Goollelal have been sampled since November 1978. One of these sites, site 3, is now sampled on a regular monthly basis (Figure 1.4). This lake contains a large biomass of the water hyacinth (*Eichornia crassipes*), which is being sprayed with herbicide in an attempt to eradicate it. It will be interesting to see how the decay of this plant affects the nutrient status of the water. The water quality of Lake Goollelal is also of interest since water flows northwards to Lake Joondalup (see section 2.1 (b)).

Access to Wallubuenup Swamp has been examined. There appears to be little open water in the swamp, which is covered with emergent vegetation. No open water was accessible for sampling in November 1978. Surface water samples might be collected next winter for nutrient analysis. Groundwater could be collected using a groundwater probe (John *et al.*, 1977) and this may give some indication of nutrient sources for Lake Joondalup.

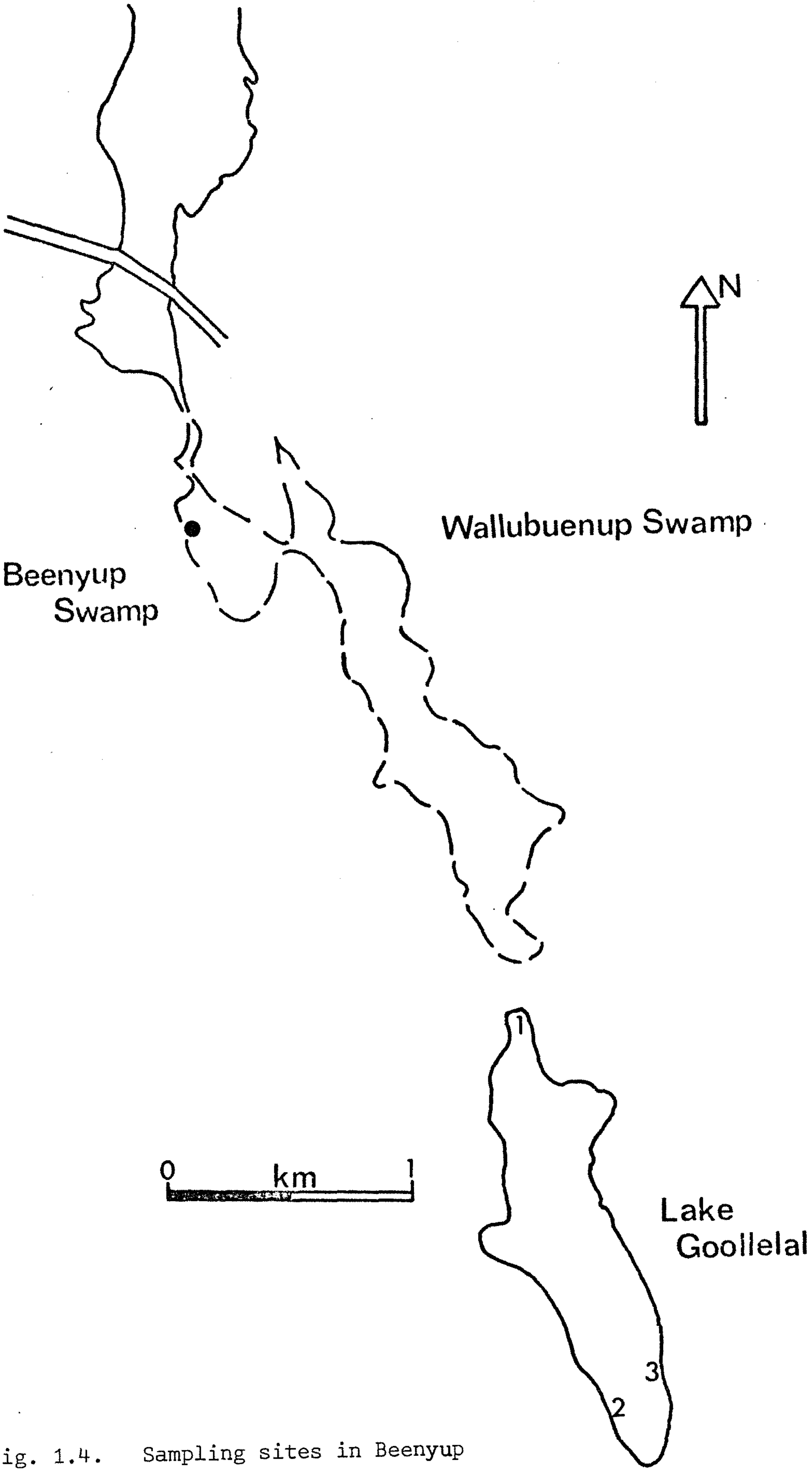


Fig. 1.4. Sampling sites in Beenyup Swamp (●) and Lake Goollelal.

2. Hydrological budget

2.1 *Introduction*

The hydrological budget of a lake can be summarised as:

$$S_i + P + GW_i = S_o + E + GW_o ,$$

where S_i = surface water inflow

P = precipitation

GW_i = groundwater inflow

S_o = surface water outflow

E = evaporation

GW_o = groundwater outflow.

Of these terms, groundwater exchange is most difficult to measure directly, and so it is usually calculated as the unknown in such an equation. Consequently, the budget may be re-expressed as:

$$\Delta S = S_i + P \pm GW - S_o - E ,$$

where ΔS = change in surface water storage, and

$\pm GW$ = net groundwater flow.

(a) Surface water storage:

Surface water storage varies considerably over a year (Figure 2.1). The change in surface water storage can be calculated from measurements of seasonal changes in lake depth and surface area when integrated with a bathymetric map. The Metropolitan Water Board prepared a bathymetric map of Lake Joondalup in August 1975. The volume of the lake has been calculated from this map, using the grid method described by Wood (1975) (Table 1.1). The method can be used to calculate volumes for different depth contours, and adjusted for changes in water level. Consequently, the change in surface water storage can be estimated.

Monthly readings of water level are taken at the lake by the Metropolitan Water Board. Water depth data were collected in 1973 and 1975 as part of botanical studies of the lake (Congdon and McComb, 1976; Finlayson, Gordon and McComb, in preparation). Water level data are being collected from two sites on a weekly basis as part of the current study (see Figure 2.2).

(b) Surface drainage:

Surface water flow is usually derived from continuous or frequent (daily) water level records and periodic measurements of discharge with a

Fig. 2.1(a). Water level at site 5 in April 1978

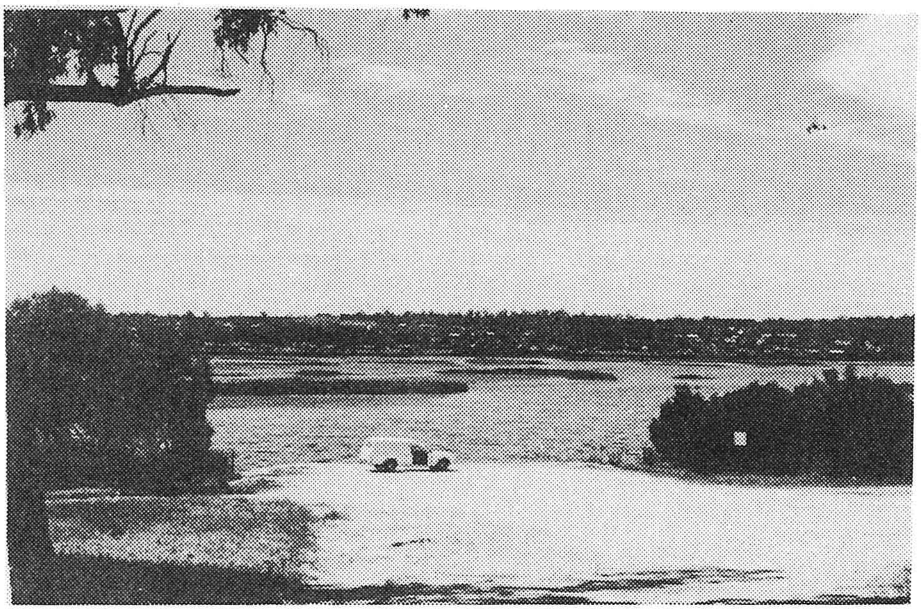


Fig. 2.1(b). Water level at site 5 in October 1978

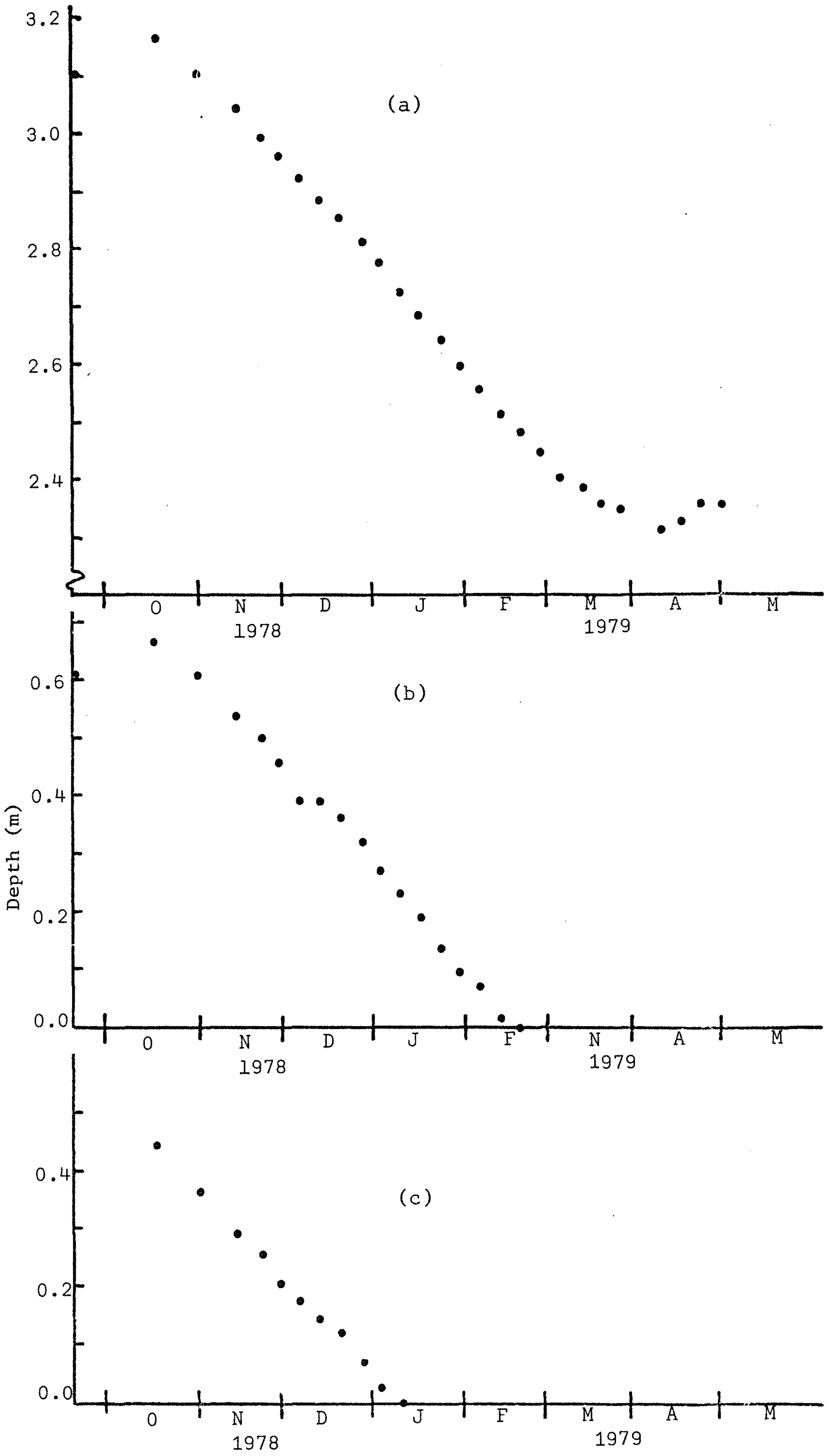


Fig. 2.2. Changes in water level at (a) site 5, (b) site 2, and (c) the Mullaloo Road culvert.

current meter (Bruce and Clark, 1966; Rosher and van den Berghe, 1977). The discharge measurements, when plotted against water level, give a discharge rating curve from which subsequent discharge figures can be calculated for a given water level.

Surface flow into Lake Joondalup appears to be restricted to flow from Beenyup and Wallubuenup Swamps to the south, and flow from storm drains. Lake Goollelal, to the south of Lake Joondalup, has a water level some 10 m above that at Joondalup (highest recorded water levels are 18.00 m for L. Joondalup and 27.60 m for L. Goollelal - M.W.B.), but is generally not connected by surface water to Wallubuenup and Beenyup Swamps. A groundwater gradient probably exists northwards, however. Beenyup Swamp flows into the southern end of Lake Joondalup when water levels are high, and this is connected to the lake proper by a culvert under Mullaloo Rd. The water depth in the culvert has been monitored since October 1978 (Figure 2.2 c).

At present the only storm drainage appears to be from a sump at the end of Central Rd, but all sumps on public open space will be replaced with simple drains, such as those planned for the estate at Edgewater.

(c) Rainfall:

The hydrologic input due to precipitation can be estimated from rainfall readings taken with a rain gauge in the lake's catchment.

Rainfall data are collected at Wanneroo for the Bureau of Meteorology (Figure 2.3).

(d) Evaporation:

A number of direct and indirect methods have been used for estimating lake evaporation (Bruce and Clark, 1966; World Meteorological Organization, 1966; Rosher and van den Berghe, 1977; Cheng Wan-Li, 1978). The simplest, cheapest reliable method relies on the measurement of evaporation with an evaporation pan and then a conversion to lake evaporation using a pan factor.

$$\text{Pan factor} = \frac{\text{lake evaporation}}{\text{pan evaporation}}$$

Pan factors derived from work on the hydrology of the Peel Inlet-Harvey Estuary system have been found to be reliable (Table 2.1, R. Black, pers. comm.). The nearest evaporation readings are taken by the Bureau of Meteorology at Perth (Figure 2.3) and can be used to give a rough estimate of lake evaporation (see below).

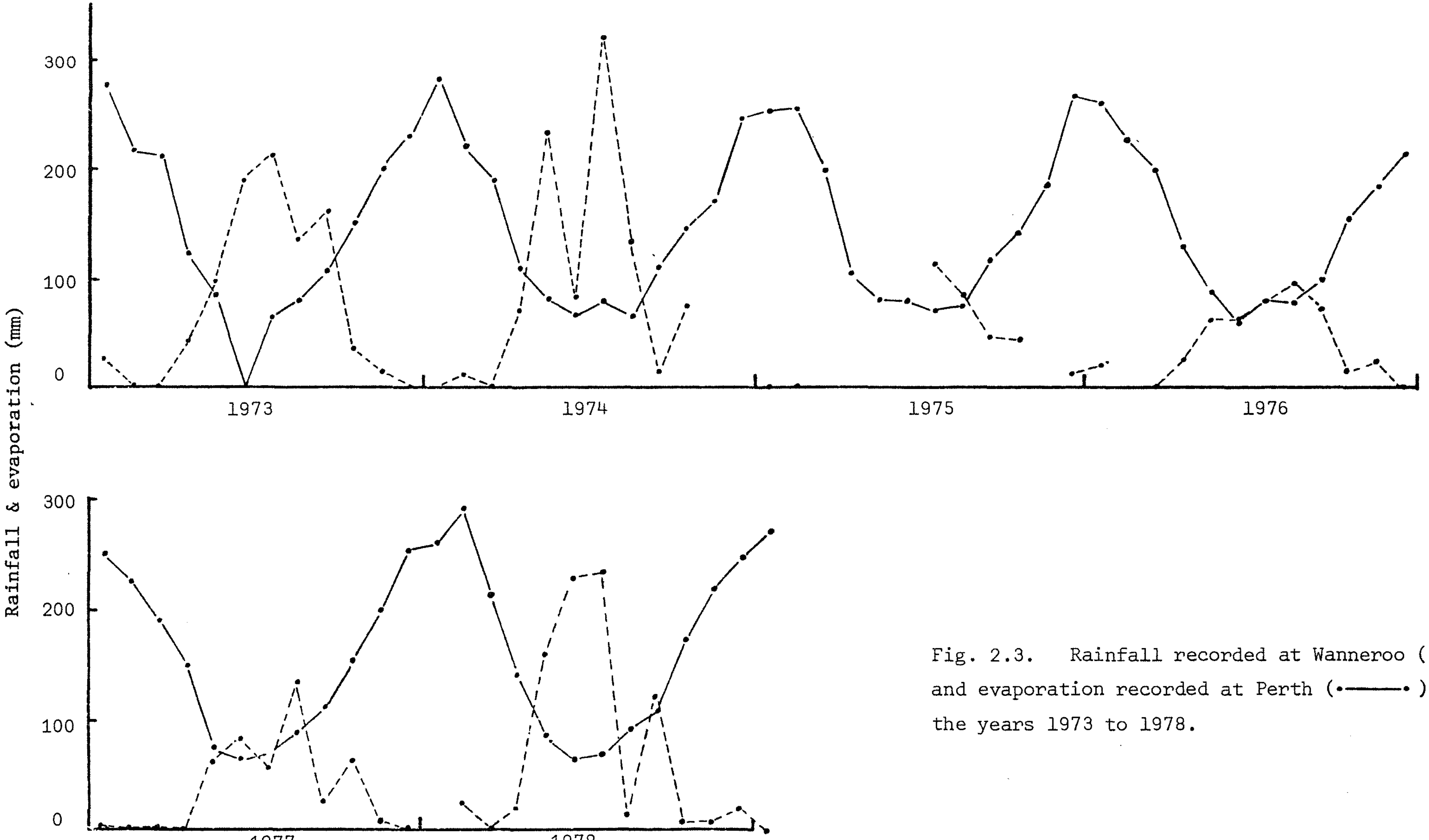


Fig. 2.3. Rainfall recorded at Wanneroo (•-------•) and evaporation recorded at Perth (•———•) for the years 1973 to 1978.

Table 2.1

Monthly lake-to-pan coefficients for the estimation of lake evaporation from class A pan evaporation (Ron Black, pers. comm., Department of Physics, W.A.I.T.)

January	0.6
February	0.6
March	0.7
April	0.9
May	1.0
June	1.0
July	1.0
August	0.9
September	0.9
October	0.8
November	0.8
December	0.7
Annual Average	0.8

(e) Groundwater:

Preliminary observations suggest that the contribution of groundwater to Lake Joondalup is very significant (see below).

Groundwater flows from east to west across the Swan Coastal Plain, with steep gradients to the east of linear lakes, such as Joondalup, and very low gradients to the west. The steep eastern gradients are possibly due to a reduction in transmissivity by lacustrine sediments, and the low western gradients to the high transmissivity of coastal limestone (Allen, 1976). Groundwater levels are generally highest in September-October and lowest in March-April, with a seasonal range of about 0.2 to 1.5 m. Geological Surveys of Western Australia drilled 23 bores in the Joondalup region between 1972 and 1975. Carbon (CSIRO seminar, 26th June 1978) found that there was a sympathy between lake water levels and groundwater levels in bore holes up to 100 m from some lakes.

Groundwater flux is difficult to quantify. Chloride, tritium and rhodamine WT have been used recently to trace groundwater flow (Allison and Hughes, 1978; Aulenbach *et al.*,1978). However, it would be very difficult to use such tracers to quantify groundwater exchange with a large linear lake such as Joondalup. The most useful tool for the examination of groundwater flux with a lake is probably the seepage meter (Lee, 1977; Downing and Peterka, 1978). This is a steel cylinder which covers 0.25 m^2 of lake bottom and collects inflowing groundwater in a heavy (0.05 mm thick) 4-litre translucent plastic bag.

It has been suggested that groundwater enters the lake through springs on the lake bottom. A number of relatively deep holes (to 2.2 m) occur around the lake margin, according to the M.W.B. depth contour map, and these may correspond with areas of increased seepage. This could be investigated by using a seepage meter to determine the rate of groundwater seepage compared with other areas. Chloride concentrations in these areas may also indicate the presence of groundwater.

There is evidence that groundwater becomes more saline as it passes beneath Lake Joondalup (Allen, 1976). Salinities of groundwater to the east of the lake are about 600 $mg.\,l^{-1}$, and to the west, about 800 $mg.\,l^{-1}$; compared with a salinity of approximately 1,200 $mg.\,l^{-1}$ in the lake water (Bestow, 1976).

(f) Surface outflow:

There is no evidence to suggest that surface outflow is significant. A rise in topography to the north of the lake prevents surface flow to swamps to the north. There is a cave on the western shore of the lake which was blasted and excavated in an attempt to control the lake level and allow market gardening on the rich lake sediments. However, this does not appear to have affected the lake level, although it may be a preferred path for infiltration into the groundwater flowing through the limestone when water levels are high.

2.2 *Preliminary observations*

The yearly evaporation from Lake Joondalup can be estimated by applying the pan factors given in Table 2.1 to evaporation readings taken in Perth (Figure 2.3). Comparing these annual evaporation estimates with the annual rainfall recorded at Wanneroo, we see that the amount of water evaporated from the lake surface always exceeds rainfall by some 50% (Table 2.2). Thus groundwater inflow, and possibly surface drainage, must make a significant contribution to the budget. This is further supported by a calculation for 1973, based on observed changes in lake depth (Table 2.3).

2.3 *Current research*

A class A evaporation pan has been constructed and will be installed on the western shore of the lake. This will provide a more accurate estimate of lake evaporation. A current meter will be used to obtain discharge rating curves for the Mullaloo Rd culvert and any drains established in the near future, once they begin flowing again. Drainage from channels without a regular cross section, such as the one draining the sump at the end of Central Rd, is difficult to monitor, but these will probably be replaced with concrete drains in the near future, and a simple V-notch weir may be installed in the meantime. Nonetheless, such drainage from small sumps may not be a significant factor in the budget.

Some attempt will be made to examine groundwater flow with seepage meters.

Chloride will be used to trace water from a number of sources. Water from the Central Rd sump and from south of Mullaloo Rd have lower chloride concentrations than water in the main lake body (Table 3.5). Inflowing groundwater may have a different chloride concentration to that of the water column (see section 2.1 (e) and Table 3.6), and this could be tested by examining the chloride content of water collected in a seepage meter. Consequently, chloride distribution patterns determined during grid studies might indicate the source and dispersion of water from different sources. The magnitude of any differences in concentration and the accuracy of the chloride determinations would determine whether this tool could be used to quantify water inputs.

Table 2.2

Comparison of estimated evaporation and rainfall for the Wanneroo area 1973-1978 (figures are in mm)

Year	Total evaporation (Perth)	Estimated lake evaporation	Rainfall (Wanneroo)	Deficit
1973	1735	1388	908	480
1974	1761	1409	937[1]	472
1975	1827	1462	- [1]	
1976	1764	1411	472[1]	939
1977	1831	1465	436	1029
1978	1968	1574	845[1]	729

[1] Wanneroo rainfall data for 1974, 1975, 1976 and 1978 are incomplete. No data are available for November and December 1974, March to June and November 1975, February 1976, and January 1978. However, little rain is expected for the summer months which were unrecorded and so data for 1974, 1976 and 1978 have been included in the analysis.

Table 2.3

Estimated hydrological budget for Lake Joondalup April to October 1973

Depth increase = 105 cm (Congdon and McComb 1976)
Rainfall (Wanneroo) = 866 mm
Evaporation (Perth) = 607 mm
Lake evaporation = 564 mm
Input from precipitation = 866 - 564 = 302 mm
Input from drainage and groundwater = 1050 - 302 = 748 mm

Thus rainfall appears to contribute $\leq$ 50% of the hydrological budget.

If the estimated lake evaporation is accurate, the drains and groundwater supply 71% of the input.

If the estimated lake evaporation is 25% too high then the drains and groundwater supply 58% of the input.

If the estimated lake evaporation is 25% too low then drains and groundwater supply 85% of the input.

2.4 *Further considerations*

Certain components of the hydrological budget will be altered as urban development increases in the region. Clearing of native vegetation will probably increase seepage into the lake, and the presence of submerged fence posts in the southern portion of the lake suggests that this began many years ago. The water level will also be increased by the concentration of run-off from roofs and roads into storm drains feeding into the lake. These two factors have resulted in a water level increase of 1 m at Star Swamp, North Beach, over the last 20 years (Burton, 1976). M.W.B. estimates anticipate a maximum water level of 20.58 m at Lake Joondalup, some 2.5 m above the present highest recorded water level, this will probably prolong flow from the south. Increased groundwater abstraction may also affect the hydrological budget, possibly private bores on the eastern shore having the greatest effect since this is the direction from which the groundwater flows. It has been estimated that pumping from M.W.B. bores may reduce water-table levels by 0.5 m at some 3 to 5 km away (Layton Ground Water Consultants, report reviewed in The West Australian, 21st March 1979) (The M.W.B. bores at Wanneroo are some 3 km from the lake). These effects on groundwater levels are antagonistic, and it is difficult to anticipate what will happen to water levels in the lake. However, in the long-term, it appears that there will be a net increase.

3. Nutrient budgets

3.1 *Introduction*

Nitrogen and phosphorus are generally considered to be the two main nutrients for consideration when examining aquatic productivity, because of the major essential elements, they are most commonly present in limiting amounts (carbon, hydrogen, sulphur and oxygen are usually abundant in natural systems). The two elements have different biogeochemical cycles in that nitrogen has a gaseous cycle whilst phosphorus has a sedimentary cycle. Consequently nutrient budgets for nitrogen and phosphorus can not be treated in the same manner.

3.2 *Nitrogen*

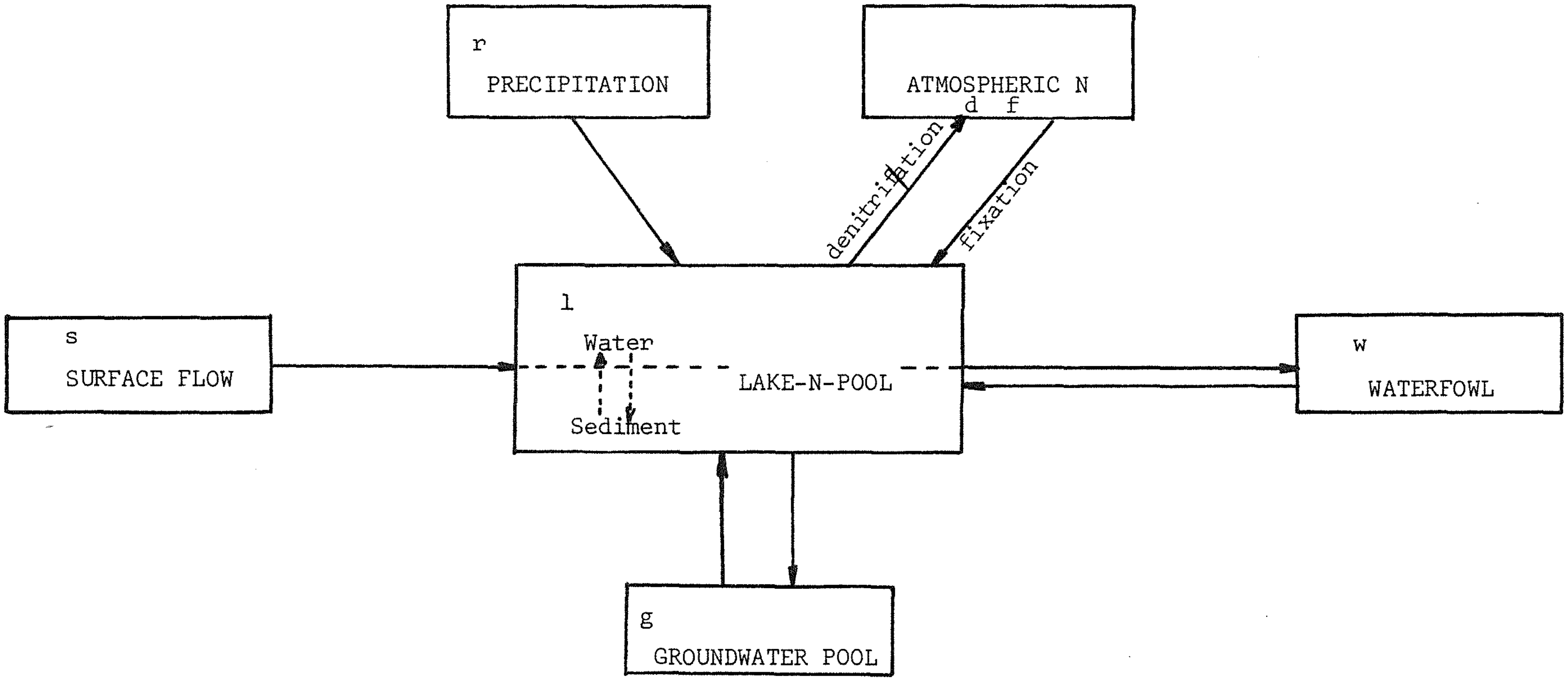
Nitrogen input to a lake can be provided by rainfall, biological fixation of atmospheric nitrogen, surface drainage, groundwater flow, and waterfowl migration (Figure 3.1). Nitrogen loss from a closed lake, such as Joondalup, would be by denitrification, groundwater flow, and waterfowl migration. This broad treatment includes the lake sediments as part of the lake and does not seek to include nitrogen exchange between the sediments and the water column. However, since the nutrient content of the water column is of principal interest, the rate of sedimentation of nitrogen is also of importance if the interaction between the nitrogen budget and algal productivity is to be examined.

A rough indication of the significance of a particular nitrogen input or loss may be gained by comparing it with the minimal pool of nitrogen found in the water column. During the present study the lowest total nitrogen concentration found at any site within the lake was 1.15 mg $N.1^{-1}$. The total volume of the lake would thus contain at least 7.35×10^3 kg N.

(a) Rainfall:

Accessions of nitrogen in rainfall at Nedlands have been measured by Drover and Barrett-Lennard (1956) (Table 3.1). The data are probably not very accurate, since the rain collectors were left for a month between collections, and mercuric chloride used as a preservative. It would be better to collect samples over as short a time as possible, during rainstorms, and to either do the determinations immediately, or rapidly freeze the samples for storage. Nevertheless, the data gives a useful indication of nitrogen accessions. O'Connell (CSIRO) recorded 0.7 kg N. ha^{-1}. yr^{-1} in rainfall at Dwellingup. 0.5 to 0.8 kg NO_3-N. ha^{-1}. yr^{-1} and 0.7 kg NH_4-N. ha^{-1}. yr^{-1} were recorded for Katherine in the Northern Territory, and 3.19 to 3.69 kg total N. ha^{-1}. yr^{-1} were recorded in South Australia

Figure 3.1 : Nitrogen exchange with a closed lake.



$$N_r + N_f + N_s + N_{gi} + N_{wi} = N_1 + N_d + N_{wo} + N_{go}$$

i = input, o = output.

Table 3.1

Accessions of nitrogen in rainfall, recorded at Nedlands W.A. (Drover & Barrett-Lennard, 1956)

Year	NH_3-N	NO_3-N	NO_2-N	Total N	Rainfall (mm)
	(kg.ha^{-1})				
1952	0.06	0.07	0.01	0.14	917
1953[1]	0.11	0.16	0.00	0.27	851
1954[1]	0.13	0.22	0.01	0.36	716
1955	0.46	0.21	0.01	0.68	1147
$\bar{x}$	0.19	0.17	0.01	0.37	908

[1] Some samples were excluded during these years because of contamination.

(Wood, 1975). It would thus appear that rainfall could supply of the order of 0.1 to 3.7 kg N. ha^{-1}. yr^{-1}. This amounts to 50 to 1865 kg N for the surface of Lake Joondalup, or 0.7 to 25.4% of the minimal estimate of the nitrogen in the water column. Thus, rainfall may be a significant input for nitrogen.

(b) Biological nitrogen fixation:

The nitrogen input due to biological nitrogen fixation is very difficult to quantify and would require an intensive study of fixation in different habitats and seasons. N_2 fixation in lakes occurs in the presence of certain blue-green algae, in sediments and the rhizospheres of aquatic angiosperms. Of these, the blue-green algae produce the higher rates of fixation (e.g. Finlayson and McComb, 1978). At present *Anabaena spiroides* is the only abundant species of blue-green alga recorded from Lake Joondalup, which can fix N_2. Consequently, rates of fixation achieved during blooms of this alga can be compared with other nitrogen sources for the lake, and the significance of N_2 fixation surmised.

The acetylene reduction method (Hardy *et al.*, 1968) is a convenient tool for monitoring N_2 fixation, although the conversion of acetylene fixed to the amount of nitrogen fixed is not simple. A wide range of conversion factors has been used (Hardy *et al.*, 1973) but it is possible to get an order of magnitude estimate of nitrogen fixed to see if it is significant compared with other inputs. The stoichiometric relationship between C_2H_2 reduced and N_2 fixed gives a theoretical conversion factor of 3. Conversion factors between 1.5 and 25 have been found, although the few reported for blue-green algae range between 2.8 and 3.6 (Hardy *et al.*, 1973).

It is possible to make a maximum estimate for N2 fixation by blue-green algae in Lake Joondalup, and compare it with the nitrogen pool of the water column. Assuming a conversion factor of 3 and an acetylene reduction rate of 1.5 nm. l^{-1}. min^{-1} (Table 3.2), we obtain a N_2 fixation rate of 7.56 x 10^{-6} mg N_2-N. l^{-1}. hr^{-1}. Fixation follows a diurnal pattern allied with photosynthesis, and so we can assume that daily fixation is given by the maximum rate over 12 hours, so that we have 9.07 x 10^{-5} mg N_2-N. l^{-1}. day^{-1}. The algal blooms appear to be near their peak for only a few weeks of the year, and so we will assume that the maximum rate over 3 months will give an overestimate of annual fixation. This gives 8.16 x 10^{-3} mg N_2-N. l^{-1}. yr^{-1} or 0.10 kg. ha^{-1} yr^{-1}. Now, assuming that this rate applied over the whole volume of the lake gives a reasonable maximum estimate of N2 fixation, we obtain a rate of 52.2 kg N2-N. yr^{-1}. We can now compare this with the nitrogen pool in the water column. Our maximum N_2 fixation estimate represents only 0.7% of our minimal estimate and so it appears that the input

Table 3.2

Rates of acetylene reduction obtained for Lake Joondalup water containing *Anabaena spiroides*

Month	Time	Site[3]	Phytoplankton standing stock (μg chloro./1)	Sample No.	Rate $\bar{x}$ ± S.E. (nm C_2H_2/1/min)	range
May 1975[1]	1200-1230		-		1.31 ± 0.11	
May 1975[1]	1300-1330		-		0.28 ± 0.06	
June 1975[1]	diurnal	LJ5	-		1.57 ± 0.08	
November 1978[2]	1200-1300	LJ2	46.7	6	1.90 ± 0.48	0.74-3.94
November 1978[2]	1200-1300	LJ3	1.90	6	1.17 ± 0.14	0.82-1.76
November 1978[2]	1200-1300	LJ2	3.32	2	1.69	1.65-1.72

Source: [1] Finlayson and McComb (1978)

[2] Congdon

[3] Sites are shown in Fig. 1.3

of nitrogen from this source to the total lake budget is not significant. Nitrogen fixation rates of 2.4 to 3.8 kg N. ha^{-1}. yr^{-1} have been recorded for two freshwater lakes in the United States (Hardy *et al.*, 1973). If the maximum rate were possible in Lake Joondalup 1,915 kg N. yr^{-1} would be produced, which is equivalent to 26% of the minimal estimated nitrogen pool in the water column. Under these circumstances nitrogen fixation would be a significant input to the system. We have not included N_2 fixation by bacteria in the sediments and rhizospheres of aquatic plants. 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}. Assuming that this rate over 12 hours approximates the daily rate, and that this is maintained for the whole year, we arrive at estimates of 0.25 μg N. g^{-1}. yr^{-1} for sediment fixation and 7.4 μg. g^{-1}. yr^{-1} for rhizosphere fixation. Further extrapolation to derive the total fixation for the lake from these sources is difficult, however. Assumptions have to be made as to the density of sediment, the depth of sediment involved and the biomass of aquatic plant roots within the lake. An extremely productive sedge swamp at Bremer Bay had about 1.2 kg. m^{-2} of below-ground biomass of *Baumea articulata* (Congdon and McComb, 1973). Assuming that this biomass is found over about 5% of the area of Lake Joondalup, we arrive at a figure of 3,000 kg of below-ground biomass for the lake. Thus we can estimate that rhizosphere fixation might supply a maximum of some 22 g of nitrogen per year, which represents only 0.0003% of our minimum estimated nitrogen pool in the water column.

If we assume that 1 cm^2 of sediment surface area represents 20 g of N_2 fixing sediment, we obtain 2.52 kg N_2-N fixed per year by sediment N_2 fixation, representing only 0.03% of the estimated minimum nitrogen pool.

These crude calculations suggest that the nitrogen contributed to the system by N_2 fixation is not significant. It may be locally significant however. The *Anabaena spiroides* blooms recorded in November and December were restricted to the southern end of Lake Joondalup. Water analyses show that the nitrogen content of the water increased following each bloom (Tables 3.3 and 3.4).

(c) Surface drainage:

Nitrogen is contributed to the lake from the south, through the Mullaloo Rd culvert, and from storm water. At present the only storm water input is from a sump at the end of Central Rd, but increased direct stormwater drainage is planned (see section 2.1 (b)). When these sites are monitored for current flow, water samples can be collected to give an estimate of nutrient input.

Table 3.3

Total nitrogen and phosphorus concentrations during and following blue-green algal blooms at site 3

Date	Chlorophyll a	Total N ($\mu g.l^{-1}$)	Total P	Ratio inorganic N/P	Ratio total N/P (atomic wt.)
14/11/78	433	-	-	-	-
23/11/78	2	1532	922	3.6	3.7
29/11/78	2	4836	707	6.8	15.6
6/12/78	13	3862	643	7.4	13.3
13/12/78	43	2387	342	4.9	15.9
20/12/78	18	1856	348	0.1	11.8
28/12/78	541	9422	888	-	24.3
3/ 1/79	28	4551	925	1.2	10.9
10/ 1/79	60	3856	1087	0.1	7.9
17/ 1/79	50	3945	1158	0.1	7.5
24/ 1/79	24	3215	930	0.04	7.9

Table 3.4

Total nitrogen and phosphorus concentrations before, during and after a blue-green algal bloom at site 2

Date	Chlorophyll a	Total N ($\mu g.l^{-1}$)	Total P	Ratio inorganic N/P	Total total N/P (atomic wt.)
19/ 9/78	2	1293	337	0.4	8.5
17/10/78	42	1163	334	0.1	7.7
1 /11/78	135	2049	214	1.8	21.2
14/11/78	47	1991	158	1.6	27.9
23/11/78[1]	3	1511	111	3.1	30.1
29/11/78	9	1962	118	4.2	36.8

[1] Prior to this date site 2 was connected to site 3 by a culvert. Water flow ceased before 23/11/78.

Most nutrients in storm water are added in the first rains after a dry spell (Cullen *et al.*, 1978), and so regular monitoring may give a significant underestimate of the nutrient contribution. Short-term studies, where storm water is monitored every 5 minutes or so, during a storm will give better resolution. This can become very time-consuming and expensive, in terms of time required for sample collection and analysis. Automatic samplers could be used for sample collection, provided an adequate preservation technique is used (possibly mercuric chloride).

The highest levels of nitrogen encountered in the present study occurred at site 3 indicating that a very significant nitrogen input may come from the south when there is flow (Table 3.5). Ammonia and nitrate levels have been up to ten times higher at site 3 than at any of the other sites in the lake, and organic nitrogen levels have been 25 to 50% higher. Site 6, in the drainage sump on the eastern shore, has provided low ammonia and organic nitrogen levels relative to the other sites, but nitrate levels have been quite high (Table 3.5). It would appear that stormwater drainage may supply significant amounts of nitrate. When flow rates are taken into account, quantities of other nutrients may also be significant.

(d) Groundwater flow:

Groundwater flow is very difficult to monitor (see section 2.1 (e)), and the nutrient contribution of groundwater would similarly be very difficult to quantify. Probably one of the most useful tools available is the seepage meter (Lee, 1977), which would give a rough estimate of the significance of the quantity of nitrogen contributed by this source. Care must be taken, however, since the seepage meter may impose anaerobic conditions which might increase nitrogen loss from the sediments.

Carbon (CSIRO Seminar, 26th June 1978) reported that total nitrogen concentrations in groundwater were variable, with levels up to 300 μg. 1^{-1}. He reported groundwater levels of 1,200 μg. 1^{-1} for Booragoon Lake and 1,870 μg for Blue Gum Lake.

The only significant nitrogen losses through leaching are as nitrate since ammonium-N is bound to soil cation exchange sites, and nitrate losses are greater in lighter sandy soils than in heavy clay types (Wood, 1975). Ammonium-N is most abundant under anaerobic conditions. Groundwater collected up to 1.5 m below the sediment surface in January 1979 contained up to 18 times the NO_3 and 96 times the NH_4-N present in the overlying water (Table 3.6).

Nitrate brought under the lake by groundwater flow is probably rapidly lost by denitrification or reduced to ammonium-N and held within the sediments. Sediment-water column exchange would then be the dominant factor in supplying nitrogen to the water column, rather than seepage of groundwater.

Table 3.5 Comparison of data collected from the six main sampling sites from September 1978 to February 1979 (Chloride as mg.1^{-1}; all others as μg.1^{-1})

Station		Chlorophyll a	Phaeophytin	PO$_4$-P	Organic P	NH$_4$ -N	NO$_3$-N	Organic N	Chloride
1	$\bar{x}$±S.E.	8.3±0.8	3.7±0.5	20±2	22± 6	51±10	8±2	1901±124	475±52
	n	19	19	19	19	19	19	19	17
	range	4.1-16.0	1.4-9.2	6-40	0-111	19-218	1-29	1036-2753	100-894
2	$\bar{x}$±S.E.	18.2±7.2	5.3±0.9	149±17	74±20	85±12	12±2	2032±119	464±55
	n	19	19	19	18	19	19	19	19
	range	1.5-135.0	0.9-17.4	60-293	0-154	10-183	4-35	1149-2935	108-964
3	$\bar{x}$±S.E.	79.9±37.7	18.9±7.8	595±44	196±31	373±149	49±28	3173±510	222±26
	n	17	17	15	15	15	14	15	15
	range	1.0-541.0	1.8-141.9	260-911	0-400	0-1864	2-383	456-9422	96-472
4	$\bar{x}$±S.E.	13.6±2.5	5.3±0.8	38±4	57±15	66±23	7±2	2010±136	435±41
	n	18	18	18	15	18	18	18	17
	range	4.0-43.4	1.4-12.9	18-65	15-246	5-371	1-31	1240-3138	217-666
5	$\bar{x}$±S.E.	10.9±3.0	3.1±0.5	18±2	26±8	69±13	7±2	1986±123	429±49
	n	18	18	19	19	19	19	19	19
	range	0.6-58.5	0.5-8.6	4-29	0-142	15-206	1-39	933-3029	91-874
6	$\bar{x}$±S.E.	10.9±1.4	4.0±0.4	23±3	34±11	22±3	28±15	790±43	139±13
	n	17	17	18	18	18	18	18	17
	range	1.3-19.8	0.6-8.0	9-43	0-151	7-47	1-240	504-1056	20-211

Table 3.6 A comparison of nutrients in groundwater[1] with that in the overlying water (17/1/1979) (N and P as $\mu g.l^{-1}$, Cl as $mg.l^{-1}$)

Site	Sample	Depth	PO_4	Org. P.	NH_4	NO_3	Cl
4	Surface water	-	53	41	17	2	538
	Groundwater	1.5m	-	-	-	36	163
	Groundwater	2	-	-	-	-	166
5	Surface water	-	28	0	40	3	577
	Groundwater	0.5	50	-	3832	20	353
	Groundwater	0.3	80	29	1096	14	421

[1] Samples were obtained with the groundwater probe described by John *et al.* (1977).

(e) Waterfowl migration:

Wood (1975) estimates that a wild duck may contribute 0.24 to 0.48 kg N. $duck^{-1}$. yr^{-1}. Brandvold *et al.* (1976) found that populations of 46,000 to 48,000 waterfowl, resident in a river system for 3 months, increased the amounts of nitrogen and available phosphorus. However, these increases were relatively small.

Waterfowl usage of Lake Joondalup is greatest over summer months when water levels are decreasing and algal blooms are most prominent. The lake has a peak waterfowl population of about 3,500, with 500 permanently resident (H. Bekle, pers. comm.). Assuming that the migrant population resided on the lake for 6 months on average, the annual nitrogen contribution of the waterfowl would be 960 kg. Their main effect, however, would be in recycling nutrients within the lake system - converting organic forms to inorganic forms in wastes, and removing nutrients as increased body weight when they migrate elsewhere.

The effect of waterfowl on the nutrient budgets of the lake is probably not very significant when compared with the nutrient content of the water column plus sediment.

(f) Denitrification:

Under anaerobic conditions present in the sediments or in micro-environments, nitrate can be reduced to N_2 gas and lost from the system ($NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$), or it can be reduced to ammonium-nitrogen, converted to organic forms and recycled.

It is very difficult to measure denitrification. One promising technique involves the use of ^{15}N-tracer and acetylene (Sørensen, 1978a). The acetylene inhibits the reduction of N_2O to N_2, and N_2O is readily measured by gas chromatography. However, this 'acetylene blockage technique' apparently does not work under all conditions and needs to be tested (W.J. Wiebe, pers. comm.). Sources of error include nitrifying bacteria which may produce N_2O, and N_2-fixing species which may reduce N_2O (Sørensen, 1978b).

To gain an accurate quantitative estimate of denitrification in a large lake over a year would be very difficult, but a crude estimate may serve to show the significance of the process in a particular water body.

Denitrification can make a considerable contribution to the nitrogen budget of a lake. Andersen (1974) found that it accounted for 0 to 54% of the total nitrogen loading in 6 shallow Danish lakes. Koike and Hattori (1978) have shown that reduction to ammonium may be important in coastal sediments off Japan, while Sørensen (1978a) suggests that both reduction to ammonium and to $N_2$are equally significant in the turnover of nitrate in coastal marine sediments. Denitrification in a freshwater canal was examined by van Kessel (1976) who found that reduction to N_2 was more significant than to NH_4, and that denitrification became fairly constant when dissolved oxygen exceeded 1.5 mg/l.

Vollenweider (1971) estimated denitrification to be 1 to 20 g N. m^{-2}. yr^{-1} for 6 Swiss lakes, while Jørgensen *et al.* (1973) obtained an estimate of about 20 g N. m^{-2}. yr^{-1} for a productive, small shallow Danish lake. If denitrification was of the order of 20 g N. m^{-2}. yr^{-1} for Lake Joondalup, the whole lake would account for a loss of some 1008 kg N. yr^{-1}. This is 14% of our minimal water column nitrogen estimate. In fact the rate of denitrification in Lake Joondalup could be much higher due to the absence of really cold winters. Consequently it appears that denitrification could make a large contribution to the lake's nitrogen budget.

Andersen (1974) recorded denitrification amounting to up to 47 g N. m^{-2}. yr^{-1}. Such a rate would amount to 32% of the minimal water column value for Lake Joondalup. It should be noted that these estimates of denitrification in European lakes have been derived as unknowns in nitrogen budget calculations, and that the inherent errors could be significant. For instance, if groundwater contributions have been ignored in the calculations and they are significant, then the denitrification figure could be a significant overestimate.

Andersen (1974) notes that in shallow unstratified lakes, wind action can suspend the surface sediments allowing nitrate to be added to the interstitial water from the overlying water, and also allowing the oxidation of nitrogen compounds in the well oxygenated surface sediments to nitrate. These shifts in oxidizing-reducing conditions would be favourable to denitrification.

(g) The lake nitrogen pool:

The nitrogen content of the water column can be estimated by partitioning the lake into a number of compartments, integrating measured concentrations over the volume of each compartment, and summing to get a total mass. Figure 3.2 presents a possible partitioning scheme for Lake Joondalup. This approach allows the flux between compartments to be integrated into the model, if flows are known.

The nitrogen content of the sediment can be analysed to a specified depth (of active sediment), calculated per unit area, and summed to obtain a total for the lake.

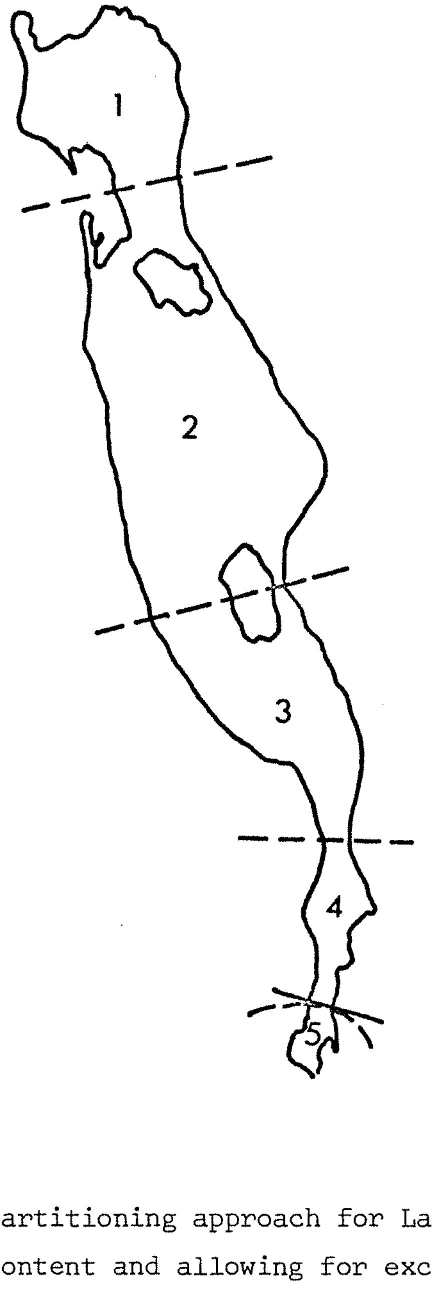


Fig. 3.2. A possible partitioning approach for Lake Joondalup, for summing total nutrient content and allowing for exchange between compartments.

The choice of time-step for such an approach is important; longer time-steps may allow sediment-water flux to be ignored but may result in larger errors due to variation in nitrogen concentrations in the water from week to week. In view of the need for samples to be taken over a wide area of the lake to give a reasonable estimate for each compartment, a monthly time-step may be appropriate.

Another approach for estimating the nitrogen pool in the lake involves the use of the Symap computer programme (see Appendix 2). The programme maps the distribution of nitrogen in the lake, on a running mean basis, and can be used for water column or sediment data. The areas for each nitrogen concentration range can then be calculated and summed to give a total nitrogen content for the lake.

(h) Conclusions:

In considering our nitrogen budget equation (Figure 3.1) it appears that N_2- fixation, waterfowl migration and possibly groundwater exchange do not have a significant effect. The data available at present suggest that N_2-fixation would account for less than 0.7% of the pool of nitrogen in the water column.

Rainfall may contribute of the order of 1 to 25% of the minimal nitrogen pool, while denitrification may release 30 to 55% of this pool. No estimates can be made of the contributions of surface drainage or groundwater exchange. Direct measurement of the inputs due to rainfall and surface drainage will clarify their significance. The use of a seepage meter may indicate the significance of groundwater exchange. Denitrification is probably best estimated as an unknown in the equation, as an intense study would be necessary to quantify its contribution.

The nitrogen budget can probably be simplified to:

$$N_r + N_s + N_{gi} = N_l + N_d + N_{go}$$

where r = rainfall, s = surface drainage, gi = groundwater inflow, l = lake N pool, d = denitrification, and go = groundwater outflow.

3.3 *Phosphorus*

Recently an extensive analysis of the phosphorus budget of Lake Burley Griffin was performed by Cullen *et al.* (1978). This provides an extensive literature review on the subject, and is a useful model for attempts to document other lake phosphorus budgets. Among their suggestions for future studies, they state that nutrient budgets should be constructed over at least 5 years to cope with seasonal variability in rainfall; that sampling must be based on runoff patterns rather than a set time interval; and that internal cycling of phosphorus within the lake needs consideration (particularly the release of phosphorus from sediments under various conditions).

Sources of phosphorus for Lake Joondalup are rainfall, surface drainage, groundwater flow, and waterfowl influx (Figure 3.3). Phosphorus loss would be by waterfowl egress or groundwater flow. Lakes with hydraulic retention (residence) times of many months tend to be very efficient phosphorus traps. Schaffner and Oglesby (1978) state that lakes with a hydraulic retention time of years retain 75 to 95% of the phosphorus input, while those with retention times of a few months retain 30 to 40% of the input. Lee *et al.* (1978) state that lakes with a hydraulic residence time of more than a few months incorporate 80 to 90% of phosphorus input into their sediments. Since there is no surface flow from Lake Joondalup, its hydraulic residence time is probably in excess of a few months.

(a) Rainfall:

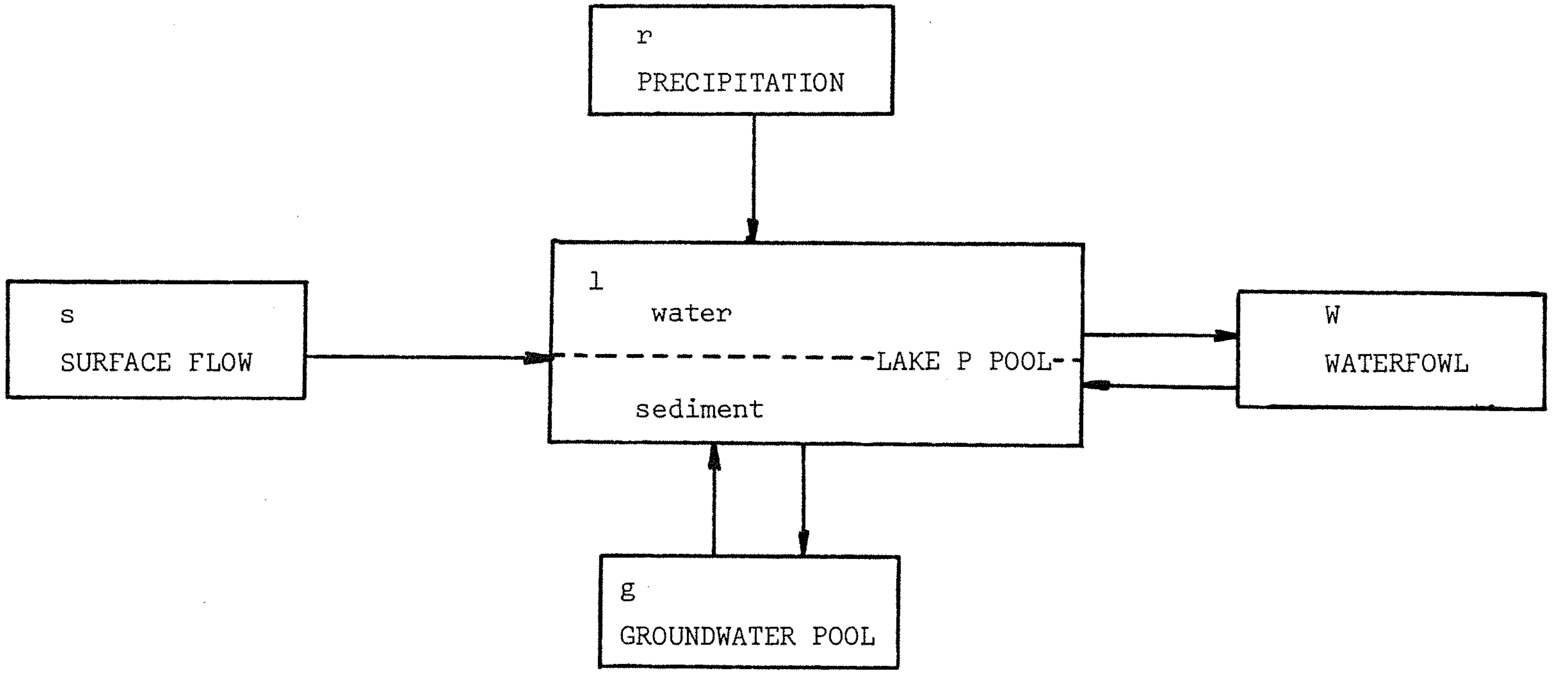
The atmospheric supply of phosphorus to a lake can be substantial, particularly if the lake's area is large relative to the catchment area (Cullen *et al.*, 1978). Total phosphorus concentrations in rainfall may range from 7 to 80 mg P. m^{-3}, the lower value being recorded in the Canberra region (Cullen *et al.*, 1978). 0.12 to 0.14 kg P. ha^{-1}. yr^{-1} has been recorded in South Australia (Wood, 1975), and 0.15 kg P. ha^{-1}. yr^{-1} for Dwellingup (A.M. O'Connell, CSIRO). If the latter figure is applied to Lake Joondalup, rainfall could contribute 75.6 kg P. yr^{-1}. The range of 7 to 80 mg P. m^{-3} is equivalent to 0.64 to 7.2 kg P. ha^{-1}. yr^{-1} for an annual rainfall of 900 mm. This gives an estimated range of 320 to 3,630 kg P for the area of Lake Joondalup.

The lowest concentration of total phosphorus recorded for Lake Joondalup in the present study is 12 µg P. l^{-1}. This gives a minimal estimate of 76.74 kg P for the water column. Consequently the contribution of phosphorus to the lake in rainfall can be very significant.

(b) Surface drainage:

Phosphorus in urban runoff is high relative to other land-use sources but is also very variable diurnally and seasonally, so requiring fairly extensive sampling programmes (Schaffner and Oglesby, 1978). Organic phosphorus is very susceptible to erosion into surface waters, and significant quantities of dissolved phosphorus can be contributed during storms. The literature review of Cullen *et al.* (1978) shows that many workers have demonstrated that high nutrient loads can come from runoff. Samples taken

Figure 3.3: Phosphorus exchange with a closed lake



$P_r + P_s + P_{gi} + P_{wi} = P_l + P_{wo} + P_{go}$ i = input, o = output.

every 5 minutes gave a peak phosphorus concentration of 1,200 μg P. l^{-1}, from a catchment of 50 ha during a storm of 91 mm of rain following a 2 week dry period (Kluesner and Lee, 1974). This study showed that nutrient and suspended solid concentrations were usually greatest during the early stages of the runoff event, decreasing with time, and that phosphorus generally resulted from accumulated litter and possibly automotive exhaust discharged to the streets. A peak phosphorus concentration obtained for Canberra runoff was 600 μg.l^{-1}, while a mean concentration of up to 2,950 μg.l^{-1} has been obtained in an urban area in Sydney (Cullen *et al.*, 1978). During their Canberra study, these authors found that 69% of the total phosphorus load was contributed during only 9% of the time (storms).

Surface flow into Lake Joondalup at present is restricted to flow from a sump at the end of Central Rd, and through a culvert from the south. From September 1978 to January 1979 total phosphorus concentrations in the Central Rd sump have varied from 17 to 172 μg P.l^{-1}, but the contribution to the lake cannot be estimated until flow rates are known. The southern end of the lake has had 348 to 1,158 μg P.l^{-1} in the same period, suggesting that a substantial input of phosphorus may come from the south. The highest levels of reactive orthophosphate and organic phosphorus obtained during the present study have been at site 3 (Table 3.5). Concentrations of these phosphorus forms at site 6, in the Central Rd sump, have been comparable to those found elsewhere in the lake.

(c) Groundwater flow:

There is evidence that groundwater may supply large amounts of phosphorus, depending on the geochemistry of an area (Schaffner and Oglesby, 1978). The contribution of phosphorus from septic tanks varies with the soil type, vegetation cover, groundwater depth, system design, maintenance and loading, and Schaffner and Oglesby (1978) estimated that 0.75 kg P. capita $^{-1}$. yr^{-1} reached a lake in New York. Phosphate is leached less readily than nitrate since it is adsorbed onto soil particles and organic matter, although phosphorus compounds in animal wastes are not readily adsorbed and might lead to enrichment of water (Wood, 1975). Wood also reports that septic tanks can cause problems if there is more than one family per acre, and each tank could supply 1 to 2.4 kg N and 0.01 to 0.1 kg P. yr^{-1}. In reviewing the literature, Cullen *et al.* (1978) found that leaching of phosphorus may only be substantial in acid sandy soils, and so they ignored it in their phosphorus budget. Carbon (CSIRO Seminar, 26th June 1978) reported that phosphate levels in local groundwater were very low, of the order of 100 μg. l^{-1}, with a reading of 340 μg. l^{-1} being recorded for groundwater near Booragoon Lake. However, he emphasised the role of the lake bed in controlling nutrient exchange between the groundwater and lake water.

Groundwater collected 0.3 to 0.5 m below the sediment surface in January 1979 contained up to nearly 3 times the concentration of phosphate present in the overlying water (Table 3.6). Nevertheless, it appears that groundwater may not contribute a significant amount of phosphorus to the lake P budget, although the influence of the lake sediments is undoubtedly very important. The seepage meter is probably a useful tool to investigate groundwater - sediment seepage flux.

(d) Waterfowl migration:

Wood (1975) estimates that a wild duck may contribute 0.05 to 0.09 kg P. yr^{-1}.

The discussion pertaining to the role of waterfowl in the nitrogen budget is relevant here. It would appear that they would not make a significant contribution to the budget.

(d) The phosphorus pool in the lake:

The discussion pertaining to the nitrogen pool in the lake is relevant here (see Section 3.2 (g)).

(f) Conclusions:

Of the terms in our theoretical phosphorus budget equation, it appears that waterfowl migration and groundwater exchange may not be significant. Rainfall may be very significant, accounting for 100 to 500% of our minimal phosphorus pool in the water column. The literature suggests that the input of phosphorus in storm water can be very significant. The directly discharging stormwater drains planned for Lake Joondalup contain sediment traps, but these may not trap fine particulate matter, known to contain large amounts of phosphorus, particularly when flow rates are high. A detailed documentation of this phosphorus source would be of great value.

While it would be useful to obtain more groundwater data, the budget equation can probably be simplified to:

$$P_r + P_s = P_l$$

where r = rainfall,
s = surface inflow,
l = lake phosphorus pool.

3.4 *Exchange of nutrients between sediment and water*

We have considered the lake nutrient pool to include the sediments and have not considered sediment-water interactions other than groundwater seepage. However, the sediment has a large role to play in determining the actual concentrations of nutrients in the water column, and it is these nutrients that control phytoplankton production. There is a very extensive literature pertaining to sediment-water interactions and a review of this is not attempted here. However, some of the main considerations are examined.

(a) Nitrogen:

Sediments are an important nitrogen sink (Table 3.7) and do not normally release much to overlying waters under aerobic conditions (Brezonik, 1972; Keeney, 1973). Undisturbed sediments lose only about one-third of the total soluble nitrogen present in the interstitial water. NH_4-N is generally the most abundant form of inorganic nitrogen in interstitial water (see Table 3.6), and its concentration may exceed that in the overlying water by more than a hundred-fold. This NH_4-N is produced from excretion and bacterial deamination, and its concentration has been shown to increase with sediment depth (Goering, 1972). Rowe *et al.*(1975) have shown that NH_4-N is released from marine sediments under a range of oxygen concentrations through sediment respiration, and sufficient nitrogen is made available to satisfy observed algal populations.

Denitrification occurs under anoxic conditions, and also NH_4-N is released at a low but fairly constant rate from sediments under anoxic waters (Austin and Lee, 1973). Under aerobic conditions, nitrification occurs, nitrifying bacteria convert NH_4 to NO_3 which can diffuse from the sediments to the overlying water (Mortimer, 1941, 1942, 1971; Goering, 1972; Graetz *et al.*, 1973).

Flooded swamp and marsh soils have a high capacity for removal of nitrate from overlying water (Lee *et al.*, 1975; Engler *et al.*, 1976). The mechanism is dependent on the nitrate being absorbed into the anaerobic layer, although nitrate loss is not inhibited by the presence of a small amount of molecular oxygen.

(b) Phosphorus:

Cullen *et al.* (1978) review the role and nature of phosphorus in lake sediments.

Sediments generally contain a large pool of phosphorus (Table 3.7). (It may be present in dissolved form in the interstitial water, as organic matter, adsorbed on hydrous ferric oxides, adsorbed on clay minerals, and as

Table 3.7

Chemical analysis of lake sediments collected during December 1978 (7th and 13th)

Site	Sediment	Organic matter (%)	Carbonate (%)	Total nitrogen		Total phosphorus	
				(mg/g)	(%)	(mg/g DW)	(%)
8	surface	32.8	14.7	11.1	1.1	0.20	0.02
	15- cm	34.1	12.6	11.1	1.1	0.21	0.02
9	surface	54.9	6.0	11.8	1.2	0.30	0.03
	anaerobic	40.6	9.7	11.8	1.2	0.15	0.02
10	surface	61.0	1.2	21.5	2.1	0.46	0.05
11	surface	46.1	7.5	9.9	1.0	0.17	0.02
12	surface	20.5	17.5	6.5	0.6	0.15	0.02
13	surface	49.3	2.9	18.8	1.9	0.97	0.10
14	surface	55.0	7.2	15.9	1.6	0.85	0.09
15	surface	65.7	3.8	17.5	1.8	0.31	0.03
16	surface	22.8	17.9	9.6	1.0	0.23	0.02
17	surface	18.5	19.2	8.0	0.8	0.16	0.02
$\bar{x}$		42.8	10.0	12.8		0.35	
S.E.		4.6	1.8	1.3		0.02	

minerals such as various forms of apatite (Mortimer, 1941, 1971; Syers *et al.*, 1973; Hallberg *et al.*, 1977).

Release of sediment phosphorus to the overlying water can occur through resuspension of particulate forms or transport of dissolved forms through turbulent mixing and diffusion. There is much evidence that sediments buffer the concentration of orthophosphate in the overlying water, as the interstitial water is in saturation equilibrium with the inorganic phosphorus phases (Rochford, 1951; Pomeroy *et al.*, 1965; Stumm and Stumm-Zollinger, 1972). So release of dissolved phosphorus to the overlying water can occur if the concentration of interstitial dissolved P exceeds that in the lake water. Radiotracer experiments with ^{32}P have shown that exchange takes place even where the lake waters are aerobic, and a constant concentration of phosphate in the water overlying a sediment need not mean that no exchange is taking place. Turnover times ranging from 2 to 22 days have been found for sediment P. Lean *et al.* (1975, 1976) showed release rates as high as 18 mg P. m^{-2}. day^{-1} even though the water column was neither stratified nor deoxygenated. Furthermore, even in the situation where there was no net movement of P from or to the sediments the flux to the sediments was measured as 7.69 mg P. m^{-2}. day^{-1}.

Andersen (1974) found a very pronounced liberation of orthophosphate from the sediment of Danish lakes in summer and attributed this to a change in the redox conditions. In shallow, non-stratified lakes with good oxygen conditions in the water an oxidized sediment surface is usually found. This oxidized zone can be broken down, if the oxygen consumption of sedimented plankton exceeds the oxygen transfer to the sediment of the overlying water. Andersen (1974) also concluded that wind-induced stirring of the surface sediments increased the release of phosphorus by reducing the diffusion distance.

Anaerobic soils have been shown to buffer phosphate concentrations in soil solutions better than aerobic soils (Patrick and Khalid, 1974). The ability of silts to adsorb phosphate is proportional to the amounts of Fe and organic matter present. Organic matter depresses phosphate adsorption, whilst silts can adsorb 80 to 90% of phosphate in solutions of 0.55 to 2.55 mg P. l^{-1} (Jitts, 1959).

Phosphate exchange between sediments and water can also occur by microbial uptake (Pomeroy *et al.*, 1965). Most exchange occurs by adsorption onto clay minerals in undisturbed sediments and the biological exchange is trivial. In suspended sediments, however, the microbial activity is as important as clay mineral adsorption. By incorporating orthophosphate into organic compounds that do not participate directly in the solubility equilibria, bacteria would tend to increase the concentration of soluble phosphorus in the water (Stumm and Stumm-Zollinger, 1972).

While studying the phosphorus status of eutrophic lake sediments, Wildung *et al.* (1977) found that changes in the sediment inorganic phosphorus were directly related to the productivity of the surface waters. Poltz (1978) found low phosphorus levels in sediments of a shallow lake and attributed this to high decomposition rates resulting from high temperatures and frequent resuspension of the sediments.

Macrophytes are known to take up phosphate from sediments and release it into the overlying water (De Marte and Hartman, 1974). Phosphorus uptake by the roots of submerged freshwater aquatic plants has been demonstrated by a number of people (Bristow and Whitcombe, 1971; Waisel and Shapira, 1971; Denny, 1972; Bole and Allan, 1978; Gentner, 1977).

Bioassay tests showed that 42 to 52% of the total phosphorus in Lake Burley Griffin sediments was available to algae growing under aerobic conditions (Cullen *et al.*, 1978).

(c) General:

Much of the work on sediment-water nutrient exchange may not be strictly relevant to Lake Joondalup, since this work was performed on relatively deep lakes, under different climatic conditions, in the northern hemisphere. Lake Joondalup is extremely shallow by international standards, and the surface sediments are light and flocculent, being prone to resuspension under turbulent conditions.

To quantify the exchange of nutrients between the sediments and the water column of Lake Joondalup on a seasonal basis for budget purposes would be very difficult. The input of nutrients in particulate form to the sediments could be estimated with sediment traps. An intensive study would be needed, however, to quantify sedimentation over the entire lake area throughout the year. The effects of wind-stirring of sediments and diffusion could only be examined by short-term studies, and should be done under a wide range of conditions (e.g. temperature, dissolved oxygen) as these effects could vary seasonally and spatially. The significance of these processes in the overall nutrient budgets would be indicated by such studies.

4. Phytoplankton

4.1 *Introduction*

Congdon and McComb (1976) examined the seasonal change in phytoplankton numbers in Lake Joondalup during 1973. They found the largest populations during April, dominated by the green alga *Dispora crucigenoides*. They record that significant numbers of *Anabaena spiroides* appeared in August, although this population was small compared with those of other species.

During 1975, Finlayson, Gordon and McComb (in preparation) determined monthly chlorophyll a concentrations on bulked samples taken from the lake. They record a maximum level of 8.5 μg chlorophyll a . l^{-1}, in April. They found the largest phytoplankton populations in February and May. The February peak was dominated by the blue-greens *Raphidiopsis* and *Lyngbya*, while the May peak was dominated by the green alga *Dispora crucigenoides*. Populations of *Microcystis aeruginosa* peaked in May, and *Anabaena* in April and July.

In the course of the current study, chlorophyll a levels have reached 540 μg. l^{-1}. This was due to a bloom during December 1978 at site 3 (Figure 4.1). A large bloom was also present at this site in mid-November when 430 μg chlorophyll a. l^{-1} was recorded. Since there was still some flow through the Mullaloo Rd culvert, a high chlorophyll reading (135 μg. l^{-1}) was also recorded at site 2. Chlorophyll readings of 43 μg. l^{-1} at site 4 (20/12/78), and 58 μg. l^{-1} at site 5 (14/11/78) have also been recorded. Sites sampled off-shore on 3 occasions gave a highest reading of 33 μg. l^{-1} at site 15 on 31/1/79. The blooms at the southern end of the lake have been almost entirely due to *Anabaena spiroides* (Figures 4.2 and 4.3), whilst elsewhere *Microcystis (Anacystis)* has been responsible. High nutrient levels at the southern end of the lake (Table 3.3) correlate with the blue-green blooms. With an increase in water flow from the south, due to increasing runoff as urbanisation proceeds, it is possible that the high nutrient levels and *Anabaena* blooms may become more common over a larger area of the lake. Also as the lake level rises with urbanisation, the flow through the Mullaloo Rd culvert will persist for longer periods, extending this possibility.

4.2 *Water blooms*

An exact quantitative definition of a water bloom is difficult if not impossible (Wood, 1975). Lee (1970) considers a bloom to be present when cell numbers exceed 0.5 to 1.0 x 10^6 per litre. According to this definition phytoplankton algae have been in bloom proportions in Lake Joondalup throughout the 1973 and 1975 studies, since in not one month did they fall below 0.5 x 10^6 per litre at all sites sampled (Congdon and McComb, 1976; Finlayson,

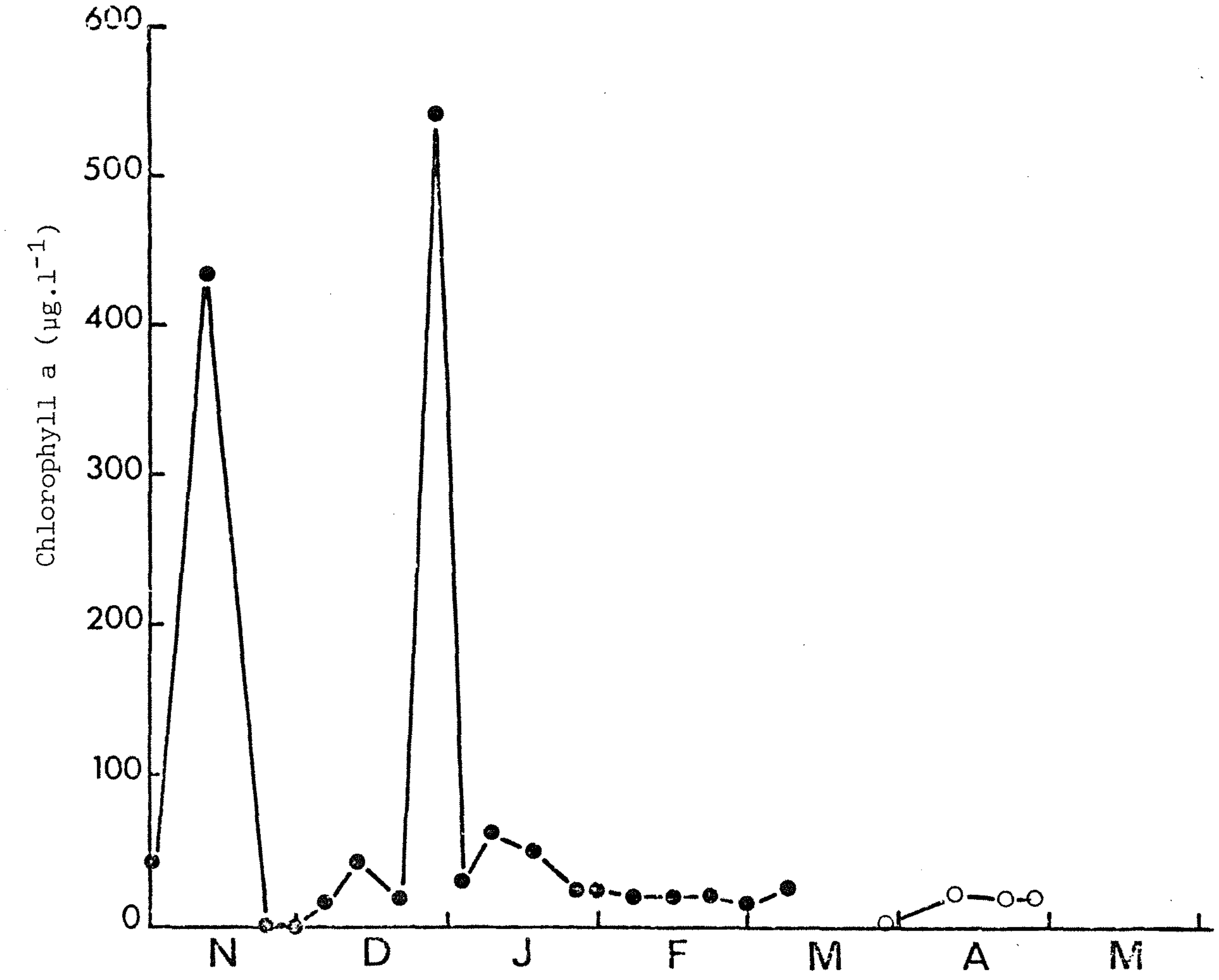


Fig. 4.1. Chlorophyll a levels at site 3 (●) and site 20 (o) during late 1978 and early 1979.

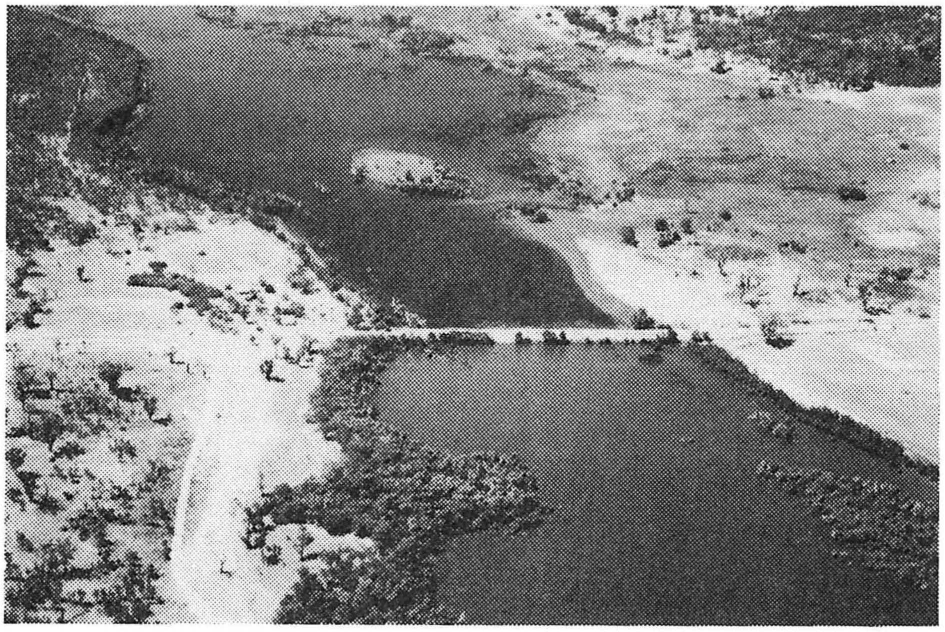


Fig. 4.2. A bloom of *Anabaena spiroides* in Lake Joondalup south of Mullaloo Road (2nd November, 1978).

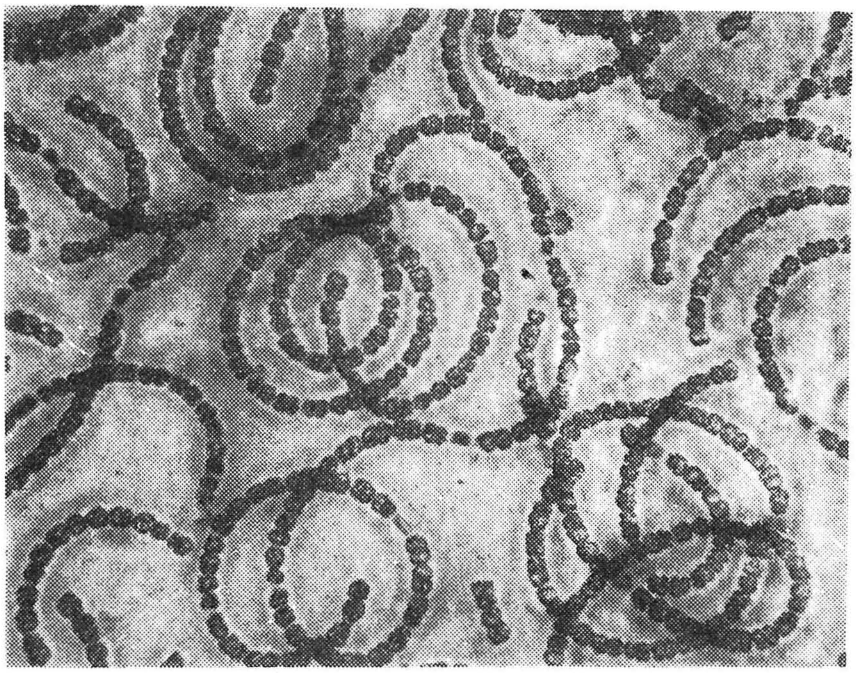


Fig. 4.3. A photomicrograph of *Anabaena spiroides*. The three dimensional helical form of the filaments is not obvious because they have been concentrated by filtration.

Gordon and McComb, in preparation). Samples of *Anabaena spiroides* collected on 17th October 1978 at site 2 contained 20 - 53 x 10^6 cells. l^{-1}, and 14 - 25 x 10^6 cells. l^{-1} on November 1st 1978.

Reynolds and Walsby (1975) define a bloom in terms of the buoyancy of the algae. Blue-green algae contain gas vacuoles which allow them to migrate to the surface during periods of reduced turbulence, so that surface bloom formation is due to buoyant behaviour rather than to exceptionally rapid growth. *Anabaena* can pass the winter on the bottom sediments as resting spores or akinetes, and germination appears to depend upon their being drawn into the full circulation of the lake provided certain minimum conditions of light and temperature are also met (Reynolds and Walsby, 1975).

Blooms of algae are very difficult to quantify when they are not widespread. The blooms of *Anabaena spiroides* which occurred in the southern end of Lake Joondalup were apparently uniform throughout the southern basin. Consequently a chlorophyll a determination could be made on samples, with some confidence that the determination would be relatively representative. *Microcystis*, however, is much more difficult to sample. Congdon and McComb (1976) found low phytoplankton numbers in samples collected in October 1973 despite the presence of a widespread bloom containing *Oscillatoria* and *Microcystis*. *Microcystis* can be seen in the lake as a patchy surface scum, or on the bottom sediments, aggregated in ripple marks. Dense collections of this alga, and also *Spirogyra*, can be seen along the lake margins in the direction of the prevailing wind. Accumulations of *Microcystis* were observed at site 4 in November and December 1978, and January 1979, and at site 5 in November 1978 and February 1979. Dense accumulations of *Spirogyra* occurred at site 1 in October 1978, and at site 4 in October 1978, and January and February 1979. Dense *Anabaena* was found along the margin of site 7 in November 1978, and a bloom which was probably *Anabaena* was present along the margin of Beenyup Swamp in February 1979. Although these accumulations of blue-green algae are difficult to quantify, it is these masses along the margins which produce odours and which people find unsightly.

4.3 *Anabaena and Microcystis literature review*

Some of the most recent literature pertaining to *Anabaena* and *Microcystis* is reviewed below.

Anabaena spiroides has been recorded in Lake Werowrap, Victoria, where Walker (1973) found 3.5 x 10^6 cells. l^{-1} producing 810 µg chlorophyll a. l^{-1}. This species is known to fix atmospheric nitrogen in direct correlation with overall growth (Kuznetsov, 1977; see section 3.2(b)).

Anabaena spiroides and *Microcystis* are also of special interest since they produce toxins and can kill fish and waterfowl. Keating (1978) has shown the allelopathic effect of blue-green algae; cell-free filtrates from blue-green dominated waters inhibited diatom growth. *Anabaena* may produce a similar toxin to the fast-death factor isolated from *Microcystis* (Olson, 1960; Fogg *et al.*, 1973). Almazan and Boyd (1978) found high rates of oxygen consumption were associated with the decomposition of *Anabaena circinalis* which could explain some fish kills associated with blue-green algal blooms. They showed that biological oxygen demand increased with the concentration of nitrogen available to the decomposers.

The optimum temperature for photosynthesis of *Anabaena* and *Microcystis* from Lake Mendota is 20 - 30°C (Konopka and Brock, 1978a). *Anabaena* doubled within 2½ days, while *Microcystis* doubled in 2 days. In Lake Mendota blue-green algal colonies were found to be buoyant during windy periods, resulting in algal accumulations in surface waters at the onset of calm conditions (Konopka, Brock and Walsby, 1978). The algae then regulated their buoyancy in response to light intensity; at high light intensities the gas vacuoles collapsed and the algae sank.

Konopka and Brock (1978b) found that pigment content was not a good indicator of physiological state. Specific photosynthetic rate (per µg chlorophyll a) was a useful physiological measure because it increased during algal growth and decreased before the decline of the algal population.

4.4 *Nutrient enrichment experiments*

4.4.1 Introduction

The most common theory for the occurrence of blue-green algal blooms is that nitrogen-fixing blue-green algae are favoured by conditions of low nitrogen concentrations in the water column provided phosphorus concentrations are still reasonably high (Stewart, 1973). Under these conditions N_2-fixing blue-green algae would have a competitive advantage over other phytoplankton species. One useful method of investigating the nutrient requirements of algae is the nutrient enrichment of laboratory cultures. Care should be taken to see that the experiment is not run too long because nutrients can become limiting and species changes can occur so that the dominant alga is no longer the one of interest (Goldman, 1962; O'Brien, 1972). The use of enclosures in the field for such experiments has certain advantages and is gaining popularity (e.g. Lean and Charton, 1977).

Samples containing blue-green algae were collected from Lake Joondalup and incubated under controlled conditions with nutrient enrichment as a preliminary investigation to see if the procedure could be useful to investigate the nutrient requirements of natural populations within the lake.

It was hoped to test two hypotheses, one that phosphorus addition would promote blue-green algal growth, and the other that the addition of nitrogen would possibly inhibit the growth of N_2-fixing blue-green algae.

4.4.2 Methods

(a) *Experiment 1*

A sample of water was collected from site 2 (Figure 1.3) on 1st November, 1978, when a bloom of *Anabaena spiroides* (135 μg chlorophyll a. l^{-1}) was present. 200 ml aliquots were decanted into thoroughly washed 1 L erlenmeyer flasks. 10 ml of deionised distilled water were added to 4 of these flasks which served as a control. 5 ml of an NH_4NO_3 stock were added to 4 flasks to give an enrichment of 155 μg $N.l^{-1}$ and 5 ml of a KH_2PO_4 stock were added to 4 more to give an enrichment of 31 μg $P.l^{-1}$. 5 ml of each stock were added to a fourth batch of 4 flasks to give an enrichment of both nitrogen and phosphorus.

The flasks were incubated in a flow-through water bath at 20°C in a glass house with ambient light. Two flasks from each treatment were removed after 7, 12, 19 and 26 days and 100 ml of water removed for analysis of chlorophyll a by the spectrophotometric method. The filtrate was analysed for nitrate and phosphate.

(b) *Experiment 2*

Water was collected from site 4 (Figure 1.3) on 23rd November 1978, when there was a bloom of *Microcystis* (14.4 μg chlorophyll a. l^{-1}) containing some *Anabaena spiroides*. Again four flasks at each treatment were set up as described above. However, small aliquots were taken after 1, 4, 5, 6, 7 and 8 days and analysed for chlorophyll a by the fluorometer technique. The fluorometer was calibrated with other samples collected at the lake, and with larger aliquots taken from some of the flasks at the end of the experiment. These samples were filtered onto glass fibre filter papers and analysed by the spectrophometric method.

4.4.3 Results and Discussion

(a) *Experiment 1*

Figure 4.4 shows that the only increase in chlorophyll a crop was recorded after 7 days in flasks enriched with phosphorus alone and nitrogen and phosphorus together. There is some evidence to suggest that the addition of nitrogen inhibited growth of the original algae. After 26 days the flasks containing added nitrogen had the higher standing crops. Figure 4.5 (a) shows that the reactive phosphorus concentrations had reached a low steady level at this time, while nitrate was apparently low in flasks containing phosphorus

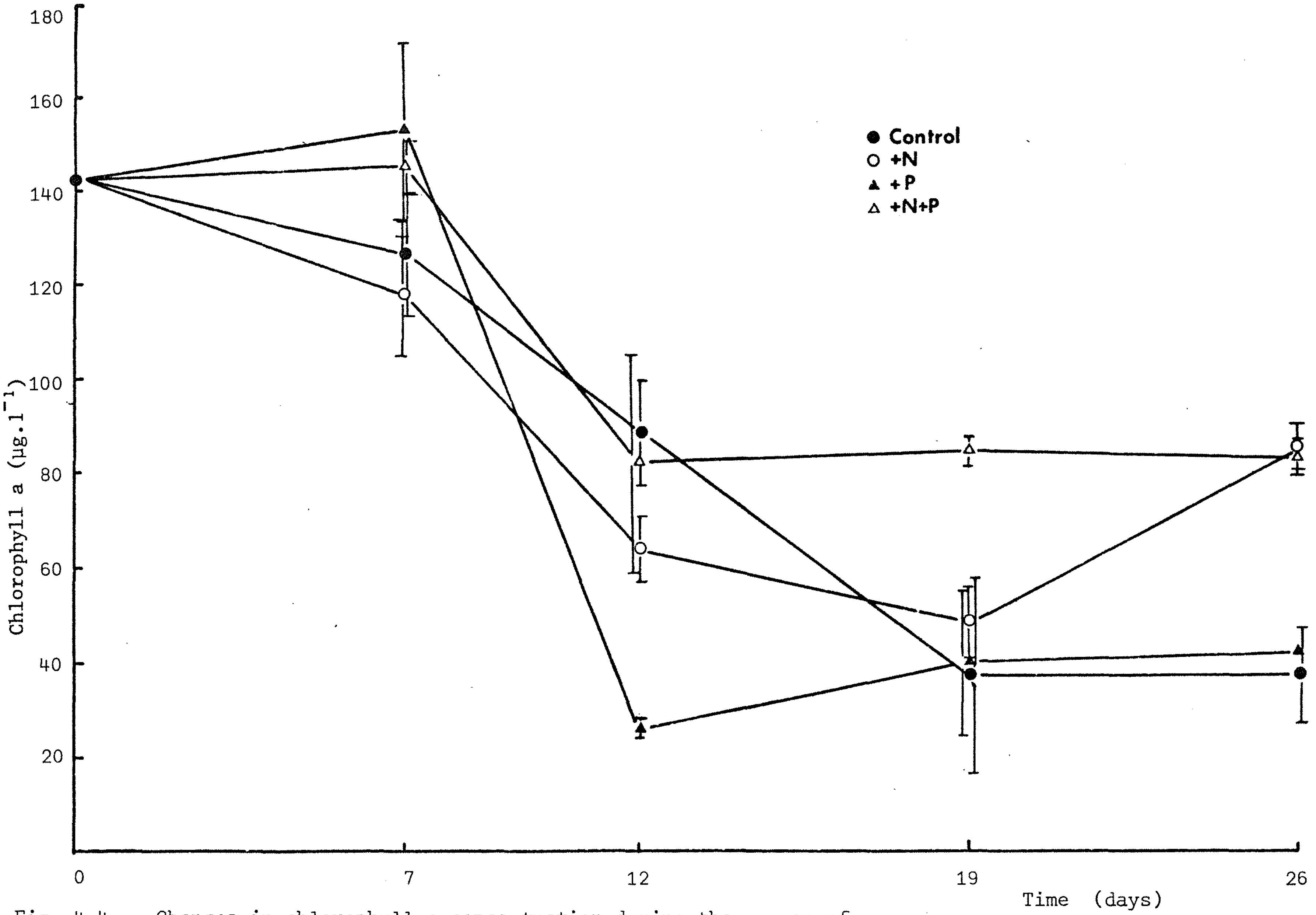


Fig. 4.4. Changes in chlorophyll a concentration during the course of nutrient enrichment experiment 1

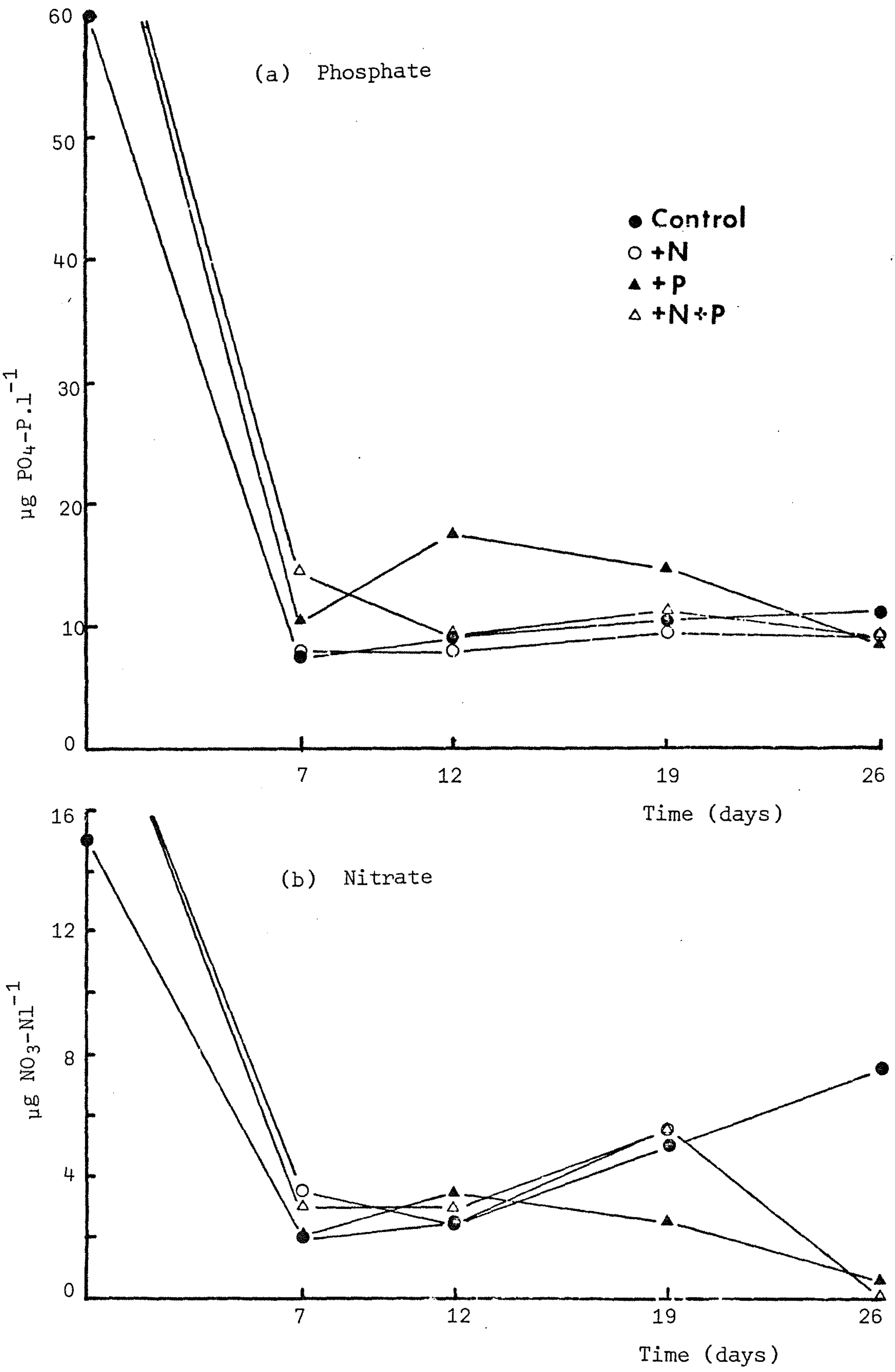


Fig. 4.5. Changes in the concentrations of (a) phosphate-phosphorus and (b) nitrate-nitrogen during the course of nutrient enrichment experiment 1.

(Figure 4.5b). This suggests that nitrogen may have become limiting after 26 days. Counts of the number of algal filaments per litre at 7 and 12 days did not correlate with chlorophyll content (Table 4.1).

The main conclusion that can be drawn from this experiment is that the response of chlorophyll crop to enrichment is rapid, taking less than 7 days, and that the time intervals chosen for the experiment were too long to give a clear indication of responses.

(b) *Experiment 2*

During the second experiment only flasks enriched with nitrogen and nitrogen plus phosphorus showed an increase in chlorophyll content (Figure 4.6). The flasks enriched with phosphorus did not show a response significantly different from that of the control flasks. Chlorophyll a concentration increased over the initial 5 days and then decreased.

The sample used for Experiment 2 contained populations of *Microcystis* and *Anabaena*, with *Anabaena* dominating. Unlike *Anabaena, Microcystis* does not possess heterocysts and does not fix atmospheric nitrogen. Consequently the increased chlorophyll in flasks to which nitrogen was added may have been due primarily to *Microcystis*. To conserve samples, few nutrient analyses were done during the course of the experiment (Table 4.2). The results show that the nitrate levels were low - suggesting ready uptake and conversion to organic nitrogen. Phosphate levels were variable but total phosphorus was definitely in much higher concentration in the flasks to which phosphate was added than in the other flasks, suggesting that it was not limiting.

Conclusions

The nutrient enrichment technique appears to be a useful tool to test hypotheses about the effects of nutrient enrichment on phytoplankton standing crop provided measurements are made at short time intervals, and the fluorometer appears to be useful for this purpose. Some complication may result from 'luxury consumption' which might explain the ability of blue-green algal populations to achieve bloom-forming proportions at times when extreme nutrient deficiency has set in (Reynolds and Walsby, 1975).

The results suggest that added phosphorus may increase standing crops of *Anabaena spiroides*, whilst added nitrogen may increase standing crops of mixed populations under certain conditions. However, much more work is required before any conclusions can be made.

Table 4.1

The number of filaments of *Anabaena spiroides* (x $10^5/\ell$) in each treatment of nutrient enrichment Experiment 1

Treatment	Incubation time (days) 0	7	12
0	9.6	62.7	34.0
+ N		84.2	26.0
+ P		58.6	2.2
+ N + P		80.6	18.6

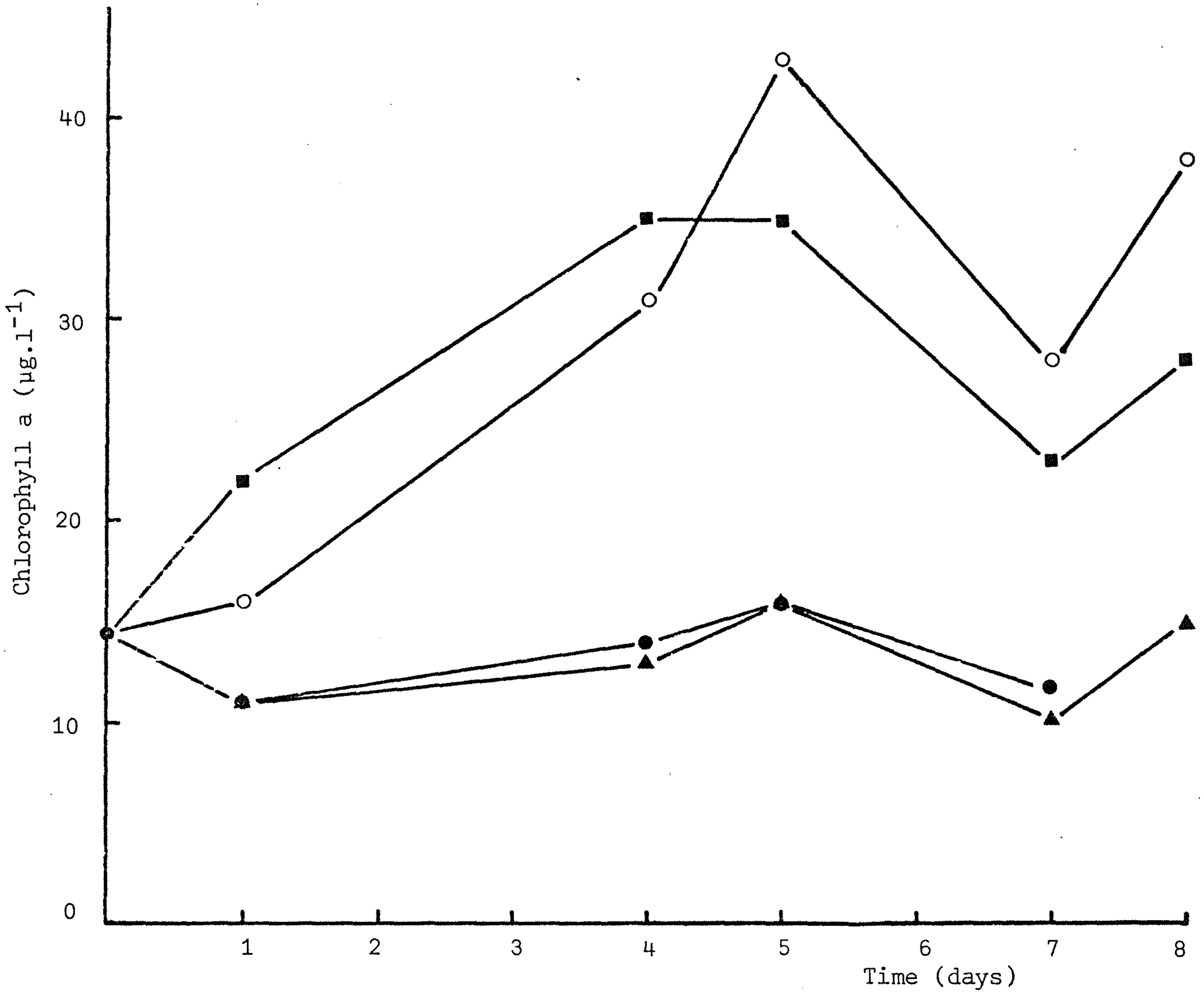


Fig. 4.6. Changes in chlorophyll a concentrations, measured as fluorescence, during the course of nutrient enrichment experiment 2.

Table 4.2

Nutrient concentrations determined during the course of nutrient enrichment

Experiment 2

Treatment	Day	PO_4-P	Organic P	Total P (μg l^{-1})	NH_4-N	NO_3-N	Organic N
	0	26	-	-	22	2	1240
+ P	1	52	-	-	-	2	-
+ N + P	5	12	-	31,96	-	1	-
+ N	7	8	13	21	-	3	-
+ P	8	70	114	184	-	2	-
+ N + P	8	11	175	186	-	2	-
+ P	8	6	-	-	-	2	-

5. Benthic macrophyte ecology

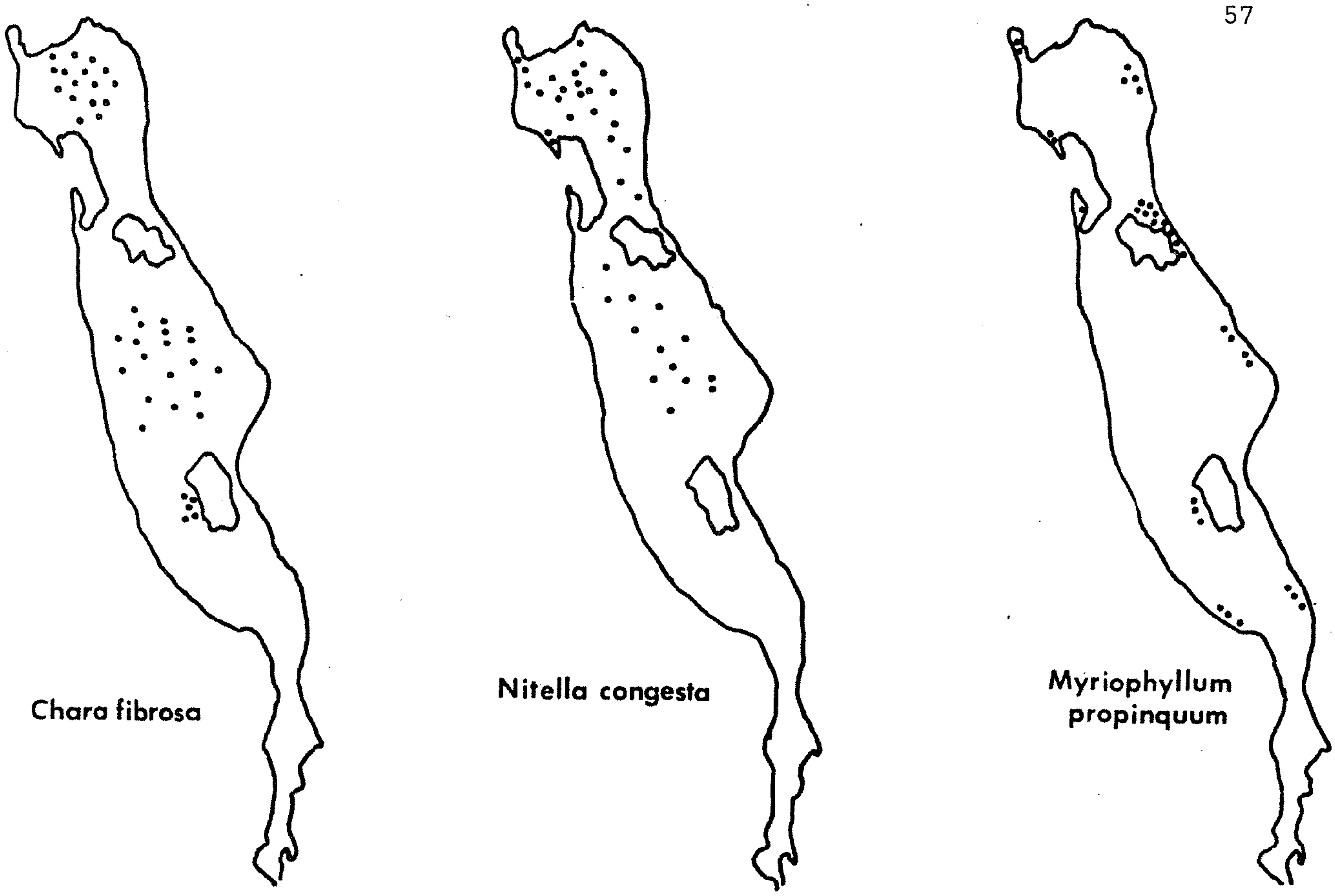
Lake Joondalup has a rich benthic flora including *Myriophyllum propinquum, Najas marina, Potamogeton pectinatus, Nitella congesta* and a number of forms of *Chara*. The dominant form of *Chara* was originally identified as *Chara baueri* (Congdon and McComb, 1976). It now appears that this may be *C. fibrosa,* with 3 or 4 different forms in the lake. These forms look, superficially, like different species and the taxonomy of the group is difficult.

Sampling of macrophytes was attempted in December 1978 in order to obtain some biomass estimates. Large cores and sampling from a tin tube (23 cm x 23 cm) was attempted, but it was found that an unrealistically large number of random cores would be necessary to obtain a representative estimate. Sampling from the tin tube quadrat was attempted with mask and snorkel, but vision was rapidly obscured by suspended sediment. This method, though difficult, might be made to work if a net were fastened over the quadrat so that plant material could not escape, and if sampling was done by touch using SCUBA apparatus. Representative samples of *Myriophyllum* would still be difficult to obtain by this method, as it has a relatively restricted distribution where it grows in very large clumps. There appears to be no simple method which can be used to harvest representative samples of each of the benthic species. A semi-quantitative estimate of abundance and distribution might be achieved with a drag-rake survey (Jupp *et al.,* 1972).

Figure 5.1 shows specific sites at which the benthic species can be found, although they occur over a much wider area. *Chara* and *Nitella* are found throughout the central area of the lake. *Myriophyllum* tends to be restricted to deep water near the lake margins. *Potamogeton* is found in shallow water near the margins. There does not appear to be a close link between distribution and water depth. On 12th December 1978 samples of *Chara* were taken in 70 to 148 cm, *Myriophyllum* in 100 to 148 cm and *Najas* in 115 cm.

Swans and ducks have been observed feeding on *Potamogeton pectinatus* at site 1 in February 1979, but I have not been able to observe any direct feeding on other benthic species. *P. pectinatus* is known to be an acceptable food source for water fowl (e.g. Delroy, 1974; Jupp and Spence, 1977).

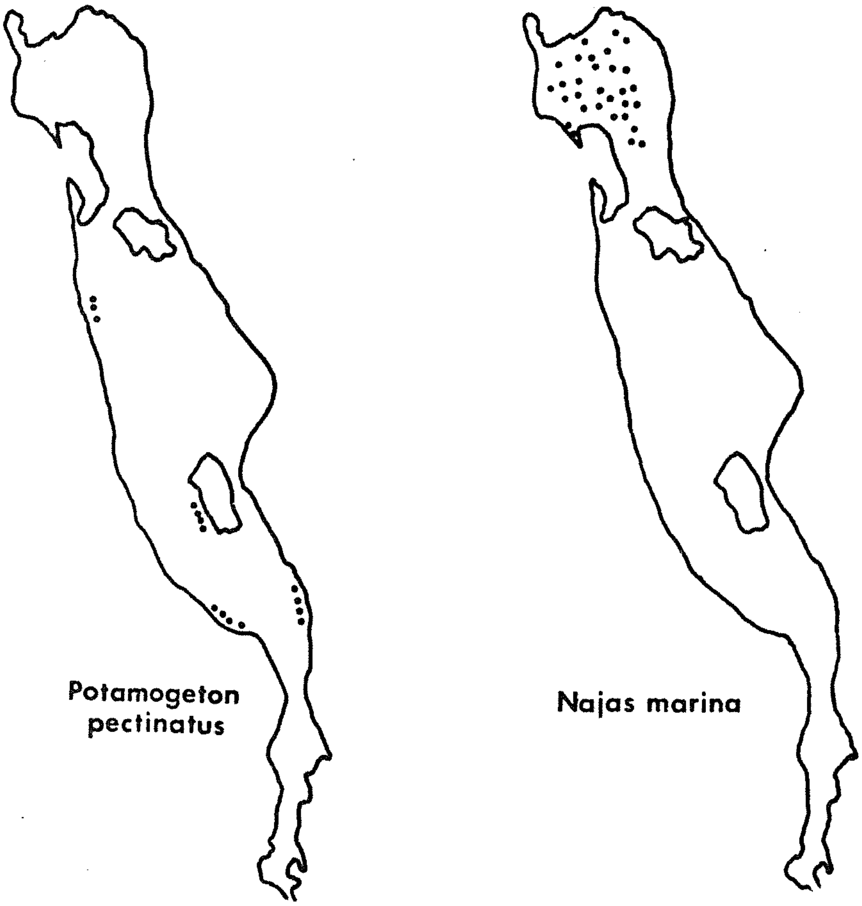
At present, it would be useful to further document the distribution of benthic species in a qualitative manner, with reference to sediment type and water depth. A literature review would indicate whether many of the species are consumed by waterfowl.



Chara fibrosa

Nitella congesta

Myriophyllum propinquum



Potamogeton pectinatus

Najas marina

Fig. 5.1. The distribution of benthic macrophyte species in Lake Joondalup. At this time the southern half of the lake has not been sampled intensively.

6. Disturbance of fringing vegetation

General observations show that a large number of species are invading disturbed areas around the lake. These include small herbs like *Anagallis, Fumaria, Vicia sativa, Arctotheca calendula, Avena sativa* and *Lupinus cosentinii;* sedges and rushes such as *Typha orientalis, Scirpus validus, Cyperus, Arundo donax (Poaceae), Juncus acutis, J. pallidus* and *J. holoschoenus;* and the Castor Oil Tree, *Ricinus communis.* As far as the vegetation on the very fringe of the lake is concerned, *Typha* is having the greatest effect, replacing the native sedge *Baumea articulata.*

An attempt was made to map the change in distribution of *Typha* with time, using aerial photographs. Black and white photographs taken in 1968 and 1970, and colour aerial photographs taken in 1976, were examined with a Carl Zeiss stereoscopic viewer. With this simple equipment it was not possible to distinguish the *Typha* from *Baumea articulata.* More elaborate equipment may allow this to be done. Black and white aerial photographs, taken in December 1953, suggest that there has not been any significant colonization of lake sediments by *Baumea articulata* in the past 25 years. This is probably a consequence of increasing water level, and the distribution of *Baumea* will probably contract in the future.

7. General conclusions and recommendations

Our country lacks the long history of data collection which has been possible for the Lakes District in England, and for the Great Lakes, Lake Mendota, Lake Wingra, etc. in the United States. Our lake ecosystems are of quite a different nature to those generally studied elsewhere, and their dynamics are complicated by the seasonal effects of our climate. This means that work done elsewhere is not readily applicable to our lakes, and any degree of study undertaken here can significantly add to our understanding of these systems.

In studying the water and nutrient budgets of a specific lake, there is a spectrum of research alternatives. Ideally the study should be done over at least 3 to 5 years, since the nuances of our climate do not allow an 'average' picture of conditions to be gained in less time. To document major processes a specialist research team would be preferable, including a hydrologist (to document drain flow, groundwater flux, etc.), an aquatic microbiologist (to study denitrification, nitrogen fixation, etc.), an aquatic soil scientist (to study sediment chemistry with emphasis on sediment-water nutrient exchange) and an algologist (to study phytoplankton taxonomy, productivity, etc.). To accurately document nutrient and water inputs, automatic samplers and continuous recording flow meters would be required. Regular intensive sampling and analysis would enhance the accuracy of nutrient and water budgets. For example, evaporation and rainfall measurements should ideally be made daily at about 9 am. If sites are only sampled on a weekly basis, the peak of blue-green algal blooms can be missed (an *Anabaena* bloom at site 3 fell from 433 mg chlorophyll a. l^{-1} to 1.9 mg. l^{-1} within 9 days in November 1978; the largest bloom occurred between Christmas and New Year's Day in 1978 and would not have been noticed if sampling had not occurred between these days!).

At the other end of the spectrum, a short-term study by a single individual can produce significant information of interest to our understanding of local wetland ecosystems, and highlight management options.

One point in favour of detailed long-term studies is the problem of disentangling variation due to short-term seasonal changes from long-term effects due to urbanization. A (less detailed) long-term monitoring programme would be useful after any study, in order to collect information on the effects of urbanization - the sort of data which is sorely lacking for Australian wetlands and which is very necessary to allow effective management of wetlands.

7.1 *Specific recommendations*

(a) The hydrological budget

1. Regular monitoring of surface drainage at storm drains and the Mullaloo Rd culvert will be required to establish the significance of this hydrological input. As a minimum effort, water depth could be monitored weekly with occasional flow measurements (requiring a current meter) taken to allow the construction of a discharge rating curve. All water depth readings could then be converted to discharge figures.

Since large volumes of water and nutrients can be discharged during brief storms, the methods described above will result in an underestimate which might be very significant. Consequently, it would be very helpful if at least a few specific storms were documented in detail. Greatest accuracy would be provided with continuous flow readings - the simplest provided by a float connected to a revolving drum to give a continuous record of water level. It may be possible to extrapolate from measurements taken at one site with a continuous recorder to give estimates for other drains where measurements are taken less frequently.

2. Evaporation provides a major output for the hydrological budget. The evaporation pan provides the simplest, cheapest reliable method for estimating lake evaporation. It would be useful to obtain pan measurements at a site near the lake for at least 12 months in order to estimate lake evaporation over a year, and compare it with other hydrological parameters. These data may then be compared with evaporation pan data collected in Perth to see how significant any differences are. It may then be possible to use Perth data to extend the study.

3. Groundwater flux is best left as an unknown in the hydrological budget since it would be extremely difficult to monitor. However, seepage into the lake could be usefully determined with a seepage meter, to gain some estimates of seepage rates at different places and times of the year.

4. Chloride appears to be a useful tracer of water origin. Its concentration in storm water and ground water is generally lower than in the lake water. Mapping of chloride distribution within the lake by the Symap computer programme might indicate the source and dispersion of water from different sources. Provided chloride concentration differences are significant and are accurately determined, this tool may be used to quantify water inputs.

(b) The nutrient budgets

1. It would be useful to examine the nutrient content of rainfall in

the Wanneroo area. Samples should be collected during rainstorms (i.e. over as short a period as possible) and quickly frozen for preservation. It would be valuable to determine if the nutrient content varied much throughout the year. If it did, a more extensive sampling programme may be necessary to quantify this nutrient input.

2. Although it appears that nitrogen-fixation is not a significant input to the lake as a whole, further acetylene-reduction assays would provide further evidence. In particular, it would be interesting to investigate the role of nitrogen-fixation in permitting blooms of *Anabaena spiroides* to develop. Do they only occur when nitrogen is limiting the growth of other species?

3. The contribution of nutrients in surface drainage depends heavily on the rates of discharge. Any investigation of this nutrient source relies on reliable discharge measurements. Most nutrient can be contributed over short periods, during storms, and so some intensive short-term monitoring of the nutrient content of stormwater during storms would be most useful. Such a study requires people to be 'on the spot' during a storm and would generate large numbers of samples. Automatic samplers could be used to sample for total phosphorus (unpreserved) or other nutrients (preserved with mercuric chloride). Such sampling programmes would be expensive.

4. The contribution of nutrients in groundwater would be very difficult to monitor and is probably not significant. The sediment bed of the lake would modify the groundwater nutrient flux, and therefore it is more appropriate to consider the sediment-water column exchange of nutrients. The seepage meter could be used to investigate the flux of nutrients in different areas and at different times of the year, provided the redox conditions within the meter are not different to the ambient conditions.

5. Denitrification would be very difficult to quantify on a seasonal basis and is probably best left as an unknown in the nitrogen budget equation. The acetylene blockage technique may be usefully employed on some occasions to give some estimate of rates of denitrification.

6. The pool of nutrients within the lake is probably best examined on a monthly basis. Samples could be collected over a grid of say 30 to 50 sites, and the Symap computer programme used to map the distribution of nutrients. The total nutrient content of the surface sediments and water column could be obtained by mapping nutrients per unit area, and summing the areas of each level of nutrient. Current flow and advection may not be significant in the lake, but could be incorporated, if need be, by using the partitioning approach.

7. Sediment-water nutrient exchange may be a very important factor in controlling water nutrient status and the occurrence of algal blooms. The study of sedimentation, by using sediment traps, would be very difficult in this shallow lake due to the resuspension of bottom sediments, but may provide some useful information. Net nutrient release from the sediment would be very difficult to determine for the whole lake surface on a seasonal basis. Short-term studies would provide much useful information and may indicate the significance of this nutrient source/sink. Studies of the effects of wind-stirring of sediments and diffusion could be made in the field as well as in the laboratory. It would be useful to study the sediment chemistry further, with particular emphasis on the interstitial and 'available' nutrient fractions.

(c) Phytoplankton

1. It will be of interest to document the occurrence and causes of blue-green algal blooms more fully. Weekly chlorophyll determinations from a few sites provide a minimum basis for study, and their correlation with nutrient levels may provide some insight into the cause of blooms. Extensive sampling could be undertaken over a grid on a monthly basis to provide an indication of the overall distribution of blooms within the lake. The use of a fluorometer with a flow-through cell would allow more extensive sampling.

2. The productivity of blooms and their effect on the concentration of dissolved oxygen in the water could be examined with diurnal studies. Some information about nutrient uptake might also result.

3. Hypotheses regarding nutrient requirements of algal blooms could be tested with nutrient enrichment of cultures. Ideally, laboratory studies should be supplemented with incubations in the field, and there are many promising techniques now described in the literature.

4. A more extensive review of the literature pertaining to *Anabaena* and *Microcystis*, and to water blooms in general, would be useful in considering the importance of control of water blooms within the lake, if this is desirable. It may aid our understanding of the factors causing the blooms.

5. A detailed documentation of the taxonomy and numbers of phytoplankton found in Lake Joondalup could be useful, particularly with regard to the bloom-forming species, which appear to include several species of colonial blue-green algae. However, such documentation is very laborious and time-consuming, and requires the services of a specialist with a particular interest in such a study.

(d) Benthic macrophyte ecology

1. The distribution of benthic plant species could be mapped in a

qualitative fashion by means of direct observation. A drag-rake survey appears to be the most practical means of obtaining a semi-quantitative estimate of abundance and distribution.

2. The importance of benthic macrophytes in the diet of waterfowl at Lake Joondalup might be usefully assessed for management purposes. If the water level increases by 1 to 2 m due to clearing in the catchment, then some species may be eliminated from large areas of the lake because of reduced light penetration, and this may affect the lake's value as a waterfowl refuge area. To allow prediction of the effects of such a water level increase, it is important that the ecology of the submerged plants is understood.

(e) Fringing vegetation

1. Disturbance of the fringing native vegetation results in the spread of exotic species, and this may not be desirable, especially if it is desirable to maintain the lake in as natural a state as possible. The MRPA policy of restricting access to the lake margin is a valuable step towards reducing disturbance. Specific studies of the competition between native and introduced species could be useful to determine whether further management proposals are required. In particular, it will be of interest to determine whether *Typha* is capable of invading undisturbed areas of *Baumea articulata,* now that it has been introduced in many disturbed areas. Increasing water levels in the lake will probably reduce the area occupied by *B. articulata*, and may allow the establishment of other species in certain areas.

2. It would be interesting if the past spread of *Typha* at the lake could be documented. It may still be possible to use aerial photographs for this purpose. This could provide information on the rate of encroachment and susceptible areas, which might be useful for future management proposals.

(f) Management implications for other lakes

1. Little detailed study has been done of the ecology of other local lakes, and so information gained from the study of Lake Joondalup will be useful when looking at the management of other lakes. The actual magnitude of various inputs and outputs will vary between lakes, but this study should indicate the relative significance of the major components, as, for example, with reference to urban runoff.

2. Information gained on the nutrient relationships of certain phytoplankton species will be directly relevant to other lakes where these species occur.

3. Symap distribution maps produced from grid studies could be usefully compared with data gained from Landsat techniques, to give a more exact understanding of what particular Landsat signatures relate to. This should enhance the study of other wetlands by Landsat.

8. References

Allen, A.D. (1976). Hydrogeology of superficial formations. In: Carbon, B.A. (Ed.) 'Groundwater Resources of the Swan Coastal Plain', pp. 12-33 (CSIRO Division of Land Resources Management, Perth).

Allison, G.B. and Hughes, M.W. (1978). The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. Aust. J. Soil Res. 16 (2): 181-196.

Almazan, G. and Boyd, C.E. (1978). Effects of nitrogen levels on rates of oxygen consumption during decay of aquatic plants. Aquat. Bot. 5: 119-126.

Andersen, V.J.M. (1974). Nitrogen and phosphorus budgets and the role of sediments in six shallow Danish lakes. Arch. Hydrobiol. 74(4): 528-550.

Aulenbach, D.B., Bull, J.H. and Middlesworth, B.C. (1978). Use of tracers to confirm ground-water flow. Ground water 16 (3): 149-157.

Austin, E.R. and Lee, G.F. (1973). Nitrogen release from lake sediments. J. Water Pollut. Control Fed. 45(5): 870-879.

Bestow, T.T. (1976). In: Carbon, B.A. (Ed.) 'Groundwater Resources of the Swan Coastal Plain', p. 190. (CSIRO Division of Land Resources Management, Perth).

Bole, J.B. and Allan, J.R. (1978). Uptake of phosphorus from sediment by aquatic plants, *Myriophyllum spicatum* and *Hydrilla verticillata*. Water Res. 12(5): 353-358.

Brandvold, D.K., Popp, C.J. and Brierly, J.A. (1976). Waterfowl refuge effect on water quality: II. Chemical and physical parameters. J. Water Pollut. Control Fed. 48: 680-687.

Brezonik, P.L. (1972). Nitrogen: sources and transformations in natural waters. In: Allen, H.E. and Kramer, J.R. (Eds) 'Nutrients in Natural Waters', pp. 1-50. (John Wiley and Sons, New York).

Bristow, J.M. and Whitcombe, M. (1971). The role of roots in the nutrition of aquatic vascular plants. Amer. J. Bot. 58: 8-13.

Bruce, J.P. and Clark, R.H. (1966). 'Introduction to Hydrometeorology'. (Pergamon Press, Oxford).

Burton, C.W. (1976). Water balance on the Coastal Plain. Future. In: Carbon, B.A. (Ed.) 'Groundwater Resources of the Swan Coastal Plain', pp. 89-109. (CSIRO Division of Land Resources Management, Perth).

Cheng Wan-Li (1978). 'A Study of Evaporation from Lake Albert, Using Meteorological and Hydrological Observations'. Flinders Institute of Atmospheric and Marine Sciences, Research Report No. 29. (The Flinders University of South Australia, South Australia).

Congdon, R.A. and McComb, A.J. (1973). Studies on wetland plant communities in the Bremer Bay Region. Report to the National Parks Board of Western Australia (Unpublished).

Congdon, R.A. and McComb, A.J. (1976). The nutrients and plants of Lake Joondalup, a mildly eutrophic lake experiencing large seasonal changes in volume. J. Roy. Soc. W.A. 59(1): 14-23.

Cullen, P., Rosich, R. and Bek, P. (1978). 'A Phosphorus Budget for Lake Burley Griffin and Management Implications for Urban Lakes'. Australian Water Resources Council Technical Paper No. 31. (Australian Government Publishing Service, Canberra).

Delroy, L.B. (1974). The food of waterfowl (Anatidae) in the southern Coorong salt water habitat of South Australia. South Australian Ornithologist 26(7): 156-163.

DeMarte, J.A. and Hartman, R.T. (1974). Studies on absorption of ^{32}P, ^{59}Fe, and ^{45}Ca by water-milfoil (*Myriophyllum exalbescens* Fernald). Ecology 55: 188-194.

Denny, P. (1972). Sites of nutrient absorption in aquatic macrophytes. J. Ecol. 60: 819-829.

Downing, J.A. and Peterka, J.J. (1978). Relationship of rainfall and lake groundwater seepage. Limnol. Oceanogr. 23(4): 821-824.

Drover, D.P. and Barrett-Lennard, I.P. (1956). Accessions of nitrogen (ammonia, nitrate and nitrite) in Western Australian wheat belt rains. J. Aust. Inst. Agric. Sci. 22: 193-197.

Engler, R.M., Antie, D.A. and Patrick Jr, W.H. (1976). Effect of dissolved oxygen on redox potential and nitrate removal in flooded swamp and marsh soils. J. Env'l Qual. 5: 230-235.

Finlayson, C.M. and McComb, A.J. (1978). Nitrogen fixation in wetlands of south-western Australia. Search 9(3): 98-99.

Finlayson, C.M., Gordon, D.M. and McComb, A.J. The trophic status of three lakes near Perth, Western Australia. (In preparation).

Fogg, G.E., Stewart, W.D.P., Fay, P. and Walsby, A.E. (1973). 'The Blue-green Algae'. (Academic Press, London).

Gentner, S.R. (1977). Uptake and transport of iron and phosphate by *Vallisneria spiralis* L. Aquat. Bot. 3: 267-272.

Goering, J.J. (1972). The role of nitrogen in eutrophic processes. In: Mitchell, R. (Ed.) 'Water Pollution Microbiology', pp. 43-68. (John Wiley and Sons, Inc., New York).

Goldman, C.R. (1962). A method of studying nutrient limiting factors *in situ* in water columns isolated by polyethylene film. Limnol. Oceanogr. 7: 99-101.

Graetz, D.A., Keeney, D.R. and Aspiras, R.B. (1973). Eh status of lake sediment-water systems in relation to nitrogen transformations. Limnol. Oceanogr. 18: 908-917.

Hallberg, R.O., Bagander, L.E. and Engvall, A. (1977). Dynamics of phosphorus, sulfur and nitrogen at the sediment-water interface. In: Nriagu, J.R. (Ed.) 'Environmental Biogeochemistry', pp. 295-308. (Ann Arbor, Michigan).

Hardy, R.W.F., Holsten, R.D., Jackson, E.K. and Burns, R.C. (1968). The acetylene-ethylene assay for N_2 fixation: laboratory and field evaluation. Pl. Physiol. 43: 1185-1207.

Hardy, R.W.F., Burns, R.C. and Holsten, R.D. (1973). Application of the acetylene-ethylene assay for measurement of nitrogen fixation. Soil Biol. Biochem. 5: 47-81.

Jitts, H.R. (1959). The adsorption of phosphate by estuarine bottom sediments. Aust. J. Mar. Freshwater Res. 10: 7-21.

John, P.H., Lock, M.A. and Gibbs, M.M. (1977). Two new methods for obtaining water samples from shallow aquifers and littoral sediments. J. Environ. Qual. 6: 322-324.

Jørgensen, S.E., Jacobsen, O.S. and Hoi, I. (1973). A prognosis for a lake. Vatten 29: 382-404.

Jupp, B.P., Spence, D.H.N. and Britton, R.H. (1972). The distribution and production of submerged macrophytes in Loch Leven, Kinross. Proc. Roy. Soc. Edinburgh, 74: 195-208.

Jupp, B.P. and Spence, D.H.N. (1977). Limitations of macrophytes in a eutrophic lake, Loch Leven. II. Wave action, sediments and waterfowl grazing. J. Ecol. 65: 431-446.

Keating, K.I. (1978). Blue-green algal inhibition of diatom growth: transition from mesotrophic to eutrophic community structure. Science 199: 971-973.

Keeney, D.R. (1973). The nitrogen cycle in sediment-water systems. J. Environ. Qual. 2: 15-29.

Kluesner, J.W. and Lee, G.F. (1974). Nutrient loading from a separate storm sewer in Madison, Wisconsin. J. Water Pollut. Control Fed. 46: 920-936.

Koike, I. and Hattori, A. (1978). Denitrification and ammonia formation in anaerobic coastal sediments. Appl. Environ. Microbiol. 35: 278-282.

Konopka, A. and Brock, T.D. (1978a). Effect of temperature on blue-green algae (Cyanobacteria) in Lake Mendota. Appl. Environ. Microbiol. 36(4): 572-576.

Konopka, A. and Brock, T.D. (1978b). Changes in photosynthetic rate and pigment content of blue-green algae in Lake Mendota. Appl. Environ. Microbiol. 35(3): 527-557.

Konopka, A., Brock, T.D. and Walsby, A.E. (1978). Buoyancy regulation by planktonic blue-green algae in Lake Mendota, Wisconsin. Arch. Hydrobiol. 83(4): 524-537.

Kuznetsov, S.I. (1977). Trends in the development of ecological microbiology. In: Droop, M.R. and Jannasch, H.W. (Eds). 'Advances in Aquatic Microbiology', pp. 1-48. (Academic Press, London).

Lean, D.R.S., Charlton, M.N., Burnison, B.K., Murphy, T.P., Millard, S.E. and Young, K.R. (1975). Phosphorus changes in ecosystem metabolism from reduced loading. Verh. Internat. Verein. Limnol. 19: 249-257.

Lean, D.R.S. and Charlton, M.N. (1976). A study of phosphorus kinetics in a lake ecosystem. In: Nriagu, J.O. (Ed.) 'Environmental Biogeochemistry', pp. 283-294. (Ann Arbor, Michigan).

Lee, G.F. (1970). Eutrophication. Univ. Wis. Water Resour. Cent. Eutrophication Inf. Program. Occas. Pap. 2.

Lee, D.R. (1977). A device for measuring seepage flux in lakes and estuaries. Limnol. Oceanogr. 22: 140-147.

Lee, G.F., Bentley, E. and Amundson, R. (1975). Effects of marshes on water quality. In: Hasler, A.D. (Ed.), 'Ecological studies 10: Coupling of Land and Water Sustems', pp 105-127. (Springer-Verlag, New York.

Lee, F.G., Rast, W. and Jones, R.A. (1978). Eutrophication of water bodies: insights for an age-old problem. Environ. Sci. & Technol. 12: 900.

Mortimer, C.H. (1941, 1942). The exchange of dissolved substances between mud and water in lakes. J. Ecol. 29: 280-329, 30: 147-201.

Mortimer, C.H. (1971). Chemical exchanges between sediments and water in the Great Lakes - Speculations on probable regulatory mechanisms. *Limnol. Oceanogr.* *16*: 387-404.

O'Brien, W.J. (1972). Limiting factors in phytoplankton algae: their meaning and measurement. *Science* *178*: 616-617.

Olson, T.A. (1960).

Patrick Jr, W.H. and Khalid, R.A. (1974). Phosphate release and sorption by soils and sediments: effect of aerobic and anaerobic conditions. *Science* *186*: 53-55.

Poltz, V.J. (1978). Investigations on the sediments of shallow waters in Niedersachsen. I. The sediments of Lake Steinhuder Meer. *Arch. Hydrogiol.* *82*: 1-19.

Pomeroy, L.R., Smith, E.E. and Grant, C.M. (1965). The exchange of phosphate between estuarine water and sediment. *Linnol. Oceanogr.* *10*: 167-172.

Reynolds, C.S. and Walsby, A.E. (1975). Water blooms. *Biol. Rev.* *5*: 437-481.

Rochford, D.J. (1951). Studies in Australian estuarine hydrology. I - Introductory and comparative features. *Aust. J. Mar. Freshwater Res.* *2*: 1-116.

Rosher, J.E. and van den Berghe, L.G. (1977). 'Physical Hydrometeorology of the Peel Inlet-Harvey Estuary System, Western Australia'. Undergraduate Report No. UG109, 111/1977/ES 5,7, Dept of Physics, W.A.I.T.

Rowe, G.T., Clifford, C.H., Smith Jr, K.L. and Hamilton, P.L. (1975). Benthic nutrient regeneration and its coupling to primary productivity in coastal waters. *Nature* *255*: 215-217.

Schaffner, W.R. and Oglesby, R.T. (1978). Phosphorus loadings to lakes and some of their responses. Part 1. A new calculation of phosphorus loading and its application to 13 New York lakes. *Limnol. Oceanogr.* *23*: 120-134.

Sørensen, J. (1978a). Capacity for denitrification and reduction of nitrate to ammonia in a coastal marine sediment. *Appl. Environ. Microbiol.* *35*: 301-305.

Sørensen, J. (1978b). Occurrence of nitric and nitrous oxides in a coastal marine sediment. *Appl. Environ. Microbiol.* *36*: 809-813.

Stephenson, G. (1977). 'Joondalup Regional Centre'. (University of Western Australia Press, Nedlands).

Stewart, W.D.P. (1973). Nitrogen fixation by photosynthetic micro-organisms. Ann. Rev. Microbiol. 27: 283-316.

Stumm, W. and Stumm-Zollinger, E. (1972). The role of phosphorus in eutrophication. In: Mitchell, R. (Ed.) 'Water Pollution Microbiology', pp. 11-42. (John Wiley and Sons, Inc., New York).

Syers, J.K., Harris, R.F. and Armstrong, D.E. (1973). Phosphate chemistry in lake sediments. J. Environ. Qual. 2: 1-14.

van Kessel, J.F. (1976). 'Influence of Denitrification in Aquatic Sediments on the Nitrogen Content of Natural Waters', Agric. Res. Rep. 858 (Centre for Agricultural Publishing and Documentation, Pudoc, Wageningen).

Vollenweider, R.A. (1971). 'Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication', (O.E.C.D., Paris) (Report first submitted to O.E.C.D. in 1968).

Waisel, Y. and Shapira, Z. (1971). Functions performed by roots of some submerged hydrophytes. Israel J. Botany 20: 69-77.

Walker, K.F. (1973). Studies on a saline lake ecosystem. Aust. J. Mar. Freshwater Res. 24: 21-71.

Welch, P.S. (1948). 'Limnological Methods'. (McGraw-Hill, New York).

Wetzel, R.G. (1975). 'Limnology'. (W.A. Saunders, Philadelphia).

Wildung, R.W., Schmidt, R.L. and Routson, R.C. (1977). The phosphorus status of eutrophic lake sediments as related to changes in limnological conditions - phosphorus mineral components. J. Environ. Qual. 6 (1): 100-104.

Wood, G. (1975). 'An Assessment of Eutrophication in Australian Inland Waters'. Australian Water Resources Council Technical Paper No. 15. (Australian Government Publishing Service, Canberra).

Wood, R.D. (1975). 'Hydrobotanical Methods'. (University Park Press, Baltimore).

World Meteorological Organization (1966). 'Measurement and Estimation of Evaporation and Evapotranspiration'. Technical Note No. 83. (W.M.O., Geneva).

Appendix 1.

Computer printout of nutrient data collected for Lake Joondalup, to the end of March 1979. See end of printout for explanation.

LAKE JOONDALUP

1973 DATA (CONGDON)

SAMPLE				PIGMENT		PHOSPHORUS			NITROGEN				RATIO	
DATE	DAY	ST	D	CHLO	PHA	PO4	ORG	TOT	NO3	NH4	ORG	TOT	N/P	CL
73 221	52	11	1	0.0	0.0	24.	17.	41.	0.	230.	2568.	2798.	21.2	450.0
73 221	52	12	1	0.0	0.0	26.	17.	43.	0.	453.	3600.	4053.	38.6	475.0
73 221	52	5	1	0.0	0.0	6.	24.	30.	0.	108.	2236.	2344.	39.9	508.0
73 221	52	8	1	0.0	0.0	4.	36.	40.	0.	153.	2286.	2439.	84.7	461.0
73 221	52	2	1	0.0	0.0	32.	62.	94.	0.	777.	3042.	3819.	53.8	511.0
73 320	79	11	1	0.0	0.0	30.	13.	43.	0.	0.	2700.	2700.	0.0	529.0
73 320	79	12	1	0.0	0.0	44.	1.	45.	0.	291.	2937.	3228.	14.7	541.0
73 320	79	5	1	0.0	0.0	29.	1.	30.	0.	216.	2533.	2749.	16.5	633.0
73 320	79	8	1	0.0	0.0	27.	16.	43.	0.	298.	3337.	3635.	24.4	593.0
73 320	79	14	1	0.0	0.0	44.	31.	75.	0.	150.	4276.	4426.	7.5	580.0
73 320	79	2	1	0.0	0.0	36.	10.	46.	0.	1110.	2458.	3568.	68.3	725.0
73 417	107	11	1	0.0	0.0	40.	44.	84.	0.	0.	2741.	2741.	0.0	552.0
73 417	107	12	1	0.0	0.0	44.	13.	57.	0.	230.	2355.	2585.	11.6	680.0
73 417	107	5	1	0.0	0.0	22.	21.	43.	0.	255.	2617.	2872.	25.7	585.0
73 417	107	8	1	0.0	0.0	4.	41.	45.	0.	473.	1920.	2393.	261.8	595.0
73 417	107	14	1	0.0	0.0	10.	42.	52.	0.	349.	2244.	2593.	77.3	602.0
73 417	107	2	1	0.0	0.0	5.	55.	60.	0.	1250.	2178.	3428.	553.5	714.0
73 626	177	11	1	0.0	0.0	4.	69.	73.	0.	44.	1481.	1525.	24.4	329.0
73 626	177	12	1	0.0	0.0	5.	32.	37.	0.	35.	1499.	1534.	15.5	355.0
73 626	177	5	1	0.0	0.0	4.	16.	20.	0.	28.	1493.	1521.	15.5	351.0
73 626	177	8	1	0.0	0.0	2.	20.	22.	0.	40.	1617.	1657.	44.3	359.0
73 626	177	14	1	0.0	0.0	2.	46.	48.	0.	62.	1509.	1571.	68.6	291.0
73 626	177	2	1	0.0	0.0	83.	39.	122.	0.	105.	967.	1073.	2.8	172.0
73 829	241	11	1	0.0	0.0	7.	57.	64.	0.	79.	2148.	2227.	25.0	216.0
73 829	241	12	1	0.0	0.0	2.	37.	39.	0.	43.	1623.	1666.	47.6	219.0
73 829	241	5	1	0.0	0.0	4.	33.	37.	0.	8.	1520.	1528.	4.4	219.0
73 829	241	8	1	0.0	0.0	5.	26.	31.	0.	8.	1407.	1415.	3.5	240.0
73 829	241	14	1	0.0	0.0	8.	61.	69.	0.	14.	2433.	2447.	3.9	147.0
73 829	241	2	1	0.0	0.0	21.	146.	167.	0.	298.	1456.	1754.	31.4	155.0
731026	299	11	1	0.0	0.0	15.	56.	71.	0.	440.	1720.	2160.	65.0	199.0
731026	299	12	1	0.0	0.0	14.	54.	68.	0.	765.	1533.	2298.	121.0	202.0
731026	299	5	1	0.0	0.0	17.	40.	57.	0.	505.	1107.	1612.	65.8	205.0
731026	299	8	1	0.0	0.0	49.	1.	50.	0.	545.	1530.	2075.	24.6	212.0
731026	299	14	1	0.0	0.0	27.	81.	108.	0.	730.	1609.	2339.	59.9	194.0
731026	299	2	1	0.0	0.0	130.	0.	130.	0.	0.	0.	0.	0.0	140.0
731217	351	11	1	0.0	0.0	9.	64.	73.	0.	330.	1423.	1753.	81.2	276.0
731217	351	12	1	0.0	0.0	7.	51.	58.	0.	340.	1090.	1430.	107.6	263.0
731217	351	5	1	0.0	0.0	15.	48.	63.	0.	255.	1240.	1495.	37.6	249.0
731217	351	8	1	0.0	0.0	5.	50.	55.	0.	176.	969.	1145.	41.9	270.0
731217	351	14	1	0.0	0.0	10.	67.	77.	0.	235.	1055.	1290.	52.0	245.0
731217	351	2	1	0.0	0.0	41.	137.	178.	0.	330.	852.	1182.	17.8	251.0

```
75 130 395  0 1        2.0  0.0   24.   1.   25.   1108.   15.     0.  1123. 103.5     0.0
75 227  58  0 1        5.9  0.0    1.  51.   52.   1160.   74.     0.  1234.2732.4     0.0
75 326  85  0 1        7.1  0.0   10.  45.   55.   1680.   34.  2087.  3801. 373.5     0.0
75 430 120  0 1        8.5  0.0   35.   9.   44.   1396.   26.  1605.  3027. 121.5     0.0
75 529 149  0 1        7.9  0.0    2.  34.   36.    812.   18.  1260.  2090. 913.9     0.0
75 7 5 186  0 1        2.5  0.0   20.  20.   40.    370.   10.  1360.  1740.  42.1     0.0
75 730 211  0 1        6.3  0.0   12.  33.   45.    420.    5.  1420.  1845.  78.4     0.0
75 830 242  0 1        2.2  0.0   32.   8.   40.    745.    5.  1650.  2400.  51.9     0.0
75 930 273  0 1        1.2  0.0   28.  34.   62.    190.    5.     0.   195.  15.4     0.0
751129 333  0 1        2.0  0.0   12.  36.   48.    400.    8.  1947.  2355.  75.3     0.0
751230 364  0 1        2.1  0.0   33.   5.   38.    903.    0.  2475.  3378.  60.5     0.0
```

1975 DATA

(FINLAYSON & GORDON)

9 SITES → BULKED SAMPLE

SITE 1.

```
78 919 262  1 1        4.1  1.4   27.  30.   57.     29.  218.  1546.  1793.  20.3   260.0
781017 290  1 1        5.1  2.6    9.   6.   15.      7.   49.  1364.  1420.  13.3   100.0
7811 1 305  1 1        4.3  1.5    6.  16.   22.      3.   65.  1036.  1104.  25.1   315.0



781114 318  1 1       11.4  9.2   21.   7.   28.      3.   53.  1291.  1347.   5.9   317.0
781123 327  1 1       10.4  4.2   19.   0.   19.      4.   50.  1684.  1738.   6.3     0.0
781129 333  1 1        5.7  3.0   15.   7.   22.     10.   40.  1676.  1726.   7.4   281.0
7812 6 340  1 1        6.9  2.1   15.   5.   20.      4.   39.  1429.  1472.   5.3     0.0
781213 347  1 1       11.1  3.5   23.  28.   51.      8.   34.  1436.  1478.   4.0   271.0
781220 354  1 1       12.2  3.0   15.   7.   22.      1.   28.  1226.  1255.   4.3   271.0
781228 362  1 1        9.6  4.5   32.   3.   35.     25.   19.  2001.  2045.   3.0   619.0
79 1 3   3  1 1       16.0  7.4  340.   1.  341.      4.   30.  2057.  2091.    .2   493.0
79 110  10  1 1        7.4  2.4   23.  10.   33.     14.   48.  2022.  2084.   5.0   455.0
79 117  17  1 1        4.7  2.3   40.   9.   49.      4.   37.  2635.  2676.   2.3   581.0
79 124  24  1 1        4.9  2.5   26.  21.   47.      4.   52.  2436.  2492.   4.8   538.0
79 131  31  1 1        6.8  3.1   11. 111.  122.      4.   40.  2247.  2291.   8.9   595.0
79 2 7  38  1 1        7.8  1.9   14.  21.   35.      4.   33.  2378.  2415.   5.9   690.0
79 214  45  1 1        8.5  4.5   17.  23.   40.      5.   51.  2726.  2782.   7.3   683.0
79 221  52  1 1        9.4  4.4   17.  43.   60.     10.   54.  2944.  3008.   3.9   703.0
79 228  59  1 1       11.8  7.2   22.  32.   54.      2.   26.  2753.  2781.   2.4   594.0
79 3 7  66  1 1       18.9  6.2   22. 215.  237.      4.   53.  2758.  2815.   5.7   899.0
79 315  74  1 1        0.0  0.0   39.  48.   87.      3.   43.  3502.  3548.   2.5   883.0
79 321  80  1 1       20.8  0.0   29.  36.   65.      4.   73.  3575.  3652.   5.9   921.0
79 328  87  1 1       17.1   .9   19.  28.   47.      1.   34.  3982.  4017.   4.1   978.0
```

SITE 2.

```
78 919 262  2 1    1.5   .5   293.   44.  337.    25.   23. 1245. 1293.   .4    124.0
781017 290  2 1  142.3  2.5   283.   51.  334.     4.   10. 1149. 1163.   .1     78.0
7811 1 305  2 1  135.0 11.4    60.  154.  214.    15.   33. 2001. 2049.  1.8    182.0
781114 318  2 1   46.7 10.5   114.   44.  158.    13.   66. 1912. 1991.  1.5    205.0
781123 327  2 1    3.3  7.7    67.   44.  111.     4.   86. 1421. 1511.  3.0    324.0
781129 333  2 1    9.0  4.9    78.   40.  118.     8.  135. 1819. 1962.  4.1    332.0
7812 6 340  2 1    9.6  8.7    67.   44.  111.    10.  102. 1440. 1552.  3.7    353.0
781213 347  2 1   11.4  5.4    80.  117.  197.     5.   49. 1688. 1742.  1.5    424.0
781220 354  2 1   14.8  4.1   169.   69.  238.     6.   38. 1932. 1976.   .6    310.0
781228 362  2 1   17.1  4.9   104.   51.  155.     7.   19. 1835. 1861.   .6    457.0
79 1 3   3  2 1    6.5  3.6   252.    1.  253.    35.  114. 2235. 2384.  1.4    434.0
79 110  10  2 1    4.5  2.9   113.    1.  114.    23.   63. 2124. 2210.  1.6    488.0
79 117  17  2 1    2.4  2.8   132.   18.  150.     9.   40. 2263. 2312.   .8    574.0
79 124  24  2 1    1.5  3.5   170.   90.  260.     5.  114. 2343. 2462.  1.6    574.0
79 131  31  2 1    1.9  2.1   191.    0.  191.    14.  143. 2163. 2320.  1.8    625.0
79 2 7  38  2 1    2.6  3.2   224.   19.  243.    15.  183. 2383. 2581.  2.0    700.0
79 214  45  2 1    4.9  4.1   154.   79.  233.     5.   89. 2935. 3029.  1.4    772.0
79 221  52  2 1    5.6  4.5   170.   94.  264.    15.  175. 2451. 2641.  2.5    806.0
79 228  59  2 1   25.4 17.4   117.  369.  486.     6.  125. 2766. 2897.  2.5    964.0
79 3 7  66  2 1   10.3  9.3   154.  246.  400.     5.  246. 2393. 2644.  3.6   1010.0
79 315  74  2 1    0.0  0.0   180.  255.  435.    80.  103. 4176. 4359.  2.3    981.0
79 321  80  2 1   16.0  0.0    60.   52.  112.     8.   83. 3076. 3167.  3.4   1019.0
79 328  87  2 1   22.4  0.0   105.   39.  144.     3.  116. 3593. 3712.  2.5   1059.0
```

SITE 3.

```
781114 318  3 1  433.0 19.2     0.    0.    0.     0.    0.    0.    0.   I       0.0
781123 327  3 1    1.9  2.0   677.  245.  922.     8. 1068.  456. 1532.  3.5    117.0
781129 333  3 1    2.1  1.8   633.   74.  707.    25. 1864. 2947. 4836.  5.6    133.0
7812 6 340  3 1   13.0  5.8   472.  171.  643.   160. 1360. 2342. 3862.  7.1    161.0
781213 347  3 1   42.5 12.4   342.    1.  343.   383.  344. 1660. 2387.  4.7    154.0
781220 354  3 1   18.3  5.0   260.   88.  348.     2.   10. 1844. 1856.   .1    171.0
781228 362  3 1  541.1141.9   488.  400.  888.     0.    1. 9422. 9423.   .0    162.0
79 1 3   3  3 1   27.5 25.0   715.  210.  925.    44.  316. 4191. 4551.  1.1     96.0
79 110  10  3 1   60.4 17.9   741.  346. 1087.    15.   22. 3819. 3856.   .1    210.0
79 117  17  3 1   49.3 20.1   911.  247. 1158.     2.   22. 3921. 3945.   .1    224.0
79 124  24  3 1   23.9 11.5   754.  176.  930.     2.   10. 3203. 3215.   .0    235.0
79 131  31  3 1   23.7  7.7   672.  239.  911.     3.   15. 2725. 2743.   .1    254.0
79 2 7  38  3 1   21.2  9.1   643.  191.  834.    10.  198. 3386. 3594.   .7    291.0
79 214  45  3 1   20.5  9.6   575.   42.  617.    10.  140. 2600. 2750.   .5    302.0
79 221  52  3 1   19.0  9.8   535.  331.  866.    15.  188. 2451. 2654.   .5    350.0
79 228  59  3 1   15.4  8.0   454.  130.  584.     3.   38. 2629. 2670.   .2    472.0
79 3 7  66  3 1   26.2 17.5   808.  133.  941.     5.  254. 3383. 3642.   .7    533.0
79 315  74  3 1    0.0  0.0   800.   35.  835.    20.  210. 3427. 3657.   .6    442.0
```

SITE 4.

78 919	262	4	1	5.3	3.6	63.	21.	84.	19.	371.	1492.	1862.	13.7	218.0
781017	280	4	1	4.9	4.2	25.	15.	40.	6.	131.	1421.	1558.	12.1	217.0
781114	318	4	1	10.5	2.4	24.	114.	138.	2.	54.	1249.	1309.	5.5	346.0
781123	327	4	1	14.4	5.7	20.	0.	20.	2.	22.	1240.	1264.	2.0	0.0
781129	333	4	1	11.1	5.0	45.	20.	65.	2.	30.	1590.	1622.	1.5	218.0
7812 6	340	4	1	16.5	5.2	30.	26.	56.	2.	34.	1752.	1788.	2.7	399.0
781213	347	4	1	13.3	4.5	25.	46.	71.	2.	31.	1573.	1606.	2.9	405.0
781220	354	4	1	43.4	12.9	23.	87.	110.	2.	18.	1717.	1737.	1.9	223.0
781228	362	4	1	13.5	3.2	51.	34.	85.	6.	11.	2075.	2093.	.7	223.0
79 1 3	3	4	1	15.6	5.7	81.	51.	132.	31.	21.	2316.	2368.	1.4	474.0
79 110	10	4	1	4.1	1.4	24.	18.	42.	22.	32.	2022.	2076.	5.0	524.0
79 117	17	4	1	35.9	8.3	53.	41.	94.	2.	17.	2432.	2451.	.8	538.0
79 124	24	4	1	1.9	2.1	65.	30.	95.	2.	5.	2452.	2459.	.2	505.0
79 131	31	4	1	4.7	1.4	18.	0.	18.	2.	29.	2126.	2157.	3.3	548.0
79 2 7	38	4	1	5.3	3.5	19.	42.	61.	2.	22.	2642.	2666.	2.8	656.0
79 214	45	4	1	13.0	7.6	34.	71.	105.	5.	50.	2784.	2839.	3.6	625.0
79 221	52	4	1	13.6	6.3	58.	0.	58.	8.	33.	3138.	3179.	1.6	608.0
79 228	59	4	1	18.1	11.5	26.	246.	272.	1.	280.	1754.	2035.	23.9	656.0
79 315	74	4	1	43.3	10.6	41.	58.	99.	2.	40.	3597.	3639.	2.3	538.0

SITE 5.

78 919	262	5	1	.5	1.0	9.	4.	13.	8.	129.	1701.	1838.	33.7	298.0
781017	280	5	1	1.5	4.2	8.	4.	12.	6.	143.	1404.	1558.	42.6	302.0
7811 1	305	5	1	4.3	.5	4.	9.	13.	6.	205.	933.	1145.	117.4	314.0
781114	318	5	1	58.5	1.2	23.	30.	53.	5.	126.	1703.	1834.	12.5	190.0
781123	327	5	1	4.7	2.0	14.	1.	15.	4.	135.	1423.	1563.	22.1	335.0
781129	333	5	1	5.7	3.0	17.	6.	23.	2.	80.	1590.	1672.	10.7	238.0
7812 6	340	5	1	19.2	5.6	22.	72.	94.	4.	73.	2272.	2349.	7.3	208.0
781213	347	5	1	14.1	2.9	23.	6.	29.	3.	43.	1606.	1657.	4.9	91.0
781220	354	5	1	10.5	8.6	11.	16.	27.	3.	76.	1453.	1532.	15.9	430.0
781228	362	5	1	9.4	2.5	26.	1.	27.	7.	25.	1879.	1911.	2.7	274.0
79 1 3	3	5	1	11.3	2.9	15.	2.	17.	39.	31.	2055.	2126.	10.3	442.0
79 110	10	5	1	6.5	2.2	21.	73.	94.	28.	29.	2108.	2165.	6.0	443.0
79 117	17	5	1	4.5	1.4	28.	1.	29.	3.	40.	2780.	2823.	3.4	577.0
79 124	24	5	1	0.0	0.0	29.	1.	30.	3.	29.	3029.	3061.	2.4	527.0
79 131	31	5	1	10.9	2.5	11.	142.	153.	3.	40.	2322.	2365.	3.7	545.0
79 2 7	38	5	1	7.1	3.4	16.	7.	23.	2.	34.	2346.	2382.	5.0	656.0
79 214	45	5	1	7.7	1.9	11.	22.	33.	5.	32.	2160.	2197.	7.4	643.0
79 221	52	5	1	7.1	5.4	24.	41.	65.	5.	15.	2312.	2332.	1.4	733.0
79 228	59	5	1	12.5	4.1	26.	10.	36.	1.	15.	2652.	2668.	1.3	874.0
79 3 7	66	5	1	10.3	4.4	14.	163.	177.	2.	44.	2717.	2763.	7.3	915.0
79 315	74	5	1	18.5	11.7	33.	27.	60.	2.	31.	3605.	3638.	2.2	874.0
79 321	80	5	1	12.8	1.6	24.	23.	47.	4.	82.	3444.	3530.	7.9	905.0
79 328	87	5	1	23.9	0.0	21.	25.	46.	1.	26.	3683.	3710.	2.8	931.0

78 919	262	6	1	1.3	.5	12.	8.	20.	160.	23.	462.	650.	34.7	20.0	
781017	280	6	1	0.0	0.0	18.	1.	19.	240.	8.	504.	752.	39.5	0.0	SITE 6.
781114	318	6	1	19.8	3.1	39.	9.	48.	1.	20.	634.	655.	1.2	127.0	
781123	327	6	1	11.9	6.4	43.	5.	48.	1.	32.	1056.	1089.	1.7	131.0	
781129	333	6	1	12.1	5.5	27.	18.	45.	15.	30.	796.	845.	4.0	13[illegible].0	
7812 6	340	6	1	12.8	5.1	21.	10.	31.	3.	33.	758.	794.	3.8	87.0	
781213	347	6	1	19.4	4.5	35.	7.	42.	2.	30.	740.	772.	2.0	95.0	
781220	354	6	1	13.7	4.6	17.	22.	39.	1.	15.	689.	705.	2.1	23.0	
781228	362	6	1	16.7	5.1	43.	1.	44.	6.	16.	888.	910.	1.1	135.0	
79 1 3	3	6	1	19.4	8.0	25.	28.	53.	35.	21.	989.	1045.	5.0	173.0	
79 110	10	6	1	10.3	4.5	30.	65.	95.	35.	21.	999.	1055.	4.1	120.0	
79 117	17	6	1	8.5	3.3	19.	128.	147.	2.	40.	984.	1026.	4.9	174.0	
79 124	24	6	1	4.5	2.6	21.	151.	172.	2.	7.	996.	1005.	.9	152.0	
79 131	31	6	1	6.4	3.5	11.	100.	111.	2.	17.	798.	817.	3.4	183.0	
79 2 7	38	6	1	5.1	2.4	10.	8.	18.	1.	13.	878.	892.	3.1	193.0	
79 214	45	6	1	7.1	2.1	9.	14.	23.	10.	16.	837.	863.	5.4	187.0	
79 221	52	6	1	8.1	2.9	19.	25.	44.	10.	47.	646.	703.	5.5	184.0	

79 228	59	6	1	7.7	3.8	14.	12.	26.	1.	17.	560.	578.	2.8	211.0	
79 3 7	66	6	1	5.8	1.6	11.	59.	70.	1.	24.	729.	754.	5.0	355.0	
79 315	74	6	1	7.6	4.5	28.	5.	33.	1.	18.	919.	938.	1.5	176.0	
79 321	80	6	1	5.0	0.0	10.	32.	42.	8.	41.	609.	658.	10.9	180.0	
79 328	87	6	1	8.5	0.0	9.	13.	22.	1.	17.	695.	713.	4.4	169.0	
7811 1	305	7	1	164.0	39.3	419.	127.	546.	3.	10.	1539.	1552.	.1	124.0	SITE 7.
7812 6	340	8	1	5.1	1.4	11.	1.	12.	2.	40.	1414.	1456.	3.5	400.0	
7812 6	340	8	3	0.0	0.0	19.	16.	35.	0.	40.	1536.	1576.	5.4	384.0	GRID - 6|12|78
7812 6	340	9	1	4.5	1.6	12.	28.	40.	3.	34.	1350.	1387.	5.3	4[illegible].0	
7812 6	340	10	1	8.1	2.3	10.	0.	10.	3.	46.	1321.	1370.	13.4	37[illegible].0	
7812 6	340	10	3	0.0	0.0	13.	1.	14.	3.	43.	1516.	1562.	7.8	0.0	
7812 6	340	11	1	13.2	4.1	17.	23.	40.	3.	36.	1628.	1667.	5.1	300.0	
7812 6	340	12	1	7.7	1.9	17.	20.	37.	3.	116.	1383.	1502.	15.5	245.0	

```
781213 347  8 1      6.5  2.1    15.   15.   31.     1.   32.  1472.  1505.   4.9        341.0   GRID - 13|12|78
781213 347 12 1      6.8  1.5    17.    6.   23.     3.   80.  1490.  1573.  10.9        217.0
781213 347 13 1     10.2  3.3    60.   93.  153.     1.   28.  1692.  1721.   1.1        274.0
781213 347 14 1     10.9  4.5    24.   15.   39.     1.   44.  1493.  1538.   4.2        289.0
781213 347 15 1     20.1  5.1    25.  111.  136.     6.   21.  1549.  1576.   2.4        317.0
781213 347 16 1     12.2  2.9    19.    7.   26.     2.   23.  1564.  1589.   2.9        112.0
781213 347 17 1     11.2  2.7    19.   73.   92.     7.   29.  1741.  1777.   4.2        333.0
79 131   31  8 1     7.3  3.4    11.   60.   71.     2.    0.     0.     2.    .4        605.0
79 131   31 11 1     6.2  3.3    11.    6.   17.     2.   29.  2088.  2119.   6.2        609.0   GRID - 31|1|79
79 131   31 12 1     7.5  1.3     9.    8.   17.     2.   55.     0.    57.  15.5        632.0
79 131   31 13 1     1.5  1.9    16.  257.  273.     2.   31.  3120.  3153.   4.6        639.0
79 131   31 14 1     5.1  2.6    10.  201.  211.     2.   25.  2510.  2537.   6.9        649.0
79 131   31 15 1    33.3  7.5    17.  159.  176.     3.   31.  2210.  2244.   4.4        653.0
79 131   31 16 1     6.8  1.7    10.  103.  113.     2.   34.  2270.  2306.   6.6        635.0
79 131   31 17 1     5.1   .8     9.  117.  126.     2.   34.  2121.  2157. [illegible]   663.0
79  3 7  66  8 1     9.0  4.2    13.   71.   84.     2.   57.  2479.  2538.  11.8        869.0
79  3 7  66  9 1    12.3  2.5    20.   69.   89.     2.   70.  2630.  2702.   4.0        832.0   GRID - 7|3|79
79  3 7  66 10 1    10.7  4.3    19.   80.   99.     2.   38.  2551.  2591.   7.0        784.0
79  3 7  66 12 1     9.1  4.4    13.  153.  166.     2.   48.  2315.  2365.   8.5        654.0
79 228   87 21 1    33.3  0.0    42.   49.   91.     1.  176.  1881.  2058.  12.2        359.0   SITE 21.
7811 1  305 91 1     5.9   .5    13.   47.   60.     2.    9.   532.   543.   2.0        158.0   LAKE GOOLLELAL
7811 1  305 92 1     4.5   .5     7.   19.   26.     3.   10.   980.   993.   4.1        145.0
781129  333 91 1     1.7  1.2     7.   14.   21.     6.  171.   883.  1060.  55.0        163.0
781129  333 93 1     5.0  2.5   127.    6.  133.     4.   37.   702.   743.    .7        130.0
781220  354 93 1     8.8  3.4   255.   60.  315.     9.   54.   728.   791.    .6         53.0
79 124   24 93 1    12.2  5.8   139.    0.  139.     2.    7.  1259.  1268.    .1        202.0
79 221   52 93 1    15.6 12.0   780.  287. 1067.   145.  529.  1309.  1983.   1.9        210.0
79 315   74 93 1    17.0  8.6   697.  100.  797.    30.   51.     0.    81.    .3        259.0
79 131   31 99 1     5.0  1.4   190.  263.  453.     3.   15.  1970.  1988.    .2        355.0
79 228   59 99 1    42.4 12.0   392.    4.  396.     2.    9.  2011.  2022.    .1        533.0   BEENYUP SWAMP
79 328   87 99 1    32.0  0.0   653.  196.  849.     1.   25.     0.    26.    .1        613.0
D=DEPTH WHERE 1=SURFACE,2=MID-DEPTH,3=BOTTOM.      CHLORIDE AS MG/L.OTHERS AS UG/L.     RATIO=INORGANIC N/P.

       0 DENOTES NO DATA, ZERO RESULT GIVEN AS MINIMUM DETECTION LIMIT.
```

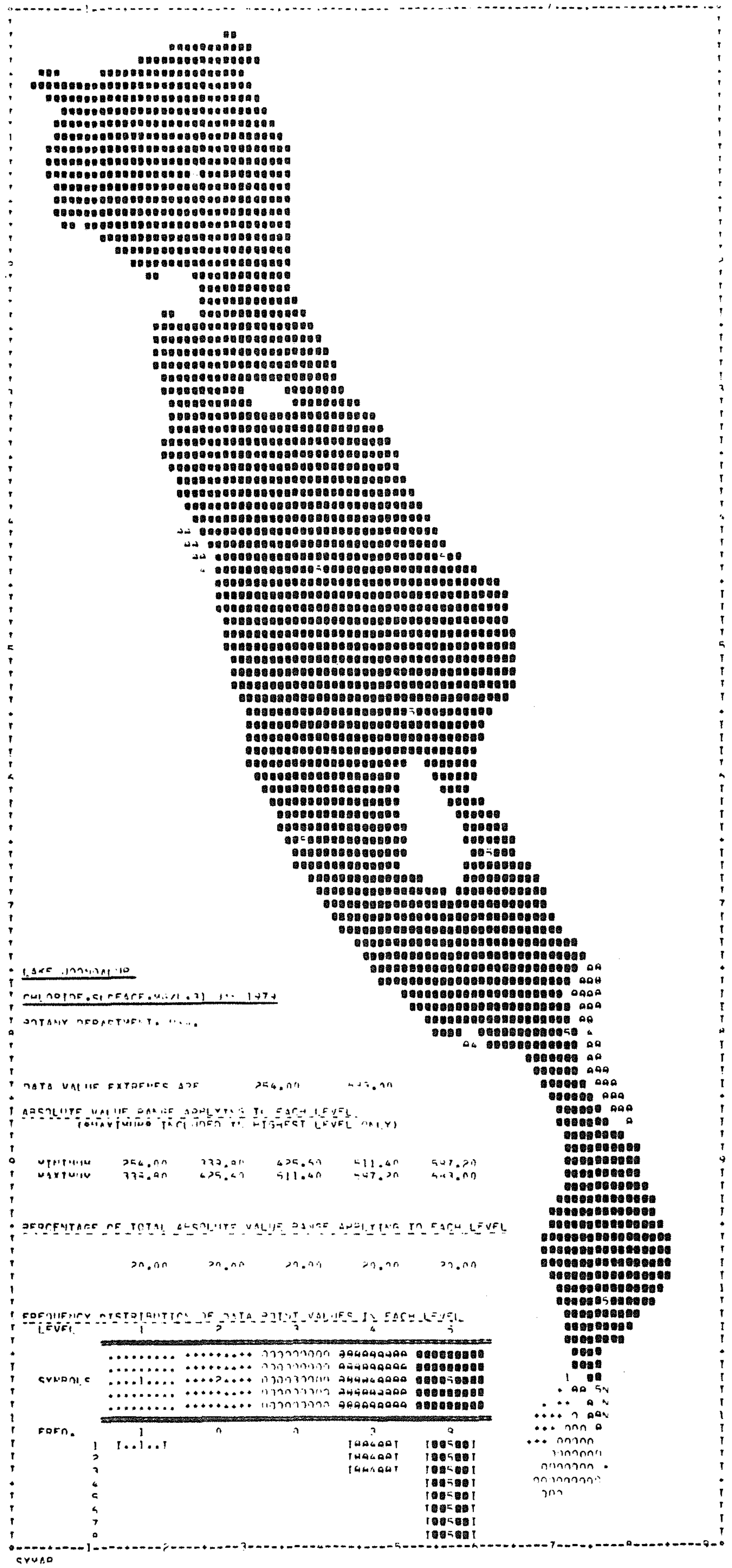
Appendix 2. Examples of the Symap computer output.

(a) Output for surface chloride on January 31, 1979

Note the lower chloride levels found south of Mullaloo Rd (at the bottom of the figure), and on the eastern shore. Recent data confirm this picture, suggesting that fresher water enters the lake through Beenyup Swamp to the south, and as groundwater from the east.

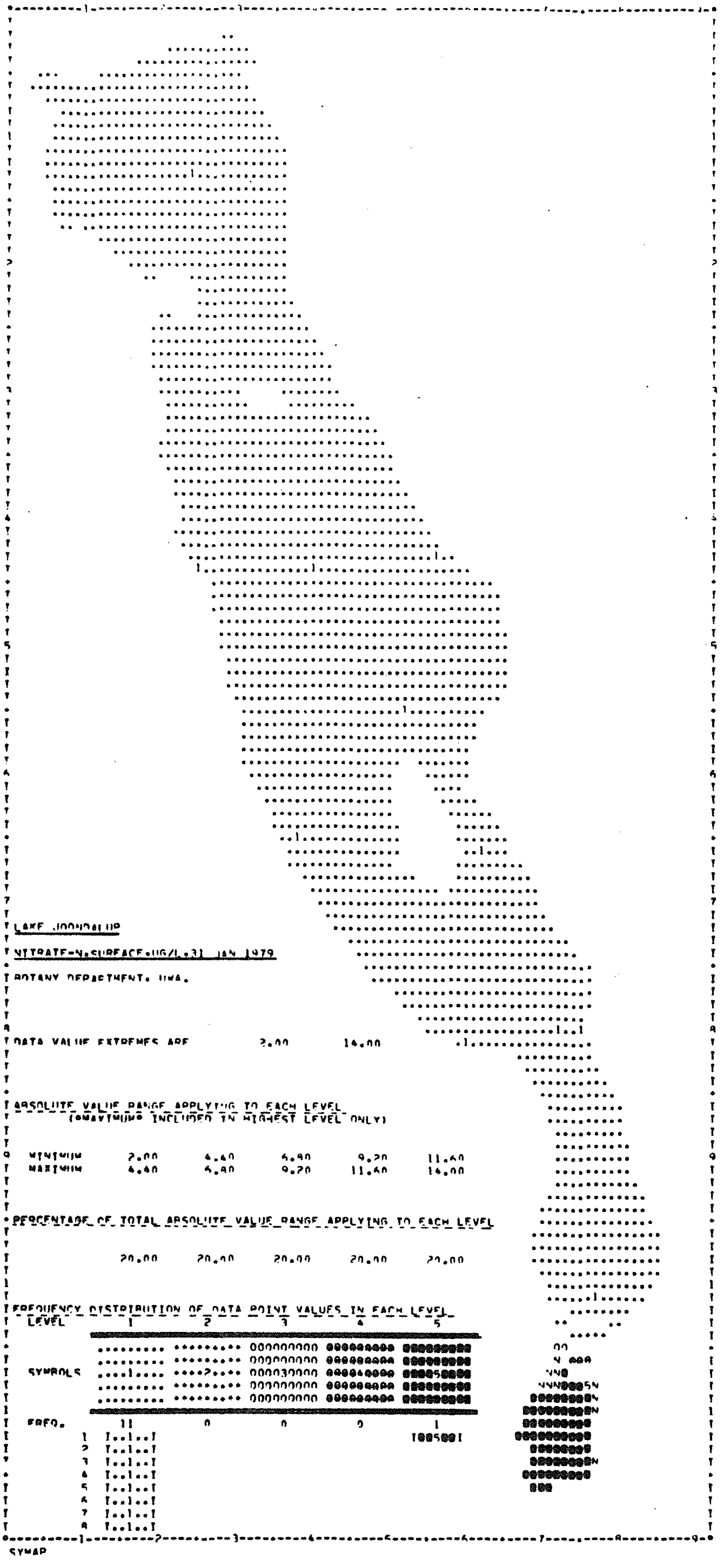
(b) Output for surface nitrate on January 31, 1979

The fresher water entering the lake from the south contains nutrients in higher concentrations from those found in the lake, and this is depicted here for nitrate-nitrogen. This method may show whether stormwater drainage contributes high nutrient concentrations during the winter period.



```
LAKE JOONDALUP

CHLORIDE,SURFACE,MG/L,31 [illegible] 1974

BOTANY DEPARTMENT, U.W.A.



DATA VALUE EXTREMES ARE        254.00       683.00

ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
        (MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY)


  MINIMUM     254.00     339.80     425.60     511.40     597.20
  MAXIMUM     339.80     425.60     511.40     597.20     683.00



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

            .......... ++++++++++ 0000000000 @@@@@@@@@@ ##########
            .......... ++++++++++ 0000000000 @@@@@@@@@@ ##########
  SYMBOLS   ....1..... ++++2+++++ 0000300000 @@@@4@@@@@ ####5#####
            .......... ++++++++++ 0000000000 @@@@@@@@@@ ##########
            .......... ++++++++++ 0000000000 @@@@@@@@@@ ##########

  FREQ.          1          0          0          3          9
          1  I..1..I                          I@@4@@I    I##5##I
          2                                   I@@4@@I    I##5##I
          3                                   I@@4@@I    I##5##I
          4                                              I##5##I
          5                                              I##5##I
          6                                              I##5##I
          7                                              I##5##I
          8                                              I##5##I
```

SYMAP



```
LAKE JOONDALUP

NITRATE-N,SURFACE,UG/L,31 JAN 1979

BOTANY DEPARTMENT, UWA.



DATA VALUE EXTREMES ARE          2.00        14.00



ABSOLUTE VALUE RANGE APPLYING TO EACH LEVEL
        (MAXIMUM INCLUDED IN HIGHEST LEVEL ONLY)


  MINIMUM       2.00       4.40       6.80       9.20      11.60
  MAXIMUM       4.40       6.80       9.20      11.60      14.00



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

             .......... ++++++++++ 000000000 @@@@@@@@@ @@@@@@@@@
             .......... ++++++++++ 000000000 @@@@@@@@@ @@@@@@@@@
  SYMBOLS    ....1..... ++++2+++++ 000030000 @@@@4@@@@ @@@@5@@@@
             .......... ++++++++++ 000000000 @@@@@@@@@ @@@@@@@@@
             .......... ++++++++++ 000000000 @@@@@@@@@ @@@@@@@@@

  FREQ.          11          0          0          0          1
          1  I..1..I                                   I@@5@@I
          2  I..1..I
          3  I..1..I
          4  I..1..I
          5  I..1..I
          6  I..1..I
          7  I..1..I
          8  I..1..I
```

SYMAP