

3.—The nutrients and plants of Lake Joondalup, a mildly eutrophic lake experiencing large seasonal changes in volume

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Abstract

Lake Joondalup is a shallow body of fresh water in a calcareous stable dune system 6 km from the ocean. The fringing and aquatic vegetation is described. Cation ratios resemble sea water apart from relatively high calcium, attributed to leaching from limestone. Seasonal changes in volume greatly affect ionic concentrations. A bloom of the green alga *Dispora* coincides with low volume and high ion levels. Total nitrogen is relatively high compared with phosphorus. The surrounding land is becoming urbanized, and the data provide a baseline for future reference.

Introduction

Problems associated with the enrichment of lakes in urban areas, with 'blooms' of planktonic algae (some of them toxic to animals), increased bacterial activity, and oxygen depletion at depth, are of worldwide occurrence (e.g. Jackson, 1964). Press reports of the death in late summer of fish and birds in certain lakes of the metropolitan area of Perth indicate that Western Australia is no exception. While it is easy to suggest that the addition of nutrients derived from septic tanks, garbage disposal, and agricultural and lawn fertilisers, are primarily responsible for the eutrophication of these waters, quantitative data concerning nutrient levels and algae are lacking.

The present paper is concerned with the nutrients and plants of Lake Joondalup, which lies in a region of rapid urbanization and development. The lake is 32 km north of the centre of Perth and 6 km from the Indian Ocean, and is one of a chain of lakes which reaches Yanchep, 20 km further north. The lakes are linear, parallel to the coast, and lie in depressions in a Quaternary dune system (McArthur and Bettenay, 1960). They are an important component of the wetlands of the Swan Coastal Plain, which are being reduced in total area by draining and reclamation (Riggert, 1966).

The aim of this work was to place on record the seasonal fluctuations in certain nutrients and in the density of planktonic algae to provide a reference against which future changes in the lake may be assessed. A description of the fringing vegetation is also included to allow comparison with Loch McNess in the Yanchep National Park (McComb and McComb, 1967), and because much of this vegetation, which must relate to the nutrient status of the water, will be altered in the future.

Materials and methods

Collection of samples

Water samples were collected from 6 sites (Figure 1) over a period of one year. Samples for oxygen analyses were collected directly into a sample bottle where the water was shallow, or with a Hale's water sampler (Welch, 1948) where the water was sufficiently deep to allow use of this apparatus. Other samples were collected with a plastic bilge pump at a depth of 5 cm. All were collected between 1000 and 1600 hr. At each site measurements were made of water temperature and pH (BpH Electrometer, N. L. Jones, Melbourne). A comparative measure of light transparency was obtained with a 20 cm-diameter Secchi disc divided into black-and-white quadrants.

Samples for metallic cations were stored in clean 250 ml glass bottles, with 1 ml of 1:1 (by vol.) nitric acid added to prevent adsorption and biological activity. Other samples were stored at 4° in thoroughly-washed, 5 l polyethylene jars.

Water analysis

Dissolved oxygen was initially measured in the field with an oxygen meter (Beckman Fieldlab Oxygen Analyser, Beckman Instruments, Fullerton, California) and subsequently by the azide modification of the Winkler Method (Anon. 1955). *Conductivity* was determined on return to the laboratory with a conductivity meter (E 382, Metrohm Ltd., Herisau, Switzerland). *Ammonia* was determined by distillation and nesslerization (Anon. 1955); *organic nitrogen* by Kjeldahl digestion (Anon. 1955) followed by titration with an automatic titrator (W. G. Pye, Cambridge, England); *inorganic phosphorus* as orthophosphate by the molybdate-blue reaction using stannous chloride as the catalyst (Anon. 1955); *total phosphorus* as orthophosphate after perchloric acid digestion (Robinson, 1941); and chloride by potentiometric titration using a Clinical Chloride Titrator (4-4415, American Instrument Co., Silver Spring, Maryland). *Carbonate/bicarbonate* was determined on one occasion using the double-indicator method (Anon. 1955).

Samples for analysis of *metallic cations* were given the pretreatment for total metals described by Parker (1972). Calcium and magnesium were then determined by atomic absorption spectrophotometry (Varian 1000, Varian Techntron Pty. Ltd., Springvale, Victoria), and sodium and potassium by flame photometry (EEL Flame Photometer, EEL International Ltd., Bayswater, Victoria).

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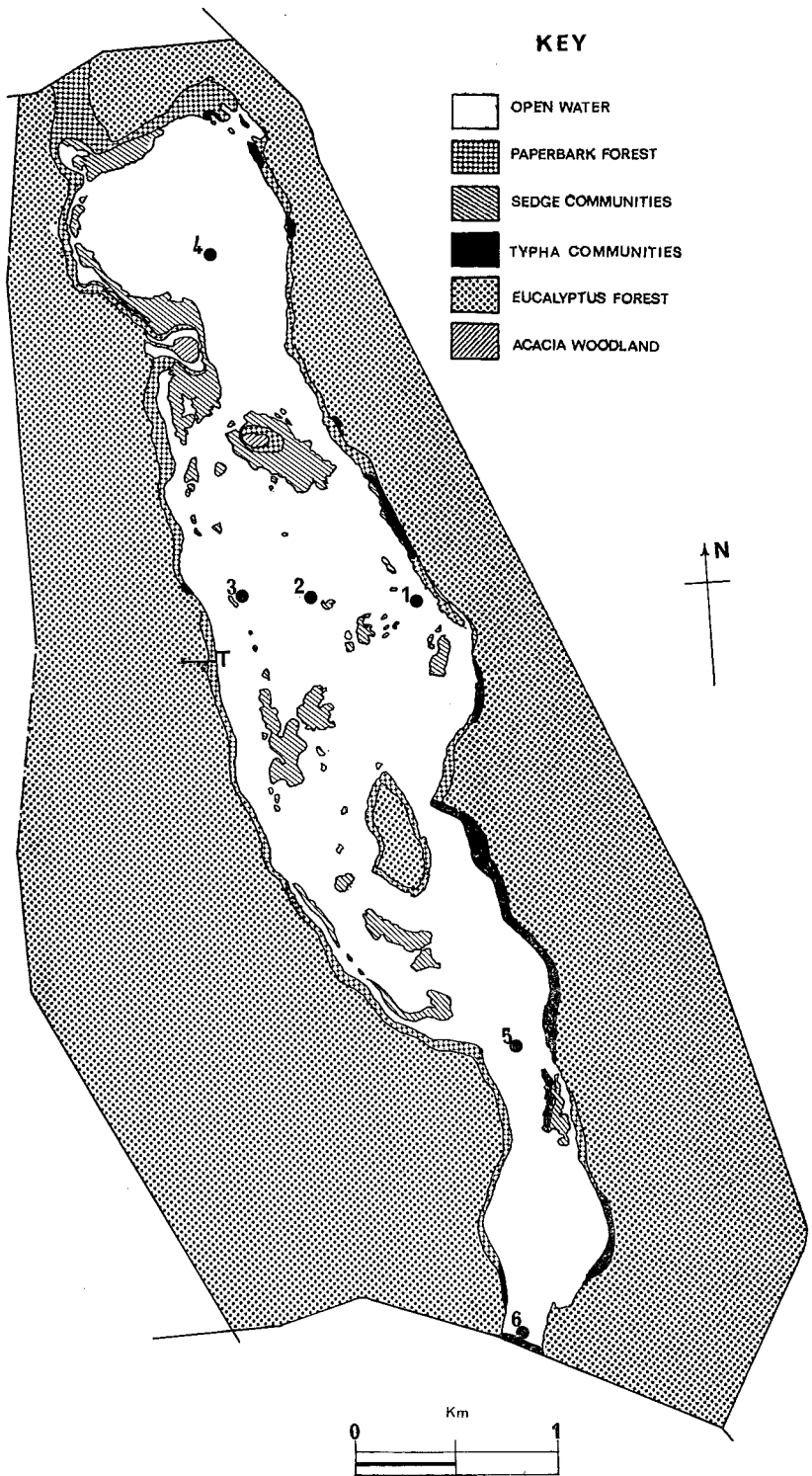


Figure 1.—Lake Joondalup, showing general features, vegetation, and sampling sites.

Productivity

Samples of 500 ml of water from each site were centrifuged (660xg; 10 min) and the supernatant removed with a suction pump to leave 10 ml of water plus centrifugate, which was transferred to a stoppered flask and stored in the dark at 4° until phytoplankton counts were made with a Neubauer counting chamber. The problem of obtaining truly representative plankton samples for the lake is great, as the large area and shallow water leads to lack of homogeneity in phytoplankton populations. For example, although in October counts were generally low at the six sites, it was clear that a bloom, primarily of *Oscillatoria* and a colonial alga, was present in parts of the lake not included by the six sites. Nevertheless, seasonal trends are clear, main species were identified, and general variability is reflected in the standard errors of the site means, as given below.

Seston productivity was estimated on duplicated 500 ml aliquots, centrifuged as for the phytoplankton counts. Each 10 ml residue was transferred to a 50 ml porcelain crucible, dried at 80° overnight, placed in a desiccator for 30 min and weighed. It was then ashed in a muffle furnace at 650° for 30 min, cooled in a desiccator and reweighed. Seston productivity was calculated as loss on ignition in grams per litre.

Observations and discussion

General features

The lake (Figure 1) is a shallow, closed body of fresh water 8 km long and 1.2 km wide at its broadest point. The depth varies seasonally but has never exceeded 3.3 m. The water surface is some 18 m above mean sea level, and the area is 6.1 km² (610 hectares). There is no surface outlet for the lake, and it is believed that water passes through the limestone on the western shore, towards the sea. The western bank is relatively steep and little disturbed. To the east the land slopes more gently, and there is a housing settlement. Deep sewerage has become available in the area, and at the time of the study about 25% of the 630 houses present had been connected to the system.¹

The mean depths of the sampling sites were between 10 and 190 cm during the period of the study, the changes in depth following changes in rainfall (Figure 2). By international standards, therefore, Lake Joondalup is very shallow, and because of this shallow character the changes in depth represent large changes in lake volume. One would therefore expect significant seasonal changes in concentrations of dissolved elements because of this factor alone. The water level has been even lower in the past, as indicated by the presence of submerged fence posts in the open water of the southern and eastern regions of the lake; there is evidence

that the general water level of wetlands in the coastal plain has increased, presumably as a result of clearing (Evans and Sherlock, 1950; Speck, 1952).

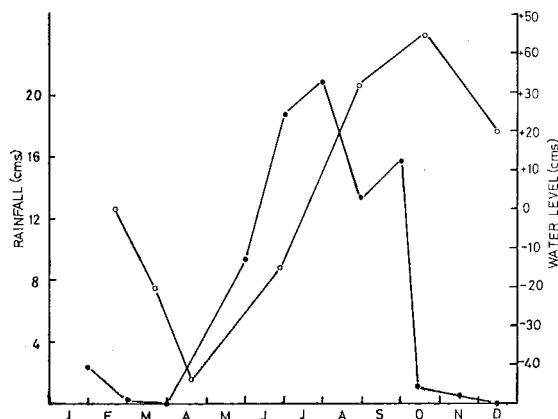


Figure 2.—The water level of Lake Joondalup (○), plotted with monthly rainfall data (●) for the townsite of Wanneroo, which lies immediately east of the Lake.

Vegetation

The distribution of main communities is shown in Figure 1, and a transect through the fringing communities on the western shore is presented in Figure 3.

Open Water and littoral fringes—Shallow waters, less than about 70 cm in summer, are densely populated with the benthic stoneworts, *Nitella congesta* and *Chara baueri*, and *Potamogeton pectinatus*. *Najas marina* and *Myriophyllum propinquum* are also found in the shallow waters, but are more common in the deeper waters at the northern end of the lake. The floating plants *Lemna minor* and *Azolla filiculoides* were collected in the fringing sedge communities, but were never numerous during the period of study.

The sedge *Baumea articulata* (*Machaerina articulata*, *Cladium articulatum*) is the dominant macrophyte of the lake, occurring generally in rare stands. It attains a height of 2 to 3 m and, through decomposition, is the main contributor to a fibrous peat of the lake margins and sedge banks. *B. articulata* is replaced by *Typha* in restricted areas where pasture or roads encroach on the lake edge. *Scirpus validus* and *Juncus pallidus* also occur in restricted areas.

Fen vegetation.—This is represented by a few small pockets of *Baumea juncea* (*Machaerina juncea*, *Cladium junceum*) located on the northern fringes of the two islands, and in scattered areas beneath swamp paperbarks. On Malap Island and on the lake margin to the north *Lepidosperma longitudinale* occurs in drier areas behind *B. juncea*.

¹ The general information included in this paragraph was provided by courtesy of the Shire Clerk, Shire of Wanneroo.

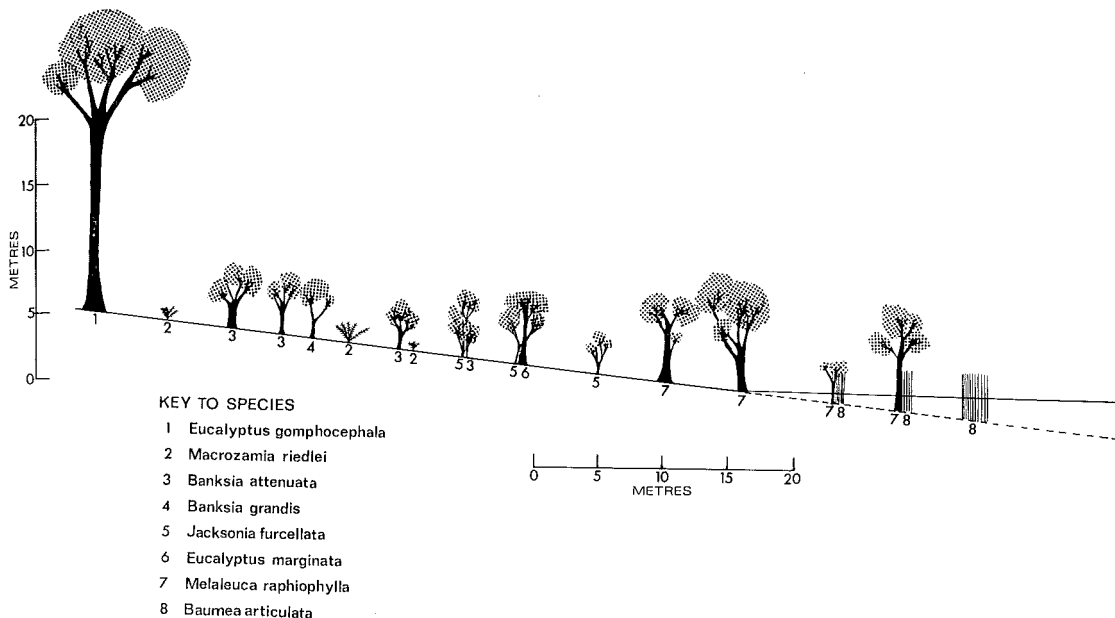


Figure 3.—The vegetation fringing Lake Joondalup. The profile was drawn from a 2 m-wide transect situated at site T, Figure 1.

Paperbark woodland.—A woodland of swamp paperbark (*Melaleuca raphiophylla*) borders the fringing sedge communities, and the bases of the trees are inundated during the winter months. The woodland consists of a narrow belt of trees with dense, touching canopies, and often includes *Eucalyptus rudis*, *Baumea juncea* and *Centella asiatica* are common. Seedlings of *M. raphiophylla* are established in meadows of *Baumea articulata* and this 'carr' is extensive on the north-western side of the lake and to the south-east of Malap Island.

Surrounding woodland.—An ecotonal community can be recognized between the paperbark woodland and the surrounding forest. It consists of a number of species which occur in both communities, including *Acacia cyclops*, *Acacia saligna*, *Jacksonia furcellata*, *Banksia littoralis* and *Banksia attenuata*. *Banksia ilicifolia* occurs in the ecotonal region on the north-eastern shore. In two small areas there are patches of *Acacia cyclops* sufficiently distinct to be designated 'Acacia woodland' (Figure 1). The surrounding forest has been described by Speck (1952) as tuart forest and jarrah-tuart-ecotone forest, and by Seddon (1972) as tuart-jarrah-marri tall open forest formation; its composition has been well documented by these authors. Much of the forest has been felled to the south for farming, and on the eastern shore is being cleared for housing developments.

General.—The fringing vegetation is in general similar to Loch McNess (McComb and McComb, 1967), but there is less species diversity at Lake Joondalup, and fen vegetation is not extensive. *Scirpus validus* is a more prominent member of the sedge communities at Loch McNess, and

this may be related to the seasonally more constant water level there. In contrast to the sedge communities, the benthic vegetation is more strongly developed at Lake Joondalup, in terms of both species number and plant density.

As there is evidence that the level of the lake has increased in relatively recent times, one might expect the swamp and fen successions to be disturbed, and it is quite possible that fen vegetation may have been more extensive in the past. The *Melaleuca* woodlands are more inundated in winter, and the root systems of the trees may be adversely affected by increased waterlogging. *Typha* appears to be associated with shore disturbance, and further disturbance may lead to an increase in this species.

Temperature and light

Water temperatures are closely correlated with mean monthly air temperatures (Figure 4). Light penetration as measured with the Secchi disc is shown in Table 1; the disc was visible to the substratum during February to June, but in August to December, when the lake was relatively deep, the limit of Secchi disc transparency was 30 to 130 cm above the substratum. As the point at which the Secchi disc becomes invisible is a useful guide to the depth at which light penetration allows the survival of benthic plants, light may well be a limiting factor for the growth of benthic plants at depth in the lake in August to December. Low light intensities and lower temperatures thus combine to reduce productivity of the benthic plants in winter. As shown below, plankton densities and seston productivity are at their lowest in August to

December, so that it is depth rather than density of suspended matter which is the prime factor influencing light penetration.

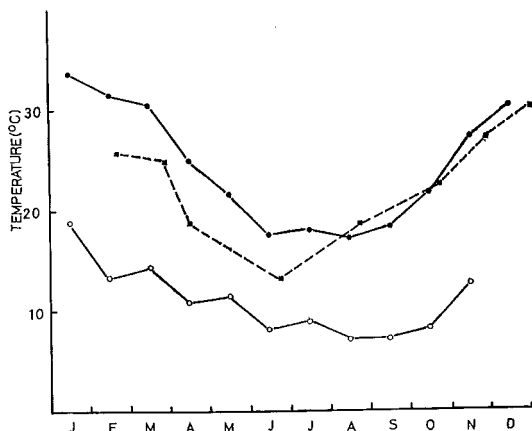


Figure 4.—The temperature of Lake Joondalup (broken line), plotted with atmospheric temperatures at the Upper Swan Research Station: (●, mean monthly maximum; o, mean monthly minimum).

Indian Ocean, and undoubtedly receive ions by wind and rain from that source. Evidence for this is discussed further below, but here we may note that the levels of chloride in the lake are relatively high. Chloride levels and conductivity show an expected trend in relation to change in lake volume, (cf. Figures 2 and 5), the increased water of the winter season diluting the dissolved ions.

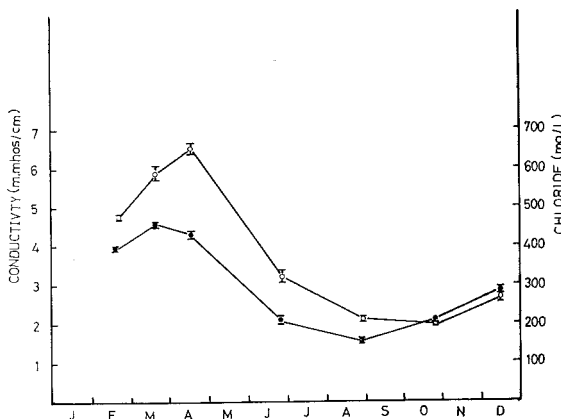


Figure 5.—Specific conductivity (●) and chloride concentrations (o) for Lake Joondalup.

Chemical characteristics

Oxygen.—The dissolved oxygen concentration varied seasonally between 6 and 9 mg l (Table 1). This range is relatively high, since the solubility of oxygen at 760 mm Hg is 8.1 mg/l at 25° and 10.3 mg/l at 13° (Hutchinson, 1957). (Oxygen becomes critical to aquatic life at 3 mg/l; Welch, 1952). These high levels are accounted for by the large surface area of the lake in relation to its volume, and exposure of the surface to agitation by wind and rain. The rich growth of benthic plants and presence of phytoplankton indicates a contribution to the oxygen concentration through photosynthesis during daylight hours. The possibility of oxygen depletion at night was not investigated in the present study.

Specific conductivity.—This ranged from 1068 to 3114 $\mu\text{mhos.cm}^{-1}$ (0.7–1.8% Total Dissolved Solids) (Figure 5). At Loch McNess a mean conductivity of 394 ($\mu\text{mhos.cm}^{-1}$) was reported on one occasion (McComb and McComb, 1967). The concentrations of dissolved salts in Lake Joondalup are comparatively high for a freshwater lake—for example Juday and Birge (1933) obtained a range of 9 to 124 (μmhos for more than 500 Wisconsin lakes, and Welch (1952) found lakes in Michigan to have a range of 10 to 330. Inland Australian lakes are characteristically much more saline (Bayly and Williams, 1973). The high conductivity is a reflection of high concentrations of individual ions (see below). The high conductivities of Lake Joondalup and Loch McNess are partially explained by their locations near aeolian limestone deposits. In addition, they are situated within 6 km of the

Acidity.—The lake is alkaline, and pH did not vary greatly with season, the range being 8.4 to 9.2 (Table 1). Constancy can be at least in part attributed to the buffering effect of carbonate and bicarbonate ions, the levels of which are expected to be high in view of the amounts of calcium and magnesium present (see below). An analysis of carbonate-bicarbonate carried out in December gave an alkalinity of 180 mg CaCO_3/l . Leaching of calcareous deposits is presumably the main factor determining the high pH. For example, a South Australian volcanic lake in contact with limestone gave a pH of 8.2 (Bayly and Williams, 1964), while 19 eastern Australian lakes in silicious dunes had a pH range of 4.3 to 6.0 (Bayly, 1964). Loch McNess has a lower pH than Joondalup, a mean of 7.8 being reported (McComb and McComb, 1967), and this correlates with the lower conductivity of that lake.

Metallic ions.—Like chloride and conductivity, the concentration of metallic ions decreases with increase in water level (Figure 6). The levels of these ions are compared with certain other lakes in Tables 2 and 3. The first of these tables gives absolute levels, and the second the equivalents of each ion expressed as a percentage of the whole. It is clear that the levels of metallic cations at Joondalup are relatively high for a freshwater lake. The relative proportions of cations resemble those found by Bayly (1964) for 19 coastal dune lakes in Queensland and New South Wales, and are also similar to those found in seawater, and in rain-water collected 16 km from the coast (Hutton and Leslie, 1958), except for the higher level of calcium. The proportions in Lake Joondalup

Table 1*Seasonal changes in light penetration, oxygen and pH at Lake Joondalup**Means are of 6 sites: standard errors are in brackets*

| | February | March | April | June | August | October | December |
|-----------------------------------|-------------------------|-------------------------|-------------------------|---------------------|------------|------------|------------|
| Secchi disc transparency (m) | > 0.90 ¹ | > 0.90 ¹ | > 0.80 ¹ | > 0.95 ¹ | 0.63(0.04) | 0.61(0.02) | 0.58(0.04) |
| Dissolved oxygen (p.p.m.) | 8.85(0.59) ² | 8.60(0.45) ² | 6.12(0.60) ² | 8.91(0.14) | 8.82(0.51) | 8.23(0.16) | 8.15(0.62) |
| pH .... | .... | 9.22(0.14) | 8.97(0.21) | 8.45(0.11) | 8.58(0.23) | 8.54(0.24) | 8.73(0.53) |

¹ maximum depth of water at time of sampling² determined with oxygen probe; other oxygen data by titration**Table 2***Concentrations of ions found in various lakes**Data are in mg/l*

| Lake | Na | K | Ca | Mg | Cl | Reference |
|--|-------------|------------|--------------|--------------|--------------|-------------------------|
| Joondalup, W.A. | 140 to 513 | 8 to 20 | 44 to 57 | 21.5 to 43.5 | 212 to 655 | This paper |
| Coastal dune lakes, N.S.W. and Queensland | 7.9 to 26.3 | 0.2 to 1.2 | 0.2 to 0.8 | 0.7 to 2.8 | 12.5 to 43.3 | Bayly 1964 |
| Croispol Loch, Scotland | 20.9 | 1.6 | 27.1 | 22.2 | .... | Spence et al. 1971 |
| German lakes .... | .... | .... | 43.6 to 46.3 | .... | .... | Hutchinson 1957 |
| Tasmanian inland lakes .... | .... | .... | 0.8 to 82.4 | 0.2 to 118.6 | .... | Williams 1964 |
| Blue Lake, S.A. | 63 | 4 | 36 | 21 | 116 | Bayly and Williams 1964 |
| Cowan, W.A. ¹ | 74 276 | 387 | 689 | 10 435 | 138 638 | Williams 1966 |

¹ Lake Cowan is a salt lake, the others are freshwater lakes**Table 3***The proportions of cations found in various waters**Data are percentages of total equivalents of the ions*

| Source of Water | Na | K | Ca | Mg | Reference |
|--|-----------------|------------|-------------|--------------|-------------------------|
| Lake Joondalup, W.A. | 56.5 to 77.8 | 1.5 to 2.4 | 9.0 to 20.2 | 11.4 to 20.9 | This paper |
| Coastal dune lakes, N.S.W. and Queensland | 78 | 2 | 4 | 16 | Bayly 1964 |
| Seawater | 77 | 2 | 3 | 18 | Bayly 1964 |
| Rainwater, Vic. | 73 ¹ | .... | 9 | 18 | Hutton and Leslie 1958 |
| Lake Cowan, W.A. | 78 | 0.2 | 0.8 | 21 | Williams 1966 |
| Sedimentary source | 5 | 8 | 53 | 34 | Hutchinson 1957 |
| Loch Croispol, Scotland | 22 | 1 | 32.7 | 44.3 | Spence et al. 1971 |
| Blue Lake, S.A. | 45 ¹ | .... | 28 | 27 | Bayly and Williams 1964 |

¹ includes sodium and potassium

are also similar to those found for Lake Cowan, a salt lake, despite the dramatically-different total ion concentrations present (Table 3 cf. Table 2). However, they contrast, (with the possible exception of calcium), with mean values for sedimentary sources (Hutchinson, 1957); and Spence *et al.* (1971) report that a truly calcareous loch in Scotland, Croispol, had higher milliequivalent proportions of calcium and magnesium. At Blue Lake, which has somewhat intermediate ratios, Bayly and Williams (1964) attribute the proportions to the combined influence of leaching from limestone in the lake's watershed, and influx of ions from the sea via precipitation. The data from Lake Joondalup, which is situated only 6 km from the ocean, are consistent with the interpretation that precipitation has been the main determining factor in controlling ionic composition, the raised value for calcium being attributable to the leaching of this metal from limestone.

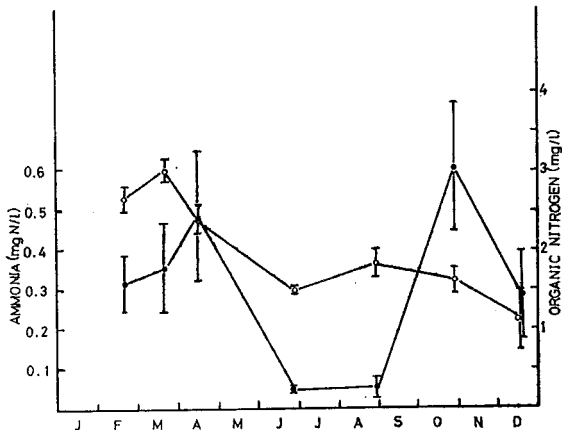


Figure 7.—Ammonia nitrogen (●) and organic nitrogen (○) in Lake Joondalup.

Phosphorus.—The curves for phosphorus are reminiscent of those for nitrogen. Inorganic phosphorus showed the familiar trend of decreasing concentration with increasing lake volume, whereas organic phosphorus increased when the levels of the lake were increasing (Figure 8). This increase may be due to increased assimilation of inorganic phosphorus by phytoplankton (see below), increased decomposition of organic material in the lake margins and floor, leaching of phosphorus into the lake, and to the release of phosphorus from the sediments because of agitation by wind.

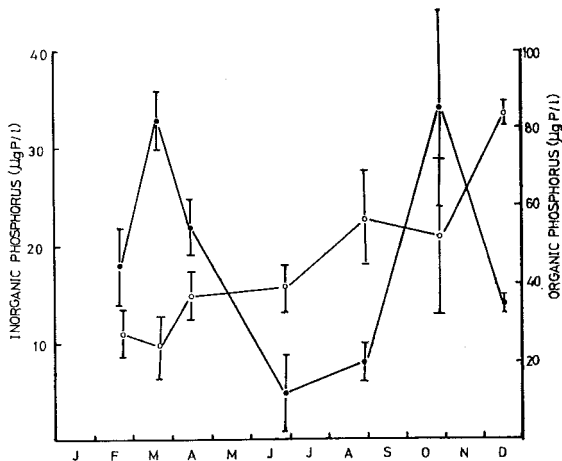


Figure 8.—Inorganic phosphorus (●) and organic phosphorus (○) in Lake Joondalup.

Inorganic phosphorus varied between 0.006 and 0.04 mgP/l which compares with the range of 0.001 to 0.04 given by Pearsall (1930) for 9 lakes of the English Lake District. There phosphate was the nutrient in relatively smallest quantity, and concentrations were lowest in the shallower lakes. At Joondalup the ratio of nitrogen to phosphorus varied between 70:1 and 140:1, and the ratio would be higher if nitrate

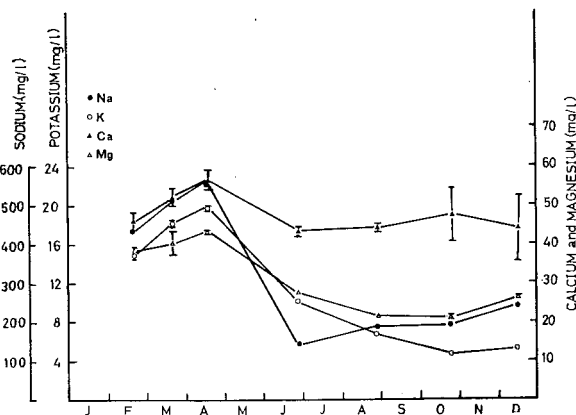


Figure 6.—Seasonal changes in concentrations of metallic cations at Lake Joondalup.

Organic nitrogen and ammonia.—Both of these parameters show the same general seasonal trend of decreasing concentration with increasing water level (Figure 7), but superimposed on this trend there is an increase in the concentration of organic nitrogen from June to August. For comparison, Lake Mendota, a eutrophic lake in Wisconsin, had an organic nitrogen concentration ranging from 0.3 to 0.6 mgN/l (Peterson *et al.*, 1925), values considerably lower than those obtained at Lake Joondalup, where the range was 1.5 to 3.00 mgN/l. One explanation for the high levels is the release of organic nitrogen by the decomposition of organic material derived from the dense macrophytic vegetation and benthic hydrophytes. Another possible source of nitrogen is seepage of nutrients from septic tanks. The concentration of ammonia-nitrogen was between 0.05 and 0.48 mg/l. Hutchinson (1957) gives a range of 0.05 to 0.54 mg/l for the Madison lakes of Wisconsin, and attributes the upper values to derivation from sewage.

had also been determined. As the ratio in plants is about 15:1 to 2:1 (e.g. Gerlaczynska, 1973), one may speculate that of nitrogen and phosphorus, the level of phosphorus is more likely to be limiting for plant growth.

Phytoplankton

Total numbers of phytoplankton are shown in Figure 9, where it can be seen that there was an algal bloom, some 4×10^7 organisms per l, in the period April to June. The highest den-

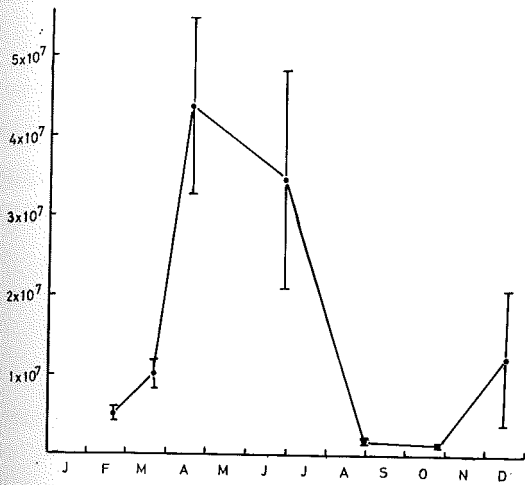


Figure 9.—The planktonic algae of Lake Joondalup. The number of individuals of all species is expressed per litre.

sity of the bloom was in mid April, coinciding with minimum lake level (Figure 2) and highest concentrations of metallic cations (Figure 6). Temperature was falling (Figure 4). Phosphate phosphorus (Figure 8) peaked a month before the maximum algal bloom, and an increase in the organic P fractions is associated with the bloom. Not surprisingly, organic N is also relatively high (Figure 7). Both organic P and N remain relatively high after the bloom, and no

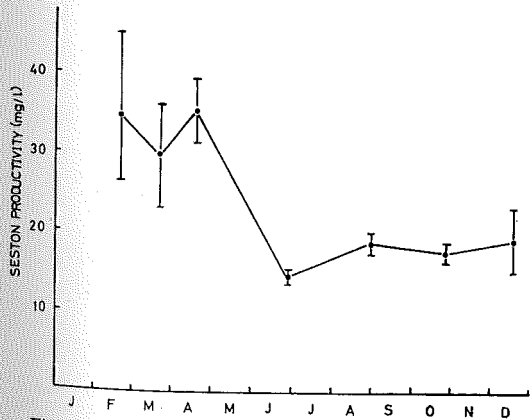


Figure 10.—Seston productivity of Lake Joondalup.

doubt part of this organic material is derived from algal decomposition and bacterial action. Seston productivity (Figure 10) is more closely correlated with organic N than with total plankton, again suggesting relatively high levels of organic material in the lake.

The distribution of particular species of algae is shown in Figure 11, and it is immediately apparent that the main bloom is due to the presence of *Dispora crucigenoides*, a green alga. In December there was a minor bloom of a blue-green, *Raphidiopsis*, but distribution in the lake was very patchy as indicated by the large standard error on the December figure in Figure 9.

Occurrence of the blue-green *Anabaena spiroides* is of interest, as this is known to fix atmospheric nitrogen (Cameron and Fuller, 1960). It appears in the lake in significant numbers in August, at a time when ammonia levels are low and organic N high, and this suggests that levels of available nitrogen may have become limiting to the growth of algae at that time. *Anabaena* and *Anacystis* (which is also present in the lake but in low numbers) can produce blooms toxic to animals (e.g. Jackson, 1964). There have been no reports, to our knowledge, of the death of fish or waterfowl in the lake, as there have been in summer for certain other Perth lakes. There is, however, a possibility of such toxic blooms occurring in Joondalup if further enrichment occurs.

General

Lake volume is the major factor determining seasonal changes in concentration in dissolved substances. The data are consistent with the view that phosphorus levels may limit algal productivity in the lake, except for a short period of the year when there is a small increase in *Anabaena*. Suitable culture experiments could be carried out to examine these possibilities. The observations indicate a need for further monitoring as urbanisation around the lake progresses, and a need for comparable data on the trophic status of other lakes, including those in national parks not affected by urbanisation. The relatively high levels of phosphorus and nitrogen in the water, and the occurrence of algal blooms, justify the provisional designation of the lake as 'mildly eutrophic'.

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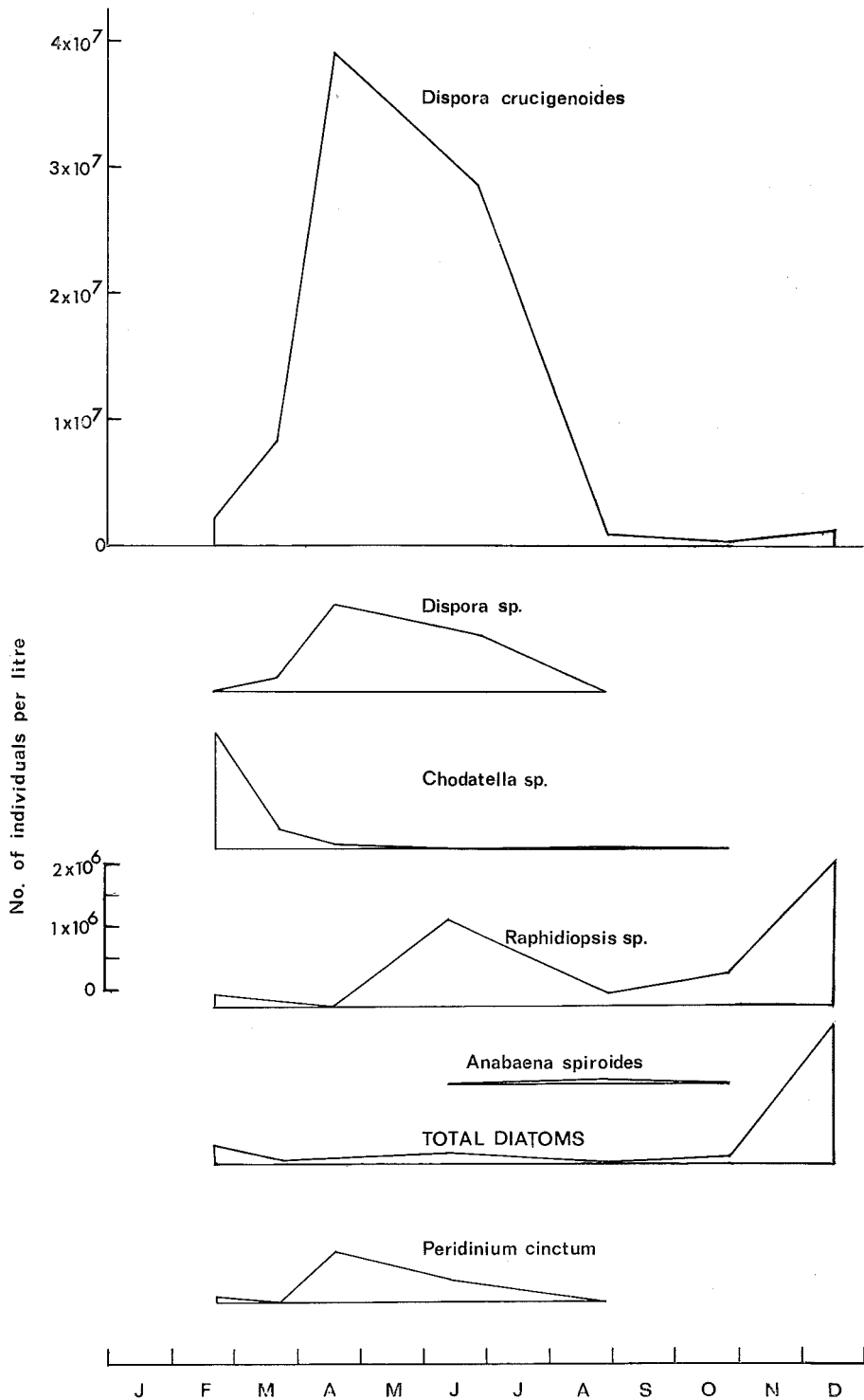


Figure 11.—Planktonic algae of Lake Joondalup, showing the number of individuals of the main taxa present, expressed per litre. Note that the scale for *Dispora crucigenoides* is reduced as compared with that for the other algae, which is the same in each case.

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