

## Water chemistry of the wetlands of the Yellagonga Regional Park, Western Australia.

A Kinnear & P Garnett

Centre for Ecosystem Management, Edith Cowan University, Bradford Street, Mount Lawley WA 6050  
e-mail: a.kinnear@cowan.edu.au, p.garnett@cowan.edu.au

Manuscript received August 1998; accepted April 1999

### Abstract

Yellagonga Regional Park was established in 1989 as an area of significant value for conservation and recreation. Its wetlands include Lake Joondalup, Lake Goollelal and Walluburnup and Beenyup Swamps, which together are an important community resource both scientifically and recreationally. We investigated the water chemistry of the Yellagonga Park wetlands over a 15-month period, based on fortnightly sampling from five wetland areas. All the wetlands in the Park can be described as eutrophic on the basis of their phosphorus and nitrogen levels. However, analysis of the physico-chemical data identified two site clusters, each with distinctive chemistries. Beenyup Swamp and the southern end of Lake Joondalup were separated from the remaining sites on the basis of their very high phosphorus levels, and their lower levels of nitrogen, chlorophyll *a*, dissolved oxygen, pH and conductivity.

Nitrogen is likely to be a limiting nutrient in the highly P-enriched waters and this, together with the strongly alkaline pH of these wetlands makes them particularly susceptible to blue-green algal blooms of increasing intensity. Substantial phytoplankton responses in Beenyup Swamp were not evident during this study, despite this wetland having the highest phosphorus loadings. It is suggested that the presence of humic substances in this well-vegetated wetland, either directly or indirectly, ameliorated the primary productivity response to the enrichment. These wetlands exhibit strong seasonal variations in conductivity and ion concentrations, and relatively high mean values for these parameters are an established feature.

The outcomes of the study have implications for the long-term management of the Yellagonga Regional Park's wetlands, which needs to address the prevention of further deterioration in water quality and the restoration and conservation of the wetland and riparian habitats.

### Introduction

The Yellagonga Regional Park, in the north-west corridor of Perth, contains some of the most important wetlands of the Swan Coastal Plain which comprise, in a north-south direction, Lake Joondalup, Beenyup Swamp, Walluburnup Swamp and Lake Goollelal (Fig 1). The Park covers an area of approximately 1400 ha, of which the wetlands make up about 550 ha. These wetlands are surface expressions of the unconfined aquifers of the Gnangara Mound, and provide some of the largest permanent sources of freshwater remaining on the Swan Coastal Plain. The groundwater inflow, which supplies the Yellagonga wetland system, is from shallow aquifers of up to 50 m in depth, flowing in an east to west direction towards the Indian Ocean.

Water levels in all the wetlands fluctuate on a seasonal basis in response to rainfall, evaporation, groundwater movement, and as a result of surface water flow between them. Lake Goollelal and the main water body of Lake Joondalup usually retain water over the dry summer periods whereas Beenyup Swamp and the southern end of Lake Joondalup are seasonal. This latter wetland area is separated from the main water body of Lake Joondalup

by Ocean Reef Road and an engineered tunnel passing underneath Ocean Reef Road connects the two waterbodies. Surface water flows from the southern region into the main water body when water levels are sufficiently high, during the winter months.

The soils (McArthur & Bettenay 1974) and vegetation of the Park (Beard 1979) have been well described. The wetlands and their surrounds are of cultural, historical as well as faunal (avian) significance (Bekle 1979) and the establishment of the area as a Regional Park in 1989 reflected its importance for both conservation and recreation. The Yellagonga Regional Park is situated in an area of intense and growing urbanisation and, like others on the Swan Coastal Plain, the wetlands are increasingly threatened by eutrophication and degradation. Large areas of land have been cleared for agricultural and recreational purposes and the Park is influenced by the impact of increasing numbers of residential dwellings, and a range of land uses including market gardens and parkland. The water quality of the wetlands is increasingly influenced by urban drainage, stormwater flows, pollution, excessive nutrient input and groundwater extraction.

Previous studies of the nutrient status of these wetlands focussed on Lake Joondalup, the largest and

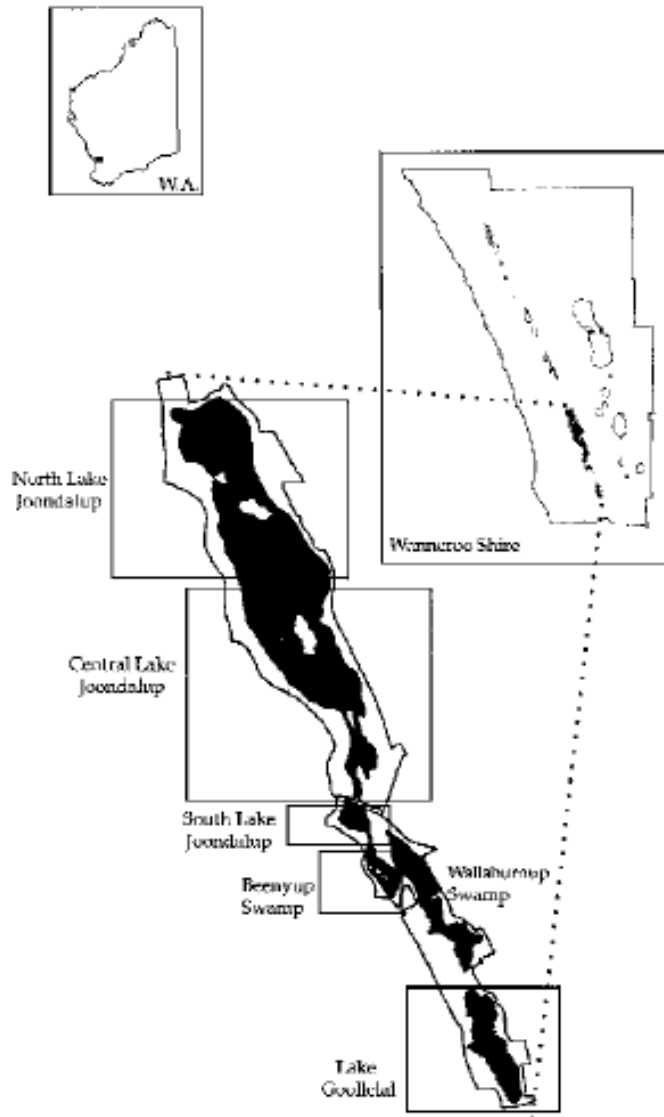


Figure 1. The major wetlands in the Yellagonga Regional Park and the locations of the five sampling areas of this study.

most visually dominant wetland in the park. The first study of Lake Joondalup (Congdon & McComb 1976) described the lake as "mildly eutrophic" on the basis of its phosphorus and nitrogen concentrations. Ten years later, the lake was described as excessively eutrophic by Congdon (1986), who concluded that substantial phosphorus enrichment was probably occurring via surface flow from Wallaburnup/Beenyup Swamp. Davis *et al* (1993) described the main water body of Lake Joondalup as mesotrophic.

This paper describes the seasonal and spatial patterns in selected aquatic physico-chemical characteristics of the three major wetlands within the Yellagonga Regional Park, Lake Joondalup, Beenyup Swamp and Lake Goollelal. The outcomes provide baseline water chemistry data for each of the wetlands as well as providing a "third decade" of water chemistry values for Lake Joondalup, providing an opportunity to identify any significant trends as a result of sustained anthropogenic loadings over the last two decades.

## Methods

### Site descriptions

Lake Joondalup is a large permanent wetland approximately 450 ha in area. Large sections retain the natural fringing vegetation of *Melaleucaraphiophylla* and sedges and two central islands are surrounded by sedge habitat. Eighty percent of the lake's area has a depth of 1.2-2.0 metres. A rich benthic flora and a suspended "sediment" of unknown origin called metaphyton (Rose 1979) inhabits the northern lake areas. The southern section of this wetland, south of the bisecting highway is seasonal, and dries out during summer. Beenyup Swamp is the smallest and shallowest water body of the three wetlands and dries out completely during the summer months. Most of the fringing vegetation has been retained and the swamp is heavily shaded throughout by *Melaleuca* sp. Lake Goollelal is a permanent wetland of approximately 50 ha. Its surrounds are heavily urbanised and it retains only a very small proportion of the natural fringing vegetation.

Previous studies had identified somewhat different chemical and botanical characters for the extreme southern and northern regions of Lake Joondalup. For example, the southernmost end of this lake is seasonal, has little benthic flora and has been described as excessively enriched (Congdon 1986). On the other hand, the deeper main water body is permanent, has been variously described as mesotrophic or mildly eutrophic, is known to support a rich benthic flora and has a suspended sediment called metaphyton distributed throughout the water column (Rose 1979). The road and sub-surface drain between the southern end of Lake Joondalup and the remaining part of this water body interrupts the natural lake contours and the south-north drainage. For these reasons, Lake Joondalup was divided into three sampling areas designated South, Central and North Lake Joondalup (Fig 1). Each of these areas was sampled separately and the data analysed as such, giving, with Beenyup Swamp and Lake Goollelal, a total of five sites in all.

### Sampling and water analysis

Replicate water samples were taken at each of the five sites at two-weekly intervals for 15 months, commencing in January 1992. Conductivity, dissolved oxygen, temperature and pH were measured *in situ* at approximately 30 cm below the surface and near the centre of each water body, using Orion portable meters, after calibration. Water levels of both Lakes Joondalup and Goollelal were measured on all sampling occasions at the Western Australia Water Authority sites.

Water samples for the remaining analyses were transported to the laboratory over ice. Analyses for sodium, potassium, magnesium and calcium followed standard procedures for atomic absorption spectrophotometry (Clesceri *et al* 1989). Chloride was measured by a modified argentometric method using a Corning 926 chloride analyser. Total alkalinity was determined by titration with HCl (Clesceri *et al* 1989) and is expressed as mg CaCO<sub>3</sub> L<sup>-1</sup>.

Samples for nutrient analyses were filtered through 0.45 µm filters and stored frozen until analysed. Nitrate/

nitrite was determined spectrophotometrically following cadmium reduction (Clesceri *et al* 1989). Ammonium nitrogen was determined by the formation of indophenol, detected spectrophotometrically (Grasshof *et al* 1983). Organic nitrogen was determined by the difference between Kjeldahl nitrogen and ammonium nitrogen. Kjeldahl nitrogen was determined by digestion followed by spectrophotometric analysis of the ammonia produced (Clesceri *et al* 1989). Total nitrogen was obtained by summing ammonium nitrogen, organic nitrogen and nitrate/nitrite.

Filterable reactive phosphorus was determined spectrophotometrically by the single solution (ascorbic acid) method (Major *et al* 1972). Total phosphorus (filterable reactive phosphorus, condensed inorganic phosphate and organic phosphate) was determined by the same method following digestion with perchloric acid using a block digester.

Chlorophyll *a* was used as an indicator of algal biomass (phytoplankton productivity). Chlorophyll *a* was determined spectrophotometrically following extraction from the glass fibre filter paper by grinding with acetone (Clesceri *et al* 1989).

#### Data analysis

The site data for each of the variables were converted to monthly mean values for identifying broad-scale seasonal patterns and environmental gradients. These gradients were further summarised as tabulated single mean values and ranges for each of the chemistry variables for each site. For identification of overall trends in the data set, classification and ordination of the 5 sites were carried out using the seasonal mean values (5 seasons in all) of seven variables, total nitrogen, total phosphorus, filterable reactive phosphorus, chlorophyll *a*, pH, dissolved oxygen and conductivity. The procedures for classification and ordination of the data followed those recommended in the PATN software package (Belbin 1989). The data were log-transformed and standardised by range. The association between pairs of mean values was estimated using the Gower Metric Association measure. To classify the samples, a hierarchical clustering strategy (FUSE) was used to identify and group the pair of samples which were most closely associated. An arithmetic averaging strategy (UPGMA) was then used to create a new association value between the newly-grouped samples and all other samples. This process was iterated until all samples had been grouped to produce an agglomerative cluster pattern. The resulting dendrogram is the graphical representation of this successive fusion of samples within groups, based on the original association values.

Ordination is a complementary technique to classification and has the objective of condensing the information in the data set so that the patterns can be displayed in only two or three dimensions. The samples were ordinated using the recommended semi-strong hybrid multidimensional scaling strategy (SSH) in PATN (Belbin 1989). When plotted in this limited number of dimensions, the similarity between the samples is measured by the plot-distance between them. Most similar samples are closest together, those most dissimilar are furthestmost apart. The "stress value" can be used as

an indication of how well the arrangement of the samples in the low-dimension space reflects the among-sample relationships in the original multi-dimensional data set. An ordination with a stress value of <0.05 is considered to provide an excellent representation, with little danger of misinterpretation (Clarke 1993).

## Results

The commencement of sampling occurred in the summer of 1991/1992, when abnormally high rainfall fell in both December and February (Fig 2). As a result of this summer rain, the normally seasonal wetland areas, South Lake Joondalup and Beenyup Swamp retained water throughout the summer/autumn period of 1992 and the hydrographs for Lakes Joondalup and Goollelal show a slower decline in water levels prior to the winter of 1992 (Fig 3). The hydrographs also emphasise the strong

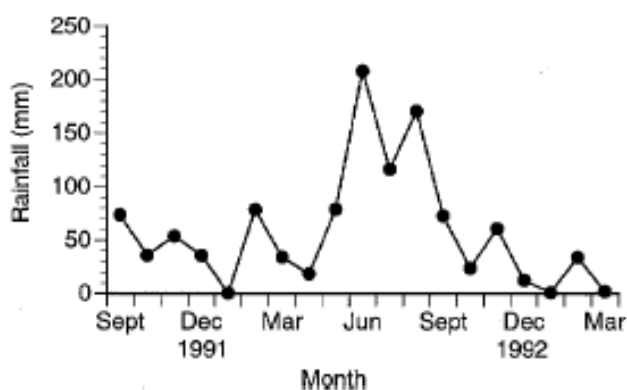


Figure 2. Monthly rainfall in Wanneroo during the period of the study (source: Wanneroo Station, Bureau of Meteorology, Perth).

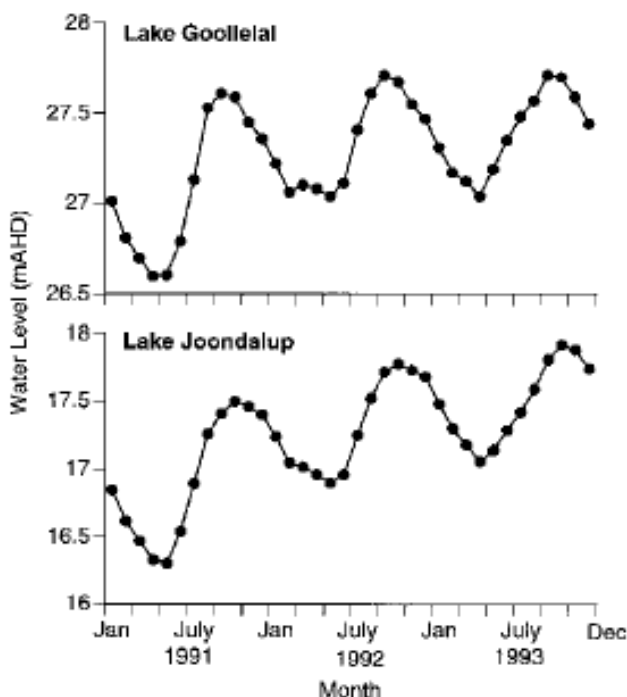
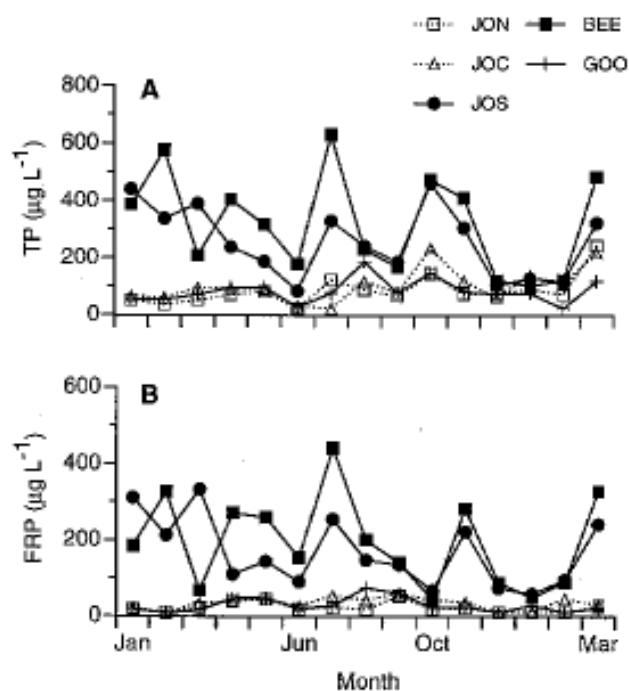


Figure 3. Hydrograph water levels for the Yellagonga wetlands for the period 1991-1993 (source: Western Australian Water Authority, Perth).

seasonal patterns in water levels occurring in these wetlands, a pattern which was reflected in the water chemistry.

#### Nutrient concentrations

**Phosphorus:** There were no obvious seasonal patterns in either total phosphorus (TP) or filterable reactive phosphorus (FRP) at any of the sites (Fig 4), but there was a clear gradient of increasing TP and FRP from north to south across the surface-connected Lake Joondalup/Beenup Swamp sites (Table 1). Consistently high levels were recorded in Beenup Swamp and South Lake Joondalup where values exceeded  $100 \mu\text{g L}^{-1}$  for most of the sampling period. Monthly mean values approached the lower values of the northern Lake Joondalup areas only in the summer months of 1992/93. At these two southern sites, peaks in TP and FRP tended to parallel each other, with FRP usually contributing >60% of TP. In Lake Goollelal and Central and North Lake Joondalup, where TP and FRP values were considerably lower, there was increased variability in TP values after the onset of the winter rains, with small increases in the winter-spring months, particularly in Central Lake Joondalup. At these sites, the FRP contribution to TP was more variable and lower (generally <50%).



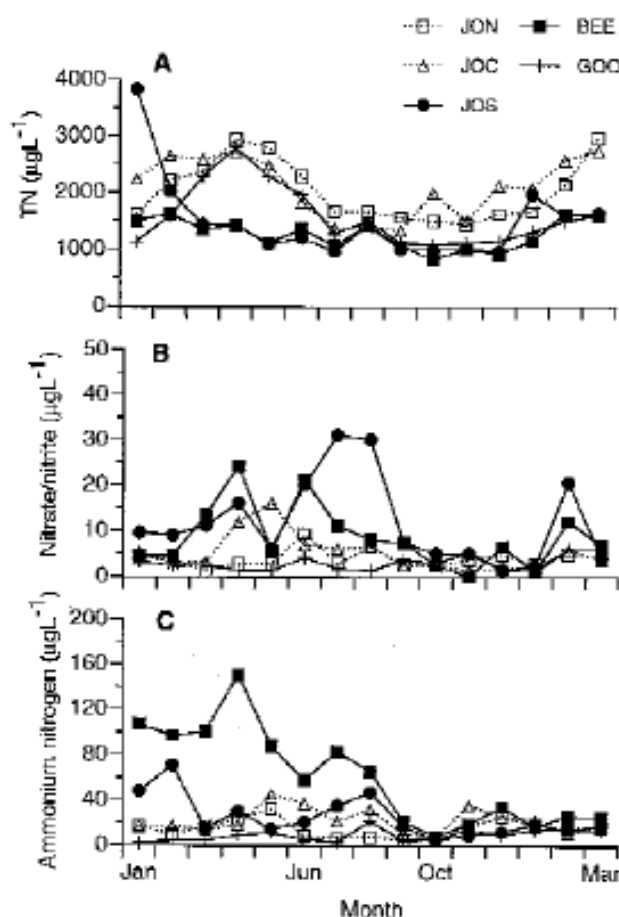
**Figure 4.** Variation in monthly mean phosphorus levels for North Lake Joondalup (JON), Central Lake Joondalup (JOC), South Lake Joondalup (JOS), Beenup swamp (BEE) and Lake Goollelal (GOO). A: total phosphorus concentration (TP); B: filterable reactive phosphorus concentration (FRP).

**Nitrogen:** At all sites, organic nitrogen concentrations were almost always at least 90% of the total nitrogen values and spatial and seasonal patterns for these two variables were therefore identical. For this reason, ON values have not been included in Fig 5. The larger, permanent water bodies of Lakes Joondalup and Goollelal had the highest TN and ON levels and there

were strong seasonal patterns, with maximum values around  $3000 \mu\text{g L}^{-1}$  in summer/autumn, falling to minimum values around  $1500 \mu\text{g L}^{-1}$  in late winter (Fig 5). Transient peaks in TN levels were recorded in Central Lake Joondalup in the spring and summer months.

In contrast, TN and ON levels in South Lake Joondalup rarely exceeded the minimum levels recorded at the other sites, and the only suggestion of a seasonal response was the transient high levels observed in South Lake Joondalup during the summer months.

Levels of inorganic nitrogen (both as nitrate/nitrite and ammonium nitrogen) were uniformly low on most sampling occasions across all the sites. One exception was Beenup Swamp which maintained relatively high ammonium nitrogen levels (around  $120 \mu\text{g L}^{-1}$ ) throughout the unusually wet summer/autumn of 1992.



**Figure 5.** Variation in monthly mean nitrogen levels for North Lake Joondalup (JON), Central Lake Joondalup (JOC), South Lake Joondalup (JOS), Beenup swamp (BEE) and Lake Goollelal (GOO). A: total nitrogen concentration (TN); B: nitrate/nitrite concentration; C: Ammonium nitrogen concentration.

#### Chlorophyll a

Chlorophyll a levels in the permanent water sites, North and Central Lake Joondalup and Lake Goollelal were maintained at levels consistently above  $5 \mu\text{g L}^{-1}$  with some high monthly mean values ( $> 50 \mu\text{g L}^{-1}$ ), particularly in Central Lake Joondalup (Table 1). Peaks in chlorophyll

a which were recorded for the warmer spring/summer months in Central Lake Joondalup were associated with highly visible algal blooms (Fig 6). The most striking feature of the chlorophyll data from the remaining two sites, South Lake Joondalup and Beenyup Swamp, was the absence of a similar phytoplankton response to the higher observed phosphorus levels at these sites. In Beenyup Swamp, chlorophyll a levels were below  $5 \mu\text{g L}^{-1}$  for most of the sampling period and levels here were the lowest for all the sites with no discernible peaks. In South Lake Joondalup, levels were also usually low during periods of south-to-north flow from the adjacent Swamp,

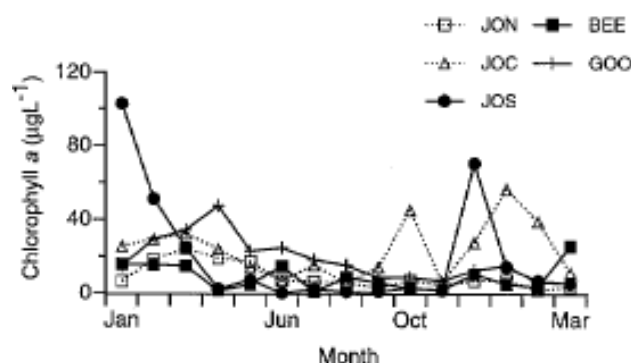


Figure 6. Variation in monthly mean chlorophyll a levels for North Lake Joondalup (JON), Central Lake Joondalup (JOC), South Lake Joondalup (JOS), Beenyup swamp (BEE) and Lake Goollelal (GOO).

but isolated high levels were observed in both summers and were associated with transient algal blooms.

#### Conductivity and ion concentrations

Conductivity values (Fig 7) and ionic concentrations showed similar, strong seasonal changes which reflected rainfall and evaporation patterns and consequent seasonal variations in water levels. For all these parameters, highest values occurred in late autumn and decreased rapidly with the onset of winter rains. The two sites comprising the largest water body (Central and North Lake Joondalup) showed the most pronounced

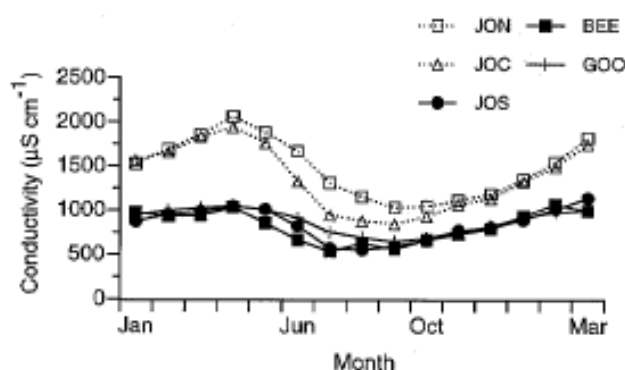


Figure 7. Variation in monthly means of conductivity for North Lake Joondalup (JON), Central Lake Joondalup (JOC), South Lake Joondalup (JOS), Beenyup swamp (BEE) and Lake Goollelal (GOO).

Table 1

Nutrient chemistry and chlorophyll a for the five sampled sites. Values are the means and ranges over the 15-month period.

SITE	Total Phosphorus ( $\mu\text{g L}^{-1}$ )	Filterable Reactive Phosphorus ( $\mu\text{g L}^{-1}$ )	Total Nitrogen ( $\mu\text{g L}^{-1}$ )	Organic Nitrogen ( $\mu\text{g L}^{-1}$ )	Nitrate/nitrite Nitrogen ( $\mu\text{g L}^{-1}$ )	Ammonium Nitrogen ( $\mu\text{g L}^{-1}$ )	Chlorophyll a ( $\mu\text{g L}^{-1}$ )
Lake Goollelal	86	26	1507	1502	3	9	16
Beenyup Swamp	13-548	0-206	854-3018	882-3011	1-18	1-67	0-62
South Lake Joondalup	322	195	1257	1179	28	60	9
Central Lake Joondalup	80-831	25-689	760-1722	656-1725	1-328	8-185	0-37
North Lake Joondalup	260	163	1425	1370	17	33	19
	71-766	40-518	807-4002	791-3606	1-325	3-590	0-199
	117	33	2134	2107	5	23	22
	8-603	0-209	976-4515	818-4496	1-193	1-225	0-134
	88	23	2094	2078	4	15	10
	9-555	0-218	1239-5901	1219-5883	1-44	1-54	0-31

Table 2

Conductivity, metal ions and chloride ions for the five sampled sites. Values are the means and ranges over the 15-month period.

SITE	Conductivity ( $\mu\text{S cm}^{-1}$ )	Sodium ( $\text{mg L}^{-1}$ )	Potassium ( $\text{mg L}^{-1}$ )	Calcium ( $\text{mg L}^{-1}$ )	Magnesium ( $\text{mg L}^{-1}$ )	Chloride ( $\text{mg L}^{-1}$ )
Lake Goollelal	871	87	11	36	18	158
Beenyup Swamp	627-1054	45-154	4-16	20-52	13-24	168-218
South Lake Joondalup	816	85	6	46	14	149
Central Lake Joondalup	479-1096	50-127	4-9	26-67	9-19	85-212
North Lake Joondalup	859	85	6	44	14	154
	526-1190	54-147	5-8	27-64	9-19	98-216
	1381	147	8	33	26	328
	620-1977	50-233	2-17	18-47	11-46	132-598
	1501	160	8	29	29	360
	980-2160	99-234	2-17	18-36	19-41	156-578

seasonal fluctuations. Noticeable in Fig 7 is the decrease in conductivity in Central Lake Joondalup in early winter as a result of seasonal water flow from South Lake Joondalup through the Ocean Reef Road culvert. With the exception of calcium, conductivity and ionic concentrations were highest in Central and North Lake Joondalup (Table 2). Calcium ion concentrations were highest in the southern end of Lake Joondalup and Beenyup Swamp.

#### Dissolved oxygen, pH and alkalinity

The alkaline pH values of the larger water areas (Table 3) would be expected from lakes overlying limestone formations. Values recorded for the small water body of Beenyup Swamp were near-neutral. Some seasonal variation was evident in three of the sites (Lake Goollelal, and South and Central Lake Joondalup) with higher pH values in summer. In South Lake Joondalup, we were able to associate the high pH values with high transient chlorophyll *a* values. Small seasonal variations were also observed in alkalinity with higher values in summer. This trend was more pronounced in the smaller water areas.

Both the spatial and temporal patterns in dissolved oxygen may reflect the sampling strategies. The shallow

nature of Beenyup Swamp, particularly in the drier months, resulted in measurements close to sediments which may have contributed to the very low values. On the other hand, the deeper water bodies had relatively high values, indicative of well-aerated conditions in the surface layers, where these measurements were taken.

#### Multivariate analyses

The agglomerative clustering routine identified two clear interpretable site clusters which separated the Beenyup Swamp and South Lake Joondalup sites from the remaining sites (Fig 8). This site pattern was also obtained when the sites were ordinated over three dimensions, with the best separation occurring over axes 1 and 3 (Fig 9). The separation of the Beenyup and South Lake Joondalup sites by both clustering and ordination strategies reflects the combination of high mean levels of total and filterable reactive phosphorus, but low mean levels of total nitrogen, dissolved oxygen, pH and conductivity.

The classification and ordination procedures indicated some separation of S1, the wet summer samples from South Lake Joondalup. The water chemistry of this site during this period was distinctive because of the isolated but very high, transient chlorophyll *a* levels.

Table 3

Dissolved oxygen, pH and alkalinity for the five sampled sites. Values are the means and ranges over the 15-month period.

SITE	Dissolved oxygen (mg L <sup>-1</sup> )	pH	Alkalinity (mg L <sup>-1</sup> CaCO <sub>3</sub> )
Lake Goollelal	8.3 5.6-13.0	8.4 7.3-10.0	104 72-137
Beenyup Swamp	3.0 0.3-10.0	7.4 6.1-8.1	153 92-230
South Lake Joondalup	6.5 1.8-9.0	8.1 6.9-9.6	160 84-226
Central Lake Joondalup	8.2 5.0-13.0	9.0 7.5-10.1	129 102-179
North Lake Joondalup	8.8 4.9-13.3	9.3 8.2-9.9	124 75-166

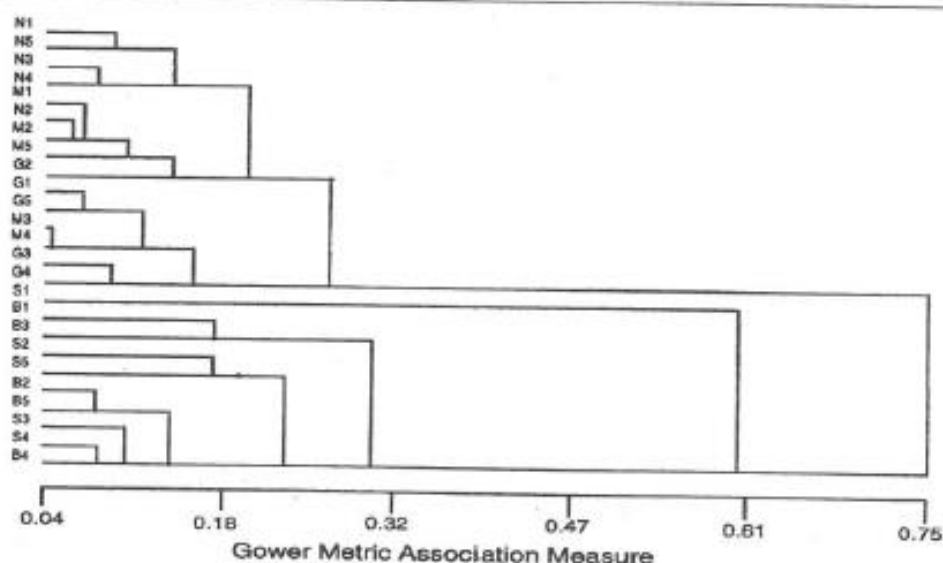


Figure 8. Hierarchical agglomerative clustering of water chemistry variables (TN, nitrate/nitrite nitrogen, ammonium nitrogen, chlorophyll *a*, pH, TP, FRP, dissolved oxygen and conductivity) of the five wetland sites sampled over five consecutive seasons, 1: summer/92 to 5: summer/93. (N=North Lake Joondalup, M=Central Lake Joondalup, S=South Lake Joondalup, B=Beenyup Swamp, G=Lake Goollelal).

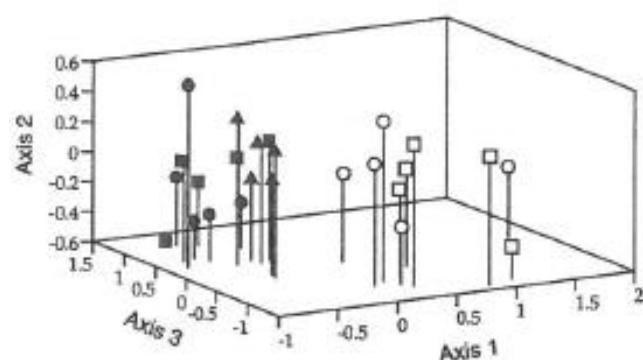


Figure 9. SSH ordination of selected water chemistry variables (TN, nitrate/nitrite nitrogen, ammonium nitrogen, chlorophyll *a*, pH, TP, FRP, dissolved oxygen and conductivity) of five wetland sites sampled over five consecutive seasons (summer/92 to summer/93). Seasonal means were ordinated over three dimensions. Stress = 0.046. (●=North Lake Joondalup, ■=Central Lake Joondalup, ○=South Lake Joondalup, □=Beenyup Swamp, ▲=Lake Goollelal).

## Discussion

Our data describe temporal and spatial patterns in water chemistry in the Yellagonga Regional Park wetlands. Within the wetlands, temporal variations reflected seasonal changes in water levels. Across the wetland areas there were clear spatial gradients of nutrients.

The seasonal rainfall pattern and evaporation rates which result from our wet winters and hot dry summers were reflected in seasonal changes in conductivity, ionic concentrations, and total and organic nitrogen. These strong seasonal variations resulted from changes in the volume of water causing summer concentration due to low rainfall and high evaporation, and winter dilution due to high rainfall and increased water flow into the wetlands. Seasonal changes were particularly obvious for the largest wetland area comprising Central and North Lake Joondalup. Here, summer maxima were considerably higher than elsewhere, as a result of higher evaporation rates from the larger surface area.

The high conductivity and ionic levels are chemical features of these wetlands, with the mean conductivities corresponding to total dissolved salts of approximately 500 mg L<sup>-1</sup> for Lake Goollelal, Beenyup Swamp and South Lake Joondalup and approximately 900 mg L<sup>-1</sup> for Central and North Lake Joondalup (using a conversion factor of 1 μS cm<sup>-1</sup> = 0.64 mg L<sup>-1</sup>). These high levels reflect proximity to the coast with consequent precipitation of ionic salts from ocean spray (Congdon & McComb 1976). In addition, the wetland chemistry is likely to be influenced by groundwater inflow together with their location within the Spearwood Dune System and associated limestone formations. The conductivity and ion concentrations were somewhat lower than those of previous studies (Congdon & McComb 1976; Davis & Rolls 1987). This is likely the result of the higher summer rainfall in the Dec 1991/Jan 1992 and the subsequent higher water levels through 1992.

It is apparent from our study that the strong phosphorus gradients across the surface-connected areas

of Lake Joondalup which were first identified by Congdon (1979) remain a feature of these wetlands. On the basis of the phosphorus and nitrogen levels the trophic status of all the wetlands in the Park can be described as eutrophic using either the CEPIS (Salas & Martino 1991) or OECD (1982) classification scheme for determining trophic category. In addition, our analysis of the nutrient ratios strongly suggests a relative increase in phosphorus in these wetlands over the last fifteen years (Table 4). Ratios of TN:TP decreased from 35:1 in 1978 to 21:1 in 1992. As well, IN:FRP ratios fell from 3.7 to 0.8 in the same period and suggest that nitrogen, rather than phosphorus, is now more likely to be the limiting nutrient for phytoplankton growth in these wetlands (Wetzel 1983). This, together with the naturally alkaline pH values renders these wetlands particularly susceptible to the formation of nitrogen-fixing blue-green algal blooms (Schindler 1977).

Table 4

Comparisons of total nitrogen (TN) : total phosphorus (TP) and inorganic nitrogen (IN) : filterable reactive phosphorus (FRP) obtained from the main waterbody of Lake Joondalup from studies conducted over the last two decades (data from Congdon 1986; Davis & Rolls 1987; and the present study).

RATIO	1978	1979	1980	1985/86	1992/93
TN/TP ratio	35	30	35	47	21
IN/FRP ratio	3.7	1.6	1.9	1.5	0.8

The strong nutrient gradients that we have described across the length of Lake Joondalup define sites within the wetland with distinctive chemistries superimposed on the seasonal patterns. This was reflected by the results of the multivariate analysis which indicated a clear separation of Beenyup Swamp and South Lake Joondalup sites from the other wetland sites within Yellagonga Regional Park. These two sites had higher phosphorus levels, lower nitrogen and chlorophyll *a* levels and were less alkaline than the adjacent main water body of Lake Joondalup to the north and the geographically disjunct Lake Goollelal to the south.

The substantially higher nitrogen levels in the main water body of Lake Joondalup compared with the other areas, are due both to higher minima in winter (means of 1500 μg L<sup>-1</sup> in the north compared with 1000 μg L<sup>-1</sup> in the south) and higher maxima in the warmer months when water volumes are lowest. The higher overall mean values for organic nitrogen in the main water body of Lake Joondalup have two possible sources, one associated with phytoplankton blooms in summer/autumn and spring/summer, and a higher minimum value natural to this wetland which varies seasonally with water volume. Relatively high organic nitrogen values in the main water body of Lake Joondalup have been recorded previously (Congdon 1979; Davis & Rolls 1987) and Congdon & McComb (1976) suggest that this may reflect the release of nitrogen from the dense macrophyte vegetation and benthic hydrophytes that inhabit these areas. These vegetation communities are not as evident in the southern section of the lake.

The distinctiveness of Beenyup Swamp and to a lesser extent South Lake Joondalup was further enhanced by

the presence of low chlorophyll *a* levels throughout much of the year, despite the higher phosphorus levels. Congdon (1986) recorded similar findings in the southern end of Lake Joondalup and suggested that factors other than nutrients may be limiting phytoplankton growth. Coloured wetlands are known to exhibit lower than expected algal growth under nutrient-enriched conditions (Wrigley *et al.* 1988). Lower pH due to acidic humic substances and reduced light penetration have both been suggested as possible reasons for this reduction in productivity. In Beenypup Swamp, it is likely that humic substances from this heavily-vegetated wetland contribute to the near-neutral pH in an otherwise strongly alkaline group of wetlands, and to the somewhat coloured water. However, gilvin levels of less than 16  $\text{g}_{440} \text{m}^{-1}$  (Upton 1996) are not sufficiently high to describe this wetland as "highly coloured" if the criterion level of 52  $\text{g}_{440} \text{m}^{-1}$  suggested by Davis *et al.* (1993) is used. The possible role of Beenypup water as an agent for ameliorating the effects of nutrient enrichment in the southern areas of this wetland complex highlights the importance of conserving vegetation and has implications for the future management of the wetlands.

The high dissolved oxygen levels in the surface water of the larger wetland sites are consistent with the relatively large surface area of the wetland system and its exposure to wind. Without more detailed measurements of dissolved oxygen, we are unable to comment on the degree of variation either diurnally or with depth in these wetlands. The very low levels of dissolved oxygen proximal to the sediments in the shallow water of Beenypup Swamp, particularly over the wet summer/autumn of 1992, may reflect enhanced microbial activity in these sediments, a suggestion supported by the relatively high levels of ammonium nitrogen. Depleted oxygen levels are also found in lakes that have high concentrations of humic compounds (Schmidt & Rosich 1993).

The presence of anoxic conditions above the sediments in the heavily-vegetated Beenypup Swamp has implications for the dynamics of sediment phosphorus and consequent management strategies. In shallow lakes with high concentrations of phosphorus in the sediments (as Congdon 1986, found for the sediments of Lake Joondalup), a sediment reservoir of labile organic material, anoxic conditions, and a high pH can each contribute to the release of phosphorus from the sediments. The subsequent internal load can then determine the trophic status of the wetland (Marsden 1989; Kleeberg & Kozerski 1997). In addition, air-drying of sediments from eutrophic lakes can induce significant increases in phosphate release, under both aerobic and anaerobic conditions (Qui & McComb 1994). Thus, it is possible that the regular drying of seasonal wetlands such as Beenypup Swamp and South Lake Joondalup may be followed by significant increases in internal phosphorus loadings when rewetting occurs. Efforts to restore shallow eutrophic lakes usually focus on reducing the external loading of phosphorus. However, this may not produce the expected reductions in phytoplankton biomass because of substantial internal loading of phosphorus from the sediments (Marsden 1989). Significant improvements to water conditions in such situations may take 5-10 years, if recovery occurs at all

(Krienitz *et al.* 1996). This possibility has management implications for the Yellagonga wetlands.

Our study provides a seasonal and spatial picture of the water chemistry of the wetlands of Yellagonga Regional Park. The wetlands are strongly eutrophic, and the nutrient enrichment is resulting in visible algal blooms in the large water body of Lake Joondalup in the warmer months of the year. Whether absolute nutrient levels are increasing or not is difficult to determine due to the different sampling designs and analytical procedures used by researchers, as well as the varying rainfall and runoff patterns which influence lake fill and dilution effects both seasonally and annually. The unique character of Beenypup Swamp water may be ameliorating the effects of nutrient enrichment in the Swamp and, to a lesser extent, in South Lake Joondalup. It was not possible for us to provide definitive causes of the relatively low standing crop of phytoplankton in these sites and this aspect is worthy of further study.

*Acknowledgments:* The research was funded by the Edith Cowan University Foundation. The authors would like to thank S Medlock, M Bannister and V Pearmine for the field work and their technical expertise and assistance. The Western Australian Department of Conservation and Land Management provided the necessary licenses to carry out the work. We thank the reviewers for their helpful comments.

## References

- Beard J S 1979 The Vegetation of the Perth area. Vegmap Publications, Perth.
- Bekle H 1979 A seasonal biogeography of Lake Joondalup. Honours Thesis, Department of Geography, University of Western Australia, Perth.
- Belbin L 1989 PATN. Pattern analysis package. CSIRO Division of Wildlife and Ecology, Canberra.
- Clarke K R 1993 Non-parametric multivariate analyses of changes in community structure. *Australian Journal of Ecology* 18: 117-143.
- Clesceri L S, A E Greenberg & R R Trussell 1989 Standard Methods for the Examination of Water and Wastewater. American Public Health Association, Washington, D.C.
- Congdon R A & A J McComb 1976 The nutrients and plants of Lake Joondalup, a mildly eutrophic lake experiencing large seasonal changes in volume. *Journal of the Royal Society of Western Australia* 50: 14-23.
- Congdon R A 1979 Hydrology, nutrient loading and phytoplankton in Lake Joondalup: a feasibility study. Department of Conservation and Environment, Perth, Western Australia, Bulletin 67.
- Congdon R A 1986 Nutrient loading and phytoplankton blooms in Lake Joondalup, Wanneroo, Western Australia. Department of Conservation and Environment, Perth, Western Australia, Technical Series 6.
- Davis J A & S W Rolls 1987 A baseline biological monitoring programme for the urban wetlands of the Swan Coastal Plain, Western Australia. Environmental Protection Authority, Perth, Western Australia, Bulletin 265.
- Davis J A, R S Rosich, J S Bradley, J E Grouns, L G Schmidt & F Cheal 1993 Wetlands of the Swan Coastal Plain: Wetland classification on the basis of water quality and invertebrate community data, Volume 6. Water Authority of Western Australia and Environmental Protection Authority, Perth, Western Australia.
- Grasshof K, M Ehrardt & K Kremling 1983 Methods of Seawater Analysis. Weinham: Verlag Chemie.



- Kleeberg A & H P Kozerski 1997 Phosphorus release in Lake Grosser Müggelsee and its implications for lake restoration. *Hydrobiologia* 432: 9-26.
- Krienitz L, P Kasprzak & R Koschel 1996 Longterm study on the influence of eutrophication, restoration and biomanipulation on the structure and development of phytoplankton communities in Feldberger Haussee (Baltic Lake District, Germany). *Hydrobiologia* 330: 89-110
- Major G A, G Dal Point, J Klye & B Newell 1972 Laboratory techniques in marine chemistry. CSIRO Division of Fisheries and Oceanography, Sydney.
- Marsden M W 1989 Lake restoration by reducing external phosphorus loading: the influence of sediment phosphorus release. *Freshwater Biology* 21: 139-162.
- McArthur W M & E Bettenay 1974 The development and distribution of soils of the Swan Coastal Plain, Western Australia. Soil Publication 16. CSIRO, Melbourne.
- OECD 1982 Eutrophication of waters: Monitoring, assessment and control. Organisation for Economic Co-operation and Development, Paris.
- Qui S M & A J McComb 1994 Effects of oxygen concentration on phosphorus release from reflooded air-dried wetland sediments. *Australian Journal of Marine and Freshwater Research* 45: 1319-1328.
- Rose T W 1979 Periphyton and metaphyton in Lake Joondalup. Honours Thesis, Department of Botany, University of Western Australia, Perth.
- Salas H J & P Martino 1991 A simplified phosphorus trophic state model for warm-water tropical lakes. *Water Research* 25: 341-350.
- Schindler D W 1977 Evolution of phosphorus limitations in lakes. *Science* 195: 260-262.
- Schmidt L G & R S Rosich 1993 Physical and chemical changes and processes. In *Wetlands of the Swan Coastal Plain: Wetland classification on the basis of water quality and invertebrate community data*, Volume 6 (eds J A Davis, R S Rosich, J S Bradley, J E Growns, L G Schmidt & F Cheal). Water Authority of Western Australia and Environmental Protection Authority, Perth, Western Australia, 29-80.
- Upton K 1996 Temporal and spatial patterns in water chemistry, phytoplankton biomass and microcrustacea in Lake Joondalup and Beenypup Swamp, Western Australia. Honours Thesis, School of Natural Sciences, Edith Cowan University, Perth.
- Wetzel R G 1983 *Limnology*. W B Saunders Co, Philadelphia.
- Wrigley T J, J M Chambers & A J McComb 1988 Nutrient and gilyn levels in waters of coastal-plain wetlands in an agricultural area of Western Australia. *Australian Journal of Marine and Freshwater Research* 39: 685-694.