HERDSMAN LAKE WATER QUALITY STUDY

Prepared for:

The Department of
Conservation and Land
Management

By :

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PREFACE

This study was commissioned in 1988 to contribute to the Herdsman Lake Management Plan being prepared by the Department of Conservation and Land Management.

The water quality data set available for analysis at that time primarily consisted of six years' data held by the State Planning Commission (now the Department of Planning and Urban Development).

The draft report was circulated to the relevant authorities in early 1989.

Earlier this year, a decision was made to finalise the report. Minor changes have been made where appropriate, in line with comments from the relevant authorities. Two sections (Chapters 8 and 9) of the draft report have been transferred to the appendices of this report because they relate to assumptions regarding management objectives for the lake. The setting of management objectives for the lake lies within the scope of the management plan, rather than this report.

We have provided water quality objectives for the protection of the integrity of the aquatic ecosystem of Herdsman Lake in Appendix 1 and management considerations regarding water quality in Appendix 2. Both appendices provide information that will be of use if the primary management objective for the lake is the protection of the integrity of the aquatic ecosystem.

ACKNOWLEDGEMENTS

This report is an analysis of six years' water quality data collected by the State Planning Commission and Riggert Consulting Ecologists Pty Ltd. The majority of these data were collected as part of an environmental monitoring programme initiated and funded by Herdsman Nominees Pty Ltd.

This analysis of the data set was initiated by Professor Arthur McComb of the Centre for Water Research and Gordon Graham of the Department of Conservation and Land Management (CALM). The preparation of this report has been directed by the Herdsman Lake project team of CALM and was made possible by funding from the State Planning Commission. This report is to contribute to the Herdsman Lake Management Plan being prepared by CALM.

We would particularly like to thank Andrew Moore of the State Planning Commission for liaison with us throughout the study.

Officers of the Water Authority of Western Australia are thanked for the provision of information on water levels and drainage patterns.

We are also grateful to Steve Appleyard of Geological Survey for the provision of records from the Urban Water Balance Study.

Bruce Kaye and Bob Mercer of Wood and Grieve Engineers provided valuable information on the hydrology of Herdsman Lake and the dredging operations which have occurred at the lake.

Neil Loneragan of Murdoch University provided valuable assistance with the statistical analysis of the data set.

The artwork for this report was prepared by Mike Roeger, Alan Rossow and Mike Van Keulen. Their efforts are greatly appreciated.

Many thanks to Noella Ross, Colleen Hubbard and Marika Gurney for word processing and to Ivor Growns for his efforts with preparing graphics and formatting the draft report.

The provision of facilities, particularly computing facilities, at Murdoch University, for this study, are also gratefully acknowledged.

CONTENTS

1. SUMMARY

1. Herdsman Lake is the largest wetland in the inner metropolitan region of Perth, Western Australia, and comprises three deep and permanent waterbodies which have been dredged (Floreat Waters, Industrial Lake and Powis Lake) and an inner seasonally inundated wetland dominated by the bullrush, *Typha orientalis* . The lake is also crossed by open channels which form part of the regional drainage system and it receives water from many small inflowing local authority drains.

2. The primary objective of this study was to analyse and interpret the water quality data set which has been collected from Herdsman Lake from April 1982 onwards under the direction of the State Planning Commission. The results of the data analysis were to provide information that would contribute to the Herdsman Lake Management Plan. In addition, modifications to the water quality monitoring programme were to be recommended where appropriate. Other water quality monitoring data has been included, where available, to aid interpretation of the SPC data set.

3. The bulk of the water quality data available consisted of surface water samples taken from the three deepened water bodies created by dredging; Floreat Waters, Industrial Lake and Powis Lake.

4. The dredging of Floreat Waters was carried out between 1979 and late 1981. The collection of water quality data from Floreat Lakes was started by the State Planning Commission in April 1982 and continued until October 1983. Industrial Lake was dredged between 1982 and 1983 and monitored by consultants for the period September 1983 to June 1985. Powis Lake was dredged between 1983 and 1985. The State Planning Commission conducted water quality monitoring at all these lakes from October 1985 to May 1988.

5. The following water quality parameters were measured at each lake: pH, total dissolved solids, turbidity, conductivity, chloride, ammonia, nitrate, total Kjeldahl nitrogen, total nitrogen, orthophosphate, total phosphorus and chlorophyll *a*. Dissolved oxygen and temperature profiles were also recorded. Heavy metal concentrations and pesticide levels were measured in Floreat Waters and selected drains in 1982-83 and in drains only in October 1985. Multiple sites were sampled at each lake to provide information on spatial variability and comparative information on deep and shallow sites. All analyses were carried out by the Government Chemical Laboratories apart from the dissolved oxygen and temperature profiles which were measured on site. The majority of samples for chemical analysis were taken from surface waters only.

6. For this data analysis changes in the water quality parameters over the sampling period were plotted using Cricket Graph software on a Macintosh SE. A multiple analysis of variance (MANOVA) with nested design was used

to test the differences between lakes on the basis of the main water quality parameters measured. This was carried out on the Sperry mainframe computer at Murdoch University using the SPSS-X statistical package.

7. The results for the MANOVA's carried out for the following water quality parameters: pH, TDS, conductivity, chloride, turbidity, TKN, nitrate, ammonia, total P, orthophosphate and chlorophyll *a*, indicated that there were:

   a) no significant difference between sites within each lake

   b) highly significant differences between lakes

   c) significant differences between seasons in each lake

   d) different seasonal patterns of change in each lake.

   The low variability in water quality data between sites in each lake indicated that the number of sites sampled per lake in the monitoring programme could be reduced. However, the differences between lakes indicated that each lake was acting as an isolated body of water and therefore each lake requires monitoring.

8. The three deepened lakes were all slightly alkaline with limited seasonal variation in pH. All three lakes were fresh, conductivities did not exceed 180 mS/m. Floreat Waters was the most turbid of the three lakes and turbidity at this lake and Industrial Lake was highly correlated with chlorophyll *a* indicating that turbid conditions were probably due to the growth of algae.

9. Floreat Waters was the most nutrient enriched of the three deepened waterbodies and could be classified as eutrophic on the basis of mean annual total phosphorus concentrations and hypereutrophic on the basis of chlorophyll *a* concentrations. Industrial Lake was classified as mesotrophic on the basis of total phosphorus and eutrophic on the basis of chlorophyll *a* . Powis Lake was classified as mesotrophic on the basis of both total phosphorus and chlorophyll *a* levels. The highest chlorophyll *a* concentrations in Floreat Waters were recorded in autumn and early winter.

10. Dissolved oxygen/temperature profiles recorded for three deep sites in Industrial Lake between September 1983 and October 1984 indicated that thermal stratification developed in spring and persisted throughout summer until overturn occurred in autumn with the lake remaining well mixed throughout winter. This cycle, with persistent stratification throughout summer, was also recorded at several deep sites in Floreat Waters by an independent study (ESRI, 1983). This is the classic cycle of a warm monomictic lake. Generally stratification only occurred at sites deeper than 5 metres. Shallow sites (<2 metres) remained well mixed throughout the year.

11. Although the water quality data set revealed that some problems of nutrient enrichment are evident at Herdsman Lake, particularly with regard to Floreat Waters, the three dredged lakes appear to be intermediate in enrichment between those that are often hypereutrophic (Jackadder, Monger, North and Bibra Lakes) and the less enriched urban lakes (for example, Lake Jandabup and Loch McNess). The occurrence of thermal stratification during spring and summer in areas that exceed 5 metres in depth may result in water quality problems if the lakes become more enriched. Nutrients appear to be released from the sediments into the anoxic hypolimnion and when brought to the surface with the autumn overturn can result in algal blooms. If large amounts of nutrients are added to the water column in this way severe algal problems may result. Nutrient concentrations in the various drains were frequently very high when recorded, indicating that they may be a significant source of nutrients to the lake system. A limited amount of data suggested that flushing of nutrients into the lakes from the catchment by the first winter rains may result in an increased nutrient load in autumn and early winter.

12. The concentrations of the organochlorine pesticides dieldrin, chlordane and heptachlor recorded at the lake during 1982 and in a detailed pesticide study from 1986-1988, exceeded the maximum levels recommended for the protection of aquatic fauna. High levels recorded in inflowing drains indicated that surface inflows play a large part in delivering pesticides to the lake.

    High concentrations of pesticides detected in fish and waterfowl resident at the lake, and the low number of species of predatory invertebrates recorded at the lake, are considered to indicate that the aquatic food chains have been affected by high pesticide concentrations. Probable sources of pesticides include the Argentine ant control programme and commercial and domestic pesticide applications within the catchment.

13. The results of limited monitoring for heavy metals indicate that problems of heavy metal pollution may exist at the lake. Sampling of Floreat Waters in 1982/83 revealed concentrations of cadmium, copper, lead and zinc in excess of criteria recommended for the protection of aquatic ecosystems by Hart (1982). ESRI (1983) detected high concentrations of zinc in the Selby and Flynn St drains from non-specific point sources in 1982/83. Very high levels of lead were recorded in the Balgay drain in 1985. It is not known whether heavy metal concentrations are still high in Floreat Waters nor the condition of other sections of the lake.

14. Recommendations for modifications to the water quality monitoring programme are made. Future management and interpretation of monitoring data requires that specific objectives be set with regard to water quality in accordance with primary management objectives. It is important that a nutrient budget and water balance be established for the lake system to allow determination of effective management strategies for the control of water quality in the future.

2. INTRODUCTION

Herdsman Lake is located approximately 7 km northwest of the central business district of Perth, Western Australia (Fig. 1), and is the largest wetland (220 ha) within the inner metropolitan region. The lake is surrounded by urban and light industrial development and has had a long history of human disturbance. The lake presently comprises an inner seasonally dry wetland (160 ha in area), dominated by the bulrush, *Typha orientalis,* and an outer region containing three deep and permanent water bodies which have been formed by dredging operations. The lake is also crossed by artificially created channels which form part of the regional drainage system.

The three permanent waterbodies were the subject of this study and their location in relation to the rest of the lake is given in Figure 2. These dredged waterbodies are essentially separate, isolated lakes although they overflow into the shallow central wetland region after heavy rainfall during the winter months. The two large drains which carry water from Perth's northern suburbs across the lake are isolated from the lake proper by earth banks, however, they spill over into the lake during times of peak flow. Many smaller drains flow directly into the lake from a catchment area which contains housing, light industry and market gardens.

Floreat Waters was the first lake to be dredged as part of the development of the residential area of Floreat Waters Estate. A water quality monitoring programme was initiated as part of the Environmental Review and Management Programme (ERMP) for the Estate and collection of water quality data from Floreat Waters was started by the State Planning Commission (SPC) in April 1982.

The main section of Industrial Lake, which lies on the north-eastern margin of the lake, was completed in 1983 as part of the development of the light industrial area known as Herdsman Park Estate. Monitoring of water quality in this lake was undertaken by consultants for the period September 1983 to June 1985. Monitoring in Floreat Waters ceased at the start of this monitoring programme in Industrial Lake. When the third lake, Powis Lake, was completed on the eastern margin of Herdsman Lake (part of the Herdsman Park Estate project), the responsibility for monitoring all three lakes was handed over to the State Planning Commission again.

The primary objective of this study is to analyse and interpret the water quality data that have been collected since 1982 under the direction of the SPC and review the monitoring programme. Specific objectives are as follows:

(i) to analyse and interpret the SPC water quality data set collected from Herdsman Lake for the period April 1982 to April 1986 and for further 1986/87 data where available;

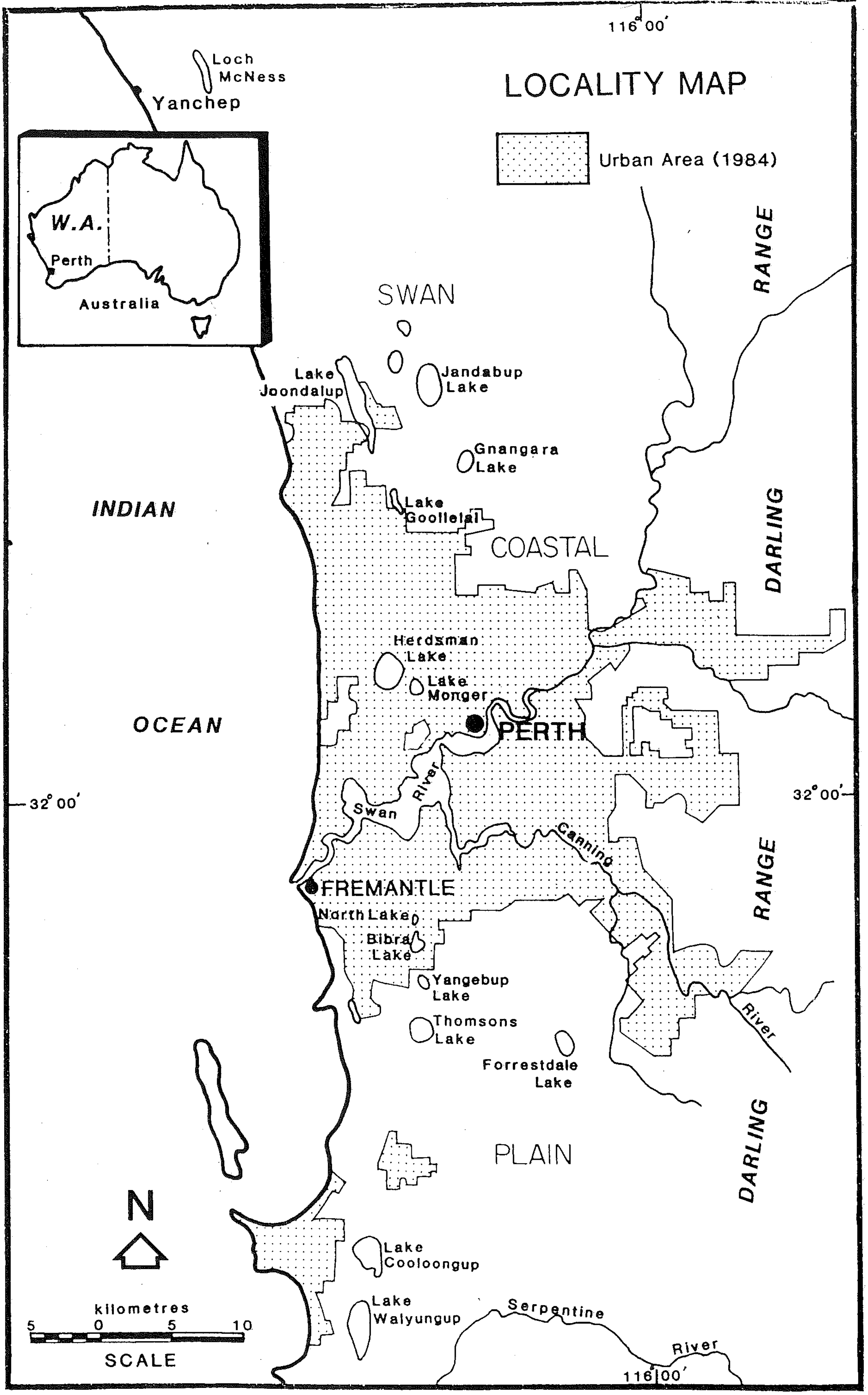


Fig. 1. Location of Herdsman Lake.

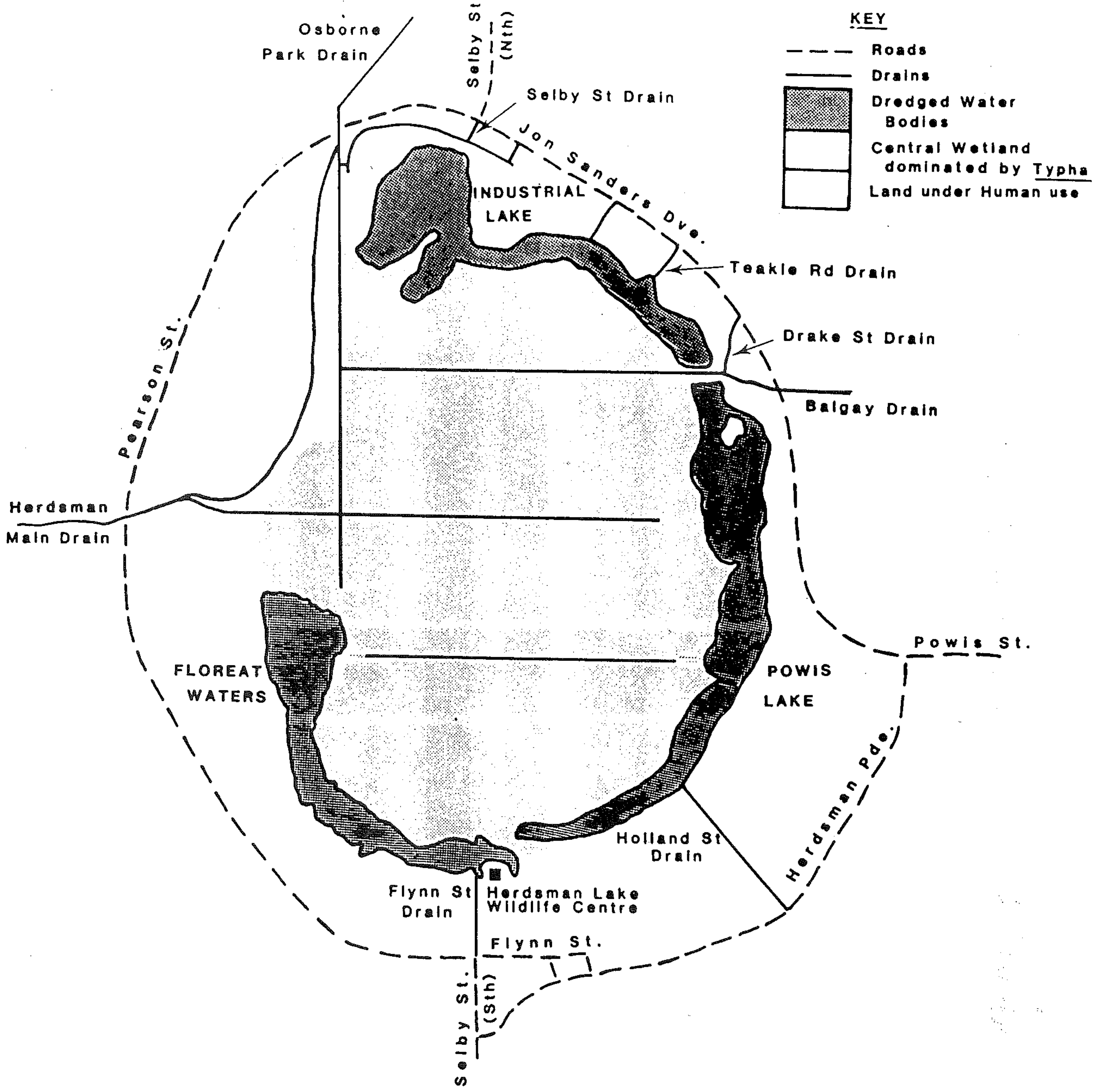


Fig. 2. Location of the three deepened waterbodies and other features associated with Herdsman Lake, April 1988.

(ii) to present the results of the data analysis in a format that provides information for and contributes to the preparation of the Herdsman Lake Management Plan by the Department of Conservation and Land Management;

(iii) to investigate causal mechanisms of events apparent from the data;

(iv) to consider other available data to aid interpretation of the SPC data set and expand the base for understanding of water quality in the lake;

(v) to make comparisons with other wetlands in the metropolitan region;

(vi) to suggest modification to the water quality sampling programme to ensure that the most appropriate data is collected for management.

3. BACKGROUND

3.1 HISTORY

Herdsman Lake was originally known as "Great Lake" by European settlers until it was surveyed by J.S. Roe in 1937 and titled Lake Herdsman (Blyth and Halse, 1986). Early accounts indicate that the lake carried a thick growth of the bulrushes *Cladium* sp. and *Typha austifolia* (Teakle and Southern, 1937) but that the lake was more open and less choked in the early 1800s than it is today (Blyth and Halse, 1986). The dominant bulrush in the lake at present is *Typha orientalis* (Arnold, 1987).

The original Herdsman Lake was essentially a marsh of about 420 ha total area (Blyth and Halse, 1986), which flooded to depths of up to 2 m in winter (Bekle, 1981) and dried out by the end of summer to a "wet and puggy" condition (Teakle and Southern, 1937). In 1848 a plan to drain Lake Monger into Herdsman Lake was proposed but never eventuated (MRPA, 1976). In 1854 a large area of land on the shores of Lake Monger was granted to a group of Benedictine Monks and by the 1900s the majority of the Herdsman Lake area was owned by the Roman Catholic Church (Blyth and Halse, 1986). Land use consisted mainly of stock grazing. In 1912 the Osborne Park area was made suitable for market gardening by drainage into Herdsman Lake (Blyth and Halse, 1986). In 1916 the soils of Herdsman were tested for agricultural potential and found inferior to those in Osborne Park (MRPA, 1976). Despite this a Soldier Settlement Scheme began in 1920 through purchase of land from the Roman Catholic Church (Blyth and Halse, 1986) and the initiation of an ambitious drainage scheme to reclaim land from the lake.

Drainage work commenced in 1921. An open drain was constructed from Osborne Park to pass through the north-western corner of Herdsman Lake and flow, via a 3 km long tunnel, out to the sea near Floreat Beach. A system of subsidiary drains, connected to the Osborne Park drain, drained Herdsman Lake itself (Fig. 3). Irrigation of the reclaimed lake was effected by way of locks on the drains. Thus, the drains could be made to overflow into the surrounding lands when irrigation was required (Teakle and Southern, 1937).

The drainage scheme was completed in 1925. The sale of long narrow blocks of land radiating out around the edge of the lake began in 1928 but the project was never successful (Blyth and Halse, 1986). Soils were of poor quality and the area still flooded in winter. This led to a detailed soil survey by Teakle and Southern in 1934 to fully assess agricultural potential (MRPA, 1976).

Since then the lake has been used for cattle grazing, some market gardening and as a compensating basin for urban drainage with most of the land remaining under freehold title (Blyth and Halse, 1986).

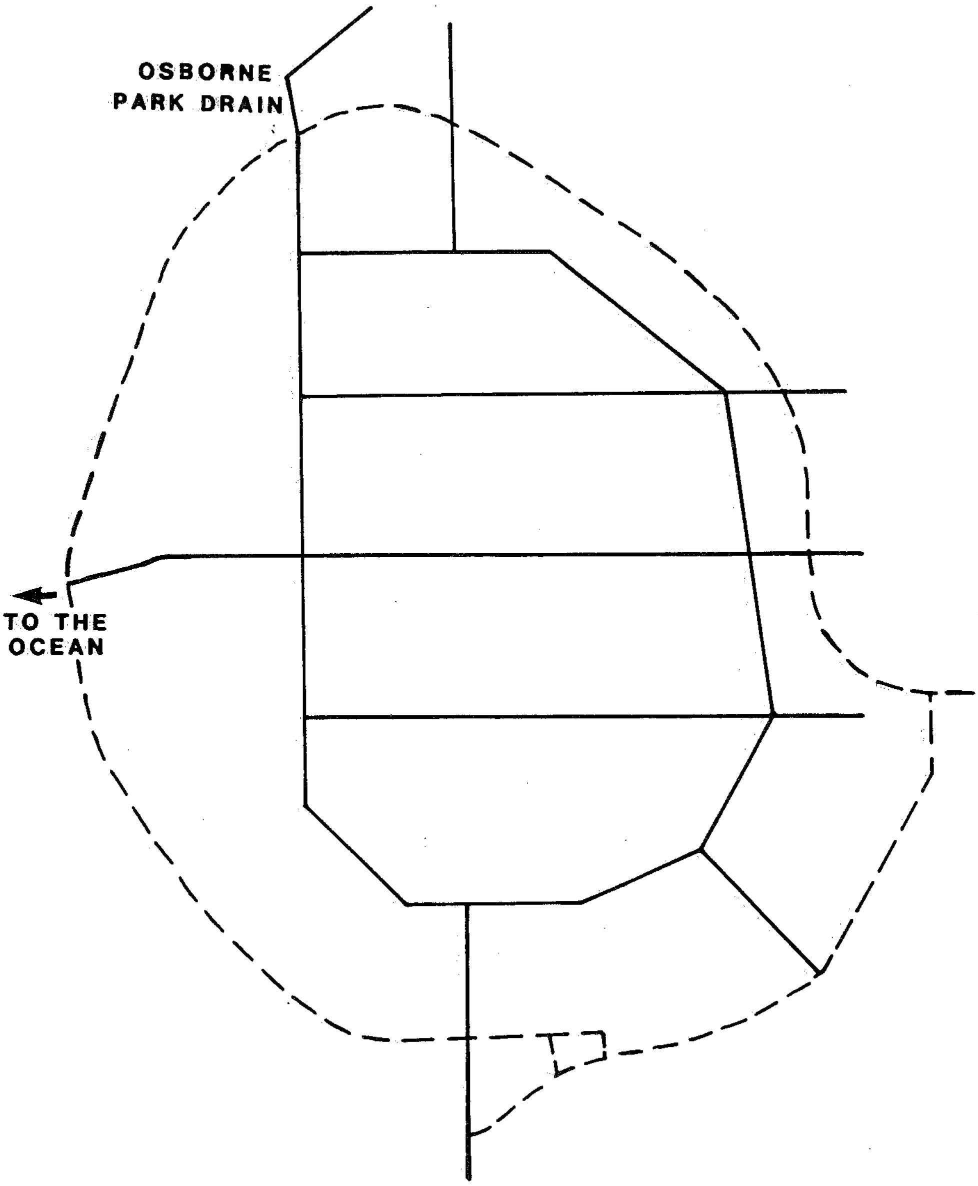


Fig. 3. The drainage system at Herdsman Lake in 1925. The 1988 boundary roads have been included to facilitate interpretation of this map.

The pressures of urban development have gradually led to the encroachment of residential and industrial developments upon the lake. The Stephenson-Hepburn report of 1955 recommended reservation of the lake area for parks and recreation. This was subsequently implemented in the Metropolitan Region Scheme, established in 1963 (MRPA, 1976). However, the scheme allowed for the development of several important regional roads around and through the lake.

In 1975 the MRPA produced a "Plan for Herdsman Lake" which, after review by various organisations, was modified and officially adopted by the government as a concept plan for Herdsman Lake (MRPA, 1976). The plan incorporated the development of several of the regional roads around but not through the lake, the development of an industrial zone to the north-east (which was being advocated by a local committee of adjacent land owners which subsequently became Herdsman Nominees Pty Ltd) and a residential development on the south-western shore. The value of the natural environment was recognised and a plan for enhancement of the central wetland area, reserved for parks and recreation, was prepared. This involved the creation of deep channels with open waters to form a moat around the lake to increase the diversity of habitats available to wildlife. Thus, dredging was required and it was proposed that this occur in conjunction with development on the swampy shores of the lake to provide the fill required for development.

Subsequently, three deep lakes were formed, known as Floreat Waters, Industrial Lake and Powis Lake, each with shallow extensions to form part of the moat proposed for the whole lake.

Floreat Waters was developed in the south-west sector of Herdsman Lake in conjunction with landscaped open space on the shores of the lake. The developers were Katanning Holdings. Dredging was carried out by Cooper Dredging in conjunction with Wood and Grieve as consulting engineers. With the successful completion of Floreat Waters, Herdsman Nominees Pty Ltd engaged Cooper Dredging and Wood and Grieve to develop Herdsman Estate (now known as Herdsman Business Park) in the north-east sector of the lake. This led to the creation of Industrial Lake and Powis Lake.

In 1985, the State Planning Commission prepared Improvement Plan No. 21 for Herdsman Lake which updated the original Concept Plan and provided more detail. This was gazetted in January 1986.

After the completion of Powis Lake by Herdsman Nominees Pty Ltd, the State Planning Commission gained approval from the Environmental Protection Authority to extend Powis Lake south to link up with Floreat Waters and further extend the moat.

In May 1988 a Public Environmental Report for assessment of development in the north-west sector, in accordance with Improvement Plan No. 21, was released (Sherwood, 1988). If this is approved, dredging operations will form another deep lake in this sector and complete the moat surrounding Herdsman Lake.

To facilitate interpretation of the water quality data set, a description of the dredging operations undertaken at each lake is included as a separate section.

3.2 DREDGING OF HERDSMAN LAKE

3.2.1 Floreat Waters

Construction began in 1979 and finished late in 1981. Floreat Waters was formed by the dredging of three deep holes with the connection of these deep areas by wide shallow channels. The deep areas were constructed at the northern end of Floreat Waters, outside the Herdsman Lake Wildlife Centre site (to provide fill for this site) and immediately west of this site. The majority of the shallow water exists as a channel connecting the deeper northern area to the two deep southern areas (Figs 4a,b,c,d).

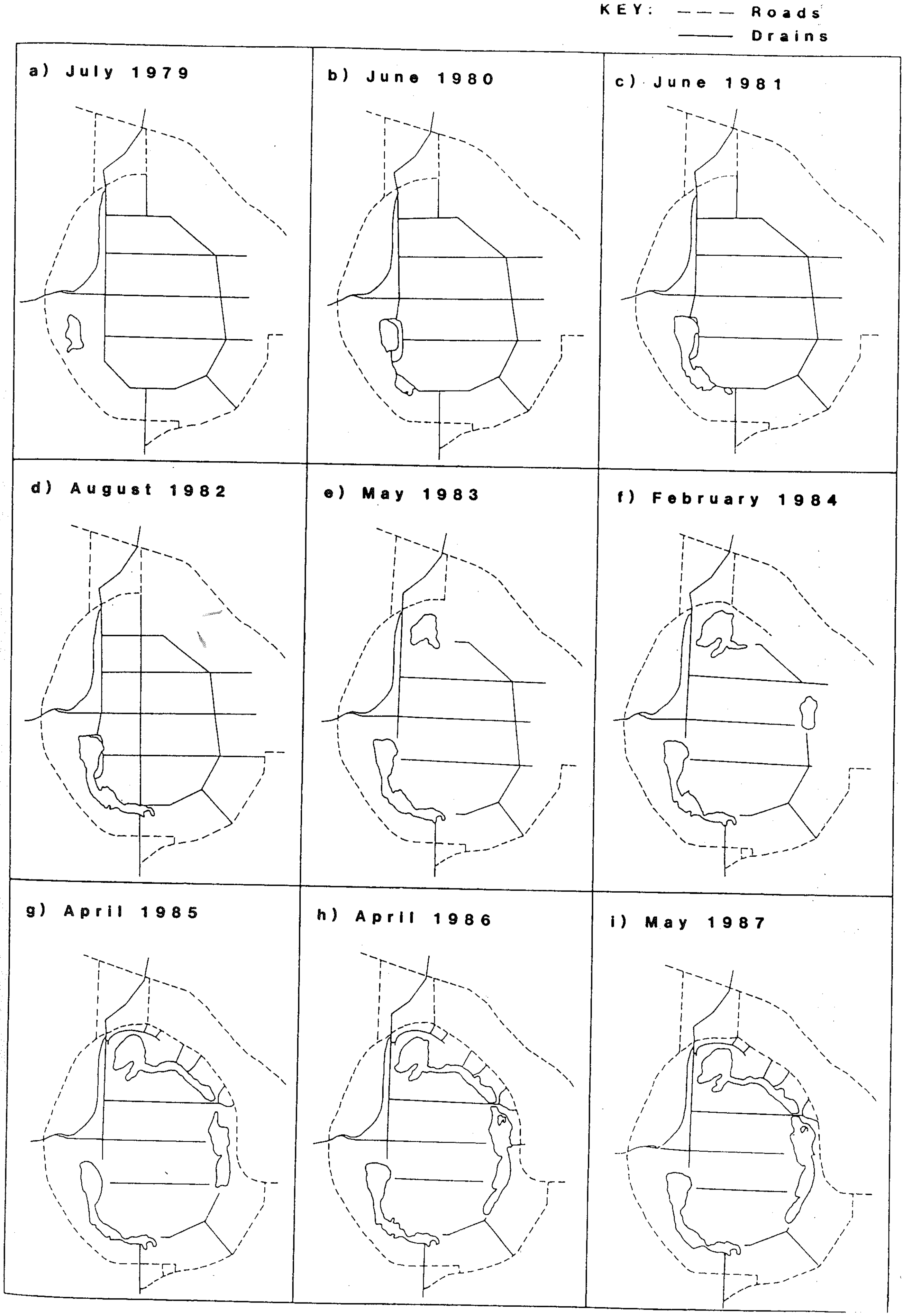
Most of the peat removed from these areas was used to develop the recreational parkland on the immediate shores of the lake. Although some was returned to the areas from which it was removed, half the peat from the shallow channel was pumped on top of the *Typha* reed bed on the eastern shore, while the remainder was pumped into the deep area of the lake at the northern end.

3.2.2 Industrial Lake and Powis Lake

Dredging began in 1982 to form the deep northernmost section of Industrial Lake (Fig. 4e). Peat was stripped before excavation of the sand from the lake bed and stockpiled on the shores of the lake. This was later bulldozed back into the lake.

When development of the sand pad for the Business Park had proceeded too far south for the dredge discharge boom to reach, the dredge had to be shifted further south to provide fill for the remainder of the Business Park area and for the development of Jon Sanders Drive. This occurred at the end of 1983 and the new dredge site formed Powis Lake (Fig. 4f). Dredging proceeded in a southerly direction until July 1984 when the dredge was moved up to cut through the Balgay Drain and begin excavation of the shallow connecting section of moat proposed between Industrial Lake and Powis Lake. This moat section was completed in December 1984.

The dredge was then moved back into Powis Lake to extend it further south to the boundary of the Herdsman Nominees Pty Ltd development zone, level with Powis Street. This was completed in April 1985. In addition, Balgay drain was reconnected so that incoming waters bypassed the newly formed lakes. Thus, Industrial Lake and its southern arm were disconnected from Powis Lake (Fig. 4g).



a) July 1979

b) June 1980

c) June 1981

d) August 1982

e) May 1983

f) February 1984

g) April 1985

h) April 1986

i) May 1987

Fig. 4. Maps drawn from aerial photos showing the development of Floreat Waters, Industrial Lake and Powis Lake within Herdsman Lake between July 1979 and May 1987.

For the first half of construction of the moat section between Powis and Industrial Lakes, peat discharge was pumped back towards Powis Lake. In the second half, peat was pumped towards Industrial Lake thus changing the original contours of the lake basin as the peat slurry settled.

The construction technique used for Powis Lake differed from that used in the first deep section of Industrial Lake. In Powis Lake both peat and sand were removed by the dredge and transported to the fill site. Here separation was achieved and the watery peat by-product was directed back into the lakes via flow over the northern and eastern shores. This process formed a wide shallow delta in the northern section of Powis Lake which was deepened by dredging at the end of the project (about May 1985) and a thin channel was cut to form an island at this end of Powis Lake (Fig. 4h). This finalised developments by Herdsman Nominees Pty Ltd.

In 1985 the State Planning Commission proposed works in the south-east sector of Herdsman Lake to form a section of moat between Powis Lake and Floreat Waters. Construction began in late 1985 with the dredge boom discharging material back into the centre of Powis Lake. As the dredge progressed south the discharge point also moved south trailing behind the dredge. In April 1988 this section was almost complete although the final connection to Floreat Waters was still to be made (Fig. 2).

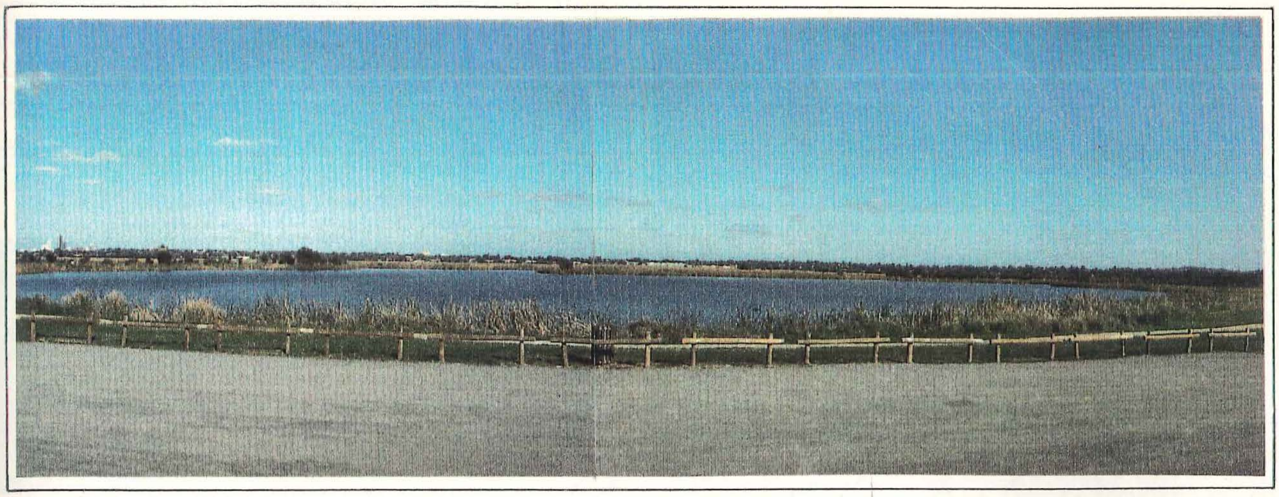
During the construction of Industrial and Powis Lakes several local authority drains which had previously discharged over the swampy north-east shores of Herdsman Lake on the site proposed for the Business Park, were redirected.

Two local authority drains (one being the Teakle Road drain) were connected by pipes below the new Business Park and Jon Sanders Drive to discharge into open channels feeding into the southern arm of Industrial Lake (Fig. 2). In addition, the Selby Street drain, which originally passed through the area in which Industrial Lake was formed, was redirected into the Osborne Park main drain and a channel was cut to direct flow from the Drake Street drain into the Balgay Drain (Fig. 2).

The EPA proposed that all these north-east sector drains, including the Balgay drain, be linked via an outer ring drain beside Jon Sanders Drive to connect up with the Osborne Park main drain. Construction of this outer ring drain was attempted but unsuccessful. Only one, weed-choked, section remains along the northern perimeter of the parking area at Industrial Lake which redirects the flow of the Selby Street drain and one other local authority drain (Fig. 2).

The two local authority drains extended by Herdsman Nominees Pty Ltd and the connection of the Drake Street Drain to the Balgay Drain are all now choked with *Typha* and overflow back onto Jon Sanders Drive in heavy rain.

Plates 1-13 show the open water bodies of Herdsman Lake and some of the drains entering the lake system as they appeared in September 1988.



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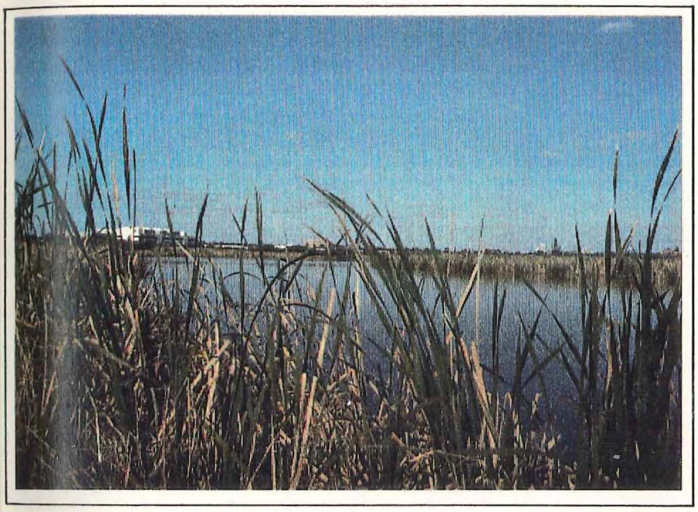

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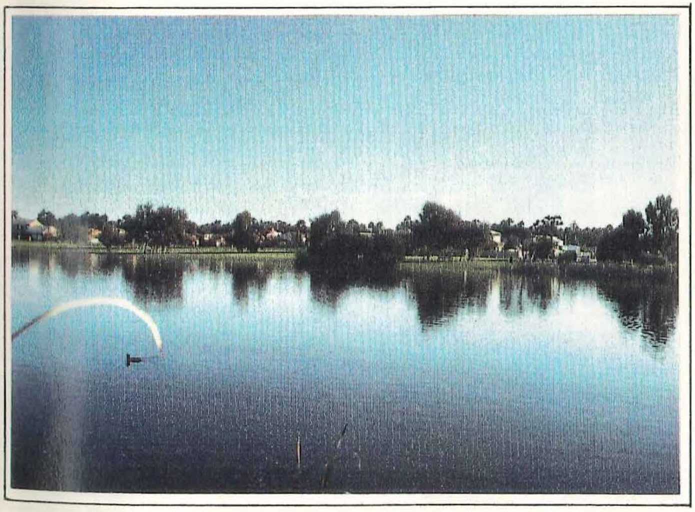

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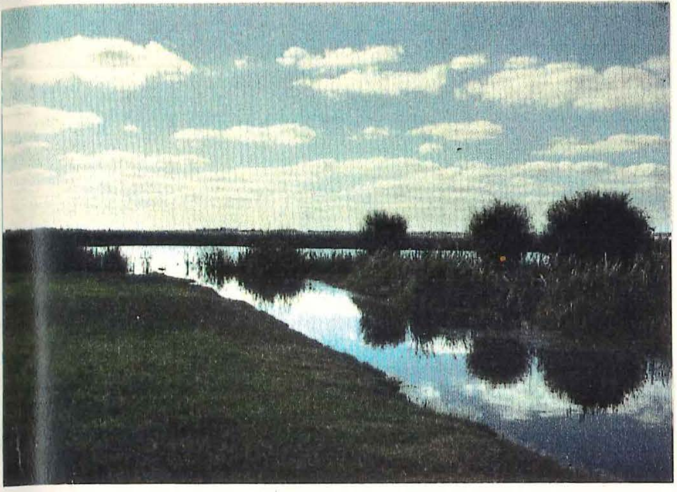
Photographs of the Open Water Bodies and Drains of Herdsman Lake

Plate 1	The deep northern section of Industrial Lake. (Sample sites 1H, 2H, 3E, 9M, 11M and12M all occur in this section of the lake.)
Plate 2	The southern extension of Industrial Lake looking towards Powis Lake.
Plate 3	The northern extension of Powis Lake looking south. (The marker buoy for sample site 16 is in the foreground.)
Plate 4	The northern end of Floreat Waters, looking towards Floreat Waters Estate from the obersvation walkway.
Plate 5	Flynn St drain outfall at the intersection of Flynn St and Selby St (south).
Plate 6	Flynn St drain entering Floreat Waters.
Plate 7	Teakle Rd drain outfall, this drain flows via an open channel into the southern extension of Industrial Lake.
Plate 8	Connecting section of the Drake St drain to the Balgay drain. Note the appearance of the water.
Plate 9	As for Plate 8. Note the petrol films on the surface of the water.
Plate 10	Balgay drain outfall.
Plate 11	Path of the Balgay drain through the original Herdsman Lake basin. Drake St drain connection on the right. The southern extension of Industrial Lake is visible through the trees on the right and the northern end of Powis Lake is just visible on the left.
Plate 12	Osborne Park drain outfall in the north-eastern corner of Herdsman Lake.
Plate 13	Outlet of the Herdsman Main Drain at Pearson St on the west side of Herdsman Lake.



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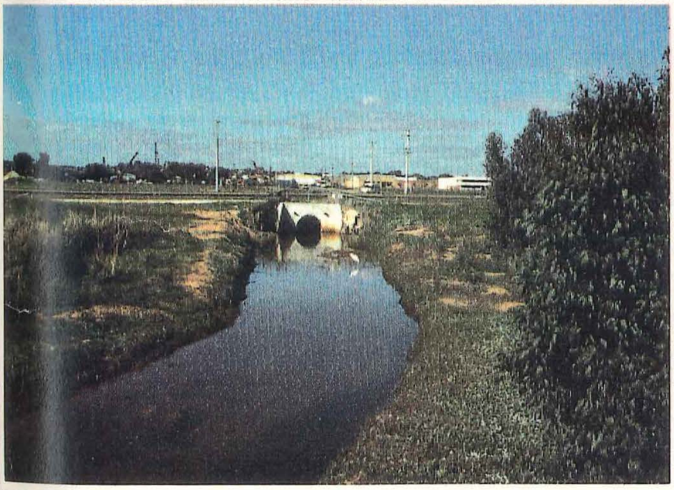

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3.3 HYDROLOGY

Prior to the 1920s, Herdsman Lake was primarily an expression of the groundwater with a considerable inflow of groundwater along its northern and northeastern boundaries, from the Gnangara mound.

In winter the level of the lake rose as the underlying aquifer was recharged. In summer the lake slowly dried out due to evaporation. Surface runoff was only a minor contributor to the lake water level.

With the introduction of the drainage system for the soldiers' settlement scheme, Herdsman Lake became a compensating basin for drainage waters from the surrounding areas. The lake now receives inputs from both local and main drain systems. Figure 5 shows the drainage system which is the responsibility of the Water Authority of Western Australia with the associated catchment and sub-catchment areas. The area of the total catchment is 3330 ha. Figure 6 shows the local authority drains as they are known to exist.

Little information is available on the flow rates of the drains. Table 1 provides the available information on design flow rates for the main drains. The outflow drain for the main drainage system flows at 700 l/sec on average but can take up to 1600 l/sec at full output. This does not accommodate the full input to the lake. The drainage system is designed to produce a maximum lake level of 7.4 m AHD (Australian Height Datum) in the event of flooding by a 10 year storm event. This is three metres lower than levels recorded prior to installation of the drainage system in the 1920s.

Figure 7 shows the surface water levels recorded in Floreat Waters over the study period (recorded by the Water Authority at a staff gauge beside the Herdsman Lake Wildlife Centre).

Figure 8 shows the level of groundwater on the south-west side of the lake, near the Churchlands campus of WACAE, over the study period (Water Authority of Western Australia, Gnangara Mound Monitor No. GD5). Groundwater contours are shown in Figure 9. The 8.0 m contour of the Gnangara mound circles around the northern, eastern and southern shores of the lake, with the 7.0 m contour lying along the south-western shore. Groundwater flow is from the north-east towards the south-west. Groundwater movement is slow, therefore, changes in groundwater level are not directly linked to changes in surface level at a given time, there is a lag phase.

In summary, the volumes of water entering the lake and the relative significance of different sources of input are unknown. Water enters via the drains, direct runoff, rainfall and as groundwater. It leaves the lake via the main drains, evaporation, evapotranspiration and outflow to the groundwater.

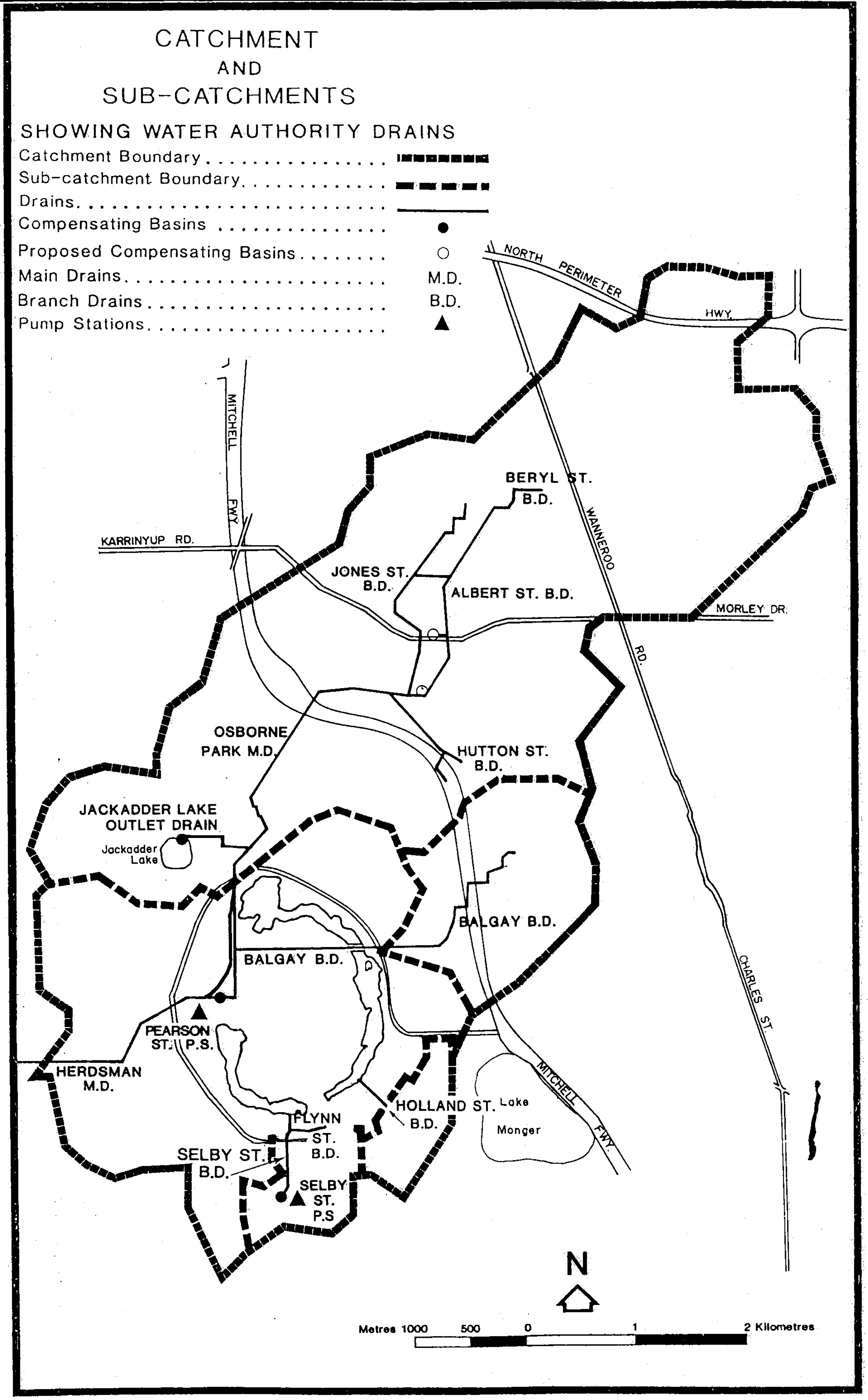

Fig. 5. Map showing Water Authority drains with associated subcatchment areas and the total catchment area.

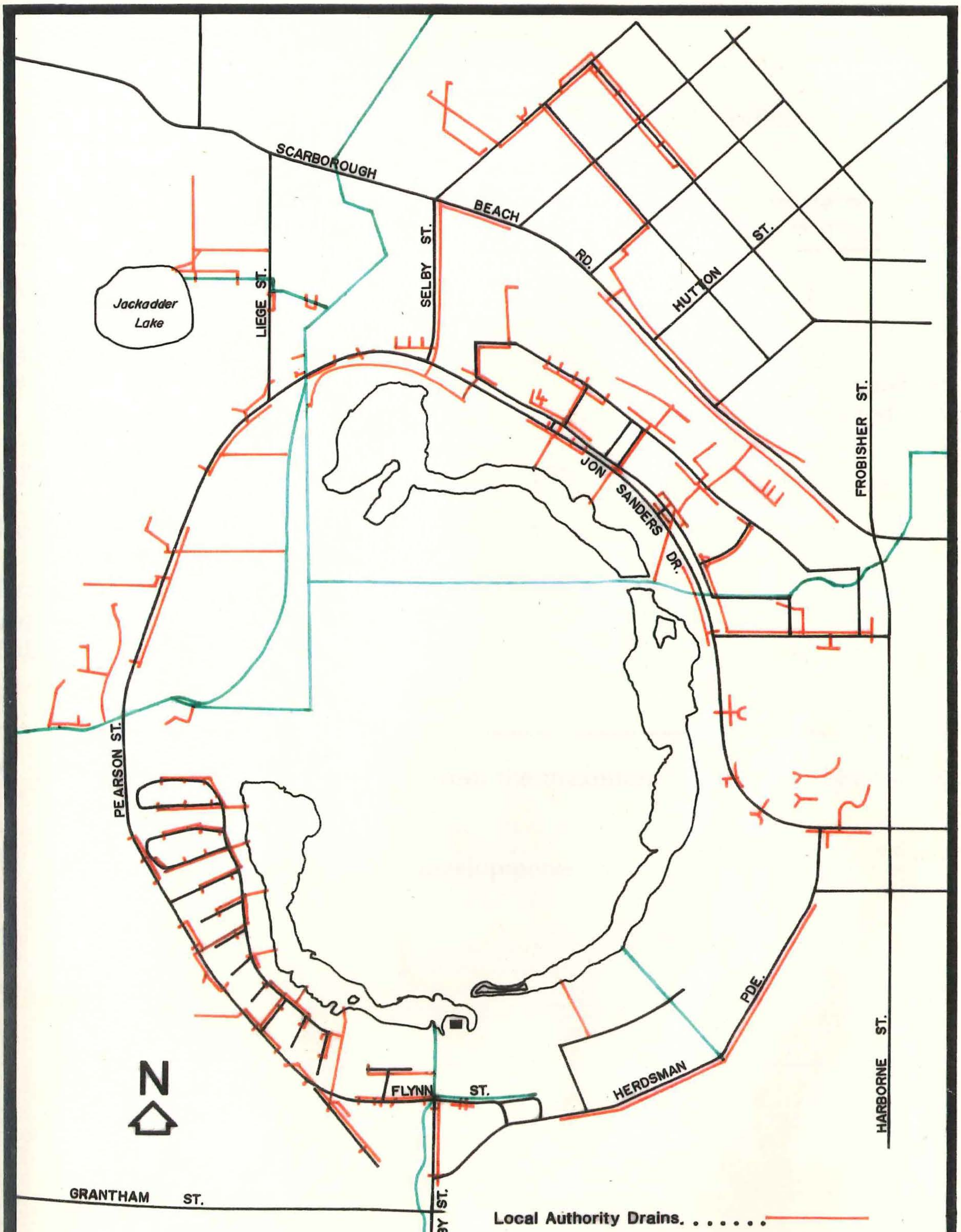

Fig. 6 Map showing both the Local Authority and Water Authority drains which enter or pass through Herdsman Lake.

Table 1. Design flow rates for main drains into Herdsman Lake

Drain	Catchment (Ha)	Peak flow* (l/sec)	Ultimate peak flow** (l/sec)
Balgay	254	3000	7000
Osborne Park	1797	5000	4000 (if compensation basins constructed)
Flynn Street	46	1000	1200
Holland Street	83	1500	2000
Drake Street (now feeds into Balgay Drain)	-	6000	-

* Calculation based on peak flow from the maximum storm event likely in a three year period.

** After completion of proposed developments.

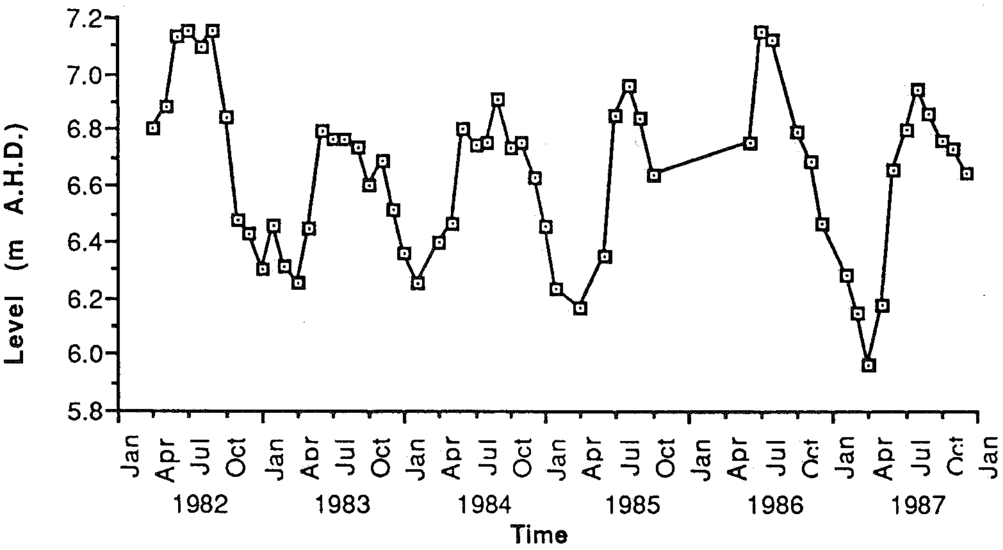

Fig. 7. The surface water levels recorded at the Water Authority guage in Floreat Waters over the study period (1982-1987). Data provided by the Water Authority of Western Australia.

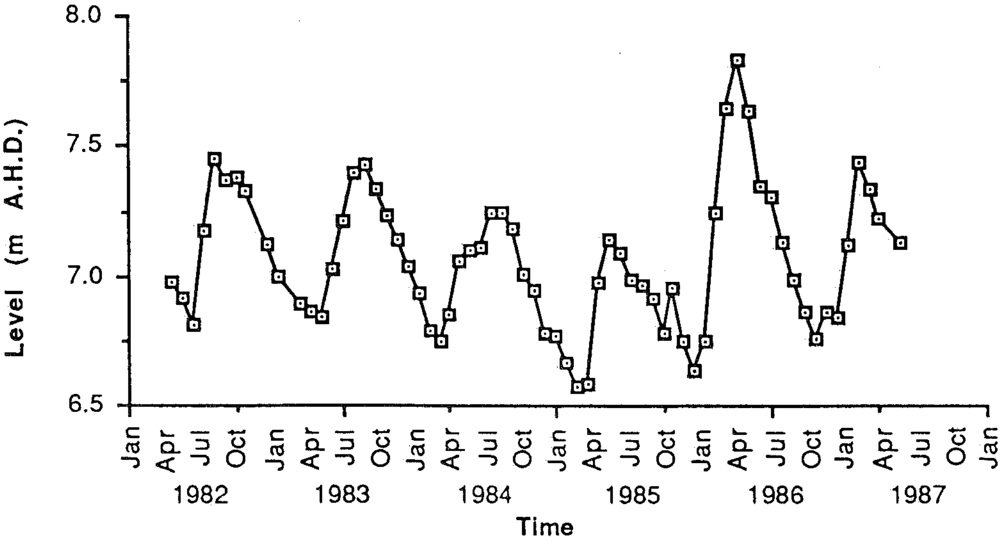

Fig. 8. The groundwater levels recorded at the Water Authority Bore, Gnangara Mound Monitor No. GD5, which was situated on the southwest side of the lake near the Churchlands campus of WACAE, over the study period 1982-1987. Data provided by the Water Authority of Western Australia.

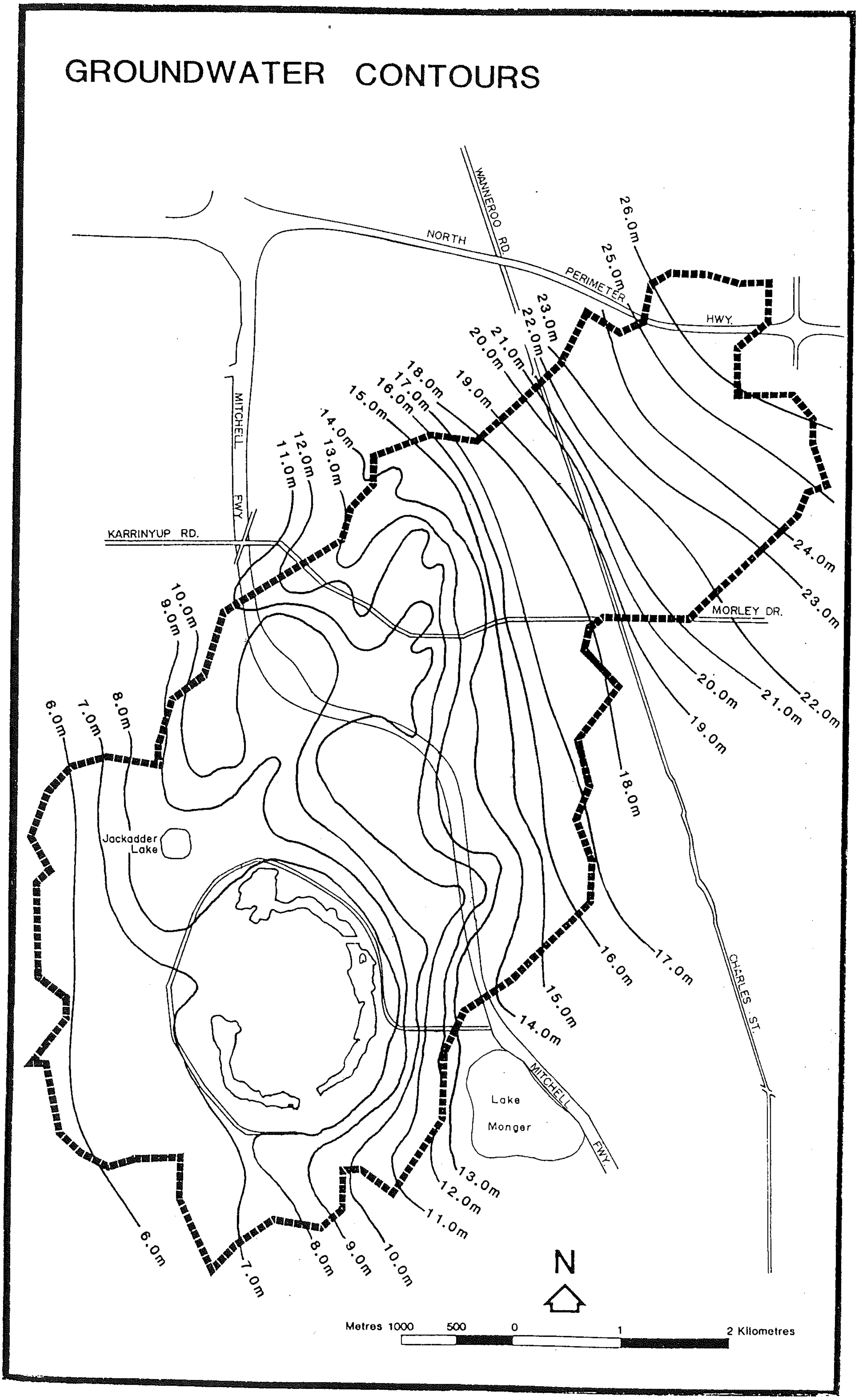

Fig. 9. The groundwater contours within the catchment of Herdsman Lake as provided by the Water Authority of Western Australia.

The quality of the water in the lake is influenced by the quality of these incoming waters in addition to the following factors:

1. biological processes,
2. seasonal fluctuations in physico-chemical parameters as a result of evaporative concentration,
3. sediment/water interactions,
4. water/vegetation interactions,
5. meteorological conditions and
6. flow patterns within the lake.

3.4 CLIMATE

Perth is situated at latitude 32°S and as a consequence its climate is mainly controlled by the movement of the high pressure cells of the sub-tropical ridge. These high pressure systems circle the globe at about 30°S and move north during the winter and south during summer. During winter, frontal systems from the Southern Ocean reach the southwest coast of Western Australia and bring winter rains.

The climate of the Perth region is classed as Mediterranean with mild wet winters and hot dry summers. Annual rainfall is 883 mm occurring over 119 rain days. Figure 10 shows monthly rainfall for 1982 to 1987. Rainfall is usually of the showery type and often for short periods with many hours of sunshine throughout winter.

During summer the high pressure systems produce hot, strong, easterly winds drawn from the interior of the continent. Consequently, relative humidity is low. Afternoon westerly sea breezes sometimes cool the coast but their strength rapidly diminishes with distance from the coast. In winter, winds are predominantly from the south-west.

Climatic data from the Perth meteorological station are shown in Table 2 for 1982 to 1987.

3.5 SOILS

Herdsman Lake is part of a chain of wetlands that extend north-south parallel to the coast, in the Spearwood dune system.

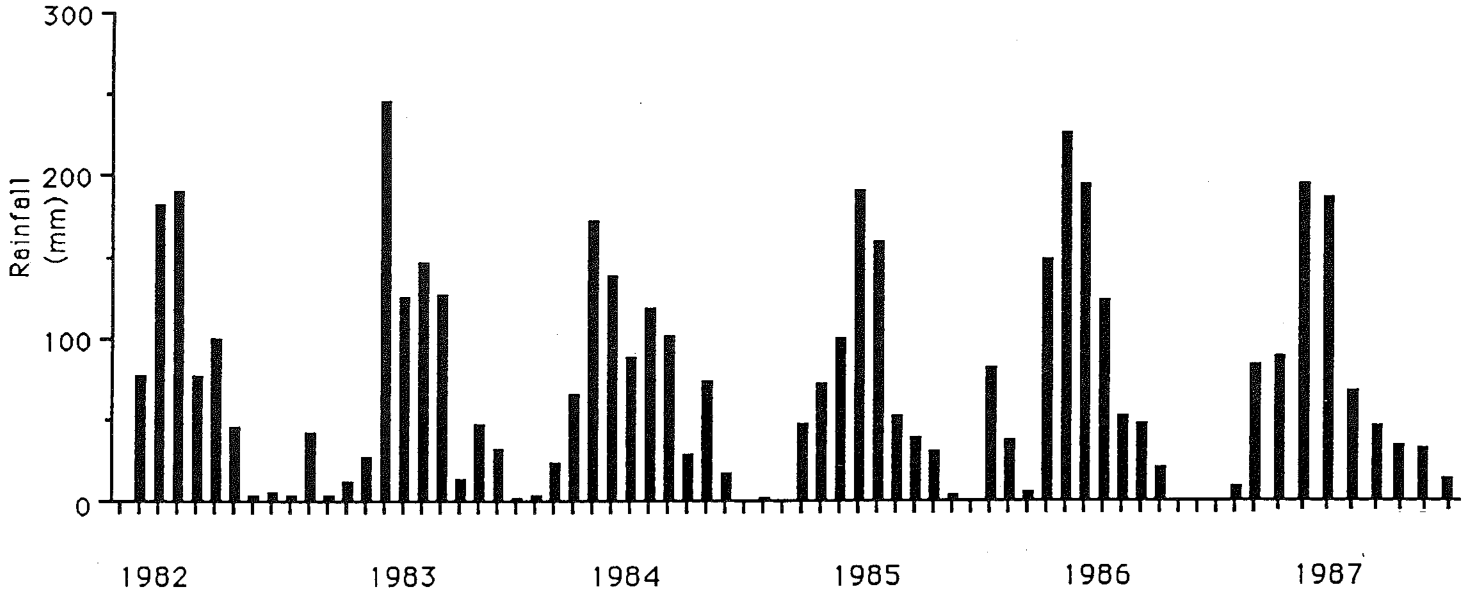

Fig. 10. Monthly rainfall (mm) recorded at the Perth Meterological station over the study period 1982-1987. Data provided by the Bureau of Meterology.

Table 2. Meteorological conditions over the study period recorded at the Perth station.

	Year					
	1982	1983	1984	1985	1986	1987
Mean Daily Maximum Temperature (^{o}C)	23.8	24.5	23.5	24.5	23.2	24.3
Mean Daily Minimum Temperature (^{o}C)	14.0	14.8	13.9	14.6	13.7	14.2
Total Rainfall (mm)	818	821	827	691	930	769
Number of Raindays	103	114	115	103	122	104
Mean Relative Humidity - 9am (%)	64	62	63	60	63	61
Mean Relative Humidity - 3pm (%)	49	49	48	46	48	46
Mean Daily Evaporation Rate (mm)	4.6	4.7	4.6	4.6	4.4	4.5

The soils underlying and on the shores of Herdsman Lake are of the Karrakatta soil association of this dune system (Seddon, 1972).

Karrakatta soils are deep yellow brown sands. Within the Karrakatta unit the larger swamp areas are classified as the Herdsman unit. The soils of this unit are black organic sands, peaty loams, black clays and true peats (DCE, 1980).

Teakle and Southern (1937) describes the soils of Herdsman Lake in great detail. Different types of peat have been laid down in the lake basin indicating that they have been formed under varying conditions of inundation.

4. METHODS

4.1 OVERVIEW OF THE MONITORING PROGRAMME

4.1.1 Floreat Waters 1982/83

The monitoring programme began in February 1982 when the State Planning Commission recorded dissolved oxygen and temperature profiles at four of twelve sites selected at Floreat Waters (sites 9, 10, 11 and 12) (Fig. 11). In April 1982, sampling for a wide range of parameters was initiated for all twelve sites, four of these being near the outlets of incoming drains (sites 1, 3, 5 and 7). The parameters measured were:

Surface:	pH total dissolved solids (mg/l) turbidity (NTU) total Kjeldahl nitrogen (mg/l) ammonia (mg/l) nitrate (mg/l) total phosphorus (mg/l) orthophosphate (mg/l) chlorophyll *a* (mg/l)
Depth profiles:	dissolved oxygen (mg/l) temperature (^{o}C).

Sites 2, 4, 6 and 8 were sampled only on two occasions (April and May 1982) and then monitoring ceased in preference for sites 9, 10, 11 and 12. Sites 2, 4, 6 and 8 were close to the reed beds where mixing was limited and so were not representative of the open water body. The "drain" sites (1, 3, 5 and 7) were monitored only up until February 1983. Thus the bulk of information available from Floreat Waters is for sites 9, 10, 11 and 12.

Measurements of pesticides and heavy metals were made on several occasions. In April 1982, sites 1-8 were tested for cadmium, copper, lead and zinc. In February 1983, sites 1, 3, 5 and 7 were again tested for these metals. In April 1982 and May 1982, sites 2, 4, 6 and 8 were tested for the common organochlorine pesticides and in July 1982, sites 9, 10, 11 and 12 were tested.

The State Planning Commission ceased sampling Floreat Waters in September 1983 when the responsibility for monitoring was handed over to consultants with the completion of the main section of Industrial Lake.

4.1.2 Industrial Lake 1983/84

Six sites were selected in Industrial Lake (Fig. 11) with sampling for the same range of parameters as in Floreat Waters. However, only dissolved oxygen and temperature profiles were taken at regular monthly intervals. The remaining

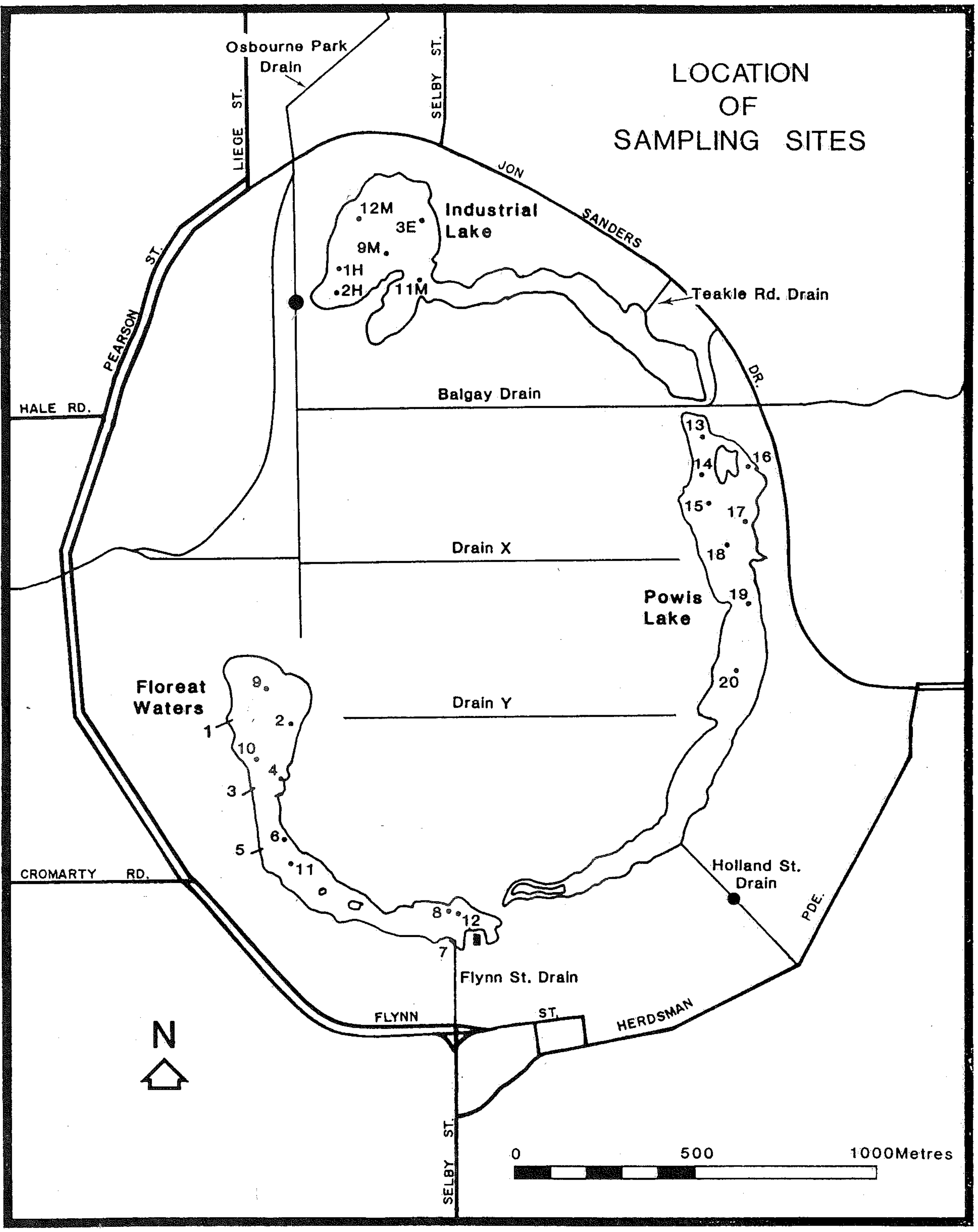

Fig. 11. Location of the sampling sites at Herdsman Lake.

parameters were measured only in November, December 1983 and February, March, May 1984. On these occasions samples were taken from both the surface and bottom of the lake. Sampling ended in October 1984 due to dredging operations to complete the moat extending south from Industrial Lake. At this stage Powis Lake was only partially completed.

4.1.3 Floreat Waters, Industrial Lake and Powis Lake 1985-1987

In September 1985, the State Planning Commission resumed sampling of sites 9, 10, 11 and 12 in Floreat Waters, began sampling the six sites established in Industrial Lake by the consultants and selected eight new sites in Powis Lake (Fig. 11), two of which (Sites 14 and 17) were monitored only briefly. All the parameters previously recorded were measured. In addition, chloride ion concentration (mg/l) was measured from February 1986 onwards and conductivity (mS/m) from July 1986 onwards. Both surface and bottom water samples were taken at selected sites in January 1986.

The State Planning Commission also took samples for pesticide and heavy metal analysis from a number of drains in October 1985. Samples were taken for analysis of dieldrin, heptachlor, aldrin and chlordane levels from the Holland Street drain, drain x*, drain y*, Balgay drain, Teakle Street drain and Osborne Park drain (Fig. 11). Cadmium, copper, lead and zinc were determined in samples from the Balgay drain and drain y.

Table 3 provides a summary of the data available from the sampling programme from 1982 to the present.

4.2 SITE DESCRIPTIONS

Sites were generally chosen to give a wide spatial coverage of each lake (as it existed at the time); to provide comparative information on deep and shallow sites and to provide some information on drain inputs to the lake.

The water depth at sampling sites in each lake was not measured separately but was provided as part of the dissolved oxygen and temperature profiles. The recordings for Floreat Waters from February 1982 to September 1983 indicated that sites 9, 10 and 12 were consistently deep and site 11 was shallow. The range of depth values are shown below:

Site 9	7-10 m
Site 10	6-7 m
Site 11	1-2 m
Site 12	5-7 m

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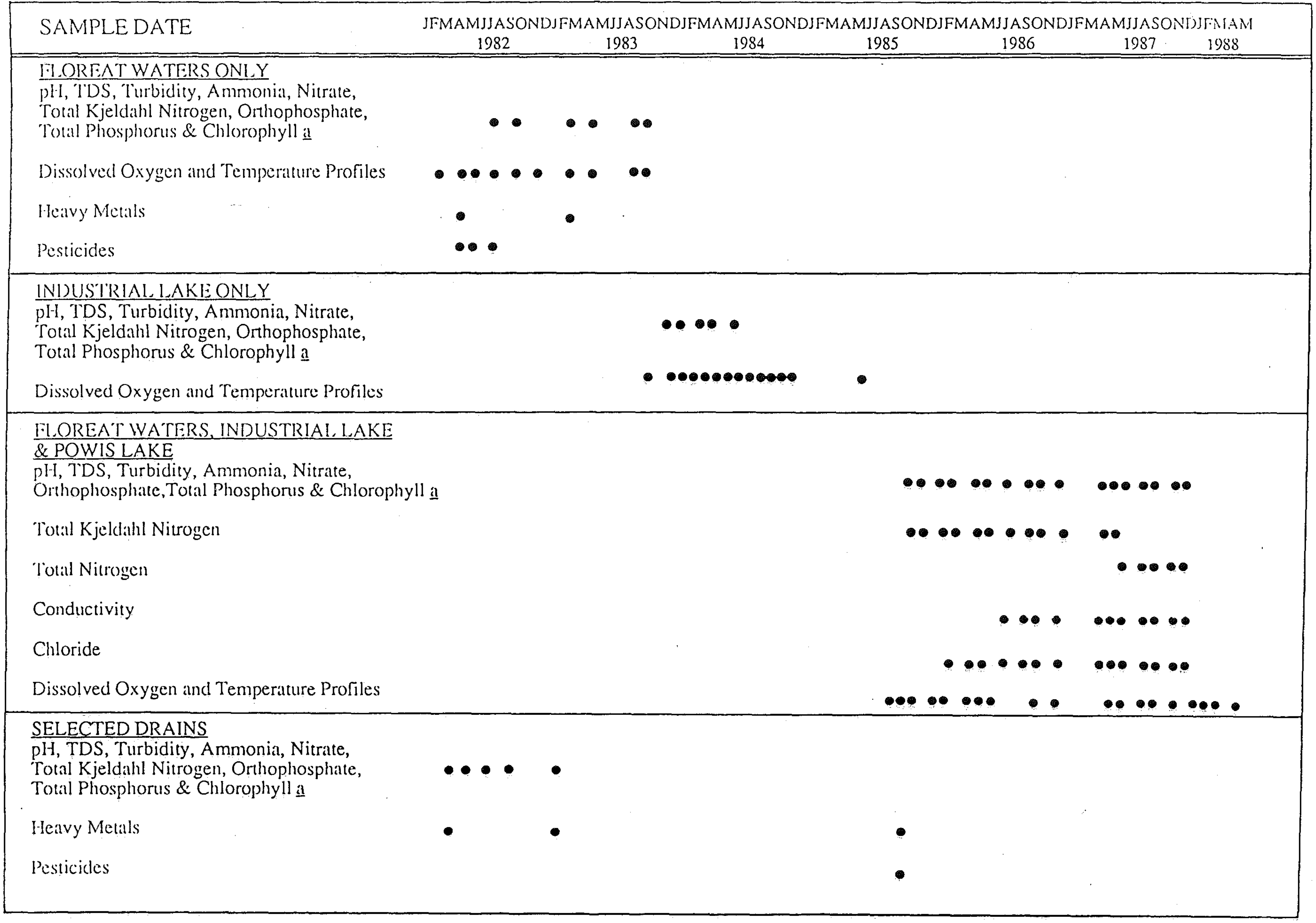
* These drains have no established names.

Table 3: Summary of sampling programme conducted from 1982 onwards under the direction of the State Planning Commission. Black dots indicate when samples were taken.



Recordings made between September 1983 and October 1984 indicated that three sites at Industrial Lake were consistently deep (3E, 9M and 12M) and three were consistently shallow (1H, 2H and 11M). The range of depths recorded at each site are given below:

Site 1H	0.5	-	1 m
Site 2H	1	-	3 m
Site 3E	10	-	11 m
Site 9M	10	-	11 m
Site 11M	0.5	-	1 m
Site 12M	5	-	6 m

Recordings made for the sites in all three lakes between September 1985 and the present show large variations in depth which are not consistent across sites. There are three sites which were relatively shallow at all times, these being site 11 in Floreat Waters (ranging from 0.5 - 2 m), and sites 13 and 16 in Powis Lake (ranging from 2-4 m and 1-3 m respectively). However, the other sites show a large range of values for depth which cannot be attributed to changes in lake water level. It is likely that some variation is attributable to drift of the boat from the site at which the measurements were taken. In addition, theft of the site marker buoys during the six year monitoring programme made the relocation of sites difficult. Settling of the sediments in the lake basin would also have occurred. In the case of Industrial and Powis Lakes, extensions to these lakes were still being dredged while the monitoring programme was operating.

Between the time Industrial Lake was monitored by the consultants and the time it was monitored by the State Planning Commission, Sites 1H, 2H and 11M, which were initially very shallow sites, became deep sites and site 3E changed from a deep site to one of medium depth. The reasons as to why these particular changes occurred are not known. It is possible that the location of the sites used by the State Planning Commission were different to those used by the consultants. It should also be noted that depth is very difficult to measure in these lakes due to the flocculent nature of the bed. Probes dropped into these lakes sink into the soft bed and slowly come to rest as the density of the bed increases. Depth measurements made in this way can be inaccurate in this substsrate.

4.3 SAMPLING

Sites were reached by a boat powered with a small outboard motor. Sediments which had been disturbed by the propellor were allowed to settle before water samples were taken. Two samples of 100 ml and one of 500 ml were collected just below the surface at each site in plastic bottles supplied by the Government Chemical Laboratories. Dissolved oxygen and temperature measurements were made at the surface and at subsequent 1 m depth intervals using a Syland Digital Test Meter (Model 4000) with remote stirrer.

The water samples were taken to the Governmental Chemical Laboratories upon the completion of sampling at all sites. Analyses for all other parameters were conducted by the Government Chemical Laboratories using their standard methods of analysis. It should be noted that total dissolved solids values were calculated from measurements of conductivity (mS/m) multiplied by a standard conversion factor of 5.5 for fresh water. In additon, the Government Chemical Laboratories changed from measuring total Kjeldahl nitrogen (TKN) to measuring total nitrogen in June 1987. TKN and total nitrogen are not equivalent and must be considered separately.

4.4 DATA PROCESSING AND ANALYSIS

At the start of this study the data set consisted of a series of tables and graphs in the document titled "Herdsman Lake Water Analysis 1982-86" (State Planning Commission, 1986), as field recording sheets of dissolved oxygen and temperature measurements and Government Chemical Laboratory reports. Inspection of the tabulated data showed some anomalies and, as a consequence, the original recording sheets and Government Chemical Laboratory reports were used to compile the data set used in this assessment.

The data were set up as a number of spreadsheets on a Macintosh SE personal computer using Microsoft's "Excel" package. Graphs were drawn using the "Cricket Graph" software package. Data files were transferred from the Macintosh to a Sperry mainframe computer to enable statistical analyses to be undertaken using SPSS-X.

Analysis of variance (ANOVA) was conducted to test for significant differences between sites and lakes. To perform ANOVAs only the records compiled from October 1985 onwards could be used as measurements made prior to that date were for disjointed periods and/or at irregular intervals.

An assessment of temporal changes using Time Series Analysis was not possible for any of the lakes due to the presence of discontinuities in the monitoring record.

Because the data set was characterised by the presence of large fluctuations in many of the parameters measured (particularly in Floreat Waters) and considerable seasonal variation was evident, a multiple analysis of variance (MANOVA) with nested design was used to test for differences between lakes on the basis of the following parameters: pH, total dissolved solids, turbidity, conductivity, chloride ion concentration, total phosphorus, inorganic phosphorus, total Kjeldahl nitrogen, nitrate, ammonia and chlorophyll *a*. The data were grouped into four seasonal categories as follows: data from December, January and February comprised the summer data set; March, April and May comprised autumn; June, July and August comprised winter; and September, October and November comprised spring. Cochran's C test was used to test for homogeneity of variance and where variances showed heterogeneity a number of transformations were tested including log 10, natural log, square root and inverse hyperbolic sin.

4.5 ANALYSIS OF DISSOLVED OXYGEN AND TEMPERATURE PROFILES

Dissolved oxygen and temperature profiles usually vary seasonally due to large scale heating and cooling effects and are affected daily by wind strength and direction, water movement, air temperatures and cloud cover. Thus, it is important for meteorological conditions to be known at the time when measurements were made as diurnal changes can be quite dramatic, and for the time of measurement to be noted. Unfortunately much of the data collected for this study was not accompanied by time recordings. The remainder were taken at about the same time of day on each sampling occasion and it is believed that these times apply to the rest of the data. However, this means that morning and afternoon profiles are not available for comparison at a given site in a given month. In many cases, comparative data are not available from month to month. In addition, depth was highly variable at most sites for the data collected from October 1985 to the present. Water depth has a large influence on the type of dissolved oxygen and temperature profile observed and so comparisons over time can only be made for sites at which depth remains constant.

The most complete record exists for the period between September 1983 and October 1984 when Industrial Lake was monitored and measurements were made regularly at the end of each month with times and meteorological conditions recorded. Only this data set was complete enough to warrant interpretation, however, it provides an insight into the nature of the processes of mixing and stratification that were also occurring in the other two lakes.

5. ANALYSIS AND INTERPRETATION OF THE WATER QUALITY DATA

A series of MANOVAs was conducted on all parameters (Table 4) enabling the following conclusions to be made:

1. there are no significant differences between sites within a given lake;
2. there are highly significant differences between lakes;
3. significant differences are occurring between seasons within a given lake;
4. the differences between seasons are themselves of a different pattern in the different lakes; that is, each lake has a different expression of seasonality.

For all parameters except pH, the Cochran's C-test was highly significant, indicating that the variances of the seasonal means were themselves highly variable. As a consequence the results from MANOVA must be interpreted with caution and it was of little value to resolve the nature of the various interactions between lakes and seasons within the MANOVA analysis.

In the case of pH, Industrial Lake showed only minor fluctuations with little difference between the seasons, whereas in Floreat Waters and Powis Lake, pH values in summer and autumn were significantly higher than those in winter and spring.

The implications of these MANOVA results are that the values of most parameters vary seasonally but that sudden changes occur, seemingly at random throughout the various seasons.

It is most likely that rainfall events and the amount and quality of runoff into the lakes are the key factors in interpreting these changes in water quality. This would account to some degree for the differences between the lakes and the fact that they are behaving differently at a given time and from year to year. Each water body has its own distinct catchment and each has a different number of drains emptying into it.

Due to the nature of the data collected it was not possible to run statistical tests at a finer resolution than attempted by seasonal grouping. For example, it was not possible to formally analyse monthly rainfall data in relation to the data set. However, a great deal can be determined purely by considering plots of the data over time.

The following analysis and interpretation of the data set is primarily based on graphical representation. Individual parameters will be considered in isolation for each lake and then interrelationships between them will be discussed. Drain inputs, heavy metal and pesticide levels will be considered separately.

Table 4. F Values and significance levels from the results of the MANOVA conducted on the water quality data set.

Parameter	Cochran's Number	F value				
		Source of Variation				
		Site within Lake	Lake	Season	Season by Site within Lake	Season by Lake
pH	0.18	0.79 ns	0.03*	0.00***	1.00 ns	0.00***
TDS	0.00	0.97 ns	0.00***	0.00***	1.00 ns	0.00***
Conductivity	0.01	0.99 ns	0.00***	0.00***	1.00 ns	0.00***
Chloride	0.00	1.00 ns	0.00***	0.00***	1.00 ns	0.00***
Turbidity	0.00	0.93 ns	0.00***	0.00***	1.00 ns	0.00***
Total Kjeldahl Nitrogen	0.00	0.96 ns	0.00***	0.00***	1.00 ns	0.00***
Nitrate	0.00	1.00 ns	0.00***	0.00***	1.00 ns	0.00***
Ammonia	0.02	0.96 ns	0.00***	0.00***	1.00 ns	0.00***
Total Phosphorus	0.00	0.20 ns	0.00***	0.00***	0.96 ns	0.00***
Inorganic Phosphorus	0.00	0.55 ns	0.00***	0.00***	0.92 ns	0.00***
Chlorophyll a	0.00	0.95 ns	0.00***	0.00 ***	0.93 ns	0.00***

ns = not significant
* = $p < 0.05$
*** = $p < 0.001$

Since sites within a given lake were not significantly different, data were pooled across sites to provide a mean value (and associated standard error) for each lake on a given sampling occasion. The only exception to this was for the early measurements made in Industrial Lake (Nov 1983-May 1984) where sites 9M, 11M and 12M had much higher values for total phosphorus, total Kjeldahl nitrogen and total dissolved solids than sites 1H, 2H and 3E, thus a large standard error is associated with the mean values on these occasions.

5.1 PHYSIOCHEMICAL AND NUTRIENT DATA

5.1.1 pH (Fig.12)

The pH of a water body is a measure of the hydrogen ions present in solution. In lakes the pH may be affected by the amount of carbon dioxide dissolved in the water body, biological activity and the pH of incoming waters from the catchment. In most lakes pH is regulated by the CO_2 - HCO_3^- - CO_3^{-2} buffering system which is in equilibrium with atmospheric CO_2 and allows pH to fluctuate between 6.0 and 9.0 (Bayly and Williams, 1973).

The records of pH for the three lakes (Fig. 12) indicate that the lakes are slightly alkaline and that pH varies seasonally over a fairly limited range. Floreat Waters and Powis Lake exhibit similar seasonal changes with the lowest pH values in spring and highest values towards the end of summer/early autumn. The seasonal variation of pH is less pronounced in Industrial Lake and the recent monitoring record shows a slight downward trend in pH values.

5.1.2 Total Dissolved Solids (TDS) (Fig. 13)

TDS normally refers to the material left in a vessel after evaporation of a filtered sample at a defined temperature (usually 180°C). It is a measure of organic and inorganic materials (Bayly and Williams, 1973). It can be estimated in mg/l by multiplying conductivity (µS/cm) by an empirical factor, which ranges between 0.55 and 0.9 depending on soluble components and the temperature of measurement. Under conditions of constant temperature and constant relevant ionic proportions, TDS is very nearly directly proportional to conductivity (Bayly and Williams, 1973).

Since TDS was estimated from conductivity in this study it reflects the concentration of ions in solution. Figure 13 gives the TDS values recorded for the three lakes. Floreat Waters has higher levels of TDS than either Industrial Lake or Powis Lake and each lake exhibits a different pattern of change in TDS. The early measurements made in Floreat Waters in 1982/83 indicate that TDS has been relatively high since construction of this lake and that little change has occurred. In contrast, just after the construction of Industrial Lake it had TDS values similar to those found in Floreat Waters, but recent measurements show a considerable decrease in TDS and a continuing downward trend in values. Powis Lake is different again. Here values are similar to the lower recent values in Industrial Lake but there is an upward trend.

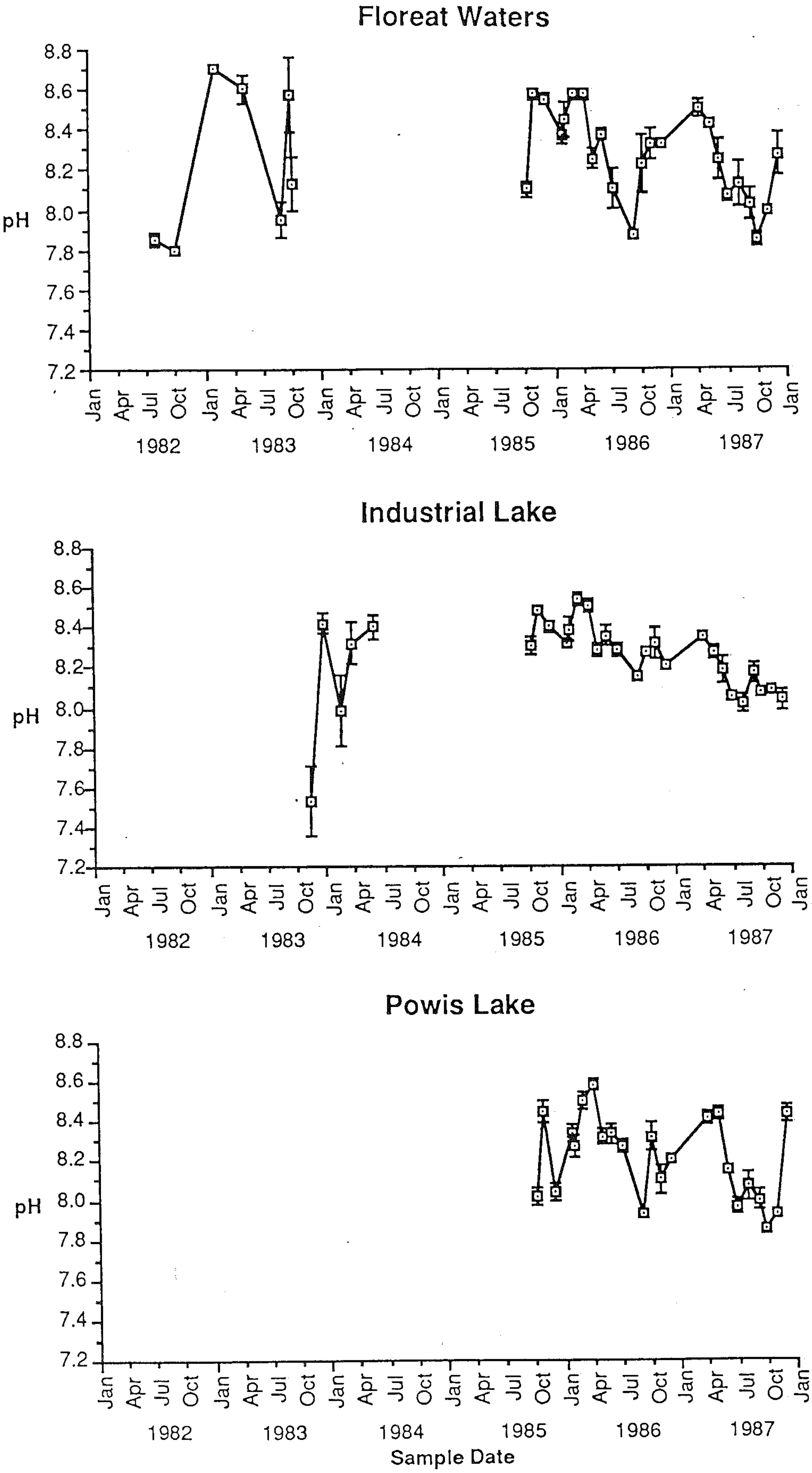


Fig. 12. Mean pH values (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

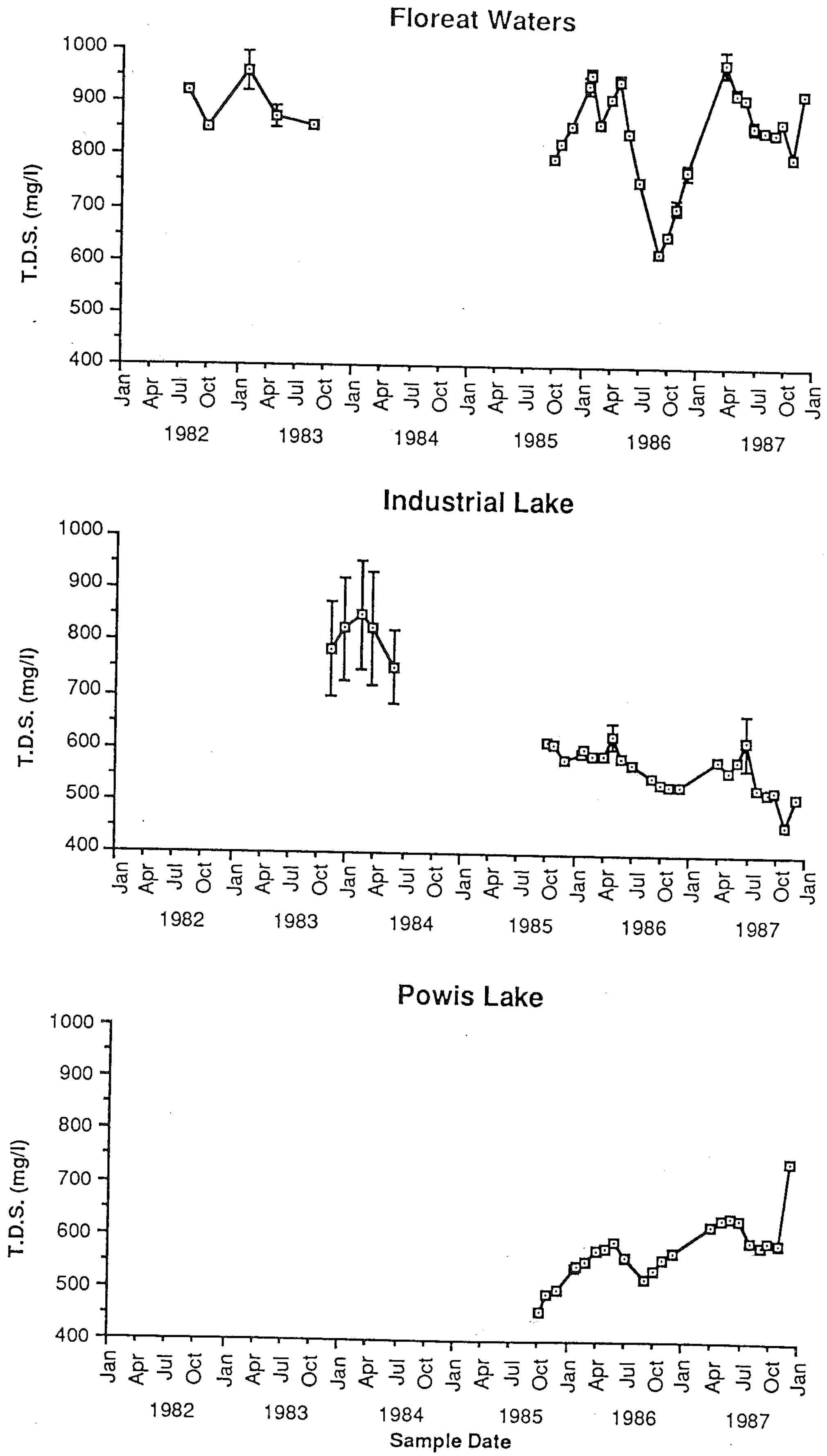


Fig. 13. Mean total dissolved solids (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

The greatest variation of TDS was seen in Floreat Waters. Levels were lowest in the late winter/early spring of 1986 but were relatively high throughout the previous summer and spring, and throughout 1987. In Industrial Lake no seasonal pattern was obvious. However, in Powis Lake levels were lowest in late winter/early spring and appeared to peak in late autumn/early winter.

5.1.3 Conductivity (Fig. 14)

In addition to TDS, the conductivity values were reported (in mS/m) from July 1986 onwards. Conductivity is a measure of the ability of a solution to carry an electric current which depends upon the presence and concentration of ions, particularly the simple inorganic ions Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^- and SO_4^{2-}. Conductivity is often used as a measure of salinity as salinity is usually defined as the total concentration of the aforementioned ions (Bayly and Williams, 1973).

The conductivity values in all three lakes are relatively low (Fig. 14) and indicate that the water is fresh. A salinity of 3 ppt, corresponding to a conductivity of about 600 mS/m, is the arbitrary cut-off point between fresh and saline systems (Bayly and Williams, 1973). Australian standards allow drinking water to have a conductivity of up to 200 mS/m . Figure 14 indicates that Floreat Waters has slightly higher values for conductivity than the other two lakes.

5.1.4 Chloride Ion (Fig. 15)

Changes in chloride ion concentrations almost exactly follow the changes in conductivity (Fig. 15). This reflects the fact that chloride ions are the predominant anion in Perth wetlands (Davis and Rolls, 1987) and are a major constituent of lake ionic composition. Sodium and chloride ions tend to dominate fresh water bodies close to the ocean due to the atmospheric transport of oceanic salts (Bayly and Williams, 1973).

5.1.5 Turbidity (Fig. 16)

Turbidity is a measure of the clarity of a water body. Turbid conditions are produced by suspended matter (such as clay or silt), fine particles of organic and inorganic matter, soluble coloured organic compounds (e.g. tannin) and cells of algae and other microscopic organisms. Turbidity can be measured by determining the amount of light scattered and absorbed by a solution in comparison to the amount of light which passes straight through. Using this method the result is expressed in Nephelometric Turbidity Units (NTU). Turbidity can also be expressed in Jackson Turbidity Units (JTU) using a slightly different methodology, however, NTU and JTU are roughly equivalent (APHA, 1985).

Turbidity is strongly cyclic in Floreat Waters with less pronounced and different patterns of change being observed in Industrial Lake and Powis Lake (Fig. 16). Turbidity changes over a wider range in Floreat Waters than in the other two lakes. Peak values occur around April with the lowest values in October. In Industrial Lake and Powis Lake the pattern of change is less clear. In

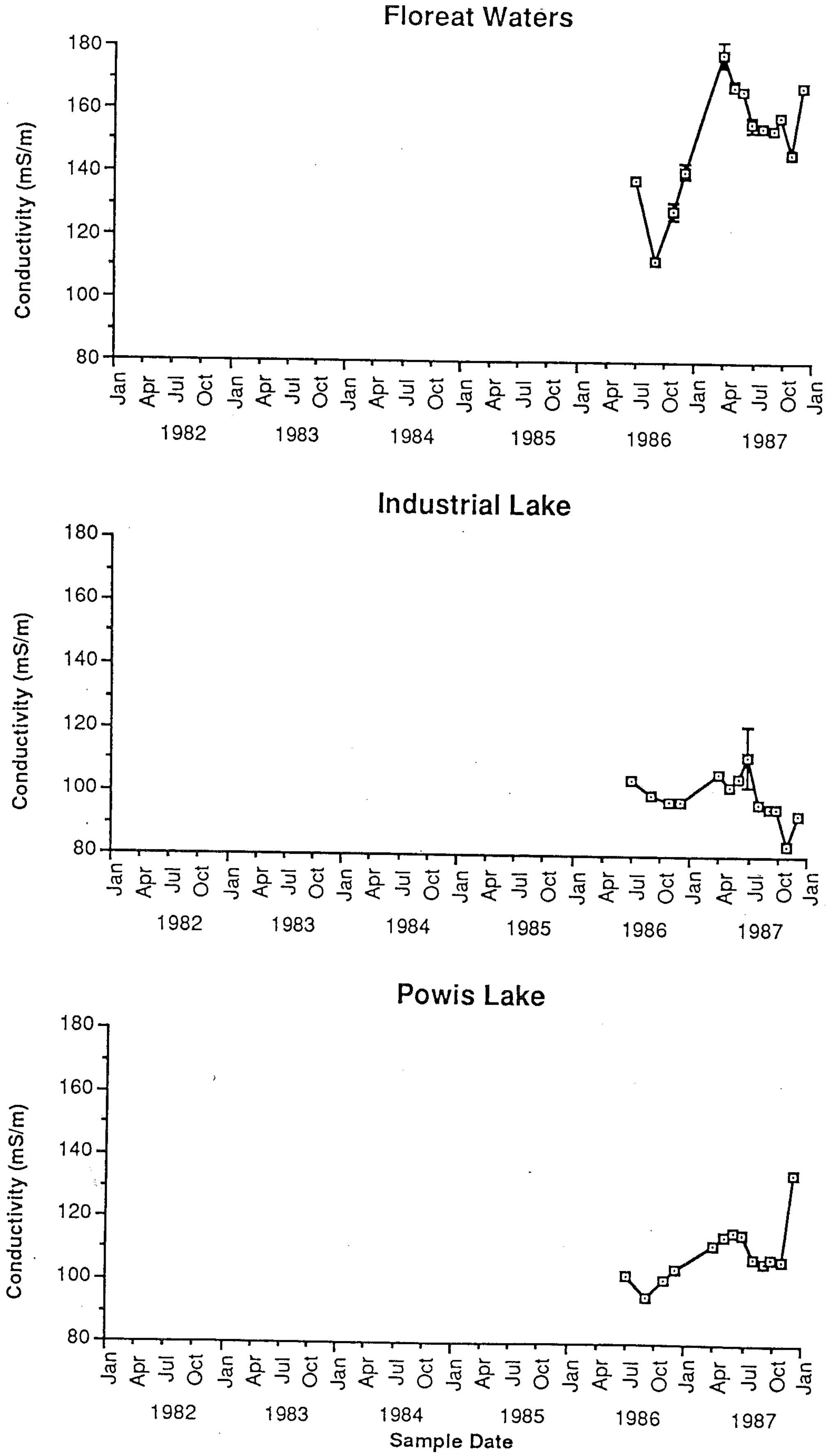


Fig. 14. Mean conductivities (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between July 1986 and December 1987.

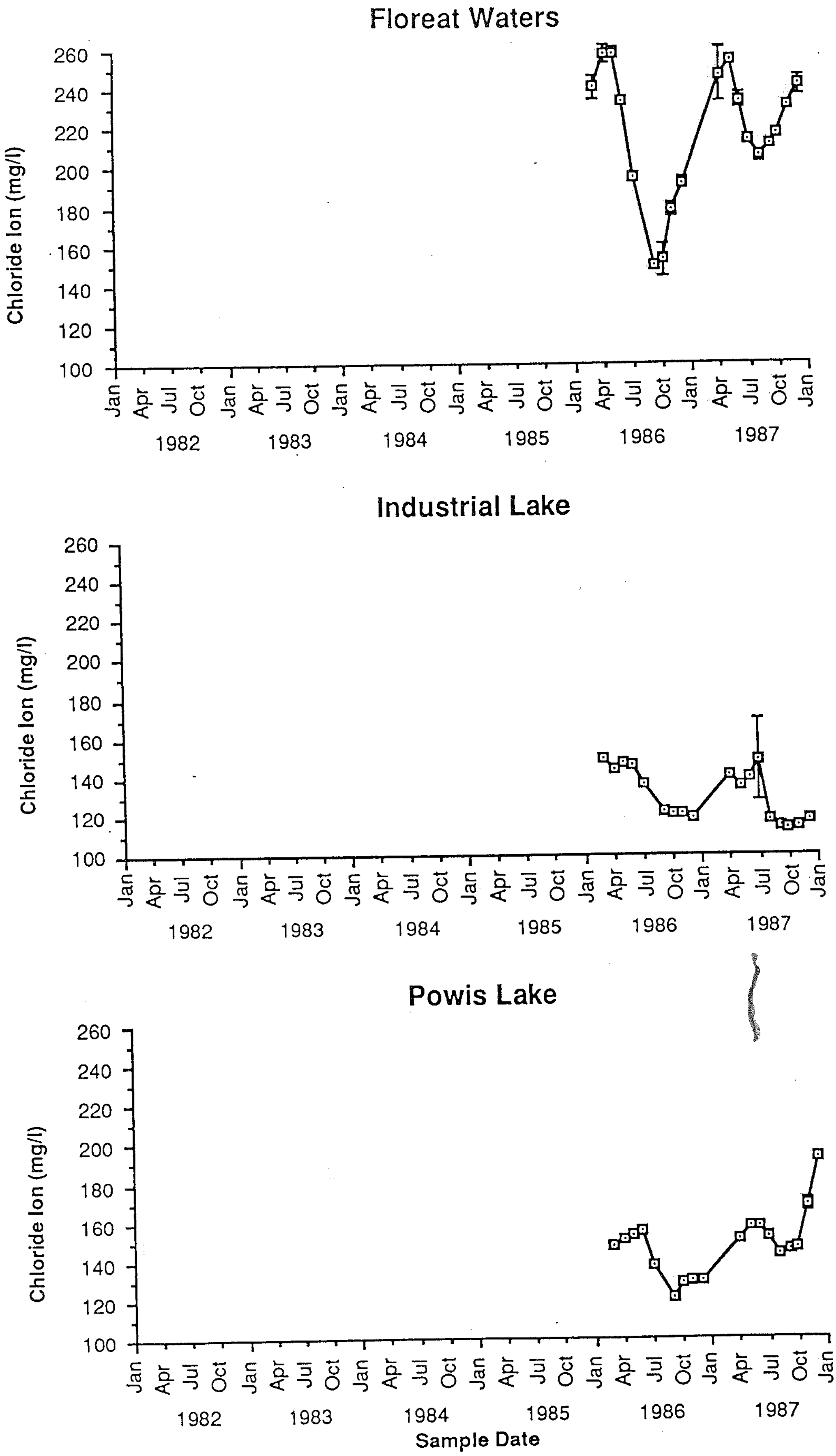


Fig. 15. Mean chloride (Cl⁻) concentrations (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between January 1986 and December 1987.

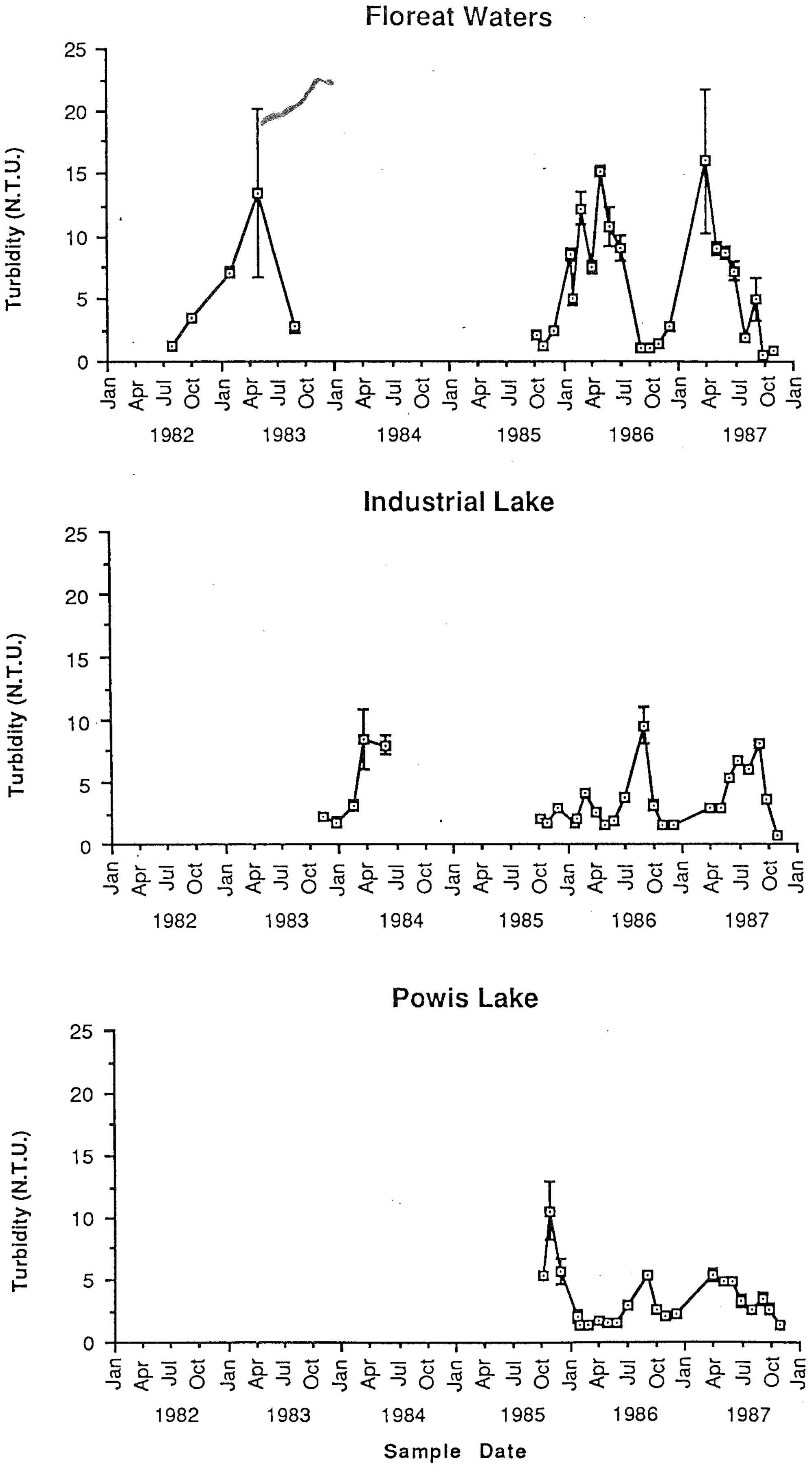


Fig. 16. Mean turbidities (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

Industrial Lake peaks tend to occur in late winter/early spring. In Powis Lake peaks appear to occur at random.

There are no long term trends apparent in turbidity values for any of the lakes.

5.1.6 Total Kjeldahl Nitrogen, Total Nitrogen and Organic Nitrogen (Figs 17-19)

Total Kjeldahl Nitrogen (TKN) is a measure of the organic nitrogen compounds (proteins, etc.) in a water body plus the ammonia present. Total nitrogen includes a measure of nitrate and nitrite in addition to organic nitrogen and ammonia. Nitrate, nitrite, ammonia and organic nitrogen are the major forms of nitrogen present in water bodies. Ammonia is produced mainly by the breakdown of organic material and urea. Nitrification by specific nitrifying bacteria oxidises ammonia into nitrite, and then nitrite into nitrate (Hutchinson, 1975). These bacteria are usually associated with lake sediments (Hutchinson, 1975). Nitrate is the form of nitrogen most often utilised by aquatic plants, algae and bacteria as a nitrogen source for growth and thus the production of organic nitrogen.

The more extensive records in each lake are for TKN (Fig. 17) and organic nitrogen (Fig. 18). The highest values of TKN occurred in Floreat Waters and the greatest fluctuations (which were also of a cyclic nature). Peaks appeared to occur in late summer and throughout winter with troughs in late spring/early summer. Values in Industrial Lake also fluctuated but no clear cycles were evident and Powis Lake has had relatively constant values of TKN for the past two years except for an isolated peak in October 1985. Changes in the concentrations of organic nitrogen recorded in the three waterbodies were very similar to those recorded for TKN and indicate that organic nitrogen was the dominant form of nitrogen present in the water column of the three waterbodies. Total nitrogen showed similar patterns (Fig. 19) based on very limited data.

No long-term trends were apparent.

5.1.7 Nitrate (Fig. 20)

The concentrations of nitrate in Floreat Waters and Industrial Lake were relatively low and constant between 1985 and 1988. However, large seasonal changes were evident at Powis Lake. Levels of nitrate were particularly high just after completion of the lake. Both Floreat Waters, and to some extent Industrial Lake, showed high values initially, which suggests that there has been a drop in nitrate values in the lakes as they have aged. In Powis Lake peak values occurred in spring and were at their lowest in early winter.

5.1.8 Ammonia (Fig. 21)

Concentrations of ammonia were relatively low in all three lakes. The lowest values were recorded at Industrial Lake. Floreat Waters and Powis Lake were similar, although Powis Lake reached higher peak values. Distinct seasonal cycles were evident in Floreat Waters with the lowest levels occurring during summer and autumn and peak levels during winter and spring. In Powis Lake very high levels occurred in October 1985 and in August/September 1987.

5.1.9 Total Phosphorus (Fig. 22)

Total phosphorus is a measure of the organically bound phosphates, orthophosphate (PO_4^{2-}), and inorganic condensed phosphates present in the water column. Orthophosphate and organic phosphates are the most important forms in lakes (Hutchinson, 1975). Orthophosphate is released upon the breakdown of organic material. Large amounts of orthophosphate are also washed into lakes from agricultural or urban areas where fertilisers are applied (APHA, 1985). Organic phosphates are formed primarily by biological processes and occur in the bodies of aquatic organisms (APHA, 1985).

Phosphorus is essential for the growth of organisms and is often the nutrient that limits productivity in a water body. The ratio of phosphorus to other elements required by organisms tends to be greater than the ratio of these elements available in the external environment (Hutchinson, 1975).

The highest levels of total phosphorus were recorded at Floreat Waters and pronounced seasonal changes occurred each year (Fig. 22). The lowest concentrations occurred in the late spring/early summer and peak levels occurred from late autumn to late winter. Both Industrial and Powis Lakes exhibited similar seasonal changes but with a smaller amplitude and less definition. No long term trends are evident.

The trophic condition of a lake is often assessed on the basis of total phosphorus and chlorophyll *a* levels. However, a lake can be in one category with regard to total P and another with regard to chlorophyll *a*. In addition, a lake classed as eutrophic, for example, may not show all the problems considered to be associated with eutrophication. This is because classification systems of trophic status use isolated parameters to "measure" a complex system of interactions.

Table 5 shows the fixed boundary trophic classification system given in Rast and Holland (1988), based on OECD (1982). In reality there can be no definite boundary between each trophic state as there is a continuum of conditions and events associated with eutrophication processes. This applies to both natural eutrophication and accelerated cultural eutrophication induced by human activity.

The probability of a lake being in a given trophic condition can be calculated from the trophic probability classification scheme developed by OECD (1982) which is shown in Figure 23.

Table 6 shows the mean annual in-lake total phosphorus concentration for the three dredged lakes for 1986 and 1987 (annual averages cannot be calculated for the other years).

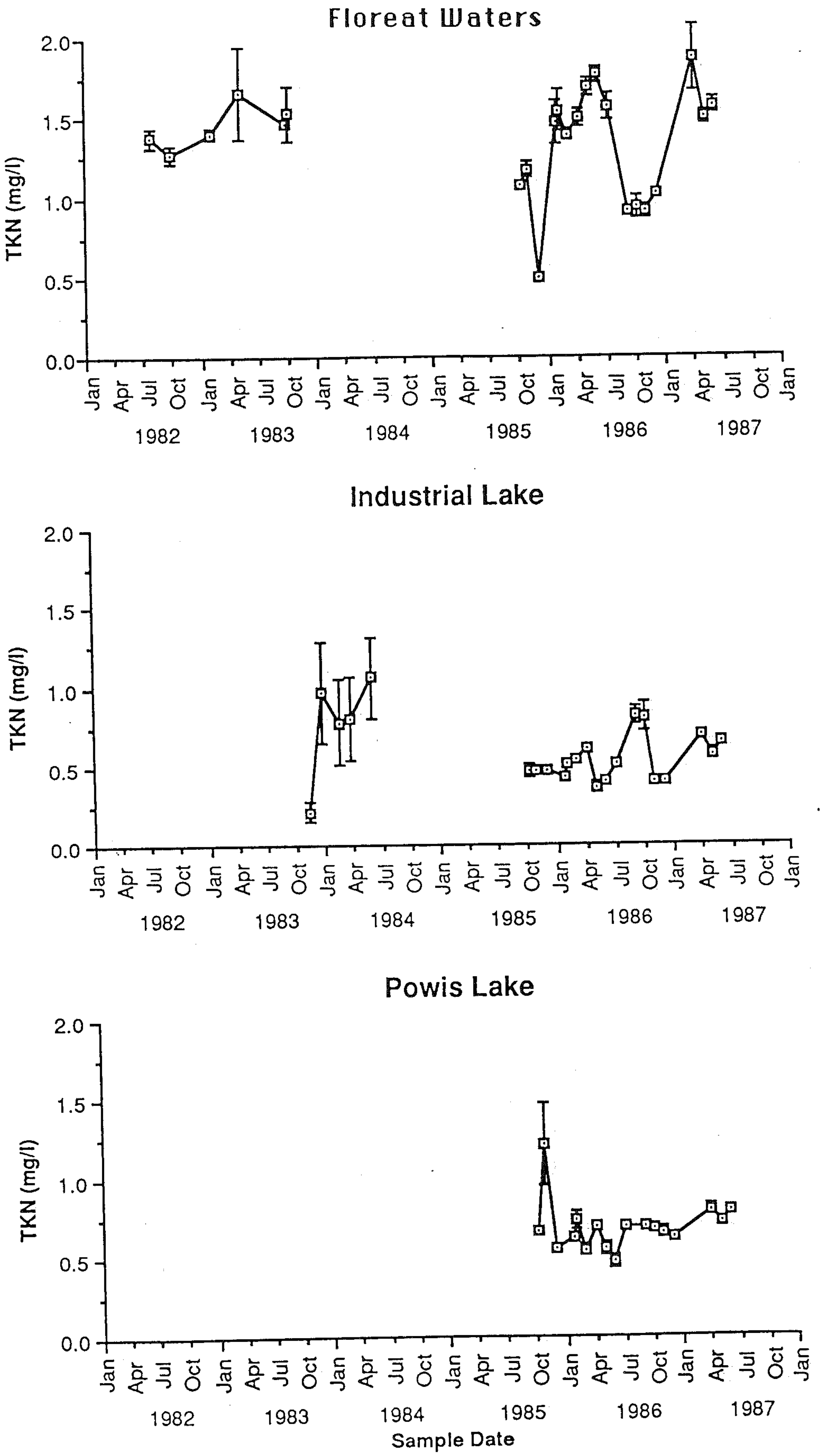


Fig. 17. Mean total Kjeldahl nitrogen (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

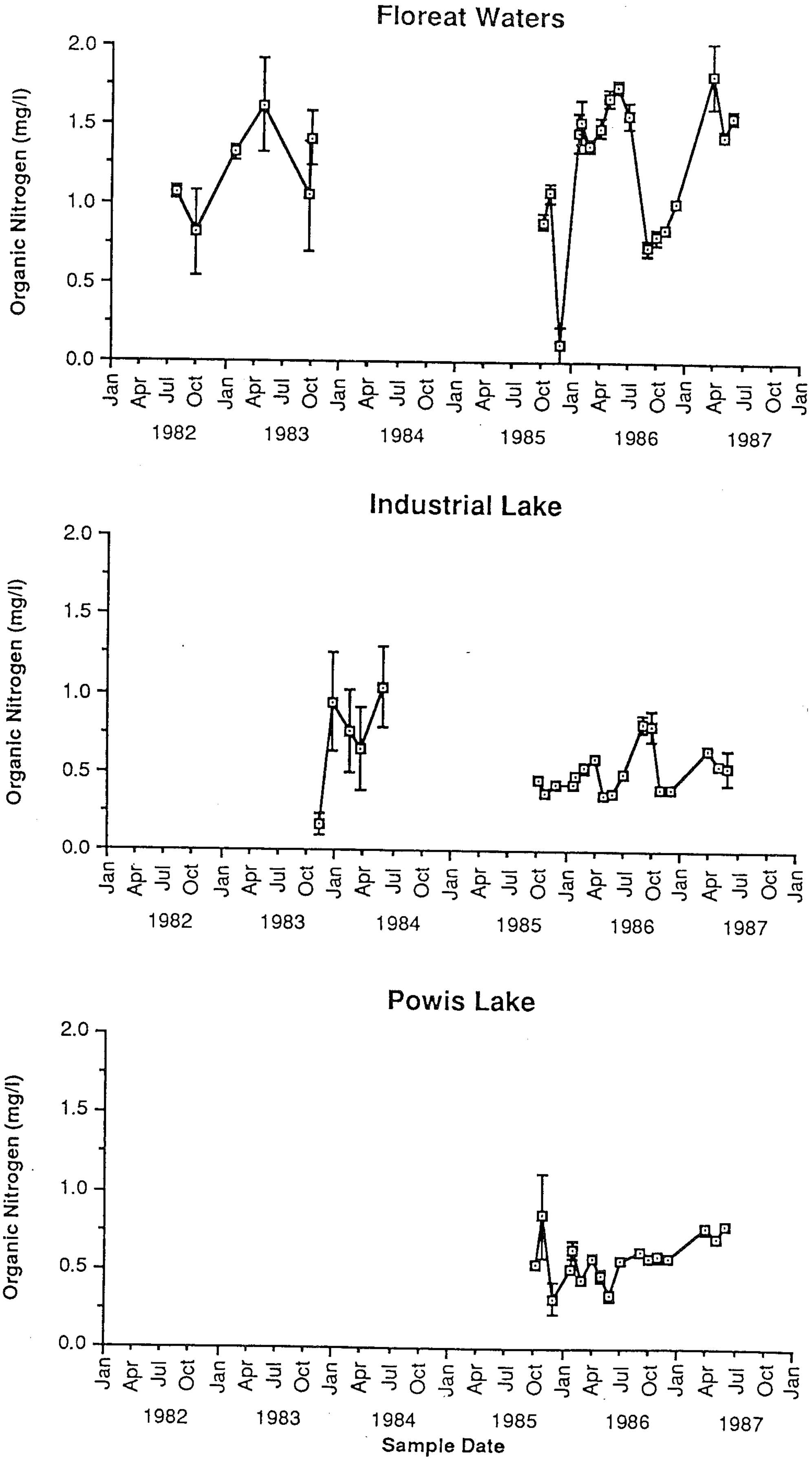


Fig. 18. Mean organic nitrogen concentrations (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

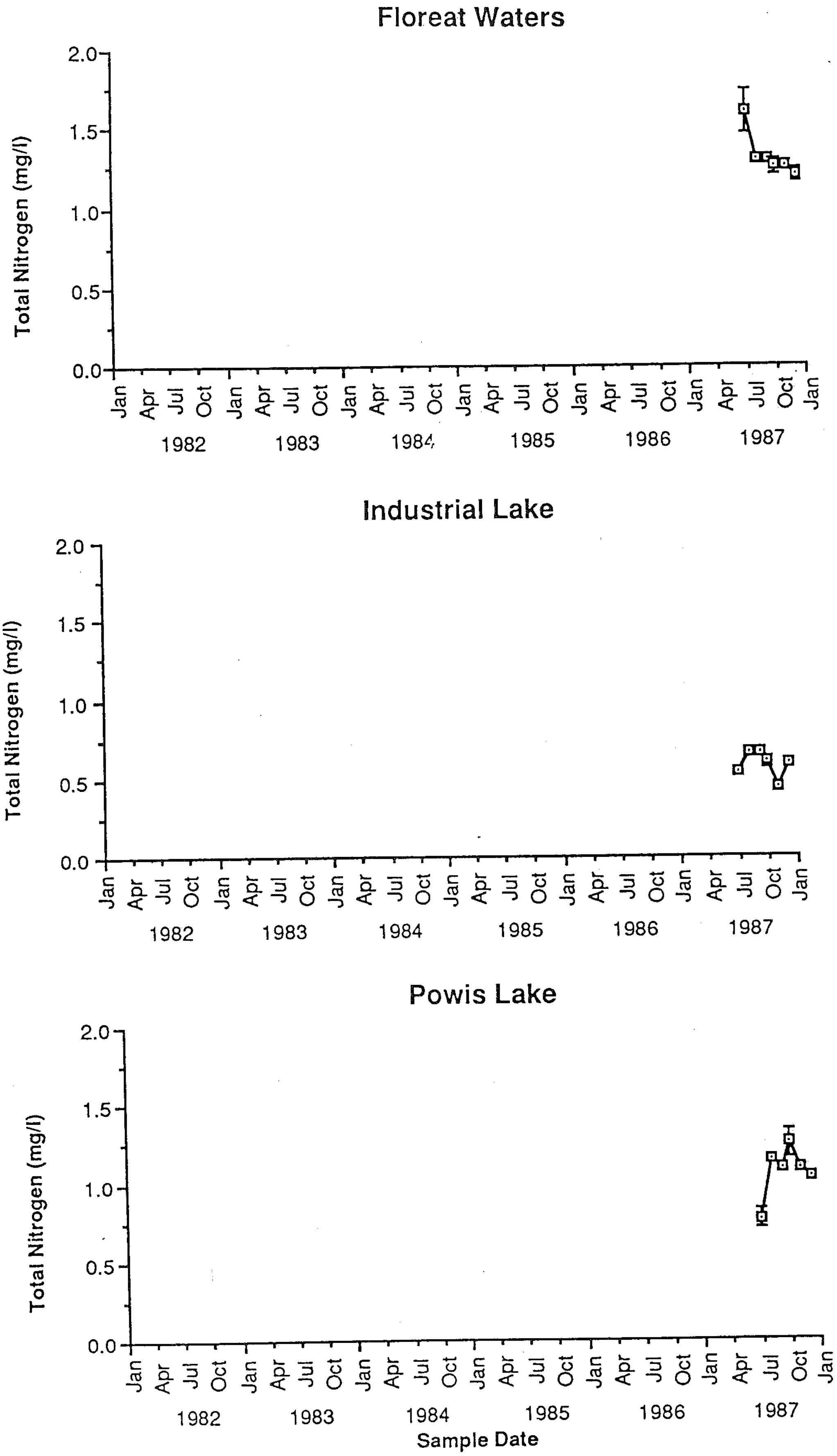


Fig 19. Mean total nitrogen concentrations (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between July 1987 and January 1988.

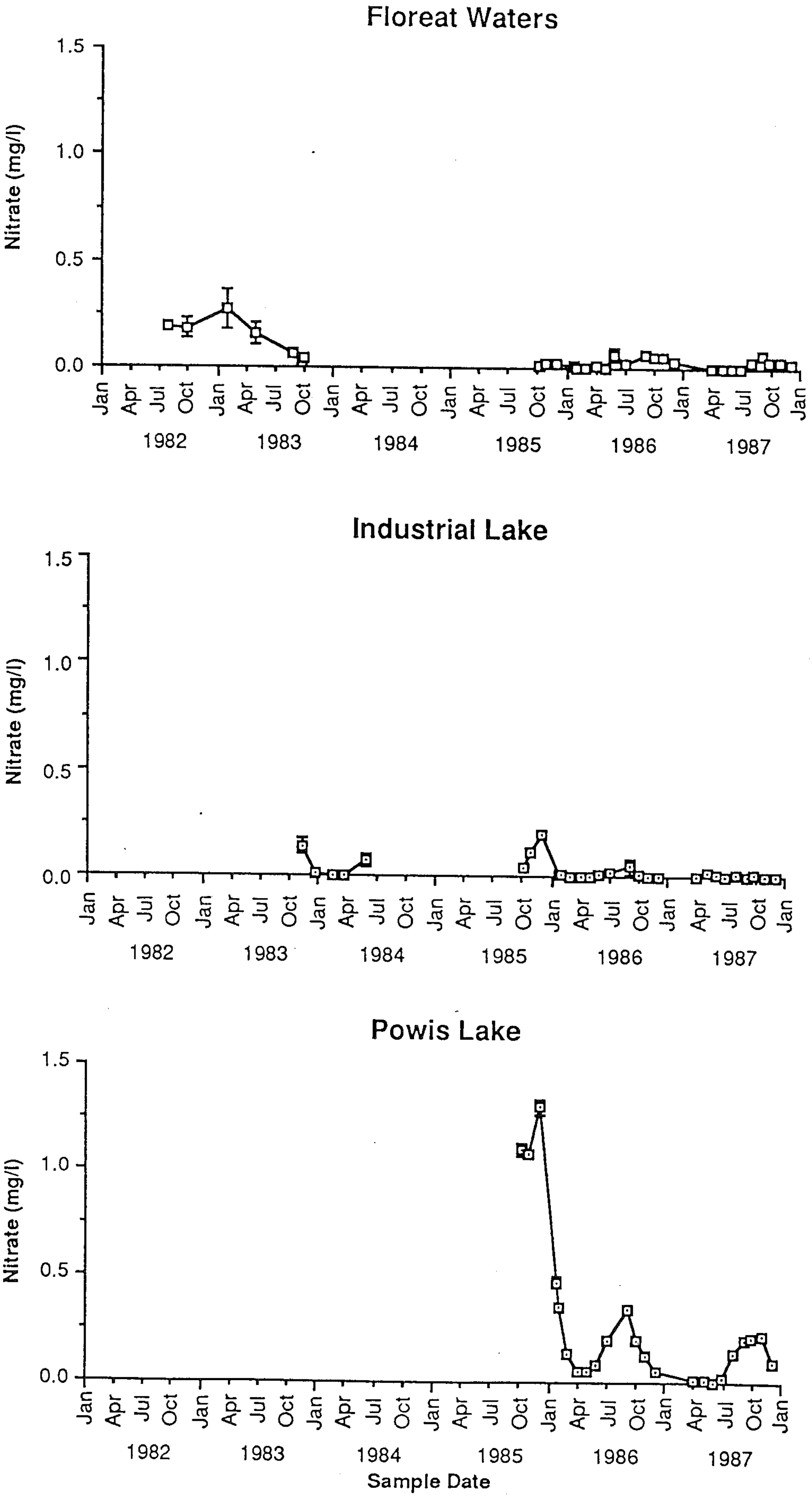


Fig. 20. Mean nitrate concentrations (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

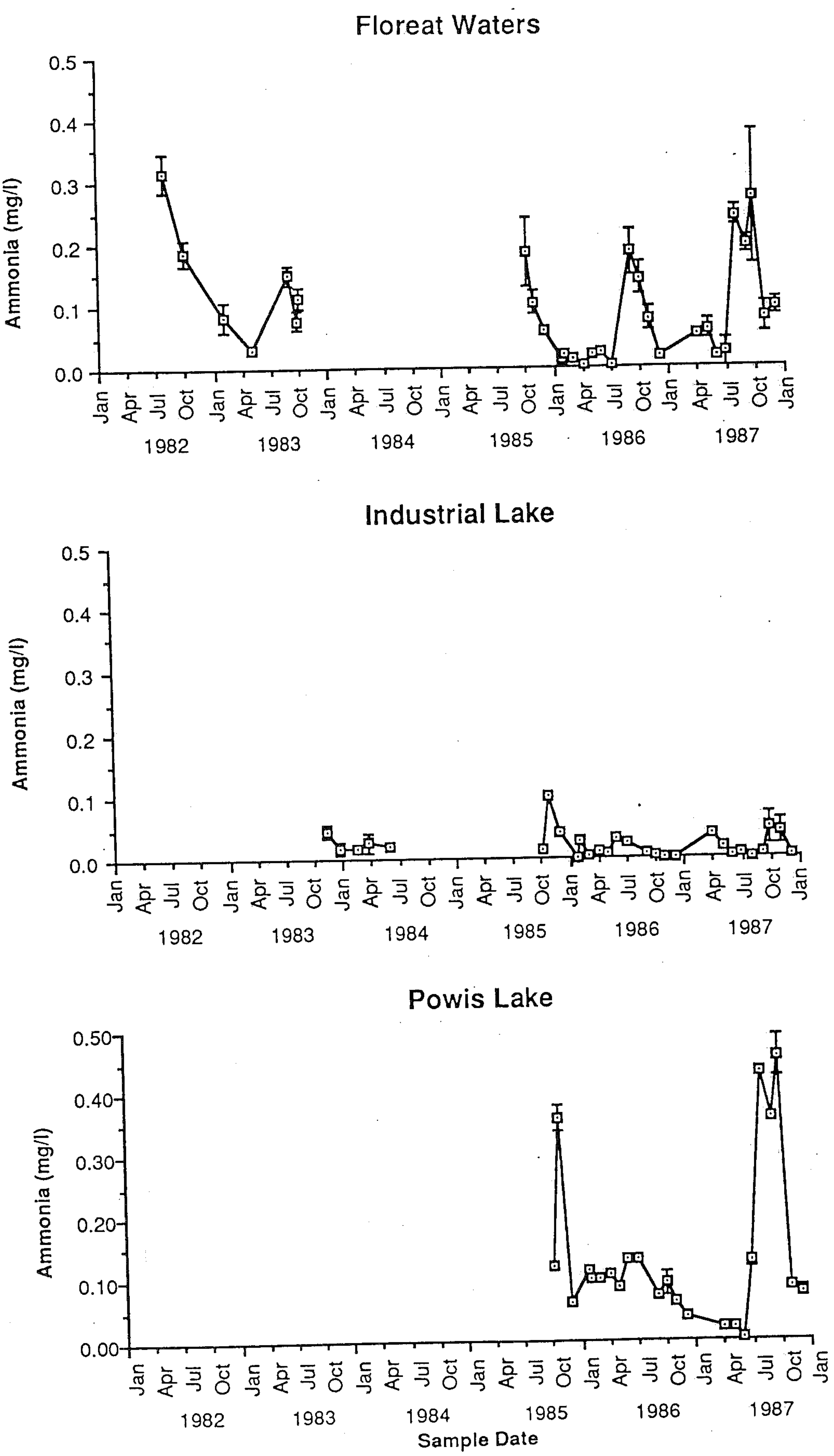
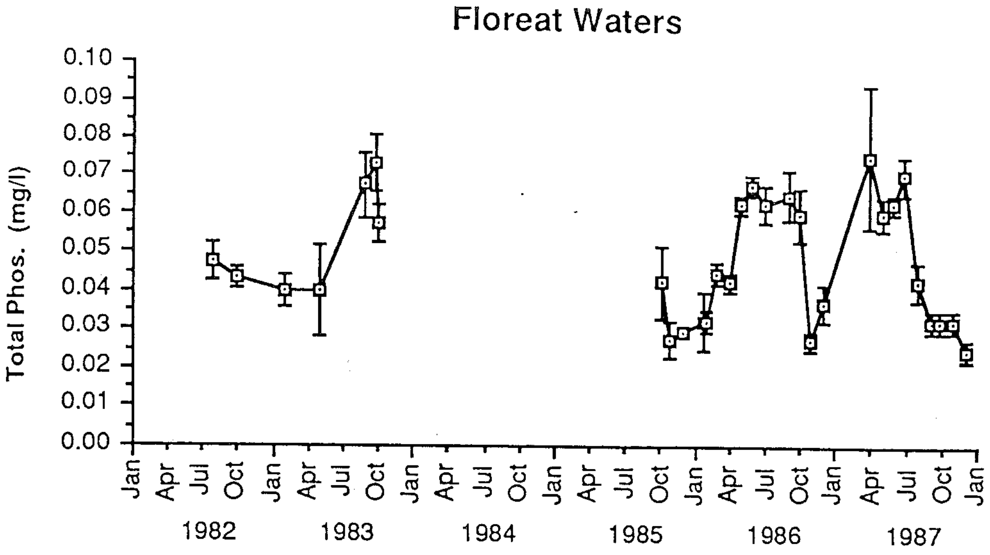
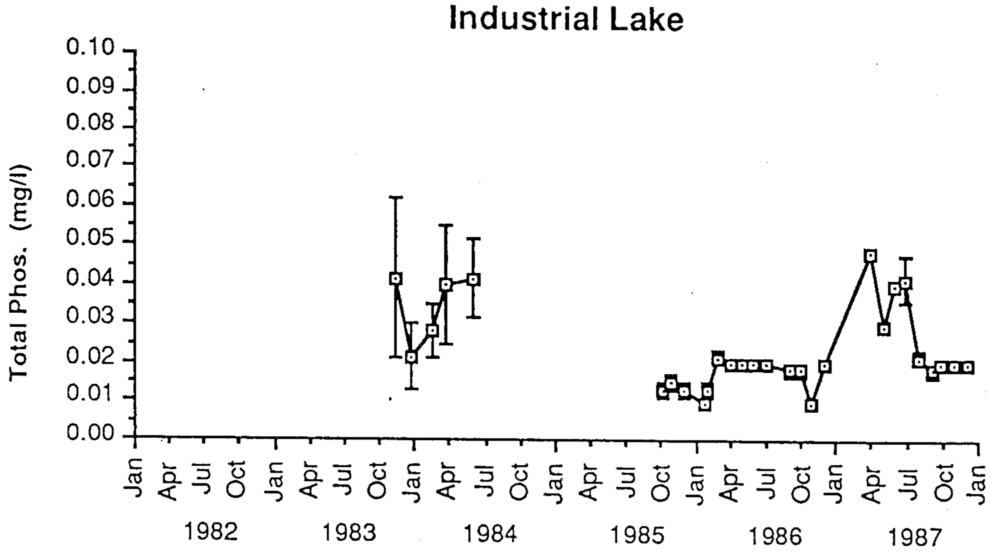


Fig. 21. Mean ammonia concentrations (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.





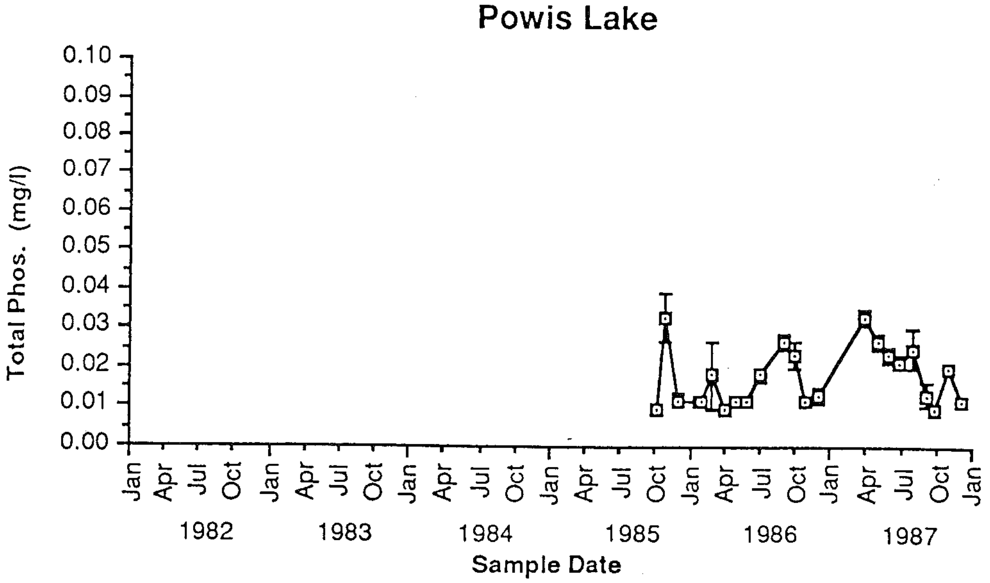


Fig. 22. Mean total phosphorus concentrations (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

Table 5 Boundary values for fixed trophic classification system
(Rast and Holland, 1988)

CATEGORY	TOTAL PHOSPHORUS* (mg/l)	CHLOROPHYLL *a* (mg/l)	
		mean**	maximum***
Ultra-oligotrophic	<0.004	<0.001	<0.0025
Oligotrophic	0.010	0.0025	<0.008
Mesotrophic	0.010 - 0.035	0.0025 - 0.008	0.008 - 0.025
Eutrophic	0.035 - 0.100	0.008 - 0.025	0.025 - 0.075
Hypertrophic	>0.100	>0.025	>0.075

* Mean annual in-lake Total Phosphorus concentration.
** Mean annual surface water Chlorophyll *a* concentration.
*** Peak annual surface water Chlorophyll *a* concentration.

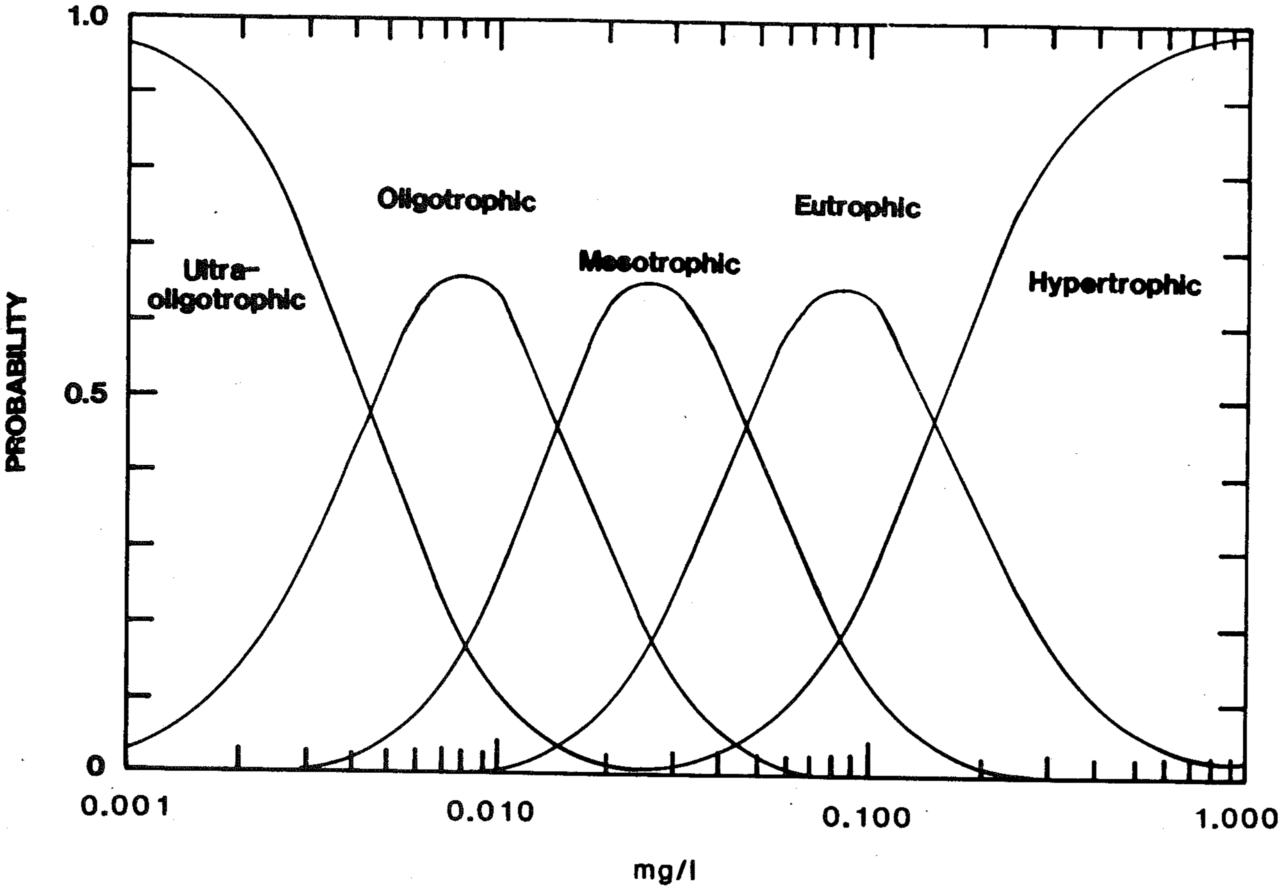


Fig. 23. Trophic probability classification scheme based on the mean annual total phosphorus concentration (Rast and Holland, 1988).

Table 6. Mean annual total phosphorus concentrations for the three dredged lakes

	Total Phosphorus (mg/l)		Trophic Status	
	Mean value 1986	Mean value 1987	Fixed boundary classification	Probability classification
Floreat Waters	0.049	0.047	Eutrophic	Eutrophic/ mesotrophic
Industrial Lake	0.017	0.029	Mesotrophic	Mesotrophic (1987)
Powis Lake	0.015	0.021	Mesotrophic	Mesotrophic (1987)

Using the fixed boundary classification scheme, Floreat Waters was eutrophic with respect to total phosphorus and both Industrial Lake and Powis Lake were mesotrophic during 1986 and 1987.

Based on the probability classification, Floreat Waters had an equal probability of being either eutrophic or mesotrophic in both years. The other two lakes had a high probability of being mesotrophic according to 1987 mean values for total phosphorus.

5.1.10 Orthophosphate (PO_4^{2-}) (Fig. 24)

Concentrations of orthophosphate were usually very low in all the lakes. There was no clear pattern to the changes in levels of orthophosphate in any of the lakes. The levels in Floreat Waters were the most variable and displayed the highest peak values. No long term trends are apparent.

5.1.11 Chlorophyll *a* (Fig. 25)

Chlorophyll *a* is used as an indicator of algal biomass. All algae contain chlorophyll *a* as about 1-2% of dry weight (APHA, 1985). Powis Lake had little variation in chlorophyll *a* up until 1987. In late autumn/early winter of 1987 a peak in values occurred corresponding to an algal bloom. Industrial Lake and Floreat Waters have shown several peaks each year in early autumn and throughout winter. This seasonal change was very evident in Floreat Waters where the peaks were very high in comparison to the other two lakes. The May 1987 bloom in Powis Lake may indicate a trend towards increased chlorophyll *a* levels in this waterbody. Peak levels in Industrial Lake were also higher in 1987 than in 1986 which may indicate a trend towards increasing algal growth in the lake. Figure 26 gives the probability scheme for trophic classification using chlorophyll *a*.

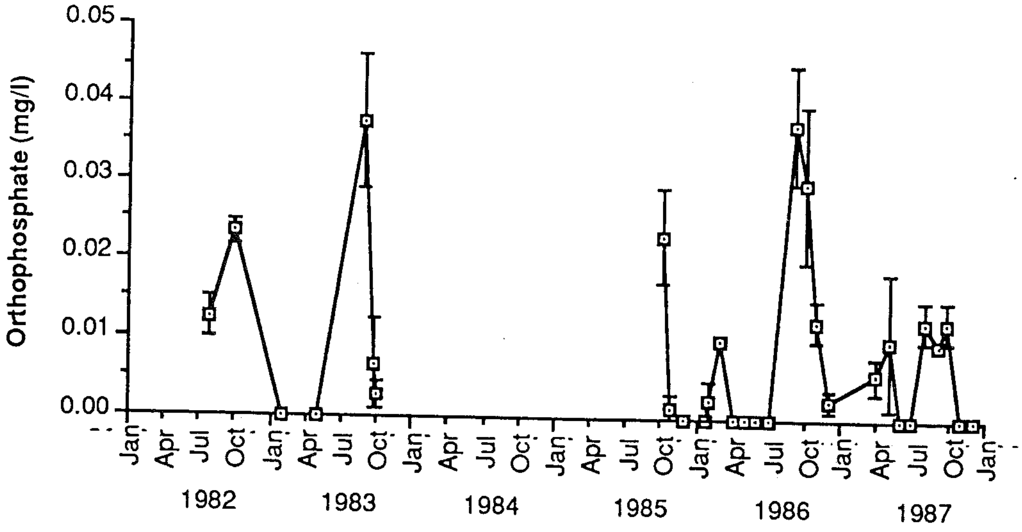
Table 7 shows the annual mean and peak chlorophyll *a* values for the three lakes in 1986 and 1987. Based on the fixed boundary classification system (Table 5), Floreat Waters was hypertrophic in both years, Industrial Lake was eutrophic with a hypertrophic peak in 1987 and Powis Lake was mesotrophic in both years.

Based on the probability scheme for trophic classification, Floreat Waters had a 65% chance of being hypertrophic in 1987, Industrial Lake had a high probability of being eutrophic and Powis Lake had an equal probability of being either eutrophic or mesotrophic.

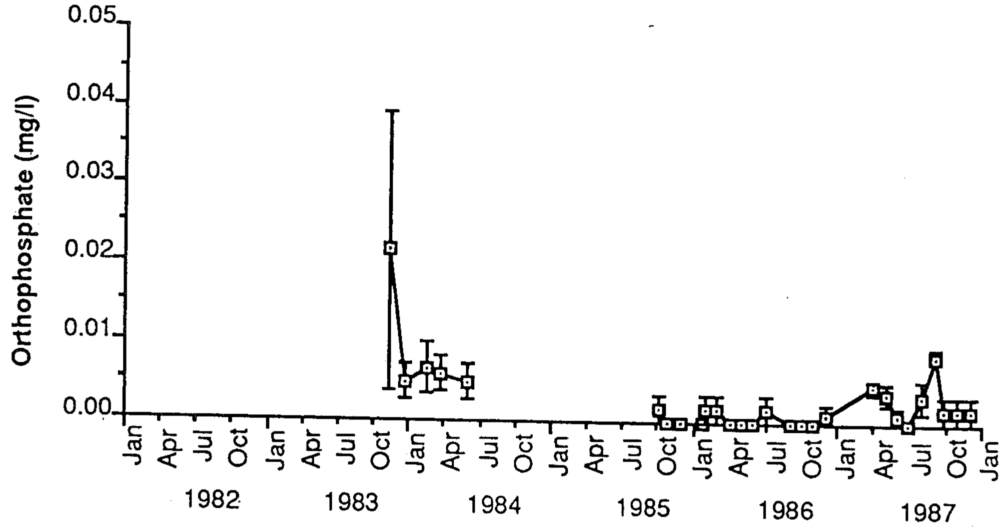
5.1.12 Water temperature at the surface

Water temperatures recorded at the surface were very similar in all three lakes and reflected large scale seasonal fluctuations in air temperature. The highest values occurred in late summer/early autumn due to heating of the water bodies

Floreat Waters



Industrial Lake



Powis Lake

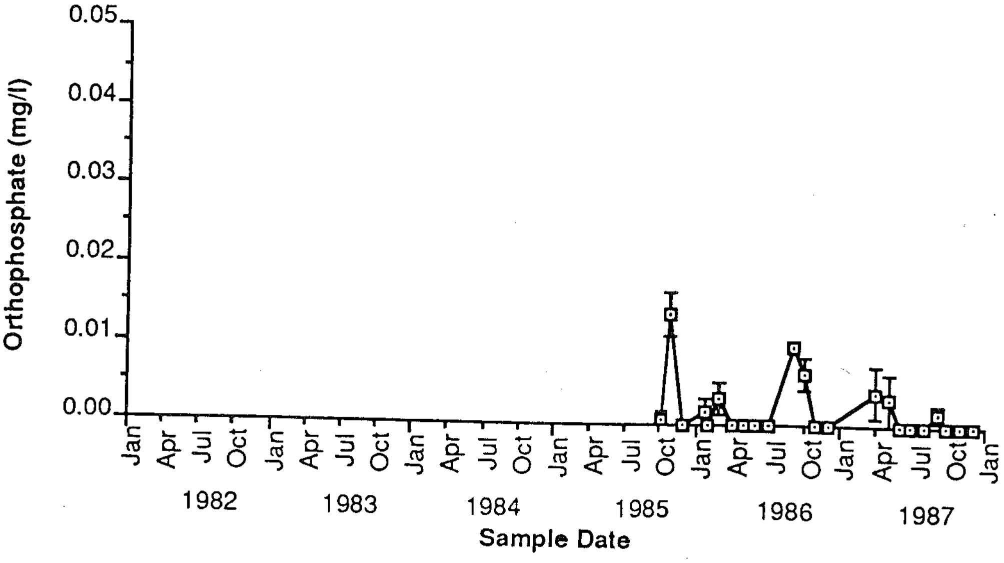


Fig. 24. Mean orthophosphate (PO_4^{2-}) concentrations (with associated standard error) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

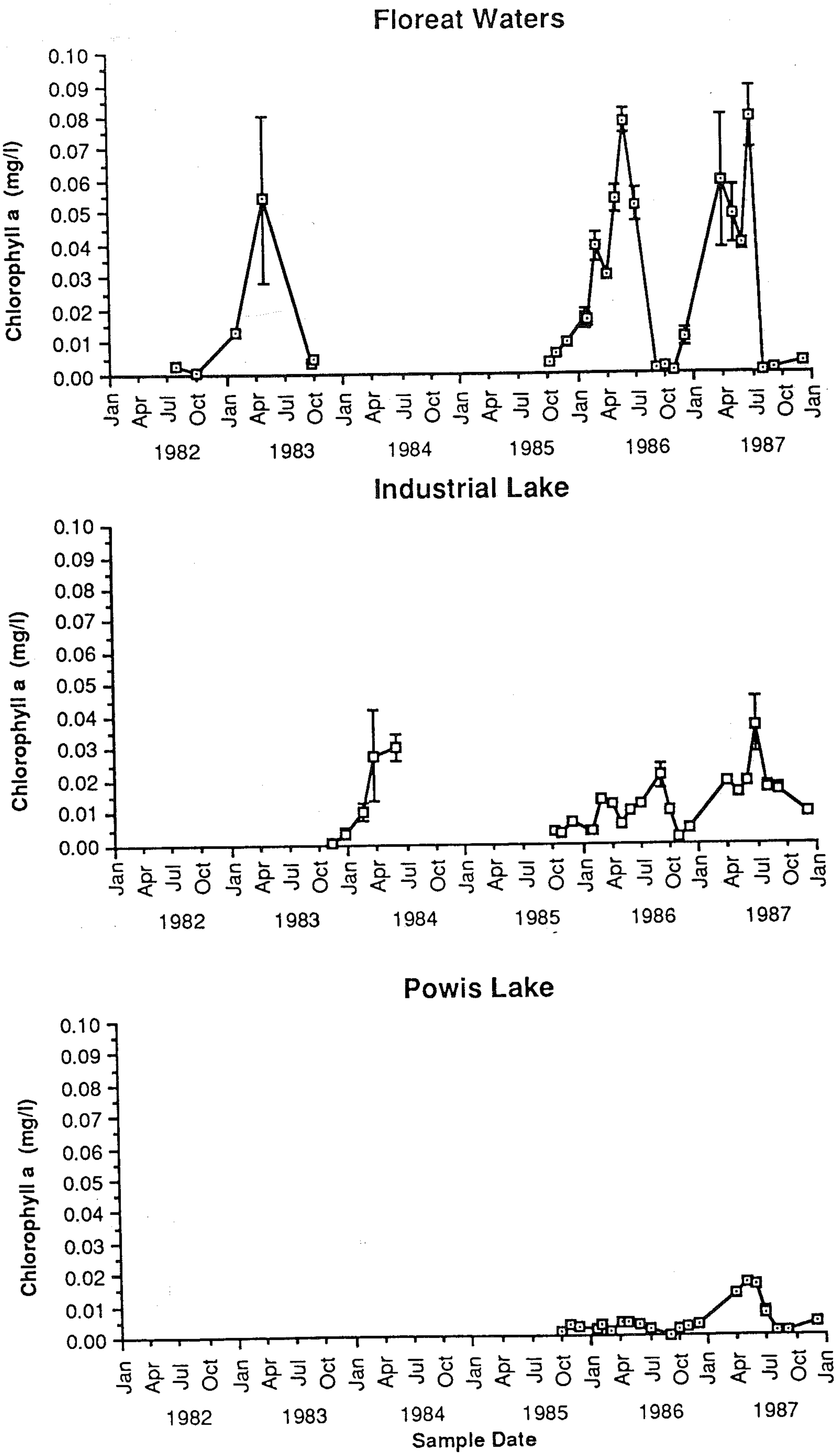


Fig. 25. Mean chlorophyll *a* concentrations (with associated standard errors) recorded at the three dredged water bodies at Herdsman Lake between 1982-1987.

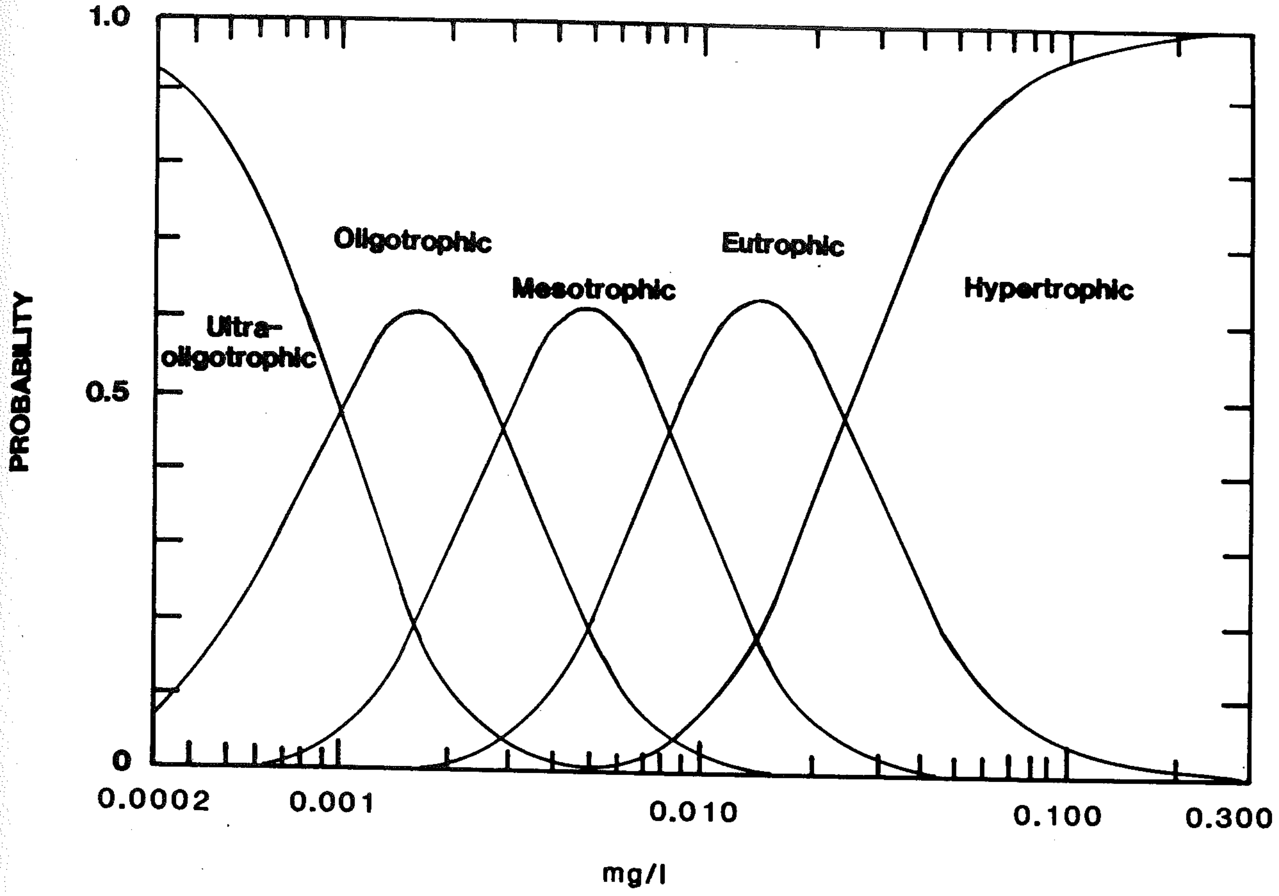


Fig. 26. Trophic probability classification scheme based on the mean annual chlorophyll *a* concentration (Rast and Holland,1988).

Table 7. Mean annual and maximum annual chlorophyll *a* values for the three dredged lakes

	Chlorophyll *a* (mg/l)				Trophic status	
	1986 mean	1986 max.	1987 mean	1987 max.	Fixed boundary Classification	Probability Classification
Floreat Waters	0.027	0.087	0.032	0.120	Hypertrophic	Hypertrophic (1987)
Industrial Lake	0.009	0.031	0.019	0.079	Eutrophic (1986) Hypertrophic (1987)	Eutrophic
Powis Lake	0.003	0.006	0.008	0.019	Mesotrophic	Eutrophic/ Mesotrophic

over summer. The lowest temperatures occurred in early winter and early spring.

The maximum and minimum temperatures that were recorded at the surface of each lake are as follows:

	Temperature (°C)	
	Maximum	Minimum
Floreat Waters	27.5	10.2
Industrial Lake	26.4	12.8
Powis Lake	26.8	12.8

5.1.13 Dissolved oxygen at the surface

Maximum dissolved oxygen levels occurred at the surface and varied from lake to lake at a given time. In general, levels were highest in winter and lowest in summer, reflecting broad scale temperature changes, but fluctuations were imposed upon this cycle by biological activity (photosynthesis and respiration).

Dissolved oxygen values were generally below saturation levels, indicating that a fairly high level of biological activity was occurring.

5.1.14 Dissolved oxygen and temperature profiles

Thermal stratification of deep water bodies is a common occurrence and the focus of much research and categorisation amongst limnologists. Most of the lakes in Australia and New Zealand are termed warm monomictic lakes because they thermally stratify only once a year and water temperatures always remain above 4°C, so preventing ice formation (Bayly and Williams, 1973). Most of Perth's wetlands are too shallow to develop thermal stratification at all. If they do, strong winds usually break down the stratification quite rapidly, as has been shown by recent studies on North Lake (S. Macintyre, pers. comm.). As a consequence of their shallow nature, very little work has been done on stratification in Western Australian lakes. The creation of deep water in Herdsman Lake and the subsequent monitoring programme has provided a unique opportunity to consider the nature of stratification and its consequences in a local wetland.

Thermal stratification has important implications because it affects oxygen distribution in a water body and the cycling of nutrients. The combination of thermal stratification and cultural eutrophication, the latter of which increases productivity and thus the demand for oxygen, can be quite drastic.

Oxygen is supplied to a water body by direct transfer from the atmosphere to the surface waters. The rate of transfer is increased by turbulence and mixing at the air/water interface. Dissolved oxygen is distributed throughout the water body by circulation within the lake.

Thermal stratification is primarily induced by seasonal changes in air temperature and leads to the development of layers of water of different temperature (and therefore density) between which little mixing occurs.

The following description from NCDC (1981) explains the consequences:

"When stratified, the lower levels of a water body (the hypolimnion) are physically cut off from atmospheric oxygen; consequently, if sufficient organic matter is present, conditions may become anaerobic (all oxygen is depleted). In turn, when the water body becomes mixed, many substances - including certain nutrients - which have changed from an insoluble to soluble state at depth become dispersed through the upper layers."

Figure 27 illustrates the seasonal changes in stratification and mixing that occur in a warm monomictic lake. In winter the lake is of uniform temperature throughout and circulation occurs right down to the bottom of the lake. As air temperatures rise, localised heating at the surface establishes a temperature gradient throughout the water column. The warmer surface water is termed the epilimnion, the layer of water in which the temperature gradient is greatest is termed the metalimnion and the cooler, deep water below this is termed the hypolimnion.

As heating continues with the progression of summer, the epilimnion deepens and water circulation becomes restricted to this layer. However, strong winds can increase the depth of the mixed layer even further and may break down thermal stratification temporarily. In autumn, as temperatures decrease, thermal stratification finally breaks down completely.

Figure 28 illustrates the chemical changes associated with the development of thermal stratification. Total phosphorus, total nitrogen, ammonia and orthophosphate concentrations usually increase in the hypolimnion due to the decomposition of organic matter in the isolated layer of water. In addition, the release of phosphorus and nitrogen compounds from the sediments is usually greater than their rate of sedimentation under anoxic conditions. Finally, carbon dioxide accumulates as a by-product of respiration and subsequently pH decreases.

The amount of oxygen dissolved in water is dependent upon the temperature of the water and can be modified by biological activity and chemical reactions. Oxygen is introduced to the water body during the day as a by product of photosynthesis by algae, but this can only occur in the sunlit surface waters. Outside this sunlit zone, respiration by aquatic organisms, chemical reactions, and bacterial decomposition of organic material, all deplete oxygen levels.

The dissolved oxygen and temperature profiles plotted for the three deep sites in Industrial Lake from September 1983 - October 1984 show thermal stratification developing in spring (Figs 29-41). This stratification seems to persist throughout summer and then breaks down in autumn to form a well mixed water column throughout winter. This is the classic cycle of a warm monomictic lake.

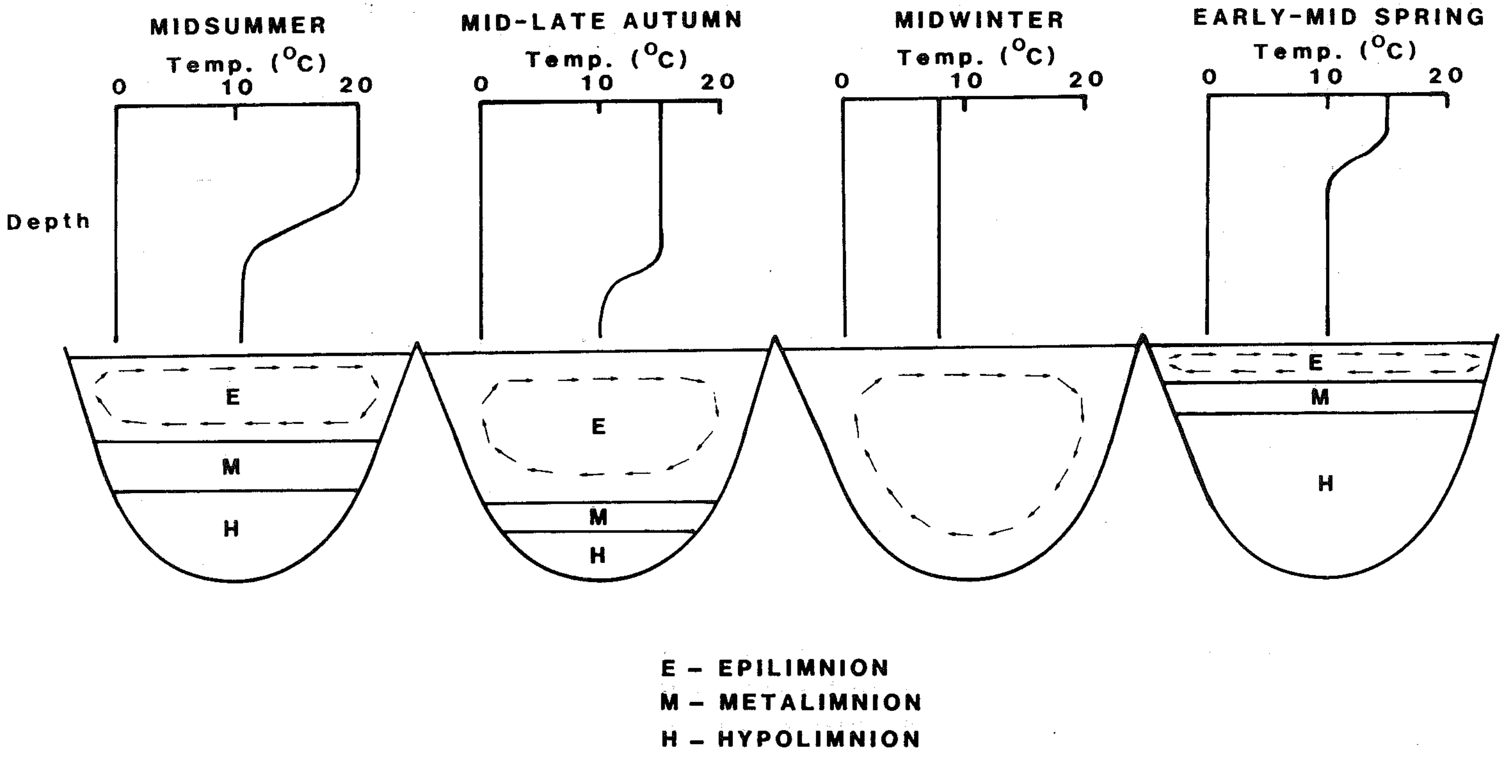


Fig. 27. A diagrammatic summary of the seasonal changes that take place in the circulation patterns of a warm monomictic lake. After Bayly and Williams (1973).

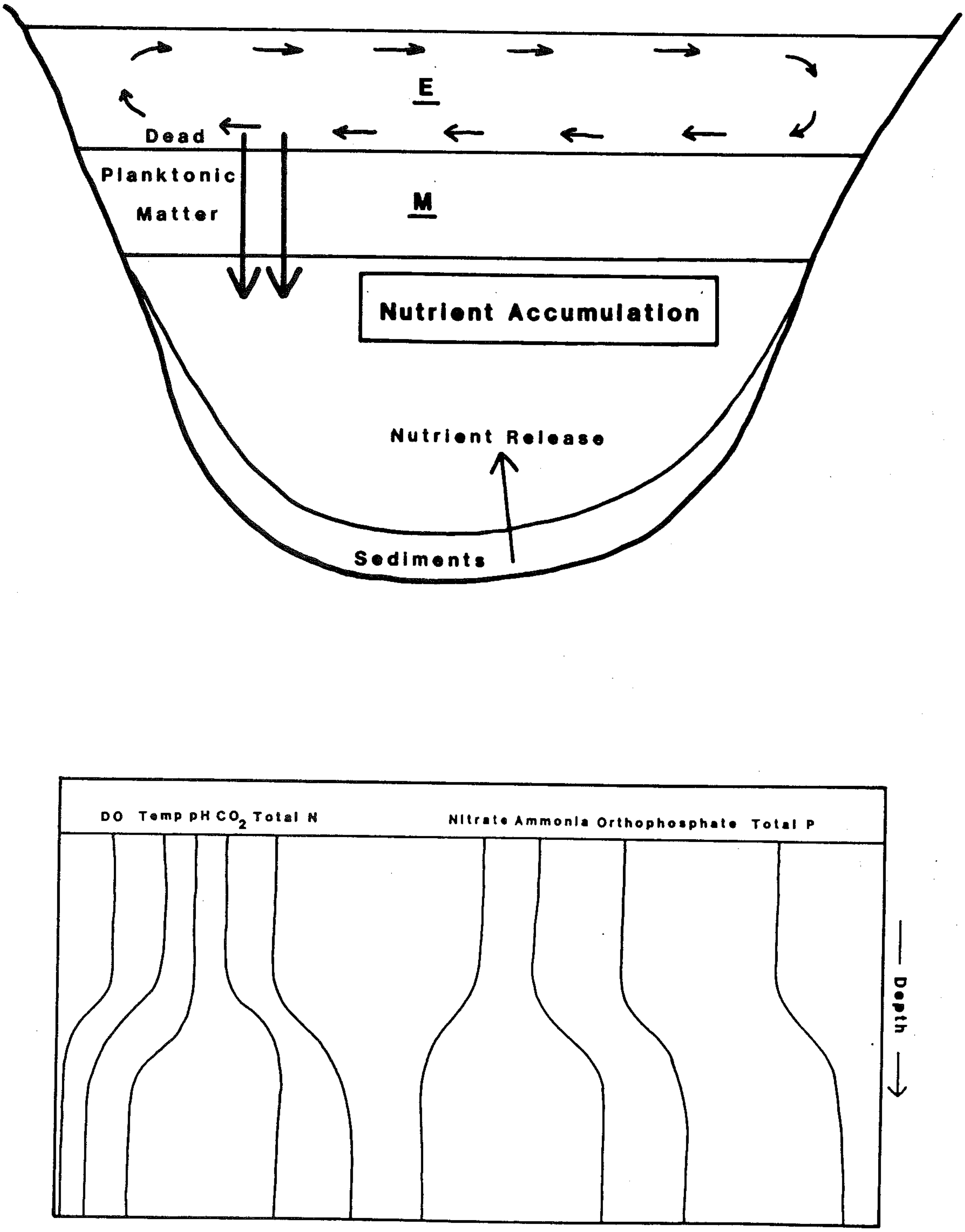


Fig. 28. The changes in physicochemical parameters and nutrient cycling associated with thermal stratification.

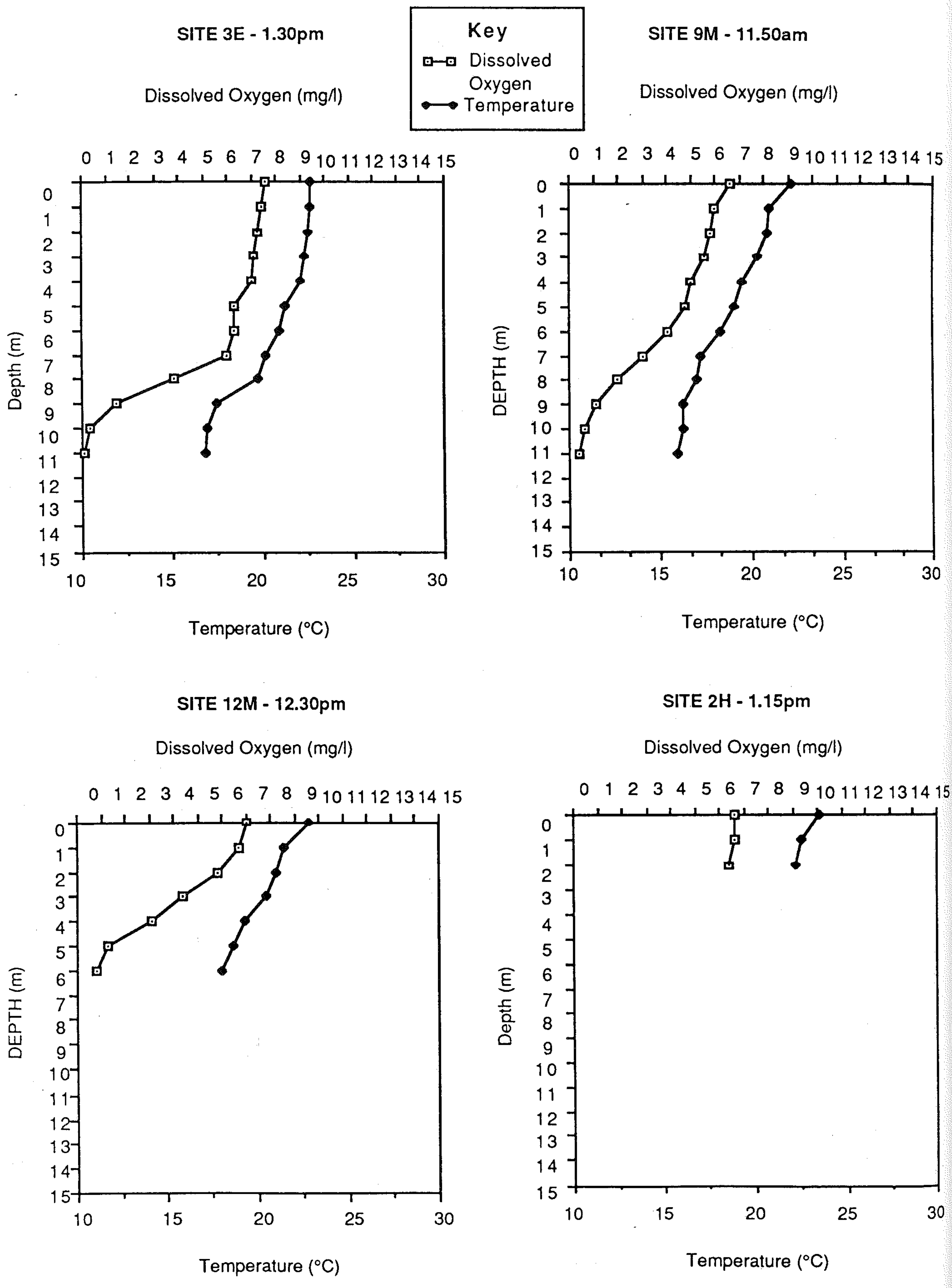


Figure 29. Dissolved oxygen and temperature profiles for Industrial Lake 13/9/83

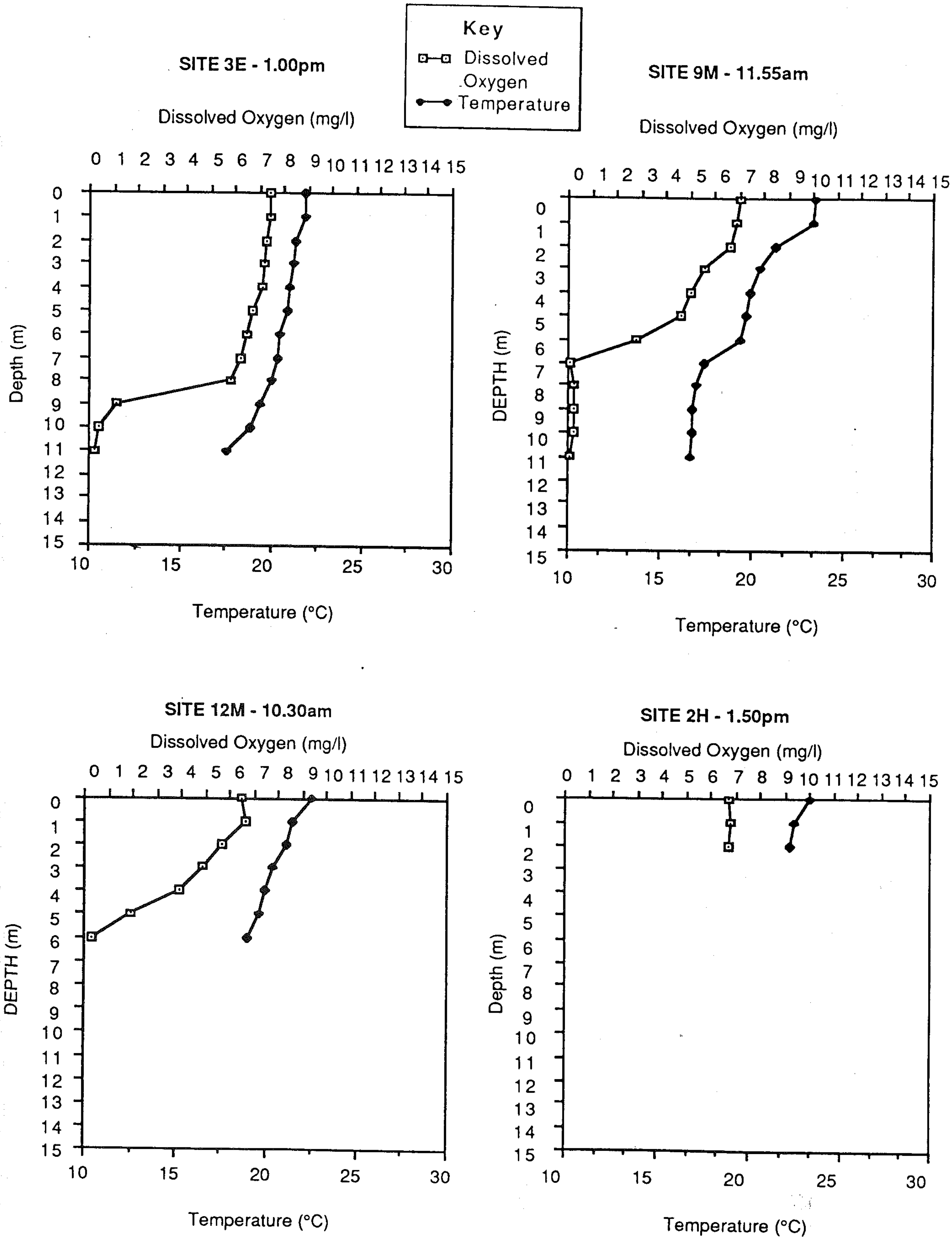


Figure 30. Dissolved oxygen and temperature profiles for Industrial Lake 10/11/83

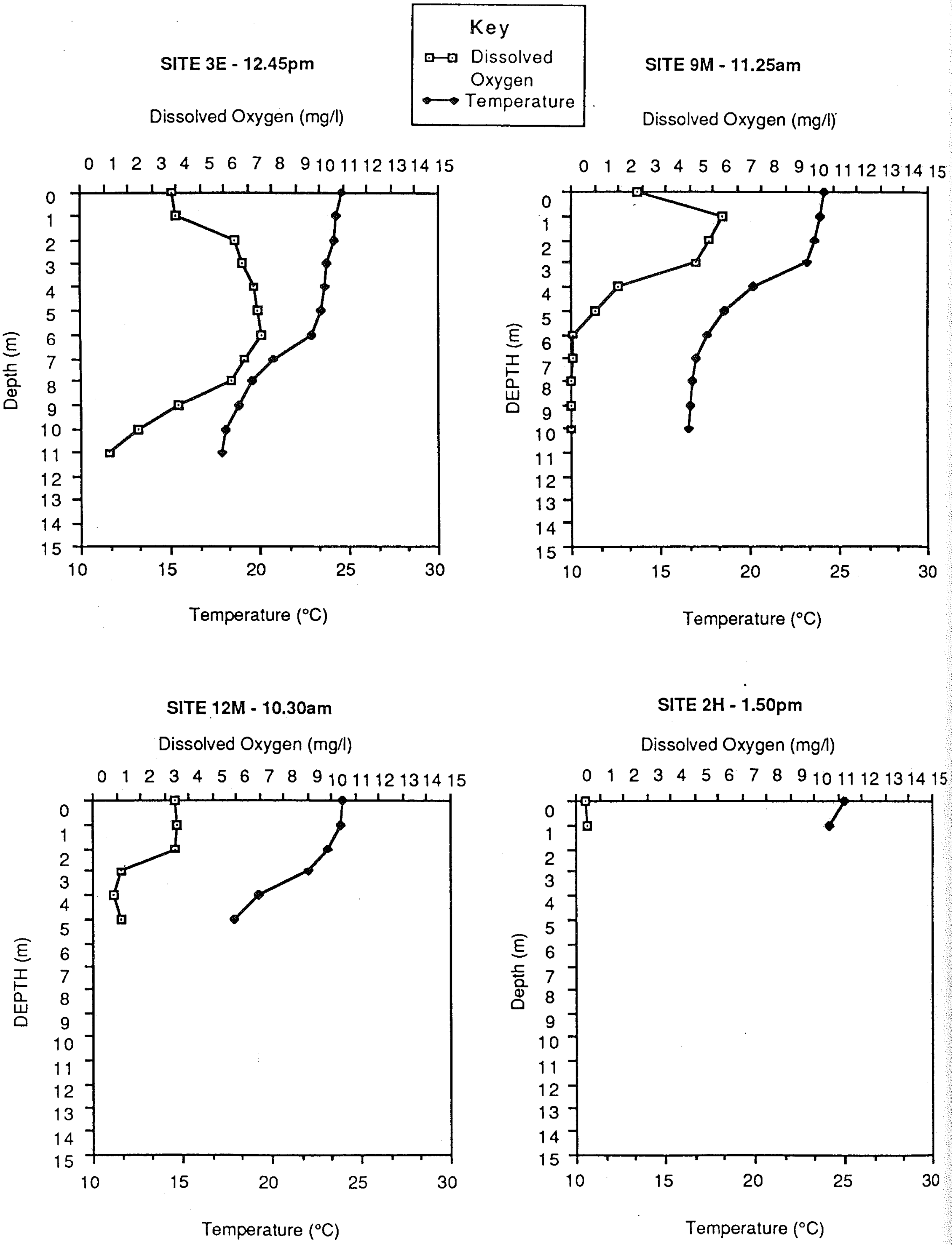


Figure 31. Dissolved oxygen and temperature profiles for Industrial Lake 21/12/83

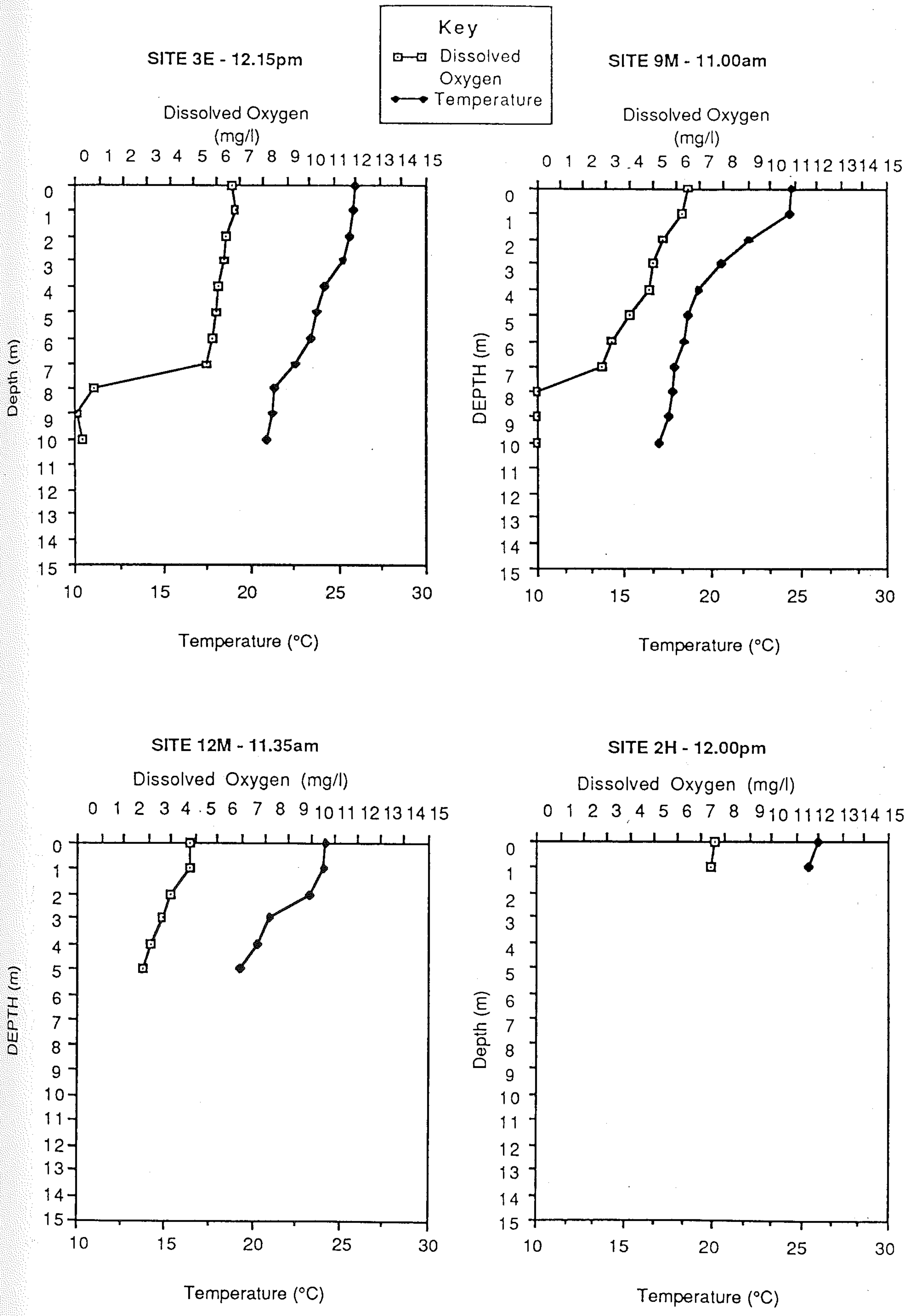
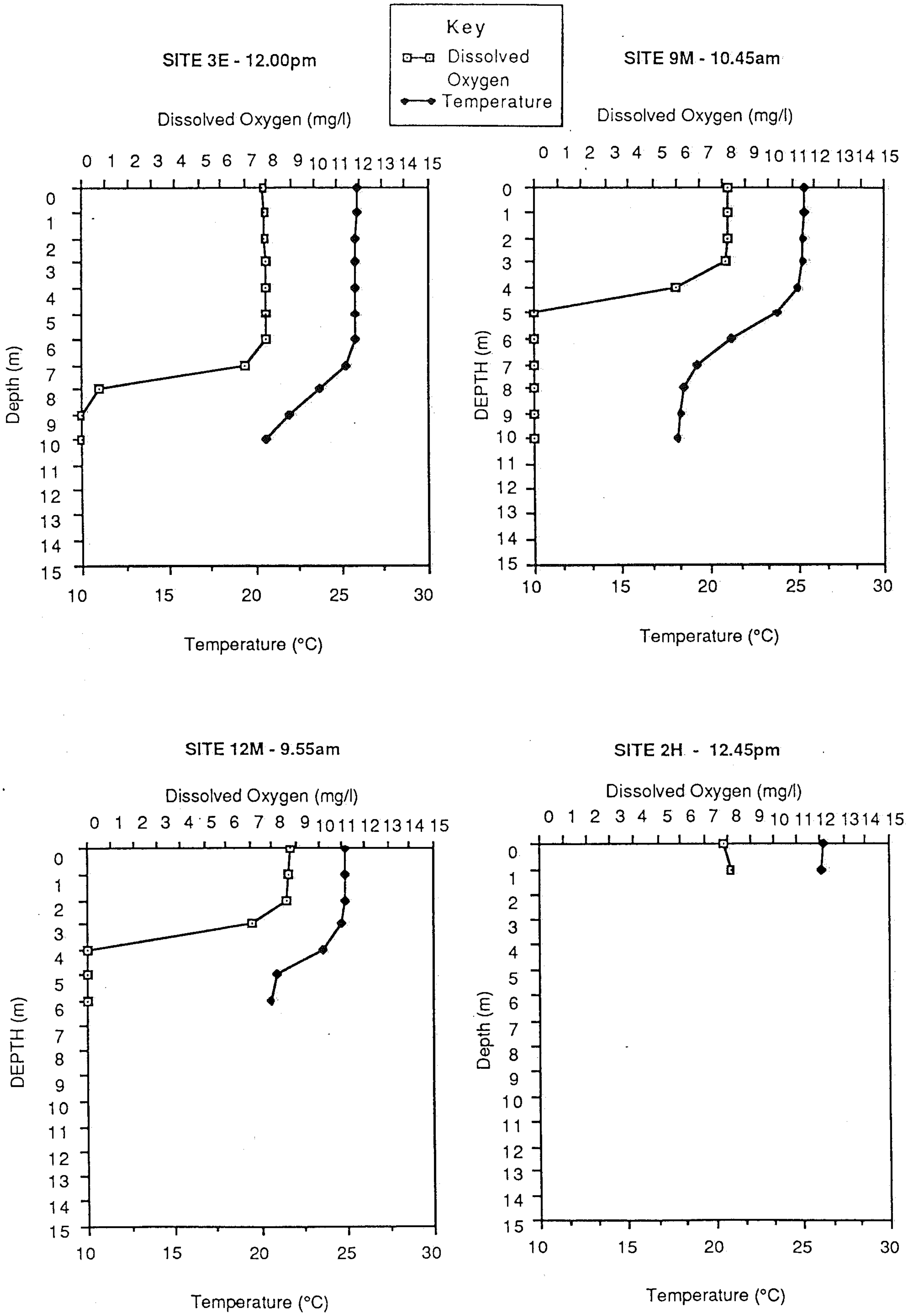


Figure 32. Dissolved oxygen and temperature profiles for Industrial Lake 29/1/84.



SITE 3E - 12.00pm

SITE 9M - 10.45am

SITE 12M - 9.55am

SITE 2H - 12.45pm

Figure 33. Dissolved oxygen and temperature profiles for Industrial Lake 16/2/84

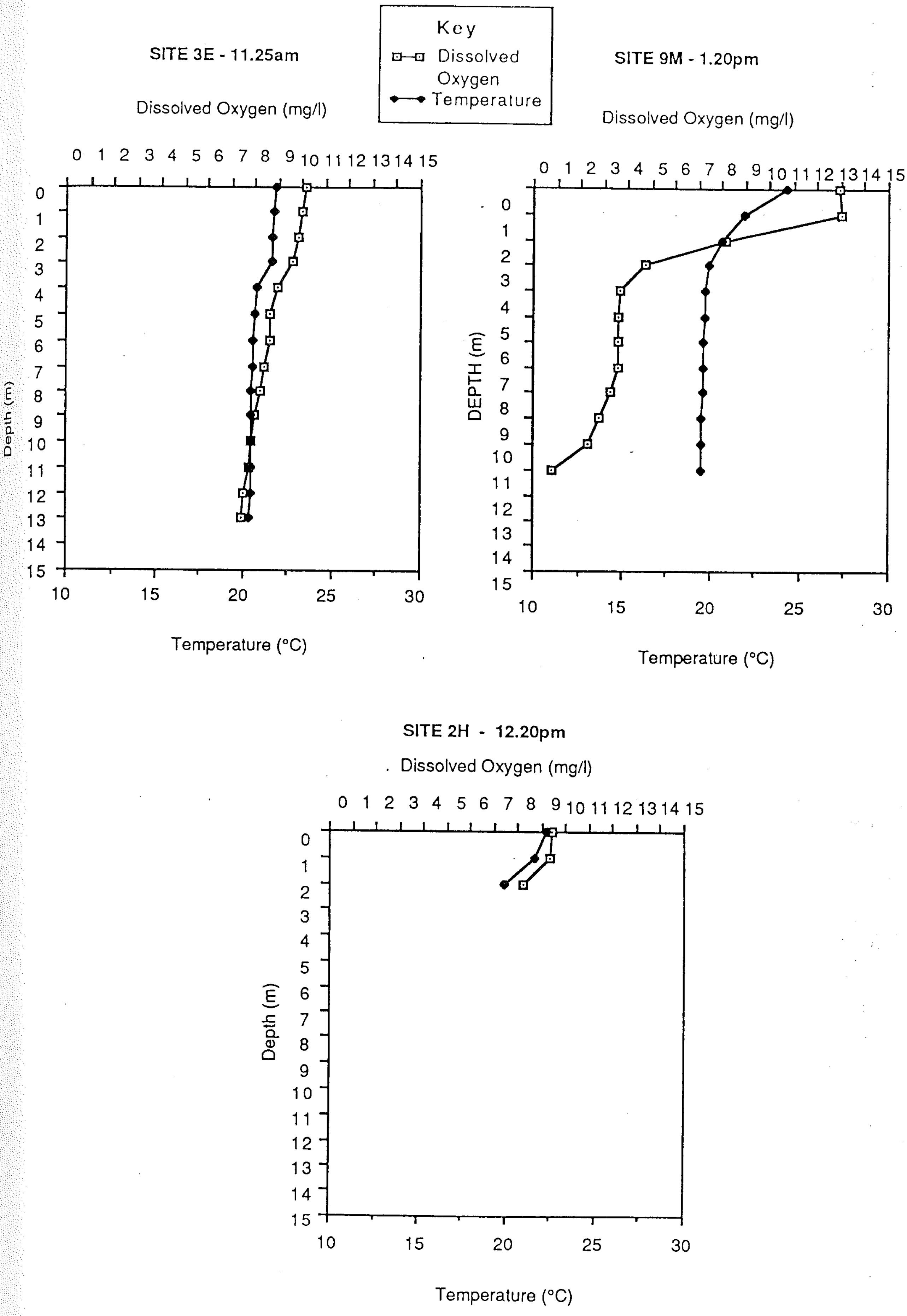


Figure 34. Dissolved oxygen and temperature profiles for Industrial Lake 23/3/84

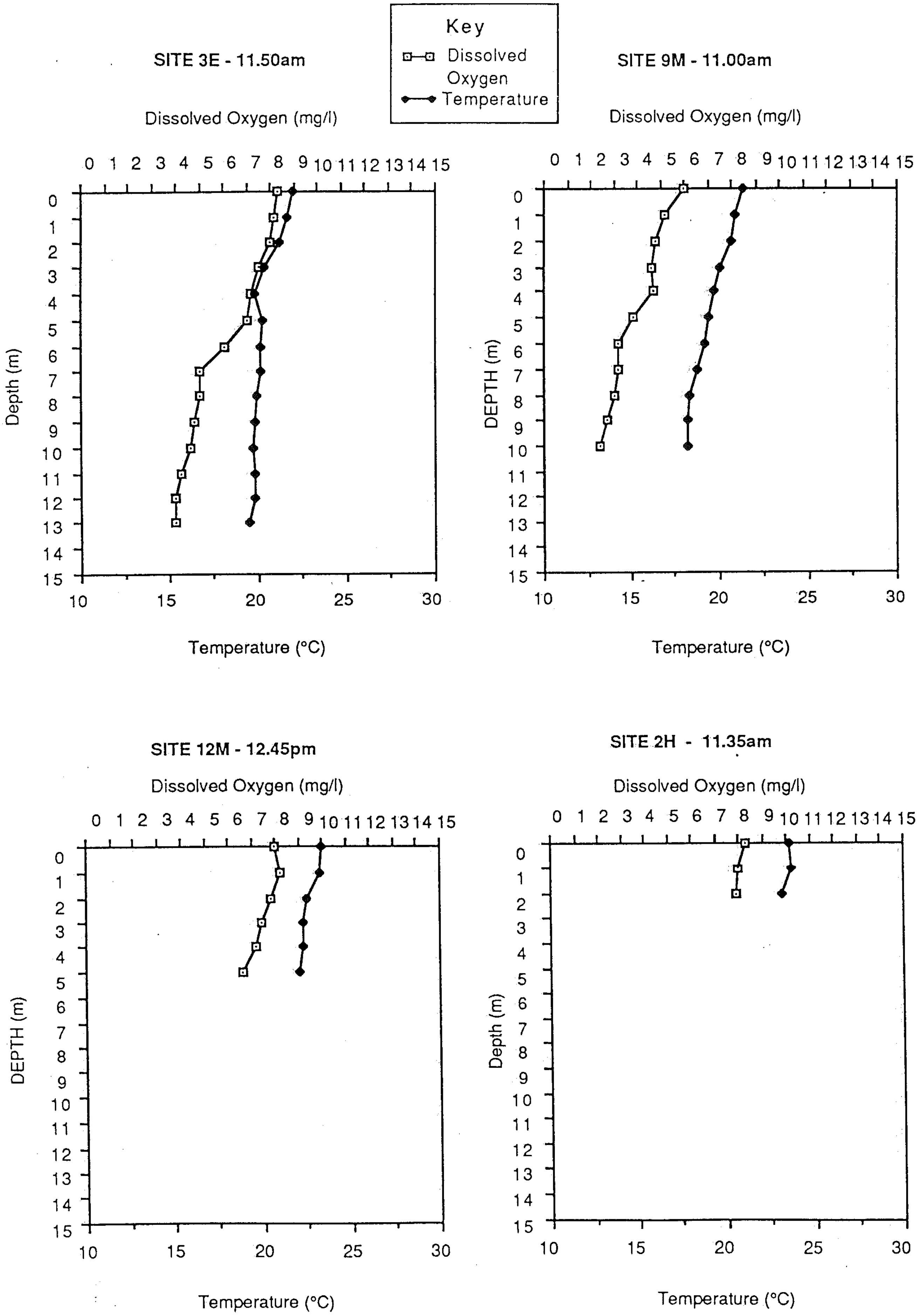
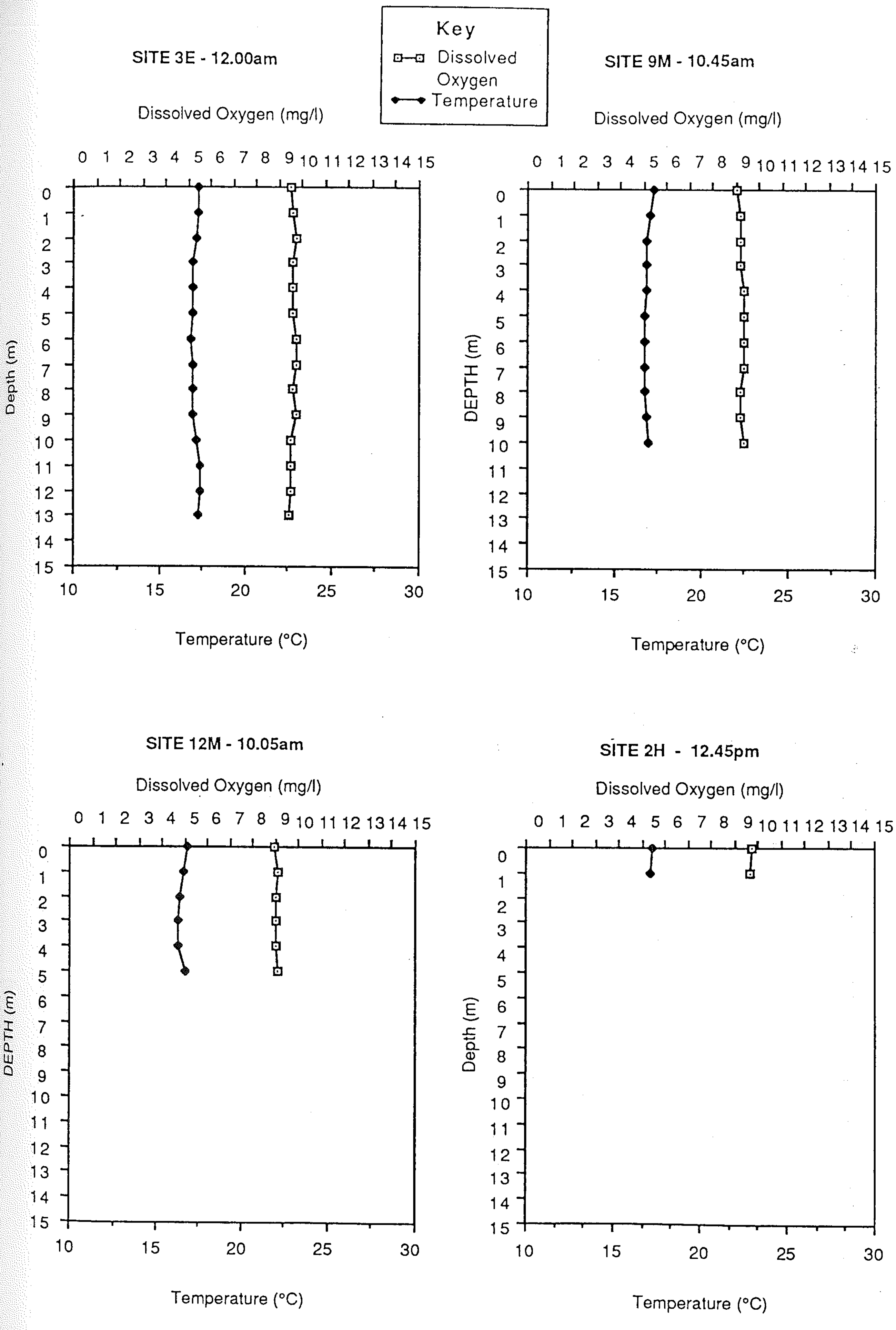


Figure. 35. Dissolved oxygen and temperature profiles for Industrial Lake 29/4/84



SITE 3E - 12.00am

SITE 9M - 10.45am

SITE 12M - 10.05am

SITE 2H - 12.45pm

Figure 36. Dissolved oxygen and temperature profiles for Industrial Lake 31/5/84

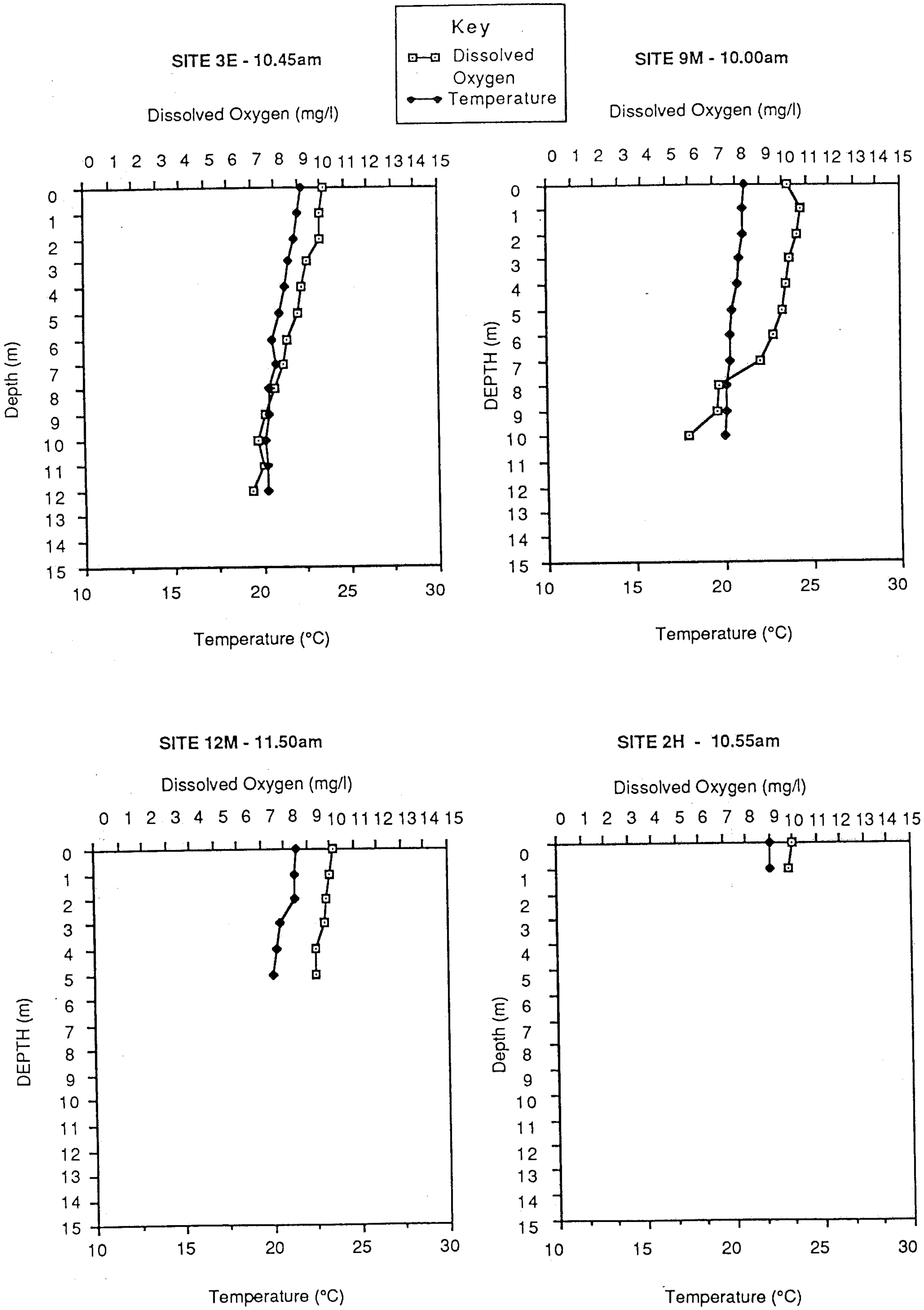


Figure 37. Dissolved oxygen and temperature profiles for Industrial Lake 24/6/84

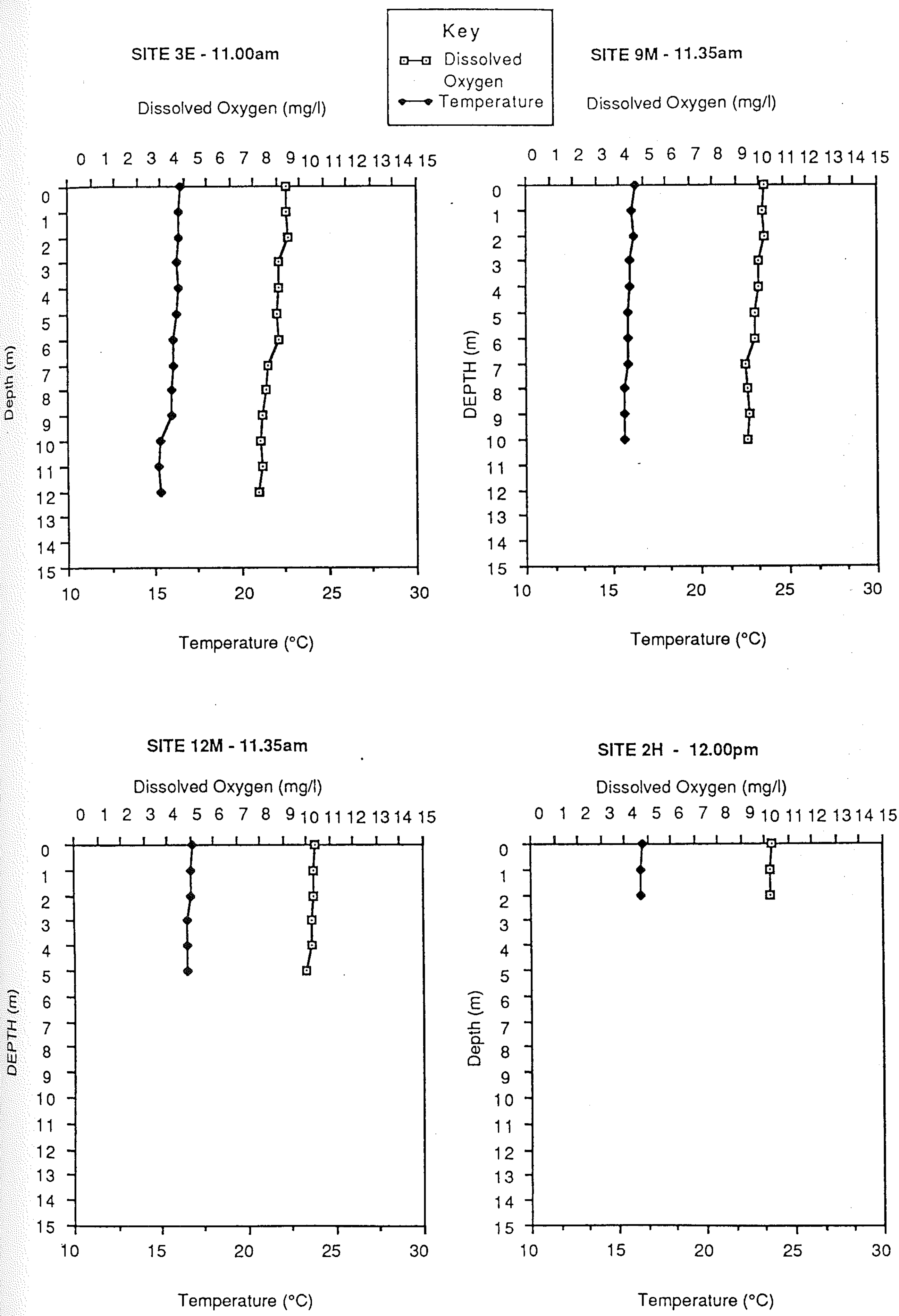


Figure 38. Dissolved oxygen and temperature profiles for Industrial Lake 28/7/84

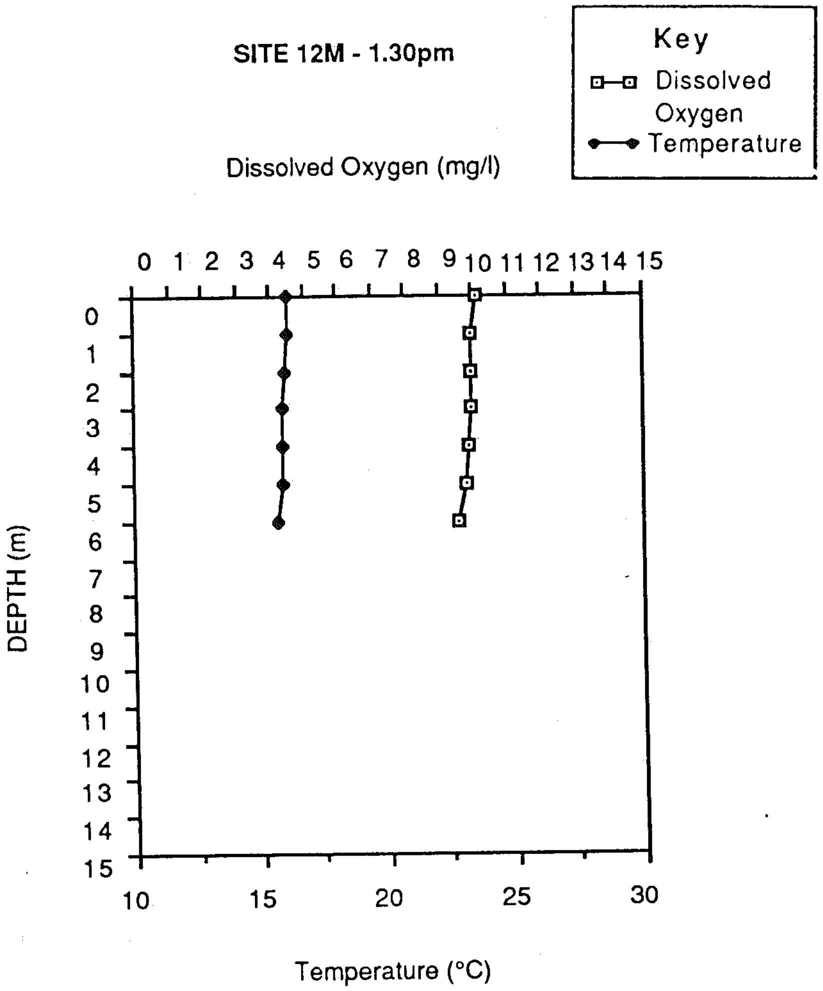


Figure 39. Dissolved oxygen and temperature profiles for Industrial Lake 26/8/84

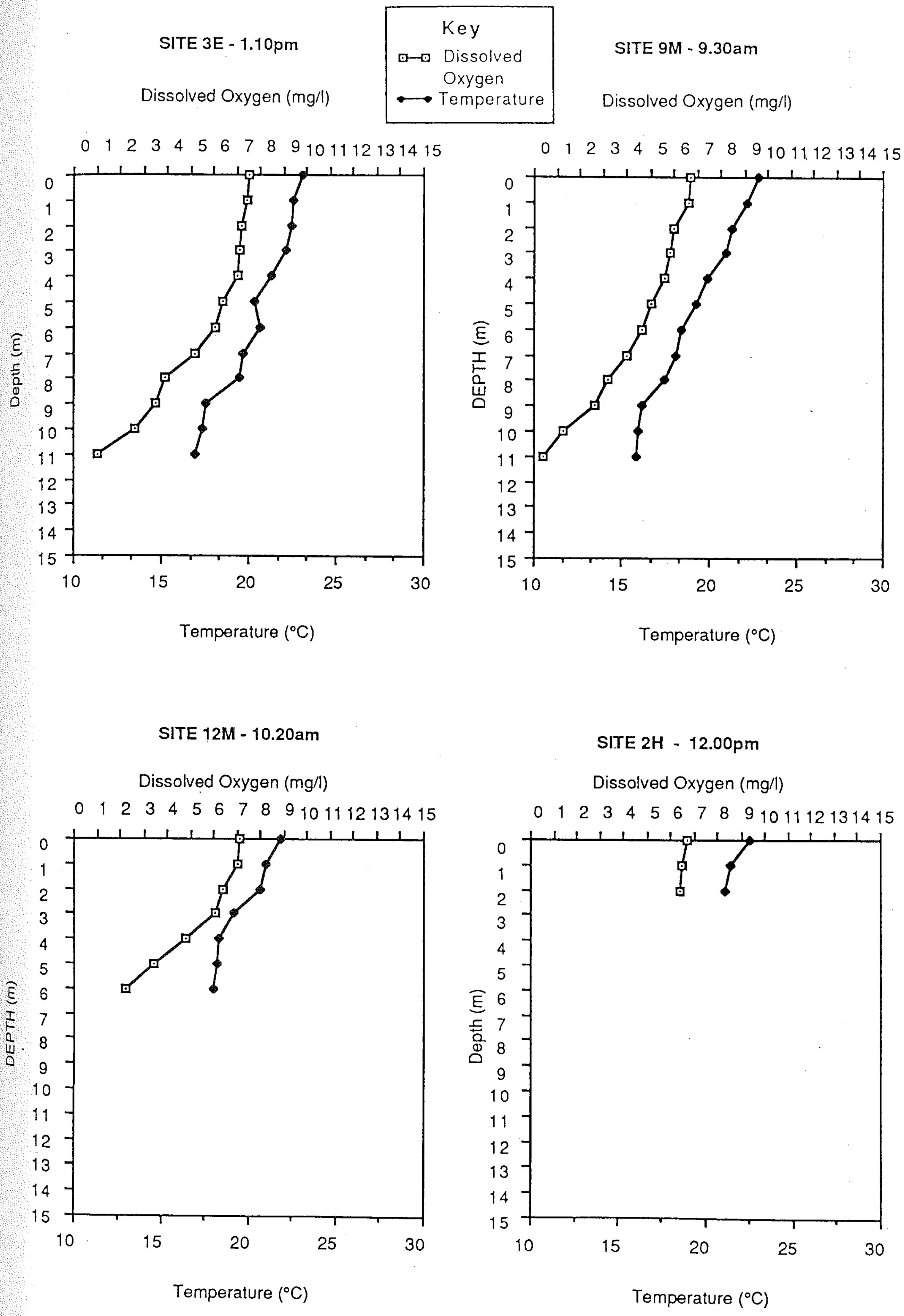


Figure 40. Dissolved oxygen and temperature profiles for Industrial Lake 30/9/84

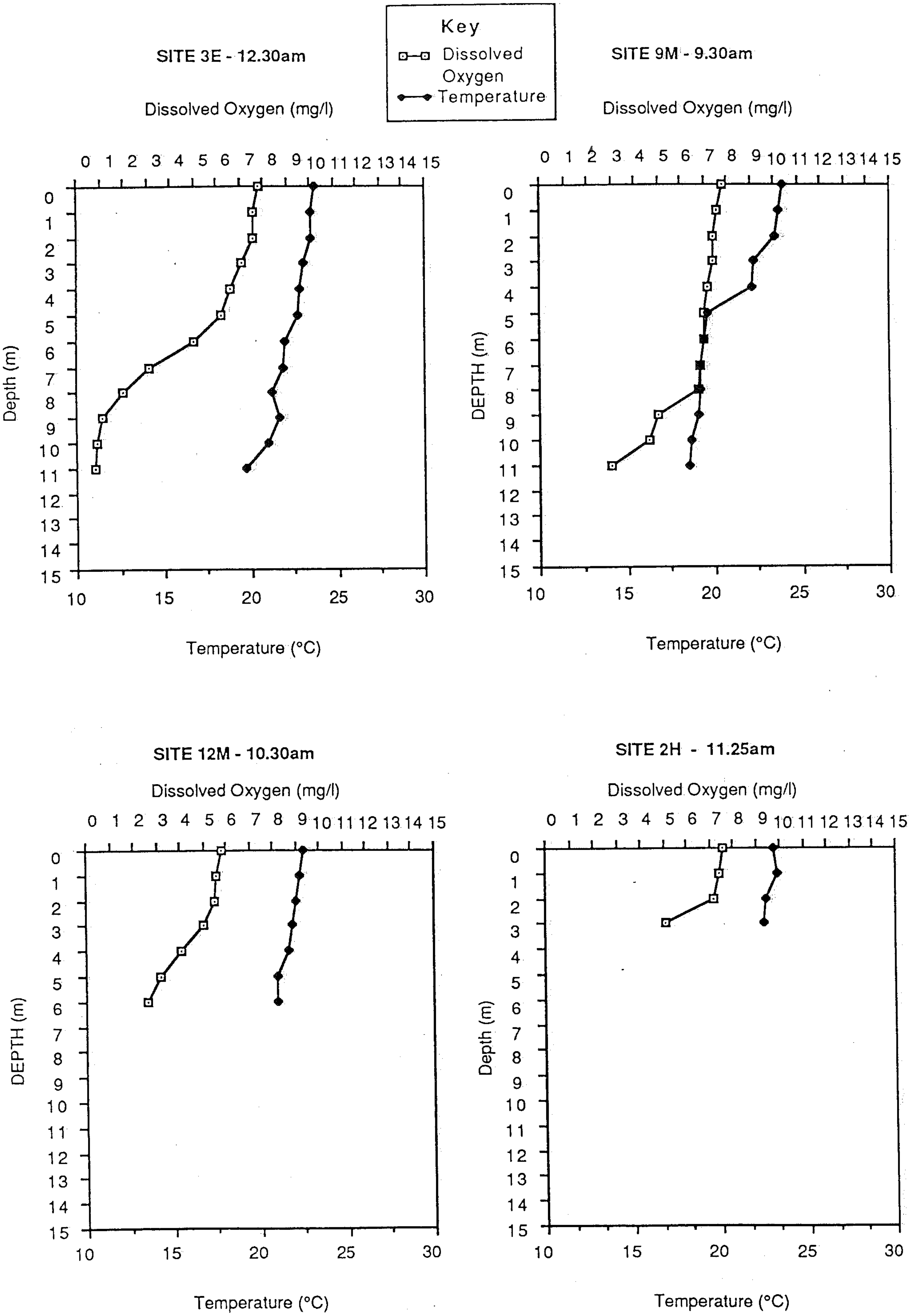


Figure 41. Dissolved oxygen and temperature profiles for Industrial Lake 28/10/84

It can be seen from the dissolved oxygen profiles in Industrial Lake (Figs 29-30) that dissolved oxygen levels at the deeper sites (3E, 9M and 12M) begin decreasing with depth in September with the deepest sites developing a completely anoxic bottom layer of water as early as November. The plots for sites 3E and 9M in December (Fig. 31) show raised dissolved oxygen levels below 1 m before a drop back to low dissolved oxygen levels at depth. This was probably due to a sub-surface algal bloom.

The profiles for sites 3E and 9M in January (Fig. 32) indicate that the depth of mixing extended to between 7 and 8 m with waters below this being anoxic.

By February, the shallower of the three deep sites, 12M, had also developed an anoxic bottom layer. Mixing was only occurring to 3-4 m at site 12M, with slightly deeper mixed layers at sites 3E and 9M. In March, thermal stratification seemed to have broken down at site 3E, but it still persisted at site 9M (Fig. 34). However, in April all sites show fairly uniform profiles (Fig. 35) with complete mixing achieved by May (Fig. 36) and maintained throughout winter until the following spring (September 1984) (Figs 37-41).

Profiles for the shallow site 2H (Figs 29-41) were representative of the other two shallow sites, 1H and 11M. Dissolved oxygen levels in these shallow waters in summer were generally below saturation levels. Levels on 21 December 1983 were particularly low, with the surface water being almost anoxic (Fig. 31). This is unusual and may have been due to a high oxygen demand for decomposition processes at that time.

In winter, saturation levels were higher and on occasion surface waters were supersaturated such as on 28 July 1984 (Fig. 38). This was probably due to the production of oxygen during the day by algae. Winter algal blooms are a particular feature of these lakes. Other features were observed in the profiles from Powis Lake and Floreat Waters. Deoxygenation of the water directly above the sediments was seen in many cases (Fig. 42). This is attributable to the high oxygen demand of sediments due to bacterial activity and chemical reaction. On other occasions and at other sites strong gradients in dissolved oxygen levels developed without any thermal stratification apparent (Fig. 43).

5.2 INTERRELATIONSHIPS AND CAUSAL MECHANISMS

Chlorophyll *a* levels represent algal biomass, although the types of algae present are not known unless samples are taken for identification. The growth of algae in the water column is dependent on a number of factors with different species dominating under different conditions. Excessive algal growth tends to occur when levels of inorganic phosphorus and inorganic nitrogen are high, light intensity is high, the water is clear and water temperatures are warm.

In Perth, the warm, sunny winters contribute to the development of algal blooms in winter, which is considered to be an unusual occurrence in lakes elsewhere.

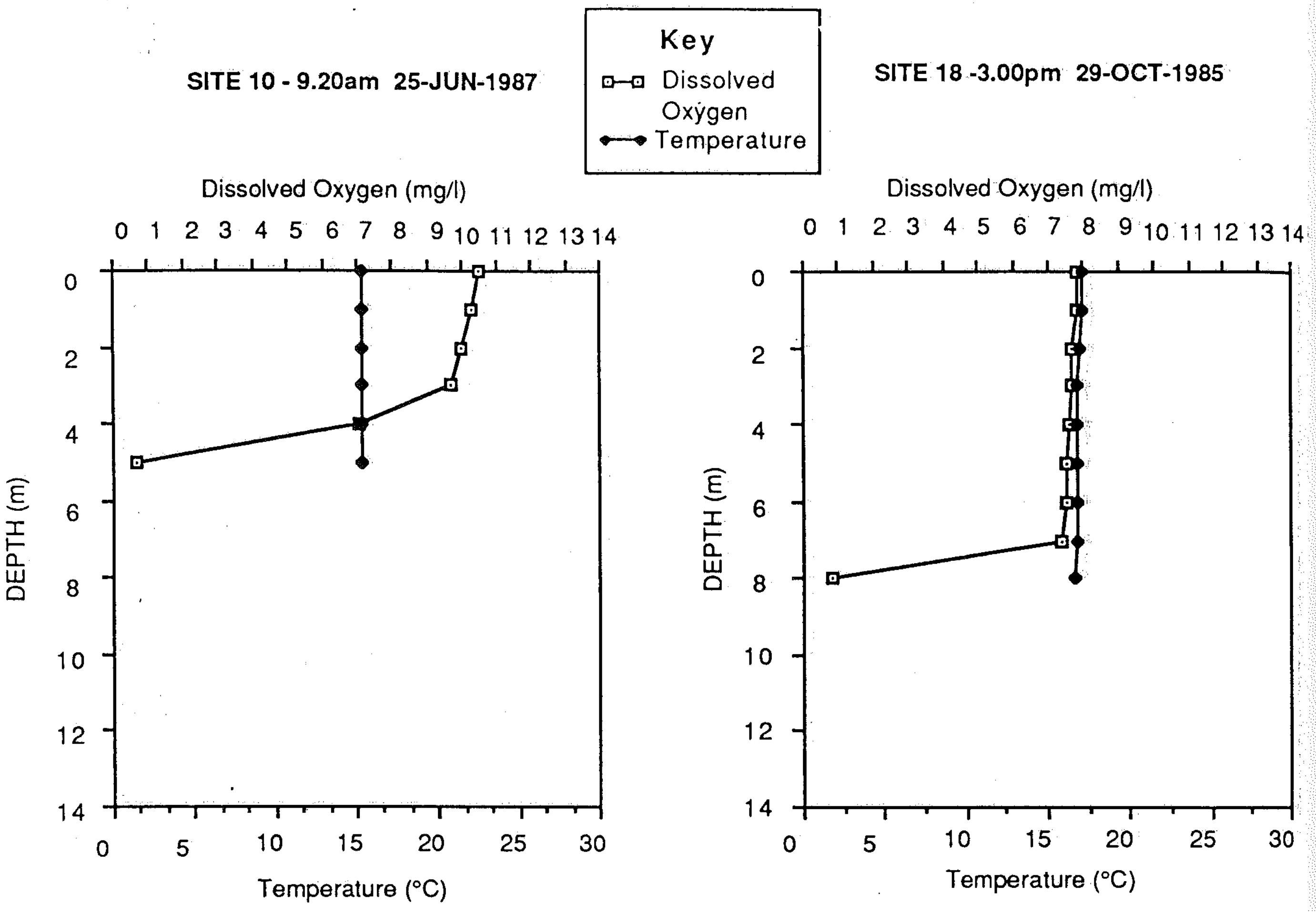
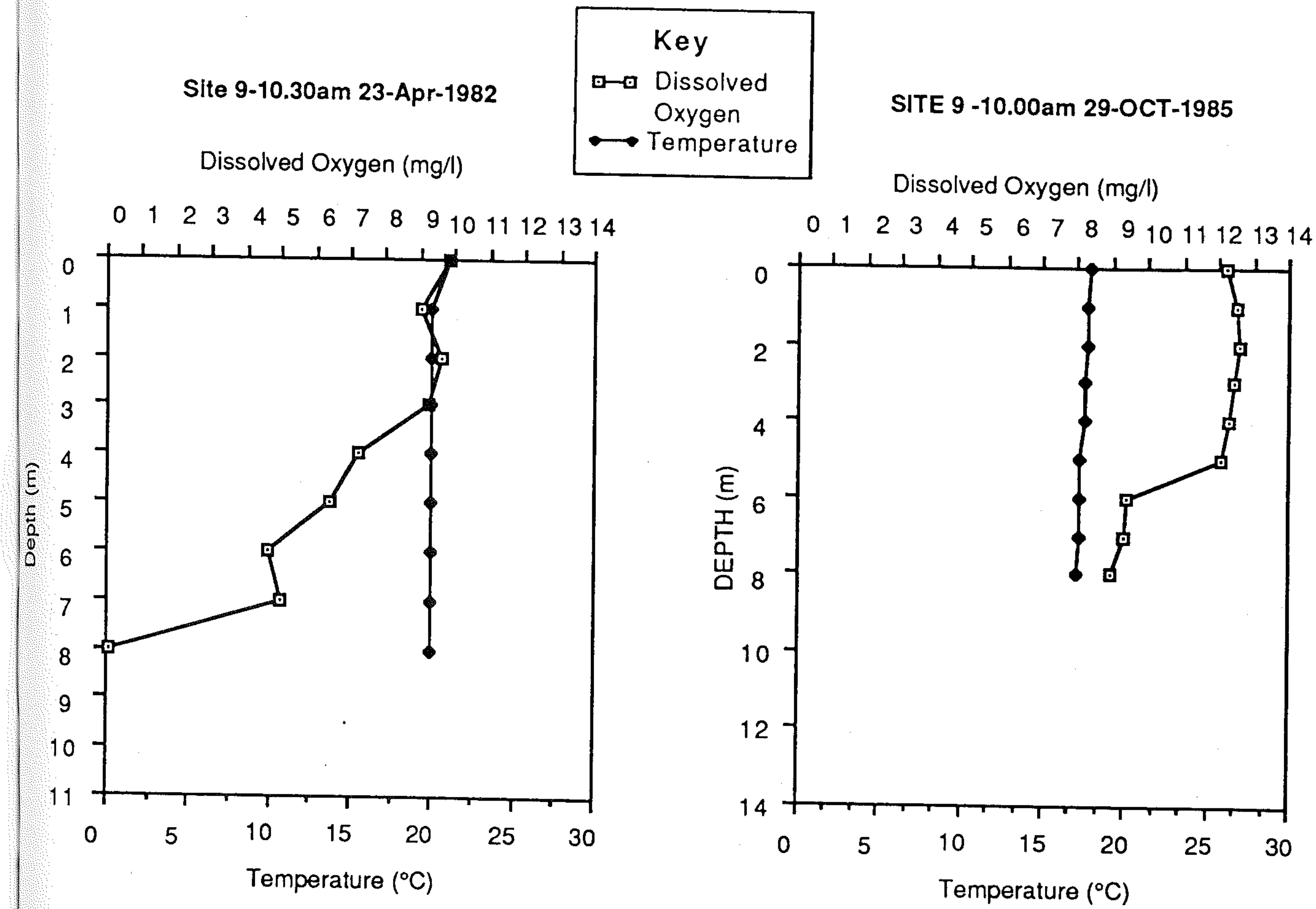


Fig. 42. Dissolved oxygen and temperature profiles showing deoxygenation of the water directly above the sediments.



Site 9-10.30am 23-Apr-1982

SITE 9 -10.00am 29-OCT-1985

Figure 43. Dissolved Oxygen and Temperature Profiles Showing Gradients in Dissolved Oxygen Levels in the Absence of Thermal Stratification.

Nutrient supply is very important and algal blooms are characteristic of lakes with high nutrient loadings. Although the level of inorganic phosphorus is normally considered the key factor in determining whether an algal bloom develops, inorganic nitrogen (nitrate and ammonia) can be the limiting factor in some systems. The latter often seems to be the case in Herdsman Lake.

Nitrate levels were low in all lakes except initially in Powis Lake. Levels of ammonia were also low in the three lakes. These low levels of inorganic nitrogen suggest a system that is nitrogen limited. Nitrate in particular seems to be assimilated as soon as it becomes available.

In general, chlorophyll *a* levels in Floreat Waters and Industrial Lake follow a seasonal cycle with algal blooms developing over summer and persisting throughout autumn and winter until the following spring when the blooms collapse. The collapse and decomposition of each year's bloom releases nutrients which contribute to development of the next bloom the following summer.

The collapse of each year's algal bloom was quite dramatic in Floreat Waters. Algal blooms collapse when nutrient supplies are exhausted and/or when algal growth is so dense that self-shading severely cuts down the light available for photosynthesis. Nutrients are removed from the water column as the algae grow and the nutrients are converted to organic compounds. Dilution of the water body by rainfall directly onto the lake and in the catchment also significantly lowers nutrient concentrations. In Herdsman Lake, winter rains eventually lead to overflow of the dredged lakes and main drainage channels into the whole lake basin, late in winter. This would have a significant effect on nutrient distribution and concentration.

As the algal blooms collapsed in Floreat Waters (Fig. 25), the normally low levels of ammonia rose due to decomposition of the algal cells (Fig. 21). This pattern can be seen in the other lakes. In Powis Lake, ammonia levels rose dramatically after the collapse of the first algal bloom recorded in this lake (April and May 1987).

A peak in ammonia levels in Powis Lake was also recorded in October 1985 which may have been due to the collapse of a bloom, but the lake had only just been completed and it is likely that decomposition of macrophytes which had been disturbed during dredging was occurring.

Orthophosphate was also present at very low levels in the lakes. Orthophosphate levels were inversely related to chlorophyll *a* levels in Floreat Waters with the orthophosphate levels decreasing as algal blooms developed, indicating that orthophosphate was being taken up by algal cells.

Relationships between orthophosphate and chlorophyll *a* in the other two lakes were not as clear. Total phosphorus and inorganic phosphorus were present in approximately the same ratio in Powis Lake for 1985, 1986 and 1987 until an algal bloom developed in April 1987. At this time orthophosphate remained low while total phosphorus increased, indicating the utilisation of orthophosphate by algal cells to produce organic phosphorus (as measured by total phosphorus).

It is probable that both inorganic phosphorus and inorganic nitrogen compounds are the key factors in limiting algal growth in these systems with each nutrient being limiting on different occasions.

There are several events which are likely to stimulate the growth of algae in the dredged lakes, these are:

1. the first heavy rainfall in late summer or autumn which flushes nutrients into the lakes, and

2. overturn of the water column due to the breakdown of thermal stratification bringing nutrients to the surface.

In Floreat Waters at the end of January 1986, chlorophyll *a* levels had begun to rise and were recorded around 0.017 mg/l. However, on the 21 and 22 February 1986, an unseasonal storm occurred and 74.8 mm of rain was recorded. By 27 February, chlorophyll *a* levels had jumped to 0.039 mg/l. A similar pattern of events occurred in Industrial Lake, although the algal bloom was of smaller magnitude.

The following year, little rainfall occurred until mid-April. Despite this, chlorophyll *a* levels were very high in Floreat Waters in early April. On 1 December 1986, 0.011 mg/l was recorded. When the next measurement was made on 1 April 1987, 0.060 mg/l was recorded. Between these two dates, only 10.4 mm of rain fell as light showers, spread over four months. Clearly, a large algal bloom had developed independently of flushing of the catchment. However, it is not known when it developed. The peak in chlorophyll *a* levels in February 1986 due to flushing of the catchment was followed by a second, much higher peak in late April 1986.

High nutrient concentrations may have triggered these peaks in chlorophyll *a* levels in both April 1986 and 1987 if overturn of the water column had occurred as a result of the breakdown of thermal stratification at deeper sites. When measurements were taken on 27 February 1986, the two deep sites in Floreat Waters were thermally stratified. On 3 April 1986, the deepest site (Site 9) was stratified but on 28 April none of the sites were stratified.

No dissolved oxygen or temperature profiles were available for the relevant dates in 1987 due to equipment malfunction, so it is not possible to determine whether stratification occurred and subsequently broke down. However, by 3 May 1987 the water column was well mixed with no thermal stratification. The 1983/84 data for the deep sites in Industrial Lake shows autumn overturn occurring and it is highly likely that autumn overturn also occurs in Floreat Waters.

Chlorophyll *a* levels rose in Industrial Lake between November 1983 and May 1984 and this appeared to be due to a combination of events leading to an increase in nutrient concentrations. There were heavy showers on 31 December 1983, 4 March 1984, 11, 21 and 30 April 1984 and throughout May 1984. The breakdown of stratification at the deep sites in late March/early April may explain the large spatial variation in chlorophyll *a* levels recorded on 22 March 1984 as temporary and localised pockets of surface water with high nutrient concentrations occurred. However, spatial variation often occurs in chlorophyll *a* levels due to the action of wind in distributing algae across lakes. In addition, some algal species such as *Microcystis aeruginosa* grow in clumps.

Table 8 shows the concentration of nutrients in both surface and bottom waters at sites sampled by the State Planning Commission on 31 January 1986. In Floreat Waters and Industrial Lake levels of ammonia, total Kjeldahl nitrogen, orthophosphate and total phosporus were all much higher in the bottom waters than at the surface. In Powis Lake the magnitude of change between the surface and bottom of the lake was small in comparison to the other two lakes. Ammonia increased by a factor of 500 at the bottom of site 12 in Floreat Waters. pH was also lower at the bed at all sites. Due to the flocculant nature of the lake bed, turbidity was very high in some of the bottom water samples.

Results of this type were also available for four of the sites at Industrial Lake between November 1983 and May 1984. At the three deep sites, 3E, 9M and 12M, and especially at site 9M, levels of total Kjeldahl nitrogen, ammonia, nitrogen, total phosphorus and orthophosphate were all much higher in the bottom water samples but only up until March 1984 (Figs 44 -47). By this time mixing of the water column at some sites was evident. Thermal stratification had broken down at all sites by the end of April 1984. Surface and bottom water samples at the shallow site, site 2H, and at the deep sites after overturn, showed very similar values for all parameters.

Peaks in total Kjedahl nitrogen levels corresponded closely to the occurrence of peaks in chlorophyll *a* in both Floreat Waters and Industrial Lake. In these lakes, total Kjeldahl nitrogen represented mainly organic nitrogen. This indicates that the majority of the organic nitrogen present in the water column was in the form of algal material. Peaks of TKN and chlorophyll *a* were not related in Powis Lake. In this lake a larger proportion of TKN comprised inorganic nitrogen. Levels of chlorophyll *a* were very low and the organic nitrogen present was probably in the form of decomposing plant material disturbed by dredging.

The peak of TKN recorded in Powis Lake in October/November 1985 was associated with peaks in ammonia and nitrate, suggesting decomposition of organic material. A peak in total nitrogen was recorded in October 1987 in Powis Lake. Ammonia levels were exceptionally high on this occasion due to the collapse of the algal bloom previously discussed. Although a relatively minor bloom in comparison to those seen in Floreat Waters and Industrial Lake, it lead to a release of ammonia into this system.

Total phosphorus levels also reflected the changes in chlorophyll *a* in Floreat Waters and to a certain extent these two parameters are related in Industrial Lake.

Table 8. Water Quality of Surface and Bottom Waters at Selected Sites on 31 January 1986

	Waterbody											
	Floreat Waters				Industrial Lake				Powis Lake			
Parameter	Site 9		Site 12		Site 2H		Site 9M		Site 15		Site 19	
	S	B	S	B	S	B	S	B	S	B	S	B
Site depth (m)		8		-		12		9		6		7
pH	8.2	7.9	8.5	7.6	8.4	7.7	8.5	8.1	8.3	8.2	8.3	8.1
Turbidity (NTU)	4.5	2.0	6.0	120.0	2.9	3.0	1.4	2.5	0.9	12.0	1.1	4.4
TDS (mg/l)	950	860	980	1090	600	630	600	600	550	550	540	550
Ammonia (mg/l)	0.02	3.00	0.02	9.90	0.02	2.00	0.04	0.92	0.10	0.11	0.08	0.15
Nitrate (mg/l)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.02	0.03	0.36	0.38	0.37	0.32
TKN (mg/l)	1.3	4.1	1.9	13.0	0.6	2.6	0.4	1.4	0.6	0.8	1.0	0.8
Orthophosphate (mg/l)	<0.01	0.36	<0.01	0.43	<0.01	0.19	<0.01	0.09	<0.01	0.01	<0.01	0.01
Total phosphorus (mg/l)	0.03	0.38	0.04	1.00	0.01	0.24	0.01	0.10	0.10	0.02	0.01	0.02
Chlorophyll *a* (mg/l)	0.013	-	0.021	-	0.004	-	0.004	-	0.003	-	0.003	-

S - Surface measurements
B - Bottom measurements

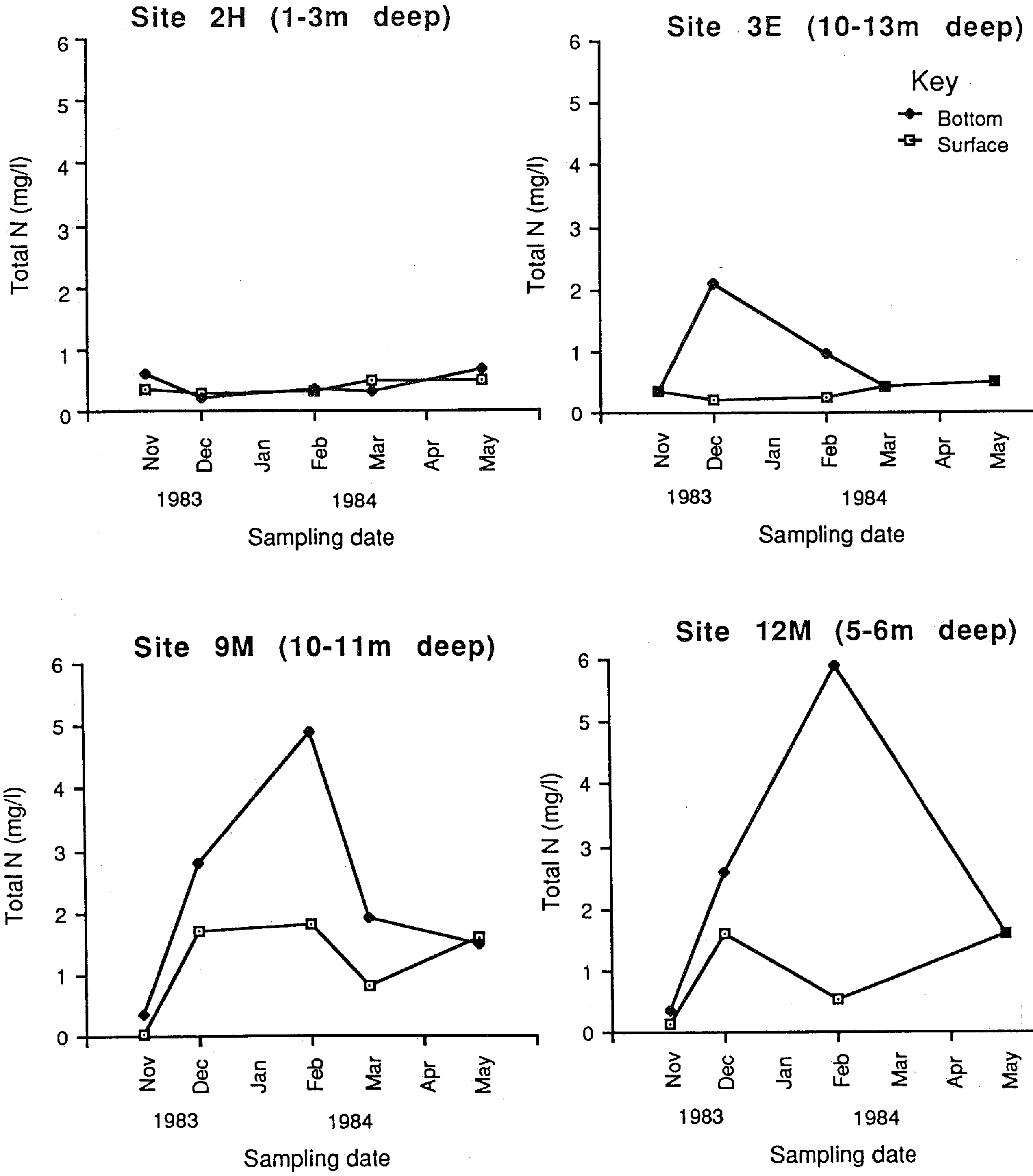


Figure 44. Concentrations of Total Nitrogen in the Surface and Bottom Waters of Industrial Lake Between November 1983 and May 1984.

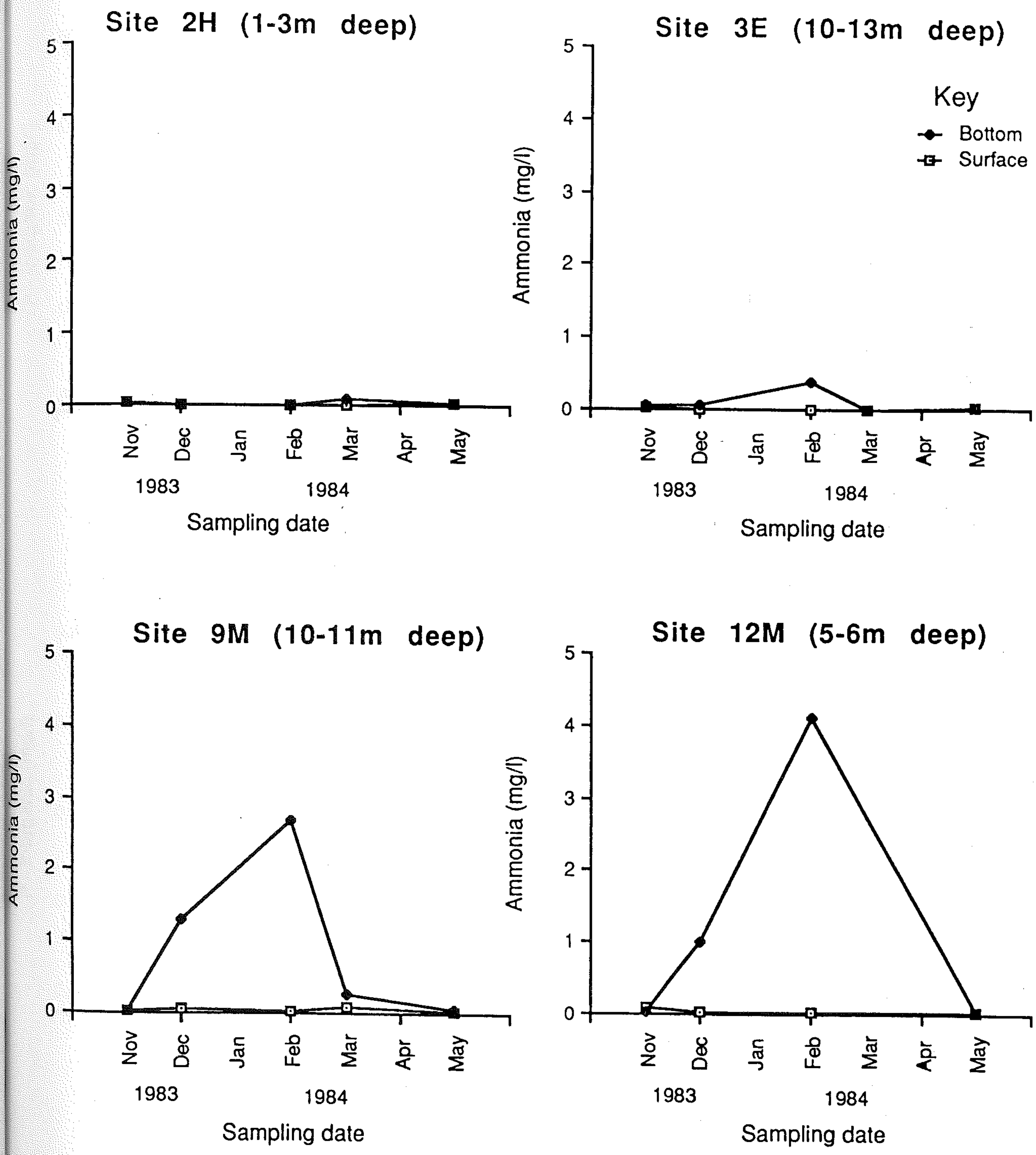


Figure 45. Concentrations of ammonia in the Surface and Bottom Waters of Industrial Lake Between November 1983 and May 1984.

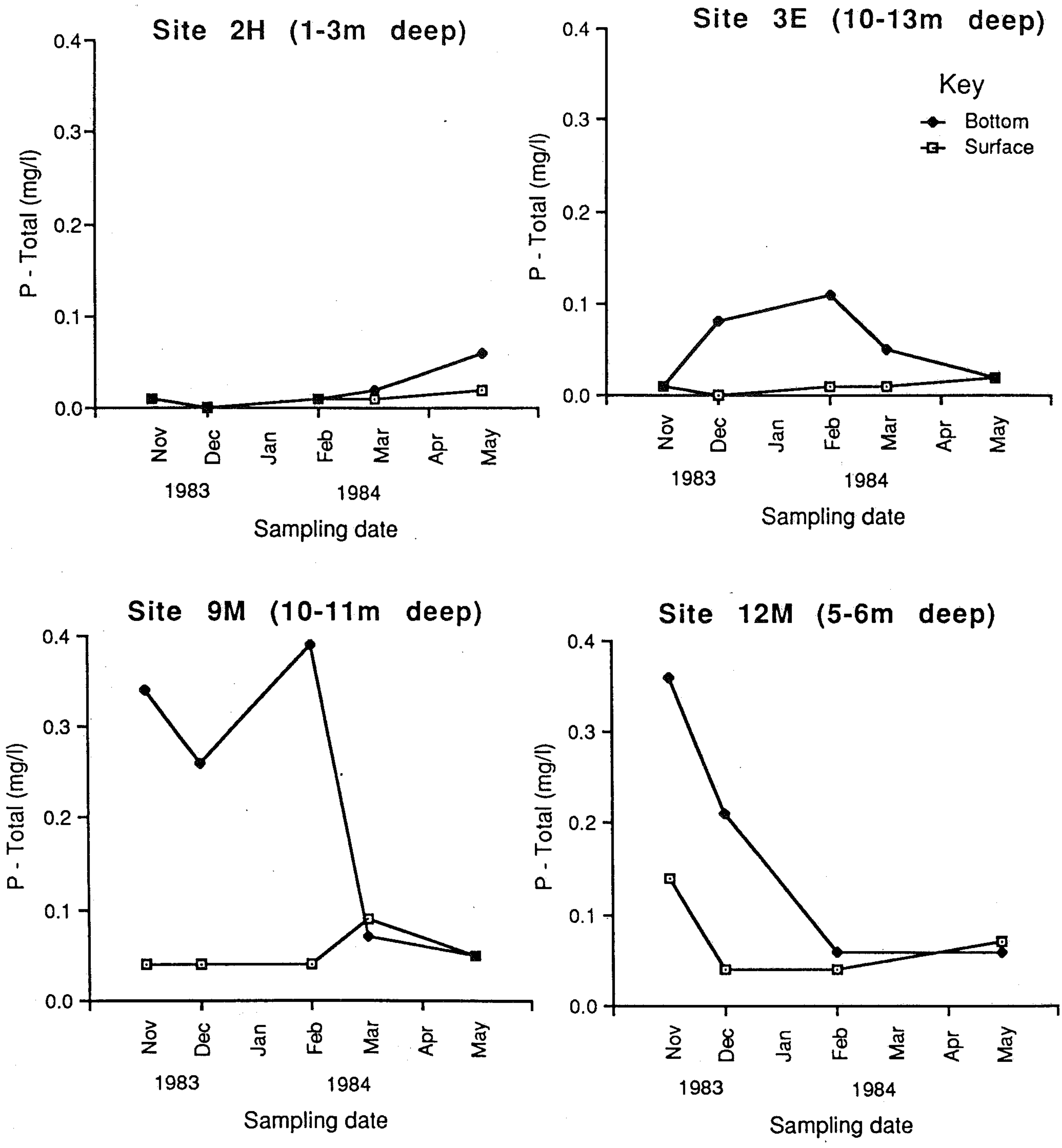


Figure 46. Concentrations of Total Phosphorus in the Surface and Bottom Waters of Industrial Lake Between November 1983 and May 1984.

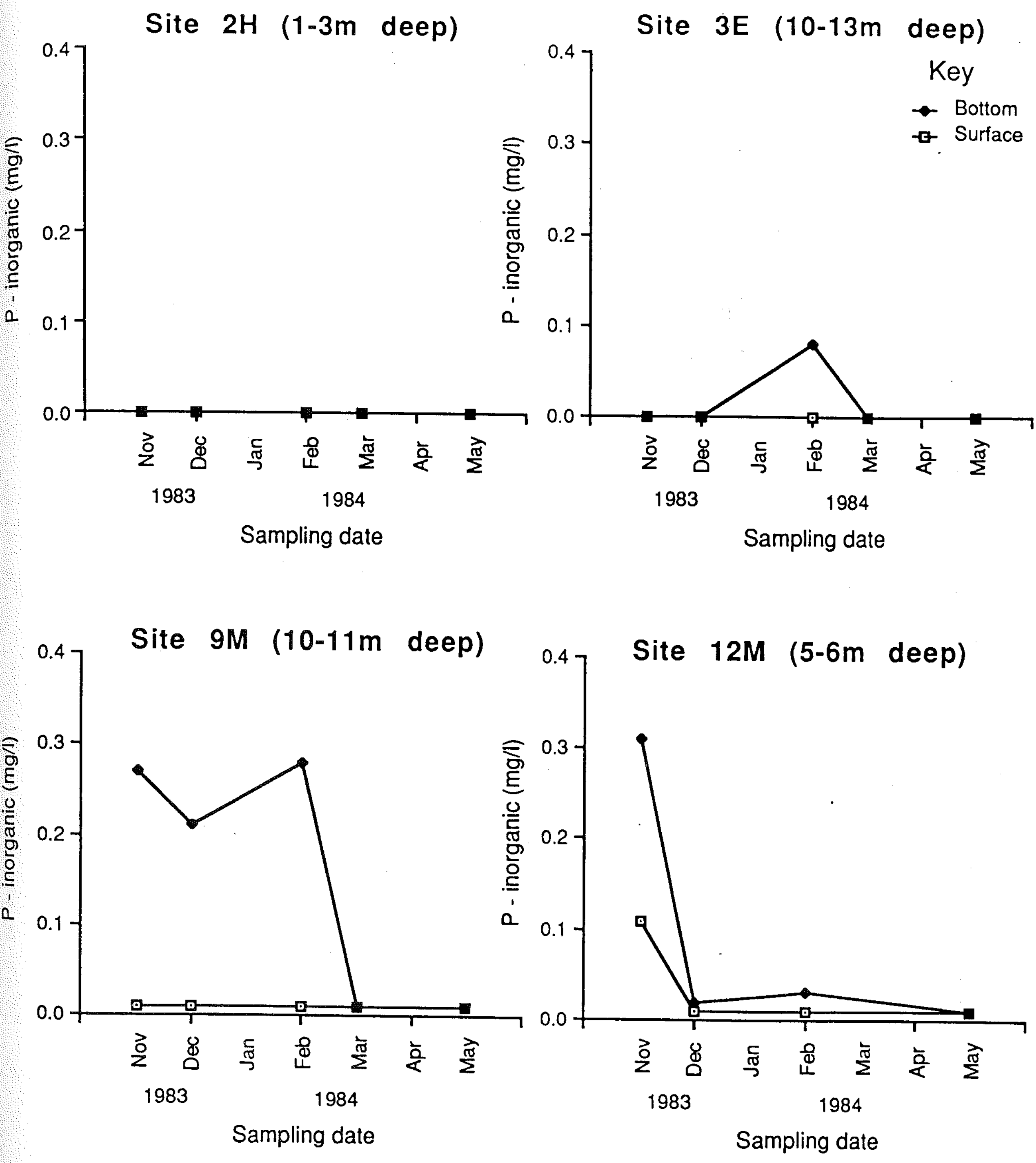


Figure 47. Concentrations of Orthophosphate in the Surface and Bottom Waters of Industrial Lake Between November 1983 and May 1984.

Figure 48 gives the correlation between total phosphorus and chlorophyll *a* at individual sites in each waterbody. Total phosphorus in Floreat Waters was largely comprised of organic phosphorus which again probably represented algal biomass.

Turbidity was closely related to chlorophyll *a* levels in Floreat Waters and Industrial Lake. It is likely that high turbidities were mainly the result of growth of algae in these two lakes. Figure 49 gives the correlations between chlorophyll *a* and turbidity at individual sites in each lake. The correlation is low for sites in Powis Lake, indicating that turbidity was usually due to another source. Disturbance of sediments during construction of the lake would have produced turbid conditions until settling occurred. In addition, dredge spill was being deposited in the centre of Powis Lake during the monitoring programme as the southern extension was cut towards Floreat Waters. However, it should be noted that turbidity values were low in Powis lake in comparison to the values recorded in Floreat Waters.

The concentration of major ions fluctuates seasonally in wetlands in response to dilution by incoming waters in winter and concentration by evaporation in summer (Davis and Rolls, 1987). This seasonal fluctuation can be seen in all three dredged lakes although it is less marked in Industrial and Powis Lake. Total Dissolved Solids (TDS), conductivity and chloride ion concentrations all exhibited this seasonal pattern of change and did not appear to be related to any of the other parameters measured. These three parameters are closely related as they are all measurements of ion concentration (see Section 5.1). The relatively large drop in TDS in Floreat Waters during winter 1986 is probably related to the high rainfall that occurred that winter (689.6 mm over May, June, July and August, only 549.8 mm were recorded during the same period in 1987).

Fluctuations may be less marked in Industrial and Powis Lakes due to the supplementation of lake volume throughout summer by groundwater inputs. The hydraulic gradient for groundwater flow is much greater on the shores of Industrial and Powis Lake than Floreat Waters (Fig. 8).

5.3 DRAINS INPUTS

Little information is available from the monitoring programme on the input of the drains into the lakes. Sites 1, 3, 5, 7 provide the only physiochemical and nutrient data for the drains. These sites were not in the drains but in Floreat Waters near the outfall of four local authority drains, where mixing with the lake water would have already occurred. Thus, these sites are neither truly representative of the drains nor the lake itself.

Table 9 shows the results obtained for the parameters measured at these sites. Data from these four sites can be compared with data from other sites in the lake. From this the following comments can be made.

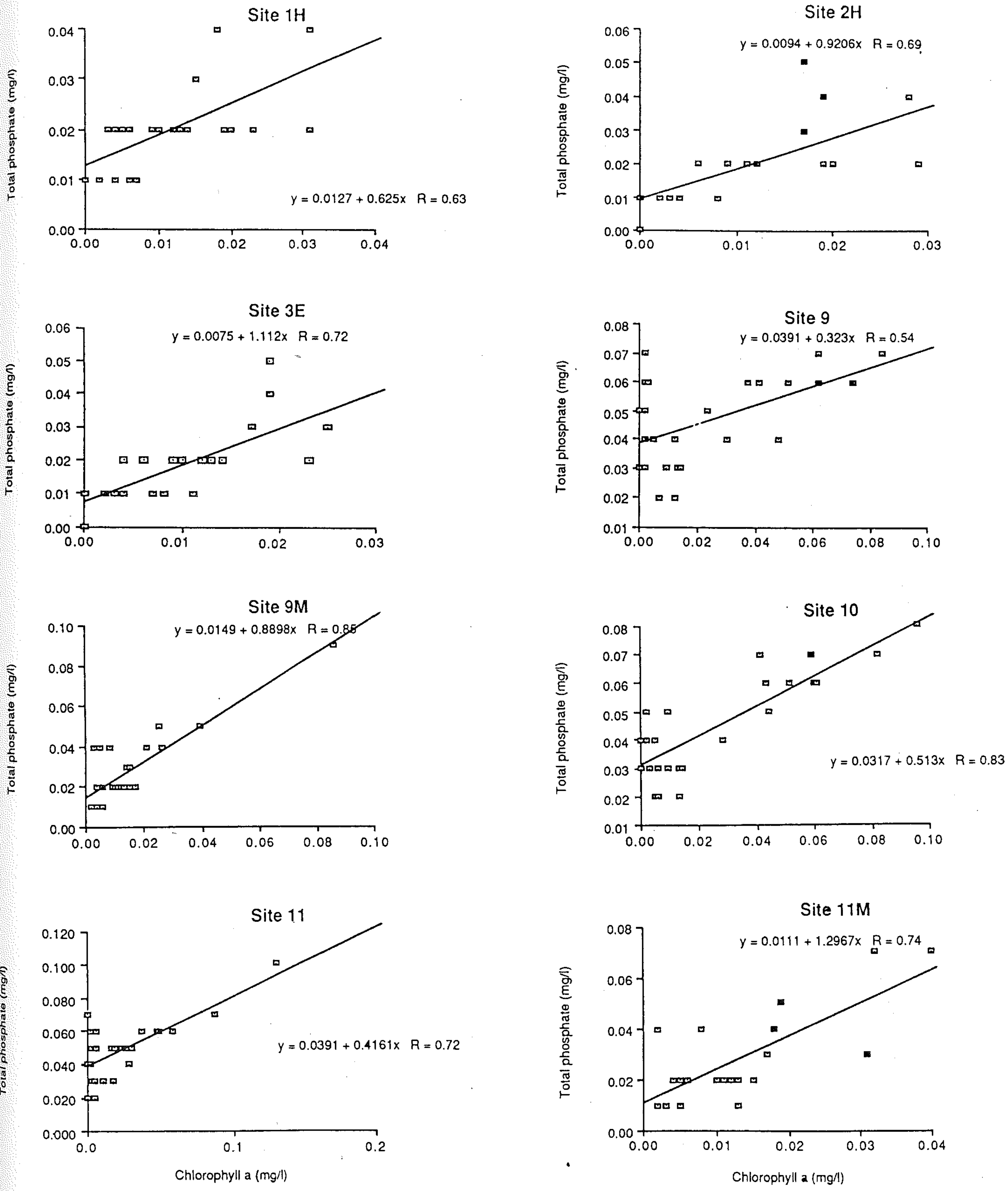


Fig. 48a. The relationship between chlorophyll *a* concentration and total phosphate (sites 1H-11M).

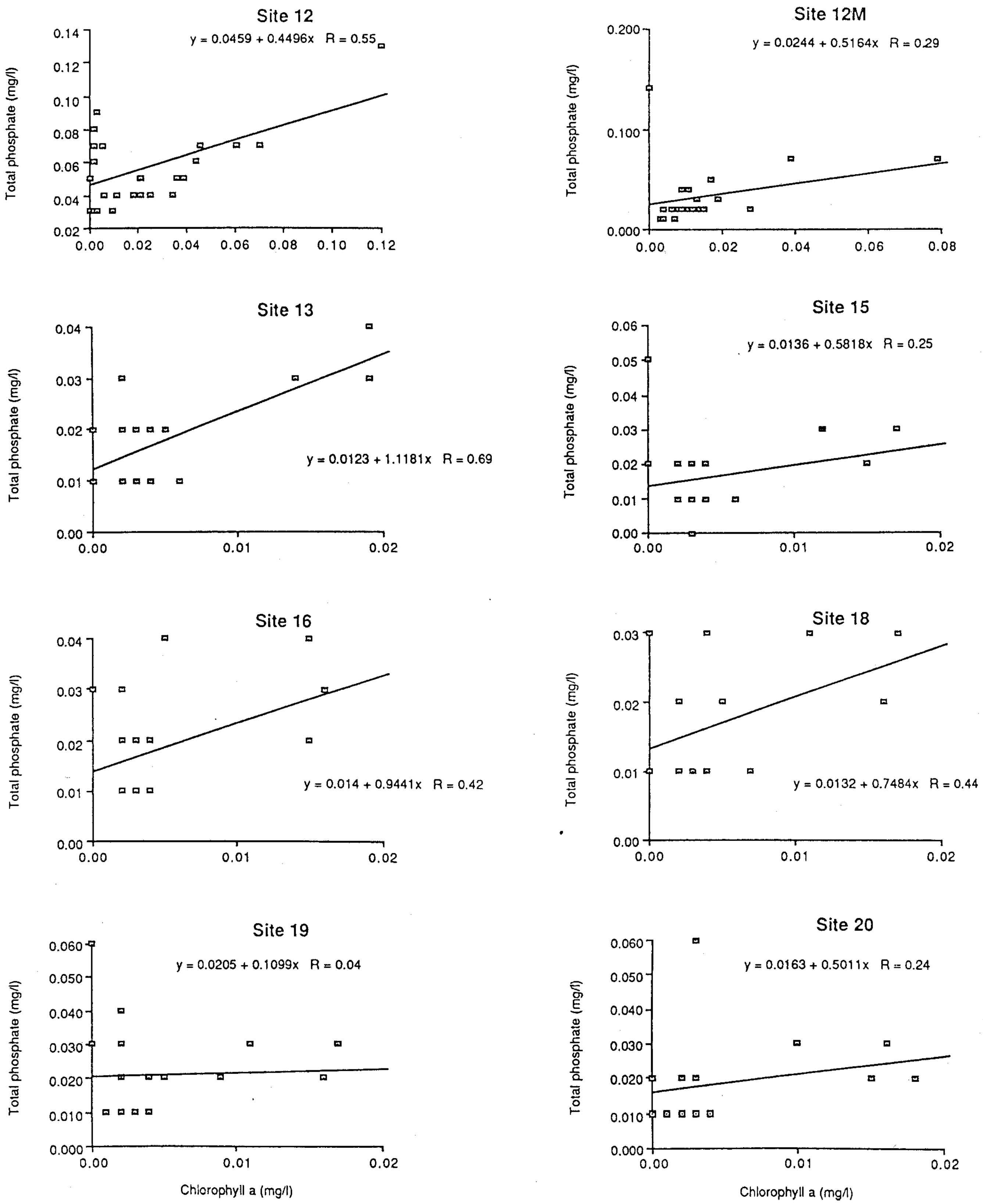


Fig. 48b. The relationship between chlorophyll *a* concentration and total phosphate (sites 12-20).

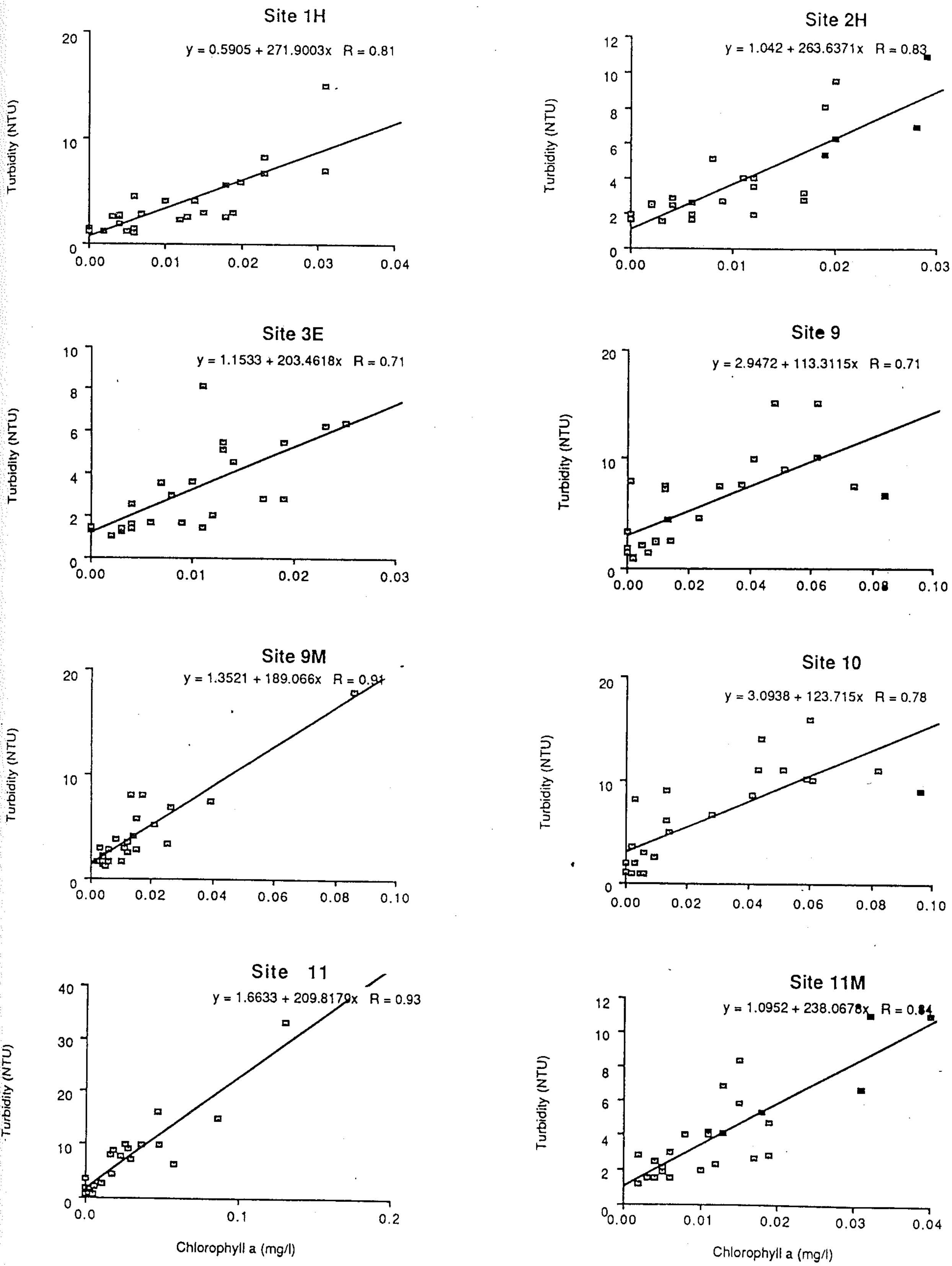


Fig. 49a. The relationship between chlorophyll *a* concentration and turbidity (sites 1H-11M).

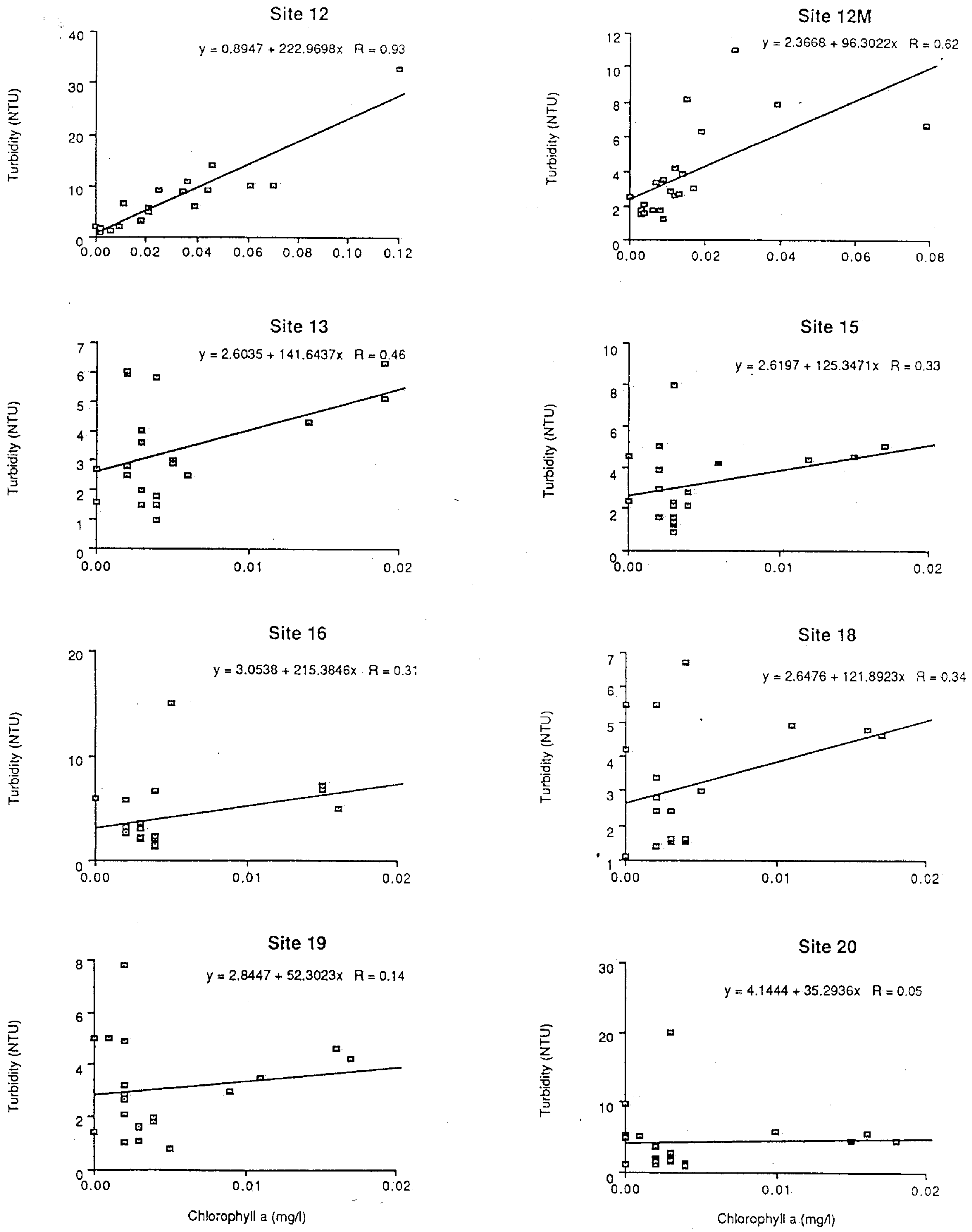


Fig. 49b. The relationship between chlorophyll *a* concentration and turbidity (sites 12-20).

Table 9. Water quality in drainage waters upon entering Floreat Waters

Parameter	Date	Site number			
		1	3	5	7
pH	05.04.82	8.6	8.2	8.0	7.7
	28.05.82	8.0	7.9	7.7	8.1
	27.07.82	8.0	7.2	7.3	6.9
	28.09.82	7.8	7.0	7.9	7.1
	03.02.83	7.4	7.9	8.1	8.1
TDS (mg/l)	05.04.82	1020	1020	1240	1160
	28.05.82	1220	1220	1090	1370
	27.07.82	910	370	590	240
	28.09.82	770	1250	850	550
	03.02.83	1410	1250	1000	930
Turbity (NTU)	05.04.82	4.6	3.3	2.5	4.2
	28.05.82	1.5	27.0	22.0	3.0
	27.07.82	2.8	6.0	3.5	8.5
	28.09.82	2.5	65.0	3.8	25.0
	03.02.83	70.0	8.5	7.5	55.0
TKN (mg/l)	05.04.82	1.6	2.0	2.4	1.9
	28.05.82	2.0	2.0	14.0	1.8
	27.07.82	1.3	0.4	1.0	1.0
	28.09.82	1.3	1.6	1.4	1.6
	03.02.83	5.2	7.0	3.7	26.0
Ammonia (mg/l)	05.04.82	0.34	0.65	0.89	1.00
	28.05.82	0.61	0.64	0.15	0.31
	27.07.82	0.33	0.11	0.37	0.38
	28.09.82	0.16	1.60	0.11	0.56
	03.02.83	2.30	6.70	0.48	0.05
Nitrate (mg/l)	05.04.82	0.89	0.81	0.30	0.13
	28.05.82	0.53	0.41	0.19	0.38
	27.07.82	0.17	0.11	0.13	0.91
	28.09.82	0.30	0.15	0.10	2.50
	03.02.83	0.02	0.25	0.09	0.02
Total phosphorus (mg/l)	05.04.82	0.11	0.04	0.04	0.09
	28.05.82	0.07	0.34	0.22	0.04
	27.07.82	0.05	0.05	0.06	0.11
	28.09.82	0.05	0.04	0.04	0.10
	03.02.83	1.60	0.20	0.13	1.80
Inorganic phosphorus (mg/l)	05.04.82	0.05	0.01	0.01	0.01
	28.05.82	0.02	0.03	0.01	0.01
	27.07.82	0.01	0.01	0.02	0.06
	28.09.82	0.03	0.01	0.02	0.04
	03.02.83	0.00	0.10	0.01	0.00
Chlorophyll *a* (mg/l)	05.04.82	1.300	0.016	0.010	0.005
	28.05.82	0.010	0.032	0.025	0.022

Water in the incoming drains had lower TDS than the lake. Turbidity was generally low but reached exceptionally high peak values in comparison with the lake (e.g. 70 NTU were recorded at site 1 on 3 February 1983). Peak values occurred at different sites at different times, indicating that events occurring at individual drains were responsible rather than an event affecting the whole catchment area.

Total Kjeldahl nitrogen was generally slightly higher at these four sites than the other sites in Floreat Waters but very high peaks were recorded on several occasions. On 3 February 1983 very high values were recorded at all four sites but this was due to contamination of the samples by bottom sediments, as noted in the Government Chemical Laboratory report. Total Kjeldahl nitrogen was particularly high on 28 May 1982 at site 5 (14 mg/l). Ammonia was much higher at these sites than in the lake and nitrate reached higher levels on some occasions.

Total phosphorus was also often higher at these sites. The following peak values illustrate this:

Site 1	1.6 mg/l	3 February 1983
Site 2	0.34 mg/l	28 May 1982
Site 5	0.22 mg/l	28 May 1982
Site 7	1.8 mg/l	3 February 1983

Peak values for total phosphorus in Floreat Waters itself were around 0.09 mg/l.

Chlorophyll *a* levels were generally similar to the levels in the lake, ranging from 0.005 - 0.03 mg/l. A notable exception was 1.3 mg/l recorded at site 1 on 5 April 1982.

A more detailed study of drain inputs is reported by ESRI (1983)

5.4 HEAVY METALS

Heavy metals are normally present in the natural environment in very low concentrations and many heavy metals are required by organisms for their metabolism. However, adverse effects often occur at levels of exposure only slightly above the natural background levels.

The concentrations of heavy metals recorded by the monitoring programme in the water column of Floreat Waters and selected drains are given in Table 10. The recommended criteria for these heavy metals for a number of "beneficial uses" of water resources are given in Table 11.

Cadmium is very toxic and one of the few heavy metals which is not known to be required for metabolism (Hart, 1982). Australian freshwater invertebrates have been found to be very sensitive to cadmium (Hart, 1982). Due to the

Table 10. Heavy metal concentrations in Floreat Waters and selected drains

Heavy Metals (µg/l)	Drain									
	Site1	Site2	Site3	Site4	Site5	Site6	Site7	Site8	Balgay Drain	Drain Y
Cadmium										
5.4.82	<1	1	<1	<1	1	1	1	<1	-	-
15.2.83	<2	-	<2	-	<2	-	<2	-	-	-
3.10.85	-	-	-	-	-	-	-	-	<2	<2
Copper										
5.4.82	<20	40	30	70	80	40	50	60	-	-
15.2.83	30	-	8	-	80	-	14	-	-	-
3.10.85	-	-	-	-	-	-	-	-	<20	<20
Lead										
5.4.82	<10	<10	<10	<10	10	<10	<10	<10	-	-
15.2.83	340	-	300	-	280	-	410	-	-	-
3.10.85	-	-	-	-	-	-	-	-	50	<10
Zinc										
5.4.82	2100	320	140	2600	800	150	750	120	-	-
15.2.83	120	-	120	-	50	-	290	-	-	-
3.10.85	-	-	-	-	-	-	-	-	60	<20

Table 11. Recommended Australian water quality criteria for heavy metals (Hart, 1982)

Heavy metal	Beneficial Use				Typical Concentration in unpolluted water (µg/l)
	Aquatic ecosystem (µg/l)	Domestic (µg/l)	Livestock (µg/l)	Irrigation (µg/l)	
Cadmium	0.2(0.01)*	5.0	10.0	10.0	0.01-0.4
Copper	5(0.05)	1000	500-2000	200	<5.0
Lead	5(0.01)	50	500	5000	0.3-3.0
Zinc	50(0.01)	5000	20,000	2000	1-20

* Figure in parentheses is the amplification factor used to calculate the maximum acceptable safe level. Criteria for aquatic ecosystems have been calculated from 96hr LC50 values for aquatic organisms, multiplied by the amplification factor.

difficulty in detecting low concentrations of this heavy metal, most of the values recorded in Herdsman Lake were reported as less than 1 or 2 µg/l. Since the recommended criteria is 0.2 µg/l for aquatic ecosystems, it is not possible to say whether this level was exceeded. However, on 5 April 1982, sites 5, 6 and 7 in Floreat Waters recorded 1 µg/l which is likely to have had adverse effects on aquatic invertebrates.

Copper is essential to metabolism but is toxic in high concentrations. However, the concentration of the biologically active form of copper is significantly affected by the hardness of the water, pH, alkalinity and complexing capacity. The recommended criteria of 5 µg/l is for soft waters with low complexing capacity (Hart, 1982), higher concentrations may be allowable in hard water. As can be seen from Table 10 the copper concentrations recorded for Floreat Waters in 1982/83 always exceeded 5 µg/l but it is not known whether this copper was in a form toxic to aquatic organisms.

Lead is known to be both acutely and chronically toxic to aquatic organisms at very low concentrations (Hart, 1982). It is a non-essential element and a cumulative metabolic poison. On 15 February 1983 the sites sampled showed very high levels of lead well in excess of the recommended criterion of 5 μg/l. The Government Chemical Laboratory report of this date notes that almost all this lead was associated with a black deposit suspended in the water samples. The sites sampled were the "drain" sites 1, 3, 5 and 7 and a summer storm delivered 11 mm of rain on the day of sampling. It is likely that this lead deposit was being flushed from road surfaces into the catchment. Elevated levels of lead were also found in the Flynn Street, Holland Street and Teakle Road drains by ESRI (1983). They attributed this to the flushing of car exhaust deposits from roads into the drains. On 3 October 1985, 50 μg/l was recorded in the Balgay drain.

Measurements made on 5 April 1982 showed a level of 10 μg/l at site 5, while all other sites were recorded as less than 10 μg/l. Thus, while site 5 exceeded the recommended criterion, it is not possible to know whether this level was exceeded at the other sites.

Zinc levels exceeded the recommended criterion of 50 μg/l at almost every site on each sampling occasion. Zinc is required for metabolism but can be particularly toxic to algae and invertebrates (Hart, 1982). The toxicity of zinc is reduced by increased water hardness, alkalinity and the presence of organic chelators, but it is increased by low dissolved oxygen concentrations (Hart, 1982). The recommended criterion is for soft waters with low complexing capacity. The particularly high levels recorded on 5 April 1982 at sites 1 and 4 of 2100 μg/l and 1600 μg/l respectively, are of concern. These levels would have been acutely toxic to aquatic organisms.

It should be noted that a number of heavy metals have synergistic (more than additive) effects when in combination. In addition, many aquatic organisms bioaccumulate heavy metals either directly from the water or sediments or via food chains (Hart, 1982). Thus, the levels of heavy metals in the tissues of organisms can be orders of magnitude higher than those recorded in the water column. Accumulation also occurs through continued exposure over a number of years.

ESRI (1983) reported values for cadmium, chromium, copper, iron, lead, magnesium, manganese, nickel and zinc for 17 sites. Their study detected a point source of nickel, copper and chromium waste in the catchment area of the Selby Street drain. This source was subsequently removed. High concentrations of zinc were also recorded in the Selby Street drain over several months and on one occasion in the Flynn Street drain after heavy rain.

5.5 PESTICIDES

The margins of Herdsman Lake were treated with organochlorine pesticides from the mid 1950s until 1986 for the control of Argentine ants. Pesticides would also have been used for the control of insect pests in adjacent market gardens and throughout the catchment for control of termites and household pests. These may have arrived at the lake via the extensive urban drainage system.

Spraying for Argentine ant control at the lake has involved the use of dieldrin (1955 to 1969) and heptachlor (1970 to 1986) (Shewchuk 1981). In addition, chlordane was used between 1955 and 1973, and DDT, Mirexbait, diazinon endosulphin and chlorpyrifos have all been tested at the lake at various times (Porter 1982). Heptachlor, chlordane, dieldrin, aldrin and endrin all belong to the cyclodiene group of pesticides.

Dieldrin and aldrin were developed in the late 1940s and have been used extensively against agricultural pests, ants and termites. They are more toxic to insects and mammals than chlordane or heptachlor. Dieldrin accumulates in animal tissue and has been found in human tissue and in mother's milk (McEwen & Stephenson 1979). Heptachlor has been used extensively in agriculture in the US against soil insects and for fire ant control but its use is now restricted mainly to termite control. The use of heptachlor in Canada has been banned since 1968 due to concern over the occurrence of heptachlor residues in milk and the possible deleterious effects on birds (McEwen & Stephenson 1979). The only registered use for heptachlor, chlordane, aldrin and dieldrin in Western Australia in 1990 is as termiticides in the building industry (EPA, 1989).

Edwards (1970) lists the general effects of pesticides on living organisms as follows:

(1) They may be directly toxic to animal and/or plant life in the soil.

(2) They may affect organisms genetically to produce populations resistant to the pesticides.

(3) They may have sub-lethal effects that result in alterations in behaviour or changes in metabolic or reproductive activity.

(4) They may be taken into the bodies of soil flora and/or fauna and passed on to other organisms.

The degree of magnification of pesticides appears to be much greater in aquatic environments. Many aquatic organisms (invertebrates, fish and waterfowl) concentrate organochlorines in their tissues in levels greatly in excess of those in the surrounding environment. Any chemical used in the soil or in the atmosphere has the potential to be transferred to aquatic systems. This may occur via precipitation and surface or subsurface (groundwater) flows.

Organochlorines are generally not found in solution, instead they are usually carried on particulate matter suspended in water. As a result pesticides are often fairly quickly removed from the water column by sedimentation. While this will mean that many aquatic organisms will no longer be exposed to the pesticide, those that inhabit the lake bed may still accumulate pesticides and where these organisms, for example chironomid larvae, are fed upon by other organisms, the potential for biomagnification of pesticides up aquatic food chains remains.

The concentrations of pesticides recorded by the monitoring programme in the surface waters of Floreat Waters in 1982 are given in Table 12. The concentrations of pesticides in the waters of drains entering the lake, in 1985, are given in Table 13. The maximum permissible levels of pesticides for the protection of aquatic life recommended by the US EPA and the proposed criteria for pesticides in Australian inland waters (Nicholson, 1984) are given in Table 14.

Virtually all the concentrations of dieldrin and heptachlor recorded in Floreat Waters in 1982 exceeded the recommended US EPA criteria. The high levels of pesticides recorded in the inflowing drains indicate that the problem is not just restricted to activities in the immediate environs of the lake but that the lake is probably receiving pesticides from further afield in the catchment. The Argentine ant control programme was probably a major source of pesticides entering the lake but other sources are also likely. For example, the presence of aldrin in the Balgay drain in 1985 cannot be attributed to the Argentine ant control programme, which did not use this pesticide. Aldrin is used for the control of soil pests in crops such as potatoes and in termite control. Aldrin is rapidly converted to dieldrin, which may also account for the high dieldrin levels. Both dieldrin and heptachlor are persistent pesticides and the prolonged presence of these pesticides in the lake enhances the potential for their bioaccumulation by aquatic organisms.

The occurrence of high levels of pesticides in the drains entering Herdsman Lake indicates that surface flows play an important role in delivering pesticides to the lake. The extent to which groundwater flow may also contribute to pesticides entering the lake is not known. Recent testing by the Water Authority of Western Australia, of water samples taken from bores on the southwest side (the downstream side) of Herdsman Lake revealed the presence of dieldrin at concentrations of 0.002 and 0.008 μg/L. Heptachlor was not detected.

The results of this limited monitoring programme indicate that pesticides must be considered to be a water quality problem at the lake. The results of recent studies undertaken to determine the environmental effects of the Argentine ant control programme at the lake support this conclusion (see Section 6.3).

5.6 GROUNDWATER INPUTS

In addition to drainage from the catchment area, groundwater contributes to the quality of water in the lakes.

As part of the Urban Water Balance Study (WAWA, 1987), water quality was measured in a number of bores throughout the Perth metropolitan area between 1983 and 1985. Table 15 gives the information available for node 2052 located on the north-east shore of Herdsman Lake and node 2040 located on the south-west shore . Thus, these data show the quality of groundwater entering the lake (node 2052) and that of the groundwater which has passed through the lake (node 2040).

Table 12. Pesticide concentrations recorded in Floreat Waters and selected drains in 1982. All concentrations are expressed as µg/L.

Pesticide and date sampled	Site 1 (drain outfall)	Site 3 (drain outfall)	Site 4	Site 5 (drain outfall)	Site 6	Site 7 (drain outfall)	Site 8	Site 9	Site 10	Site 11	Site 12
Dieldrin											
5.4.82	0.010	-	0.009	-	0.010	-	0.050				
28.5.82	0.011	-	0.012	-	0.015	-	0.012	-	-	-	-
26.7.82	-*	-	-	-	-	-	-	0.011	0.010	0.014	0.023
5.11.82	0.018	0.013	-	0.020	-	0.040	-	-	-	-	-
Heptachlor and its epoxides											
28.5.82	0.008	-	0.017	-	0.005	-	0.005	-	-	-	-
26.7.82	-	-	-	-	-	-	-	0.013	0.015	0.012	<0.001
5.11.82	0.015	0.063	-	0.014	-	0.017	-	-	-	-	-

* No sample taken.

Table 13. Pesticide concentrations recorded in the waters of selected drains at Herdsman Lake in 1985. All concentrations are expressed as µg/L.

Pesticide and date sampled	Holland St Drain	Balgay Drain	Teakle St Drain	WAWA Drain (Osborne Park MD)
Dieldrin (3.10.85)	0.011	0.24	0.045	0.012
Heptachlor and its epoxides (3.10.85)	0.006	<0.001	0.004	0.005
Aldrin (3.10.85)	<0.001	0.08	<0.001	<0.001
Chlordane and its metabolites (3.10.85)	0.006	0.003	0.001	0.005

Table 14. Pesticides in surface waters.

	US EPA µg/L	Nicholson (1984) (proposed Australian criteria) µg/L
Chlordane	≤0.01	≤0.004
DDT	≤0.001	≤0.0005
Dieldrin	≤0.003	≤0.003
Heptachlor	≤0.001	≤0.001
Chlorpyrifos	≤0.01	
Temephos	≤0.01	

Table 15 - Groundwater quality in the vicinity of Herdsman Lake.

	1983		1984		1985		1986	
	Node 2052	Node 2040	Node 2052	Node 2040	Node 2052	Node 2040	Node 2052	Node 2040
pH	5.77	6.89	6.10	6.65	6.08	6.59	-	6.45
Conductivity (mS/m)	55	244	54	303	56	347	-	-
Chloride ion (mg/l)	95	700	100	800	95	820	-	-
Nitrate (mg/l)	3.90	-	1.15	0.04	3.50	0.12	-	-
TKN (mg/l)	-	-	1.00	1.00	0.41	1.96	-	-
Total N (mg/l)	-	-	-	-	3.91	-	-	-
Total P (mg/l)	0.003	-	0.305	0.033	0.008	0.005	-	-
Total Iron (mg/l)	0.45	4.80	4.50	2.50	0.36	3.00	-	-
Ferrous Iron (mg/l)	0.35	2.20	-	-	-	-	-	-
Total Organic Carbon (mg/l)	-	-	11.0	29.0	1.4	38.0	-	-

It can be seen from the total organic carbon and the total Kjeldahl Nitrogen values (for 1985) that the groundwater receives a considerable amount of organic material as it passes through the lake.

Conductivity and chloride ion concentrations are also considerably increased in the groundwater through evaporation and concentration which occurs in the lake basin (WAWA, 1987).

The major contribution of the groundwater to the lake system is nitrate. The incoming groundwater has high levels of nitrate which are substantially depleted in the outflowing groundwater.

The values for total phosphorus also suggest some input to the lake but it is not possible to determine whether this is in the form of organic phosphates or orthophosphate. The latter is the form which would be readily assimilated and contribute to the development of algal blooms.

In comparison to the nitrate inputs from the Osborne Park, Balgay and Flynn Street drains, the groundwater is a much less significant source of nitrate to the lake system. However, nitrate levels in the groundwater are higher than the levels recorded in the smaller local authority drains.

6. OTHER STUDIES AT HERDSMAN LAKE

6.1 COMPARISON OF THE RESULTS OF THE SPC MONITORING PROGRAMME WITH THE ESRI STUDY

Between September 1982 and May 1983, ESRI Australia Pty Ltd undertook a water quality study of Herdsman Lake for Herdsman Industrial Estate Pty Ltd which ran concurrently with the sampling of Floreat Waters by the State Planning Commission. Seventeen sites were sampled on five occasions (September, November 1982 and January, March and May 1983). Site locations are shown in Figure 50.

6.1.1 The lakes

Three sites were sampled by ESRI in Floreat Waters, sites 12, 13 and 14 (Fig. 50). Two of these corresponded to sites sampled by the State Planning Commission (site 12 being the same in both studies and ESRI site 14 corresponding to SPC site 9). Two sites in the shallow mere areas of the original lake basin were sampled, sites 15 and 18 (Fig. 50). And one site, site 3 (Fig. 50), was sampled in the hole being dredged to form the main section of Industrial Lake.

The Floreat Waters sites all showed levels of nutrients and chlorophyll *a* consistent with measurements taken by the State Planning Commission. The only exceptions to be noted were that:

1. slightly higher levels of nitrate were recorded by the ESRI study;

2. the SPC study showed a greater variation in orthophosphate levels; and

3. the ESRI study recorded an exceptionally high value for total phosphorus on one occasion (November 1982) at site 14, this being 0.48 mg/l.

ESRI recorded a bloom of *Microcystis aeruginosa* in Floreat Waters from January to May 1983 (ESRI, 1983). This corresponded to the rise in chlorophyll *a* levels recorded by the SPC. This blue-green algae grows in uneven clumps and is moved around the lake by wind. It can also cause poisoning of wildlife when it decomposes.

Site 3 in Industrial Lake displayed very high levels of ammonia, nitrate and orthophosphate at the start of dredging operations but these levels gradually dropped. The decrease in these nutrients occurred as a bloom of *Microcystis* developed (ESRI, 1983). Ammonia levels were recorded at 1.4 mg/l in September 1983 and subsequently decreased to about 0.15 mg/l for the remainder of the study. Nitrate was recorded at 0.9 mg/l initially and then decreased to about 0.3 mg/l. However, both these nutrients were still present at higher levels during the ESRI study than subsequently recorded by the State Planning Commission

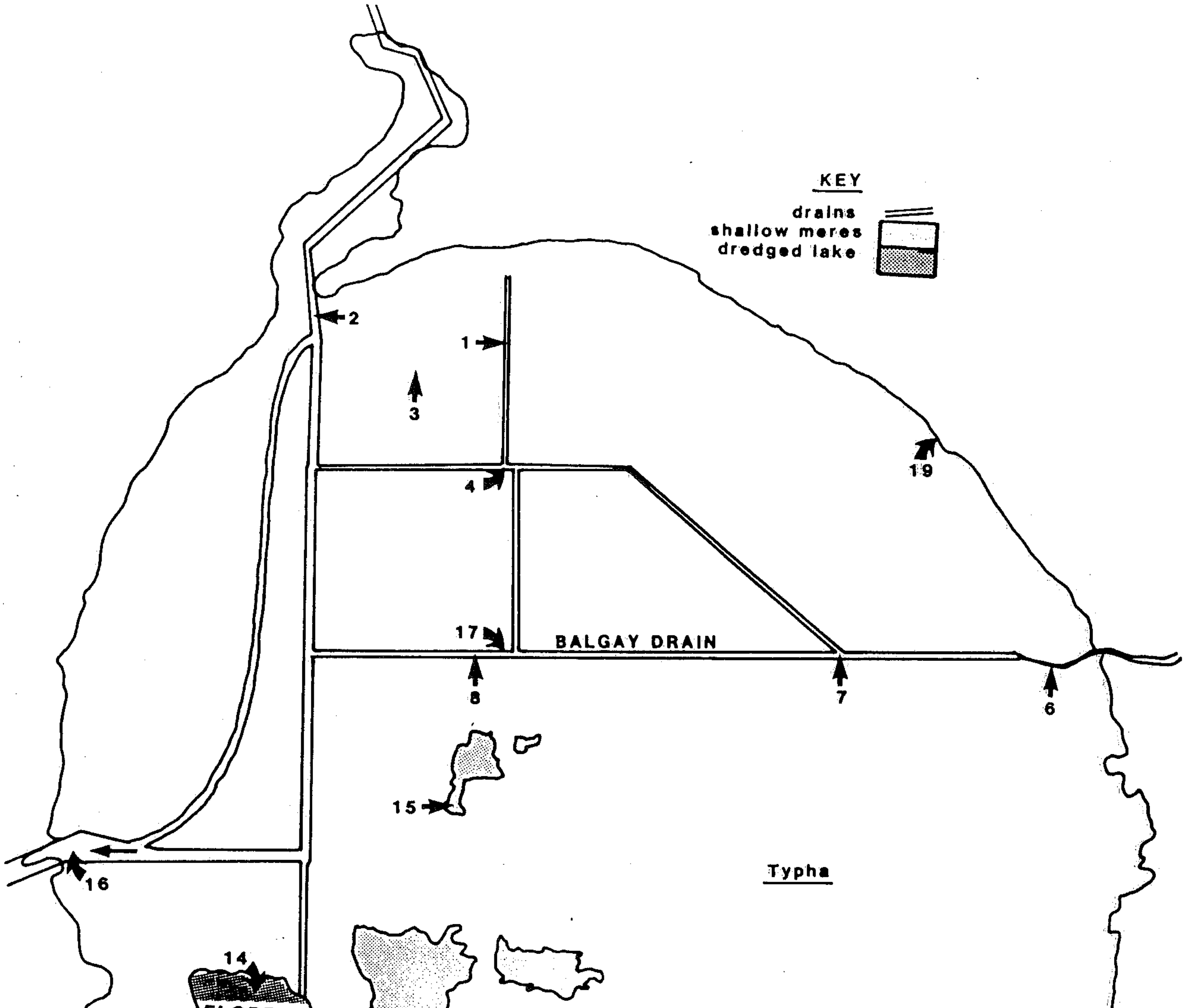


Fig. 50. Location of sites sampled by ESRI (1983).

when Industrial Lake was completed. Orthophosphate was recorded at 0.2 mg/l at the beginning of the ESRI study but decreased to non-detectable levels by May 1983. SPC subsequently recorded very low levels of orthophosphate.

The high levels of ammonia, nitrate and orthophosphate recorded during the construction of Industrial Lake indicate that dredging operations were contributing to high nutrient loading in the water column. However, at the beginning of the ESRI study the Selby Street drain was also emptying into Industrial Lake and the decrease in nutrient levels observed with time may have been due to the redirection of this drain.

The predredging condition can be determined from the shallow mere sites. When there was water at these sites, sampling showed that ammonia, nitrate and orthophosphate levels were all very low. By contrast the levels of total nitrogen and total phosphorus were often high. For example 4.03 mg/l of total nitrogen was recorded at site 15 in September 1982 and 0.38 mg/l of total phosphorus was recorded at site 18 in May 1983. This reflects the growth of macrophytes in and around these areas whereby inorganic nutrients are readily absorbed and converted to organic compounds.

6.1.2 The Drains

Table 16 summarises the nutrient data for the drains sampled. The values for ammonia, nitrate and orthophosphate were determined from graphs in ESRI (1983), and so are not the exact values recorded. Ranges for these parameters in Floreat Waters, Industrial Lake and Powis Lake are shown for comparison.

It is immediately obvious that nutrient concentrations were very much higher in the drains than in the lakes but that they were also subject to greater fluctuation. The Osborne Park and Balgay drains showed exceptionally high levels of nitrate. At the inlet of the Osborne Park drain, 19.50 mg/l of nitrate was recorded in February 1983 and 17.00 mg/l at the inlet of the Balgay drain. These peak values were associated with flushing of the catchment by 18.4 mm of rain which fell on 6 February 1983, this being the first substantial rainfall since 5 October 1982.

At the outlet point of the Herdsman Lake main drainage system (Site 16) and towards the end of the Balgay drain (Site 8) nitrate values were substantially lower, indicating removal of nitrate by the lake system. In general, all nutrient values were lower at these outlet points. Nutrient loss was likely to have occurred through sedimentation and absorption and/or uptake by aquatic plants and algae (ESRI, 1983).

The values recorded for the Flynn Street drain (Site 1-ESRI) can be compared to the values recorded by the State Planning Commission at the outfall of this drain in Floreat Waters (Site 7-SPC). Ammonia and nitrate were present in the drain at similar levels to the lake outfall point. However, orthophosphate, total phosphorus and total nitrogen values reached much higher values in the drain.

Table 16. Range of values recorded between September 1982 and May 1983 in the drains and dredged lakes of Herdsman lake, ESRI (1983) (all values mg/l)

Site	Ammonia	Nitrate	Total N (TKN+nitrate)	Ortho-phosphate	Total P
Flynn St Drain (site 1)	0.06-0.54	0.25-6.90	1.86-7.34	0.04-0.73	0.52-2.31
Holland St Drain* (site 10)	0.06	0.05	0.65	0.05	0.13
Teakle St Drain** (site 19)	0.05-0.52	0.34-0.72	1.30-2.30	0.04-0.08	0.11-0.14
Selby St Drain (site 11)	0.01-0.74	0.12-1.00	0.79-2.96	0.04-0.12	0.09-0.22
Osborne Park Drain (Inlet) (site 2)	0.36-3.77	1.23-19.50	6.33-24.24	0.01-0.34	0.02-0.57
Herdsman Main Drain (Outlet) (site 16)	0.36-2.04	0.69-2.47	2.25-6.78	0.03-0.24	0.03-0.20
Balgay Drain (Inlet) (site 6)	0.01-4.23	0.65-17.00	2.18-18.09	0.01-0.33	0.04-0.53
Mid-Balgay Drain (site 7)	-	-	2.88-47.53	-	0.04-0.97
Balgay Drain (Outlet) (site 8)	0.01-3.55	0.86-1.70	1.65-11.41	0.02-0.10	0.05-0.21
Floreat Waters	0.00-0.59	0.00-0.46	0.49-2.50	-	0.02-0.13
Industrial Lake	0.00-0.18	0.00-0.24	0.04-1.90	-	0.00-0.14
Powis Lake	0.00-0.61	0.00-1.40	0.31-2.50	-	0.00-0.06

N.B. Values for ammonia, nitrate and orthophosphate read from graphs in ESRI (1983).

* Only sampled May 1983.

** Only sampled November 1982 and February 1983.

It should be noted that much higher peak levels of nutrients were recorded from the Osborne Park drain and the Balgay drain than from the smaller Water Authority and local authority drains. This reflects the larger catchment areas of the former two drains (Fig. 5).

ESRI (1983) note that the elevated levels of orthophosphate in the Selby street drain, which were particularly high in November 1982, contributed to the bloom of *Microcystis* which occurred. Chlorophyll levels peaked in January/February 1983. Nitrate levels were also high in this drain. The Selby Street drain was subsequently re-routed to enter the Osborne Park drain.

6.1.3 Stratification

Dissolved oxygen and temperature profiles were also recorded at the deep water sites (12, 13, 14 and 3). Site 14 in Floreat Waters was the deepest (10-11 m) and showed the development of thermal stratification over summer. In September 1982 temperature, dissolved oxygen and pH gradually decreased with depth at this site but by November thermal stratification had developed and the hypolimnion had become anoxic. Through January, February and March 1983 the epilimnion deepened while the hypolimnion remained anoxic. In April 1983 overturn of the water column occurred as the thermal stratification broke down. The water column was well mixed when sampled again in May and June.

From January onwards profiles were recorded both in the early morning and late afternoon on the day of sampling. These profiles show very little difference between morning and afternoon. Thus stratification was a persistent feature of the water column on a daily basis. It is unlikely that this stratification breaks down from month to month, but rather persists throughout summer until autumn.

Depth profiles of salinity were made in April 1983 and showed that there was no difference between surface and bottom waters. A value of 1.6 ppt was recorded. This indicates that stratification of the deep water is temperature induced and is not caused by a salinity gradient in the lake.

Sites 12 and 13 were both only 4 to 5 m deep and did not develop thermal stratification during the study, although values for all parameters decreased with depth. Site 3 also showed no stratification but this was due to artificial circulation of the water by the dredging operations.

Measurements of nutrients at the surface and bottom of Site 14 were made in November 1982 and March 1983. The results are shown in Table 17.

Ammonia levels were higher in the anoxic hypolimnion, especially in March. By contrast, nitrate was low in the bottom waters. This is to be expected since the rate of oxidation of ammonia to nitrate is low under anoxic conditions. Orthophosphate was high in the hypolimnion and accounted for almost all the total phosphorus present. This may be due either to release of phosphate from the sediments or from decomposing material on the lake bed. However, if the

Table 17. Nutrient concentrations (mg/l) in the surface and bottom waters at ESRI site 14

	Ammonia	Nitrate	Orthophosphate	Total N	Total P
18/11/82					
Surface	0.344	0.660	0.030	2.410	0.060
Bottom	0.757	0.002	0.456	1.986	0.483
15/3/83					
Surface	0.258	0.605	0.027	2.598	0.070
Bottom	3.330	0.012	0.387	6.125	0.400

latter were the case, the total phosphorus value should be higher due to the large amounts of organic phosphorus which would also be present. The total nitrogen values were high but were mainly organic nitrogen. The buildup of ammonia at the lake bed in March increased the total nitrogen values at the bottom of the lake, although some of this increase was due to an increase in organic nitrogen. This could be expected as dead algal cells from the bloom of *Microcystis* present in the lake at the time, slowly settled to the bottom of the lake.

6.2 OTHER WATER QUALITY DATA

Water quality data have also been collected by Dr Ian Lantzke of Claremont Teachers' College (ESRI, 1981). Measurements of pH, surface temperature and dissolved oxygen levels, the concentration of major ions and the occurrence of invertebrates and aquatic plants were recorded at several shallow mere sites and one site in Floreat Waters from 1981-1984. The results for 1981 are reported in ESRI (1981). The remaining data are unpublished.

These results are in general agreement with the data set being considered by this report. However, the following points are noted. The dissolved oxygen levels in the shallow waters of the meres were low in comparison to the surface waters of the dredged lakes. This could be expected as biological activity would be high in the shallow waters amongst the reeds. pH was slightly lower at the shallow mere sites.

The levels of orthophosphate recorded at the shallow mere sites were high in comparison to the dredged lakes and to the shallow mere sites monitored by ESRI

(1983). Dr Lantzke recorded levels above 0.15 mg/l (ESRI, 1981), whereas the dredged lakes were usually well below 0.05 mg/l.

6.3 HERDSMAN LAKE PESTICIDE STUDY

A study of the environmental effects of the 1986 Argentine ant treatment programme at Herdsman Lake have been carried out by the Wetland Ecology Group at Murdoch University in conjunction with Dr Geoff Ebell of the Chemistry Centre and Dr Stuart Halse of the Department of Conservation and Land Management (Davis and Garland, 1986; Davis, Halse and Ebell, unpublished data). The study was initiated by a technical committee on the control of Argentine ants at Herdsman Lake chaired by Mr John Blyth of the Department of Conservation and Land Management and was supported by funding from the State Planning Commission and the Department of Agriculture.

In 1986, a 40 ha area on the northeastern edge of the lake was sprayed with two organophosphates, temephos (Abate) and chlorpyrifos (Dursban), and the organochlorine, heptachlor (the 0.5% heptachlor solution contained approximately 9% chlordane) between the period 21 March to 11 April. Temephos and chlorpyrifos are relatively non-persistent compounds of low toxicity. Heptachlor and chlordane are highly toxic and persistent pesticides. The metabolism of heptachlor results in the formation of heptachlor epoxide, a toxic compound which can undergo bioaccumulation in animal tissues.

A sampling programme was carried out to establish the level of various organochlorines and organophosphates in the water, sediments of the lake bed and two members of the aquatic fauna; the mosquito fish, *Gambusia affinis* and the corixid *Micronecta robusta*. Samples were taken prior to spraying, one week after spraying and after heavy rain. Six sampling sites were selected in the areas of the lake adjacent to the land to be sprayed, four sites in Industrial Lake and two in Powis Lake, and two control sites were selected in Floreat Waters. A semi-quantitative sampling method was used to assess changes in abundance of aquatic invertebrates following spraying.

All pesticide analyses were carried out by the Chemistry Centre of Western Australia. Because the results obtained from the initial study indicated that pesticide levels in various components of the lake ecosystem were much higher than expected the study was expanded to address the issue of pesticide levels in the lake in general and the long-term effects of the 1986 spraying programme. Further investigations included the monitoring of long-term variation in pesticide levels in the water, sediments, fish (*Gambusia affinis*) and two species of waterfowl that breed at the lake, the Purple Swamp Hen (*Porhyrio porphyrio*) and the Little Grass Bird (*Megalurus gramineus*). In addition, a once-off comparative study of pesticide levels in six other wetlands in the Perth region is being conducted. The results of the initial study were documented in a report by Davis and Garland (1986) and the results of this study together with the further investigations are currently being prepared for publication in the scientific literature by Drs Davis, Halse and Ebell.

The results of the initial study are summarised in point form below:

1. The pesticide analyses conducted in this study revealed that both the surface waters and the sediments of the bed of Herdsman Lake contained detectable levels of two organochlorine pesticides, DDT and dieldrin, that were not applied during the March/April 1986 spraying programme, suggesting that the compounds detected are residues from previous spraying programmes at the lake (prior to 1970), or within the catchments of the drains that enter the lake.

2. Levels of DDT were very low but levels of dieldrin in the lake waters exceeded the recommended maximum safe level (0.003 µg/L; Nicholson, 1984) at all sites and on all sampling occasions. Levels of dieldrin did not change significantly between the three sampling occasions, supporting the suggestion that this compound was a residue from previous sprayings.

3. DDT and dieldrin were present in the tissues of both the fish (*Gambusia affinis*) and the insects (*Micronecta robusta*) in nearly all samples analysed and may be attributed to previous spraying at the lake. The high levels of dieldrin recorded in some samples suggest that bioaccumulation of this pesticide is occurring in the aquatic fauna of Herdsman Lake.

4. Levels of chlordane and heptachlor in the water samples were low at all sites before spraying but increased significantly, and exceeded the recommended safe levels for aquatic life (0.004 µg/L and 0.001 µg/L, respectively; Nicholson 1984), at the treatment sites in both the post-spray and post-rain samples. In addition, levels of heptachlor were slightly above recommended levels at the two control sites (Floreat Waters) after heavy rain. Whether this was due to circulation of water within the lake or additional spraying (e.g., for termites by persons or agencies unknown) near the control sites is not known.

5. High levels of chlordane in the lake sediments at all sites before and after spraying indicated that chlordane is persisting from previous spraying programmes (prior to 1984). Levels of heptachlor in the sediments were generally low at all sites except the samples taken from the treatment sites after heavy rain. The presence of chlordane residues, but not heptachlor residues, prior to spraying, may be explained by the findings of previous studies, which suggest that chlordane has a persistence of five years, whilst that of heptachlor is two years (Guenzi, 1974).

6. The March/April spraying programme was regarded as the cause of the presence of chlordane and heptachlor in the post spray fish samples. these compounds were below the limits of detection in pre-spray samples, but significant increases were recorded in post-spray samples

taken from treatment sites. The high levels recorded in the fish suggest bioaccumulation and the possible development of a physiological resistance to these organochlorines. High levels of organochlorines in fish may also pose a problem to the waterfowl which feed upon them.

7. A statistically significant increase in levels of chlorpyrifos occurred in samples of water and sediments taken from the treatment sites after spraying. Levels did not exceed the recommended permissible level for the organophosphates of 10 µg/L (McEwen and Stephenson, 1979) but they may have exceeded the US EPA criterion for chlorpyrifos of 0.01 µg/L.

8. Chlorpyrifos was not detected in the tissues of the fish (*Gambusia affinis*) which supports the view that the organophosphate chlorpyrifos does not undergo bioaccumulation in the food chain.

9. Difficulties in collecting sufficient insect material for analysis after spraying meant that levels of pesticides in insect tissue could not be adequately measured. However, statistical analysis indicated that a significant reduction occurred in corixid numbers at treatment sites after spraying, whilst the abundance of corixids at the control sites did not change. Levels of chlordane, heptachlor and chlorpyrifos accounted for a large percentage of the variation in corixid abundance. Heptachlor and chlordane accounted for most of the variation. Chlorpyrifos alone did not adequately account for the decrease in abundance. However, chlorpyrifos has been shown to cause little or no mortality in corixids at concentrations sufficient to control mosquito larvae.

10. Increases in the levels of chlordane, heptachlor and chlorpyrifos in the water samples collected after heavy rain suggest that surface runoff plays an important part in the transport of pesticides into the lake. High levels of chlordane and heptachlor in the post-spray and post-rain samples of water and fish collected at one site may be explained by the fact that this site was located at the outflow of a major drain.

The results of further sampling carried out at the lake on five occasions between October 1986 and July 1988 revealed that although the levels of heptachlor appeared to have steadily fallen since the April 1986 Argentine ant treatment, levels in excess of 0.01 µg/L were still recorded at sites in both Industrial Lake and Powis Lake in July 1988. The highest levels of chlordane (in excess of 0.1 µg/L) and dieldrin (in excess of 0.02 µg/L) were recorded in the waters of Industrial Lake and Powis Lake in March 1987. The highest levels of chlordane, dieldrin and heptachlor detected in the tissues of the mosquitofish (*Gambusia affinis*) were recorded in October 1987.

A study of pesticide levels in the Swamphens and Little Grassbirds carried out by Dr Stuart Halse of the Department of Conservation and Land Management between October 1986 and July 1988 revealed that heptachlor was the main pesticide recorded in Swamphens (1.2 mg/kg in liver, in October 1987), but dieldrin, chlordane and DDT were also detected (the latter at very low levels). High levels of heptachlor, chlordane and dieldrin were recorded in the Little Grassbirds. The heptachlor levels in the birds were high enough to be cause for concern. The levels of heptachlor and dieldrin in the Swamphens were much higher than any previously recorded in this species in Australia. The Little Grassbirds appeared to accumulate substantially higher residue levels than Swamphens. Reproductive impairment and other sublethal effects may occur in these species at Herdsman Lake as a result of pesticide accumulation.

In summary, the pesticide sampling programme carried out at Herdsman Lake between 1986 and 1988 revealed the presence of concentrations of chlordane, dieldrin and heptachlor in surface waters at levels above the maximum permissible levels for the protection of aquatic life as recommended by the US EPA and Nicholson (1984) (Table 14). Although the level of heptachlor appears to have fallen since the cessation of the Argentine ant treatment programme at the lake the high levels of chlordane and dieldrin recorded in 1987 indicated that these pesticides may still be entering the lake from other pesticide treatments occurring within the catchment. High levels of organochlorines in the mosquitofish, *Gambusia affinis* , and Swamphens and Little Grassbirds indicate that bioaccumulation of pesticides is occurring within aquatic food chains at the lake. The presence of high levels of pesticides within lake sediments indicates that bioaccumulation may continue to occur with the possible transfer of pesticides into the food chain when sediment dwelling organisms such as chironomids (midge larvae) and oligochaetes (worms) are consumed by other invertebrates, fish and waterfowl. The first "flush" of the catchment at the onset of the winter rains, or after a heavy summer storm, appears to be a time when large amounts of pesticides may be transported into the lake. The extensive drainage system which enters the lake may facilitate this process.

7. COMPARISON OF HERDSMAN LAKE TO OTHER LOCAL WETLANDS

The Wetland Ecology group at Murdoch undertook a study of water quality and invertebrate community structure at Herdsman Lake as part of a chemical and biological monitoring programme for ten lakes on the Swan Coastal Plain in 1986-87 (Rolls *et al.*, 1990). This allows a comparison of Herdsman Lake to be made to nine other local wetlands.

In terms of water quality the following statements can be made.

Orthophosphate levels in all sections of Herdsman Lake were low in comparison to Bibra Lake, Lake Monger and North Lake which reached values of around 0.9 mg/l, 0.7 mg/l and 0.25 mg/l respectively in recent years. Floreat Waters showed levels similar to Thompsons Lake with Industrial and Powis Lakes showing much lower levels.

Total phosphorus ranged between 0.01 and 0.09 mg/l in Herdsman's dredged lakes which was comparable to Joondalup and Thomsons Lakes but higher than Jandabup, Goolellal and Loch McNess. North Lake, Forrestdale Lake and, in particular, Lake Monger and Bibra Lake showed much higher levels of total phosphorus than those recorded at Floreat Waters. Levels often reached 0.75 mg/l in Lake Monger.

Concentrations of ammonia were normally low in all the lakes but Lake Monger, North Lake, Bibra Lake and Jandabup Lake showed isolated peak values between 2-3 mg/l. In comparison, Floreat Waters and Powis Lake showed maximum peaks between 0.3-0.5 mg/l.

The concentrations of nitrate in Powis Lake between September 1985 and January 1986 far exceeded the levels recorded in 1985, 1986 or 1987 in any of the other lakes. Jandabup lake frequently showed peak values between 0.5-0.6 mg/l and on one occasion Bibra Lake and North Lake reached 0.7 mg/l. Nitrate levels in all the lakes were usually very low as in Floreat Waters and Industrial Lake. Only Jandabup Lake and Lake Monger showed regular peaks in nitrate concentration but this was not a regular seasonal event as occurred in Powis Lake.

Similar to the results obtained for Herdsman Lake, organic nitrogen was the major form of total nitrogen in the ten lakes studied. Total nitrogen values were higher in Lake Monger, North Lake, Bibra Lake, Lake Joondalup and on occasions in Forrestdale Lake and Thompsons Lake than in Floreat Waters, Industrial Lake or Powis Lake.

Peak chlorophyll *a* levels in Floreat Waters were low in comparison to Lake Monger which had peak values around 1.4 mg/l in 1986 and 1987. Levels in Floreat Waters were also slightly lower than peak values recorded in North Lake of about 0.2 mg/l. Floreat Waters most closely approximates the condition of

Bibra Lake with respect to chlorophyll *a* , while Industrial Lake and Powis Lake showed very low levels, similar to the less nutrient enriched lakes.

The only other parameters available for comparison are pH and conductivity. pH in Herdsman Lake was similar to that in Lake Goolellal and both these lakes showed only minor fluctuations in pH in comparison to the other lakes. Lake Monger, North Lake, Bibra Lake, Lake Joondalup and Thompsons Lake were usually more alkaline than Herdsman Lake, while Jandabup Lake was always more acidic.

Lake Monger, North Lake, Bibra Lake, Loch McNess, Goolellal Lake and Herdsman Lake all showed similar, low levels of conductivity in comparison to the more seasonal wetlands (Jandabup, Thomsons and Forrestdale lakes), which dried out substantially over summer.

As part of the 10-wetland study the macroinvertebrate fauna at two sites, one in Floreat Waters and one in Industrial Lake, were sampled at two monthly intervals over the 12 month period June 1986 to May 1987. A total of 49 species were recorded from the two sites. This was similar to the species richness recorded at Lake Joondalup (48), Lake Goollelal (46) and Bibra Lake (43) over the same period using the same sampling techniques. Five of the lakes studied contained a richer fauna: Jandabup (89), Thomsons (86), Forrestdale (69), Loch McNess (62) and North Lake (63) whilst Lake Monger was much poorer (26). In terms of species richness of the macroinvertebrate fauna Herdsman Lake appeared to be intermediate between the richest and the poorest lakes in the 10 studied.

The number of species of predatory invertebrates recorded at a wetland can be used as an indication of the state of the aquatic food chain (Rolls *et al.*, 1990). The numbers of species of two of the largest groups of predatory invertebrates, the Odonata (dragonflies and damselflies) and the Coleoptera (aquatic beetles), recorded at the ten urban wetlands during the 12-month study are given in Figure 51. Herdsman Lake was one of three lakes within this study at which low numbers of predatory invertebrates were present. Only three species of Odonata and two Coleoptera were recorded, similar to the number recorded from Lake Goollelal. Only Lake Monger had fewer species, with one species of Coleoptera and no Odonata recorded as present. The numbers recorded at Herdsman Lake were much lower than those recorded at the three nature reserves: Thomsons Lake (26), Forrestdale Lake (18) and Jandabup Lake (18). They were also lower than those recorded from lakes considered to be excessively nutrient enriched: North Lake (10) and Bibra Lake (7). The comparatively low number of species of predatory invertebrates recorded at the lake is probably a result of the effects of high levels of pesticides. High levels of organochlorines have also been recorded at Lake Goollelal. Lake Monger has water quality problems of excessive nutrient enrichment and high levels of pesticides and heavy metals.

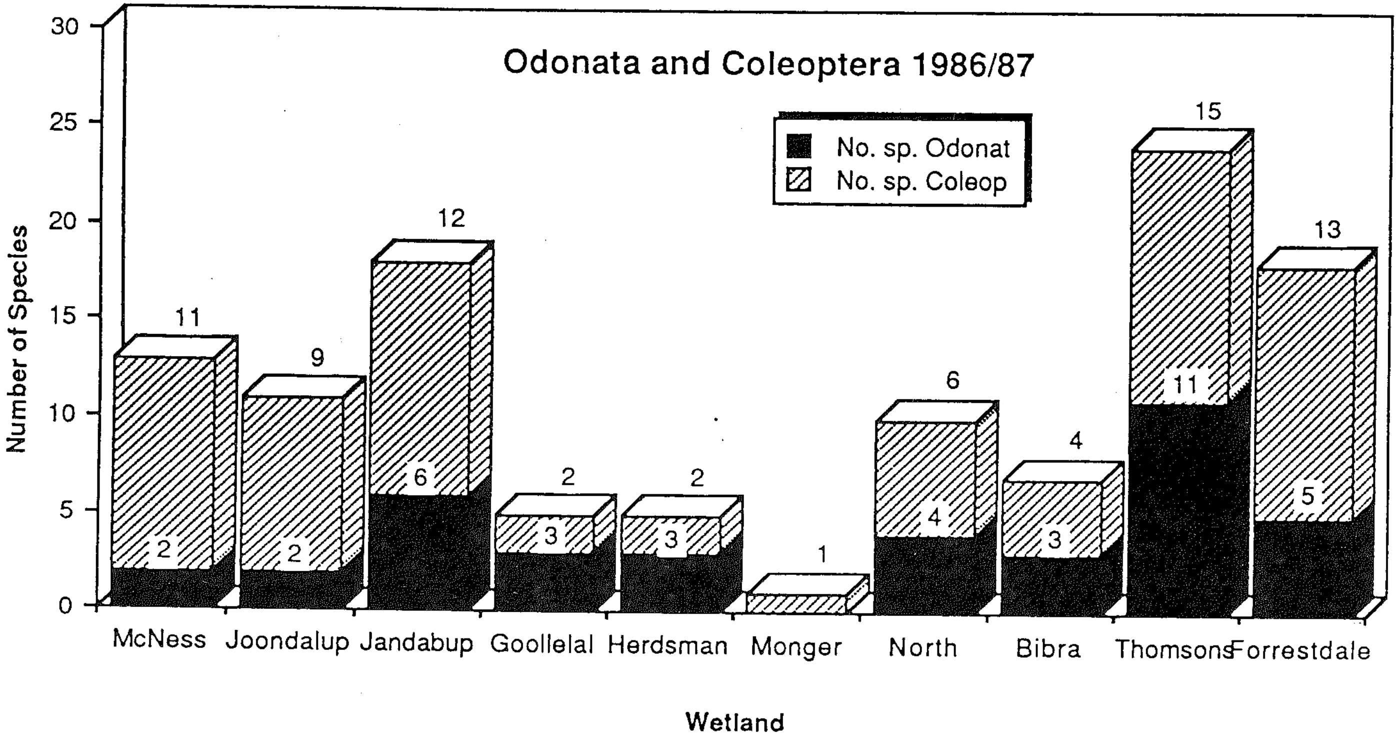


Fig. 51. Number of species of Odonata and Coleoptera recorded in urban wetlands over a 12 month period

8. RECOMMENDED WATER QUALITY MONITORING PROGRAMME

Water quality monitoring is of little use unless a purpose for the monitoring has been established. For example, to allow establishment of a baseline for future comparison or determination of whether water quality objectives are being met.

Future management of Herdsman Lake requires that water quality objectives be established in conjunction with continued water quality monitoring. The form of these objectives will depend upon the primary management objectives that are established for Herdsman lake by the Department of Conservation and Land Management. Appendix 1 discusses water quality objectives that may be appropriate for protection of the integrity of the aquatic ecosystem at Herdsman Lake if this is determined to be a primary management objective. In addition, management considerations relevant to water quality management at Herdsman Lake are discussed in Appendix 2.

The following water quality monitoring programme is recommended.

1. A nutrient budget and water balance must be obtained as a basis for effective lake management. This will allow more meaningful interpretation of nutrient monitoring data in the future and the determination of appropriate actions to control nutrient enrichment. This requires monitoring of nutrient concentrations in inflowing and outflowing waters and within the lake. Total phosphorus is the single most important nutrient to be determined. Records of water flow into and out of the lake and changes in water level will be required to determine annual nutrient load. Depth gauges are needed to determine lake water levels. Continuous flow gauging of major drains, as close as possible to where they enter and leave the lake, are needed. Groundwater level and quality must be measured in bores to determine the groundwater contribution to the lake.

2. The results of this study indicate that the number of sites sampled in each dredged lake can be reduced to determine water quality in these lakes because of the low within-lake variation. At least two of the existing shallow and two of the existing deep sites at each lake should be sampled for continuity. In addition several sites need to be added to enable new sections of the lakes to be sampled. The major drains, and preferably all drains, and at least one of the shallow meres in the central region of the lake should be sampled. Ideally automatic sampling devices activated by increased water levels should be installed on drains to enable the effects of storm events to be determined. A single large storm event may produce a greater inflow of nutrients and pollutants than several months of normal flow.

3. The following parameters should be monitored on a monthly basis at each site: pH, conductivity, turbidity, total nitrogen, total phosphorus and chlorophyll *a*. Orthophosphate, ammonia and nitrate/nitrite should also be monitored if funding permits. Both surface and bottom samples should be

taken at deep sites and mid-depth or integrated samples at shallow sites. Secchi depth, temperature and dissolved oxygen profiles should be recorded at the deep sites each month. Time of day, wind speed and direction and cloud cover should be recorded when profiles are taken.

4. A detailed study of thermal stratification and associated nutrient release is recommended in at least one lake for the first year to determine the role of nutrient release from the sediments in the total nutrient loading of the lake. The critical period for study is during spring and summer when the lake begins to stratify, through to autumn when overturn occurs. Weekly measurements of temperature, dissolved oxygen and nutrients are needed. The rate of dissolved oxygen depletion will give an indication of the severity of lake trophic condition. The more rapid the depletion the more eutrophic the lake.

5. Water and sediment samples should be collected at each site for pesticide and heavy metal analyses on the following occasions:

    1) at the end of summer when water depth is at a minimum and concentration effects will be greatest;

    2) after the first winter rains to enable assessment of the "first flush"; and

    3) in spring when water depth is at a maximum and dilution effects are greatest.

6. Annual reporting and review of the monitoring programme is needed to determine whether water quality objectives are being met or moved towards. Intermediate results must be considered, and acted upon by the managing authority if problems are identified.

9. CONCLUSION

The bulk of the water quality data available for Herdsman Lake consists of analyses of surface water samples taken from the three deepened water bodies created by dredging; Floreat Waters, Industrial Lake and Powis Lake.

Analysis of this water quality data reveals that nutrient enrichment is occurring, particularly in Floreat Waters. However, overall the dredged lakes appear to be intermediate in enrichment between those that are often hypereutrophic (Jackadder Lake, Lake Monger, North Lake and Bibra Lake) and the less enriched lakes (e.g., Lake Jandabup and Loch McNess).

The condition of Floreat Waters in relation to the other two lakes is partly a result of its age (it was dredged almost 10 years ago) due to the natural progression of any lake towards a more eutrophic state with time. However, it is likely that it also receives a large input of nutrients from its catchment. Floreat Waters has a large residential area within its catchment and is likely to have a large input of nutrients from local and regional drainage systems. Much of the fringing vegetation has been removed and large areas of the foreshore are planted with lawns that are reticulated and regularly fertilised.

Based on the data available on nutrient concentrations in the drains that enter Herdsman Lake, it seems that they are likely to be a major source of nutrient input to the lake system. This requires further investigation and it is possible that diversion or treatment of these drainage waters and catchment management may be necessary if further nutrient enrichment is to be avoided. Further nutrient enrichment at Herdsman Lake, particularly in Floreat Waters, may result in the development of water quality problems such as severe algal blooms, nuisance midge swarms or wildlife mortalities.

At sites deeper than 5 metres thermal stratification appears to be developing in spring and persisting throughout summer with overturn of the water column in autumn. A limited amount of data indicates that nutrient enrichment of the oxygen depleted bottom waters is occurring during this period of stratification and that overturn of the water column leads to nutrient enrichment of surface waters. There is an indication that this has lead to the development of algal blooms in the past. Further sampling is needed to establish the extent and persistence of thermal stratification in Herdsman Lake and to determine the role this plays in the release of nutrients from the sediment.

Recent studies have indicated that the lake has excessive levels of the organochlorine pesticides, chlordane, dieldrin and heptachlor with the highest levels present in Industrial Lake and Powis Lake. There are indications that aquatic food chains have been affected by these pesticides. Probable sources include the Argentine ant control programme (conducted up until 1986) and commercial and domestic pesticide applications within the catchment. Given the residual nature of organochlorine pesticides it is unlikely that pesticide levels in the lake can be reduced in the short term. Characterisation and management of pesticide inputs to the lake should be implemented as soon as possible to ensure pesticide levels do not increase further and that they are eventually reduced.

A limited amount of data also indicates that heavy metal contamination may be occurring at Herdsman Lake. This is likely to be a result of contaminated runoff from road surfaces and industrial discharge into drains flowing into the lake. Further sampling is required to determine whether heavy metal contamination is occurring.

The future of Herdsman lake will depend to a large extent on how activities in the catchment area, the quality of inflowing water and development activities at the lake are managed. Central to this is the vesting of one organisation with responsibility for management of the lake. Continued monitoring and further research of water quality at the lake is required to determine effective strategies for management.

APPENDIX 1 - PROPOSED WATER QUALITY OBJECTIVES FOR PROTECTION OF THE INTEGRITY OF THE AQUATIC ECOSYSTEM AT HERDSMAN LAKE

Protecting any natural ecosystem or natural resource involves management and the setting of objectives towards which management practices are directed. This requires that specific objectives be set with regard to water quality for Herdsman Lake. To do this, primary management objectives must be established to determine the level of water quality appropriate for the desired use of the waterbody. In other countries scientific criteria have been established that define concentrations of various constituents that "when not exceeded will protect an organism, an aquatic community, or prescribed water use or quality with an adequate degree of safety" (US EPA, 1968). The US EPA have developed criteria for the following specific water uses:

- protection of the aquatic environment
- production of fish suitable for human consumption
- drinking water
- water for industrial uses
- water for agricultural uses
- water for recreational uses.

The scientific information needed to establish water quality criteria for various purposes is gathered through numerous experiments in the field and laboratory on a number of ecosystems. In Australia comparatively little research relating to the establishment of water quality criteria has been undertaken. Often information derived for Northern Hemisphere waterbodies, in particular, criteria recommended by the US EPA, has been applied to Australian waterbodies.

This situation was remedied somewhat by the publication of Hart (1974) which discussed Australian water quality criteria, Hart (1982) which proposed Australian water quality criteria for heavy metals and Nicholson (1984) which proposed Australian water quality criteria for organic compounds. All three publications, however, still rely largely on data collected elsewhere in the world.

The Victorian Environmental Protection Authority has proposed water quality criteria in a four-tiered system of levels of protection (EPAV, 1983). Level I is the maximum level of protection to be used for ecosystems in a natural or pristine state. Waste water discharges are not permitted to these ecosystems. Criteria for level I are determined by the natural background level of water quality. Level IV is the minimum level of protection where water quality criteria are set at threshold levels for harmful effects allowing no safety margin. Levels II and III are intermediate to these extremes.

Nicholson (1984) noted that "if the entry of chemicals into the aquatic environment cannot be prevented absolutely then information on the effects of levels of particular chemicals on the users of the water, the flora and fauna of the aquatic environment, or the consumers of aquatic life from that environment, is essential". It is also essential to know the levels below which it may be considered safe for a particular chemical to be present.

Given that much of this required information is not available for Australian lakes it will be difficult to determine specific water quality objectives for Herdsman Lake once primary management objectives are established. The following discussion outlines water quality objectives that may be appropriate if protection of the integrity of the aquatic ecosystem is seen as a primary objective for Herdsman lake. This discussion is based on the information and considerations listed below:

- US EPA guidelines (US EPA, 1968)
- a compilation of Australian water quality criteria by Hart (1974)
- water quality criteria recommended by the Victorian EPA (EPAV, 1983)
- proposed Australian water quality criteria for organic compounds (Nicholson 1984)
- proposed Australian water quality criteria for heavy metals (Hart 1982)
- the pre-existing water quality of the lake
- consideration of conditions known to cause water quality problems in other wetlands in the Perth region as determined from studies by Davis and Rolls (1987), Davis, Harrington and Pinder (1988), and Rolls *et al.* (1990)

PROPOSED OBJECTIVES

(a) pH
6.5-8.5 (EPAV, 1983)

(b) Salinity
(i) <1.5 ppt (equivalent to a TDS of 1500 mg/l or a conductivity of 250 mS/m) in deepened waterbodies based on recorded values from 1982-1987.

(ii) no restriction on levels in central shallow mere areas when drying out is proceeding during summer.

(c) Dissolved oxygen
(i) >6 mg/l for fully mixed conditions (EPAV, 1983)
(ii) no limits set where stratification occurs.

(d) Turbidity
<25 Nephelometric Turbidity Units (NTU) (Hart, 1974).

(f) Nutrients
Total Phosphorus should not exceed 0.10 mg/L.
Total Nitrogen should not exceed 2.00 mg/L
Except in the hypolimnion during stratification.
Levels exceeding these values have resulted in water quality problems in other wetlands on the Swan Coastal Plain.

(f) Chlorophyll *a*
Chlorophyll *a* should not exceed 0.10 mg/L (maximum levels).
Levels of chlorophyll *a* exceeding this value appear to have promoted excessive midge swarms around other wetlands on the Swan Coastal Plain.

(g) Pesticides in surface waters

Chlordane	≤0.004 µg/L (Nicholson, 1984)
DDT	≤0.0005 µg/L "
Dieldrin	≤0.003 µg/L "
Heptachlor	≤0.001 µg/L "
Chlorpyrifos	≤0.01 µg/L (US EPA, 1968)
Temephos	≤0.01 µg/L "

(h) Heavy metals (Hart, 1982)

Aluminium	<50 µg/L
Cadmium	<0.2 µg/L
Chromium	<10 µg/L
Copper	<5 µg/L
Lead	<5 µg/L
Nickel	<25 µg/L
Selenium	<10 µg/L
Zinc	<50 µg/L

(i) Oil and petrochemicals
Spills and road runoff leaving surface films are unacceptable.

(j) Other
Floating debris (other than that which occurs naturally, for example, windblown vegetation, leaves, sedges, branches, etc.) is unacceptable.

The nutrient objectives are set on the basis of levels known to cause water quality problems such as algal blooms, bird deaths and nuisance midge swarms, in other wetlands in the Perth region. The proposed nutrient objectives do not apply to waters of the oxygen depleted hypolimnion during thermal stratification. During overturn dilution of the nutrient rich bottom waters of the lake may lead to exceedance of the objectives in surface waters. Further study of thermal stratification at Herdsman Lake would allow establishment of nutrient objectives for the hypolimnion to achieve the overall objectives for nutrient concentration.

It should be noted that a criterion of 0.025 mg/L total phosphorus is often quoted for lakes and reservoirs (EPAV, 1983) which is derived from studies of Northern Hemisphere water bodies. Such a criterion appears inappropriate to the naturally productive shallow lake systems which occur on the Swan Coastal Plain and could not be achieved as a management objective.

Pesticide levels at Herdsman Lake exceed proposed Australian criteria for chlordane, dieldrin and heptachlor in surface waters. The pesticides are present both within the sediments of the lake and the aquatic food chains of the lake. Because of the residual nature of organochlorine pesticides it is probably impossible to remove all pesticides from the lake in the short term. Given this consideration, the objectives listed above are unlikely to be achieved for some time.

Undoubtedly food chains at the lake have been modified by the presence of pesticides and a long term objective for the conservation of aquatic fauna at the lake must be to reduce pesticide levels to safe levels. Monitoring should be conducted and management should be undertaken to ensure that levels do not increase and active management of the lake and its catchment must be implemented to reduce existing pesticide levels. Current studies indicate that levels of chlordane and heptachlor in lake waters exceed recommended levels particularly after summer storms or the first winter rains of the year.

Concentrations of heavy metals recorded at the lake, or in drains, between 1982 and 1985, often exceeded proposed Australian criteria. Further sampling is required to determine if this situation still exists and, if so, sources need to be determined and removed.

APPENDIX 2 - MANAGEMENT CONSIDERATIONS

The water quality and overall environmental quality of a lake or wetland is determined by a complex set of physical, chemical and biological factors that vary with the historical state and current conditions of the waterbody. Important factors include hydrology, climate, watershed geology, soil absorption capacity, hydraulic residence time, wetland morphometry (area and depth), external and internal nutrient loading rates, the presence or absence of thermal stratification and the types of plant and animal communities.

Because of their shallow nature, multiple sources of nutrients, soil characteristics and the region's Mediterranean climate, many wetlands in the Perth region could be expected to be naturally productive (eutrophic) systems and management efforts to convert such systems to a less productive (oligotrophic) state are not advisable nor practical. However, a recent US EPA (1988) report on lake restoration, notes that where a wetland or lake has become excessively enriched or has developed other water quality problems as a result of catchment activities then these effects can be reversed and the condition of the waterbody restored by an appropriate combination of management efforts in the catchment and in the wetland itself. Ideally appropriate catchment management is undertaken to protect the water quality of the wetland before problems develop. In the case of Herdsman Lake the opportunity exists to prevent further nutrient enrichment that may result in the type of water quality problems that exist at lakes such as Lake Monger and Jackadder Lake.

Lake restoration work in the United States has shown that where problems have developed there is no universal or single solution for lake rehabilitation or management problems (EPA, 1988). The potential effectiveness of any method depends on the ecological soundness of its application. Often restoration methods, for example, destratification by aeration, weed harvesting, alum treatments, etc., are treating the symptoms rather than the cause.

Wetlands and their catchments are intrinsically linked both by surface and groundwater flows. As a consequence wetland management and rehabilitation must consider both catchment processes and in-lake dynamics. This requires a lot of detailed information which is not available for Herdsman lake. We are very much at the beginning of identifying problems at the lake, determining solutions and making appropriate management recommendations. The following discussion is presented as a preliminary guide for the complicated task of managing water quality at Herdsman Lake. The consequence of taking no action is likely to result in severe water quality problems at the lake in the future, particularly excessive nutrient enrichment in Floreat Waters. Summarised below are:

1) the water quality problems identified at Herdsman Lake so far;

2) the probable causes of these problems; and

3) steps that need to be taken towards solving these problems.

WATER QUALITY PROBLEMS IDENTIFIED AT HERDSMAN LAKE AND POSSIBLE CONSEQUENCES

1. Nutrient enrichment (in particular in Floreat Waters).

   Consequences
   - excessive algal blooms
   - nuisance midge swarms
   - poisoning of wildlife, e.g., birds
   - loss of ecological diversity.

2. Presence of pesticides above recommended levels for aquatic life.

   Consequences
   - loss of diversity of aquatic fauna
   - lethal effects or impairment of breeding success in waterfowl
   - reduced ability of system to cope with nutrient enrichment.

3. Presence of heavy metals above recommended levels for aquatic life.

   Consequences
   - loss of diversity of aquatic fauna
   - lethal effects or impairment of breeding success in waterfowl
   - reduced ability of system to cope with nutrient enrichment.

POSSIBLE CAUSES OF THESE WATER QUALITY PROBLEMS

Nutrients

- Nutrients carried into the lake from catchment via inflowing drains and groundwater.

- Fertiliser use on lawns adjacent to the lake.

- Removal of fringing vegetation resulting in decreased capacity of foreshore to assimilate nutrients.

- Release of nutrients from sediments into the water column.

Pesticides

- Argentine ant control programme.

- Termite control in catchment.

- Control of insect pests in market gardens and domestic gardens in catchment.

Heavy Metals

- Runoff from road surfaces in catchment.
- Industrial discharge into drains.

REQUIREMENTS FOR EFFECTING SOLUTIONS

1. Management of the lake by one organisation with the authority and resources required to guide, conduct and review monitoring programmes, initiate research required and formulate and implement management strategies to protect the lake.

2. Provision of funding for lake management from developers involved in use of the lake.

3. Establishment of appropriate water quality objectives.

4. Determination of a nutrient budget and water balance for the lake to establish major sources of nutrients and pollutants and likely hydraulic residence time in the lake. This will allow identification of where remedial action will be most effective.

5. Dependent upon water balance and nutrient budget data consider diversion of drains or treatment of some drainage waters before they enter lake. Particularly with respect to "first flush" at the onset of winter rains. Also, consider the planting of buffer strips of vegetation, where appropriate, with suitable species to reduce sediment and nutrient inputs from surface water flows.

6. Chemical analysis of sediments removed from the lake as part of future dredging activities so that sediments containing high levels of pesticides, nutrients or heavy metals are not returned to the lake.

7. Reduction of domestic pesticide and fertiliser use in the catchment, especially on the lake foreshore areas managed as public open space. Reduction of pesticide and fertiliser use in other parts of the catchment will require eduction and public awareness programmes, the effectiveness of which is ultimately reliant on the commitment of local residents.

8. Continuation of the monitoring programme (with modifications as recommended) to determine if water quality objectives for the lake are being met. Regular reporting and review of the monitoring programme is required to ensure its effectiveness. Annual reporting is recommended with a complete review of the programme in five years' time.

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