NUTRIENT LOADING AND EUTROPHICATION OF NORTH LAKE, WESTERN AUSTRALIA

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The authors dedicate this report to the late Dr Jenny Arnold who contributed greatly to our understanding of wetlands and provided editorial comment.

ii SUMMARY AND CONCLUSIONS

This section contains a summary of the main findings and conclusions (in bold) reached by the Environmental Protection Authority.

North Lake received 330 kg of phosphorus (P) and 820 kg of nitrogen (N) in surface runoff and groundwater flow during the 12 month period from the 1st of April 1987 to the 31st of March 1988. Seventy three percent of the P and 60% of the N came from Murdoch drain which drains the Murdoch University veterinary farm. Twenty percent of the P and 26% of the N entered the lake as groundwater flow from the eastern edge. Groundwaters normally contain relatively low concentrations of P and N. The nutrients in the groundwater entering the eastern edge of North Lake probably originated from Murdoch drain.

Kardinya drain collects surface runoff from an urban development to the northwest of the lake and contributed 7% of the P and 16% of the N to the lake during the 12 month study.

Nutrient inputs to North Lake have grossly exceeded the Lake's capacity to assimilate them. The resultant decrease in water quality has been accompanied by excessive blue-green algal growth, plagues of chironomid midges and occasional waterbird deaths.

Murdoch Drain

The irrigated pastures of the Murdoch University veterinary farm support a high level of production because of high application rates of plant nutrients and irrigation water. Nutrients have been applied in the form of inorganic fertilisers, animal manures and veterinary hospital wastes. The soils of the farm have a limited ability to retain nutrients, and phosphorus and nitrogen readily moves into the shallow groundwater.

Testing of the fertilised soils of the veterinary farm has indicated that no additional plant growth would be achieved by further additions of fertiliser phosphorus. This means that current levels of pasture production could be maintained without additional application of P in fertiliser, probably for several years.

Current inputs of P to North Lake must be reduced by around 70% per year if further deterioration of lake water quality is to be avoided. A continuation of current inputs will lead to a situation where algal blooms are fueled by sediment release of accumulated nutrients irrespective of drainage inputs. Management of this worst case scenario would require extensive sediment dredging.

The retention of Murdoch drainage waters on campus is highly desirable and should be rapidly implemented if technically feasible.

Collection and pumping of drainage waters to a soak located on campus may be one alternative. This would serve to recharge aquifers from which irrigation water for lawns and gardens is currently being drawn. The highest concentrations of nutrients in Murdoch drain were shown to be associated with short periods of high drain flow following storms. This means that much of the nutrient load was delivered to North Lake during short periods of high flow. Design of diversion works would need to take account of high flows produced by storms.

Diversion of Murdoch drain and on-site disposal of veterinary farm runoff would produce a substantial reduction in nutrient loadings to North Lake.

Improvements in lake water quality will follow provided there is not significant recycling of nutrients already accumulated in the lake sediments.

Should the diversion of Murdoch drain prove not to be feasible, other options are available to reduce nutrient loads to North Lake. These include removal of nutrients from drainage waters, and reduction in nutrients lost from the fertilised soils of the veterinary farm.

An investigation of methods of removing nutrients from drainage waters by chemical or other methods is considered worthwhile.

Activated alumina is currently used in Europe to remove P from moderately enriched effluents and process waters. The ability of activated alumina on other methods to remove a substantial proportion of nutrients under conditions of variable flow and nutrient content needs to be assessed.

The success of drainage nutrient stripping will be enhanced if losses from the Veterinary farm soils are minimised.

Methods for reducing the loss of nutrients from the fertilised soils of the veterinary farm should be investigated.

Soil phosphorus retention may be markedly improved by amending the sandy soils of the veterinary farm with material which strongly bind phosphorus. Neutralised red mud cultivated into the surface of sandy soils has been shown to almost eliminate P leaching losses.

A comprehensive survey of the nutrient status of soils and pastures of the veterinary farm should be undertaken to ensure that overfertilisation does not occur. Advice provided by the Department of Agriculture on appropriate rates of fertiliser application should incorporate the nutrient content of applied organic material.

Potential reductions in the current high level of production on the farm should be undertaken if nutrient losses are unmanageable by other means.

Kardinya Drain

Kardinya drain contributed 7% of the P and 16% of the N entering North Lake in the 12 month study period. It is anticipated that these inputs would be considerably greater in a wetter year. Reduction of nutrient loading via the Kardinya Drain is desirable, but will be of little use if major reductions of nutrient inputs from Murdoch Drain are not achieved.

Diversion or chemical stripping of nutrients from urban runoff are possible options, and should be investigated.

There was a considerable input of litter and other gross pollutants to the lake from Kardinya drain.

Construction and maintenance of a trash rack on Kardinya drain, should proceed.

Improvements in North Lake water quality are not likely until after current nutrient inputs are reduced. This means that algae will continue to accumulate and rot on the shoreline for the foreseable future.

Monitoring and treatment of accumulations of algae on the shoreline of North Lake should continue.

It is highly desirable that the monitoring of nutrient inputs to North Lake, and the resulting water quality responses be continued. The success of management options will be determined by these results.

Nutrient inputs from Murdoch and Kardinya drains and North Lake water quality responses should continue to be monitored.

As a general policy, the use of natural wetlands for the disposal of urban runoff should not occur.

iii INTRODUCTION

This report is the result of a collaborative study between the Environmental Protection Authority and the Murdoch University School of Environmental and Life Sciences. The North Lake Nutrient Study was established in 1987 following public complaints from residents of areas around the lake about objectionable odours, which resulted from an algal bloom at the northern end of the lake in December 1986.

Algal blooms are a typical symptom of eutrophication, or nutrient enrichment, of water bodies. Gradual eutrophication is a natural process in lakes, which typically progress from relatively deep and unproductive water bodies to shallow, highly-productive ones, and finally to ephemeral swamps.

The main cause of eutrophication is an influx of nutrients, chiefly phosphorus and nitrogen, from surface runoff, rainfall and groundwater. Under natural conditions the influx of these nutrients is small, and nutrient enrichment is a gradual process. When human activities intrude, however, the situation changes. Nutrients from agricultural and garden fertilisers, vehicle emissions, septic tank discharges and other sources can greatly increase the supply of phosphorus and nitrogen to wetlands. When this happens, the natural process of nutrient enrichment is greatly accelerated, upsetting the ecological balance of the system.

Eutrophication of lakes and wetlands is a world-wide problem, and most of the wetlands of the Perth region are showing the first signs of nutrient enrichment.

The first phase of the North Lake Study set out to identify the sources of nutrient enrichment. It undertook to estimate the water and nutrient budgets of North Lake, to find out the relative importance of groundwater and surface run-off from agricultural (Murdoch farm) and urban (Kardinya residential suburb) catchments in these budgets, and to observe the lake's response to the loads imposed on it.

This paper reports one full year of results for:

1. Gauging and sampling of the two major surface drains and calculation of their water flows and nutrient loads.

2. Estimation of groundwater flux into and out of the lake and nutrient loads in the groundwater.

3. Monitoring of nutrient levels, biological activity and other parameters within the lake to establish the lake's response.

A proposed second phase of the North Lake Study would use the results of the first phase to apply remedial measures and to assess the success of those measures.

1. NORTH LAKE PHYSICAL CHARACTERISTICS

1.1 NORTH LAKE - HYDROLOGY, MORPHOLOGY AND HYDROGEOLOGY

North Lake occupies an interdunal depression on the Swan Coastal Plain, about 14 kilometres south of Perth, Western Australia. It is situated on the western slope of the Jandakot Groundwater Mound and is part of the Cockburn Wetlands Eastern Chain, which also includes Bibra, Thomsons, Yangebup and several smaller lakes (see Figure 1). North Lake is reserved for Parks and Recreation under the Perth Metropolitan Region Scheme and forms part of the proposed Beelair Regional Park.

North Lake is roughly elliptical in shape, having a length (north-south) of approximately 750 metres and a width of about 560 m. (16 m AHD contour).

In common with most Perth urban wetlands, North Lake is shallow, having a maximum depth of 3.0 m in winter, falling to less than 1.6 m at summer levels.

The level of North Lake was in the past maintained primarily by groundwater, which flows in a generally west-northwest direction from the Jandakot Mound, shown in Figure 2. Groundwater enters the lake along its eastern boundary and exits along the western side.

Two surface drains have been constructed into the lake. Kardinya Drain, entering at the north-west corner of the lake, was completed in 1977 (Megirian 1982), and carries intermittent stormwater flow from parts of South Street and suburban roads in Kardinya. The Murdoch University Veterinary Farm Drain enters via a swamp in the south-east corner of the lake, and was established in 1975 (Megirian 1982). It is seasonal, flowing from about April to February, and drains mainly groundwater and surface runoff from the Veterinary Farm (see Figures 3 & 4).

The effect of these drains, together with a general rise in the water table from urbanisation, which causes increased runoff and decreased evapotranspiration, has been to raise the level of North Lake in the last few years. This is evidenced by the fact that in 1987, despite well below average rainfall, the lake reached a level of 15.35 metres above Mean Sea Level, the second highest level ever recorded. This increase in peak water level is likely to continue as urbanisation increases in surrounding areas.

Two other significant factors affecting lake levels are direct precipitation onto the lake surface and evaporation from it. There is no surface outflow.

North Lake is situated on the transition between the Bassendean and Spearwood dune systems (Bettenay, McArthur and Hingston, 1960; Northcote, 1979). To the east, approximately 10 metres of Bassendean Sand (fine to coarse siliceous sand, heavily leached, sometimes underlain by iron-rich organic hardpan), is underlain by approximately 20 m of Guildford Formation sands (fine to coarse, containing some clay). Beneath and to the west of the lake is the Spearwood system, present as Tamala Limestone sand (fine to very coarse, pale brown to yellow sand, becoming slightly calcareous at depth) to a depth of about 35 m (Davidson, 1983).

On the floor of the lake lie a series of lacustrine deposits having a maximum thickness of about 7 m. They exist in three distinct groups, having apparently been laid down during three separate cycles of sedimentation. They consist of saprocol diatomite, (consolidated organic matter) and clay. The deposits are overlain by a layer (up to 1.5 m thick) of sapropel (unconsolidated organic largely composed of plant remains) (Megirian, 1982).

These deposits are thickest in the deeper parts of the lake, and extend up the sides of the lake to about the 14 m (AHD) level (see Figure 3). Below this level they would tend to inhibit or prevent the movement of water through the lake bed.

1.2 NORTH LAKE - CHEMISTRY

1.2.1 SALINITY

The water in North Lake is fresh, with Total Dissolved Solids (TDS) concentrations ranging from 290 to 1060 mg/l (Megirian 1982). The higher concentrations are experienced at low water levels and are probably due to concentration by evaporation. Megirian (1982) noted that the Total Dissolved Solids/Water Level curve for Bibra Lake appeared to fall into two distinct sections, with concentrations rising sharply below the 14.2 m level. He attributed this to a sealing effect of the bottom sediments below this level which inhibited groundwater exchange and hence dilution. It may be deduced from Figure 5 that this phenomenon also occurs in North Lake, with the critical level at approximately 13.9 m.

1.2.2 NUTRIENTS

North Lake is heavily enriched with the two major plant nutrients, phosphorus and nitrogen, which it receives in both organic and inorganic forms from the two drains and from groundwater.

The result of these high nutrient levels is an acceleration of the natural process of nutrient enrichment, causing eutrophication which leads to algal blooms, odour problems and deterioration of water quality.

1.2.3 TROPHIC STATE

Various researchers (eg Reckhow 1983, Bernhardt 1986) have grouped wetlands into trophic classes based on phosphorus concentration. On this basis North Lake, with total phosphorus concentrations rarely falling below 0.1 mg/L, would be classed as hyper-eutrophic, or polytrophic. In order to maintain the lake in a mesotrophic or meso-eutrophic state, which is regarded as a desirable state for lakes used primarily for landscaping and passive recreation (Bernhardt, 1986), lake phosphorus concentrations would need to be reduced to around 0.01-0.03 mg/L (Thurlow et al, 1986). This level is considered achievable in North Lake.

1.3 NORTH LAKE - BIOLOGY

North Lake is a complex and diverse ecosystem consisting of primary producers such as algae, phytoplankton and rooted aquatic plants, grazing and predatory invertebrates, native and introduced fish, tortoises and many species of birds. Table 1 summarises the sources and range of information available on the biota of North Lake.

TABLE 1: Sources and range of information on the biota of North Lake

Group of Organisms	Notes	References
Algae	Seasonal changes in Chlorophyta, Chrysophyta, Euglenophyta and Cyanophyta	Hart, 1978: pp 144-156
Macrophytes	Overview	Murdoch Uni, Env. Sci, 1986: pp 67-80
Zooplankton	Seasonal abundance	Davis and Rolls, 1987
Aquatic Invertebrates (macrobenthic)	regular sampling; quantitive analysis 55 spp.max pop. 320,300 (+/-65 200) Jan-min popul. 60 000 (+/-20,000) April.	Davis and Rolls, 1987; Davis, Rolls & Balla, in prep.
Fish	1 native sp. <u>Lizagobius olorum</u>; 2 introduced spp.	Hart, 1978: p 149
Frogs	8 spp; nb <u>Myobatrachus gouldii</u> in adjoining woodland	Murdoch Uni, Env. Sci, 1986: p 184
Tortoise	Long-necked Tortoise, <u>Chelodina oblongata</u>	Murdoch Uni, Env. Sci, 1986: p 183
Snakes and Lizards	36 spp. in surrounding area.	Murdoch Uni, Env. Sci, 1986: pp 183-185
Birds	total of 123 spp. from 6 sets of observations; including 48 spp. of water birds and Marsh Harrier	Murdoch Uni, Env. Sci, 1986: pp 179-182

1.3.1 MACROPHYTES

In addition to the algae, North Lake supports a range of free-floating, submerged and emergent macrophytes. The Southern Swamp and Murdoch Drain contain, at times, a heavy growth of free-floating, nutrient-responsive Duckweed (<u>Lemna</u> sp.) and <u>Azolla</u> sp. Murdoch Drain also supports a large crop of Bullrushes (<u>Typha angustifolia</u>), an aggressive coloniser which has so far failed to significantly invade the lake. In shallow areas of the lake, stands of <u>Baumea articulata</u> occur, while the lake shores support stands of Swamp Paperbark (<u>Melaleuca rhaphiophylla</u>), Flooded Gum (<u>Eucalyptus rudis</u>) and <u>Melaleuca teretifolia</u>.

2. DESCRIPTION OF THE PROBLEM

2.1 ALGAL BLOOMS AND ODOURS

North Lake has probably experienced periodic algal blooms since at least the early 1970's; long-term residents of the area have reported smelling the characteristic odour of decaying blooms since that time. Certainly, spring and summer blooms have been a regular feature of the lake since the mid-1970's. However, the occurrence of near-permanent blooms such as existed throughout the winter of 1987 has not previously been reported, which suggests that the condition of the lake is worsening.

The deterioration of North Lake received wide public attention in late 1986, when mats of blue-green algae became trapped behind vegetation on the northern margin of the lake. As the water level fell, the trapped algae decomposed and gave off high concentrations of hydrogen sulphide ("rotten egg gas"), methane and other gases. Complaints from local residents quickly followed.

2.2 HEALTH ASPECTS

The public health implications of lake eutrophication depend greatly on the use to which the lake is to be put. A water body which is to be used for drinking water needs to be very much cleaner than one which is to be used only for bathing or passive recreation. North Lake is unlikely to ever be used for drinking purposes, and its use for swimming or boating is likely to be minor. Nevertheless, during the course of this study, children were observed on several occasions paddling in the lake or using home-made rafts. Even at this low level of use, the possible effects of algal toxicity or bacterial contamination become important. The senior author experienced skin rashes during the course of this study, as a result of diving in the lake to install seepage meters. It is certain that water from private bores is being, and will be used to water lawns and probably vegetable crops in the lake's outflow zone.

2.3 EFFECTS ON OTHER ORGANISMS

2.3.1 MACROPHYTIC PLANTS

Any increase in sediment nutrient levels through eutrophication is likely to favour the growth of submerged and emergent plants. Indeed, this increased growth is a normal part of the process of natural nutrient enrichment. However, massive blue-green algal blooms may adversely affect the macrophytes. In particular, bottom-dwelling plants may be severely affected by reduced light penetration.

2.3.2 INVERTEBRATES

Eutrophication affects invertebrate fauna in different ways depending upon the degree of eutrophication, the species involved and the physical characteristics of the lake. In general, natural nutrient enrichment leads to an increase in invertebrate populations and species diversity through increases in food supply and habitat availability. Under accelerated nutrient enrichment, however, several deleterious effects can arise:

1. The reduction of light penetration caused by algal blooms and the subsequent inhibition of macrophyte growth may reduce the amount of habitat available for invertebrates.

2. Reduced light penetration can also reduce the feeding success of predatory invertebrates which rely on sight to find their prey.

3. A reduction in predatory species, already observed in North Lake, favours nuisance species, such as chironomid midges. Spraying for midge larvae, currently conducted regularly in North Lake with the organophosphate insecticide Temephos, may also cause disruption in the species diversity of invertebrates.

4. Insects with bottom-feeding larvae may be adapted to the oxygen-poor, (nutrient-rich) sediments of eutrophic lakes; in other words, eutrophication may produce favourable conditions for large midge populations.

5. Massive numbers of invertebrates and vertebrates may die as a result of deoxygenation of the sediments or water column caused by the decomposition of large algal blooms. Since aquatic invertebrates are an essential part of the food chain on the whole coastal plain, any reduction in their numbers, for whatever reason, must be regarded as serious.

6. Toxins produced by some algae, particularly _Microcystis_ _aeruginosa_, may directly kill invertebrates, and vertebrates.

2.3.3 FISH

Since most, if not all, of the fish species in North Lake appear to have been artificially introduced, their fate is of little significance *per se*. However, it is likely that they act as a food source for the bird life of the lake, and any reduction in their numbers will reduce the food available to the birds.

2.3.4 REPTILES - TORTOISES

Tortoises have a varied carnivorous diet which includes water beetles, larvae and other invertebrates, tadpoles and frogs, fish, bird eggs and carrion. They are likely to be affected by any long-term reduction in animal life in the lake, as well as by the possible effects of algal toxicity and the increased risk of disease in highly eutrophic waters.

2.3.5 BIRDS

Documented cases already exist from North Lake of bird deaths resulting from algal toxicity, such as in October, 1985 (Murdoch University, 1986). The predominant algal species in that case was identified as _Microcystis aeruginosa_.

Deoxygenation of shallow sediments by decaying algal blooms can also provide ideal conditions for development of the bacterium Clostridium botulinum, which is the organism responsible for outbreaks of botulism among waterfowl. North Lake was one of 15 Perth Lakes involved in a severe botulism outbreak in 1978, at a time when lake levels were extremely low. More recently, an outbreak of botulism in Thomsons Lake in the summer of 1983-4 is believed to have been triggered by a blue-green algal bloom (Murdoch University, 1986).

One of the main conditions necessary for the initiation of outbreaks of botulism is anoxia (oxygen depletion) of shallow sediments. While this would probably be an uncommon event in North Lake, Hart (1978) measured near-anaerobic conditions in North Lake during an Anabaena bloom in 1978. As eutrophication proceeds, this will inevitably become more common.

Apart from the direct effects of algal toxicity and botulism, the birds of the lake will also be affected by any disruption to the invertebrate fauna of the lake, since this forms the basis of their food supply.

2.4 FUTURE TRENDS

It is apparent that the water quality of North Lake is steadily deteriorating. The Cockburn Wetlands Study (Newman, 1976) noted an increase in both phosphorus and nitrogen levels in the lake between 1971 and 1975. However, during both that study and the later work by Hart (1978), algal blooms were mainly a short-lived summer phenomenon. The year 1987 saw a blue-green bloom which lasted throughout the entire winter, with high chlorophyll-*'a'* readings (the main indicator of algal numbers) persisting throughout almost the entire period of this study. It appears from this that North Lake may be approaching a crisis point, with further significant nutrient loadings likely to push the lake into a fully hyper-eutrophic state. Such a situation could see permanent algal blooms, death of large numbers of invertebrates, birds and other fauna, and a nutrient store within the lake sediments which would require drastic restorative measures, such as dredging, to remove. It is therefore considered vital that curative measures are instituted as soon as possible.

3. THE STUDY PROGRAM

3.1 ORIGIN OF THE STUDY

The North Lake Nutrient Study was established in order to identify the main sources of nutrients entering the lake, and to assess the feasibility of reducing the nutrient loads from those sources. In addition, the necessity and feasibility of restorative measures within the lake itself were to be explored.

3.2 PARTIES INVOLVED

The study was a collaborative effort involving officers of the Environmental Protection Authority, Murdoch University School of Environmental and Life Sciences and the City of Melville.

Also involved were the State Planning Commission (the body with management responsibility for North Lake), the Water Authority of Western Australia and the Wetlands Conservation Society.

3.3 FIELD PROGRAM

The study took five main parts:

a. Gauging and sampling Kardinya and Murdoch drains, and calculation of water flows and nutrient loads;

b. Estimation of groundwater flux into and out of the lake using observation bores and seepage meters; sampling to estimate nutrient loads;

c. Monitoring of nutrient levels, biological activity and other parameters within the lake itself to establish the lake's response to nutrients and the degree of reduction in loadings required;

d. Calibration of an urban runoff modelling package in the Kardinya Drain urban catchment (carried out by G. Rimpas, City of Melville).

e. Determination of the Murdoch vet farm pasture nutritional status and soil nutrient levels.

3.4 METHODS

Methods are described in appendices as follows:

- Appendix 1: Measurement/estimation of drain flows and loads.
- Appendix 2: Estimation of groundwater flows and loads.
- Appendix 3: Monthly water balance and nutrient budgets.

4. RESULTS AND DISCUSSION

4.1 DRAIN FLOWS AND LOADS

A near-continuous flow record was obtained for Kardinya Drain from early June onwards, and for Murdoch Drain from mid-June onwards. Flows before this period were estimated using rainfall and groundwater data. Full details of the construction, instrumentation and sampling of the gauging weirs are given in Appendix 1.

4.1.1 KARDINYA DRAIN - FLOWS

The catchment of Kardinya Drain is fully urbanised, consisting mainly of roads (arterial & suburban), driveways, houses, lawns and several small parks. The drain was established in 1977 (Megirian, 1982) to take stormwaters from South Street and the existing Kardinya subdivision. The total catchment area is 58 hectares, including 8.01 ha of road surface (G. Rimpas, City of Melville, 1988 pers. comm.) (See aerial photograph, Figure 3.)

Most of the flow in Kardinya Drain originates as rain falling on the road or driveway crossovers - approximately 90% of rainfall on these surfaces contributes to drain flow. Because of the sandy nature of coastal plain soils, it is only during sustained heavy rainfall that grassed areas contribute significantly to runoff.

As can be seen from the hydrographs (Figures 6, 7) Kardinya Drain is extremely responsive to rainfall, with flows varying by up to several orders of magnitude over the space of a few minutes. There is no base (groundwater) component to the flow.

The total flow in Kardinya Drain during the measurement period (4 June 1987 to 31 March 1988) was 50.97 megalitres (ML). The Drain flowed on 58 days during this time. The total flow over a 12 month period (1 April 1987 to 31 March 1988) was estimated to be 60.26 ML.

4.1.2 MODELLING OF URBAN RUNOFF IN KARDINYA DRAIN CATCHMENT

Testing and calibration of the ILSAX urban runoff model was conducted by G Rimpas of the City of Melville during 1987, using flow data from the Kardinya Drain weir and rainfall data from Murdoch University.

To use the package, the characteristics of the catchment area, including areas of road surface, driveways and grass, and the length, sizes and gradients of stormwater pipes are collated in a "pipe data file". Parameters of runoff coefficients, lag times and depression storage can be altered to tailor the package to a particular catchment.

The output from the model includes peak drain flows and total flow volume. The model can also recommend changes to pipe dimensions for optimum performance.

The ILSAX package was calibrated for two storms in the Kardinya catchment, on 18 June and 3 July 1987. Program output for the first storm, which was of very low intensity, predicted a total flow which was 31% greater than the recorded flow, and peak flows 40% to 60% less than those recorded.

The model performed better on the second storm, predicting total flow within 6% and underestimating peak flow by 27%.

Rimpas concluded that the ILSAX package has great potential for use in Western Australian urban catchments. Many of the inaccuracies observed in this trial could be attributed to deficiencies in the data. Flow recordings from Kardinya Drain at that time were averaged over 12.5 minute intervals, and the rainfall pluviograph could not be accurately measured at intervals of less than one hour. Thus short-term variations in rainfall intensity, which may cause large variations in both peak and total flows, could not be considered. Another problem was the lack of any high-intensity storms with which to compare the model.

Rimpas recommends that a digital pluviometer with a recording interval of approximately five minutes be installed in the Kardinya Drain catchment in order to provide a more accurate measure of rainfall intensity.

Further details of the work described above may be found in Rimpas (1987).

4.1.3 KARDINYA DRAIN - LOADS

Estimating loads in urban drains presents special problems due to the short duration of flows and the variability of concentrations found. Kardinya Drain typically begins flowing within 15 minutes of the start of significant rain and ceases within a similar time of the rain ending. Within that time, pollutant concentrations may vary by a factor of ten or more. Kardinya Drain was sampled on an opportunistic basis by "grab" samples, and by rising-stage samplers mounted on the gauging station. Samples were collected during the period from 8 April 1987 to 23 March 1988. Nutrient loadings, calculated using the technique described in Appendix 1, are summarised below in Table 2. A graph of phosphorus loads in Kardinya Drain is shown in Figure 8.

TABLE 2: Kardinya Drain Flows and Loads 1987-88.

PERIOD	FLOW (ML)	TOTAL PHOSPHORUS (kg)	TOTAL NITROGEN (kg)
4/6/87-31/3/88 (Gauged)	51	17	102
1/4/87-31/3/88 (12 months)	60	25	129

4.1.4 KARDINYA DRAIN - LOADING FROM FREDERICK BALDWIN PARK DEWATERING

Between 18 August and 3 September 1987 the Water Authority pumped water at a rate of approximately 18 litres per second from a rising main near Frederick Baldwin Lake, Kardinya, through an old sewer line into Kardinya Drain. This was done to lower the level of Frederick Baldwin Lake and alleviate problems with flooding of septic tanks in the area. After 3 September 1987 the water was directed into a new pipe which took the water west towards the coast.

During this period the pumping delivered a total of approximately 21.4 ML of water to North Lake, carrying a load of approximately 2.67 kg of phosphorus. This represents approximately 35% of the annual flow in Kardinya Drain. Because the nutrient concentrations of this water were generally lower than normal urban runoff, it carried only 11% of the annual phosphorus load from Kardinya Drain, or 0.75% of the total annual lake phosphorus loading. While this is insignificant in terms of the total load, it was associated with algal fouling of the lower part of Kardinya Drain while the pumping was in progress, and is therefore undesirable.

4.1.5 MURDOCH DRAIN - FLOWS

The flows in Murdoch Drain are fairly typical for a coastal plain agricultural drain, being composed of a mixture of a base flow derived from groundwater drainage and, superimposed on this, a surface runoff component which is much more responsive to rainfall.

The catchment of this drain lies partly within the boundaries of the Murdoch University Veterinary Farm (see aerial photograph, Figure 3), and most of the surface runoff originates from the Veterinary Farm and its associated swamp. Significant areas of the lower paddocks in the farm become saturated during winter, so any rain falling on these areas would contribute directly to surface runoff.

Murdoch Drain was constructed in 1975 (Megirian 1982). It has a catchment area of approximately 48 ha, of which 36 ha is cleared and pastured farm paddocks.

Irrigation of the veterinary farm is carefully monitored during the drier months and is unlikely to contribute to drain flow. The irrigation rate is targeted at 60% of the evaporation rate, and the water is drawn from two bores on the farm.

Murdoch Drain was gauged from 17 June 1987 to 31 March 1988. No flow was recorded after 31 January 1988. Total flow during the gauged period was 137.68 ML. Flows during the ungauged period from 1 April to 16 June 1987 were estimated using the procedure described in Appendix 1. The total flow for the 12 months period from 1 April 1987 to 31 March 1988 was estimated to be 204.16 ML. The Murdoch Drain hydrograph for 1987-88 is shown in Figure 9.

4.1.6 MURDOCH DRAIN - LOADS

Murdoch Drain was sampled approximately weekly between 8 April 1987 and 31 January 1988, at both the weir and at the culvert near where the drain enters the lake (Figure 3). Direct interpolation between the weir sample concentrations gave daily concentrations, from which loading estimates were calculated.

Of particular interest was the occurrence of a series of very high nutrient concentrations during the period from 27 April to 18 May 1987 (see Figure 10). These coincided with the appearance of a foul odour and heavy algal growth above the weir, which was then under construction.

The flow which produced these high concentrations occurred immediately after a heavy rainfall event (36 mm on 25-26/4/87), which was the first significant rainfall following the application of approximately 180-210 m^3 of fertiliser consisting of a mixture of poultry manure, sawdust and Veterinary Hospital waste to the Veterinary Farm.

The occurrence of high peaks in nutrient concentrations in agricultural drains following fertiliser application has been noted in previous studies on the Talbot's Experimental Site in the Peel-Harvey catchment area Schofield et al, 1985). It seems likely, therefore, that the high concentrations observed in Murdoch Drain were a direct result of fertiliser application on the Veterinary Farm.

Combination of water analysis data with measured and estimated flows at the weir gives the following nutrient loading estimates for Murdoch Drain: (Table 3)

TABLE 3. Murdoch Drain Flows and Loads 1987-88.

PERIOD	FLOW (ML)	TOTAL PHOSPHORUS (kg)	TOTAL NITROGEN (kg)
17/6/87-31/1/88 (Gauged)	138	95	230
1/4/87-31/3/88 (12 months)	204	259	478

A graph of phosphorus loads in Murdoch Drain for 1987-88 is shown in Figure 11.

4.1.7 MURDOCH DRAIN - ERRORS IN FLOW/LOAD ESTIMATES

Samples taken from Murdoch Drain at the culvert generally returned lower nutrient concentrations than those taken at the weir; typically phosphorus concentrations at the culvert were around 70% of those at the weir.

Transects of the drain from weir to lake (see Figure 12) showed that phosphorus concentrations fell between the weir and the swamp, rose while passing through the swamp, then fell again between the swamp and the lake. The fall between the weir and the swamp is probably due to dilution with relatively pure groundwater which enters where the drain flows roughly south from the weir. Some phosphorus may also be taken up by vegetation, although this is probably minor as the vegetation in the drain has been present long enough to have reached a state of equilibrium.

Factors determining Phosphorus concentrations in the drain require further investigation. Increased P levels in the swamp may reflect evapoconcentration while some mixing with lake waters may influence P levels measured in the drain segment between the swamp and the lake. (see McDougall, 1988) for the drain dynamics.

After consideration of the regional groundwater gradients and the length of drain which crosses the groundwater flow path, it was concluded that the extra flow entering the drain from groundwater was likely to be 0.02 ML per day or less. Some of this would be subsequently lost by outflow from the western side of the drain, particularly when the drain is banked-up by high lake levels. Thus it is considered that the flows measured at the weir are a close approximation of the volume of water which actually enters the lake via this drain.

4.2 GROUNDWATER FLOWS AND LOADS

4.2.1 GROUNDWATER FLOWS

A detailed description of the technique used to calculate groundwater flows is presented in Appendix 2. The primary method used was a network of observation bores around the lake, calibrated by means of seepage meter measurements.

The bores were monitored approximately weekly from 24 July 1987 to 1 March 1988. Interpolation of the flows between measurement dates gave the following estimates of groundwater flow (Table 4).

TABLE 4. North Lake Groundwater Flows 1987-88.

PERIOD	FLOW IN (ML)	FLOW OUT (ML)	NET FLOW (ML)
24/7/87-1/3/88 (Measured)	118	52	66
1/4/87-31/3/88 (12 months)	210	94	116

A plot of daily net groundwater flows during the period of monitoring is shown in Figure 13. A plot of the instantaneous distribution of flow around the lake on 14.1.88 is shown in Figure 14.

4.2.2 GROUNDWATER NUTRIENT LOADS

Regular samples taken from the observation bores (see Appendix 2 for details) were analysed for total phosphorus and total nitrogen, and the concentrations thus obtained were interpolated in the same way as for the flows. The nutrient load estimates thus obtained are shown below (Table 5).See also figures 15 and 16). A plot of groundwater inflow phosphorus loads for the sampling period is shown in Figure 17.

TABLE 5. Groundwater Nutrient Loads - North Lake 1987-88.

PERIOD	TOTAL PHOSPHORUS (kg)			TOTAL NITROGEN (kg)		
	IN	OUT	NET	IN	OUT	NET
24/7/87-1/3/88 (Measured)	41	17	24	118	257	-139
1/4/87-31/3/88 (12 months)	69	28	41	210	400	-190

From this it may be seen that groundwater is a significant source of nutrients to the lake, delivering more than twice as much phosphorus over the 12 months than Kardinya Drain, and slightly more than half as much nitrogen. Of interest is the fact that groundwater appears to export considerably more nitrogen from the lake than it imports.

Plots of the distribution of phosphorus concentrations and loads between the bores (Figures 15 & 16) show that the highest inflow concentrations and loads consistently occur in the area between bores 2 and 5, which are the bores near the mouth of Murdoch Drain (Figure 4). During the monitoring period, approximately 68% of the groundwater phosphorus input came from this area, compared with only 34% of the flow volume. Over the same period, 48% of the groundwater nitrogen load came from this area. These bores are in the path of groundwater flow from the Southern Swamp and Murdoch Drain, and it is likely that this water has become contaminated during its passage through the swamp. No data are currently available on the nutrient content of the groundwater before it enters the swamp from the east, so this cannot be confirmed at this stage. However, it is possible that highly-contaminated water flowing down the drain during the early part of the season is stripped of some of its nutrients in the swamp, and that these are then leached out by the groundwater later in the season. No obvious source is apparent for these high groundwater concentrations. If the groundwater is indeed picking up large quantities of nutrients from Murdoch Drain, then the drain becomes even more important in the overall nutrient budget of the lake.

4.3 NUTRIENT LOADS FROM RAINFALL

Various researchers (Smalls, 1975; Newman & Bishaw, 1983) have suggested that rainfall may be a significant source of nutrients to wetlands. Newman and Bishaw, in a study of a new urban development at Ballajura, Western Australia, found total nitrate concentrations of 0.08 - 0.13 milligrams per litre (mg/L) and orthophosphate concentrations of <.01 - .02 mg/L in rainwater. Congdon (1986) found total nitrogen and phosphorus concentrations of 0.34 - 0.80 mg/L and 0.01 - 0.06 mg/L, respectively, in rainwater near Lake Joondalup.

At these levels, rainfall nutrient loadings in North Lake would constitute only a few percent of the loads from the other sources, which is less than the probable errors in estimation of these loads.

More accurate calculation of loads in the future may make the sampling of rainfall worthwhile, but for this study its contribution to nutrient loads was assumed to be negligible.

4.4 NORTH LAKE WATER AND NUTRIENT BUDGET

The general form of the water balance equation for lakes is as follows:

$$P + S_i + G_i + dS = E + S_o + G_o$$

where P = precipitation on the lake surface
S_i = Surface inflow
G_i = groundwater inflow
dS = change in lake storage
E = evaporation from the lake surface
S_o = surface outflow
G_o = groundwater outflow

Because North Lake is endorrheic (ie without surface outflows), the (S_O) component of this equation can be ignored. In most water balance studies, the groundwater components, being the most difficult to quantify, are usually combined as (dG) or "net groundwater flow", which is treated as the unknown in the equation. This may give rise to large errors in estimation, and also makes it impossible to quantify nutrient loads from groundwater.

For the North Lake water balance, the evaporation component was estimated using data from a Class "A" evaporation pan on the Murdoch University campus. The pan data were converted to lake estimates using pan-to-lake factors developed during the Peel-Harvey Estuarine System Study, as described in Congdon (1979).

A nutrient budget equation for North Lake follows the same formula as the water balance except that, as well as there being no surface output, there is no export of nutrients by evapotranspiration. The only nutrient export process in North Lake, apart from possible small amounts removed by birds and insect swarms, is groundwater outflow.

Using the measured and calculated flows and loads from this study, the following water and nutrient budget (Table 6) was drawn up for North Lake over the 12 months from 1 April 1987 to 31 March 1988. A full monthly budget is presented in Appendix 3.

TABLE 6: North Lake Annual Water & Nutrient Budget - 1 April 1987 to 31 March 1988

	WATER		TOTAL PHOSPHORUS		TOTAL NITROGEN	
	VOLUME (ML)	% OF TOTAL	LOAD (kg)	% OF TOTAL	LOAD (kg)	% OF TOTAL
MURDOCH DRAIN	204	28	259	73	478	59
KARDINYA DRAIN	60	9	25	7	129	16
GROUNDWATER (IN)	210	29	69	20	210	26
DIRECT PRECIPITATION	246	34	0.	0.	0.	0.
GROUNDWATER (OUT)	-94	17	-28	100	-400	100
EVAPORATION	-450	83	0.	-	0.	-
CHANGE IN LAKE STORAGE (CALCULATED)	176	-	326	-	418	-
CHANGE IN LAKE STORAGE (MEASURED)	-67	-	-	-	-	-
ERROR IN DELTA S	243	–	–		–	–

4.4.1 DISCUSSION OF WATER AND NUTRIENT BUDGET

Table 6 shows that direct precipitation on the lake surface is the largest contributor of water to North Lake, closely followed by groundwater and Murdoch Drain. Evaporation from the lake surface is by far the major output of water.

Due to the low nutrient concentrations in rainfall relative to the other sources, the contribution by rainfall to the nutrient budget is negligible.

Table 6 clearly shows that Murdoch Drain is the major source of nutrients, especially phosphorus, to the lake.

4.4.2 ERRORS IN WATER AND NUTRIENT BUDGET

All of the components in the budget are subject to errors, and the cumulative effect of these may be seen in the large discrepancy between the calculated and measured changes in volume of the lake over the year. The two largest sources of error are probably evaporation, which may be significantly affected by a small change in the pan-to-lake conversion factor, and groundwater flow. The drain flow measurements are the most reliable components of the equation, which means that the estimates of nutrient loadings are probably more accurate than the water balance would suggest.

4.4.3 EFFECT OF SEASONS

Environmental Protection Authority experience in the Peel-Harvey Estuarine System Study has shown that nutrient loads from agricultural drainage are strongly linked to volume of runoff and hence to rainfall. Urban runoff loads would be expected to follow a similar pattern, while groundwater loadings may show the same effect delayed by some months.

The season of 1987-88 was a relatively dry one, with Perth recording only 88% of its average rainfall. Thus, the runoff entering North Lake during this study was probably also well below average. Experience in the Peel-Harvey catchment has shown that nutrient loadings during a wet winter may be several times higher than during a dry season, so a wet year may deliver considerably more phosphorus and nitrogen to North Lake.

4.5 SOURCES OF NUTRIENTS

4.5.1 URBAN RUNOFF

The nutrients washed off city streets during storms may come from a number of sources. These include decaying leaf litter, animal faeces, vehicle emissions, rainfall and dry atmospheric fall-out (eg dust). During storms of short to medium duration, these contaminants are quickly washed from the streets into stormwater drains, producing a characteristic "first flush" of high concentrations which decrease as the storm continues. The water quality of urban stormwater, especially during the early part of a storm, may be as poor as or worse than that of secondary-treated sewage (Hart, 1975; Smalls, 1975).

During longer storms, grass verges and lawns may become saturated and begin contributing to runoff. This water carries with it nutrients from lawn clippings and fertilisers.

Pollutant concentrations in urban stormwater tend to be at their peak after a long dry spell, when large amounts of contaminants have accumulated on street surfaces. In Perth, this usually occurs at the beginning of winter. As the rainy season progresses, concentrations generally decrease, although loads still depend very much on the quantity of rainfall. This general trend may be upset by events in the catchment area, such as spillage or dumping of pollutants into stormwater drains. Such an event may have been responsible for a large increase in nutrient concentrations in Kardinya Drain in late November 1987, which saw instantaneous concentrations of up to 12 mg/L total phosphorus and up to 11 mg/L total nitrogen.

4.5.2 AGRICULTURAL RUNOFF

Nutrient loads from intensive agricultural land result mainly from the application of large amounts of fertiliser to the soil. On Bassendean Sands, such as exist east of North Lake, as much as 40% of this fertiliser can be lost to drainage in the year of application (Schofield et al, 1985). Other agricultural sources of nutrients include animal faeces, both from stock and applied as manure fertilisers, and decaying plant material.

Nutrient losses from sandy soils usually occur as a combination of surface runoff and groundwater contamination. The relative proportions of these depend on the degree of surface saturation over the area.

4.5.3 GROUNDWATER

Groundwater may become contaminated with nutrients from a variety of sources. Septic tank discharges from unsewered housing developments, industrial wastes, old sanitary landfill sites and intensive agriculture/horticulture may all contribute to widespread contamination of the shallow aquifer.

In the case of North Lake, it is most likely that the groundwater in the vicinity of the Southern Swamp is being contaminated with phosphorus and nitrogen from Murdoch Drain.

4.6 LAKE RESPONSE TO NUTRIENT LOADINGS

4.6.1 LAKE MONITORING

Monitoring of physical, chemical and biological parameters in North Lake was carried out during the latter part of 1987 and early 1988 as part of an Honours degree project in Environmental Science by B. McDougall of Murdoch University. The thesis, (McDougall, 1988), contains a detailed analysis of the chemical and biological processes in North Lake during the study period. A brief summary of the findings to date follows:

4.6.2 LAKE NUTRIENT LEVELS

Lake samples collected between 11 September 1987 and 14 January 1988 (11/9/87 and 14/1/88) returned mean lake total phosphorus concentrations ranging from 0.10 mg/L to 0.41 mg/L (see Figure 18) and total nitrogen concentrations ranging from 1.82 mg/L to 4.12 mg/L. Profile sampling to a depth of 1.5 m showed little variation in nutrient levels with depth, suggesting that the lake was well mixed. (confirmed by lake physical property profile; Mc Dougall, 1988).

During the period from 11 September to 12 November 1987 orthophosphate concentrations were also consistently high, ranging from 0.08 mg/L to 0.20 mg/L, suggesting that phosphorus was not a limiting factor on algal growth during this time. After 19 November, however, and preceding by a few days the collapse of the large algal bloom which had persisted throughout most of the winter, the concentration of orthophosphate dropped to near zero, and it remained undetectable until sampling ceased on 14 January 1988 (see Figure 18).

The ratio of inorganic nitrogen to inorganic phosphorus in the water column was generally less than 10:1 during winter, suggesting that nitrogen, rather than phosphorus, was the limiting nutrient for algae during this period. Following the collapse of the large algal bloom in late November 1987, both nitrate and orthophosphate concentrations dropped to very low levels.

4.6.3 SEDIMENT NUTRIENT LEVELS

Sediment samples taken in January 1988 from the layer of organic ooze in the deeper parts of the lake returned high phosphorus concentrations, which were mostly in the organic form. The organic content of the sediments was high, averaging 47.7% of dry weight. This was probably partly a result of the collapse of the algal bloom in late November 1987. Total phosphorus content averaged 1101 parts per million of dry weight, of which approximately 47% was organic, 16% was in the apatite form (acid extractable calcium phosphates) and 35% was present as non-apatite phosphorus. (iron, aluminium phosphates; adsorbed phosphorus).

The large organic fraction, coupled with the low percentage of apatite phosphorus, tends to suggest that these sediments may release phosphorus under conditions of high pH and oxygen depletion. Direct evidence was found, in laboratory experiments, of release of phosphorus from the sediments when pH was greater than 8.5 (McDougall, 1988). Indirect evidence based on estimated water column phosphorus loads also suggests that this was occurring.

On 12 November 1987, at the height of the algal bloom, the lake water column held an estimated 231.5 kg of phosphorus, which is more than 65% of the estimated total annual phosphorus loading, and an increase of more than 60 kg over the amount in the water column on 22 October 1987 when the bloom was at a low ebb. During the same period, the two drains and the groundwater delivered only an estimated 5.37 kg of phosphorus to the lake, which suggests that release of phosphorus from the sediments must have been occurring during this period at the rate of approximately 2.86 kg per day. This is a loading rate exceeded by Murdoch Drain only during the heavier winter flows, and by Kardinya Drain only twice.

Release of nitrogen from the sediments was observed, both in laboratory tests and in diurnal studies in the lake itself.

Because samples were only taken from the surface of the sediments, calculation of the total lake sediment phosphorus store was not possible.

4.6.4 BIOLOGICAL RESPONSE TO NUTRIENTS

Measurements of chlorophyll- 'a' concentration after 11 September 1987 showed the presence of a persistent blue-green algal bloom from at least that time until late November. Two main peaks in algal numbers occurred, the first in September and the second in mid-November, just before the bloom collapsed. The fact that these peaks both reached a maximum chlorophyll-'a' concentration of approximately 0.30 mg/L may be mere coincidence, or may suggest that light availability or some other factor became limiting to algal growth at those times.

The reason for the collapse in algal numbers in mid-November is uncertain, but is probably to do with a fall-off in drain flows and nutrient loads around that time. Kardinya Drain had not flowed since October 31, and that was also the last time that Murdoch Drain had carried a significant nutrient load. The link between nutrient supply and the collapse is strongly suggested by the plot in Figure 18, which shows orthophosphate concentrations dropping sharply some days before the bloom collapsed.

After the collapse, sediment release of nutrients appears to have ceased or to have been insufficient to re-establish the algal bloom. Most of the remaining phosphorus in the water column was contained in zooplankton, which dominated the lake following the demise of the algae.

4.6.5 MODELLING NORTH LAKE TROPHIC STATUS

Knowledge of nutrient inputs to a lake and the lake's response to those inputs is only useful if the knowledge can be used to determine a "safe" level of input, that is a level at which the lake will be maintained in the desired trophic state.

Vollenweider proposed a model which predicted lake trophic quality on the basis of a real or volumetric water and phosphorus loadings (Reckhow, 1981). By using the model, a lake's trophic state can be plotted on a graph such as the one shown in Figure 21. Conversely, a desired trophic state may be selected and the model used to determine the maximum permissible phosphorus loading.

The original model proposed by Vollenweider was developed for use on Northern hemisphere lakes, which are typically deep and have surface water input and output via streams and rivers. North Lake, in contrast, is shallow and has no surface water output. Water is lost mainly through evaporation and groundwater outflow, hence residence times are long and flushing is minimal. Data collected during this study indicate that approximately 92% of the annual phosphorus load is retained in North Lake. This is in accordance with phosphorus retention rates estimated by other researchers for lakes with hydraulic residence times of more than a few months (Congdon, 1986). The inflow phosphorus loading, rather than the net loading, was used in the model since all phosphorus entering the lake would be available for algal uptake for a considerable period before any of it was removed by groundwater outflow.

To use the Vollenweider model, the mean area of North Lake was calculated using measured water levels and the level/area curve in Figure 19. The mean area for the 12-month budget period was 29.9 ha. The total water input to the lake was approximately 720 ML for the same period. Thus, the total water loading for the 12 months was approximately 2.41 m. The volumetric phosphorus loading, calculated in similar fashion using the level/volume curve shown in Figure 20 and estimated total phosphorus loads, was 0.75 $g/m^3/yr$. The resulting Vollenweider plot for North Lake is shown in Figure 21, along with those for some other Western Australian water bodies for comparison.

TABLE 7. Parameters Used in Vollenweider's Phosphorus Loading Model for North Lake 1987-88.

Mean Lake Level	14.81	m
Mean Lake Area	29.9	ha
Total Water Input	720	ML
Annual Water Loading	2.41	m/yr
Mean Lake Volume	473.2	ML
Total Phosphorus Loading	354	kg/yr
Volumetric Phosphorus Loading	0.75	$kg/m^3/yr$

4.6.6 IMPLICATIONS OF THE VOLLENWEIDER MODEL

As can be seen from Figure 21, the status of North Lake in 1987-88, based on volumetric phosphorus loading, fell well into the eutrophic range. This is not surprising, considering the presence of a near-permanent blue-green algal bloom during the period of study. In order to move the lake towards a mesotrophic state, a considerable reduction in phosphorus loads is necessary.

In a light-rainfall year such as 1987-88, the maximum permissible volumetric phosphorus loading in North Lake is approximately 0.28 $g/m^3/yr$, which translates to a total loading (assuming the lake volume remains the same) of approximately 132.5 kg of phosphorus from both drains and groundwater. This represents a phosphorus load reduction of approximately 63%. Given the lack of historical data it is probably realistic to assume a 70% load reduction for a range of rainfall years.

4.6.7 UNCERTAINTIES IN THE MODEL

As with all models, the Vollenweider plot contains errors and uncertainties which must be taken into account before drawing any conclusions. Some sources of uncertainty in this application of the model are:

1. Inaccuracies in the model itself, which arise from any attempt to simulate a dynamic system with an incomplete series of equations.

2. Variations in the response of different lakes to nutrient inputs, depending on physical parameters not accounted for in the model, e.g. depth, light intensity, temperature etc.

3. Errors in the measurement/estimation of water and phosphorus loadings.

4. Effects of minor components not included in the water and nutrient loadings e.g. import/export by birds, midges, litter etc.

A statistical analysis of errors was not undertaken for this study, as many of the sources of error are unknown, and any attempt to quantify them would itself be subject to large and unknown errors. In addition, the purpose of the study was not to produce a precise model of the situation in North Lake, but to identify the main causes of the problem and to suggest solutions: this can readily be achieved without the need for exhaustive mathematical modelling.

4.7 VETERINARY FARM SOIL AND PASTURE TESTING

4.7.1 SAMPLE COLLECTION AND ANALYSIS

Preliminary soil testing was carried out on the Murdoch University Veterinary Farm paddocks in January 1988, after it became obvious that very large amounts of nitrogen and phosphorus were being carried by Murdoch Drain. Samples were collected from three paddocks on the farm: 'B', 'M' and 'Q' (see Figure 22). The samples were collected with a "pogo" style core sampler which takes a core from the top 10cm of soil. Twenty cores taken randomly from each paddock were divided into 0-2 cm and 2-10 cm horizons. These were then aggregated to produce a single sample of each horizon for each paddock.

The samples of soil were analysed by Government Chemical Laboratories for phosphorus content (various forms), phosphorus retention capacity and reactive iron content.

4.7.2 RESULTS OF SOIL ANALYSES

Results of the soil analyses are shown in Table 8.

TABLE 8 - Veterinary Farm Soil Analysis Results

SITE	HORIZON (cm)	pH (CaCl2)	PRI	RI (mg/kg)	BIC-P (mg/kg)	INORG-P (mg/kg)	ORG-P (mg/kg)	TOT-P (mg/kg)
Mur. 'B'	0 - 2	7.4	-1.9	590	150	1000	250	1200
	2 -10	7.3	-0.1	410	55	460	130	620
	0 -10	-	-	446	74	-	-	-
Mur. 'M'	0 - 2	6.7	-4.7	560	240	3200	320	3800
	2 -10	6.2	-2.2	180	52	550	130	720
	0 -10	-	-	256	90	-	-	-
Mur. 'Q'	0 - 2	6.5	-4.1	480	180	2200	350	2600
	2 -10	6.8	-2.1	200	50	500	50	580
	0 -10	-	-	256	76	-	-	-

PRI - Phosphorus Retention Index. A measure of how much P a soil can currently adsorb. A negative value means it cannot adsorb any more P and is releasing P.

RI - Reactive Iron. Determines the total P adsorption that is possible in a soil.

Bic P - P extractable in 0.5M Na HCO_3 (plant available P).

INORGANIC P - P extractable in H_2SO_4.

ORGANIC P - Ignition method.

TOT-P - Total P after digestion of the sample.

4.7.3 DISCUSSION OF SOIL ANALYSIS RESULTS

The levels of all forms of phosphorus in the Table 8 show that the paddocks sampled are grossly over-enriched with P. Most of the P is in the inorganic form which is the most readily leachable (Allen 1986). The proportion of P in the inorganic form is remarkably constant (83%, 84%, 85%) in the 0-2 cm horizon of paddocks 'B', 'M' and 'O' and above 75% of the total P from 2-10 cm depth.

Bicarbonate extractable P (BicP) levels in the 0-10 cm horizon show that these soils were well above median values found in similar soils of the Peel-Harvey catchment (Figure 23). In soils with reactive iron levels from 201-300 mg/kg, the median Peel-Harvey BicP value was around 23 mg/kg. Paddocks 'M' and 'O' of the veterinary farm have BicP levels of 74 and 90 mg/kg. In soils with reactive iron levels from 301-400 mg/kg the median Peel-Harvey BicP value was around 35 which was half of what was found in Veterinary Farm paddock 'B'.

Soil test values (BicP) at which maximum pasture growth would be attained without additional fertiliser input are estimated to be around 40, 21, and 21 mg/kg for paddocks 'B', 'M' and 'O' respectively. These figures were generated using data from annual clover-based pastures and the irrigated perennial pastures of the Veterinary Farm may have a slightly higher P requirement. However, it is clear that the levels of P currently found in these Veterinary Farm soils indicate that no additional plant growth would be achieved by further additions of P for one or more years, provided adequate supplies of N, S and K are provided.

The P Retention Index is negative for all three paddocks sampled, indicating that their adsorption capacities have been exceeded and they are losing P by leaching. By leaching undisturbed cores of soil with water equivalent to several years rainfall (Weaver et al, 1988) an indication of the potential leachable P may be gained. Figure 24 shows an almost linear relationship between cumulative P leached and cumulative rainfall equivalents, indicating that there are considerable quantities of readily leachable P in the soils of the veterinary farm. This information also suggests that considerable quantities of P will leach from these soils for a number of years.

4.7.4 RESULTS OF PASTURE ANALYSES

Results of the pasture analyses for phosphorus (P), nitrogen (N), sulphur (S) and potassium (K) are presented in Table 9 below. All results are given as a percentage of dry weight (%dw). Also shown for comparison are the minimum tissue concentrations of phosphorus and sulphur required by Kikuyu grass for 100% yield during its maximum growth phase (from Reuter and Robinson, 1986). Kikuyu, although not a preferred pasture species, formed the bulk of the pasture at the time of sampling. Nitrogen and potassium requirements for Kikuyu were unavailable.

TABLE 9. Veterinary Farm Pasture Analysis Results

SITE	P (%dw)	N (%dw)	S (%dw)	K (%dw)
Mur. 'B'	0.58	2.40	0.16	2.59
Mur. 'M'	0.63	2.30	0.24	2.81
Mur. 'Q'	0.54	3.09	0.24	3.23
Kikuyu min. req.	0.24	na	0.12	na

4.7.5 DISCUSSION OF PASTURE ANALYSIS RESULTS

The analytical results show that the Veterinary Farm pastures contain phosphorus well in excess of their requirements for maximum growth, demonstrating that phosphorus application could be eliminated, possibly for several seasons, without adversely affecting productivity.

4.7.6 VETERINARY FARM FERTILISER PRACTICES

Information supplied by Murdoch University shows that the Veterinary Farm was fertilised with both organic and inorganic fertilisers during 1987.

From February to September 1987 the farm received an estimated 4243 kg of fertiliser as coastal super, KA, ammonium sulphate and Agram. This translates to a phosphorus application rate of 4 kg/ha (total 150 kg) and a nitrogen rate of 11 kg/ha (total 380 kg).

In addition to the commercial fertiliser, approximately 310-365 m^3 of organic material, consisting of a mixture of poultry manure, sawdust and Veterinary Hospital waste was applied over the same period. The exact weight, composition and nutrient content of this material is unknown and is likely to be highly variable; however some estimations of the poultry manure/sawdust component can be made, based on estimated density, average moisture content and nutrient analysis data supplied by Murdoch University(1), the South Australian Department of Agriculture and Fisheries(2), and poultry manure suppliers(3):

Assume 340 m^3(1) of mixture at
estimated density of 500 kg/m^3(3)
with poultry manure comprising
70% of total(1) = 119 tonnes of manure
(5.67 tonnes/ha)

Assume lowest grade of commercially available poultry
manure ("broiler litter")(1)
and average 24%(2) moisture content
containing 0.9% P, 2.93% N (2) = 1.07 tonnes P (= 30 kg/ha)
3.49 tonnes N (=100 kg/ha)

When combined with the quantity of NPK fertiliser applied, the total rates for 1987 are approximately 34 kg/ha phosphorus and 111 kg/ha nitrogen. The fertilizer applications were in line with Department of Agriculture recommendations at that time.

5. MANAGEMENT OF THE PROBLEM

5.1 OPTIONS FOR MANAGEMENT

The cleaning-up of North Lake can be approached in two ways: by removing or treating the symptom of the problem (ie the algae), or by treating the cause of the problem - ie reduce the input of nutrients. A symptom-oriented approach is most appropriate when a problem is short-term and critical, such as the situation caused by the build-up of algae in December 1986. In that instance, the immediate problem was solved by the State Planning Commission removing the algae and fringing vegetation from that part of the lake shore. This type of approach is immediate in effect, but its benefits are usually short-lived and do not address the basic problem.

The preventative approach, on the other hand, is generally slower to take effect, but has the potential to cure the problem permanently. This approach often is less costly in the long term, and generally produces less side-effects than the approach of treating symptoms alone.

In the case of North Lake, a combination of short and long-term measures will be necessary to quickly and permanently solve the problems of eutrophication and public nuisance.

5.2 SHORT-TERM OPTIONS

5.2.1 LANDSCAPING

The immediate cause of the odour problem in Christmas 1986 was the trapping of decaying algae behind fringing vegetation. Removal of this vegetation by the State Planning Commission solved that immediate problem. Some entrapment of algae still occurred around parts of the northern shore during 1987, and further work in this area would minimise the frequency and degree of this.

5.2.2 USE OF ALGICIDES

Selective algicides such as Terbutryn have been used extensively overseas to treat eutrophic waterways. Their toxicity to other aquatic organisms is generally low. However, considerable testing would be required before their use in local lakes could be recommended. Algicides generally need to be applied during the germination phase of an algal bloom, and would be of limited use against a permanent bloom such as existed in North Lake during 1987. The decay of large numbers of algae following treatment may be a problem, as sufficient nutrients may be released into the water column to start another bloom growing almost immediately. This may not be a major problem in North Lake, as the sediments showed little phosphorus following the collapse of the bloom in November 1987.

Nevertheless, use of algicides should be regarded as a last resort only be contemplated when all other, less hazardous means have been tried.

5.2.3 LAKE DREDGING/SEDIMENT REMOVAL

Dredging has often been been proposed as a means of lake restoration, the idea being to remove the sediments' store of nutrients which would otherwise be available to algae. The technique has been used successfully in Europe (Bernhardt & Clasen, 1985), in deeper lakes where the sediment-water interface is usually or often anaerobic, thus encouraging the release of phosphorus. Some evidence was found of significant sediment phosphorus release in this study, but this would need to be confirmed before dredging was contemplated. The great cost of dredging and the inevitability of damage to other parts of the lake ecosystem would make this also an option of last resort. If the massive input of P is not reduced, this option will become inevitable.

5.3 LONG-TERM MEASURES

The root cause of the eutrophication problem in North Lake is the excessive influx of algal nutrients, chiefly phosphorus and nitrogen, from the drains and groundwater. Therefore, any long-term solution to the problem must centre around reducing the loads from these sources.

Of the two nutrients, phosphorus is most often the limiting factor determining algal growth. During the period in 1987 when nitrogen appeared to be the limiting nutrient, the growth of nitrogen-fixing algae such as Anabaena spiroides may have been inhibited by the high phosphorus concentrations present at that time, by grazing, or simply by competition from Microcystis aeruginosa. If lower nitrogen levels prevented blooms of Microcystis, however, they may simply be replaced by Anabaena blooms. Bernhardt (1986) pointed out that phosphorus is the only controllable nutrient which is limiting to all types of algae, and concludes that, even in normally nitrogen-limited systems, inputs of phosphorus should be reduced to a stage where it becomes the limiting factor.

Based on Vollenweider's phosphorus loading model as described in Section 4.6.5, phosphorus loading in North Lake during a light rainfall year such as 1987-88 needs to be reduced by approximately 63% in order to maintain the lake in a mesotrophic state. This should be regarded as the minimum degree of reduction required. Loads will inevitably be higher in a wet year due to higher drain flows, though this may be counter balanced somewhat by a smaller contribution from groundwater. Without several years of data it is difficult to make firm estimates of phosphorus loadings in a wet year, however a reasonable target may be an average reduction in phosphorus loadings of 70%.

5.4 DIVERTING MURDOCH DRAIN

Table 6 showed that for the 12 month period from 1 April 1987 to 31 March 1988 more than 70% of P reaching North Lake came from Murdoch Drain. Groundwater contributed 2% of the total P but much of this probably also came from Murdoch drain. The 12 month period studied was characterised by very low annual rainfall. In a "normal" rainfall year the amount of P leaving the veterinary farm would be considerably greater.

Eliminating flow from the veterinary farm would considerably reduce nutrient inputs to North Lake. The reduction in nutrient input would probably be sufficient to return the Lake to an acceptable level of water quality. The input of nutrients over the 1988 winter was considerable and would have greatly increased the sediment store of nutrients.

The Murdoch University campus is reasonably short of irrigation water for lawns and gardens (P Buck pers comm). It is possible to prevent runoff leaving the veterinary farm by damming the drain and installing bores and pumps around the drain exit area. Water could be pumped to a central soak on the University campus where it would serve to recharge aquifers used to irrigate the university grounds in summer.

Pumpage of water from this aquifer in summer is likely to be sufficient to prevent nutrient-rich groundwater moving toward the Swan River. The effect of diverting the veterinary farm drainage to a control soak on campus should be investigated in terms of the small swamp on the veterinary farm. The lowering of the local water-table may dry this area out causing its destruction. This land could then be converted to agricultural production however.

5.5 REDUCING MURDOCH DRAIN PHOSPHORUS LOADINGS

Two methods are available to reduce the amount of phosphorus being delivered to North Lake via Murdoch Drain, and both will be necessary if the loads are to be reduced in the short term.

5.5.1 ON-FARM MEASURES

To reduce the export of nutrients from the Veterinary Farm, it is vital that the store of leachable phosphorus in the soil be substantially reduced.

5.5.1.1 Maintaining the current level of production

Since the supply of plant-available phosphorus currently held in the soil is vastly in excess of requirements, it should be possible to apply no phosphorus-containing fertiliser (including manure) for several years without loss of production. Experience with sandy soils in the Peel-Harvey catchment demonstrated that, on a pasture previously fertilised at typical dryland application rates (approximately 18 kg/ha), no loss of productivity was observed for three years after phosphorus application ceased. Even after maintenance level dressings of phosphorus were resumed, phosphorus export was approximately 60% less than at the start of the experiment. During the nil-phosphorus application period, dressings of non-phosphatic fertilisers were continued in order to maintain levels of nitrogen, sulphur, potassium and trace elements.

A further measure with potential to reduce phosphorus export dramatically while at the same time maintaining productivity is soil amendment with iron- and aluminium-rich clay which improves the capacity of the soil to hold phosphorus. Laboratory column experiments at Murdoch University (Kayaal et al, 1988) and field trials conducted in the Peel-Harvey catchment area using bauxite residue ("red mud") supplied by Alcoa of Australia Ltd and neutralised with gypsum have shown that this material has the ability to increase the phosphorus adsorption capacity of sandy soils greatly, while at the same time improving the water retention capacity of the soil and improving crop yield. These experiments were designed to test the possibility of disposing of red mud in this manner and the application rates used (500 - 2 000 t/ha) were high. Reductions in the leaching of P are possible at much lower rates of red mud addition, however, there is less likelihood of improving water-holding capacity or plant production at lower rates of soil amendment. Additions of red mud have several disadvantages including:

- The process is expensive.
- The residue must be mixed into the top 10 cm of soil using earthmoving equipment. Productivity of the treated area is curtailed until pasture re-establishes following treatment. During this time, export of large amounts of particulate matter may occur.

- Long-term leaching of undesirable substances, including salts such as sodium sulphate, is a possibility. This may be circumvented by the use of a lateritic loam instead of red mud as the amending agent.

Of these problems, economics and short-term loss of productivity are the most serious.

A more practical alternative may be to apply the soil amendment to a strip around the swamp in the centre of the farm, in order to intercept surface flows from the surrounding areas. Some experimentation may be necessary to find the best way of carrying out this procedure.

5.5.1.2 Reducing the current level of production

Since 1983 the number of stock carried on the irrigated (25.2 ha) and non-irrigated (24.4 ha) pastures of the veterinary farm has varied from 1100 to 1640 DSE (Dry Sheep Equivalents). This is an extremely productive farm and, due to its soils being highly P leaching, and its proximity to North Lake, it may be appropriate for this farm to reduce the numbers of stock carried, hence fertiliser applied. Any reduction in stock numbers may cause considerable disruption to teaching and research programs at the School of Veterinary Science however.

There should be discussion with the Murdoch University School of Veterinary Science as to the desirability of maintaining the current high level of animal production on the veterinary farm.

5.5.2 OFF-FARM MEASURES

The reduction of phosphatic fertiliser applications to the Veterinary Farm will produce a significant long-term reduction in phosphorus loadings to the lake. If, however, the problem is to be solved in the short term, some further treatment is necessary. This means treating the water in the drain before it enters the lake. Various methods have been proposed for achieving this.

5.5.2.1 Biological Filters

These consist of an area of dense wetland vegetation which is designed to take up nutrients from the water which seeps slowly through. This method is used extensively in Europe with varying degrees of success (Davies, 1988). Problems include:

- long establishment time (up to several years for full efficiency);
- decrease in efficiency over time, leading to eventual equilibrium, with export of nutrients almost equalling inputs;
- great reduction in efficiency if surface flow occurs; this would be difficult to avoid in the area of the Southern Swamp, where the ground is largely saturated during winter;
- wide variations in performance caused by flaws in design.

For these reasons, and because the establishment of an efficient wetland filter would involve substantial disruption to the southern swamp, this method is considered impractical.

5.5.2.2 Adsorption of phosphorus by lime

The possibility of using a crushed limestone filter bed in conjunction with a retention basin was raised at the beginning of this study. Limestone acts by binding dissolved phosphate ions, forming insoluble calcium phosphates such as apatite. This process may be initially effective, however removal efficiency decreases with time because surface encrustations of calcium phosphates which inhibit further reactions. When the adsorption capacity of the lime is exhausted the filter bed must be removed and renewed, which requires the shifting of a large volume of material. The loss of efficiency is more rapid when the water being treated contains large amounts of organic matter, such as would occur at times from pastures heavily fertilised with manure.

5.5.2.3 Adsorption of phosphorus by activated alumina

The use of activated alumina for phosphorus adsorption has been described in detail by Bernhardt & Clasen (1985). Briefly, activated alumina is aluminium oxide, produced so as to have a large surface area (200-300 m^2/g). It has the capacity to adsorb up to 110 mg of dissolved orthophosphate per kg at removal efficiencies of up to 95%. Due to its fine porous nature it can also filter out fine suspended solids which may carry large amounts of phosphorus.

The design described by Bernhardt & Clasen consists of porous drums containing the material, situated in the outlet of a holding basin. All water from the basin flows through the drums at low velocity (<2 m/hr). When the filter becomes clogged with particulates it can be cleared by simple high-velocity backflushing with water into the holding pond, where the particles settle out. When the adsorption capacity is exhausted the drum can be removed and regenerated by flushing with caustic soda (NaOH).

The system appears to have several advantages including:

- low-technology, low-maintenance operation;
- highly efficient removal of phosphorus (typically 80% of orthophosphate, 75% of total phosphorus);
- simple backwashing and regeneration of the filters requiring no heavy machinery;
- long lifetime of the filter (>1 yr between regenerations). In a seasonal drain such as Murdoch Drain, the filter could be left in place for the entire winter flow period, then regenerated during summer;
- chemically inert; no reported release of harmful ions (eg Al^{+++}) in the outflow.

Activated alumina is available at reasonable cost. Murdoch University School of Biological and Environmental Sciences has agreed to carry out laboratory column tests on the phosphorus adsorption capacity of the material. If it is proven to be efficient, it should be possible to have an operating system in place in Murdoch Drain in time for the 1989 winter season. A conceptual illustration of an activated alumina adsorption system for Murdoch Drain is shown in Figure 25.

The main disadvantage of this method would appear to be the size of the treatment system required. In Murdoch Drain, where a large part of the annual phosphorus load is carried in the early heavy flows, the system would have to be large enough to trap and treat all of these flows. The peak flow in Murdoch Drain on 10 May 1987 was 4.88 ML (estimated), which carried an estimated phosphorus load of 26.35 kg. To treat all of this volume in one day would require a filter bed area of approximately 102 square metres and a holding pond capable of retaining the entire day's flow. Regardless of this problem, the efficiency of the activated alumina adsorption system appears to make this the best option for in-drain removal of phosphorus.

5.5.3 ACHIEVABLE PHOSPHORUS LOAD REDUCTIONS - MURDOCH DRAIN

The combination of changes to current farm management practices and drain water treatment should combine, in the long-term, to make possible a reduction of up to 90% in the total phosphorus input to North Lake via Murdoch Drain. In the short term, drain treatment alone may be able to remove approximately 75% of phosphorus.

Treatment of the drain water should not be seen as an alternative to proper fertiliser management of the Veterinary Farm, as the leaching of phosphorus which is polluting the drain must inevitably also be contaminating the groundwater table to the west of the farm. In addition, the continuing influx of phosphorus-laden groundwater to North Lake for at least the next several years, whether originating from Murdoch Drain or not, means that all controllable inputs of phosphorus must be reduced as soon as possible.

5.6 REDUCING KARDINYA DRAIN PHOSPHORUS LOADS

The options for treatment in this case are very much less than with Murdoch Drain. The phosphorus in urban runoff comes from a very wide variety of sources, none of which are very amenable to management. The only option which remains, therefore, is in-drain treatment.

Because of the characteristic distribution of pollutant concentrations in urban runoff and the short duration of flows, a substantial percentage of the pollutant load may be removed without the need to treat the entire volume of flow. By intercepting and treating the most heavily-polluted "first flush" a relatively small retention pond and adsorption system may remove phosphorus with almost the same efficiency as a much larger and more expensive full-treatment system.

Analysis of the flow record for Kardinya Drain during 1987 (see Figure 9) reveals that approximately 60% of the flow volume occurred at rates of less than 2 ML/day, and that this flow carried approximately 70% of the annual phosphorus load. To trap and treat all of these flows would require a large retention pond (say, 40 x 25 x 2 m) and a filter area of about 42 m^2. It should be possible to reduce the size considerably without seriously affecting the effectiveness of phosphorus removal, but more detailed information is required on the exact relationship of flow volume, duration and phosphorus concentration in the drain before designing of an installation can begin.

Since Kardinya Drain at present makes a fairly minor contribution to the over-all lake nutrient loadings, its treatment is not so urgent as that of Murdoch Drain, although it will be a necessary part of any long-term solution to North Lake's problems.

5.7 OTHER POLLUTANTS IN KARDINYA DRAIN

Of more importance in the short term is the removal of gross pollutants from the waters of Kardinya Drain such as plastic bags, bottles, plastic binders from beer can "six-packs", and other garbage. These items regularly cause the death of waterbirds by entanglement or ingestion, are unsightly, and have no place in a wetland. A simple well-maintained "trash rack" constructed of mesh or grating would remove most of this pollution from the runoff.

5.8 CONSEQUENCES OF NO ACTION

5.8.1 PRESENT TRENDS

It is apparent that the condition of North Lake has deteriorated over the last few years, with algal blooms becoming more common and more prolonged as a result of increasing nutrient loadings. Although it appears that little permanent damage has yet been done to the lake ecosystem, this fortunate situation cannot be expected to continue indefinitely.

The majority of the phosphorus entering the lake remains there, most of it held in the bottom sediments. This store of phosphorus has the potential to be released back into the water body to fuel algal growth. As the store of phosphorus builds up this will become more significant. The fuelling of algal blooms by nutrient released from sediments is well-documented.

5.8.2 THE FUTURE

If no action is taken to reduce nutrient loadings, the deterioration of North Lake will continue, probably at an increasing rate. Algal blooms will become more common, perhaps even permanent. Nuisance odours will be stronger and more widespread. Algal toxicity will take an increasing toll of aquatic organisms and make the lake increasingly hazardous to humans. Massive algal blooms will create anaerobic conditions within the lake with increasing frequency, causing mass death of invertebrates and creating ideal conditions for outbreaks of botulism among waterfowl.

Eventually, the lake may reach a stage where the amount of nutrients released from sediments ("internal loading") is sufficient to sustain major algal blooms without any external nutrient inputs. At that point, the situation will be beyond repair without the use of costly and/or environmentally hazardous engineering or chemical methods such as sediment dredging or algicides.

5.9 TIMESCALE FOR ACTION

The most pressing measure to be taken in North Lake is the reduction of phosphorus loadings from the Veterinary Farm. This should commence immediately, with no phosphatic fertiliser being applied to the farm for at least the next season. Thereafter, soil and tissue testing should be used, preferably in consultation with the Department of Agriculture, to determine maintenance phosphorus requirements.

An investigation of the possibility of directing Murdoch drain waters to a central campus soak is highly desirable.

An adsorption system for Murdoch Drain should also be investigated beginning with laboratory studies of adsorption media. Consideration should be given to soil amendment of all or part of the Veterinary Farm.

Intensive gauging and sampling of Kardinya Drain during winter 1988 should provide information which will aid the assessment of the possibility of a similar system for that drain.

6. REFERENCES

Allen, D, G, (1986). Organic Phosphorus in Soils of the Peel Harvey catchment area. Western Australia Government Chemical Laboratories, February 1986.

Belanger, T V, Mikutel, D F, and Churchill, P A, (1985). 'Groundwater Seepage Nutrient Loading in a Florida Lake', Water Research 19: 773-781.

Bernhardt, H, (1987). 'Strategies of Lake Sanitation', Schweiz. Z. Hydrol. 49/2: 201-219.

Bernhardt, H, and Clasen, J, (1985). 'Recent Developments and Perspectives Of Restoration For Artificial Basins Used For Water Supply', Lakes Pollution and Recovery - International Congress, Rome, April 1985.

Bettenay, E, McArthur, W M, and Hingston, F, (1960). The soil associations of part of the Swan Coastal Plain, Western Australia. CSIRO, Australia. Division of Soils. Soils and Land Use Series No 35.

Bouwer, H, and Rice, R C, (1968). 'Review of Methods For Measuring and Predicting Seepage', Proceedings of 2nd Seepage Symposium, Phoenix, Arizona, 1968. United States Agricultural Research Service Report No. ARS 41-147.

Brock, T D, Lee, D R, Janes, D, and Winek, D, (1982). 'Groundwater Seepage as a Nutrient Source to a Drainage Lake; Lake Mendota, Wisconsin', Water Research 16: 1255-1263.

Chapman, V J, and D J, (1977). The Algae. MacMillan, London, U K.

Clasen, J., and Bernhardt, H, (1986). 'Chemical Methods of P-elimination in the Tributaries of Reservoirs and Lakes', Schweiz. Z. Hydrol. 49/2: 249-259.

Congdon, R A, (1979). Hydrology, Nutrient Loading & Phytoplankton in Lake Joondalup. Department of Conservation and Environment, Perth, Western Australia, Bulletin 67.

Congdon, R A, (1985). The Water Balance of Lake Joondalup. Department of Conservation and Environment, Perth, Western Australia, Bulletin 183.

Congdon, R A, (1986). Nutrient Loading and Phytoplankton Blooms in Lake Joondalup, Wanneroo, Western Australia. Department of Conservation and Environment, Perth, Western Australia, Technical Series Bulletin 6.

Congdon, R A, and McComb, A J, (1976). 'The Nutrients and Plants of Lake Joondalup, a Mildly Eutrophic Lake Experiencing Large Seasonal Changes in Volume', J. Royal Soc. of W.A. 59: 14-23.

Davidson, W A, (1983). Bibra Lake Groundwater Appraisal. Geological Survey of Western Australia, Hydrogeology Report No. 2528.

Davis, J A, and Rolls, S W, (1987). A Baseline Biological Monitoring Programme For The Urban Wetlands of the Swan Coastal Plain, Western Australia. Environmental Protection Authority, Western Australia, Bulletin 265.

Grantham, G R, (1975). 'Improvement of Quality of Stormwater Discharges to Rivers and Lakes', Water in the Urban Environment: Summer School, Canberra, 1975. Australian Water & Wastewater Association.

Hart, B T, (1975). 'Urban Stormwater Quality', Water in the Urban Environment: Summer School, Canberra, 1975. Australian Water & Wastewater Association.

Hart, L A, (1978). Wetland Ecosystems: A Study of Several Swan Coastal Plain Wetlands, With Implications For Management. Murdoch University, Western Australia, unpublished honours thesis.

Height, M, Bayley, P, and Bettenay, E, (1987). Talbot's 1985-86 Groundwater Studies. Environmental Protection Authority, Perth, Western Australia (unpublished).

John, P H, and Lock, M A, (1977). 'The Spatial Distribution of Groundwater Discharge Into the Littoral Zone of a New Zealand Lake', Journal of Hydrology 33: 391-395.

Kayaalp, N, Ho, G., Mathew, K, and Newman, P, (1988). 'Phosphorus Movement Through Sands Modified by Red Mud', Water 15: 26-29.

Lee, D R, (1977). 'A Device for Measuring Seepage Flux in Lakes and Estuaries', Limnology and Oceanography 22: 140-147.

Lee, D R, Cherry, J A, and Pickens, J F, (1980). 'Groundwater Transport Salt Tracer Through a Sandy Lakebed'. Limnology and Oceanography 25: 45-61.

Leupold & Stevens, Inc. (1978). Stevens Water Resources Data Book. Leupold & Stevens, Inc., Oregon, USA.

Linsley, R K, and Franzini, J B, (1964). Water-Resources Engineering. McGraw-Hill Kogakusha Ltd, Tokyo, Japan.

Lloyd, R D C, (1975). 'Improvement of Quality of Stormwater Discharges to Rivers and Lakes', Water in the Urban Environment: Summer School, Canberra, 1975. Australian Water & Wastewater Association.

McBride, M S, and Pfannkuch, H O, (1975). 'The Distribution of Seepage Within Lakebeds', J. Res. US. Geological Survey 3: 505-512.

McDougall, B (1988). Unpublished Honours Thesis. Murdoch University.

McFarlane, D J, (1980). Groundwater Management in the Northern Perth Area With Particular Reference to Wetlands. Faculty of Agriculture, University of Western Australia.

Massey, B S, (1975). Mechanics of Fluids. Van Nostrand Reinhold Co., Berkshire, UK.

Megirian, D, (1982). The Hydrogeology of North and Bibra Lakes, Perth, Western Australia. Department of Geology, University of Western Australia, unpub. Honours thesis.

Murdoch University. Environmental Management (1986). North Lake Draft Management Plan. Murdoch University (unpublished).

Newman, P, and Bishaw, M, (1983). 'Stormwater Quality in an Urbanising Watershed in Perth', Water Res. Foundation Conference: 'Water Quality - its Significance in WA.', 1983.

Newman, P, and Hart, L, (1984). 'Deepening Urban Wetlands: An Assessment of Water Quality in Four Wetlands on the Swan Coastal Plain, Western Australia' Water, June 1984: 12-16.

Newman, P, et al (1976). The Cockburn Wetlands: An Environmental Study.

Northcote, K H, (1979). A factual key for the recognition of Australian Soils. Rellim Technical, Adelaide, South Australia.

Orange, K. The Utilisation of Poultry Manure. Department of Agriculture and Fisheries, South Australia.

Reckhow, K H, (1981). Lake Data Analysis and Nutrient Budget Modelling. US. Environmental Protection Agency, Corvallis, Oregon, USA.

Reuter, D J, and Robinson, J B, (1986). Plant Analysis: An Interpretation Manual. Inkata Press, Melbourne, Victoria.

Rimpas, G, (1987). Validation of the ILSAX Program in an Urban Catchment. City of Melville, Western Australia. Municipal Engineering Project No.592, 1987. (unpublished).

Schofield, N J, Bettenay, E, McAlpine, K W, Height, M I, Hurle, D H, Ritchie, G S P, and Birch, P B, (1985). Water and Phosphorus Transport Processes in Permeable Grey Sands at Talbot's Site Near Harvey, Western Australia. Department of Conservation and Environment, Perth, Western Australia, Bulletin 205.

Skulberg, O M, Codd, G A, and Carmichael, W W, (1984). 'Toxic Blue-Green Algal Blooms in Europe: A Growing Problem'. Ambio 13: 244-247.

Smalls, I C, (1975). 'Nutrient Effects of Stormwaters on Lakes and Streams', Water in the Urban Environment: Summer School, Canberra, 1975. Australian Water & Wastewater Association.

Te Chow, V, ed. (1964). Handbook of Applied Hydrology. McGraw-Hill, USA.

Townley, L R, and Davidson, M R, (1987). 'Definition of a Capture Zone For Shallow Water Table Lakes'. (Submitted to Journal of Hydrology, November, 1987)

Urbonas, B, and Roesner, L A, eds (1986). Urban Runoff Quality - Impact and Quality Enhancement Technology. American Society of Civil Engineers, New York, USA.

Weaver, D M, Ritchie. G S P, Anderson G C, and Deeley, D M, (1988). P leaching in sandy soils. 1 short-term effects of fertilizer application and environmental conditions. Aust Soil Research. 26, 77-90.

Western Australia. Department of Conservation and Environment (1984). Potential for Management of the Peel-Harvey Estuary. Department of Conservation and Environment, Perth, Western Australia, Bulletin 160.

Western Australia. Department of Conservation and Environment (1985). Peel-Harvey Estuarine System Study: Management of the Estuary. Department of Conservation and Environment, Perth, Western Australia, Bulletin 195.

Water Authority of Western Australia,(1987). Perth Urban Water Balance Study, Vol 3. Water Authority of Western Australia, Leederville, WA.

Whelan, B R, ed. (1981). Groundwater Resources of the Swan Coastal Plain, 1981. Commonwealth Scientific and Industrial Research Organisation (Australia).

Yeates, J S, (1985). Management of agricultural phosphorus losses from the soils of the Peel-Harvey estuarine system catchment. Western Australian Department of Agriculture, Division of Plant Research Annual Report 1984/85.

1. MEASUREMENT/ESTIMATION OF DRAIN FLOWS AND LOADS

1.1 WEIR CONSTRUCTION, CALIBRATION AND GAUGING

Water flows in the two drains were measured by means of "V-Notch" weirs. The Kardinya Drain weir was a broadcrest type, built of concrete with an angle of 1 in 4 and a downstream slope of 1 in 20. The weir rested on a concrete foundation which extended about 0.5 m below the floor of the drain.

The Murdoch Drain weir was built of steel sheet piling which was driven about 1m into the drain floor and cut in the shape of a "V" with an angle of 1 in 2.5. Both weirs allowed some leakage but in each case this was considered to be insufficient to cause significant errors in flow measurement.

A stilling well was installed in the pond upstream of each weir to measure water level behind the weir. The levels were recorded with Unidata Shaft Level Encoders (model 8509B) connected to Unidata Data Loggers (model 6003A).

Discharge measurements were made downstream of each weir to establish a relationship between water level and flow rate. For Murdoch Drain this was done on two occasions with a Hydrological Instrument Services current meter (model number OSS/B1) using the method described in Linsley & Franzini (1964). Measurement of discharge from the Kardinya Drain weir was done by measuring, with a stopwatch, the time taken to fill a 60 litre drum held under the overflow of the weir at several different flow rates. For both weirs, the water level-Vs-discharge points thus obtained fell close to the theoretical rating curves given by Leupold & Stevens (1978) for V-Notch weirs. The theoretical ratings were therefore used for all subsequent flow calculations.

The water levels at the weirs were initially measured by the loggers every two seconds, with an averaged level being logged every 12.5 minutes. These were later changed to a scan interval of five seconds and a logging interval of five minutes. When converted using the rating curve, this produced a record of the mean flow per 12.5 or 5 minutes, and daily and cumulative flows.

1.2 ESTIMATION OF UNGAUGED DRAIN FLOWS

1.2.1 KARDINYA DRAIN

For medium rainfall events (approximately 3 - 35 mm/day) the daily flow in Kardinya Drain bears an an approximately linear relationship to daily rainfall, with some variation due to differences in evaporation and short-term rainfall intensity (Figure A1-1). Less than 3 mm of rain on the dry catchment generally produces no flow, while extremely heavy and sustained rainfall would tend to produce proportionately more flow as grassed areas became saturated. This relationship enabled ungauged flows outside the measurement period to be estimated using rainfall data from the Murdoch University pluviometer (approximately 2 km east of the catchment).

1.2.2 MURDOCH DRAIN

Because the flows in Murdoch Drain are made up of two components, a groundwater-dependent base flow and a rainfall-dependent surface flow, these were considered separately in estimating ungauged flows for this drain.

The base flow component varies slowly with time and, in 1988, ceased on 31 January. Examination of the flow record in Figure 9 shows the base flow to have been about 0.6 ML/day in June 1987, following heavy rainfall in May. Before that rainfall it was assumed to be insignificant.

The surface flow component was estimated from the hydrograph by subtracting base flow from total flow, and plotted against daily rainfall. This produced an approximately linear relationship between surface flow and rainfall, similar to that for Kardinya Drain (see Figure A1-2). This was used in conjunction with estimated base flows to infer daily flows for the rainfall events in April and May, 1987.

1.3 ESTIMATION OF DRAIN NUTRIENT LOADS

1.3.1 KARDINYA DRAIN

Because of the great variability of nutrient concentrations in urban drains it was not possible to simply interpolate concentrations between samples in Kardinya Drain. Instead, a system of extrapolation was used, based on the plot of total phosphorus concentration-Vs-flow duration shown in Fig A1-3. A similar relationship was found to exist for total nitrogen-Vs-flow duration.

As each sample was collected from Kardinya Drain, the time of collection was noted, and its position on the concentration-Vs-duration curve was plotted. The curve was then used to estimate a starting concentration for the flow event, and interpolation was used to estimate periodic concentrations between this and the known concentrations for that flow event. After 3 September 1987, three rising-stage samplers collected samples as the water level reached 0cm (start of flow), 10cm and 20cm above the weir, thus providing data on concentrations during the early part of each flow.

On those occasions when no samples were collected during a flow event, concentrations were estimated based on the known concentrations of preceding and subsequent flows.

It is anticipated that the installation of a flow-triggered, high-intensity automatic sampler on Kardinya Drain during 1988 will provide much more accurate data on the nutrient loads in this drain.

1.3.2 MURDOCH DRAIN

Load estimation in Murdoch Drain was a much simpler task, as the concentration varied relatively slowly. Only in April and May 1987, when the concentrations were very high and changing rapidly (see Figure 10), does the likelihood of significant errors arise. All load calculations for Murdoch Drain were based on direct interpolation between the once- or twice-weekly samples.

1.4 REFERENCES

Leupold and Stevens, Inc (1978), Stevens Water Resources Data Book. Leupold and Stevens, Inc., Oregon, USA.

Linsley, R K and Franzini, J B, (1964). Water Resources Engineering. McGraw-Hill Kogakusha Ltd, Tokyo, Japan.

2. ESTIMATION OF GROUNDWATER FLOWS AND LOADS

2.1 ESTIMATION OF GROUNDWATER FLOWS

Traditionally, when calculating lake water balances, groundwater exchange is not measured but is simply treated as the "unknown" in the water balance equation. This is mainly because of the difficulty of measuring groundwater flow compared to other components of the water budget. This method simply gives a net groundwater input or output, and gives no indication of the actual amounts of inflow and outflow occurring. When calculating a nutrient budget where groundwater is suspected of being a significant contributor of nutrients, this method is unsuitable.

Three different methods were used in this study to provide measurements or estimates of groundwater exchange. The first involved measuring the gradient of the surface of the water table using pairs of observation wells spaced around the lake shore, a method used successfully by Height et al (1986). The second employed seepage meters installed at various points in the lake bed and fitted with plastic bags to trap seepage influx. The construction and usage of these seepage meters (see Figure A2-1) was as described in Lee (1977).

Finally, the groundwater was treated as the unknown in a traditional water balance equation to check the flows computed by the other methods.

2.1.1 METHOD 1 - OBSERVATION BORES

2.1.1.1 Installation

A ring of bores in pairs was installed around the perimeter of the lake at approximately 100m spacing. The innermost bore of each pair was situated approximately 10m from the water's edge (on 16/7/87; lake level 14.86m), and the outer bore was 10m from the inner, on a line perpendicular to the shore. The bores were constructed of 32mm PVC tube, and perforated over their full length with 0.5mm slots. Each was sunk approximately 2m into the water table with a hand auger and sludge pump, and the hole was then backfilled with spoil. The levels of the bore casings and adjacent ground were surveyed with reference to a nearby Water Authority benchmark (R L 17.244m AHD).

Faint traces were found in several holes of a weakly-developed organic hardpan at around the 2 m depth, as found on the Talbot's experimental site in the Peel-Harvey catchment area (Height et al, 1987). However, only at bores 20.1 (at 2.8 m depth) and 21.1 (at 2.5m) was it developed into a solid hardpan, capable of impeding the vertical movement of water. Even where it was well-developed it did not extend closer than 10m from the lake, so should have minimal effect on the depth of aquifer able to interact with the lake.

2.1.1.2 Monitoring

The depth to water in the bores was measured approximately weekly using a hand-held electronic measuring device. The depths were then converted to relative levels. The lake level was measured simultaneously by means of a Water Authority staff gauge at the northern end of the lake. On every second monitoring date, the bores were sampled for nutrients as described in Section A2.2.

The water levels obtained from the bores were used to calculate groundwater flows as described in Section A2.1.1.3.

The flows thus calculated, together with the sample concentrations, were used to calculated nutrient fluxes as described in Section A2.2.

2.1.1.3 Calculation of Flows

Bore water level data for 31 dates from 24 July 1987 to 1 March 1988 were used to calculate the hydraulic gradient at each bore pair. These gradients were then used to calculate groundwater flows at each bore pair using Darcy's Law, which states that the velocity of groundwater flow is determined by the hydraulic gradient and the permeability, or conductivity, of the soil:

$$v = Ks.m$$

where v = velocity of groundwater (m/day)
Ks = saturated hydraulic conductivity (m^3/m^2/day or m/day)
m = hydraulic gradient

(Te Chow, 1964)

Saturated Hydraulic Conductivity is defined as the volume of water passing through a 1 m^2 cross-section of soil in a day, given an hydraulic gradient of 1 (ie 45o). The value of Ks depends upon the porosity of the soil (the percentage of the soil not actually occupied by soil particles), the size of the soil particles, and the distribution of those particles. Height et al (1987) measured a Ks of approximately 12 m/day in the shallow aquifer on Bassendean sands at the Talbot's experimental site, and that value was used for the bores on the Bassendean sands to the east of North Lake.

On the western side of North Lake, the Spearwood sands contain a shallow, eastward-dipping clay horizon (Megirian 1982), which would be expected to cause a decrease of Ks in that area. This is evidenced by the fact that the groundwater flows in this area, as measured by seepage meters, are similar to those on the eastern side of the lake, but the hydraulic gradients are considerably steeper. As a result of comparing these flows and gradients, a Ks of 4 was selected for this area, covering bore pairs 5 to 17.

To translate groundwater velocities into flow volume, the perimeter of the lake was divided into a series of 21 straight line segments, each having two consecutive bore pairs as its endpoints. The length of each segment was approximately 100 m with the exception of segment 21 (see figure 4), whose length was approximately 125 m. A representative flow velocity for each segment was calculated by averaging the velocities of the two endpoints.

The thickness of the aquifer at each segment was calculated as the average of the heights of the water table at each of the four end points above an arbitrary base, which was defined as ten metres below the lake water level. The depth of 10m was suggested by Davidson (1983) after exploratory drilling at Bibra Lake, which is similar in form and immediately south of North Lake. Advice from the Mines Department Geological Survey suggests that this is due to both the geometry of the lake (see also Townley and Davidson, 1987) and to the fact that the ratio of vertical to horizontal hydraulic conductivity (anisotropy ratio) is about 1:100 in the top 10m of the aquifer but may be as high as 1:1000 in the lower 20 to 25m. This means that water in the lower levels would have more difficulty in rising up to enter the lake.

The volume of flow at each segment was calculated as the product of velocity, segment length and aquifer thickness:

$$Q = v.L.T$$

where Q = flow volume through segment (m^3/day)
v = flow velocity (m/day)
L = length of segment (m)
T = average thickness of aquifer over segment (m)

2.1.2 METHOD 2 - SEEPAGE METERS

2.1.2.1 Construction and Installation

Seepage meters consist of a section cut off the bottom of a 200-litre drum (see figure A2-1), in the base of which a hole is cut and an exit tube is fitted. In use, the open end of the seepage meter is pushed slowly into the floor of the lake so as to form a watertight seal, and a plastic bag is attached to the exit tube. Any water seeping into the lake will be trapped in the plastic bag. By knowing the area covered by the seepage meter, the volume collected and the time taken, the velocity of seepage can be computed. This method is described more fully in Lee (1977). If water is seeping out of the lake, the bag can be filled with a known volume of water, and the remainder measured after a certain time. The volume lost is then used to calculate seepage flux.

In this study, twenty seepage meters were used in different parts of the lake. They were initially positioned in transects opposite bore pairs 1, 6 and 12 to determine the variation in seepage rate with distance from the shore. They were then sited around the perimeter of the lake, one opposite each bore pair (except pair no. 11, where the slope of the bottom was too great) in about 0.5m of water, to study the spatial distribution of seepage around the lake.

2.1.2.2 Monitoring

Seepage was measured three times with the seepage meters in their initial positions opposite bore pairs 1, 6 and 12. They were then moved to their new positions around the perimeter of the lake and were measured a further five times.

On each occasion the method used was the same. A rubber bung containing a plastic tube was fitted to the hole in the top of the seepage meter. A 25cm x 45cm plastic oven bag (capacity approx. 2.5 litres) was then attached to the top of the tube with a rubber band. In areas where the seepage was into the lake (bore pairs 1-6, 18-21) the bag was initially empty. Where seepage was expected to be out of the lake (bore pairs 7-17), the bag was filled with a measured volume (approximately 1.5 litres) of lake water before fitting to the seepage meter. The bags were left in place for two to three hours, then removed and the remaining volume measured.

Results from the seepage meter measurements on four occasions were used to calculate groundwater flows into and out of the lake. Since this is a more direct measurement of flow than the observation bore method, results from the seepage meters were used to calibrate the flows calculated from the bores.

2.1.2.3 Seepage profile

Results from three measurements of seepage meters in a transect opposite bore pairs 1, 6 and 12 showed that seepage velocity decreased exponentially with increasing distance from the shore. This phenomenon is described by John & Lock (1977), McBride & Pfannkuch (1975) and Lee *et al* (1980). A mathematical explanation is proposed by Townley & Davidson (1987). The situation is conceptually represented by the flow diagram in Figure A2-2.

Analysis of the results showed that the seepage velocity at these sites decreased by a factor of ten for every 7.1 metres distance from shore (see Figure A2-3). This value was used in all seepage meter flow calculations.

2.1.2.4 Seepage distribution

Measurement of seepage rates around the lake shore on four occasions in November 1987 revealed seepage entering the lake on the eastern side, between bore pairs 18 and 7 inclusive, and exiting on the western side, between pairs 8 and 17. A stagnation point existed between bores 7 and 8, and another between bores 17 and 18. Inward seepage increased opposite bore 7 as November progressed. This suggests that the stagnation point was moving to the west, indicating that inflow was becoming more dominant over outflow as the lake level fell due to low drain flows and high evaporation.

Seepage velocity varied considerably between adjacent seepage meters on some occasions, and some locations displayed large variations between measurement dates. The spatial variation may be due to the existence of preferred flow paths in the lakebed, or to the influences of vegetation or topography. The reason for the temporal variation is unclear, since it seemed to bear little relationship to either rainfall or the measured gradients.

2.1.2.5 Calculation of Seepage Flux

Because seepage velocity decreases exponentially with increasing distance from the shore of a lake, the seepage velocity at a given distance from shore is approximated by:

$$\mathrm{Log}(Vs) = \mathrm{Log}(Vo) - s/dS$$

where s = distance from shore
Vs = velocity at distance x
Vo = velocity at shoreline (x=0)
dS = distance over which seepage velocity decreases by one order of magnitude (factor of 10)

(After McBride & Pfannkuch, 1975)

Thus, if seepage velocity at a certain distance from shore is measured, the velocity at the shoreline can be calculated by:

$$\mathrm{Log}(Vo) = \mathrm{Log}(Vs) + s/dS$$

or

$$Vo = Vs \,.\, 10^{(s/ds)} \qquad (1)$$

The total seepage velocity on a line out from the shore can now be calculated by the integral:

$$Vt = Vo . \int_{x=o}^{x=t} 10^{(s/ds)} dx \quad (2)$$

where t = total distance
Vt = total integrated velocity
x = variable of integration

(After McBride & Pfannkuch, 1975)

In this study, the seepage velocity at the shoreline was calculated using equation (1), from the measured velocity at the seepage meter and the known distance from shore of the seepage meter.

For the calculation of total integrated velocity, the total distance was taken as the distance from shore of the bottom sediments (see Figure 4). Megirian (1982) noted an apparent sealing effect of the bottom sediments in Bibra Lake, where the sediments are likely to be similar to those in North Lake. In practice, the question of whether the sediments do seal the bottom of the lake is of importance only at water levels of close to 14 metres (the approximate level of the sediment line) since at higher levels most of the seepage would take place inshore of the sediment line.

In the past, North Lake has regularly fallen below 14 m in summer (11.85 m in April 1963). This has not occurred since June 1986, despite below-average rainfall, and may be due to urbanisation and increased runoff.

The total seepage flux for North Lake was calculated in a similar way to that used for the bores: the total velocities for each two adjacent seepage meter positions were averaged, and multiplied by the area bounded by the shore, lines perpendicular to the shore, and the edge of the sediments.

An example of the distribution of seepage flux thus obtained is shown in Figure A2-4.

2.1.3 RECONCILIATION OF BORE AND SEEPAGE METER FLOW CALCULATIONS

Initial calculations of flows by the observation bore method indicated a consistent loss of groundwater from the lake, with outflow occurring at all points on its perimeter except at bore pair 1. This conflicted with the results of the seepage meter measurements, which showed that water was flowing into the lake at all points between bore pairs 18 and 7 inclusive on most occasions.

When the flows calculated from bores and seepage meters were plotted and a simple visual comparison made, it was observed that the flows matched very closely in most cases if the gradient of the groundwater was simply increased by 0.005 toward the lake at all points (see Figure A2-4). This discrepancy is believed to be a result of the convergence of groundwater flow lines as they approach the lake (see Figure A2-2). The problem may have been avoided by positioning the observation bores further away from the lake, but this would have created problems with sampling, since the groundwater may then have undergone significant chemical change between the sampling point and the lake. Problems may also have arisen regarding the direction of flow: seepage tends to be perpendicular to the shoreline when close to the lake, but soon reverts to the regional flow direction at longer distances from the lake.

The plot of daily net groundwater flows shown in Figure 13 shows that the net flow was lowest in the months of late winter, when drain flows, rainfall and hence lake levels were high, which would have the effect of impeding ground-water inflow and increasing outflow. Net inflow was in fact lowest in early September, shortly after a period of sustained heavy rainfall and at the time when the lake was at its highest level for the year. As the lake level fell, net inflow increased to a maximum at the end of January 1988, before declining groundwater-table levels probably caused it to decrease.

2.2 CALCULATION OF GROUNDWATER NUTRIENT LOADS

Nutrient loads from groundwater were calculated using the flow calculations as described in Section 2.1, and concentration data collected as follows.

2.2.1 BORE SAMPLING

After measurement of water levels, the inner bore of each pair was sampled using a stainless steel bucket of 150mL capacity which was lowered on a cord to the bottom of the bore. Before sampling, approximately 450mL of water was removed from the bore to rinse the bucket and bottles, and to mix the water in the bore. Two 250mL samples were then taken. One was left to stand overnight at room temperature to allow particulates to settle before being decanted into new containers and analysed by Government Chemical Laboratories for total phosphorus, conductivity and pH. The other was held close to 0°C overnight before decanting, then frozen and sent to Government Chemical Laboratories to be analysed for total nitrogen, ammonia nitrogen and nitrate. The samples contained no appreciable quantities of clay or other non-settling particulates, so settling and decanting before analysis was considered to be an acceptable alternative to filtering. This was supported by occasional analysis for dissolved orthophosphate, which showed little difference between concentrations of orthophosphate and total phosphorus.

On average, the bores were sampled on every second monitoring date, i.e. approximately fortnightly. Concentrations were interpolated between these dates. For the periods during which no samples were collected, i.e. before 24 July 1987 and after 1 March 1988, concentrations were extrapolated using the flow-weighted mean concentration for each bore during the sampling period.

2.2.2 CONCENTRATION VS DEPTH

Concentrations of nutrients are rarely uniform throughout the entire depth of an aquifer. Particularly where the nutrients originate from leaching of nutrients from soils or swamps, the concentration is generally highest in the shallow part of the aquifer and decreases with increasing depth.

Samples from slotted bores such as those used in this study provide a mean concentration of the section of the aquifer over which the slots extend (Height et al, 1987). In the case of the North Lake bores, this was approximately the top two metres of the aquifer.

In the case of the bores with high nutrient concentrations (bores 2 to 5), the top two metres of aquifer would probably contain most or all of the high-concentration water, since water at greater than that depth would have had little chance to interact with the soils of the Southern Swamp. The exact depth of water covered by each bore was calculated for each sampling date by subtracting the relative level (AHD) of the bottom of the bore from the measured water level on that date. For the remaining depth of the aquifer (approximately eight metres), background concentrations of 0.05 mg/L phosphorus and 1.1 mg/L nitrogen were assumed. These values were based on the approximate concentrations in Murdoch Drain late in the season, when all of its flow was derived from ground-water, and are within the range reported in the Perth Urban Water Balance Study (Cargeeg et al, 1987) for groundwaters in the Applecross Flow Line of the southern Perth region. These background values were used for all bores where groundwater inflow was occurring.

For the bores where groundwater outflow was occurring, the whole depth of the aquifer (approximately 10 metres) was assumed to have originated in the lake, and therefore to be well-mixed. The concentration measured in these bores was therefore taken to represent the concentration of the entire aquifer.

2.3 REFERENCES

Davidson, W A (1983). Bibra Lake Groundwater Appraisal. Geological Survey of Western Australia. Hydrology Report No.2528.

Height, M, Bayley, P, and Bettenay, E (1987). Talbot's 1985-86 Groundwater Studies. Environmental Protection Authority, Perth, Western Australia (unpublished).

John, P H and Lock, M A (1977). The Spatial Distribution of Groundwater Discharge into the Leltoral Zone of a New Zealand Lake. Journal of Hydrology 33: 391-395.

Lee, D R (1977). A Device for measuring Seepage Flux in Lakes and Estuaries. Limnology and Oceanography 22: 140-147.

Lee, D R, Cherry, J A and Pickens, J F (1980). Groundwater Transport Salt Tracer through a Sandy Lake-bed. Limnology and Oceanography 25: 45-61.

McBride, M S and Pfannkuch, H O (1975). The Distribution of Seepage within Lake-beds. T. Res. U S Geological Survey 3: 505-512.

Megirian, D, (1982). Bibra Lake Groundwater Appraisal. Geological Survey of Western Australia. Hydrology Report No.2528).

Te Chow, V, ed. (1964). Handbook of Applied Hydrology. McGraw-Hill. USA.

Townley, L R and Davidson, W A (1987). Definition of a Capture Zone for Shallow Water Table Lakes. (Submitted to Journal of Hydrology, November 1987.

Water Authority of Western Australia (1987). Perth Urban Water Balance Study. Water Authority of Western Australia, Leederville.

3. MONTHLY WATER BALANCE AND NUTRIENT BUDGETS

3.1 MONTHLY WATER BALANCE

TABLE A3.1: North Lake Monthly Water Balance - April 1987 to March 1988 (All quantities in megalitres)

MONTH	MURDOCH DRAIN	KARDINYA DRAIN	GROUND-WATER IN	GROUND-WATER OUT	RAIN -EVAP (NET)	LAKE VOL CHANGE (CALC)	LAKE VOL CHANGE (MEAS)
APRIL	23.28	4.75	19.77	-8.12	-5.46	34.22	10.56
MAY	28.76	4.54	19.71	-9.10	1.80	45.71	23.76
JUNE	28.60	5.81	18.37	-9.49	12.78	56.07	61.68
JULY	37.21	12.17	18.45	-10.51	41.96	99.28	88.60
AUGUST	34.37	24.37	16.39	-8.89	-4.31	61.93	73.84
SEPTEMBER	21.63	5.52	13.02	-8.58	-25.32	6.27	-2.52
OCTOBER	14.55	1.24	14.16	-8.23	-32.20	-10.48	-25.24
NOVEMBER	8.62	0.73	14.46	-6.37	-35.19	-17.75	-40.96
DECEMBER	5.95	0.81	16.67	-5.87	-39.53	-21.97	-50.72
JANUARY	1.20	0.00	19.52	-5.39	-38.03	-22.70	-66.04
FEBRUARY	0.00	0.00	18.37	-5.81	-47.64	-35.08	-78.24
MARCH	0.00	0.32	20.65	-7.58	-33.10	-19.71	-59.37
TOTAL	204.16	60.26	209.53	-94.00	-204.24	175.71	-64.65

3.1.1 ERRORS IN MONTHLY WATER BALANCE

Considerable differences can be seen between the calculated and measured monthly changes in lake volume. In general, the calculated water balance over-estimates increases in lake volume and under-estimates decreases. The most likely reasons for these differences, in probable order of magnitude, are:

1. Errors in conversion of evaporation pan data to lake evaporation;
2. Errors in calculation of groundwater inflows and outflows;
3. Errors in conversion of lake surface elevation data to lake volume;
4. Errors in measurement of rainfall and drain flows.

Because the major source of nutrients (Murdoch Drain) is also the one which is probably the least subject to errors in measurement, the effect of these discrepancies in the water balance should have only minor impact on the accuracy of the nutrient budget.

3.2 MONTHLY NUTRIENT BUDGET

TABLE A3-2: North Lake Monthly Nutrient Budget - April 1987 to March 1988 (All quantities in kilograms)

MONTH	MURDOCH DRAIN		KARDINYA DRAIN		GROUND-WATER IN		GROUND-WATER OUT		CHANGE IN LAKE STORE	
	TP	TN	TP	TN	TP	TN	TP	TN	TP	TN
APR	40.78	93.54	4.05	13.74	6.33	19.00	2.25	29.68	48.91	96.60
MAY	106.32	121.36	3.87	13.13	6.09	19.99	2.41	30.56	113.87	123.92
JUN	32.55	54.11	5.01	17.83	5.45	19.69	2.40	29.47	40.61	62.16
JUL	29.43	60.34	3.53	21.24	5.19	20.07	2.54	30.35	35.61	71.30
AUG	24.80	48.15	2.95	45.09	4.81	21.06	2.92	30.24	29.64	84.06
SEP	14.31	42.57	0.92	9.26	3.87	20.23	2.42	28.98	16.68	43.08
OCT	7.00	34.05	0.46	2.05	6.32	15.19	2.74	36.25	11.04	15.04
NOV	2.65	13.84	2.22	3.14	5.87	10.71	2.83	44.65	7.91	-16.96
DEC	1.62	9.08	1.54	2.40	5.92	13.93	1.97	39.65	7.11	-14.24
JAN	0.11	1.45	0.00	0.00	6.67	15.58	1.75	36.98	5.03	-19.95
FEB	0.00	0.00	0.00	0.00	6.12	15.47	1.76	31.15	4.36	-15.68
MAR	0.00	0.00	0.42	1.23	6.79	18.68	2.20	31.99	5.01	-12.08
TOTAL	259.37	478.48	24.98	129.11	69.43	210.24	28.19	399.95	325.59	417.88

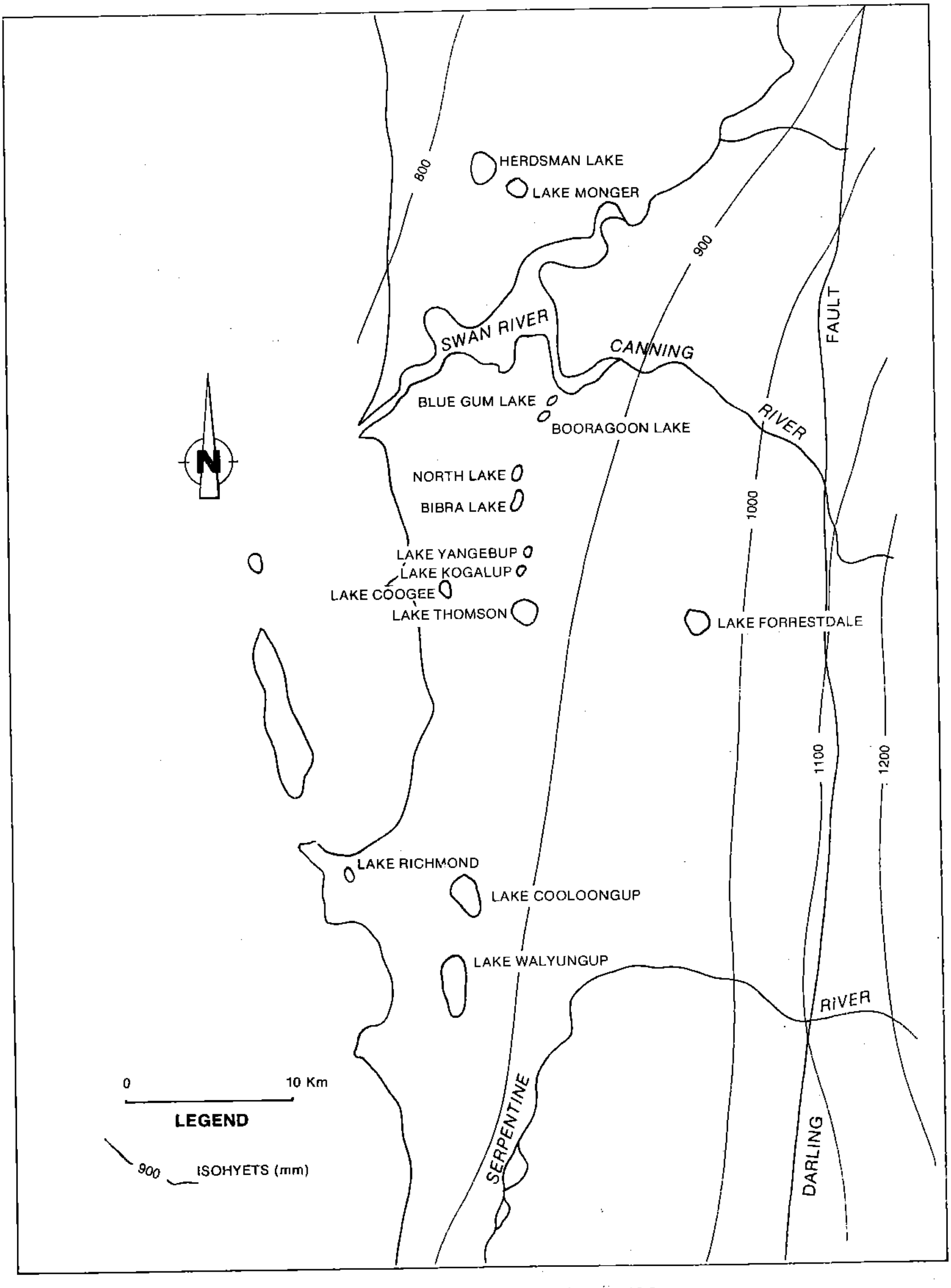

FIGURE 1. **LOCALITY MAP WITH RAINFALL ISOHYETS**

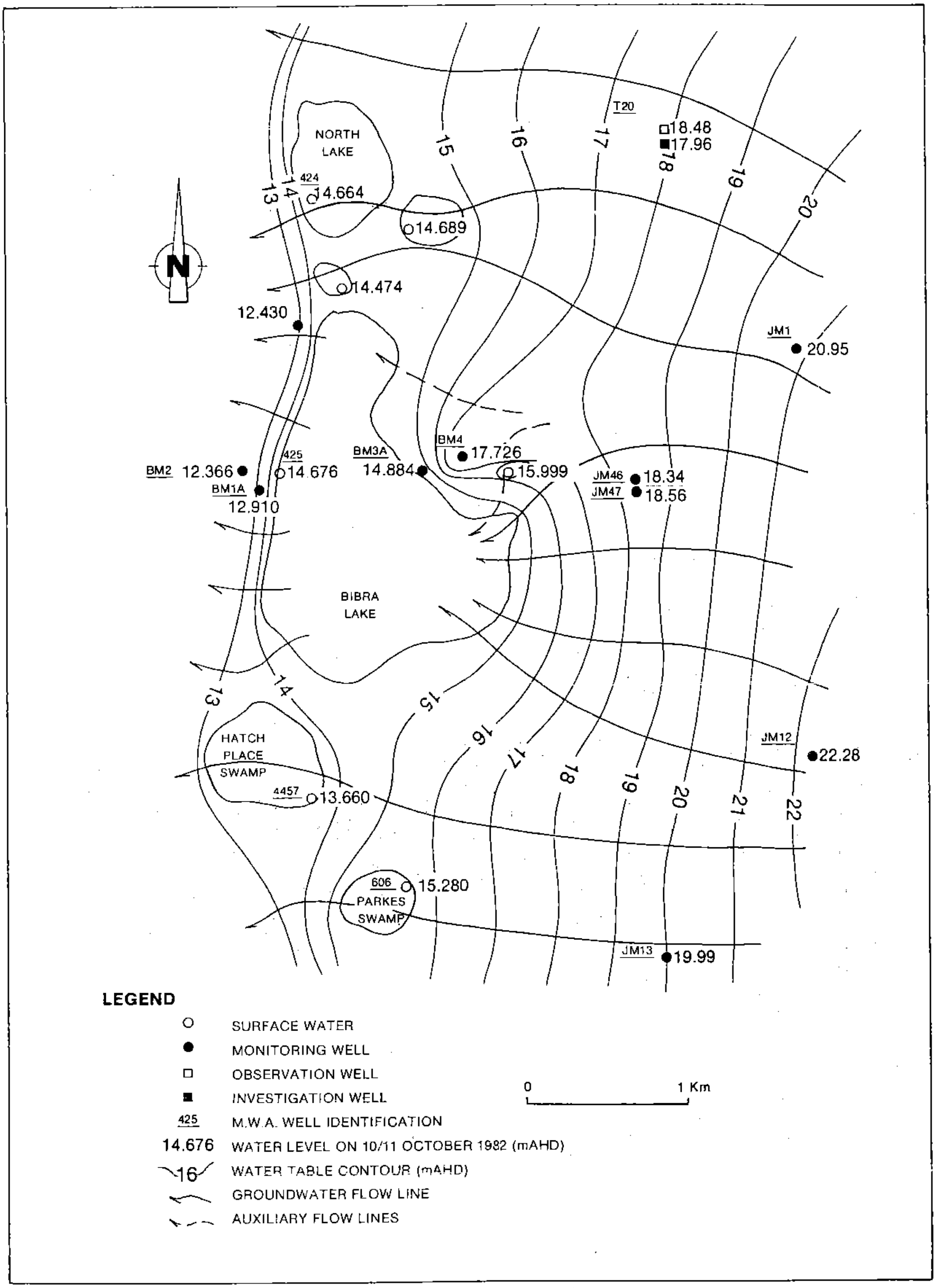

FIGURE 2. **LOCAL GROUNDWATER FLOW NET FOR OCTOBER 10/11, 1982**

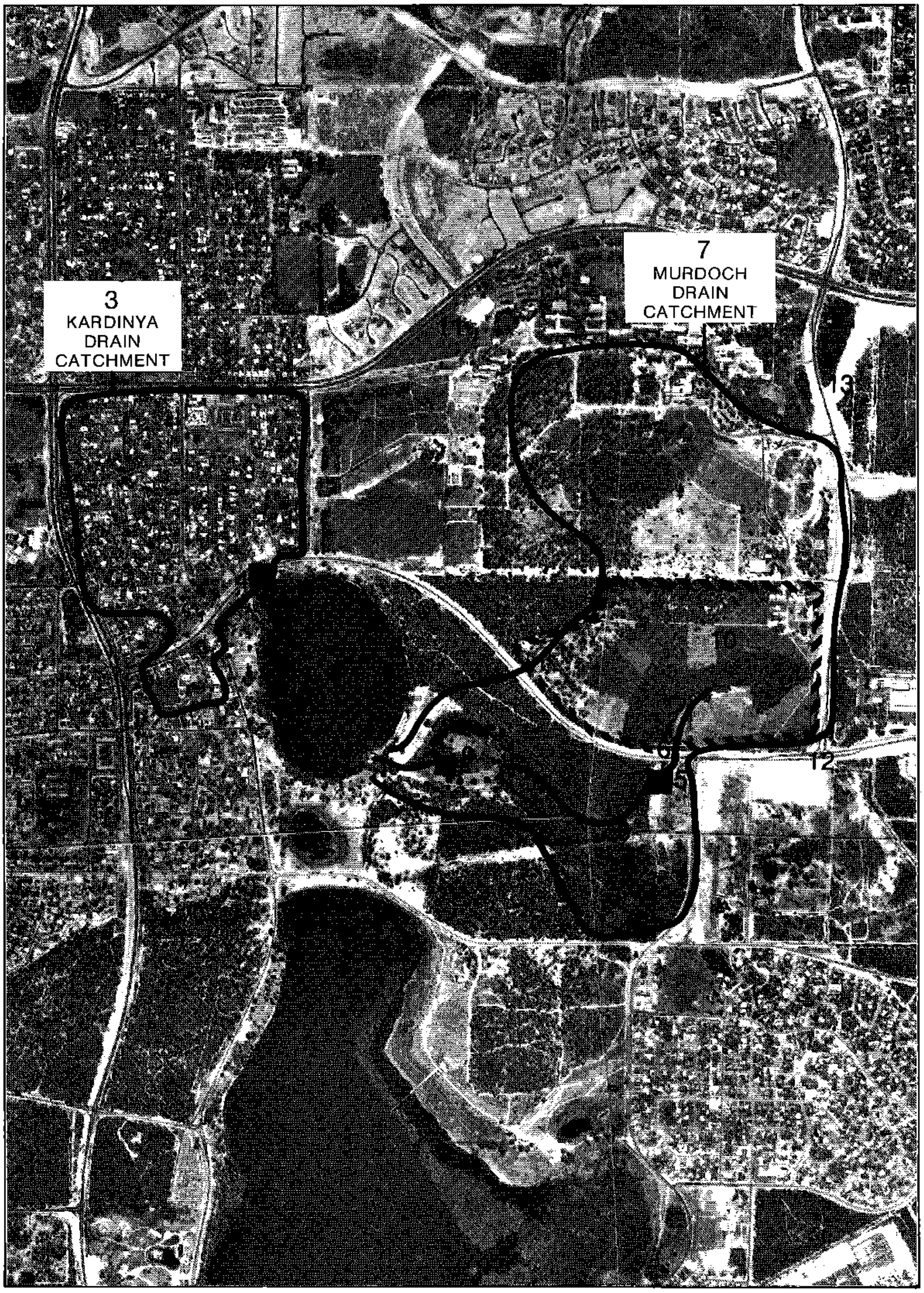

FIGURE 3.

1. NORTH LAKE
2. BIBRA LAKE
3. KARDINYA DRAIN CATCHMENT
4. KARDINYA DRAIN WEIR ■
5. MURDOCH DRAIN WEIR ■
6. MURDOCH DRAIN CULVERT
7. MURDOCH DRAIN CATCHMENT
8. MURDOCH DRAIN
9. SOUTHERN SWAMP
10. MURDOCH VETERINARY FARM ▬ ▬ ▬
11. SOUTH STREET
12. FARRINGTON ROAD
13. MURDOCH DRIVE

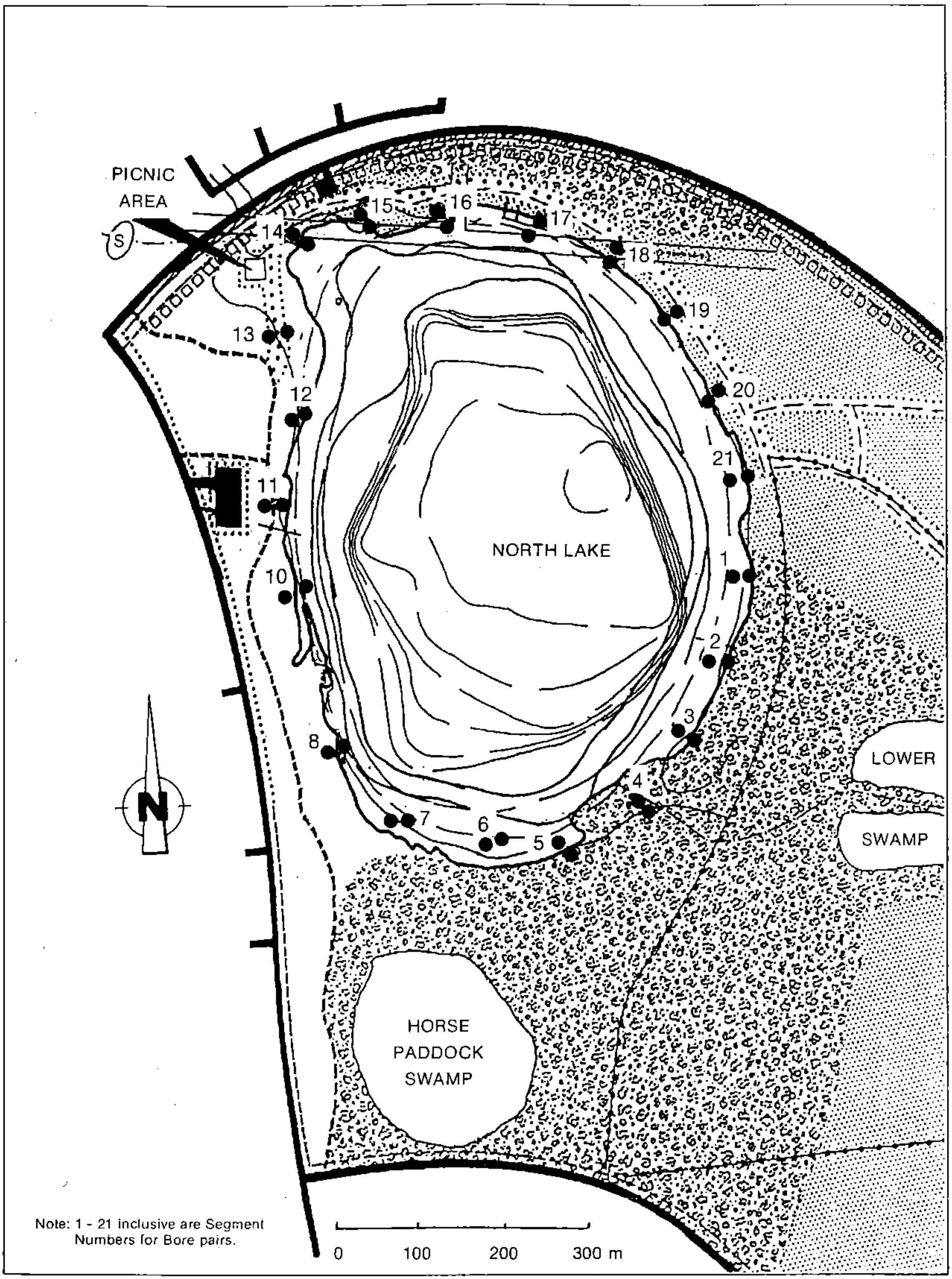

FIGURE 4. **BATHYMETRY, MONITORING BORES, LIMIT OF BOTTOM SEDIMENTS**

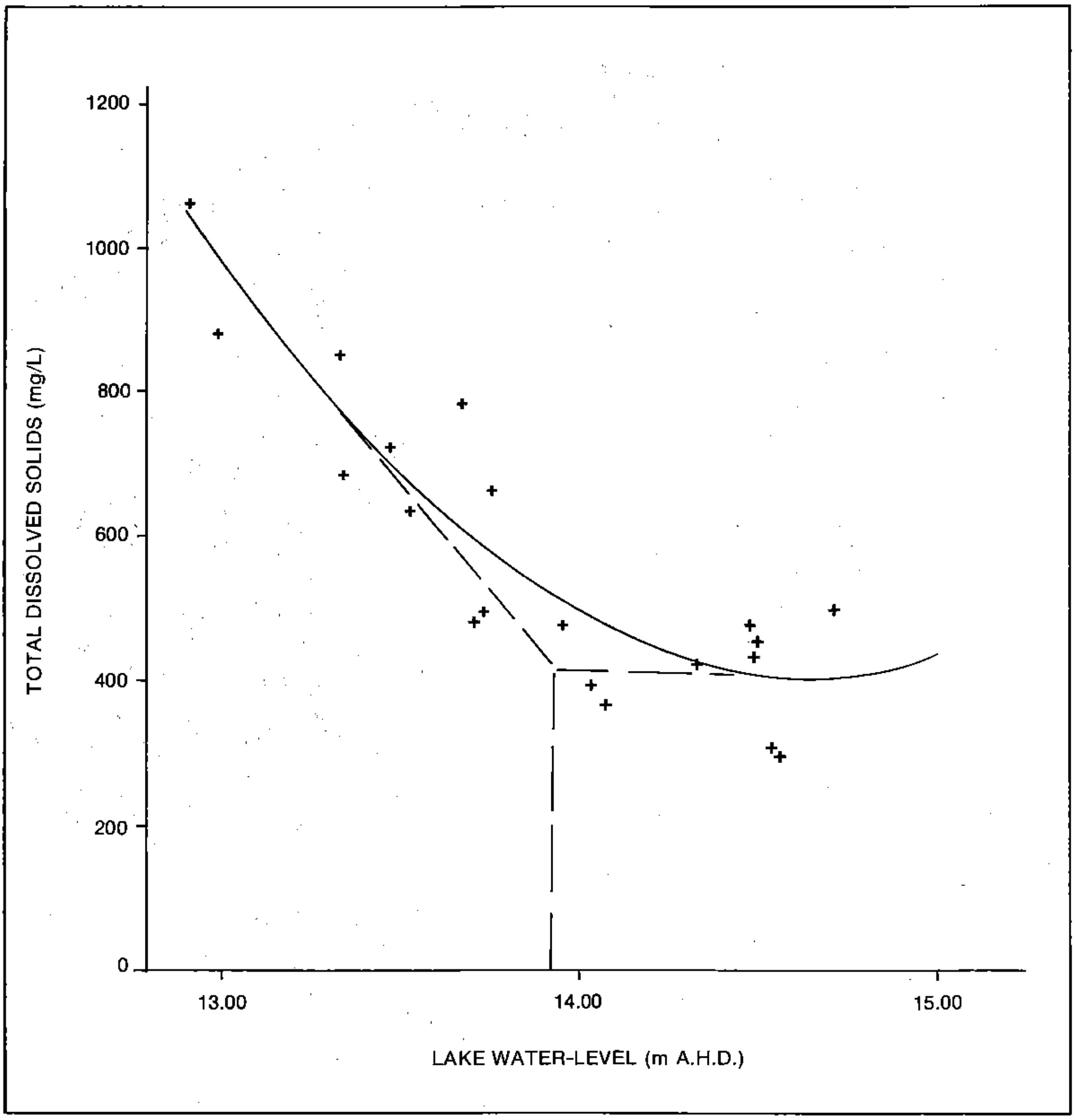

FIGURE 5.

TOTAL DISSOLVED SOLIDS/WATER-LEVEL CURVE; NORTH LAKE

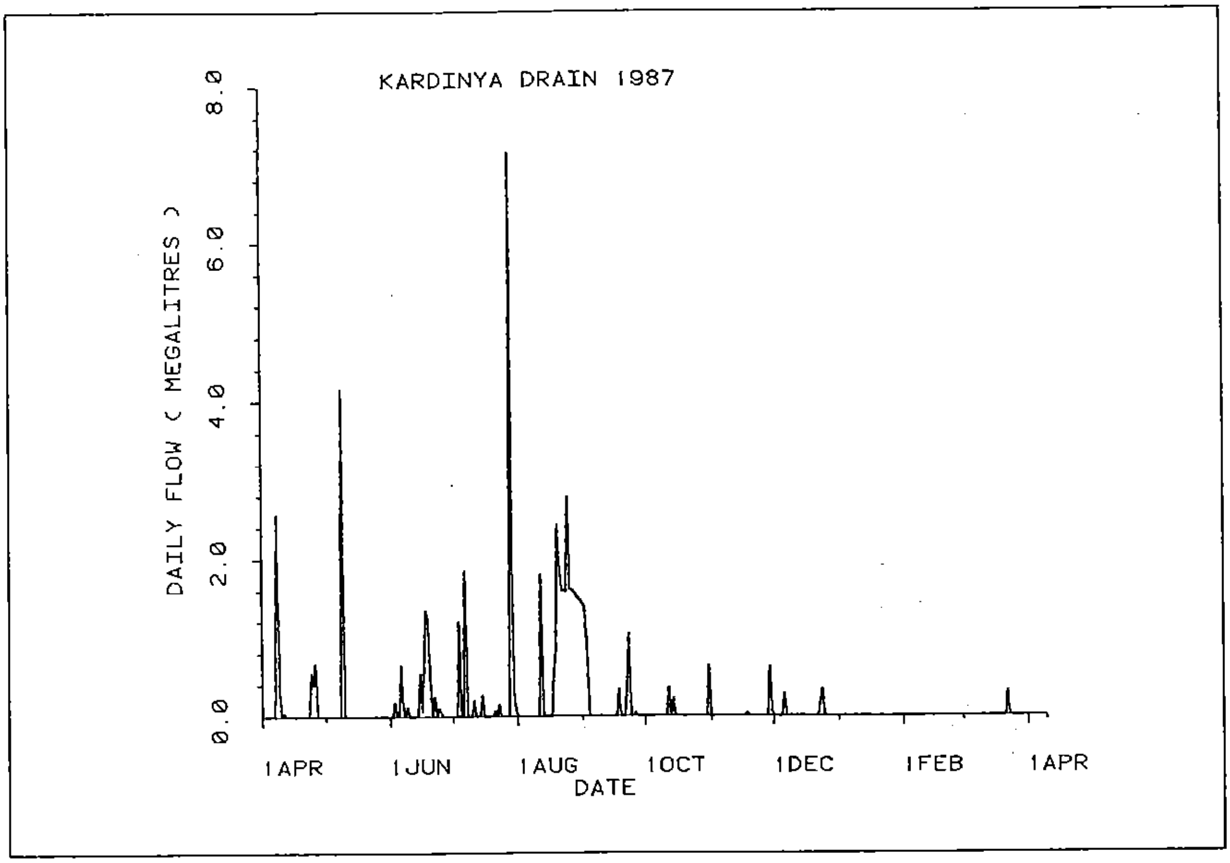

FIGURE 6. **DAILY FLOW IN KARDINYA DRAIN**

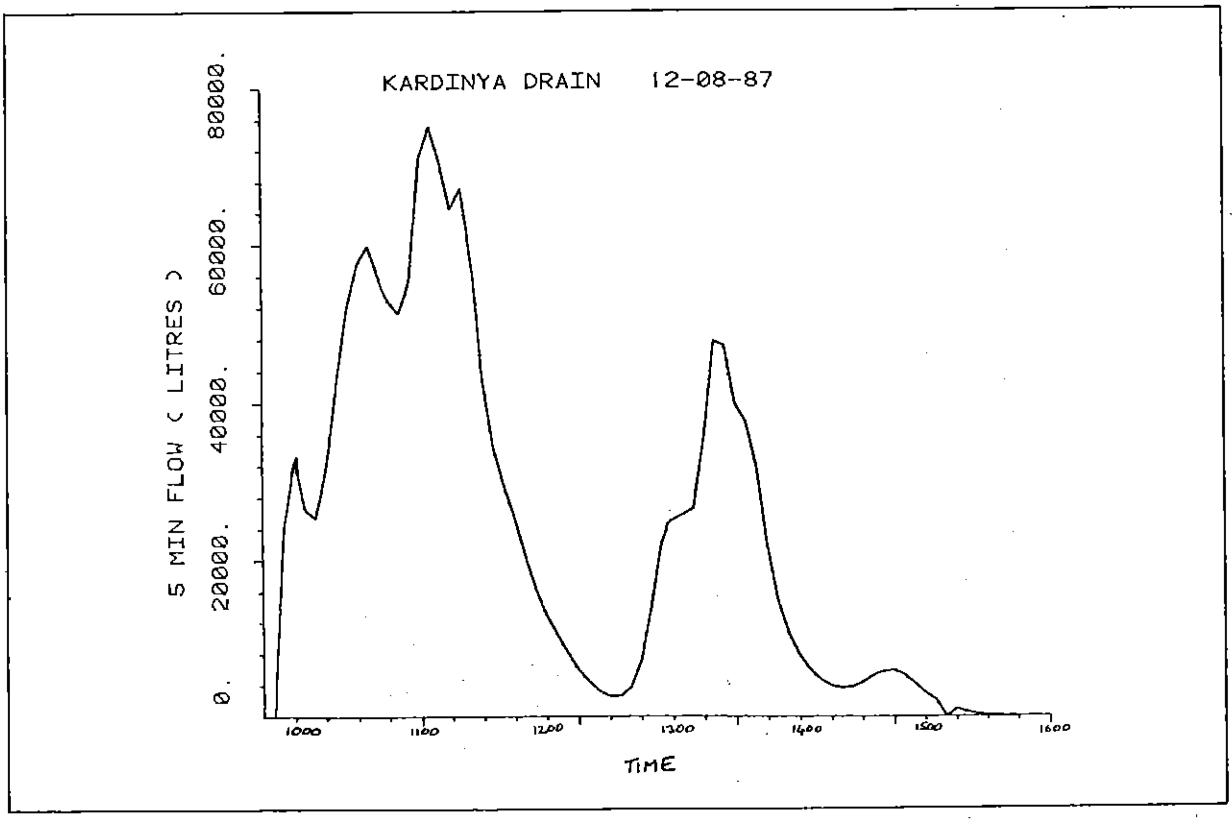

FIGURE 7. **INSTANTANEOUS FLOW KARDINYA DRAIN**

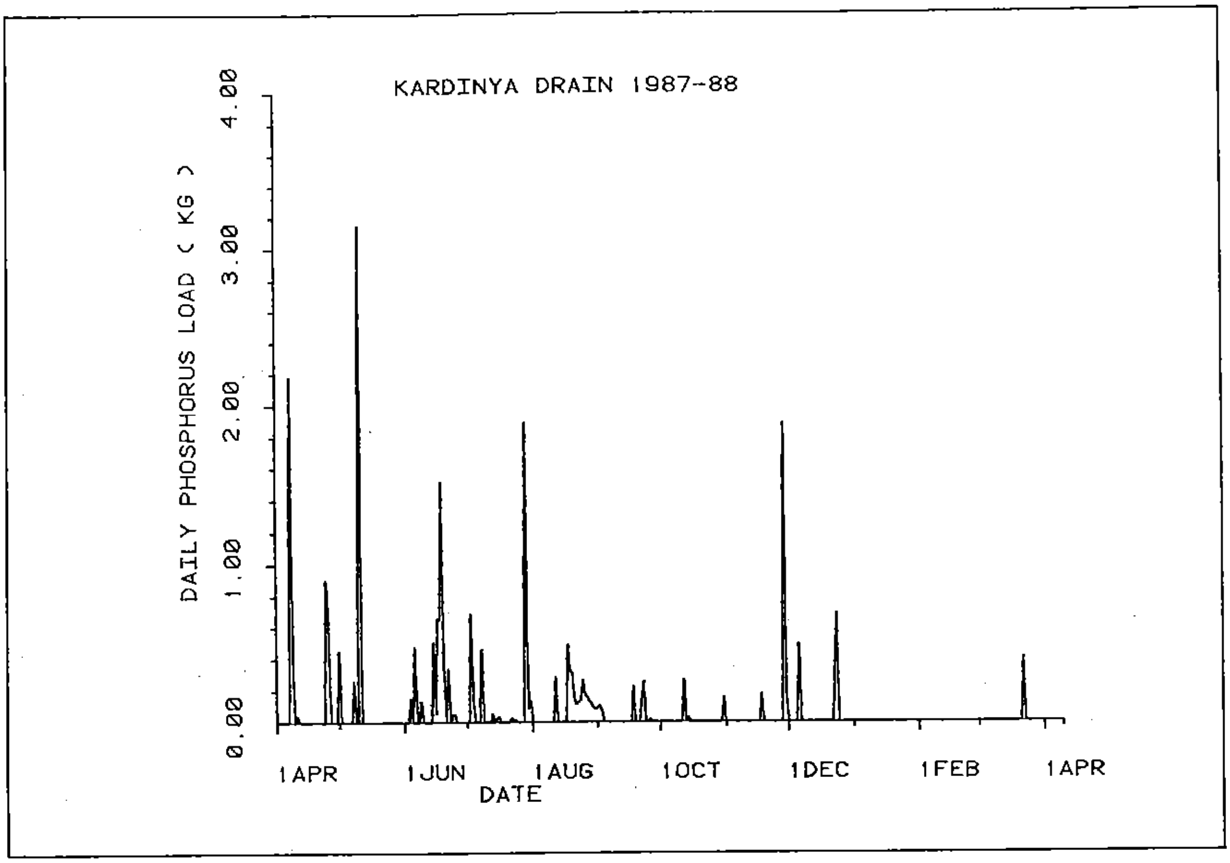

FIGURE 8. **DAILY PHOSPHORUS LOAD KARDINYA DRAIN**

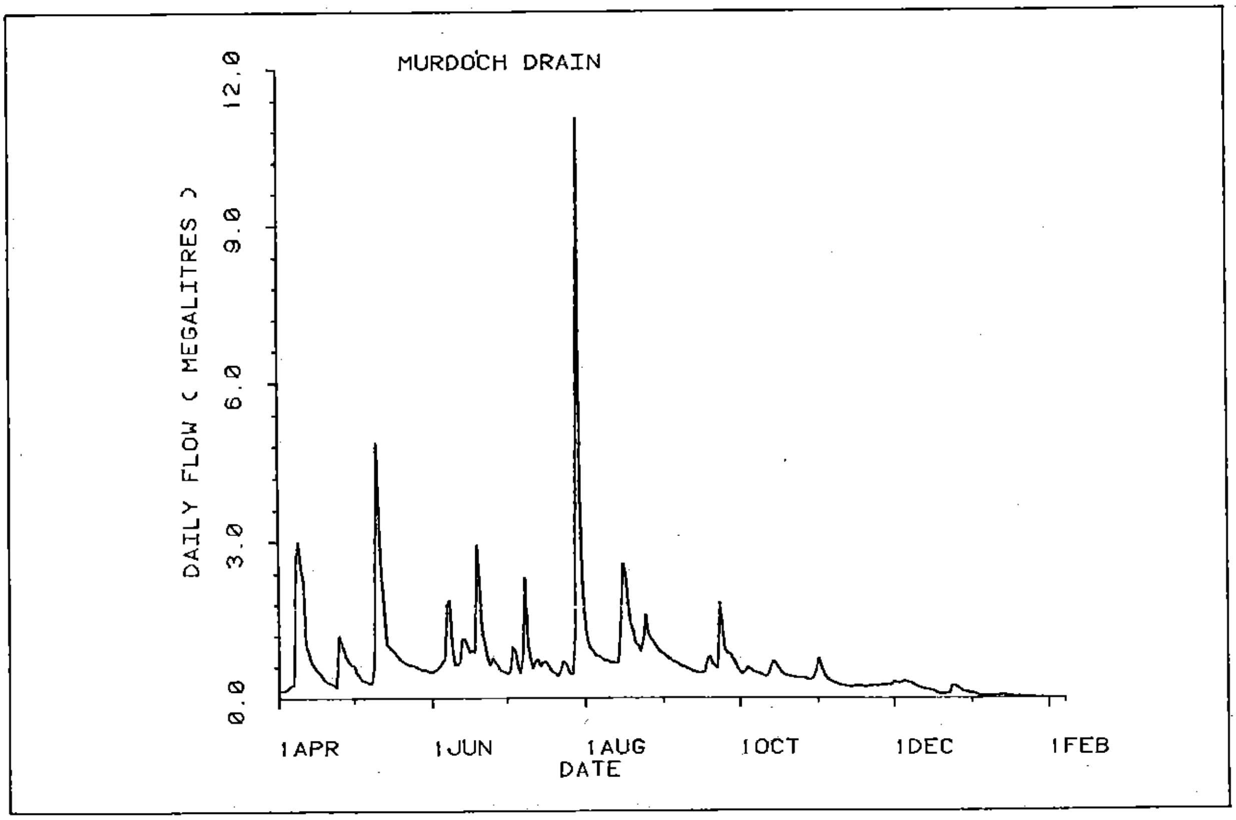

FIGURE 9. **DAILY FLOW IN MURDOCH DRAIN**

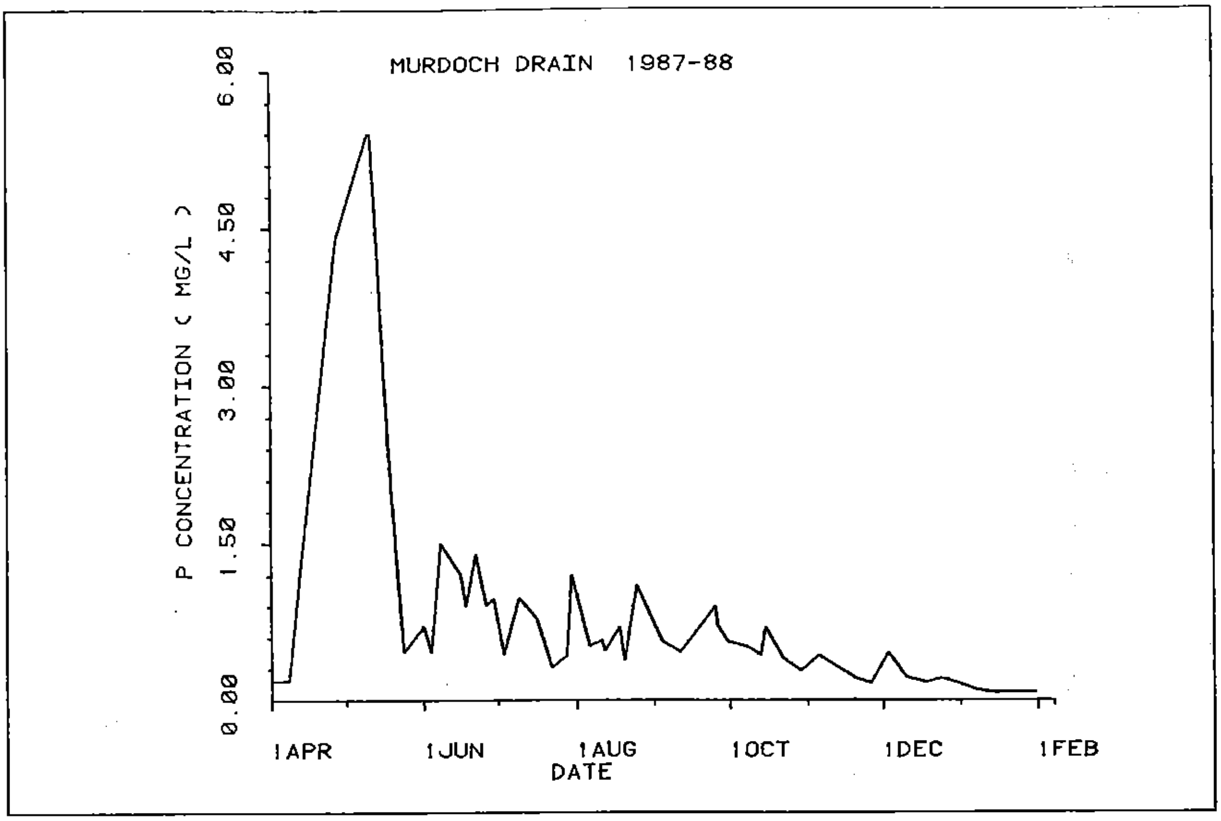

FIGURE 10. **DAILY P CONCENTRATION IN MURDOCH DRAIN**

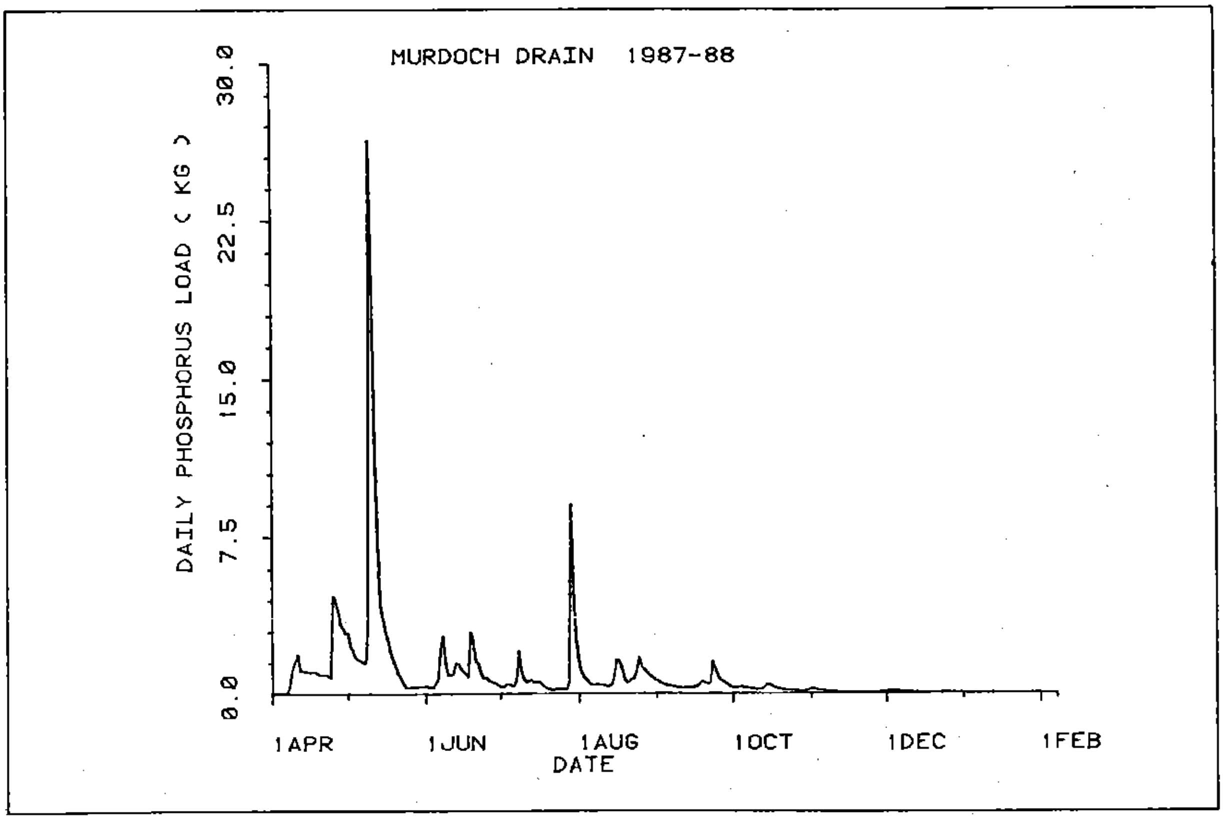

FIGURE 11. **DAILY PHOSPHORUS LOAD IN MURDOCH DRAIN**

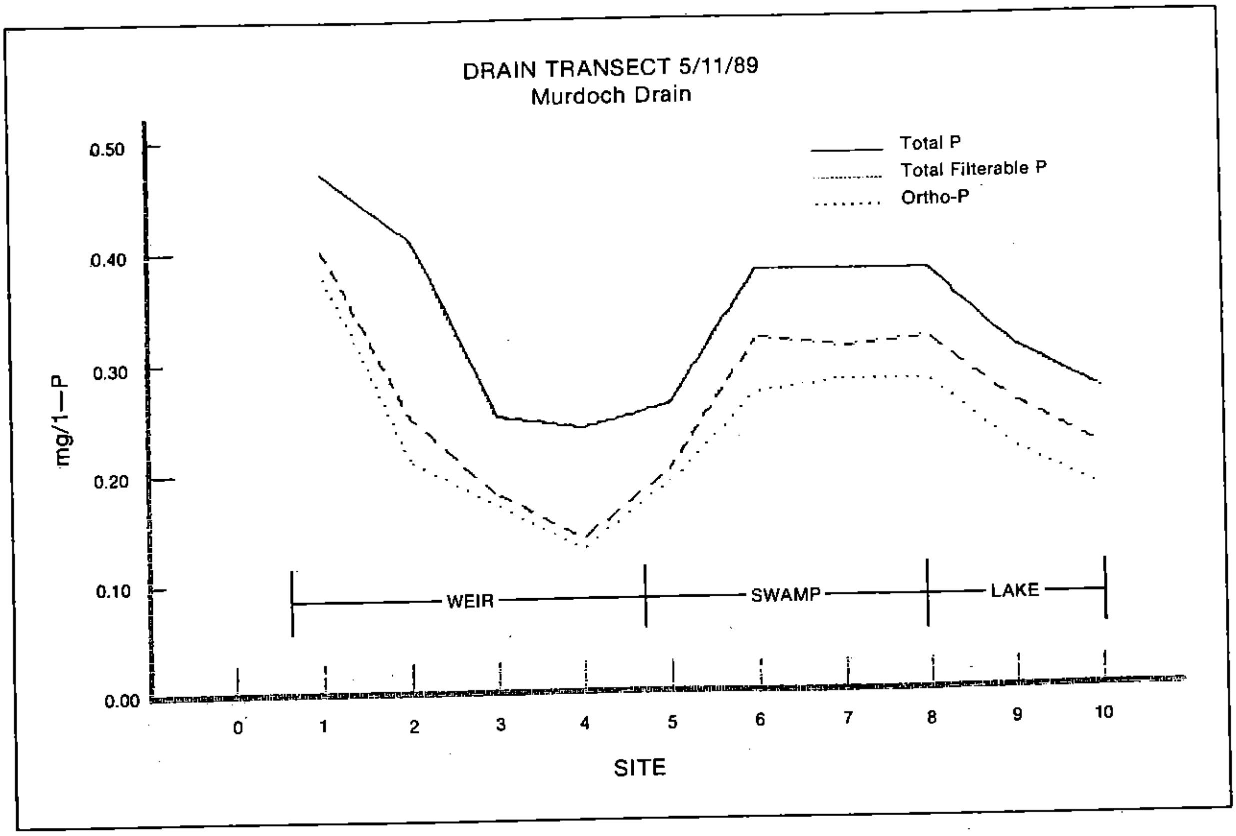

FIGURE 12. **PHOSPHORUS CONCENTRATIONS IN MURDOCH DRAIN TAKEN FROM A TRANSECT FROM THE WEIR TO NORTH LAKE, 5/11/89**

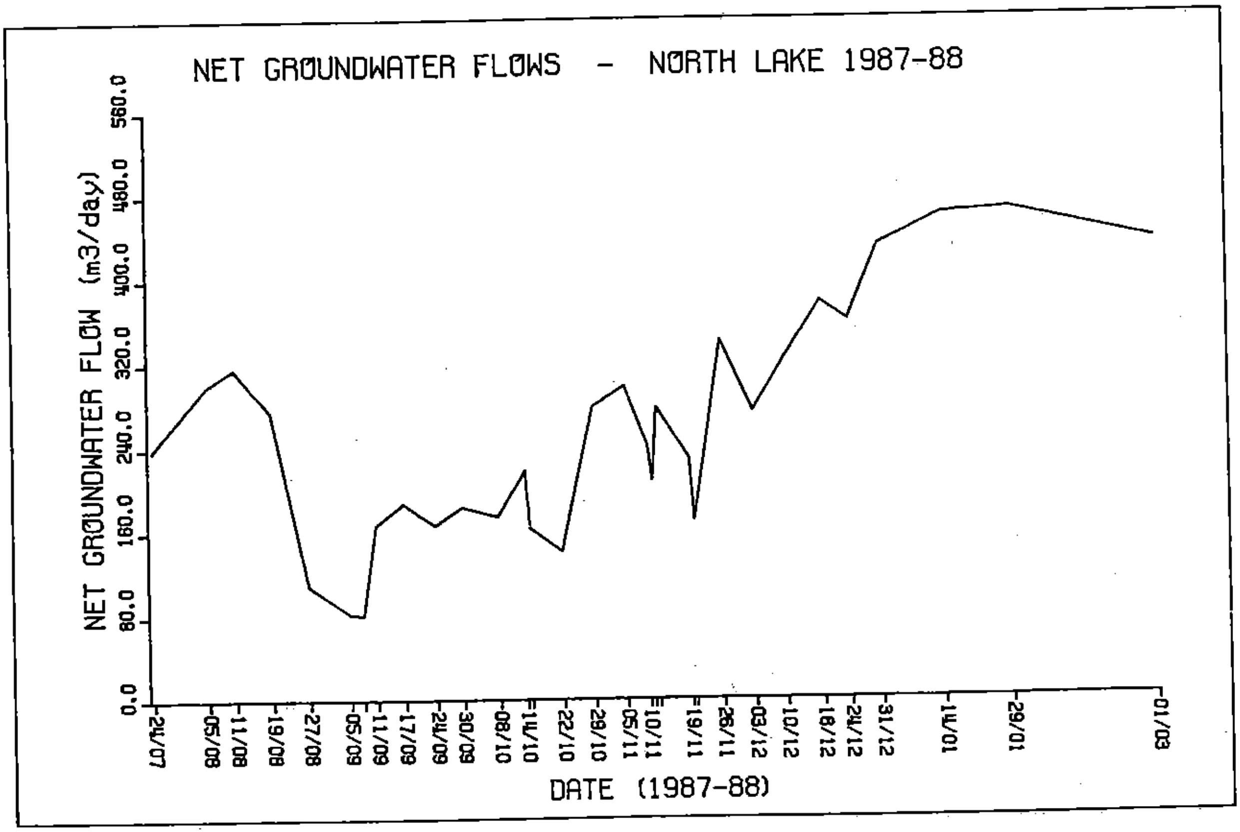

FIGURE 13. **DAILY NET GROUNDWATER FLOW TO NORTH LAKE**

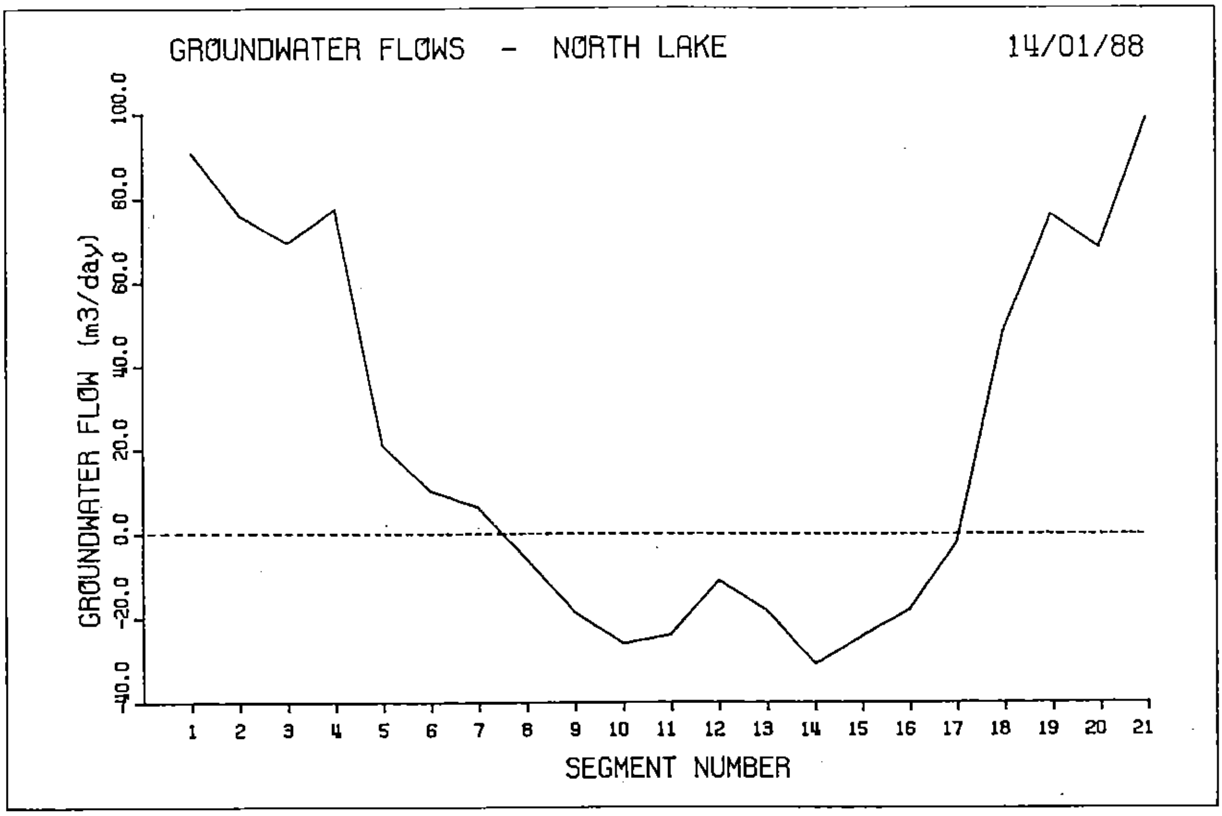

FIGURE 14. **GROUNDWATER FLOW AT NORTH LAKE 14.1.88**

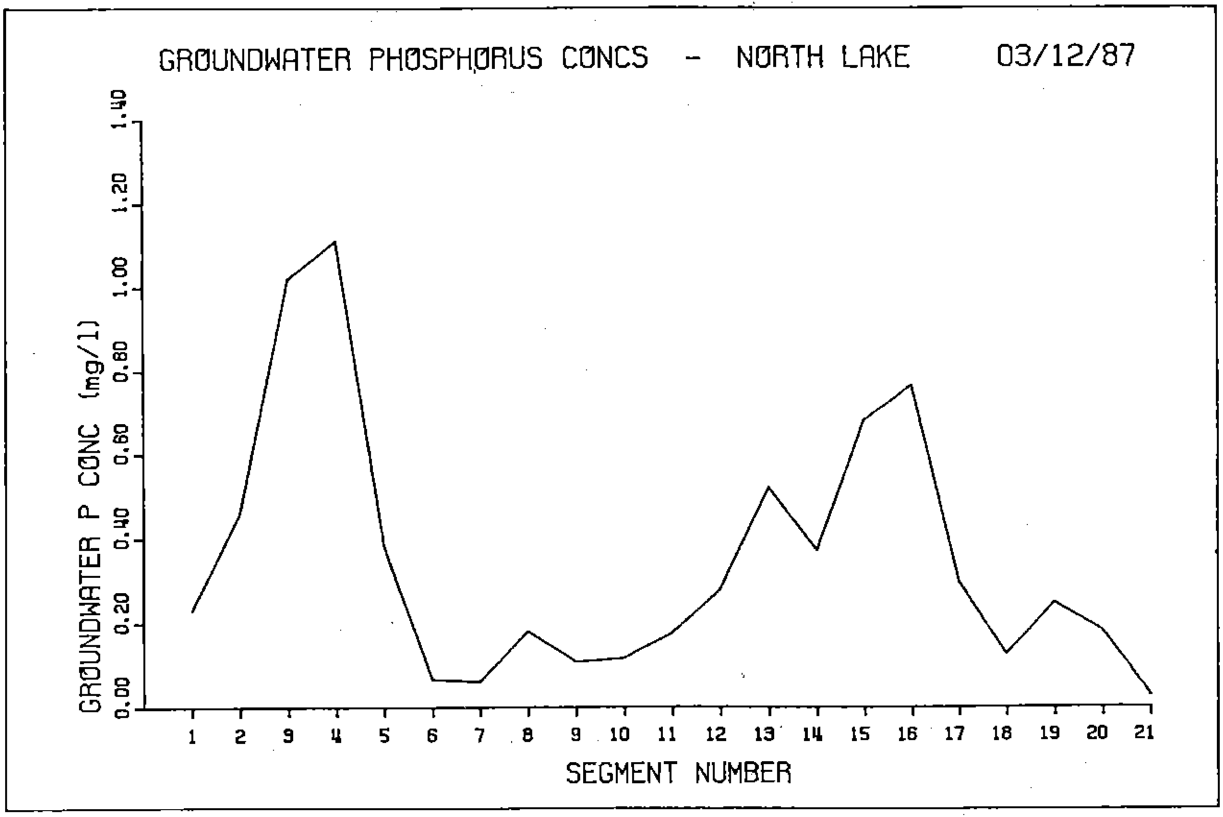

FIGURE 15. **GROUNDWATER PHOSPHORUS CONCENTRATIONS FROM SAMPLES TAKEN FROM PERIMETER BORES**

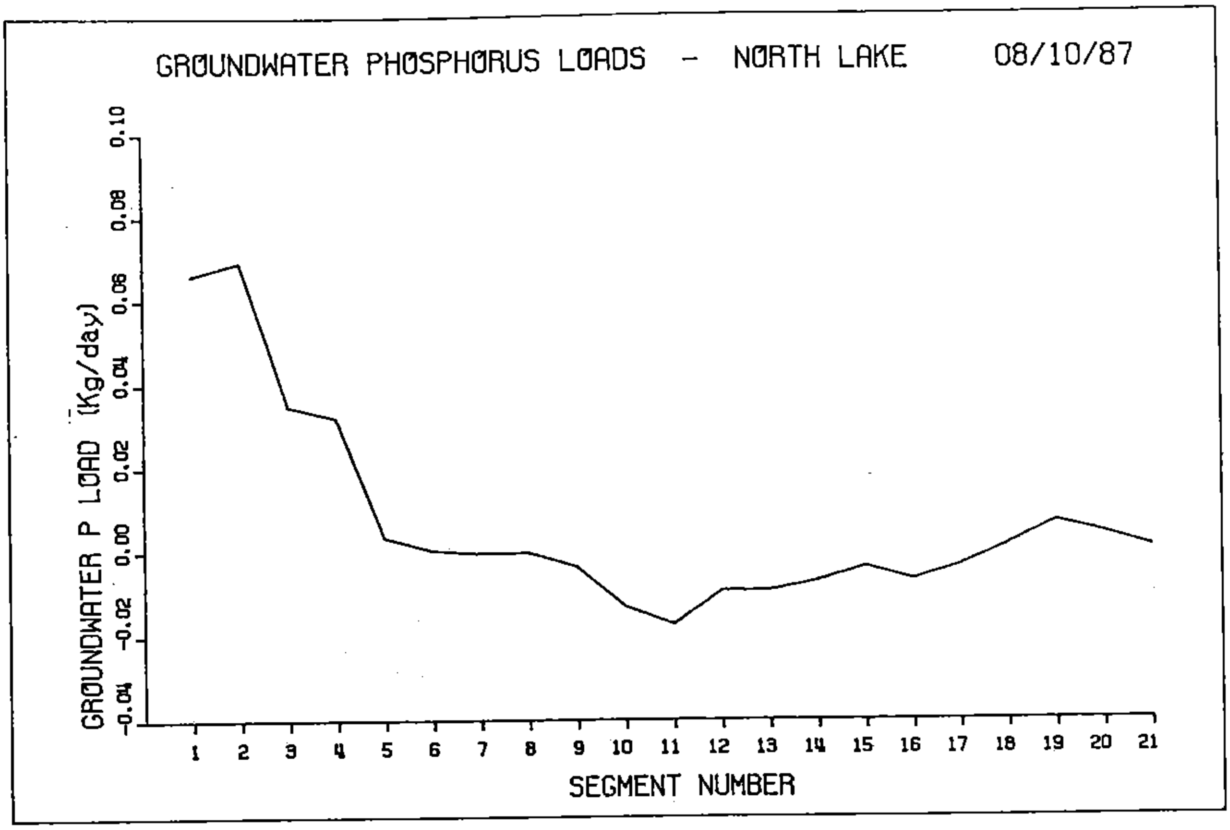

FIGURE 16. **GROUNDWATER PHOSPHORUS LOADS (kg/day) IN SAMPLES TAKEN FROM PERIMETER BORES AROUND NORTH LAKE**

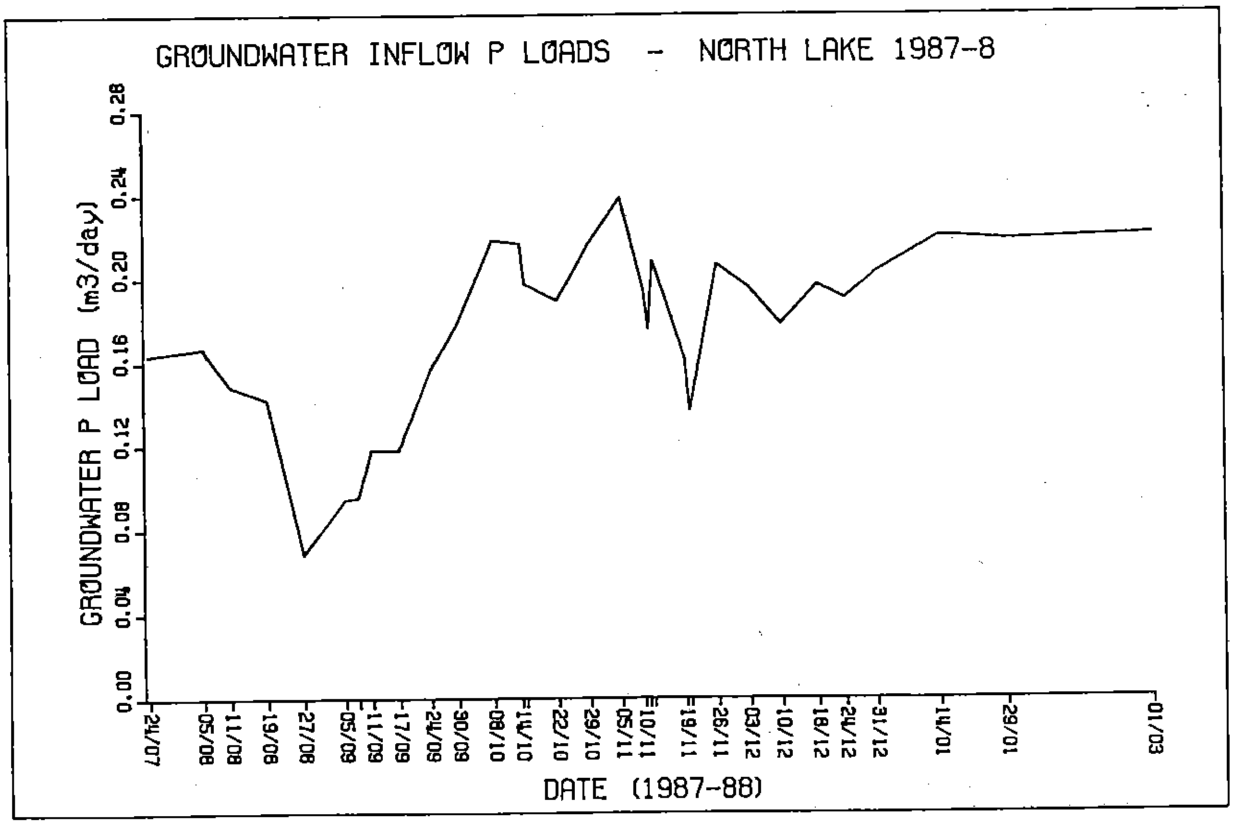

FIGURE 17. **GROUNDWATER INFLOW PHOSPHORUS LOADS TO NORTH LAKE**

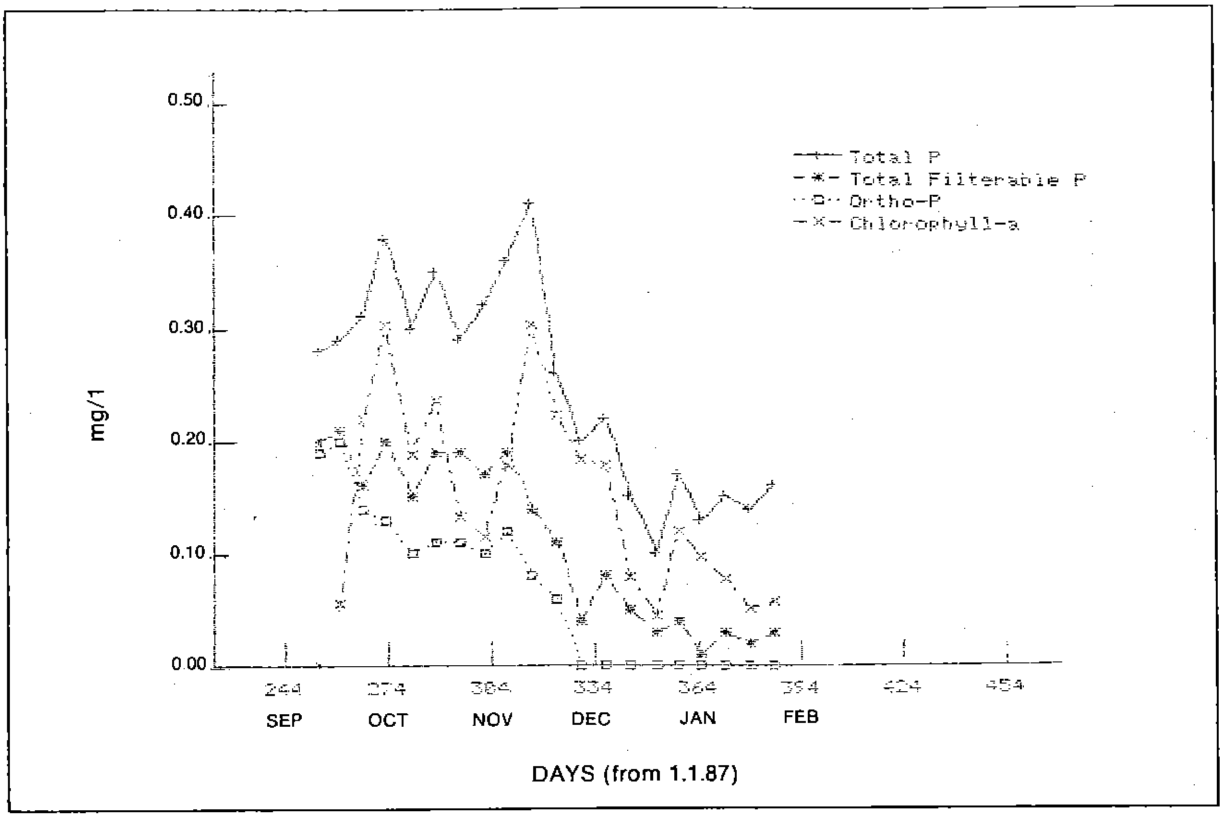

FIGURE 18. **WEEKLY AVERAGE NUTRIENT STATUS IN NORTH LAKE FOR TOTAL P, TOTAL FILTERABLE P, ORTHO—P AND CHLOROPHYLL—A**

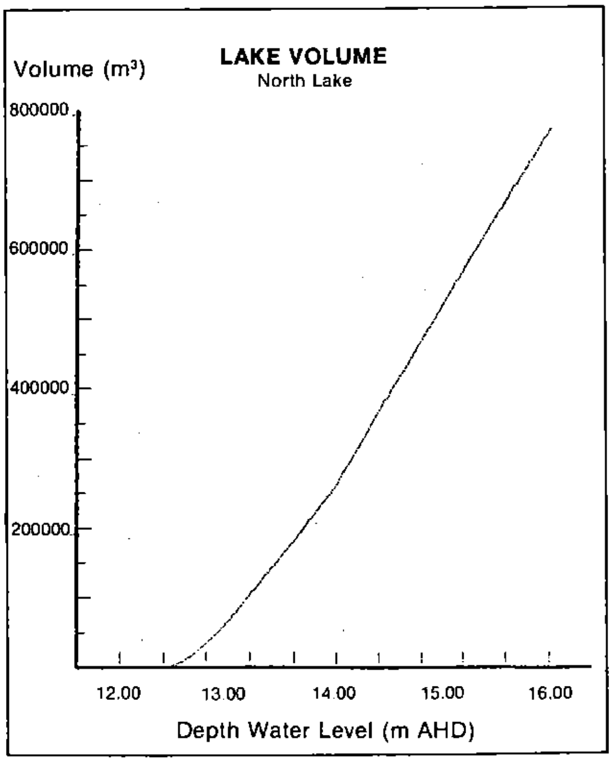

FIGURE 19. **NORTH LAKE CURVE OF LAKE VOLUME (m^3) VERSUS WATER LEVEL**

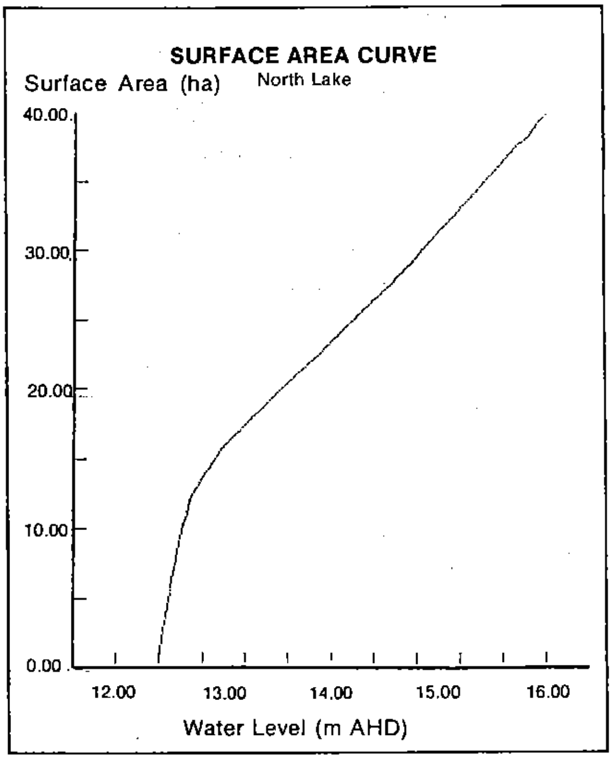

FIGURE 20. **NORTH LAKE CURVE OF SURFACE AREA (ha) VERSUS WATER LEVEL**

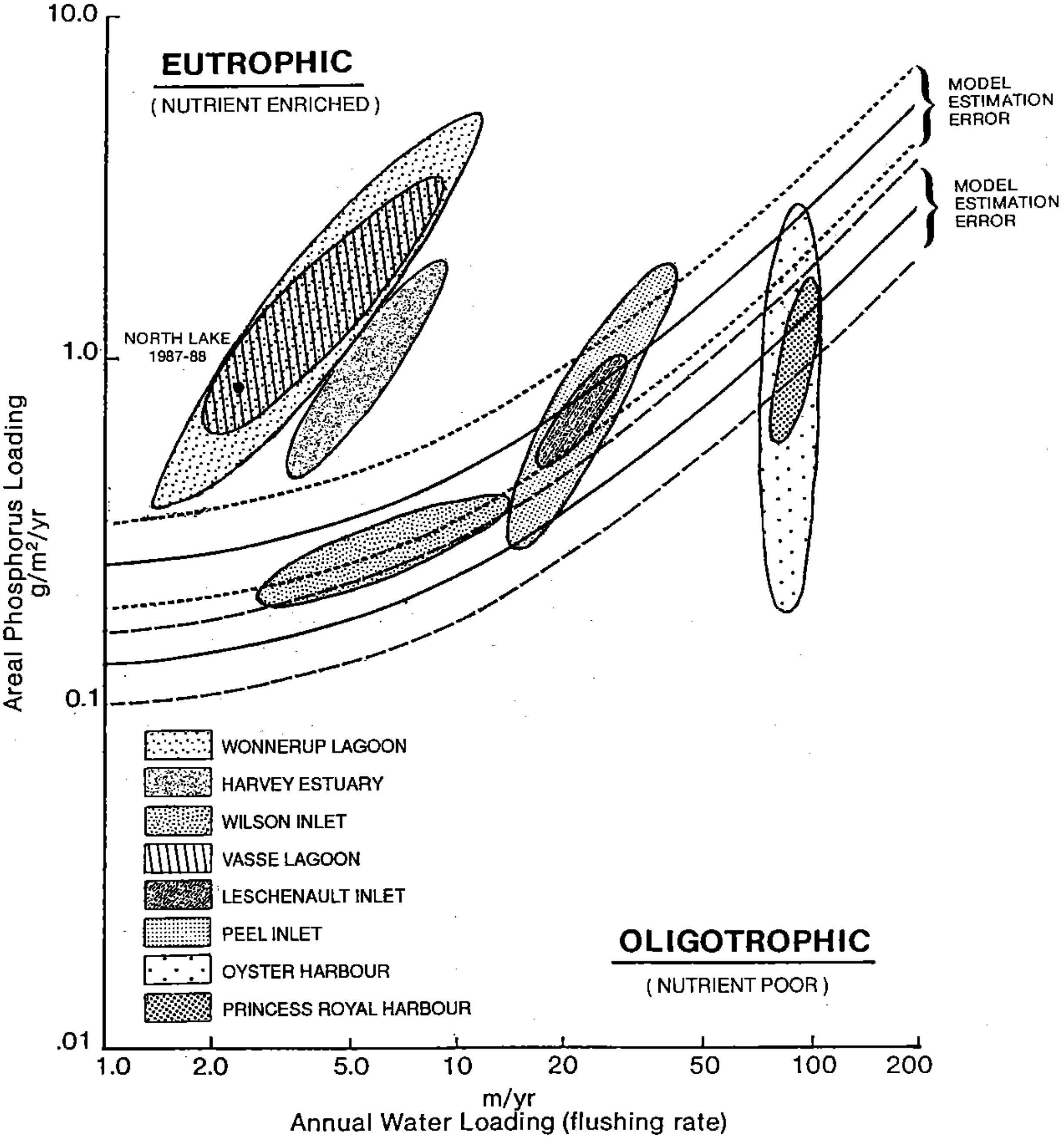

FIGURE 21.

Trophic status of some south west estuaries estimated from Vollenweiders phosphorus loading criteria (as adapted from KH Reckhow, Lake Data Analysis and Nutrient Budget Modelling).

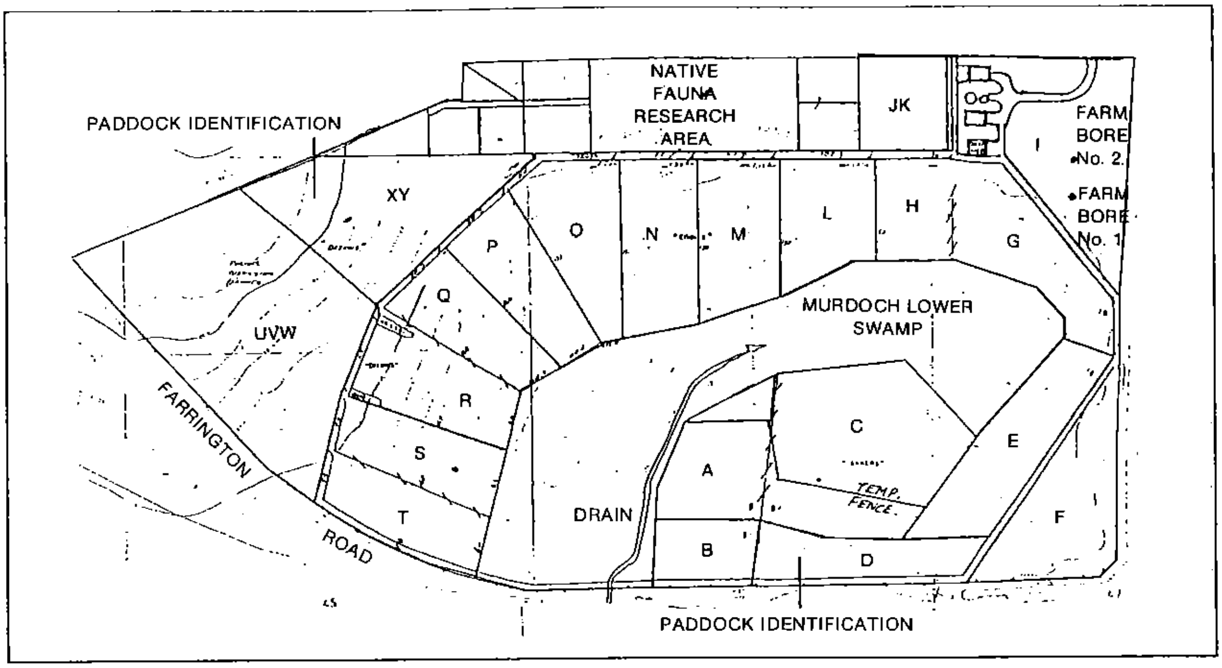

FIGURE 22. **MURDOCH UNIVERSITY VETERINARY FARM**

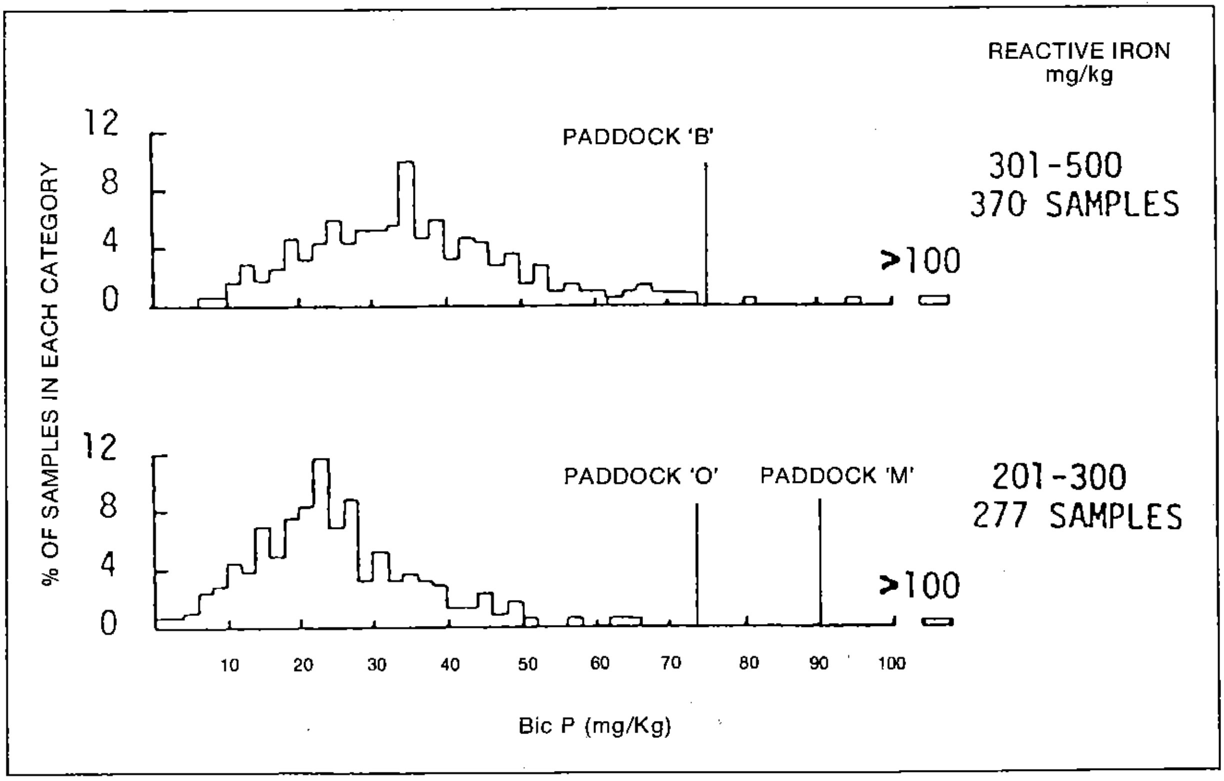

FIGURE 23.

Results of Bicarbonate extractable P measurements on 0-10 on soil samples collected from developed soil of the Peel — Harvey Estuarine system catchment of the Swan Coastal Plain, Summer/Autum 1985 (after Yeates 1985) compared with samples from the Murdoch Veterinary Farm

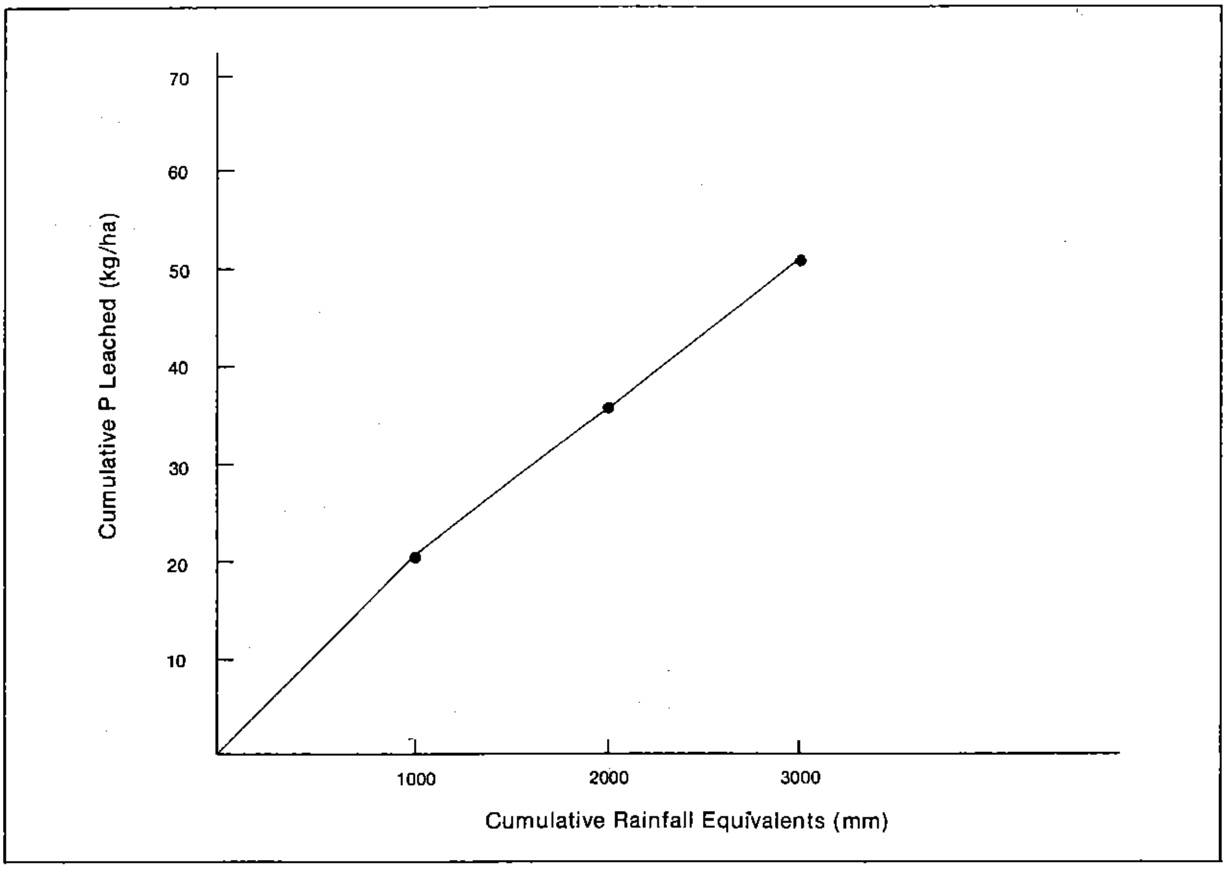

FIGURE 24. **P LEACHED FROM AN UNDISTURBED CORE OF VETERINARY FARM SOIL AS A FUNCTION OF RAINFALL EQUIVALENTS**

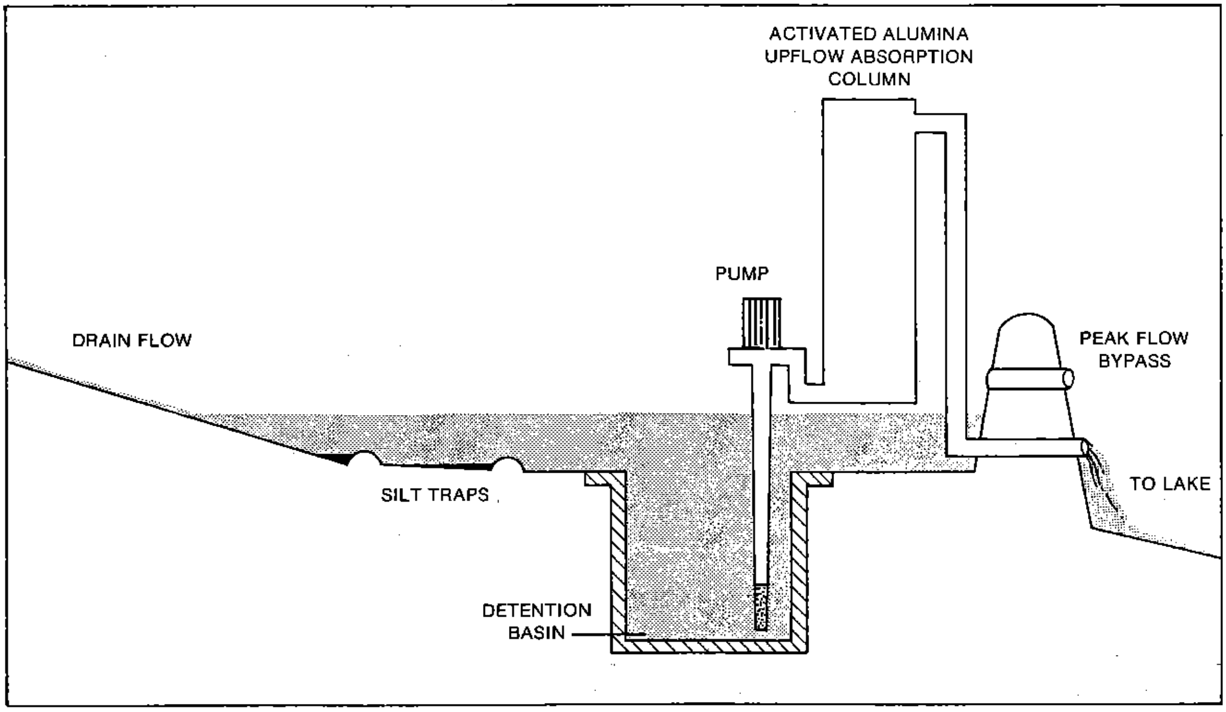

FIGURE 25. **CONCEPTUAL SKETCH OF ACTIVATED ALUMINA ADSORPTION SYSTEM**

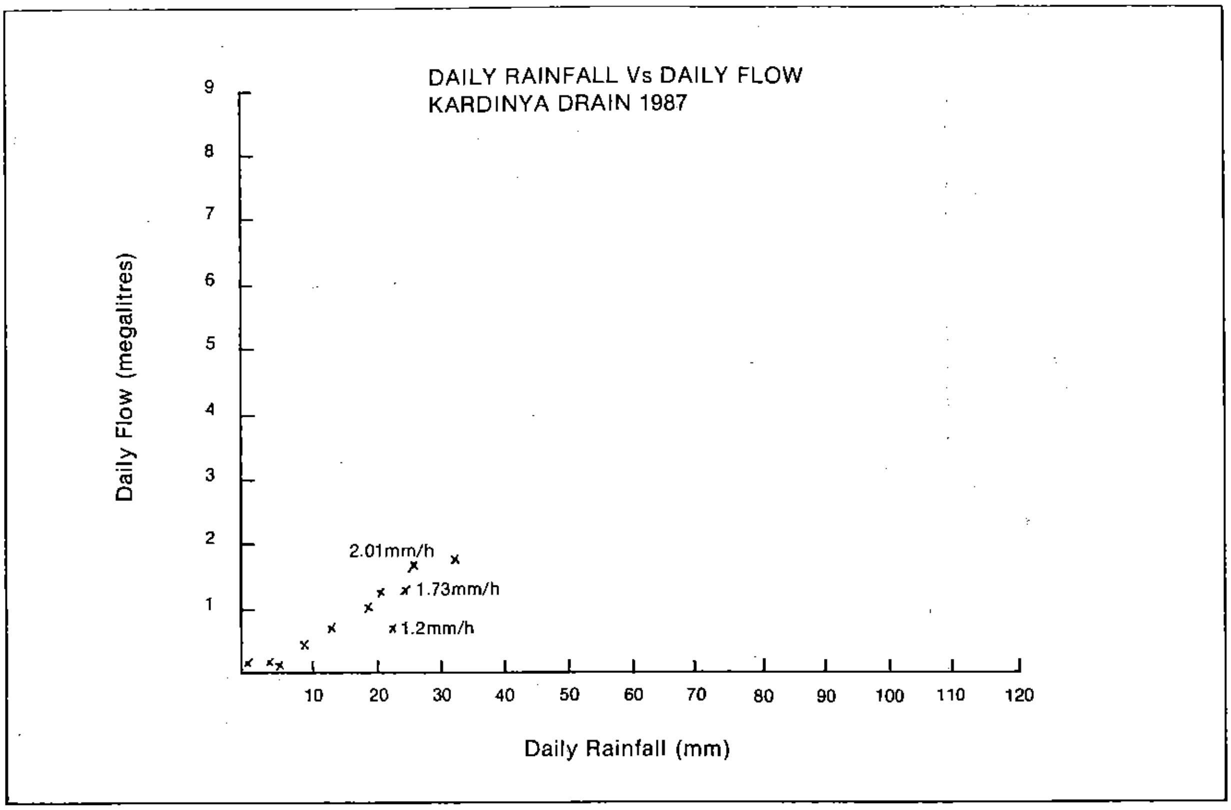

FIGURE A1-1 **DAILY RAINFALL VERSUS DAILY DRAIN FLOW KARDINYA DRAIN**

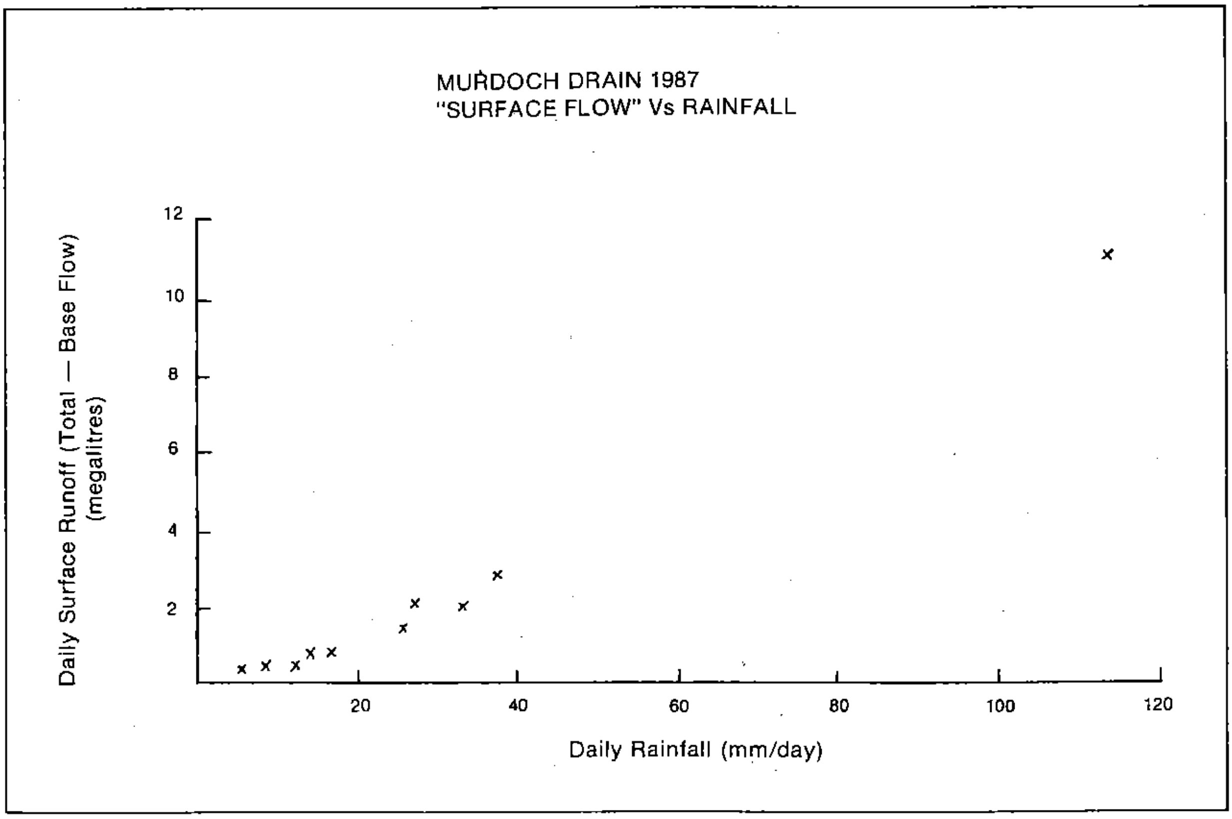

FIGURE A1-2 **DAILY RAINFALL VERSUS DAILY DRAIN FLOW MURDOCH DRAIN**

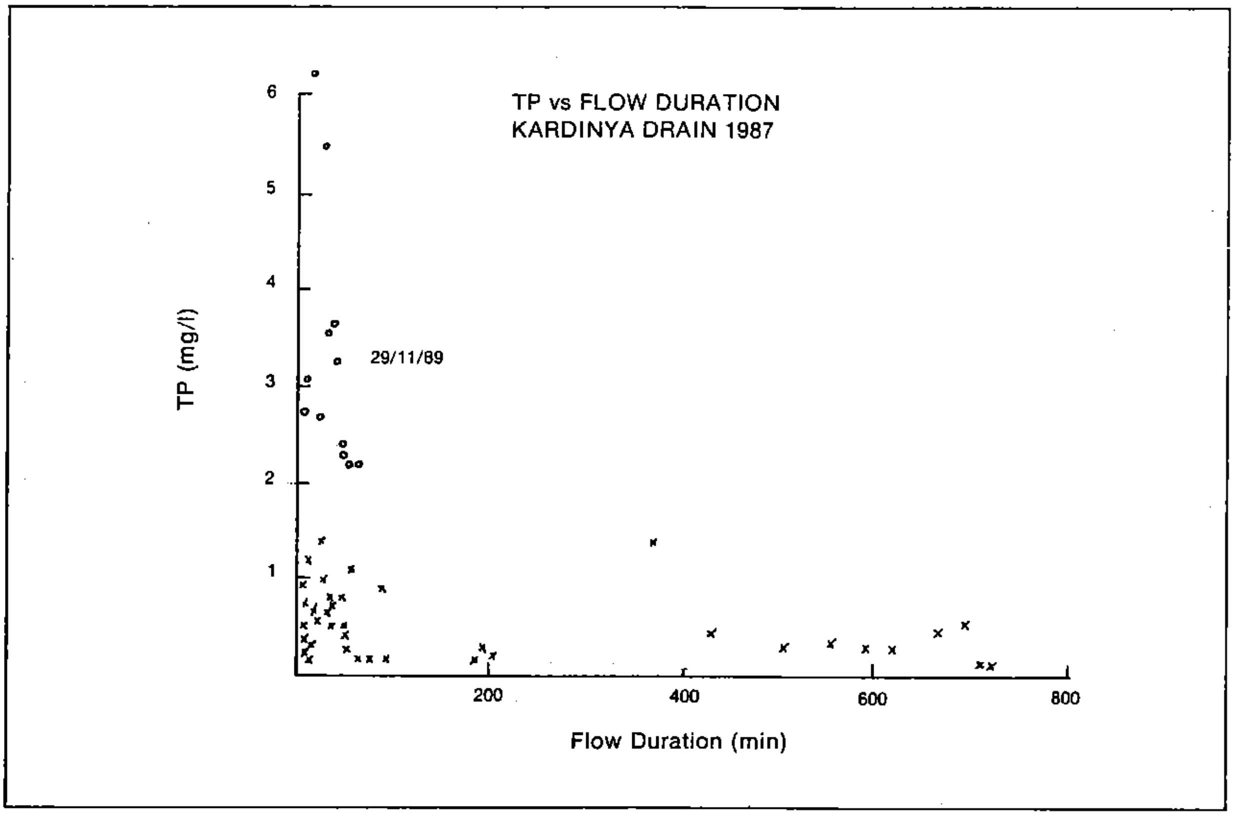

FIGURE A1-3 **TOTAL PHOSPHORUS VERSUS FLOW DURATION FOR KARDINYA DRAIN**

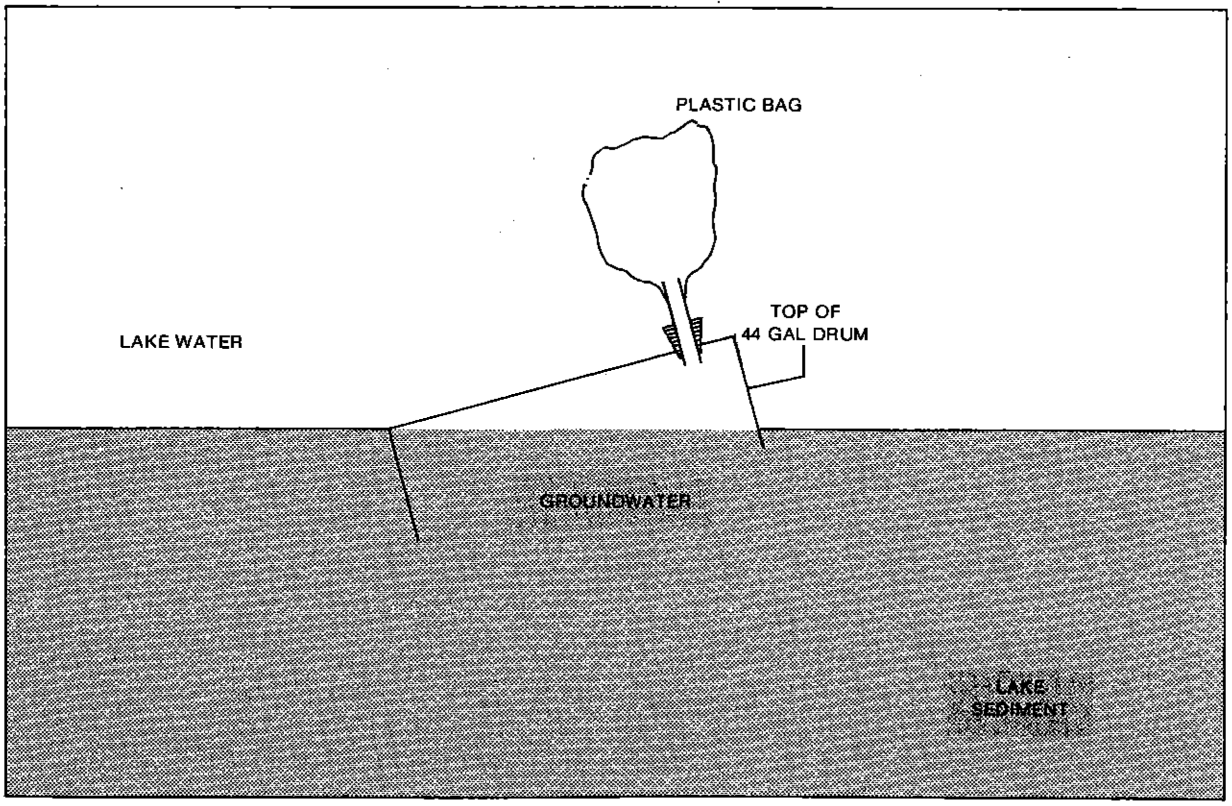

FIGURE A2-1 **STRUCTURE AND INSTALLATION OF A SEEPAGE METER**

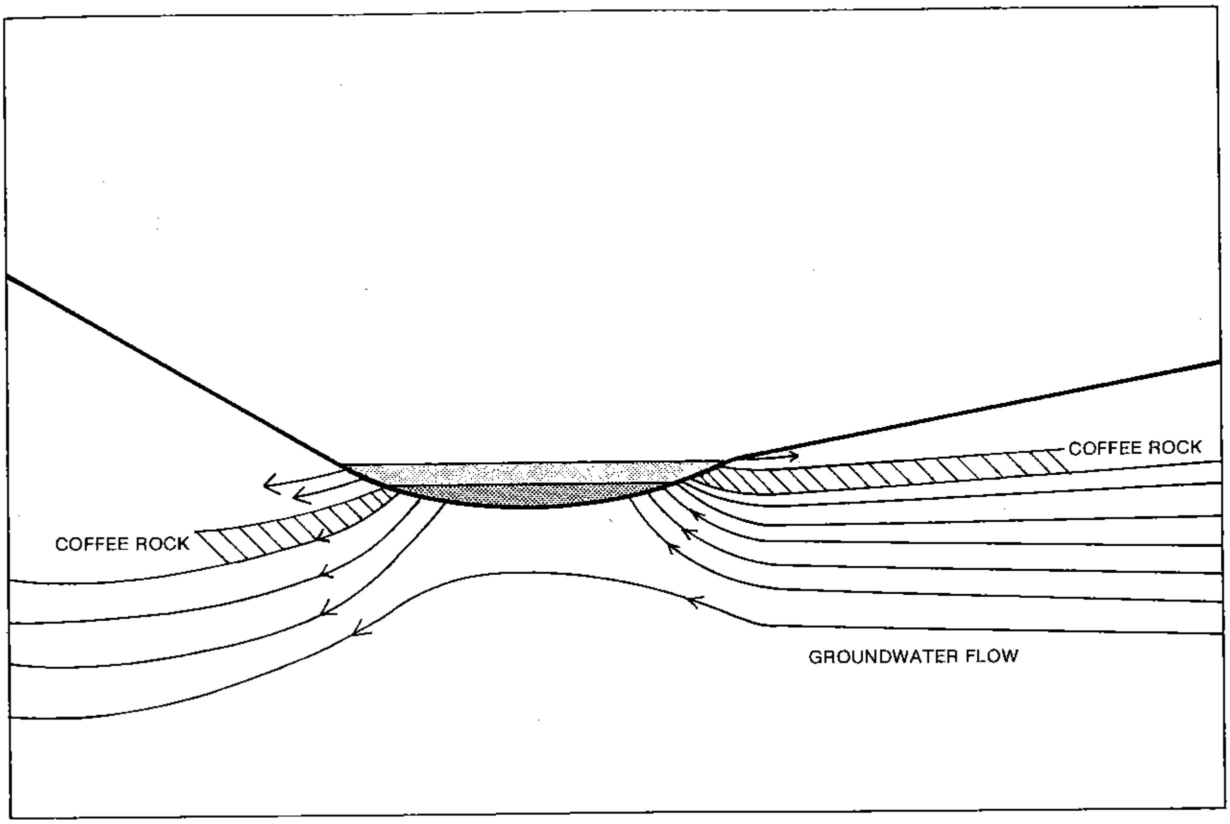

FIGURE A2-2 **CONCEPTUAL REPRESENTATION OF GROUNDWATER FLOW THROUGH LAKE**

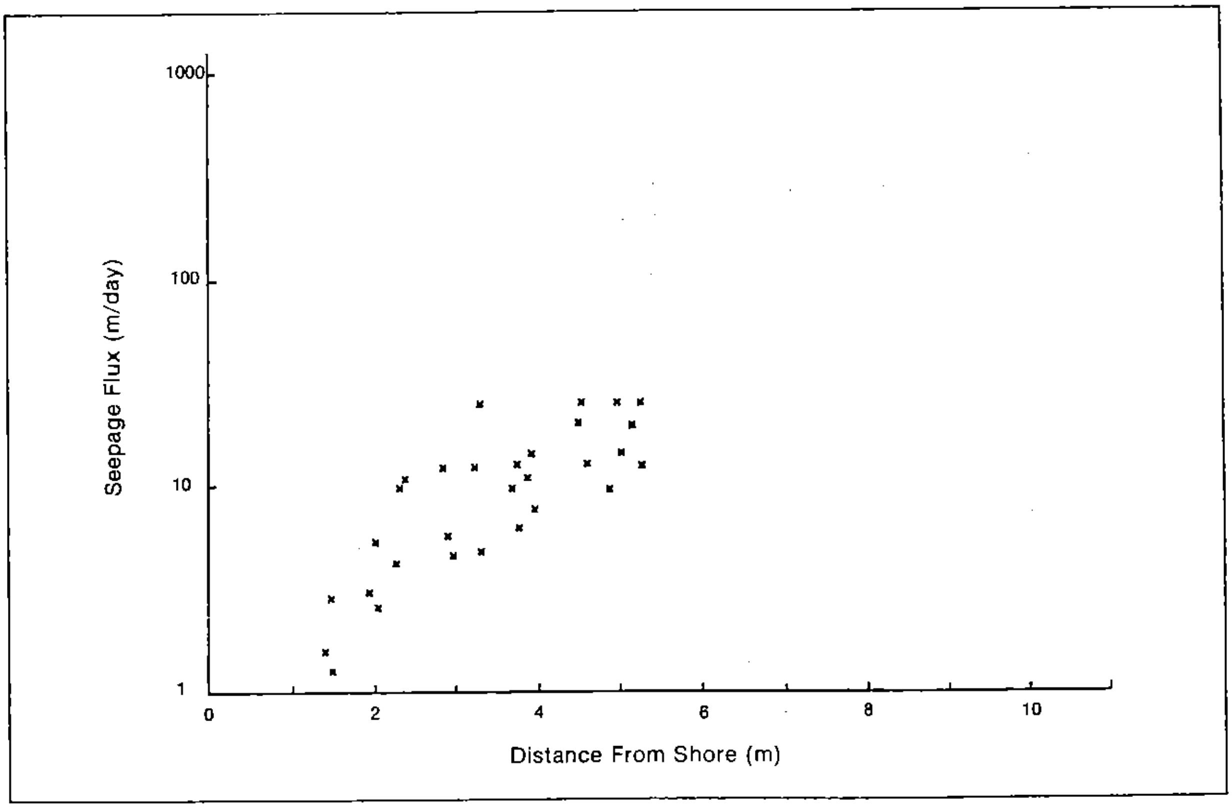

FIGURE A2-3 **GROUNDWATER SEEPAGE FLUX VERSUS DISTANCE FROM SHORE**

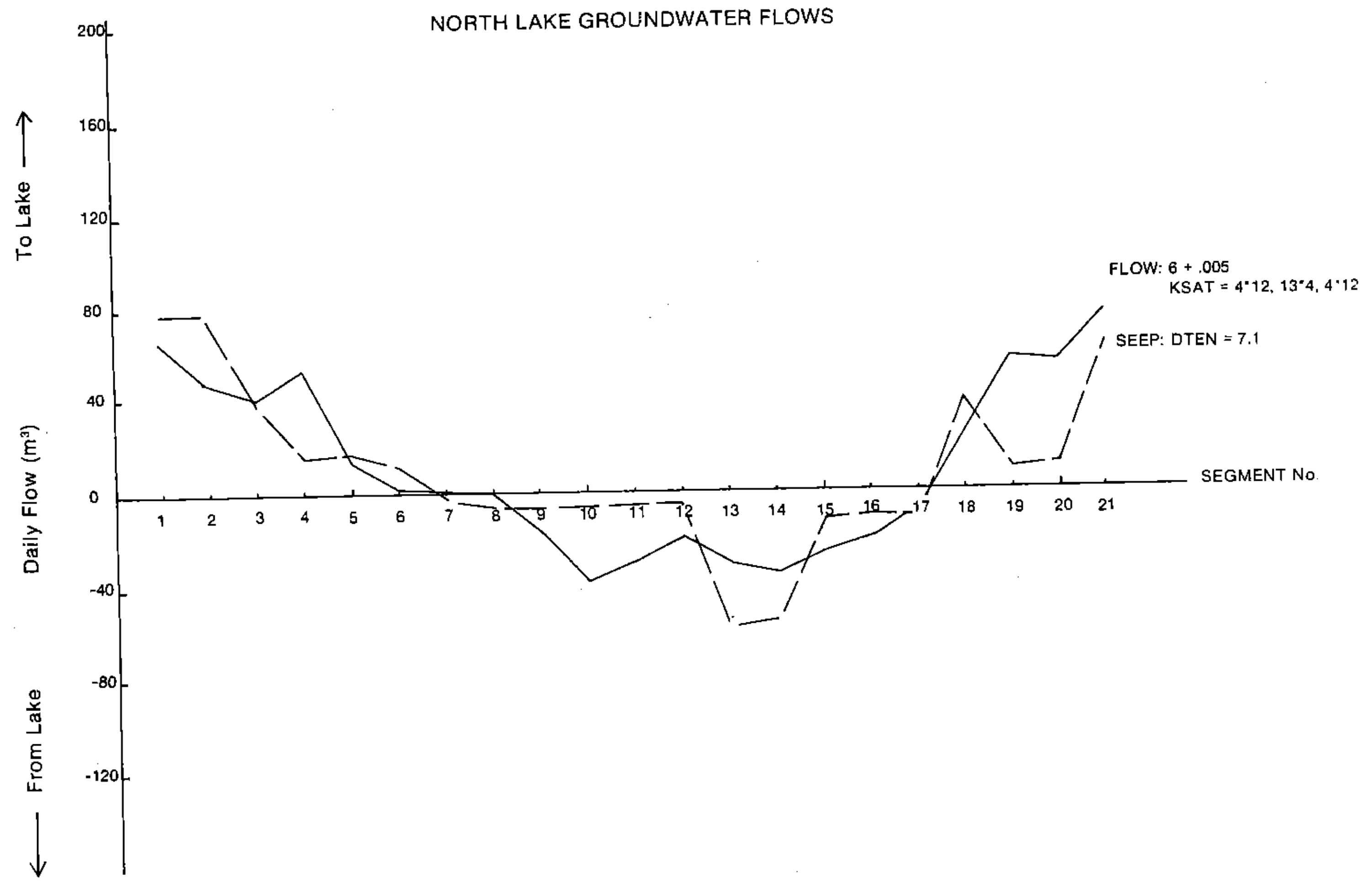

FIGURE A2-4 **DISTRIBUTION OF GROUNDWATER FLOWS MEASURED BY SEEPAGE FLUX AND PERIMETER BORES**