

AN INTRODUCTION TO THE STUDY OF PHOSPHORUS DYNAMICS IN RONDEVLEI

by

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Thesis submitted in fulfillment of the requirements for
the degree of Master of Science in the Department of
Zoology, University of Cape Town, under the
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ABSTRACT

Phosphorus is one of the most important nutrients in aquatic environments because of the role that it plays in eutrophication. Increased amounts of phosphorus stimulate excessive growth of nuisance plants, which have negative impacts on waterbodies. Urban runoff and sediment fall under various sources of phosphorus. Sediments act as sources as well as phosphorus storage tanks. Processes of adsorption and desorption which occur at the sediment water interface make phosphorus available for excessive plant growth. Information relating to these processes, and other limnological processes, serves as a guideline to the understanding of the courses and methods of control of eutrophication.

In the study of phosphorus dynamics in Rondevlei, a small eutrophic lakelet in southern Africa, five stations were monitored during spring, summer, autumn and winter of 1988. Temperature, oxygen, electrical conductivity and pH were determined in the field. Soluble Reactive Phosphorus (SRP), calcium (Ca), Total Dissolved Solids (TDS), Total Suspended Solids (TSS) and Particulate Organic Matter (POM) were measured in the laboratory.

Temperature varied inversely with rainfall, water-level and flow. A seasonal variation was observed for these characteristics. Maximum temperature was recorded in summer, and minimum temperatures were recorded in winter. Values of Total Suspended Solids (TDS) and Particulate Organic Matter (POM) were high in late summer and autumn. pH values were high in summer and autumn. No seasonal pattern was observed with oxygen. Percentage oxygen saturation fluctuated above South African general, as well as, special effluent standard of 75%. Maximum saturation was approximately 170%, an indication of eutrophic condition. Except for Princessvlei canal that carries water of low

ionic concentrations, conductivities were generally high, above the standard of 250 mSm^{-1} . Low Soluble Reactive Phosphorus (SRP) values were recorded during the winter season, a period of heavy rainfall and high water levels. No relationship was observed between calcium and other limnological characteristics of water.

Loading, sedimentation and retention of particulate phosphorus were determined by laboratory analysis of solids in sediment traps from five stations during spring, summer, autumn and winter. Results of the analysis reveal high loading rates during spring and early summer. A mean value of $162.22 \text{ g/m}^2/\text{day}$ has been recorded during spring, and a mean value of $96.79 \text{ g/m}^2/\text{day}$ has been noted during early summer. Furthermore, there is an indication that material that has accumulated is of organic origin. However, there is no correlation between trapped solids and particulate phosphorus.

Sediment cores were collected during March 1988 and they were analysed for phosphorus in various forms. A study of distribution of phosphorus indicates a high content of phosphorus in sediments of less than 80mm depth. A decline in quantities of total phosphorus was observed for all stations at this depth. There is a high positive correlation between total phosphorus and organic, as well as inorganic, phosphorus. Adsorbed phosphorus is related to inorganic phosphorus at $r = 0.76$ and $p < 0.05$.

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CHAPTER 1

• INTRODUCTION

1.1 THE PROBLEM

The problem of eutrophication (excessive fertilization by nutrients such as phosphorus and nitrogen) occurs in aquatic systems altered by human interference throughout the world. One of the most evident features of many urban lakes and wetlands is siltation resulting from accelerated growth of algae and other plants due to excessive availability of phosphorus compounds in water. In order to model such systems, it is necessary to understand the dynamics of various nutrients implicated in the process of eutrophication.

Amongst all the nutrients which stimulate the growth of "nuisance" plants in aquatic environments, phosphorus and nitrogen have been found to be the most important in limiting growth nutrients. (Walmsley and Butty 1980.) In order to control eutrophication, a thorough understanding of the characteristic behaviour of these individual elements in aquatic environments is necessary.

Of the two macronutrients, phosphorus has the more profound impact on growth and development of plants in freshwater ecosystems. Tisdale and Nelson (1975) for instance, have found that successful reproduction, maturity and seed formation depend on adequate supplies of this nutrient during the early growth stages of plants, while its shortage has manifested itself in reduced plant growth.

This thesis addresses various aspects of the quantification of phosphorus in Rondevlei, a shallow eutrophic lakelet in the Southern Suburbs of Cape Town in South Africa.

In the next section we shall look at the nature of phosphorus and its

different functions in the environment. Various forms of phosphorus which occur in nature will be discussed. Particular reference will be made to inorganic calcium compounds because they involve (PO_4) which is a major soluble form of phosphorus. This soluble phosphorus is of primary importance because it forms the pool of phosphorus available to plants. Therefore it is responsible for the success of plant growth in terrestrial as well as aquatic environments.

1.2 NATURE, FUNCTION AND FORMS OF PHOSPHORUS: A BRIEF REVIEW

Literature on the dynamics of phosphorus in South African freshwater systems and those of other parts of the world is very wide and varied. In this chapter an account on the sources, functions and forms as well as dynamics of phosphorus will briefly be discussed. The importance of phosphorus in relation to eutrophication of freshwater systems will be included.

Phosphorus was discovered in 1665 by Brandt. Phosphorus atoms exist as symmetrical, tetrahedral P molecules in the liquid phase, solid phase and in the vapor phase at temperatures below $800^\circ C$. At temperatures above $800^\circ C$ it dissociates to P_2 molecules (Tisdale and Nelson 1975; Foth 1978; and Winhols 1986). In solid phase it occurs in nature in the form of phosphates mainly in the minerals fluorapatite $[3Ca_3 (PO_4)_2 \cdot CaF_2]$ and chlorapatite $[3Ca_2 (PO_4)_2 \cdot CaCl_2]$. Phosphorite (mineral phosphorus) occurs in small quantities in granite rocks and it also occurs in fertile soils.

Phosphorus plays an important role as part of adenosine triphosphate in energy transfer within biological systems. It also constitutes many proteins, coenzymes, nucleic acids, and metabolic substrates and is an essential element in bones, teeth, and nervous tissue. (Brady 1974; Foth 1978.) So it is an

essential nutrient. Thus its availability can also control the growth of plants and animals. Because increased phosphorus increases plant growth, high levels of phosphorus can cause problems of excessive plant growth, especially in waterbodies used for storage of water and/or recreation.

Phosphorus occurs as a variety of compounds in gaseous, solid and soluble forms. Most solid inorganic compounds of phosphorus fall into two categories, i.e. the hydrous oxides of aluminium and iron, and the calcium compounds (Larsen 1967). In increasing order of solubility, the latter include compounds in Table 1.1

TABLE 1.1 INORGANIC CALCIUM COMPOUNDS OF PHOSPHORUS OFTEN FOUND IN SOILS. (BRADY 1974).

COMPOUND	FORMULA
Fluor apatite	$3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaF}_2$
Carbonate apatite	$3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaCO}_3$
Hydroxy apatite	$3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{Ca}(\text{OH})_2$
Oxyapatite	$3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaO}$
Tricalcium phosphate	$\text{Ca}_3(\text{PO}_4)_2$
Dicalcium phosphate	CaHPO_4
Monocalcium phosphate	$\text{Ca}(\text{H}_2\text{PO}_4)_2$

solubility
increases
↓

So (PO_4) is the major soluble form, i.e. as PO_4^{3-} ions.

The organic phosphorus compounds are rather complex. A lot is known about them but only within living organisms. What happens to them in the environment is very poorly known. Present information indicates that three main groups of these compounds found in plants are also present in the soil. These groups include nucleic acids, phospholipids, and phytin and phytin derivatives. Derived from numerous seeds, grains, potato juice etc., phytin is defined by Windhols (1986) as "phytic acid magnesium salt

$[\text{Ca}_5\text{Mg}(\text{C}_6\text{H}_{12})\text{O}_{24}\text{P}_6 \cdot 3\text{H}_2\text{O}_2]''$. It contains approximately 0.12% Ca, 1.5% Mg, and 22% phosphorus (Posternak 1921; Young 1936). Due to their complexity, very little work has been done on these compounds; as a result, their characteristic behaviour in the environment is not well known.

Organic phosphorus compounds constitute an important portion in the basic structure of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). The structure of these two forms of nucleic acids consists of alternating components of phosphoric acid and sugar residues. In addition to glycerol, fatty acids and a nitrogenous base, phosphorus is a key component of phospholipids which are common in plant, animal, and bacterial tissues (Brady 1974; Conn and Stumpf 1976).

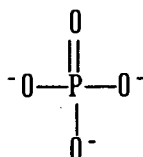
Tisdale and Nelson (1975) have found that plants take up nucleic acids as well as phytin from sterile sand. Since these compounds may occur as degradation products of decomposing organic matter, they can be absorbed directly by plants. It is assumed that nucleic acids are broken down by enzymes at the root surface, and phosphorus is thereafter absorbed in either organic or inorganic form. The availability of the inorganic form of phosphorus is low because its physical adsorption under acid conditions is remarkable, particularly in the presence of montmorillonitic clays. This creates a greater tendency to adsorption than to dissolution. In the same increasing order of solubility as that of inorganic phosphates, phytin forms compounds with iron, aluminium, and calcium to form phytates (soluble phytic substances) (Tisdale and Nelson 1975). Presumably little is known about the quantities and proportions of organic phosphorus compounds. Their importance in aquatic systems in particular is hardly known. The major gaseous form of phosphorus is phosphine. Its role in the biogeochemical cycling is discussed in Section 1.4. In the following section an account on the availability of phosphorus will be given, with special reference to orthophosphate in aquatic environments.

1.3 AVAILABILITY OF PHOSPHORUS

In the present context, available phosphorus denotes that portion of phosphorus water and sediment, which can be readily absorbed and assimilated by growing plants. The major processes which determine the availability of phosphorus to plants are mineralization (i.e. conversion from an organic form to inorganic state) and solution or desorption (Foth 1978). The major types of fixed (that which has been converted from a readily available, to a less available form) phosphorus compounds in soil are a function of soil age. In youthful soils, most of the fixed phosphorus is in the form of calcium phosphate, which is relatively soluble and thus more available.

Available phosphorus occurs in solution either as primary orthophosphate [H_2PO_4^-] or as secondary orthophosphate [HPO_4^{2-}] ions. Plants have a high affinity for the former since they are about ten times as many absorption sites on plant roots for H_2PO_4^- as there are for HPO_4^{2-} . Soil reaction pH has a great influence on the amounts of the two forms of phosphorus ions absorbed by the plants. For values of pH higher than 7, there is a remarkable increase in the absorption of the HPO_4^{2-} form, while lower pH favours an increase in absorption of the H_2PO_4^- ions (Foth 1978).

In aquatic systems there are various classes of phosphorus-containing compounds. Snoeyink (1980) has observed the central bonding of the P atom to the oxygen atoms in the orthophosphate anions. Their structure is represented below:



orthophosphate

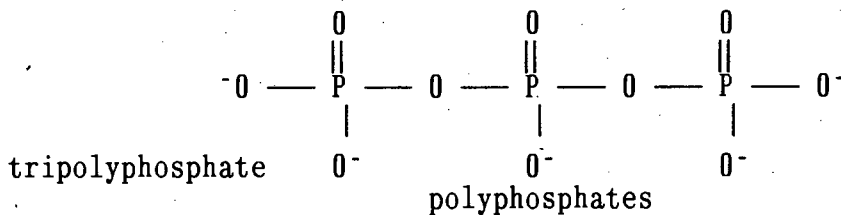
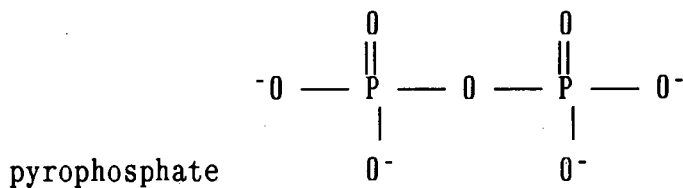
In order of their acid ionization constants at 25°C, important species

of orthophosphate are shown in the following table:

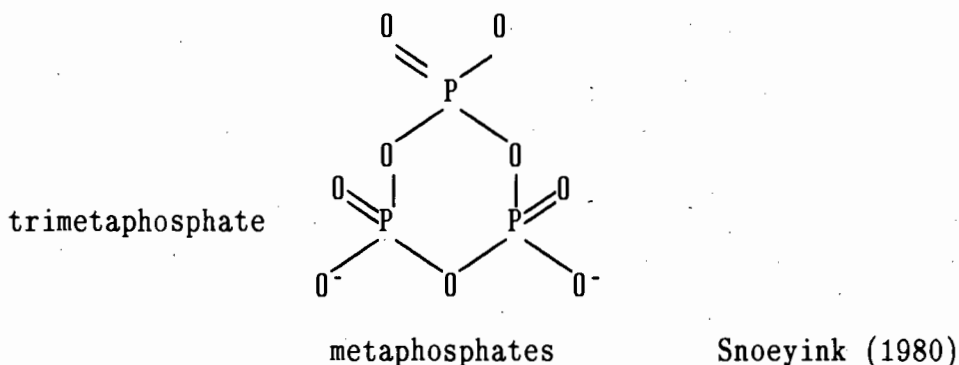
TABLE 1.2 SPECIES OF ORTHOPHOSPHATE IN AQUATIC SYSTEMS (Snoeyink 1980)

Species of Importance	Acid Ionization Constants (25°C)
H_3PO_4 , H_2PO_4^-	$\text{pK}_{a,1} = 2.1$
HPO_4^{2-} , PO_4^{3-}	$\text{pK}_{a,2} = 7.2$
HPO_4^{2-} complexes	$\text{pK}_{a,3} = 12.3$

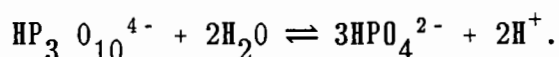
Besides the above mentioned species of orthophosphates which remain soluble, and the reactive forms (hence the name "Soluble Reactive Phosphorus"), there are other forms which originate from the condensation of two or more orthophosphate groups. Although these have the characteristic P - O - P linkage, their structural configuration is different. For example, polyphosphates are linear molecules. Like orthophosphates they differ in species but share a basic structure as shown below.



Like polyphosphates, metaphosphates are products of complexation of orthophosphates. Their structure, however, is cyclic.



Soluble reactive phosphate (SRP) is available to plants while condensed phosphates remain unavailable. Prolonged contact with macro-organisms results in hydrolysis, reversion of this condensed phosphate to orthophosphate. In the case of tripolyphosphate for example



Because the H^+ ion is an essential catalyst in this reaction, which takes place at different rates under varying temperature conditions, it is clear that pH and temperature play a major role in determining availability of phosphorus in aquatic environments (i.e. in determining whether phosphorus is in the available form or not).

As mentioned before, nucleic acids and phytin, which occur as degradation products of decomposing organic matter in soil, are directly utilized by growing plants (Tisdale and Nelson 1975). These forms are very sensitive to microbial activity. Their importance as sources of phosphorus for higher plants is limited under natural conditions. Microbes have been found to present adsorption sites for phosphorus, particularly that which is derived from phytin and phytin derivatives.

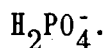
Micro-organisms are believed to liberate organic acids which dissolve insoluble inorganic phosphate compounds in the soil (Tisdale and Nelson 1975),

although the level at which this kind of phosphate is available is only about 0.2% of the total available phosphorus. Besides the abovementioned available forms, phosphorus is readily mobilized within plants (Foth 1978). In case of deficiency, the element contained in older tissues is transferred to the active meristematic region.

1.4 THE ROLE OF SOILS AND SEDIMENTS IN PHOSPHORUS DYNAMICS: WITH REFERENCE TO PHOSPHORUS CYCLE

In aquatic ecosystems the amount of phosphorus in solution depends to a large extent on the amount fixed and retained in the sediments (Bailey G.W. 1968). Soluble compounds tend to adsorb onto particles and therefore to accumulate in sediments. These compounds can be "lost" or can periodically be remobilized in various ways. Therefore the importance of sediments in phosphorus dynamics has been a subject of interest to workers in both fresh and marine systems. In comparing the two systems, Thornton (1986) has indicated that in both systems, phytoplankton, zooplankton and fish play a major role in the transformation and/or regeneration of phosphorus. Part of the excreta of these organisms and their decomposed tissues get lost to sedimentation, a process which is preceded by biochemical weathering and release of phosphorus.

Up to date five major processes in the cycle of soil and sediment phosphorus have been documented (Foth 1978). They include weathering, immobilization, mineralization, fixation and solution. In this study, weathering includes physical and chemical processes which entail the unconsolidation of apatites (naturally occurring complex calcium phosphate e.g. $3\text{Ca}_3(\text{PO}_4)_2 \cdot \text{CaF}_2$ which is the original source of most of the phosphate fertilizers). There is also biochemical weathering, that is, disintegration of organic material which may be found above the parent material (Bailey G.W. 1968). The final product of this weathering process is "solution phosphorus"



Solution phosphorus may either be transported to the bottom layers of the unconsolidated material, or it may be immobilized by plants and micro-organisms resulting in organic phosphorus which forms part of the sediment material. The process which follows that of immobilization is mineralization, that is degradation of organic residues by heterotrophic microflora, and release of solution phosphorus. The rate at which this process takes place depends on the environmental conditions. A fair amount of phosphorus remains bound in organic material. Solution phosphorus is either made available to plants or reacts quickly with other ions in the soil solution or sediment. These ions include calcium, iron and aluminium as well as clay. The rate of adsorption varies with the type of ion with which phosphorus forms a compound.

In decreasing order of solubility of the fixed forms (forms which have been changed to less soluble forms as a result of reaction with the sediment) there is tricalcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$), which may change to apatite, an even less soluble form. Other forms are clay-absorbed phosphate, and iron and aluminium phosphates. The latter two may crystallize into strengite ($\text{FePO}_4 \cdot 2\text{H}_2\text{O}$) and veriscite ($\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$) respectively. In this form phosphorus is even less soluble than when it is untransformed. Where extreme weathering has occurred under tropical conditions, phosphorus may be coated with iron or aluminium oxides. This is called "occluded" phosphorus which is highly insoluble. Solution of any one of the fixed forms of phosphorus completes the cycle of phosphorus according to Foth (1978), Hawker and Linton (1979).

1.5 LOSS OF SEDIMENT PHOSPHORUS AND ITS REGENERATION FROM SEDIMENTS

The role of phosphorus in limiting organic matter production, and in causing eutrophication, is a subject that has been under discussion for at

least the past 30-50 years. Recently new ideas concerning phosphorus dynamics were developed by Devai et al. (1988). While previous studies indicated that all major biogenic elements, with the exception of phosphorus, can leave aquatic systems in gaseous form, a recent report that phosphine, a gaseous phosphorus compound, may do the same, has called for a revised understanding of the budgets and cycle of phosphorus. Studies made by Devai et al. (1988), in sewage treatment plants and shallow (1m-2m deep) waters indicate that phosphine accounts for 25-50% of the phosphorus deficit in open-air sewage treatment plants. It is therefore possible that phosphorus, like other biogenic elements, can be volatile. Since Devai's paper is the only one so far that mentions this matter, his observations must be treated with caution. The significance of this discovery, if it is confirmed, is considerable for an understanding of phosphorus dynamics.

The manner in which aquatic systems may be enriched with a soluble form of phosphorus has been discussed in many papers. For example, Tilton (1979) and Dolan et al. (1981) have observed that reactive phosphorus derived from fluvial sediment can undergo adsorption onto, or desorption from, sediment particles. Although waste water treatment has shown an improvement in reduction of transport of phosphorus in most lakes, it is not the case in shallow lakes (Forsberg and Ryding, 1985). Internal loading from sediments has remained a major problem in most of these lakes.

Regeneration (restoration to soluble form) of phosphorus is higher in marine systems than in freshwater systems. Loss to sedimentation is also higher in the marine systems. Chapman and Thornton (1986) have reported regeneration % values of 29-100% P in marine ecosystems, and 7-35% P in freshwater ecosystems. Phosphorus loss by sedimentation is $0,01-4\text{mg m}^{-2} \text{d}^{-1}$ in marine ecosystems and $0,12-0,88\text{mg m}^{-2} \text{d}^{-1}$. Values of sediment-water exchanges are $0,6\text{g P m}^{-2} \text{y}^{-1}$ in marine ecosystems and $3,3\text{g P m}^{-2} \text{y}^{-1}$ in freshwater ecosystems. Bailey G.W. (1987) made a study of the role of

regeneration from the sediments in the supply of nutrients to the euphotic zone. His investigation was conducted in the Benguela ecosystem on the south-western coast of Africa. He found a higher concentration of nutrients in the bottom waters than in the upwelling waters and attributed his observations to regeneration of nutrients from the sediments.

Unlike marine systems, freshwater systems are open systems with clearly defined inputs and outputs. Besides riverine inflows, some freshwater lakes receive sewage effluents, storm water and waste water. The use of iron and aluminium salts and other advanced waste water treatment methods results in the reduction of orthophosphorus transportation to water bodies. (Karlsson et al. 1988.) According to Karlsson et al. (1988), there is a reasonable rise of allochthonous supplies of total phosphorus in time in water bodies, particularly if treatment methods like the one above are not employed. The result of this accumulation of phosphorus is eutrophication of receiving water bodies. Phosphorus can be immobilized or removed either biotically or abiotically. Studies show that abiotic removal is dominant.

Studies on the mechanism of phosphorus removal from treated waste water by sand were conducted by Donald et al. (1988). Their observations, like those of Viner et al. (1981), confirm that phosphorus dynamics are dominated by abiotic factors. In fact Donald et al. (1988) came to a conclusion that "phosphorus removal is primarily a physical-chemical process, rather than a biological one". Sediments have been found to be nutrient sinks by De Jong (1976), Kadlec and Tilton (1979), Howard-Williams (1980), Brezonik (1983a), and Rogers et al. (1985). Most of the above mentioned work has been done on artificially enriched wetlands.

The process of fixation (adsorption and reduction in solubility) and retention both play a major role in modifying the additional phosphorus loads in sediments. Both processes are influenced by several factors, which include the type of soil, the phosphorus status of the soil, time of reaction, soil

reaction, redox potential, temperatures and organic matter content of the soil. Further details relating to these factors are found in Bailey G.W. (1968) and Tisdale and Nelson (1975). In the following paragraphs, the evidence for adsorption and desorption processes will be discussed together with the significance of molecular oxygen in these processes.

Lennox (1984) made a quantitative investigation of sediment-water exchange, with particular reference to phosphorus. He found that internal loading, that is, autochthonous input, is a major contributing factor in the continuing eutrophic status of Lough Ennell. His investigations have revealed that the process of remobilization and a resultant bioavailability of phosphorus take place more actively in the epilimnetic zone than in the hypolimnetic zone of the lake. Lennox noticed that aerobic conditions promote maximum release of sediment phosphorus which is immediately bioavailable. Similar studies were made by Silberbauer (1982) in the monimolimnion of Swartvlei (a meromictic, humic lake), where the rate of release under anaerobic condition was found to be $2.5 \text{ mg P m}^{-2} \text{ d}^{-1}$.

Lennox found that in shallow areas of the lake, there is continuous mixing of overlying water without mass resuspension of sediments. This promotes the release of phosphorus from the aerobic epilimnetic sediments. He concluded that sediments are a source of phosphorus for "algal growths of nuisance proportions in the water column". Furthermore, according to Lennox (1984), various mechanisms are involved in the natural removal of phosphorus from the lake ecosystem. Besides being flushed out of the lake, particulate or soluble forms of phosphorus may move to the deeper areas of the lake or it may form unavailable forms, such as apatite in the lake water and in sediments.

On the other hand Silberbauer (1982) obtained results which reveal that there is a higher release of phosphorus under anaerobic conditions. In his report he makes it clear that wind conditions, which are responsible for the

rate of overturn in a lake, determine concentrations of phosphorus in the limnetic zones of the lake. According to Silberbauer, phosphorus goes to the surface during a rapid overturn, and in the case of "gradual deepening of the oxygenated layer, reprecipitation of phosphorus can occur". This makes it unavailable for primary production in the euphotic zone.

Studies made by Yamada and Kayama (1987) reveal that dissolution of precipitated phosphorus under aerobic as well as anaerobic conditions is a function of the species involved in the process. During their investigations organic phosphorus did not dissolve under anaerobic conditions. Aluminium phosphates and iron phosphates dissolved in a similar way under weakly and strongly anaerobic conditions.

After completing the investigation on the processes controlling phosphate adsorption by hydroxides in estuaries, Lucotte et al. (1988) concluded that the adsorption of phosphorus on to phosphorus-saturated particulate matter is reversible under low-reducing conditions. Further evidence, and the effects of internal loading under anaerobic conditions, are found in Bengtsson (1975), Son-Zogni et al. (1977), Larsen et al. (1981). Another important factor which affects the release of bioavailable phosphorus is the amount of organic matter in the sediment.

The availability of phosphorus to plants is obviously determined by the amount of phosphorus in the soil solution (Foth 1978). The presence of organic matter is believed to increase solubility as well as availability of phosphorus in many ways.

In their study of the effect of organic matter on phosphate fixation, Hashimoto and Okud (1962) observed that humates retard phosphate fixation, particularly in reactions of phosphates with $\text{Fe}(\text{OH})_3$, CaCO_3 , and clays from solutions containing H_3PO_4 , ammonium, nitrohumate and ammonium humate as well as sodium humate. However under certain circumstances (e.g. in the presence of $\text{Fe}(\text{OH})_3$), phosphorus fixation is enhanced.

Grobler and Davies (1979) studied availability of sediment phosphate to algae. They found a significant correlation between the amount of phosphate used by algae and the inorganic phosphate content of the sediment.

Tisdale and Nelson (1975) and Skiba *et al.* (1988) found that evolution of carbon dioxide during decomposition of particulate organic residues results in the formation of carbonic acids which contribute to decomposition of some primary soil minerals. As a result of this, phosphorus is released and made available to the plants. At high levels of carbon dioxide, phosphorus is utilized more efficiently by plants, and is leached more from the soil because of a change in equilibrium between the soil particles and interstitial waters. A remarkable increase in phosphorus availability due to carbonic acid formation has been observed in calcareous soils by Tisdale and Nelson (1975).

Availability of inorganic phosphorus is influenced mainly by rapid decomposition of organic matter and a consequent abundance of microbial tissue on to which inorganic phosphate is temporarily tied. Organic acids and humus, which result during decay, engage iron and aluminium compounds by forming complexes with them (e.g. SRP-Fe-humic complexes: Gardiner, A.C. 1988). This reaction results in reduced inorganic phosphate fixation (i.e. reduced adsorption and absorption: Brady 1974; Guildford *et al.* 1987). Humic acids tend to keep phosphorus in a more soluble form. Low fixation of mineral phosphorus in soils which are high in organic matter has been studied in detail by Swenson *et al.* (1949), Reddy (1983). Observations of Reddy (1983) indicate that sediments with organic soils have less effect on the removal of phosphorus than those with calcareous loam. Exchange rates depend on the capacity of sediments to adsorb or desorb phosphorus. The presence of hydrous oxides of iron and aluminium, encourages precipitation of phosphorus at low pH, while the presence of carbonates of calcium and magnesium encourage precipitation at high pH.

The ions found in the soil solution are a function of pH (Foth 1978). At pH values below 5.5 soluble iron and aluminium increase. This results in a high probability of fixation of phosphorus by aluminium and iron, hence a high concentration of iron phosphate and aluminium phosphates in the soil solution. At pH 6 precipitation of calcium begins. In addition to apatite formation, which occurs above a pH of 7, there is reaction of excess OH^- ions with H_2PO_4^- , with a resultant formation of HPO_4^{2-} . This form of phosphorus is less taken up by plants than H_2PO_4^- , a situation which reduces availability of phosphorus at pH above 7. Although the general view is that phosphorus is maximally available between 5.5 and 7.5 (Foth 1978), it remains a fact that pH tolerance of plants is important in determining the availability of their nutrients.

Since soils have different abilities to fix phosphorus, the amount of phosphorus and the relative proportions of its species may be expected to vary from soil to soil (Bailey G.W. 1968). For example, soils containing large amounts of 1:1 clays (i.e. those of the kaolin group) retain a greater amount of phosphorus than those containing 2:1 clay (i.e. those of the montmorillonite mica groups). Both groups of clay are composed of units consisting of two silica tetrahedral sheets, with a central octahedral sheet. In the mica group, however, "the charge deficiency is balanced by potassium ions which act as a bridge between unit layers binding them together and preventing expansion or swelling" (Bailey G.W. 1988). They consist of a single silica tetrahedral sheet and a single alumina octahedral sheet, tied together to form a common sheet shared by oxygen to form kaolin unit layer. This is because these finest clays expose a larger surface area, and contain larger amounts of hydrous oxides of iron and aluminium than soils of coarser particles (Tisdale and Nelson 1975).

Ostrofsky (1987) suggests that, although there may be little variation in physical characteristics of sediments, the ability of different sediments to precipitate different species of phosphorus depends to a large extent on

their chemical composition. He found that sediments that are high in sedimentary "iron" had a higher concentration of NH_4^+ Cl^- and NaOH^- extractable phosphorus. These, he says, are species that are most likely to contribute to "internal" loading of phosphorus, that is release of biologically available phosphorus.

The influence of temperature on dissolution of phosphorus has been investigated by Mark et al. (1960) and Brady (1974). They found an increase in temperature to be responsible for the rise in quantities of water-soluble phosphorus. In his laboratory investigation, Mark (1960) realised that more phosphorus could be leached from soils that had been frozen, than from soils that had not been frozen. Although he knew little about the field conditions, he assumed that soils of warmer climates are generally much greater fixers of phosphorus than the soils of more temperate regions. Studies made by Lucotte et al. (1988) reveal that spatial and temperature differences in the distribution and behaviour of phosphorus depend on the differences in magnitude of the influence exerted by each of a variety of environmental factors. In his studies of the processes controlling phosphate adsorption by iron hydroxides in estuaries, for instance, he observed that the adsorption of phosphorus on phosphorus-saturated particulate matter is reversible under low reducing conditions. At the same time he realized that the influence of pH for example becomes insignificant on reaction rate if the pH range is narrow and if pH is in competition with redox potential.

In the preceding paragraphs I have discussed phosphorus cycle and the role played by soils and sediments in the various processes involved in this cycle. Of the processes mentioned, fixation and retention play a significant role in delaying the process of eutrophication in water bodies. Solubility of phosphorus is reduced through fixation. In this way it becomes unavailable to nuisance plants which grow as a result of excessive available phosphorus in aquatic systems. Various environmental factors influence the process of

fixation. Studies made on the factors mentioned in this chapter, indicate that the effect of one factor is not independent of the influence of other factors. The next section is a summary on eutrophication, its economic importance as well as environmental hazards which result from this problem of eutrophication.

1.6 EUTROPHICATION

The importance of phosphorus in the eutrophication process in aquatic environments has been documented earlier in this chapter. Under natural circumstances eutrophication follows a pattern of long term environmental changes. Haggett (1975) views a lake as a "living model of an intertwining of long term erosional changes". A lake may begin, he says, as a deep body of clear, nutrient-poor (oligotrophic) water. Owing to sediment accumulation, and accumulation of organic debris, vegetation succession develops from mosses and floating plants to reed, sedges, swamp and bog plants as well as woody plants. The final stage of this succession is complete colonization by terrestrial shrubs and trees. Haggett (1975) describes this phenomenon as eutrophication and "lake death". The accelerated rate of evolution and "death" of lakes by human intervention is emphasized by Davies and Day (1986).

Anthropogenic lake eutrophication is an old problem worldwide. Blue-green algal blooms were reported from Switzerland's lake Zurich as long ago as 1896. In recent years, this process has been speeded up by the increasing use of fertilizers and synthetic detergents containing phosphorus. Due to various environmental hazards of pollution turbidity and siltation of water bodies and resultant loss of life and habitats that have been experienced recently, the problem of eutrophication has attracted a lot of attention and research interest in South Africa as well as various other parts of the world.

The effects of turbidity have been documented by Brehmer (1965). He regards turbidity as well as siltation as "man-made" aspects that reduce the value of water. In his discussion of the role played by suspended solids and sediments, he puts the former into two categories: that is, non-living organic matter and inorganic "suspensoids". Apart from their effect on water's aesthetic quality and the water's value for recreational purposes, suspended solids, particularly inorganic solids, have considerable effects on the biota.

They decrease light penetration with a resultant decrease in the "compensation depth" - the level at which the rate of photosynthesis equals the rate of respiration. Degradation of the biological community follows a decrease in compensation depth. Other effects of inorganic suspended solids include negative impacts on zooplankton and higher aquatic animals like shellfish and finfish. Feeding activity of filter feeders, for example, is inhibited by high suspended solid levels.

Fluctuations in population of estuarine species like "menhader croaker, striped bass, members of the herring family, summer and winter flounder and spot" which complete their juvenile stages between fresh and salt water, is attributed to Brehmer (1965) to high levels of suspended solid loads during larval and juvenile stages. Finally, turbidity leads to siltation. This causes damage to benthic habitats.

Viljoen and Hynes (1985) have discussed the financial implications of eutrophication on the human community. Besides the activities of recreation, riparian owners, agriculture and industry, Viljoen and Hynes (1985) have found that water purification problems are mounting due to excessive growth of macrophytes and algae. Costs involved in the control of these plants vary according to intensity of their growth and the control measures employed in each case. Amongst the above mentioned costs, is loss of wild life as a result of poisoning by herbicides which are used as control measures. Use of fires and dredging of lakes and many other control measures have resulted in

the destruction of habitats of wild life as well as loss of rare floral and faunal species. Introduction of exotic species as biological control has not often proved to be a successful method either. These species take over the habitats of indigenous species and may drive them to extinction. In a report on the health impacts associated with the development of algal blooms, particularly blue-green algal blooms, Scott et al. (1985) discuss the formation of various toxins, including organohalides. Toxic compounds which have been observed during chlorination of water, incur serious health hazards. Phenolic compounds for example have been described by Van Steenderen (1987), as "organohalogen precursors". Chlorination induces the participation of phenols in haloform reactions which result in the formation of trihalomethane (THM) compounds. Chloroform is predominant in this group, and it is a volatile halogenated hydrocarbon compound which is known to be toxic. It is clear that continuous chlorination of water as a means of counteracting eutrophication will result in an increase in concentration of organohalides in water, a condition which is not favourable for aquatic life.

Wiechers (1985) recommends control of phosphorus as a proper solution to the problem of eutrophication. Of the three forms of phosphorus that occur in natural water, i.e. orthophosphates, condensed phosphates and organically bound phosphates, orthophosphates are directly available to algae (Walmsley and Butty 1980). It is therefore necessary to examine all possible sources, and to study the behaviour of this biologically available phosphorus which causes eutrophication, in order to control it.

1.7 OBJECTIVES

Because of the immediate threat that it poses to wildlife, the problem of eutrophication in Rondevlei, a bird sanctuary, has recently attracted a lot of attention. Management has expressed dissatisfaction with the quality of

municipal water entering Rondevlei through stormwater canals. Various mathematical models have been developed to predict the likely response of the fresh water bodies like Rondevlei to increased nutrient loading. These models are a basic tool in successful planning and management. Selection of the model appropriate to the needs of a specific management problem is a keynote to success (Reckhow and Chapra 1983). The basic requirements of appropriate models include a sound knowledge of the composition and the functioning of a specified system of interest, in this case of phosphorus in Rondevlei.

The aim of this work, then, is to examine various aspects of the dynamics of phosphorus in Rondevlei. Later this information will be useful in providing some of the parameters required for a model of a kind mentioned above.

An exchange of nutrients between lake sediments, which act as nutrient sinks, and the overlying water depends upon chemical characteristics of both water and sediment (Mortimer 1971; Wildung et al. 1974). It is therefore necessary to examine both sediment and water. This thesis focuses on the aspects concerning the concentration of phosphorus in water and the sediments of the lake. Phosphorus is given preference to other nutrients because it is one of the major growth limiting macronutrients, and a universally recognised causal indicator of eutrophication. In this study, a seasonal pattern of selected physico-chemical properties of water has been monitored, together with a temporal variation of phosphorus loading by allogenic, as well as by autogenic, suspended sediments.

Release of biologically available phosphorus by sediments is partly regulated by the chemical species of phosphorus present in the sediment (Numberg and Peters 1984, in Ostrofsky 1987). Furthermore, a relationship established between different fractions of phosphorus and other sediment variables could be useful in predicting the existing quality and quantity of phosphorus. In view of these observations, this thesis attempts to answer the

following questions:

1. What are the seasonal variations of the physical and chemical characteristics of water in Rondevlei?
2. What are the seasonal sedimentation and phosphorus loading and retention rates in Rondevlei?
3. Is phosphorus-loading related to particulate organic matter content of the sediments?
4. What is the present spatial distribution rate of phosphorus and some of its soluble fractions?
5. What is the relationship between phosphorus distribution and its fractions, as well as characteristics of sediment for example particulate organic matter and pH?

CHAPTER 2

STUDY AREA

2.1 LOCATION AND CHARACTERISTICS

Rondevlei ($34^{\circ}04'S/18^{\circ}30'E$) is a monomictic, fresh water, coastal lake, located in the middle of a developed suburb of Cape Town (Figure 2.1). It is underlain by Cape granite, and its bed consists of sediments that are derived from aeolian sands originating from sandstones of the Table Mountain Series. Besides aeolian deposits, unconsolidated limestones form the western boundary of the lake (Haughton 1933 in Middlemiss 1975).

The lake intercepts flow from a catchment that covers approximately 1492 ha. This catchment consists of the slopes of Table Mountain and developed residential suburbs (Figure 2.2). Two large canals and one small one enter Rondevlei. These canals were originally streams. The Princessvlei canal, which is also known as the Italian Road canal (Station 1), transfers municipal water from the neighbouring suburbs and stormwater flow from Princessvlei. The Perth Road canal (Station 2) discharges domestic water as well as storm water into Rondevlei. Both canals experience a seasonal flow of water. There is one other non-perennial channel (Station 3) in which water flows only after heavy rain during the rainy winter season. This canal is choked by terrestrial weeds during dry summer periods. Station 4 is located a few metres away from the weir. Water flows over the weir only during peak rainfall periods, that is when the water-level is above the 4.9 metre mark. This station experiences rapid growth of *Typha* beds and other terrestrial weeds. Stations 5 and 5A are both located inside the lake. While Station 5 is situated on the open water where there is no vegetation, Station 5A is

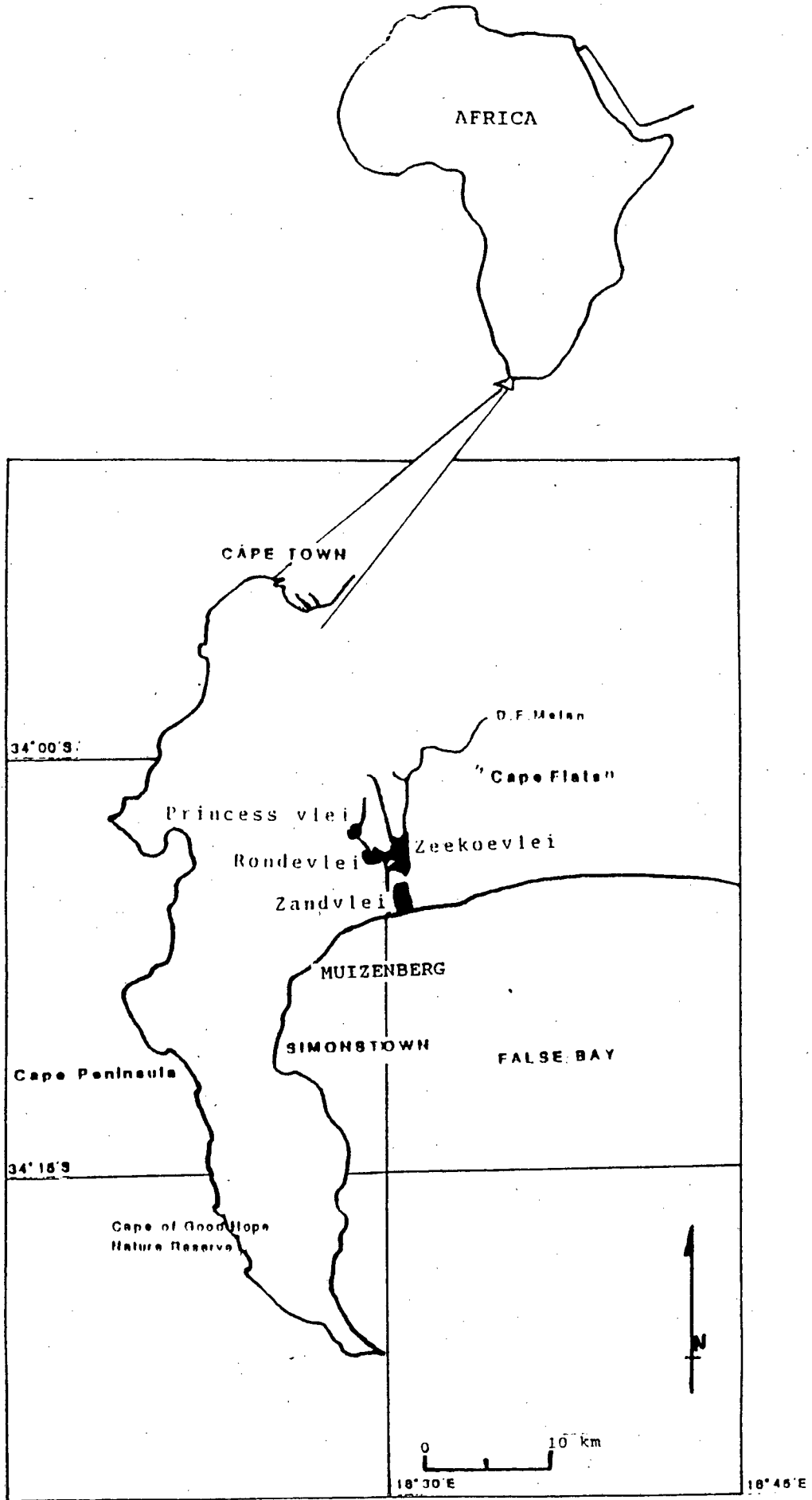


Figure 2.1 Position of Rondevlei
Source: Reader's Digest Atlas of Southern Africa 1984.

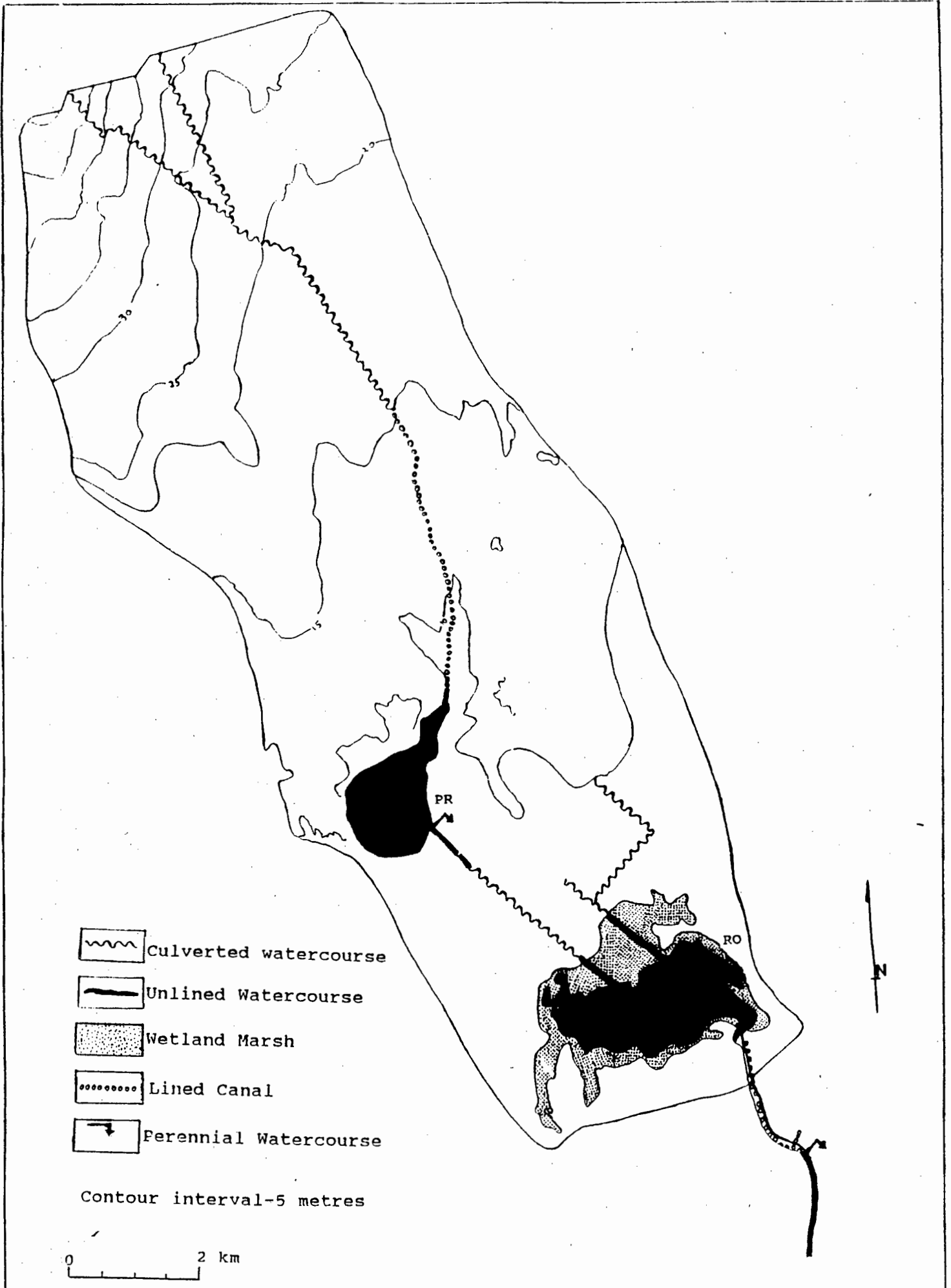


Figure 2.2 Rondevlei catchment , PR-Princessvlei , RO-Rondevlei
 Source: City Engineer's Department , Sewerage Branch 1987

RONDEVLEI

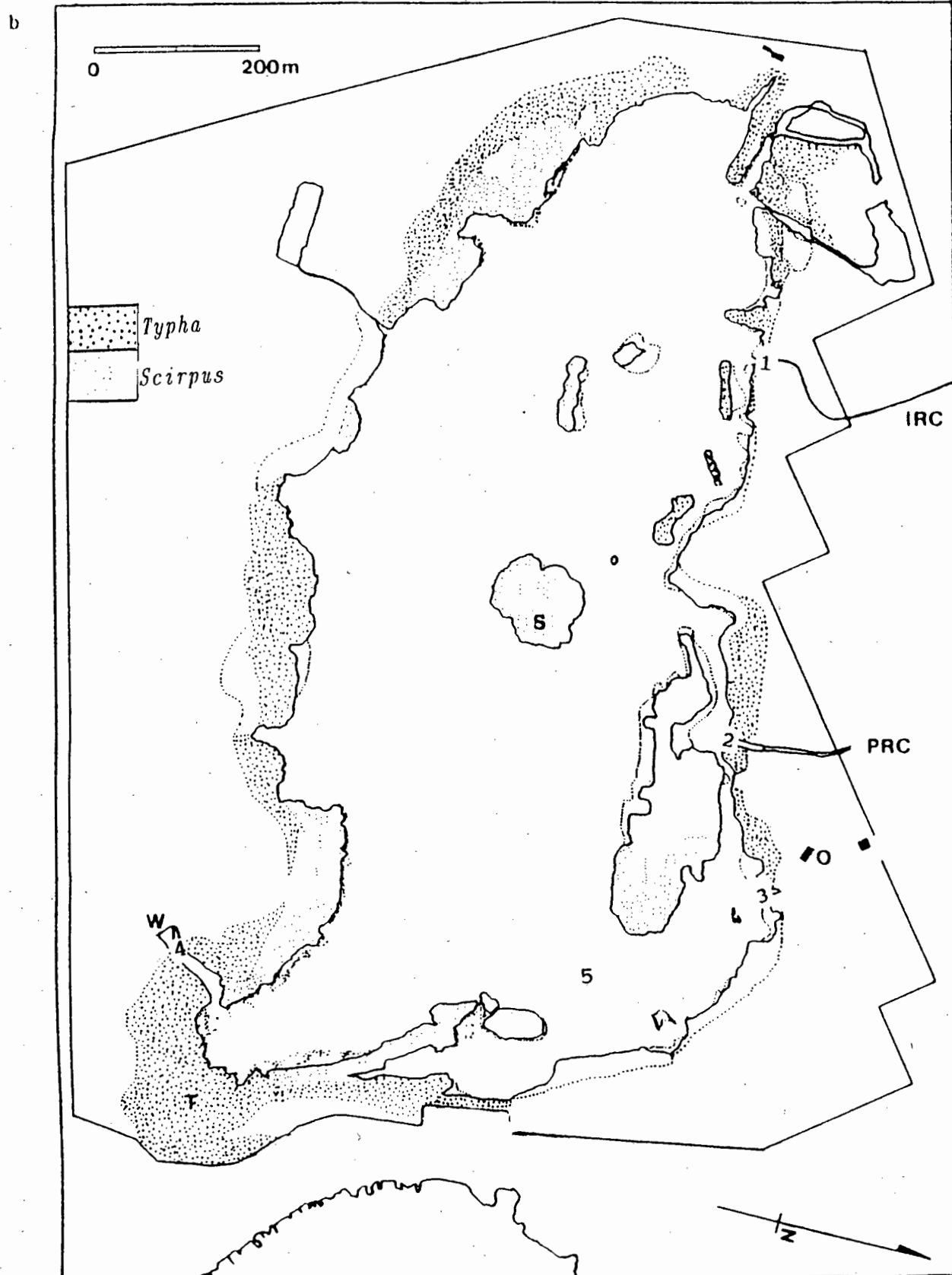
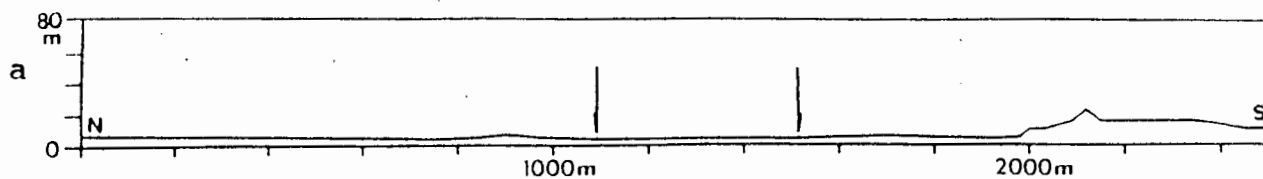


Figure 2.3a Profile of the major catchment slope.

Figure 2.3b The vlei Rondevlei (Cape Flats). T-*Typha capensis* beds, S-*Scirpus littoralis* beds, W-weir, O-office, IRS-Italian road canal, PRC-Perth road canal, GP-Grassy Park, 1 to 5 sampling stations. (Source: Gardiner (1988))

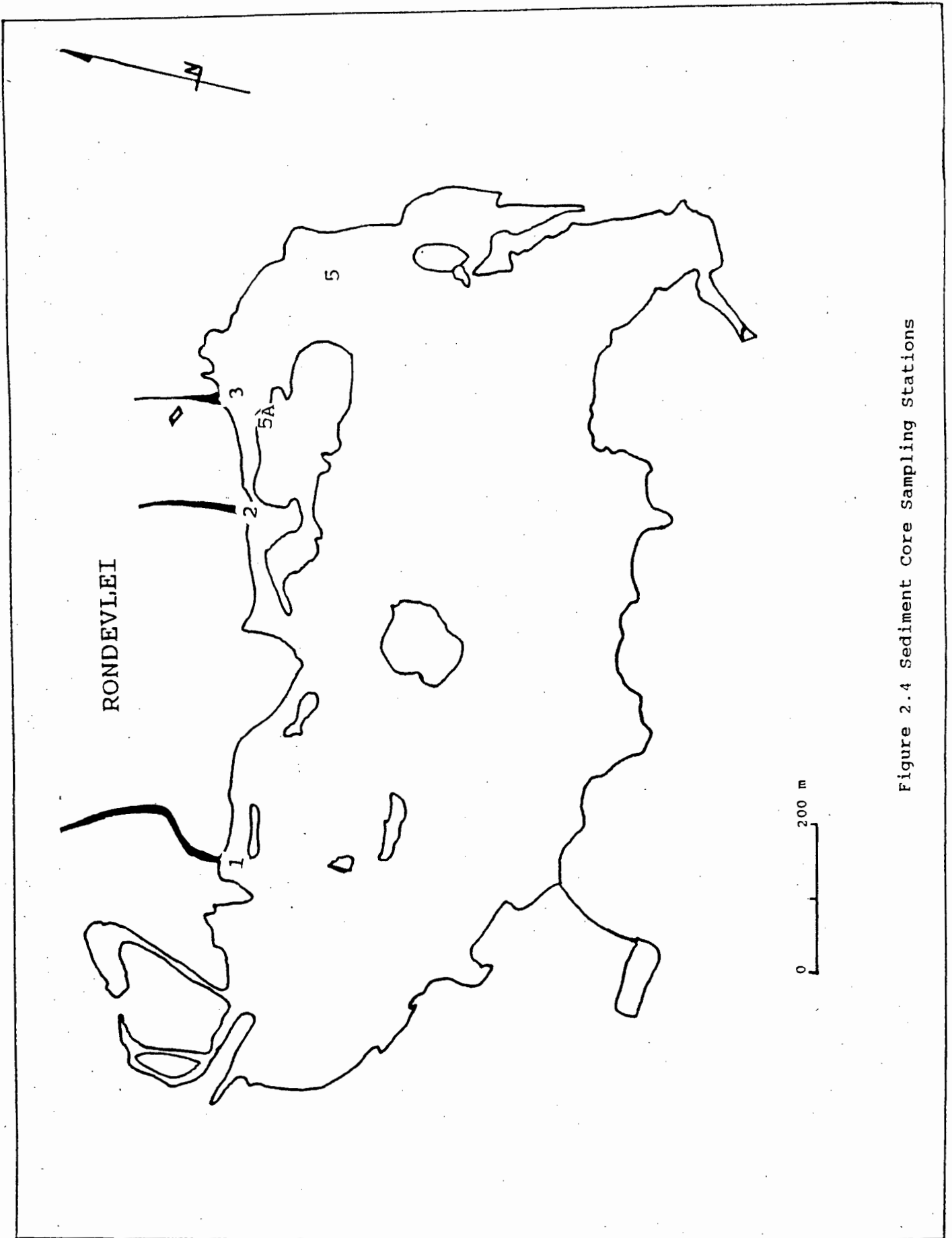


Figure 2.4 Sediment Core Sampling Stations

located on the mudflats which form the outer edge of *scirpus littoralis* beds. Figure 2.3b.

Rondevlei is a nature reserve, and in order to preserve it, a fence has been erected along the perimeter length of the nature reserve. Wire netting has been placed along the fence, inside the canals, to prevent litter and other undesirable large particulate matter from entering the lake. Particulate matter from the surrounding suburbs include empty plastic bags, cans, bottles and all sorts of disposable materials. There is only one outlet, the weir, which joins the Zeekoevlei outflow stream. This outlet allows floodwater outflow during the highflow rainy season of the year.

The lake is approximately 1232m long with a surface area of 475000m². It has a mean width of 386m and a shore line length of 6232m with a development of 2.55m; Gardiner, A.C. (1988). The lake maximum depth is 1.6m. The *littoral* fringe of Rondevlei consists of *Typha capensis* beds which occupy the marshes and shallow water. *Scirpus littoralis* is found in slightly deeper water. Small patches of *Phragmites* are found and, with an increase in eutrophication of water, *Typha* is spreading very rapidly. *Paspalum vaginatum* occupies the marginal areas. A variety of other plants such as terrestrial grasses grow along the margins.

2.2 HISTORICAL BACKGROUND

Rondevlei is one of the major "vleis", i.e. bodies of standing water, that originated in the last century as a result of the migration of aeolian marine sands. The sands are believed (Stephens 1929) to have cut a large bay off Zeekoevlei (Figure 2.1), thereby creating an entirely fresh water body which presently supports over 220 species of birds (Middlemiss 1975), and a variety of vertebrate and invertebrate organisms (Gardiner, A.C. 1988). While

the neighbouring Sandvlei, an estuarine lake, is still open to the sea, Zeekoevlei and Rondevlei were cut off from the sea when, in the early 1940s, the introduction of *Acacia* species resulted in the stabilization of the mobile sand dunes (Mabuth 1952; Middlemiss 1975). As the acacias spread, the indigenous hippopotamus became extinct. The hippopotami were reintroduced in 1981 for reasons that will be discussed later in this chapter.

Located in the winter rainfall region of Southern Africa, Rondevlei has a regular seasonal inflow of water from late autumn to early spring. Up to the early 1940's, there was an outlet that was located towards the centre of its neck. During that time the water had "high" salinities and alkalinities as a result of the marine influence, thereby maintaining a "depauperate zooplankton fauna and marine fish" (Stephens 1929; Hutchinson et al. 1932). While no specific values of alkalinities have been given, according to Hutchinson et al. 1932, "pH varied from 7.8 on 20 January 1928 to 7.3 on 5 February and 6.9 on 17 June 1928 the salinity was almost as great as that of the sea water (.4 Na.Cl.)" "The bottom is composed of mud smelling of H₂S." In the mid 1950's, a series of weirs were introduced between Zeekoevlei and the sea to stop the marine influence, to separate the waters of Zeekoevlei and Rondevlei, and to control the water level. Following the construction of the present weir in 1958, the vlei water gradually became fresh, as seawater could no longer enter the vlei, and, as salinities were lowered, marine fish disappeared. Gardiner, A.C. (1988) recorded mean pH of 8.60, mean bicarbonate alkalinity of 1.70 mmol ℓ⁻¹ and mean carbonate alkalinity of 0.13 mmol ℓ⁻¹ over a period of a year.

Today Rondevlei supports a variety of freshwater floral and faunal communities. The latter includes the introduced exotic carp (*Cyprinus carpio*). Carp was introduced in 1928 ostensibly for the purpose of feeding the population of white pelicans. According to Sterba (1962) and Jubb (1965, 1967) in Gardiner, A.C. (1988) the introduction of carp has resulted in the

increase of the problem of turbidity. This is a problem which is unusual in most South Western Cape vleis, except those on the Cape Flats. Presently an important feature of Rondevlei, turbidity appears in records dating back to 1928, during which time the vlei was presumably free of major human intervention. From that time to date, physical and chemical properties of the water have been regulated by alternating climatic periods of drought and wetness, marked by water clearness and turbidity respectively. The resultant fluctuations in the growth of vegetation has reflected these hydrological changes. Thick phytoplankton blooms have been observed during wet turbid periods, while growth of *Potamogeton pectinatus* (sago pondweed) has marked dry periods with a clear water state (Stephens 1929, Middlemiss 1975).

These fluctuations have been reflected in the abundance of birds. The abundance of shovellers (*Anas smithii*) depends to a large extent on phytoplankton density, while the numbers of redknobbed coot (*Fulica cristata*) decrease or increase with the presence of *Potamogeton pectinatus* (Snook et al. 1988). So there tend to be more shovellers in wet periods and more coot in dry periods.

2.3 MANAGEMENT OF THE VLEI

Both turbidity and the control of water level have been subjects of management concern for a long time. Soon after Rondevlei became a nature reserve, the water level problem was given first priority and the present weir was constructed, as discussed in the previous section, to lower the water level. This was, of course, a great advantage to wading birds because of increased *littoral* area.

According to Guillet and Crowe (1987), the variation in water level plays an important role in determining fluctuations in prey, and foraging and nesting habitats. Thus in order to increase shallow water and mud habitats,

exotic *Acacia* woodlands surrounding the vlei were removed and small islands were created by bulldozing in 1967 and 1970.

Soon after the implementation of these measures, an invasion by other plants, particularly *Typha latifolia* (a bulrush) and *Paspalum vaginatum* (a terrestrial grass) followed. The growth of these grasses, which do not provide suitable habitats for wading birds, was a great disappointment to management. At present, Rondevlei reserve is gradually losing the scenic value which originally made it one of the major tourist attractions in the Western Cape. This is because of the excessive growth of reeds which form "hides" and create obstruction to the viewers of the lake and its natural resources. After the growth of terrestrial weeds, it became clear that the purposes for which the modifications had been made were being defeated. Furthermore, lowering of the water-level by build-up of sediments posed a disadvantage to swimming and diving birds.

An invasion by weeds such as *Typha Latifolia* became such a serious management problem that immediate steps had to be taken to eradicate them.

Water buffalo were therefore introduced in 1979 to control the weeds. Although the method of biological control was a good idea, the buffalo did not bring about any significant change, so, in 1981, two hippopotami were brought in to replace the water buffalo. The hippopotami made a great success of reducing *Paspalum vaginatum*. In the meantime, *Typha latifolia* had grown excessively: removal of *Paspalum vaginatum* has left open spaces and enough nutrient resources. These are favourable conditions for the growth of *Typha*. Hippopotami, which are used specifically for the biological control of weeds in Rondevlei, cannot eat *Typha* because of its tough fibres.

At present there are five hippopotami in Rondevlei. Their breeding and foraging activities have led to the trampling and stirring of the bottom sediments, thereby intensifying the existing problem of turbidity. Turbidity is an optical property of water which results from the scattering of light by

particulate matter present, e.g. suspended clay, silt, finely divided organic and inorganic matter, plankton and other micro-organisms, (Faber 1978). It becomes clear from this definition that the presence of suspended solids in water causes opaqueness or turbidity. Solids like those mentioned above, remain in suspension because of the forces which limit or prevent them from settling. These forces include friction, turbulent motion with vertical upward components, flotation and friction (in the case of organisms). The settling of solids due to reduction of the effect of the above mentioned forces is known as siltation.

In Rondevlei siltation is encouraging growth of reeds. This is a matter of great concern to management. Although turbidity has contributed enormously to the degradation of Rondevlei system as a natural biological habitat, the consequences of the acceleration of this phenomenon by human activities has not yet become an issue of great concern to management in Rondevlei.

2.4 EUTROPHICATION AND MANAGEMENT PROBLEMS IN RONDEVLEI

The problem of reed encroachment and the growth of nuisance plants, including algae, on the other hand, is presently of primary importance and has aroused great interest on the part of management. Research aimed at solving this problem is in progress at the University of Cape Town, and it is partly funded by the Cape Regional Services Council. Records released by this Council reveal that water entering Rondevlei is nutrient-rich, thereby enhancing eutrophication in Rondevlei.

Studies by Thornton and Walmsley (1982) document phosphorus exports exceeding $50\text{mg m}^{-2} \text{y}^{-1}$ from some South African catchments receiving municipal wastewater discharge. Rondevlei is the only lake in the South Western Cape receiving inputs of this degree Gardiner, A.C. (1988). Besides this rich allochthonous source of nutrients, the water in Rondevlei has a considerable

autochthonous input. This originates from a biological regeneration of nutrients resulting during the process of excretion, particularly by birds and hippopotami, as well as stirring by carp. Decomposition of organic material may be another major source of nutrients, although accelerated organic siltation in Rondevlei has recently become a significant subject of concern to management. A question that arises is, whether the changes brought about by this nutrient-loading lead to an improvement in the value of Rondevlei as a nature reserve (in terms of species diversity and abundance), or whether they pose the threat of irreversible geophysical and biological problems. Although the answer to this question is beyond the scope of this thesis, information gathered during this study will lead to the answer in the long run.

Unpublished records released by the Divisional Council for the Cape (predecessor of the Regional Services Council) and studies made by Hutchinson *et al.* (1932) and by Gardiner, A.C. (1988) appear to be the only sources of information presently available on the water chemistry of Rondevlei, while no work whatever has previously been done on the chemistry of the sediments of this system. Differences in information from varying sources may be of interest to the reader. For example, in his report on a 15-month comparative study of the six blackwater lakelets of the South Western Cape, Gardiner, A.C. (1988) has indicated a mean value for Rondevlei of $48 \text{ ug}/\ell^{-1}$ (i.e. $1.55 \times 10^{-3} \text{ mmol } \ell^{-1}$) for Soluble Reactive Phosphorus (SRP), with late summer to autumn peak of $142 \text{ ug}/\ell^{-1}$ ($4.58 \times 10^{-3} \text{ mmol } \ell^{-1}$) and a spring minimum value of $12 \text{ ug}/\ell^{-1}$ ($3.87 \times 10^{-4} \text{ mmol } \ell^{-1}$).

According to figures from the Divisional Council the mean value for SRP is $0.33 \text{ mmol } \ell^{-1}$ with a peak value of $0.55 \text{ mmol } \ell^{-1}$ and a minimum value of $0.1 \text{ mmol } \ell^{-1}$. Of the four lakelets studied by Gardiner, A.C. (1988) and the Divisional Council, (that is, Suurdam, Gillidam, Sirkelsvlei and Rondevlei), Rondevlei has the second highest values in the category of SRP levels based on

figures from the Divisional Council, and third in the category based on figures from Gardiner, A.C. (1988).

Although it has been pointed out in the previous section that sediments could be one of the major sources and sinks of phosphorus in aquatic environments (see Introduction), no work has previously been done to verify this assumption for Rondevlei or for any other aquatic system in the South Western Cape. Mitchell (1984) and Mitchell and Witkowski (1987) have reported on variations in soil phosphorus in the fynbos biome, however. (The term "fynbos biome" denotes a major regional ecological community of plants in the Cape floristic kingdom: Cape Department of Nature and Environmental Conservation, 1964.) The fynbos biome is generally oligotrophic, but aeolian sands are usually less so, particularly those that occur near the sea. Phosphorus is especially lacking in the mountains. Although the work of Mitchell and Witkowski is not specific to Rondevlei, it does give an indication of the quantities and the fractions of phosphorus found on some Table Mountain Sandstone (TMS)-derived deposits, calcareous or lime-rich sands, as well as acid sand deposits.

Rondevlei sediments are derived mainly from Fernwood soils of the strandveld and lowland fynbos. Owing to the presence of granite which forms the bedrock of the lake and Table Mountain Sandstone which covers a portion of Rondevlei catchment, mountain fynbos soils are also found in the vlei. Table 2.1 is a summary of some of the characteristics of these soils, and their varying phosphorus concentration.

TABLE 2.1 RONDEVLEI SEDIMENT CHARACTERISTICS. (Data from Witkowski and Mitchell 1987.)

Soil type	Total phosphorus dry mass $\mu\text{g g}^{-1}$	Resin-extractable phosphorus dry mass $\mu\text{g g}^{-1}$	Organic phosphorus %	Inorganic phosphorus %	pH	Organic matter %
Strandveld soils	338-422	13-40	10-15	85-90	6.6-7.5	1.4-2.2
Lowland fynbos soils	29-403	1.0-3.2	58-70	30-42	5.2-8	2.4-10
Mountain fynbos soils	12-46	0.1-0.2	60-77	23-40	3.3-4.5	1.8-5.6

Observations made by Gardiner, A.C. (1988), who only looked at water, indicated no significant effects of the varying soil phosphorus concentration on the overlying water. However he has pointed out that supplies from undisturbed soils of the Rondevlei catchment may be high compared to those of other catchments that he examined. This might influence the concentration of phosphorus in Rondevlei.

CHAPTER 3

RATIONALE AND METHODOLOGY

3.1 RATIONALE

3.1.1 CHARACTERIZATION AND SAMPLING GUIDELINES

In characterizing the limnological properties of water in Rondevlei, the following general limnological characteristics were examined: oxygen, temperature, conductivity, total dissolved solids. In addition to these, pH and calcium levels, were investigated. In order to minimize error due to handling and preservation of samples, field observation is preferable whenever possible. In situ evaluation of temperature, pH, dissolved gases and conductivity, is therefore necessary to avoid unnecessary error in measurement (APHA 1985).

Having examined the limnological characteristics of water, one must look at the characteristics of sediment. This is because the interchange of phosphorus, a key nutrient to eutrophication, takes place between sediments and overlying water. This occurs through physical and chemical as well as biological processes functioning in the overlying water and underlying sediments (Reddy 1982). The study of nutrient loading and status of the system involves collection of samples and a proper examination of these samples in the laboratory. Sediment traps may be used for the purpose of investigating the loading rates.

As indicated in the previous paragraphs, handling and preservation of samples incorporates some sort of error in the measurements. This can be taken care of by a proper choice of, and careful handling of equipment. Proper shipment of samples to the laboratory and additional care in the

storage and analysis of these samples are cornerstones to obtaining reliable results.

3.1.2 SUSPENDED SOLIDS MEASUREMENT

Suspended solids are measured particularly because of their effect on turbidity and light penetration as well as for their nutrient content. According to Grobler, Toerien and Rossouw (1986), the depth of the euphotic zone may be reduced if light penetration is limited by the presence of suspended solids.

Suspended solids thus have negative impacts on primary production, and their measurement gives an estimate of the trophic response of a water body, particularly in relation to the presence of macrophytes and blooms of phytoplankton which contribute to the bulk of solids in suspension after their death.

Besides the effect of turbidity and light penetration, suspended solids play an important role in the dynamics of organic and inorganic compounds in aquatic systems. In this experiment, phosphorus content of suspended solids was measured.

3.1.3 SEDIMENT TRAPS

"Sediment traps" were used for the purpose of collecting material settling down at the sediment-water interface. Those used in this experiment were chosen for their accessibility, reasonable cost and above all their trapping efficiency. Sediment traps are collecting tools that have been used for many decades. Gardiner W.D. (1979) made a laboratory evaluation of their dynamics and calibration. His was not the first evaluation of sediment traps. According to him, "over one hundred papers concerning sediment traps" had been

written since the work of Heim (1900). Besides Gardiner W.D. (1979), Blomquist and Håkanson (1981) have also reviewed sediment traps in aquatic environments. According to the latter, the purpose of the investigation must govern the type of sediment trap to be used.

Blomquist and Håkanson (1981) identified two major types of sediment trap: bottom sediment traps and buoy-carried sediment traps. These traps vary according to requirements. For example, in the case of bottom sediment traps, vessels could be placed either at the sediment surface or above the sediment surface in the water phase. On the other hand, the buoy-carried traps can be either moored or free-drifting. In this study, the bottom sediment traps were used because they have been recommended for zones of accumulation where fine material is being continuously deposited. Rondevlei is such an environment.

Of the 125 papers published on sediment traps since the work of Heim (1900), Blomquist and Håkanson (1981) have indicated that 45% came from marine research while 55% were from limnological research.

After the type of sediment trap, various workers including Knauer et al. (1978), Gardiner W.D. (1979), Blomquist and Kofoed (1981), Blomquist and Håkanson (1981), Stabel and Chondrogianni (1988), Bailey G.W. (Pers. Comm.), have agreed that geometry and size of sediment vessel are the most important factors controlling the results.

According to Gardiner W.D. (1979), the efficiency of a trap is a function of residence time and circulation pattern of fluid within the trap. These, he says, are processes which are controlled mainly by trap geometry and secondarily by current velocity. Gardiner W.D. (1979) compared 5 categories of trap, that is, cylinders, funnels, wide-mouthed jars, containers with bodies much wider than the mouth and basin-like containers with width much greater than height. Of all these, the average efficiency of cylinders was found to be closer to 100% than other configurations. Tests were conducted in

both flowing water and still water. Blomquist and Håkanson (1981) made a similar observation and arrived at a conclusion that cylinders yield the best results, particularly if a proper height/diameter ratio (H/D value) is maintained. A height/diameter ratio (H/D) > 3 , and a reasonable orifice diameter had to be maintained to ensure adequate trapping. According to Smith (1975, in Blomquist and Lars Håkanson 1981), these two factors play an important role in controlling the water motion in a vessel. Blomquist and Kofoed (1981) obtained adequate results with cylinder diameter of 21-57mm and a H/D ratio > 3 .

For the above mentioned reasons, cylindrical sediment traps were used in this study. However, due to shortage of equipment, and also due to shallowness of the water, the best H/D ratio (8) suggested by Blomquist and Kofoed (1981) and recommended by Bailey G.W.(Pers. Comm.) was not maintained. The ratio maintained was that of Knauer et al. (1979), that is > 3 . Although it is not the best ratio, in an in situ experiment, Blomquist and Kofoed (1981) found adequate results with cylinder diameters of 21-57mm and H/D ratios ≥ 3 .

Owing to a broad diversity of environmental conditions, the choice of sediment traps suitable for a specific area is a very difficult matter. Apart from problems related to weather conditions and lake bed characteristics, one has to consider factors which may bias one's results. These include overtrapping as a result of disturbance by animals. Activities of the mudfish (carp), for example, lead to the stirring of bottom muds, which results in overtrapping of sediments. The trampling of the hippopotami on the mud has a similar disadvantage, or even worse. Complete loss of samples of sediment may result through total destruction of sediment traps by animals. It is therefore important to realize that current velocity is not the only extrinsic factor that is important in sediment trapping. Other environmental factors include behaviour of the faunal population within a system of interest.

3.1.4 SEDIMENT CORES

For studies of the sediment characteristics, for example pH, particle size distribution, nutrient dynamics and others, sediment coring method was employed. Like sediment traps, sediment cores are widely used. The choice of equipment and sampling procedures depend on the specific information required.

In this experiment, hand-operated, open-ended plastic cylinders were employed for various reasons. Firstly, they are cheap and easily accessible. Secondly, a choice of size is almost unlimited. This, of course, is an advantage in shipment and storage of samples. Sample analysis in limited space (for instance in an anaerobic box) becomes less of a headache. Workability of samples in open-ended cylinders is another advantage of this kind of equipment.

Coring sediment has been applied in studies of sedimentary rocks (Griffiths 1967) as well as muddy sediments. (Silberbauer 1982; Lennox 1982; Reddy 1983; APHA 1985 and Ostrofsky 1987.) Core or cylindrical samplers vary from hand-pushed tubes to explosive-driven and automatic-surfacing models (APHA 1985). Recovery of core sample varies a lot, that is from 60-90 per cent in sedimentary rocks to 100 per cent in muddy sediments.

In the case of muddy sediments, migration of ions as a result of handling and transportation of samples may bias results. This means that absolute care must be taken in this respect. In the present experiments, hand-pushed plastic cylindrical tubes were used. The cylinders were open-ended and tight-fitting rubber stoppers were used to close both ends. As much care as possible was taken to plug the ends without introducing excess air into the tubes. This was done by working beneath the surface of the water.

3.2 FIELD OBSERVATIONS

3.2.1 ASSESSMENT OF WATER CHARACTERISTIC

Field observations were made during spring, summer, autumn and winter, i.e. between December 1987 and October 1988. Measurements of temperature, electrical conductivity, pH, and dissolved oxygen concentration were recorded seasonally for 5 stations (Figure 2.3). Temperature measurements were made with a mercury thermometer, graduated to 0.1°C.

A Crison conductimeter, portable model 523, with built in temperature compensation, was used to measure electrical conductivity. Precision and accuracy of this method have been determined by testing three synthetic samples in the laboratory (APHA 1985). Although there was a slight variation in the results, according to APHA (1985), 120 readings of one of the samples with a conductivity of 30.3mSm⁻¹ showed a standard deviation of 7.8%.

Dissolved Oxygen concentration was measured with a YSI Model 57 Oxygen Meter with automatic temperature condensation. The instrument was calibrated by reading against air. Readings were recorded to the nearest 0.5mg/ℓ. This commercially available membrane electrode system has an accuracy of ± 0.1/mg ℓ⁻¹ and a precision of + 0.05mg/ℓ⁻¹ (APHA 1985).

Measurements of pH were made by the use of the Hellige Lilliput pH meter Model No. 750/750p. The meter has provision to compensate for "slope" or "pH". This is necessary for the correction for the difference between the actual potential difference between the two electrodes at a given pH and the theoretical one calculated from the values of the half couples. The instrument was calibrated with buffer solutions of pH 4 and pH 7.

3.2.2 ESTIMATIONS OF FLOW VELOCITY AND WATER VOLUME

In addition to the characteristics of water and sediment, water volumes and movement play a significant role in determining the nutrient status of a system. Increase and decrease in concentrations depend on the status and movement of the input and output volumes. For these reasons measurement of water volumes flowing in and out of the water body should form an integral part of the eutrophication studies of such a system.

Spot measurements of current speed were made for channels 1, 2 and 3 during the rainy winter season of 1988. During the dry summer period measurements could not be made owing to inadequate depth or absence of water flowing in the channels. For all channels depth measurements amounted to less than 300mm in summer. This, and growth of terrestrial as well as aquatic weeds, created a condition which was unfavourable for measurement of channel discharge by means of velocity/area technique.

Under favourable winter weather conditions, an OTT Kemtn Z 30 flow meter with a quartz timer was used to measure current flow at two different points along each channel. Depth measurements were taken at intervals of 100mm across the channel. These measurements were done in order to estimate current velocity using Manning's formula used in simulation of flow data, i.e.

$$V = k \frac{R^{\frac{2}{3}} S^{\frac{1}{2}}}{n}$$

where V = mean channel velocity

k = constant

R = hydraulic mean radius i.e. $\frac{\text{stream cross sectional area}}{\text{wetted perimeter}}$

S = slope of water surface

n = Manning's roughness coefficient (Gregory and Walling 1973).

Having obtained values of velocity, discharge was calculated by finding the product of velocity and cross-sectional area. The sum of the values of discharge from all monitored channels was to be compared to a computer simulated discharge value obtained from the Cape Town City Council, with the help of Thornton J. and Darroch A. Darroch (1988) used a program called "Shower" version 2.1 in order to simulate seasonal runoff volumes from rainfall for Rondevlei for the years 1983-1988. This simulation procedure was adopted from United States Soil Conservation Service TR-55 method (SCS) used to calculate daily runoff volumes. Two sets of data utilized in the execution of this procedure are land-use of the catchment and rainfall. Soil characteristics were modified within "Shower" by recognising a 5-day antecedent moisture condition. The simulation procedure was, however, not very satisfactory as it did not take into account the after-effects of rainfall over the whole catchment, that is, continued flow of water, hours after the actual rainfall.

3.3 SAMPLE COLLECTION AND PRESERVATION

3.3.1 WATER

Samples were collected seasonally from Stations 1-5 during January to November 1988. Water collected for phosphorus (SRP) and for calcium (Ca) analysis was filtered on site through a glass fibre Whatman G/F F filter (0.45 μ m pore size), and stored in duplicate in 20ml plastic autoanalyser vials. All equipment was pre-cleaned by using a phosphorus-free detergent (Contrad) diluted with de-ionised water. Storage containers were soaked for at least 12 hours in a dilute HCl solution and then rinsed thoroughly in distilled water before use. A hand-operated vacuum filter pump was used, and clean plastic bottles were rinsed with filtered sample water before samples

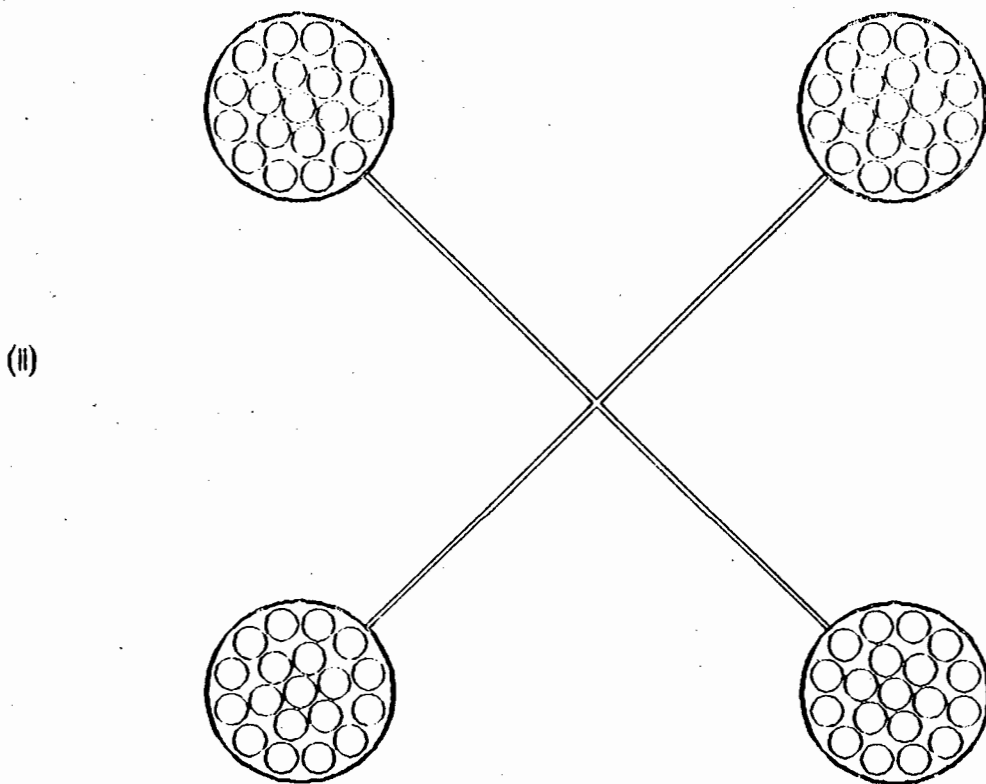
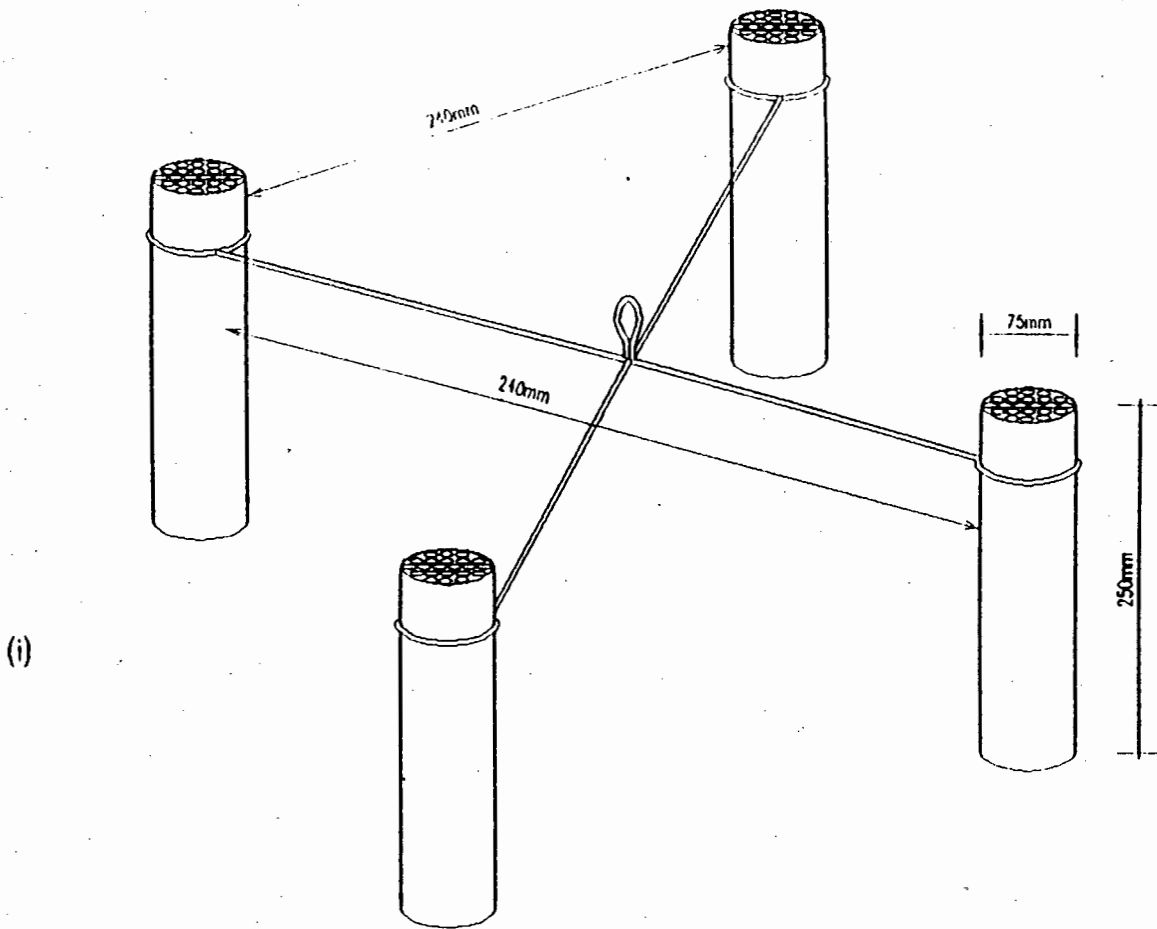
were collected. Dry ice was used to freeze samples immediately at -20°C . At least 10% of the container capacity was left to allow for thermal expansion. These samples were analysed within 6 months of storage. Information relating to sample field number, source and date, as well as analyses requested, was displayed on the label attached to the plastic bottle.

Water collected for total suspended sediment and for dissolved solids was run through an $80\mu\text{m}$ sieve, and stored in 1 litre plastic bottles. These samples were labelled as indicated above, and were refrigerated immediately at 4°C . The samples were analysed within 7 days of storage.

3.3.2 SEDIMENT

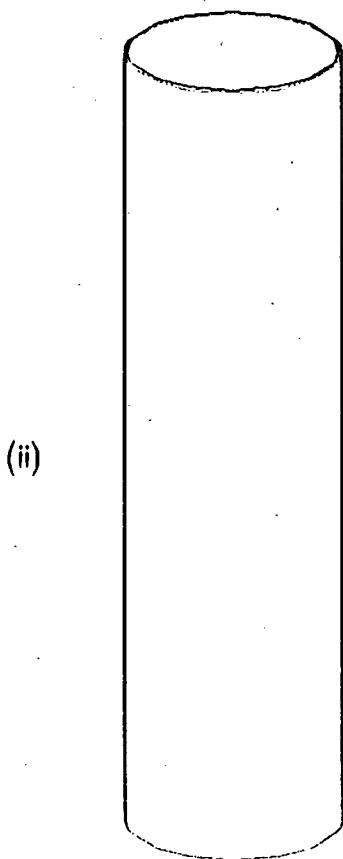
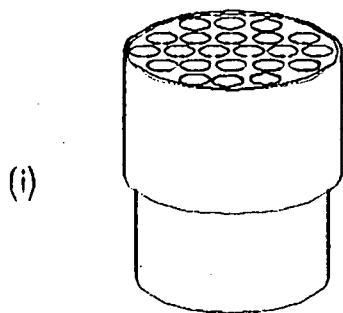
During spring, summer, autumn and winter, 4 replicate samples of material settling to the bottom of the vlei were collected from each of the above mentioned sampling stations. This was done by means of bottom sedimentation traps. Traps were made out of plastic cylindrical containers, 4 of which were mounted on a plastic-coated, metal cross frame (Figures 3a and 3b) designed according to Knauer *et al.* (1978). Each container measured 250mm in height and had an internal diameter of 75mm and a sealed bottom. The top had a baffle system of tubes made out of at least 16 smaller plastic tubes, each of which was 74mm long with an internal diameter of 13.5mm. A baffle system served to keep out large organisms, to reduce turbulence within the vessel and to secure trapped material inside the vessel. A distance of at least 240mm was maintained between individual trap containers.

Well equipped with a baffle system, cylinder tops were covered with plastic sheets secured by means of rubber bands in order to stop material from settling into the traps while they were being sunk into the water. Traps were left to stand for about 10 minutes before the plastic covers were removed. Standing at an angle of 90° to the bottom and at a height of 250mm, traps were



(i) Replicate collector assembly
(ii) Top view, baffle grid system

Figure 3a Sediment Trap Assembly



- (i) Removable baffle system
- (ii) Single collector

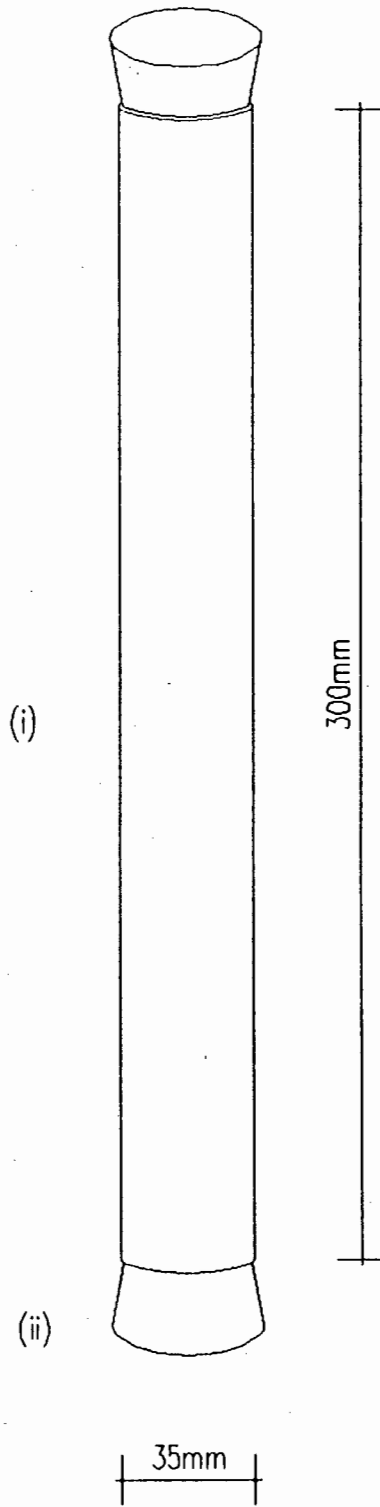
Figure 3b Single Collector Assembly

left out in the field for a minimum period of 7 days and a maximum of 14 days, depending on the weather conditions. Before submersion, formalin of 8% concentration was poured into the containers to reduce fragmentation and decomposition of trapped material, as well as activity of micro-organisms, and microbial growth during a sampling period.

After the water had been drained and filtered, sediment samples were halved and weighed. One half of the remaining trapped material was stored at 4°C and was analysed for total solids and for organic solids (see Section 3.3) within 14 days of sampling. The other half of the sample was air-dried and later analysed for Total Phosphorus.

For sediment core sampling, cylindrical plastic pipes 300mm long, with an internal diameter of 35mm, were used. (Figure 3c.) Sediment core sampling was carried out during March 1989. Core samples were taken from station shown in Figure 2.4. Atmospheric air was prevented as much as possible from contaminating core samples during sample-collection as well as during preliminary processing. Cores were closed with airtight rubber stoppers and this was done under surface of the water and as close to the sediment surface as possible. Within 24 hours of sampling, the top 160mm was divided into eight 20mm-long fractions. 15ml of each fraction were centrifuged at 3,000 rpm for 15 minutes in order to separate the interstitial water from the sediment, using a Beckman model J2-21 centrifuge. The interstitial water was then filtered through a Whatman GF/F filter paper (0.45µm), and frozen immediately. Sediment was dried in an oven at 110°C. Fractionation of sediment and separation of interstitial water were carried out under anaerobic conditions.

The importance of the anaerobic environment in the phosphorus exchange rates for sediments has been documented in Fillos and Molof (1970), Andersen (1974), Kamp-Nielsen (1974), Bengtsson (1975), Sonzogni et al (1977), and Silberbauer (1982). Most of the work done by these different observers was



- (i) Sediment corer
- (ii) Rubber stopper

Figure 3c Sediment Corer

conducted by using cored samples. With an exception of Kamp-Nielsen (1974), results showed release of phosphorus by sediment under anaerobic conditions. The rate of release, however, varied with environmental conditions. While Bengtsson (1975) found a high figure of $36\text{mgP m}^{-2}\text{d}^{-1}$ for eutrophic lakes in Southern Sweden, Silberbauer (1982) found only $2.5\text{mgP m}^{-2}\text{d}^{-1}$ for oligotrophic Swartvlei in South Africa. Aerobic conditions on the other hand have resulted in uptake of phosphorus by sediments (Andersen 1974; Silberbauer 1982), or lower release rates than those experienced under anaerobic conditions (Fillos and Molof 1970; Banaub 1975). It is, however, necessary to conduct other experiments related to this issue as Kamp-Nielsen (1974) found higher release rates for aerobic conditions than anaerobic conditions during his investigations on core samples from both eutrophic and oligotrophic environments.

As recommended by Kamaya and Yamada (1987) work on the sediment cores from Rondevlei was done with the hope of encouraging as much release of phosphorus as possible from core samples by exploiting the anaerobic environment.

3.4 SAMPLE ANALYSIS

3.4.1 WATER

I PHYSICAL EXAMINATION

Water samples collected from 5 sampling stations (Figure 2.3a) were analysed for Total Suspended Solids (TSS), Total Dissolved Solids (TDS) and Particulate Organic Matter (POM). Water collected from each of the 5 stations was first run through an $80\mu\text{m}$ mesh sieve and then filtered through pre-weighed Whatman GF/F paper ($0.45\mu\text{m}$). Prior to filtration, filter paper was soaked in

distilled water and oven-dried at 500°C for three hours to remove dissolved material that might be present in the filter papers. The volume of water filtered depended on the solid load of the sample. For high concentrations, 50ml of sample was used, and for low concentrations, up to 1000ml of sample was filtered. Filter papers were dried in numbered containers at 60°C for at least 24 hours and then transferred to a desiccator where they were left to cool for approximately 15-20 minutes. Then filter papers were weighed as rapidly as possible to avoid reabsorption of atmospheric moisture. After the weights had been noted, the concentration of Total Suspended Solids (TSS) concentration was calculated and the results were recorded in mg/l. The filter papers were then burned for 3 hours at 500°C in a muffle furnace and reweighed. Concentrations of organic solids were calculated and results were recorded as percentage organic material in suspension.

II CHEMICAL ANALYSIS

(a) TOTAL DISSOLVED SOLIDS (TDS)

TDS was determined by evaporation of at least 250ml of filtered water at 70°C for 96 hours. [400ml beakers of known mass were used for this purpose.]

(b) CALCIUM

A Varian Techtron model 750 Atomic Absorption Spectrophotometer was used to determine the concentration of calcium in the water samples. A hollow cathode lamp for calcium was installed and the machine was set at 422nm wavelength, 0.2nm slit width and 4.0 MA lamp current. An air/acetylene gas combination was used and measurements were taken at maximum sensitivity.

A 1000mg ℓ^{-1} calcium stock solution was used in the preparation of a range of standard solutions, and a calibration curve was prepared. Prior to sample analysis, a nebuliser was rinsed by aspirating distilled water. The blank was atomized and the instrument was zeroed before standards and samples were atomized. Measurements were taken at 20°C - 25°C. Standards were run periodically during analysis to check the reliability of the calibration curve. A blank was run between samples and standard readings to ensure stability of the instrument.

Concentration of calcium in samples was determined by interpolation from the standard calibration curve, and results were recorded in mg/ ℓ . Precision and accuracy of this method have been determined by means of direct and indirect analysis of various metal ions (APHA 1985): direct analysis showed relative standard deviation and relative error values ranging from 8.2% to 26.4% and 0.4% to 10.6% respectively. Values depended on the sample concentration and number of sample participants. For example, for 42 analysed samples of magnesium, with a concentration of 200 $\mu\text{m}/\ell$, relative standard deviation of 10.5% was found, within an error of 6.3% (APHA 1985).

(c) SOLUBLE REACTIVE PHOSPHORUS (SRP)

Soluble Reactive Phosphorus (SRP) analysis was carried out by the use of the TECHNICON Auto Analyzer (AA11). This automated method, described by Mostert (1983), is based on the procedure of Murphy and Riley (1962) "in which trivalent antimony ions are incorporated as catalyst and ascorbic acid is used as a reducing agent". During the reaction of phosphate and molybdate, in the presence of the above mentioned reagents, a coloured complex developed is reduced molybdoantimony phosphoric acid, and the ratio $[\text{H}]/[\text{MoO}]$ is selected for optimal colour development (Murphy and Riley, 1962; Going and Eisenreich, 1974, in Silberbauer, 1981). The absorbance was measured at 660nm in a 50-mm

flowcell. Readings were recorded as $\mu\text{m}/\ell$ to two decimal places.

The use of the Murphy and Riley method has been recommended by Strickland and Parsons (1965). They found it simple, reliable and superior to all other methods due to its high precision and accuracy. According to Strickland and Parsons (1965), six samples were analysed in septuplicate. At an average (PO_4^-) concentration of $0.340\text{mg}/\ell$, an average standard deviation found was $0.015\text{mg}/\ell$ and a coefficient of variation of 6.2%. Recoveries of 89% and 96% were made in two samples with added (PO_4^-).

3.4.2 SEDIMENT

I PHYSICAL EXAMINATION

Sediment core samples taken from the 4 stations, that is Stations 1, 2, 3 and 5 (Figure 2.4), were examined for texture and their organic content. Although pretreatment was not done as prescribed by Morgans (1966), samples were air-dried to avoid unnecessary aggregation.

Dry sieving was preferred to wet sieving to avoid retention of small particles by a film of water, which is experienced during wet sieving (Krumbein and Pettijohn, 1938, in Morgans, 1966). Sieves of -1 Phi (θ) to approximately 5 Phi (θ) mesh sizes were mounted on a shaker in decreasing order of mesh size, and 100g of dry sediment was placed on the top sieve. The stack was allowed to shake gently for 10 minutes. Material from each sieve was weighed, and its mass was recorded as a percentage of the initial mass of the sample. Analysis of silts and clays was done by the pipette method of sedimentation which is based on Stokes Law. The law states that "the velocity of fall of a sedimentary particle through a viscous medium (e.g. water) is directly proportional to its diameter". For each station, 20g of dry sediment was placed in a measuring cylinder which was filled up to the 500ml mark with

water. A drop of Contrad (a commercially available detergent for cleaning glassware) was added to disperse the particles, and the mixture was stirred thoroughly. The cylinder was shaken and then allowed to stand. A 10ml pipette was used to draw samples from 10cm depth at the following intervals, 0 minutes, 3 minutes 50 seconds, and 8 hours 10 minutes. Samples were dried at 60°C in petri dishes, labelled A, B and C respectively. After weighing the samples, the percentages of sand, coarse silt, medium-fine silt and clay were calculated.

II CHEMICAL ANALYSIS

(a) pH

The pH of a 1:2,5 sediment/water suspension was determined by the use of a pH meter fitted with a ground glass sleeve-type calomel electrode (see Section 3.1). Within 3 hours of sampling, 15ml of sediment sample was placed into a 100ml beaker, and 50ml of distilled water was added to make a mixture that was stirred with a solid glass rod. The mixture was stirred after 50 minutes, and was allowed to stand for 10 minutes before the suspension was stirred for the last time. The pH was measured immediately and the results were recorded to 0.1 units. The above procedure was repeated for every 20mm depth of each of the sediment cores from the 5 sampling sites.

(b) TOTAL PHOSPHORUS (TP)

Three steps were involved in the analysis of sediment for TP, i.e. digestion, standardization and sample analysis. Prior to digestion, a sample of known mass from each air-dried sample of sediment was run through a 2mm sieve. The sample was heated in a crucible in a muffle furnace at 240°C for 2

hours, and then allowed to cool to 100°C before removal. Each sediment sample was transferred to a 50ml digestion tube, and the remnants in the crucible were rinsed with 5ml concentrated HCl. The rinse was poured into a digestion tube, and another 5ml of HCl was added to the tube to rinse sediment from the sides of the tube. The samples were left to boil on a digestion block at 100°C for 30 minutes, then 20ml of distilled water was added to each of the samples, which were allowed to stand for another 30 minutes on a digestion block. Diluted digests were filtered into 100ml volumetric flasks, through Whatman No. 30 filter paper.

Each tube was rinsed with distilled water (20ml aliquots), and after making up to volume, the solution was well mixed. 4ml of diluted digest was transferred to 50ml volumetric flask, and 8 ml of reagent (Murphy and Riley, 1962) (see Appendix A) were added to each sample. The volume was made to 50ml with distilled water. The mixture was well shaken and left to stand for at least 30 minutes for colour development. Blanks and standard solutions were prepared and absorbance read at 882nm using a Bausch and Lomb type Spectrophotometer. The concentration of phosphorus was determined by the use of a calibration curve and phosphorus levels in different samples was obtained by calculations.

(c) TOTAL INORGANIC PHOSPHORUS (IP) AND ADSORBED PHOSPHORUS (AP)

Determination of IP was carried out by the use of ascorbic acid - molybdenum blue method (Section 3.4). Digestion of samples was done according to Kayama and Yamada, 1987. 0.5 grams of sediment measured from dry samples of core fractions each, was placed into a glass beaker, to which 20ml of 1M HCl added. The samples were left to shake at room temperature for 24 hours, after which time they were centrifuged at 8000 rpm for 15 minutes. 8ml of the supernatant from each sample was analysed for phosphorus as described in the

preceding section.

The method followed in analysis for AP is the one outlined by Kamaya and Yamada, 1987. 0.5 grams of each of the samples measured from dry core sediment was placed into a glass beaker, and 20ml of 1M NH_4Cl was added. The mixture was allowed to shake for 30 minutes at room temperature, and then centrifuged at 8000 rpm for 15 minutes. 8ml of the supernatant from each sample was analysed for Phosphorus as above.

CHAPTER 4

PHYSICAL AND CHEMICAL PROPERTIES OF WATER IN RONDEVLEI

Variations in temperature, rainfall and water level, flow and suspended solids are displayed in Figures 4.1, 4.2, 4.3 and 4.4 respectively

The inorganic chemical parameters of Dissolved Oxygen, pH, Conductivity, and the major inorganic ions of calcium and phosphorus are shown in Figures 4.1, 4.6, 4.7, and 4.9 respectively. Total Dissolved Solids (TDS) and Particular Organic Matter (POM) are displayed in Figures 4.10 and 4.11. Table 4.1.1 is a summary of the records on the physical and chemical properties of water in Rondevlei. For all variables except flow and water level, values represent overall means ($n=42$) and ranges for the samples taken from all 5 stations. For water level and flow, mean monthly readings were used, therefore values represent overall means ($n \approx 12$).

Results of the limnological characteristics of water in Rondevlei indicate a seasonal pattern for most variables. For example, minimum values of temperature were recorded during mid-winter, while peak values were recorded during mid-summer (Figure 4.1). In contrast to temperature, readings of rainfall, water level and catchment flow were high during the winter season and low during the summer season (Figures 4.2 and 4.3).

High values of Total Suspended Solids (TSS) and Particulate Organic Matter (POM) were noted during late autumn and early winter. Spearman rank correlation analysis suggests a positive correlation between Total Suspended Solids (TSS) and Particulate Organic Matter (POM). ($r=0.54$ at 5% level of significance.)

Dissolved oxygen levels and pH are high during summer and autumn. These variables correlate with one another significantly; that is, $r=0.41$ at 3% level of significance. pH and Soluble Reactive Phosphorus (SRP) correlate,

($r=0.39$ at 4% level of significance). Electrical conductivity values ranged between 74.26 mSm^{-1} and 741.60 mSm^{-1} . A significant relationship exists between this variable and catchment flow as well as Soluble Reactive Phosphorus (SRP). For electrical conductivity and catchment flow, $r=0.52$ at 4% level of significance. Between electrical conductivity and Soluble Reactive Phosphorus (SRP), $r=0.42$ at 3% level of significance.

There is a considerable spatial variation for some of the measured variables. For example, a maximum temperature value recorded for Station 5 is 27°C while a value of 23°C has been recorded at Station 4. However, both stations exhibit higher values than other stations for Total Suspended Solids, (TSS) and Particulate Organic Matter (POM). This feature could be attributed to the abundance of phytoplankton algae observed at these stations during mid-summer. Highest values of pH and dissolved oxygen were recorded at Station 1. pH readings were exceptionally high at Station 5.

Station 3 is dry most of the year. During winter, a period of high rainfall and peak water flows, very high values of pH, dissolved oxygen, conductivity and calcium were obtained at this station. Of all stations monitored, Station 3 had the largest quantities of Total Dissolved Solids (TDS) and organic matter during the winter season. Plant debris accumulates in this canal as a result of senescence and death of terrestrial grasses and *typha* which grow during the rest of the year.

Finally, dissolved solid load was noted at Station 2 during mid-summer. A corresponding high reading was taken for Soluble Reactive Phosphorus (SRP) at this station. It is possible that water used for domestic purposes which is flushed into the lake through this canal is responsible for the increase in dissolved solid load. As a matter of fact, it has been indicated earlier in this thesis that domestic water contains a considerable amount of phosphorus from detergents, and other phosphorus-rich compounds. Summer is a dry season, therefore dilution by rainwater which contains low phosphorus

quantities is not possible. It is however necessary to note that the value recorded for phosphorus at this station in January appears to be incredibly high. Further studies should be made to explain this rise in phosphorus levels.

TABLE 4.1.1 MEAN VALUES OF PHYSICAL AND CHEMICAL VARIABLES OF WATER IN RONDEVLEI

Variable description	Variable	Mean	Standard Deviation	Maximum	Minimum	Range
Physical ↑ ↓	Temperature °C	18.88	4.39	27.00	9.00	18.00
	Catchment Flow m ³ /sec	0.01	8.24x10 ⁻³	0.02	4.24x10 ⁻³	0.02
	Rainfall m	0.04	0.04	0.10	0	0.10
	Lake water level m	4.56	0.03	4.94	4.15	0.08
	TSS mg/l ⁻¹	39.54	48.76	190.00	0.90	189.20
Inorganic Chemical ↑ ↓	Dissolved O ₂ mg/l	8.51	2.32	14.60	5.20	9.40
	pH		0.44	9.00	7.45	1.55
	SRP μmol/l ⁻¹	0.15	0.24	1.19	0.00	1.19
	Ca μmol/l ⁻¹	0.50	0.25	1.40	0.22	1.14
	Conductivity mSm ⁻¹	230.03	161.40	741.60	74.26	667.30
	TDS mg/l ⁻¹	1926.88	2403.10	13522.80	730.00	12792.90
Organic Material ↓	POM mg/l ⁻¹	34.23	40.06	144.00	2.80	141.20

Ca : Calcium
 POM : Particulate Organic Matter
 SRP : Soluble Reactive Phosphorus
 TDS : Total Dissolved Solids
 TSS : Total Suspended Sediment

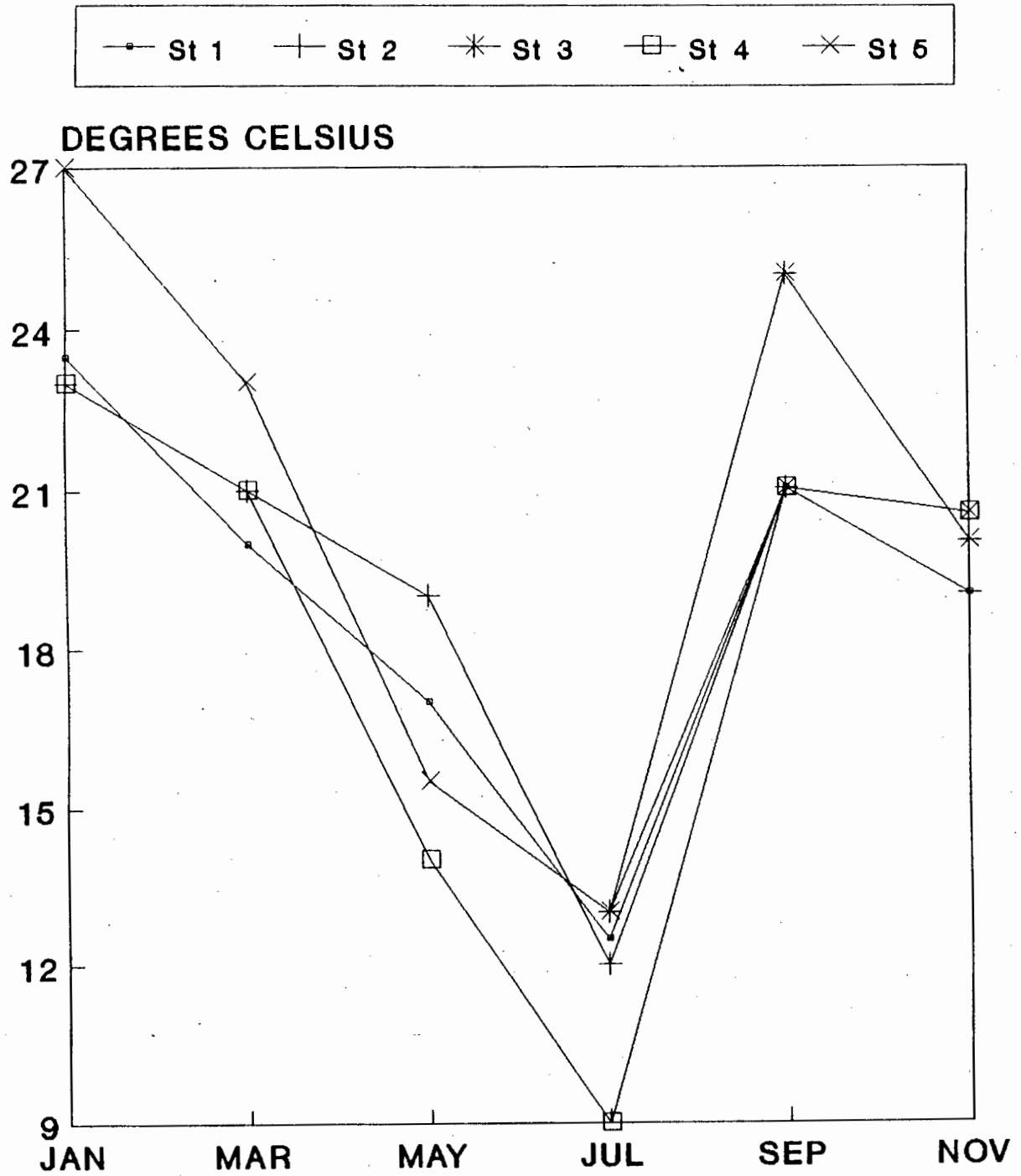


Figure 4.1 Monthly temperature variation 1988

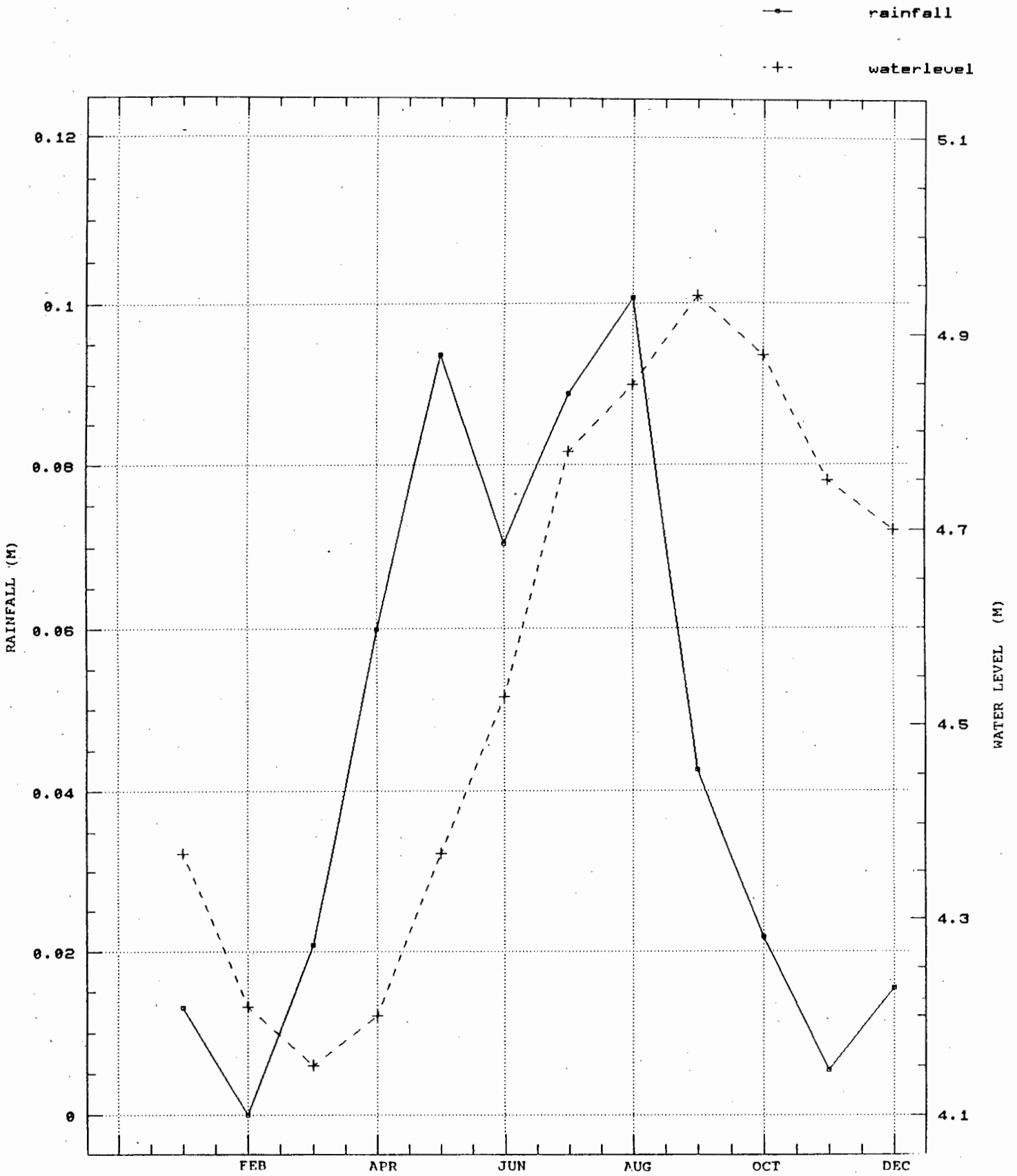


Figure 4.2 Mean monthly rainfall and water levels
1988
Data from Rondevlei Management Staff

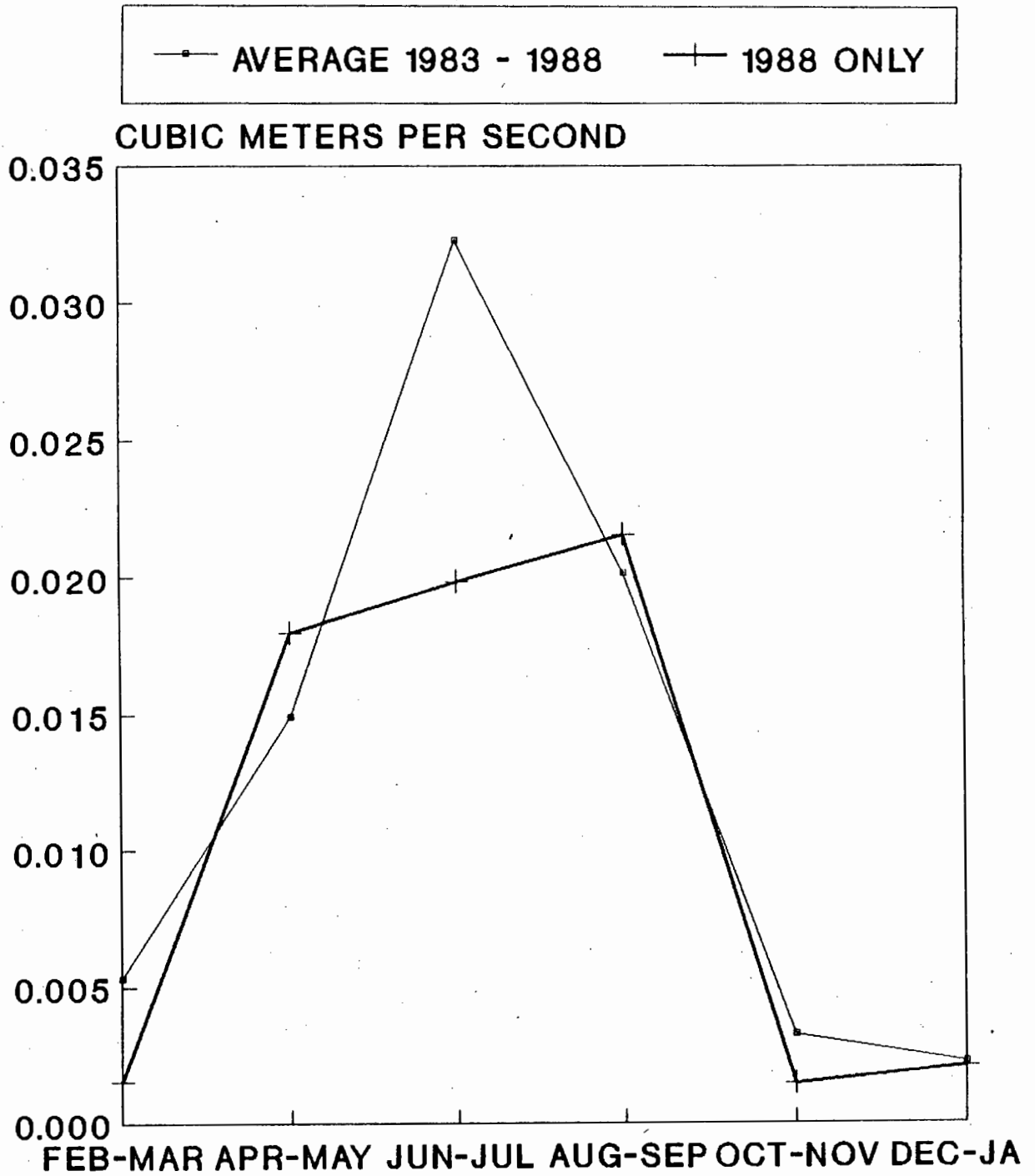


Figure 4.3 Rondvelé catchment flow; simulated data

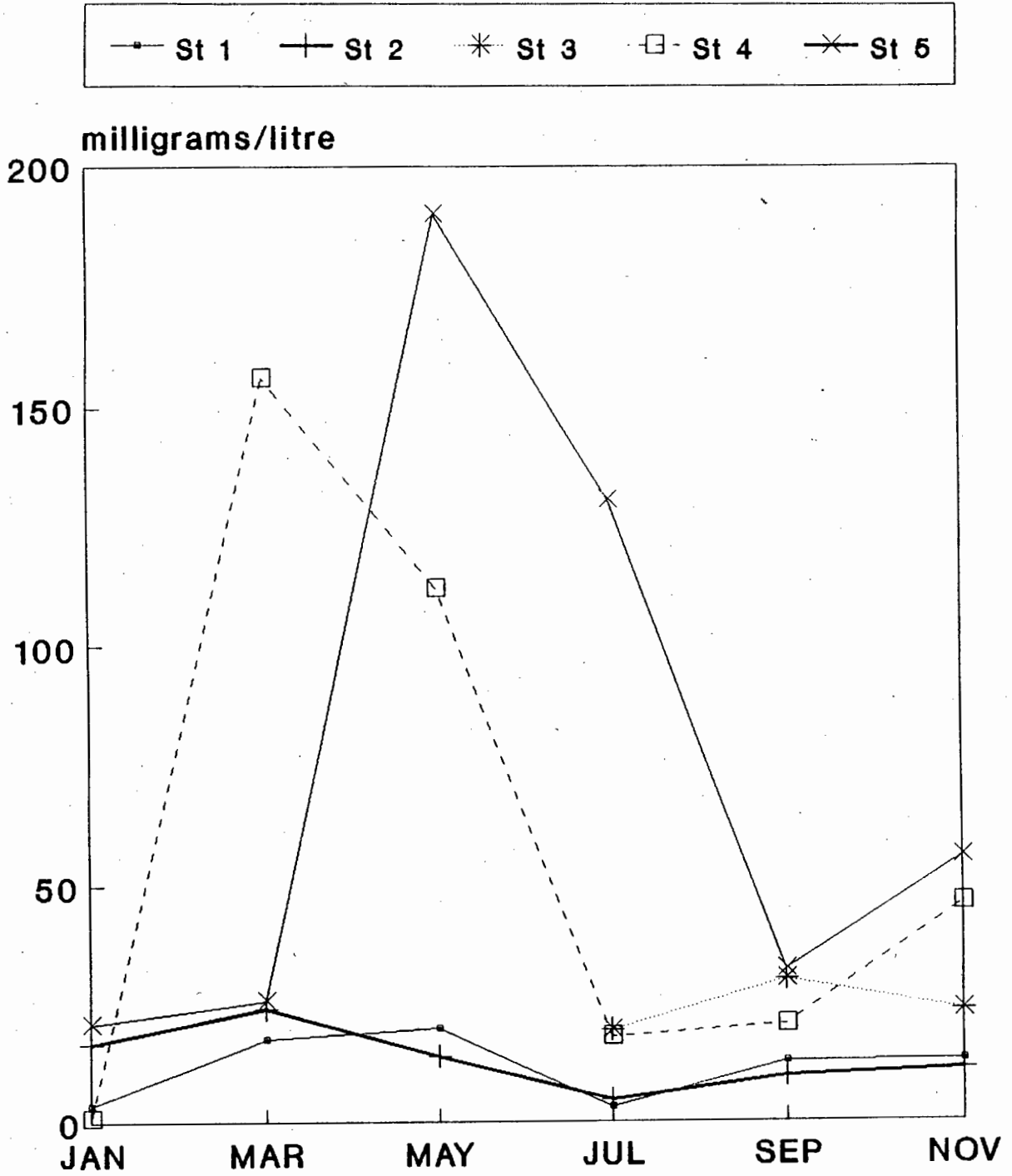


Figure 4.4 Monthly total suspended solids 1988

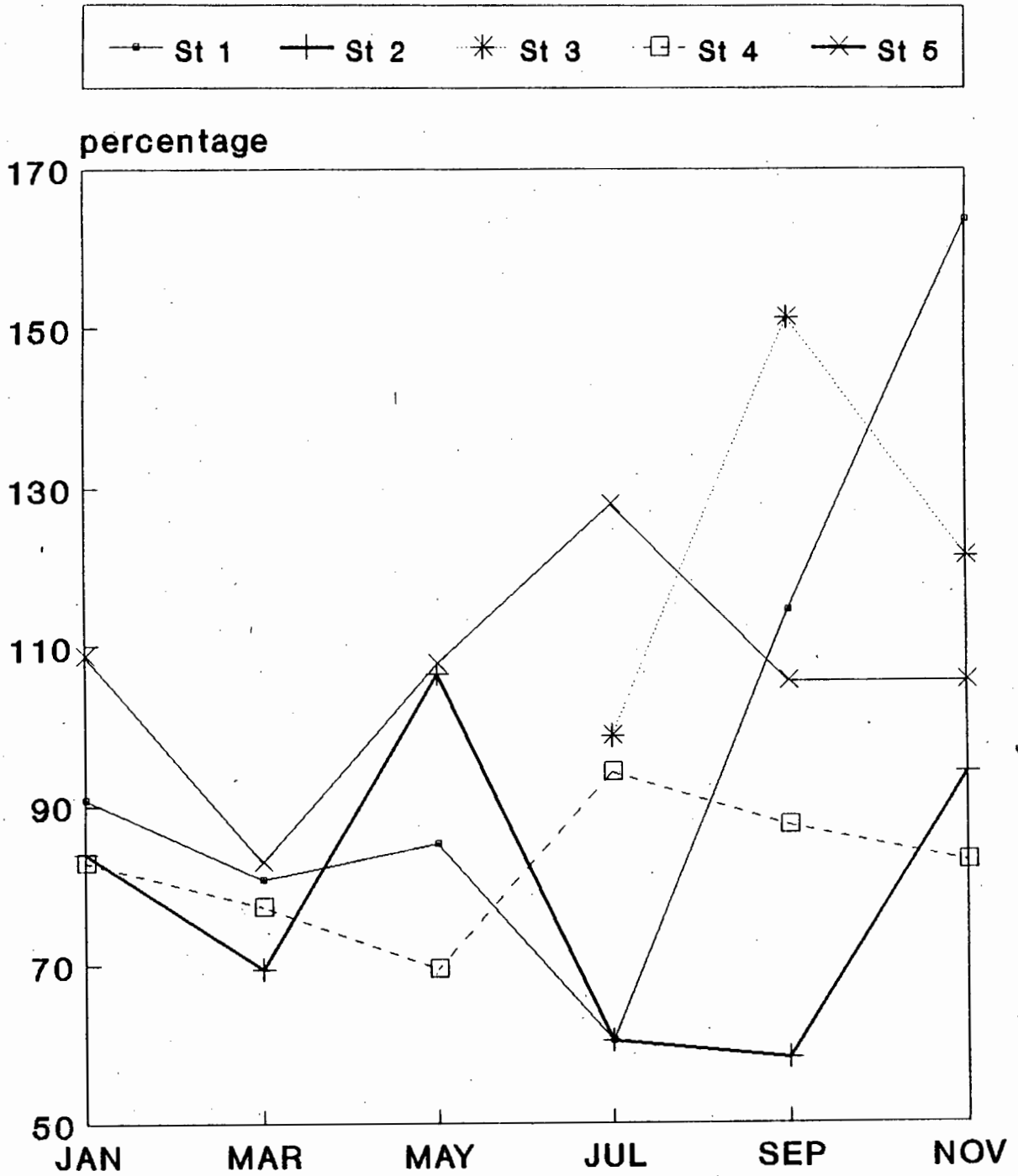


Figure 4.5 Monthly oxygen % saturation 1988

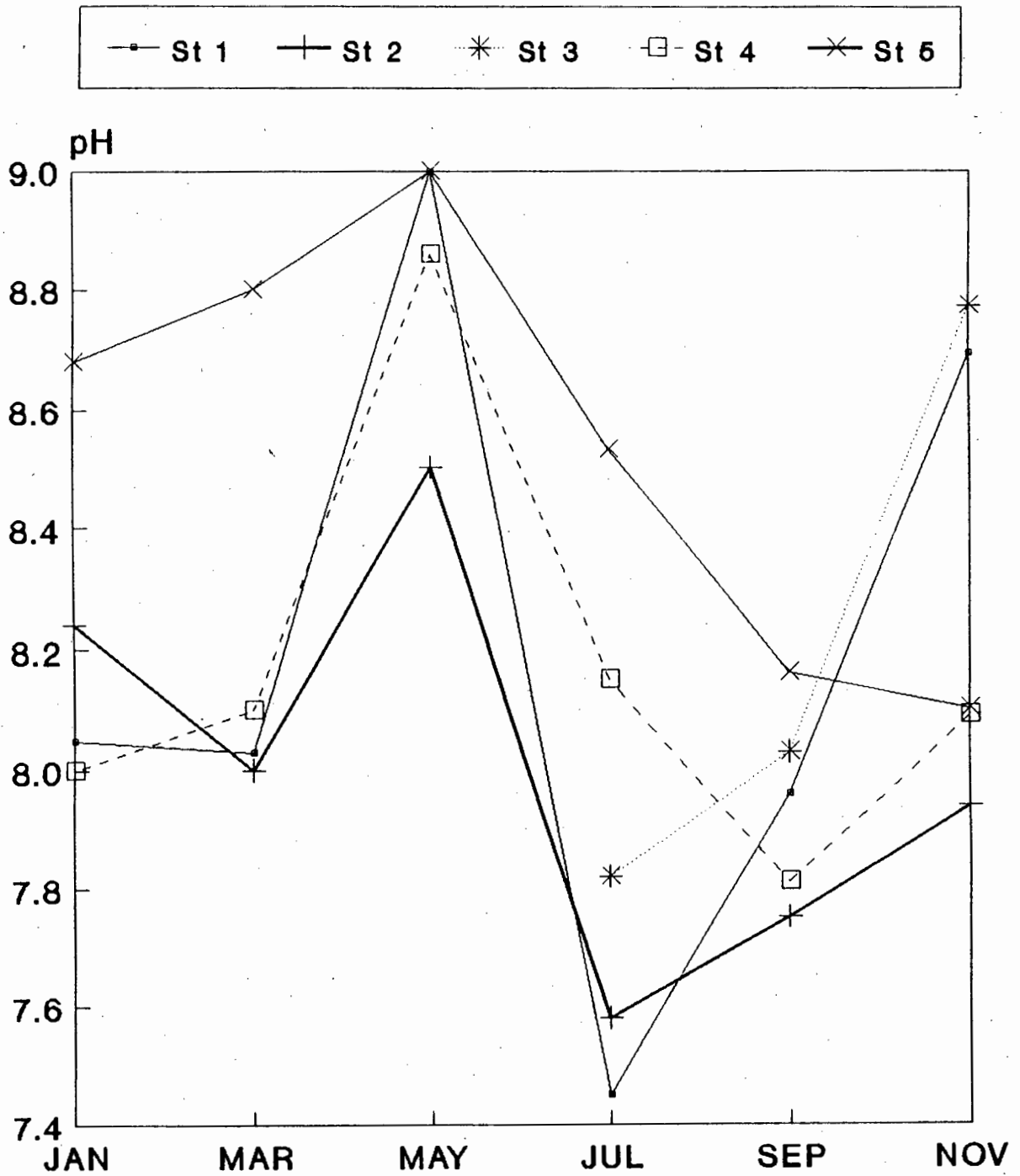


Figure 4.6 Monthly pH 1988

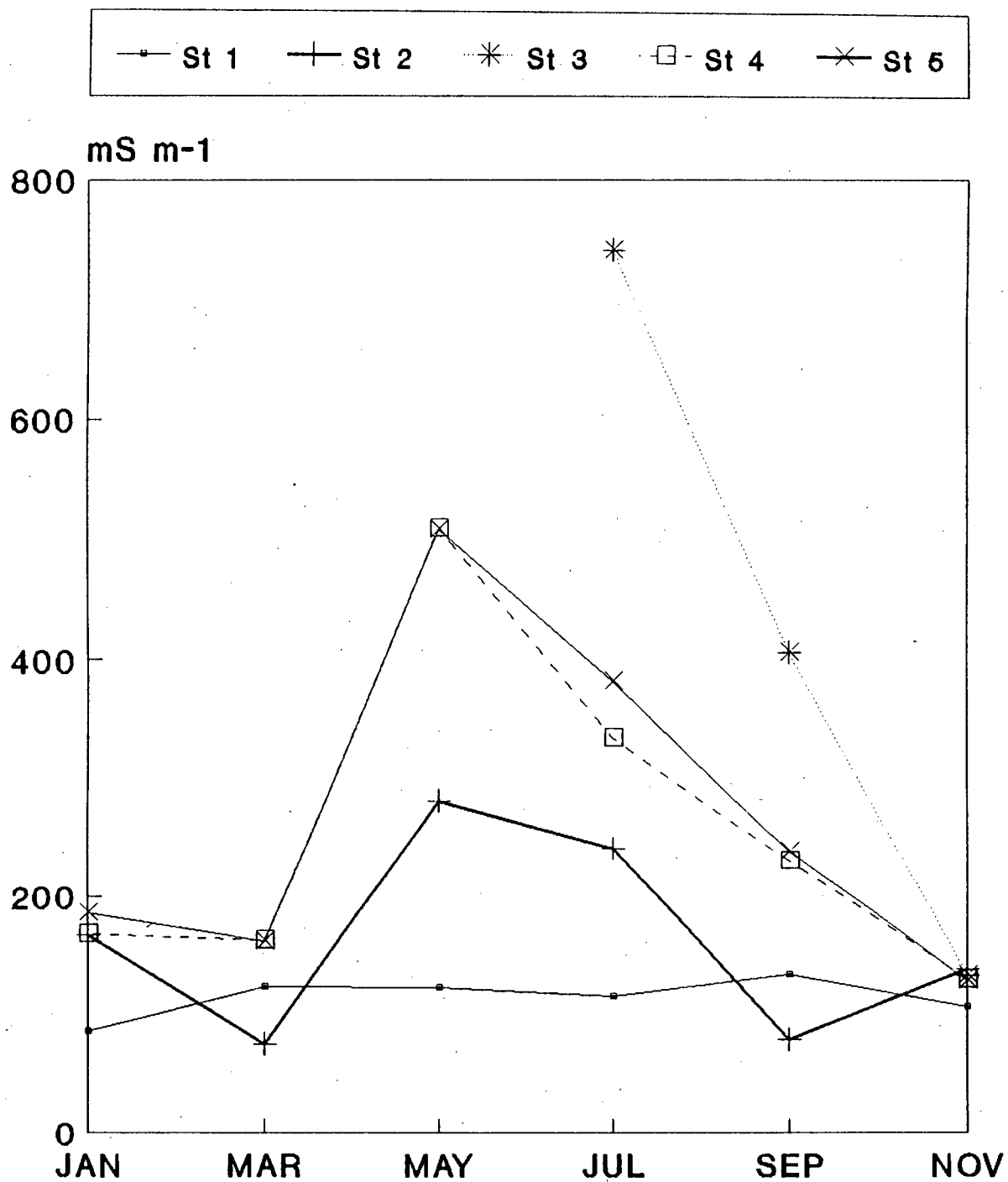


Figure 4.7 Monthly electrical conductivity 1988

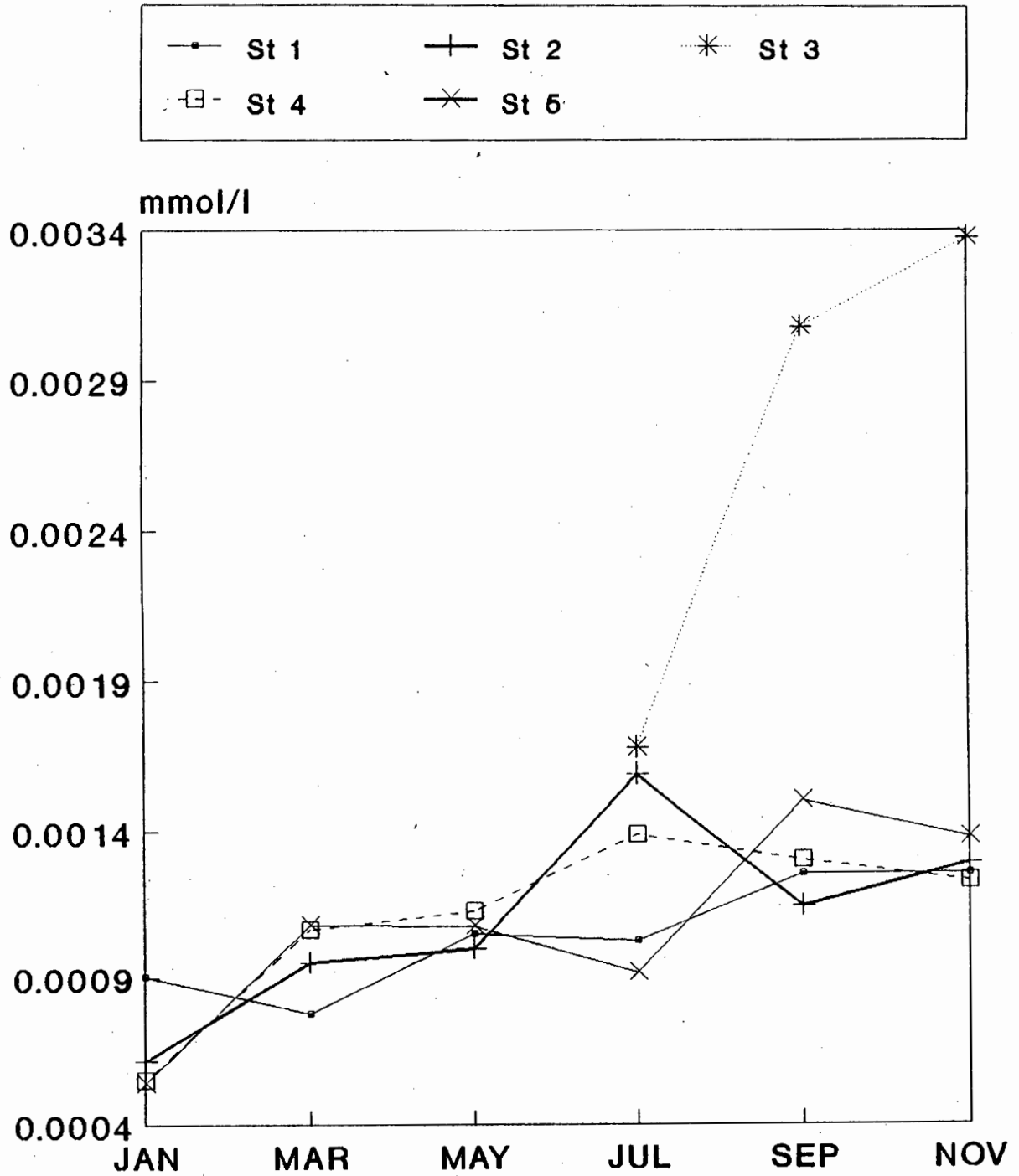


Figure 4.8 Monthly calcium 1988

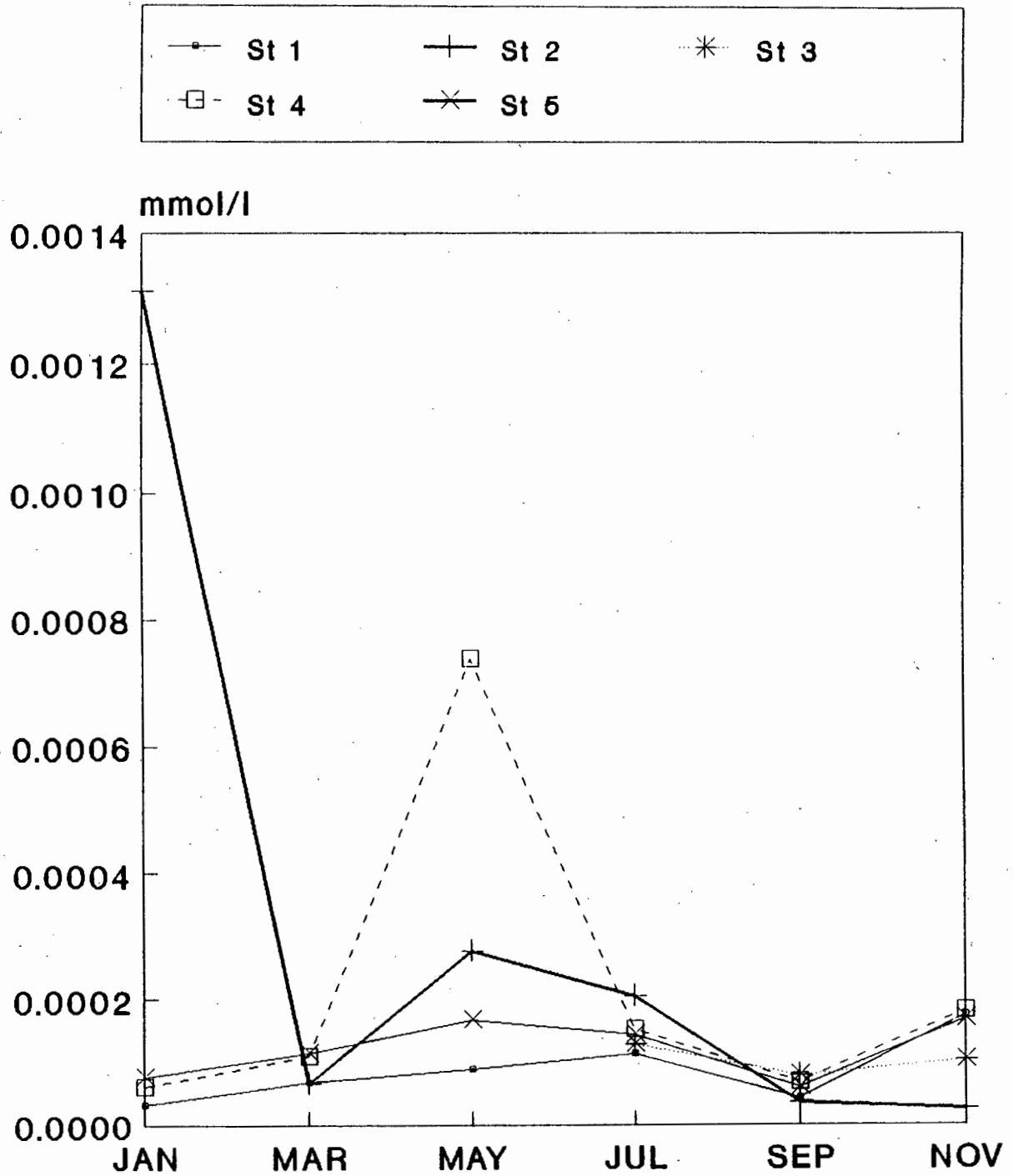


Figure 4.9 Soluble reactive phosphorus 1988

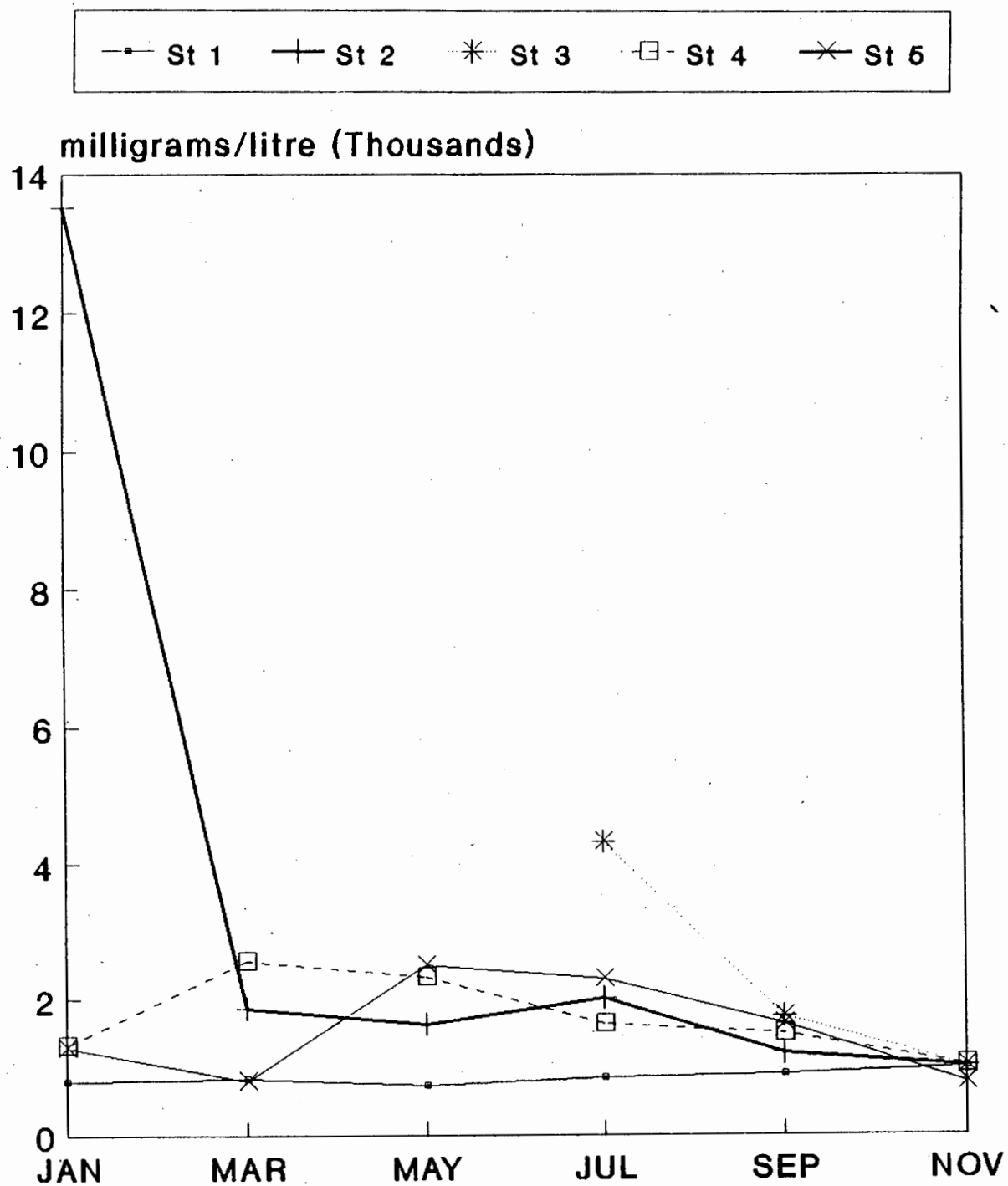


Figure 4.10 Monthly total dissolved solids 1988

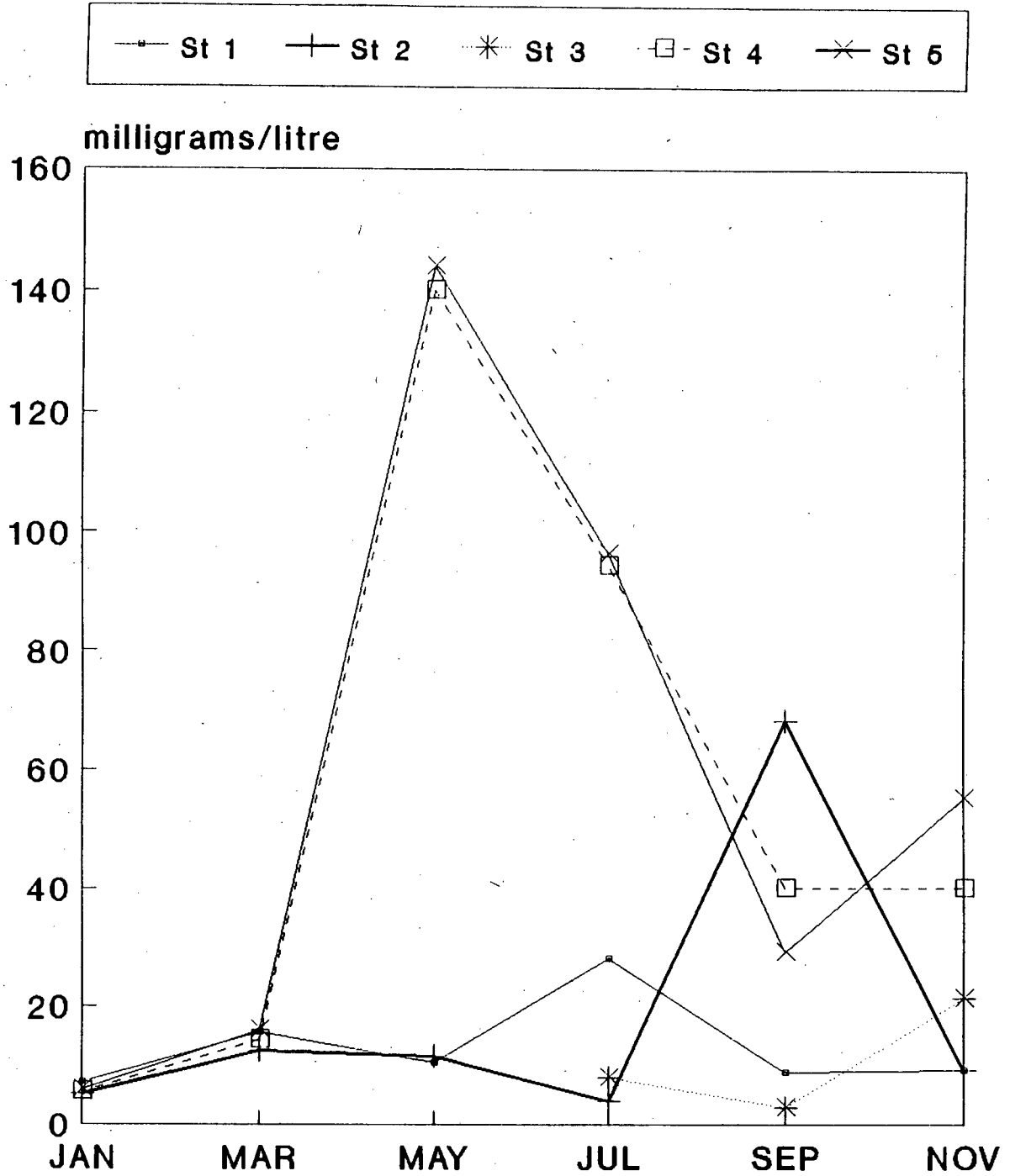


Figure 4.11 Monthly particulate organic matter 1988

CHAPTER 5

PROPERTIES OF SEDIMENTS IN RONDEVLEI

5.1 PHOSPHORUS LOADING, SEDIMENTATION AND RETENTION

During the four seasons, average values of replicate samples, $n=64$, of dry mass of sediment trapped, ranged between 18.2mg and 940.5mg. In flux rates, these amount to between $4.6\text{g/m}^2/\text{day}$ and $235.1\text{g/m}^2/\text{day}$ of suspended material reaching the sediment. The maximum value of $235.1\text{g/m}^2/\text{day}$ was recorded at the weir, at the outflow during the peak flow in July. At the same time a maximum influx value of $232.75\text{g/m}^2/\text{day}$ was recorded at Station 2. Table 5.1.1 is a summary of the seasonal sediment loads trapped at 5 stations in Rondevlei.

TABLE 5.1.1 MEAN SEASONAL VALUES FOR MASS OF SOLIDS TRAPPED (TS), PERCENTAGE OF TOTAL SOLIDS (TS) PARTICULATE ORGANIC MATTER (POM) AND MASS OF TOTAL PARTICULATE PHOSPHORUS (TPP), COLLECTED IN SEDIMENT TRAPS, FROM 5 STATIONS IN RONDEVLEI; $n=64$ PER VARIABLE.

Season	Variable	Mean	Standard Deviation S.D.	Maximum	Minimum	Range
Summer	TS $\text{g/m}^2/\text{day}$	96.79	73.74	201.60	29.80	171.80
Autumn	" " "	11.39	11.00	24.08	4.55	19.53
Winter	" " "	32.53	26.48	60.80	8.33	52.48
Spring	" " "	162.22	69.89	235.13	64.08	171.05
Summer	% POM	25.70	16.03	37.89	3.90	33.99
Autumn	" "	24.25	13.38	35.71	9.55	26.16
Winter	" "	27.66	0.58	28.17	27.03	1.14
Spring	" "	44.21	18.79	66.72	18.15	48.57
Summer	TPP $\mu\text{g/g}^{-1}$	15.95	3.78	20.30	10.00	10.30
Autumn	" "	13.64	4.33	17.96	7.72	10.24
Winter	" "	12.65	4.24	17.31	9.00	8.31
Spring	" "	10.72	1.78	13.10	8.69	4.41

By size fraction, 61-87% of trapped material was $< 63 \mu\text{m}$ in diameter. Spatial variation in size fraction of the samples was notable. Of the five stations sampled, Stations 4 and 5 had the highest percentages of large size fractions than the other stations. Stations 2 and 3 had the highest percentages of silt and clay when compared to other stations. The lowest mean value of particulate organic solids was recorded at Station 2. (Table 5.1.2.)

TABLE 5.1.2 MEAN SPATIAL VALUES OF TOTAL SOLIDS (TS), PARTICULATE ORGANIC MATTER (POM), AND TOTAL PARTICULATE PHOSPHORUS (TPP) COLLECTED IN SEDIMENT TRAPS FROM 5 STATIONS IN RONDEVLEI. $n=64$.

Variable		Station 1	Station 2	Station 3	Station 4	Station 5
TS $\text{g/m}^2/\text{day}$	Mean	58.06	92.03	74.90	169.19	100.41
	SD	88.71	98.17	15.31	93.25	88.43
	Max	190.62	232.75	85.73	235.13	201.60
	Min	5.50	4.55	64.08	103.25	24.08
	Range	185.12	228.20	21.65	131.88	177.51
	n	16	16	8	8	16
POM %	Mean	29.48	26.36	47.62	55.11	23.62
	SD	5.15	7.46	13.76	16.43	22.29
	Max	37.16	35.71	57.35	66.72	53.34
	Min	26.23	18.15	37.89	43.39	3.83
	Range	10.93	17.56	19.46	23.23	49.51
	n	16	16	8	8	16
TPP $\mu\text{g/g}$	Mean	15.41	11.68	11.63	10.63	13.88
	SD	4.28	3.38	0.88	0.88	4.80
	Max	17.96	15.44	12.25	11.25	20.30
	Min	9.00	8.69	11.00	10.00	7.72
	Range	8.96	6.75	1.25	1.25	12.58
	n	16	16	8	8	16

TS : Total Solids trapped (dry mass)
POM : Percentage Particulate Organic Matter
TPP : Total Particulate Phosphorus
SD : Standard Deviation from the mean
Max : Maximum
Min : Minimum
n : Number of samples.

For Stations 1, 2 and 5, the results represent a seasonal record. Only spring samples could be obtained for Station 4, while spring and summer

records were obtained for Station 3. (Table 5.1.2.) This is because the water level drops drastically in summer, leaving Stations 3 and 4 dry.

Table 5.1.1 shows a drop in autumn followed by a sudden rise in sediment accretion during late winter and spring. Peak levels are recorded during the spring months of August and September, particularly for Stations 2 and 4. The percentage of Particulate Organic Matter (POM) shows the same pattern. No statistically significant relationship is reflected between Total Particulate Phosphorus and the other variables.

TABLE 5.1.3 CORRELATION MATRIX SHOWING THE RELATIONSHIP BETWEEN TOTAL PARTICULATE PHOSPHORUS (TPP), TOTAL SOLIDS (TS) AND PARTICULATE ORGANIC MATTER (POM). n=64

	TS	POM	PIS	TPP
TS	*	.62	.94	*
POM	*	*	-.36	-.37
PIS	*	*	*	*
TPP	*	*	*	*

Level of significance = 5%

TS = Total Solids trapped

POM = Particulate Organic Matter

PIS = Particulate Inorganic Solids

TPP = Total phosphorus

Between 4% and 67% of the material that accumulates is of organic origin. The highest values were recorded during spring and early summer. A mean peak value of $15.9 \mu\text{g/g}^{-1}$ of Total Particulate Phosphorus (TPP) was attained in summer, and a mean value of $10.7 \mu\text{g/g}^{-1}$ during spring. A spatial pattern shows the highest value of $17.4 \mu\text{g/g}^{-1}$ at Station 5 and the lowest value of $10.00 \mu\text{g/g}^{-1}$ at Station 4.

5.2 GRAIN SIZE COMPOSITION AND ORGANIC MATTER CONTENT OF SOME SEDIMENT SAMPLES FROM RONDEVLEI AND THE CONFLUENCE OF ITS THREE CHANNELS.

Figure 5.1 is the representation of the results of the investigation on the characteristics of the bottom sediment samples obtained from Stations 1, 2, 3 and 5. For all stations between 80 and 88 percent of sediment consists of sand. Half of this is medium sand, that is approximately between 1.4 phi and 2.9 phi size; the other half consists of fine sand of 3 phi to 4 phi size.

Silt comprises a very small percentage while clay is minimal. Of the four stations monitored, Stations 1 and 2 have a higher percentage of Particulate Organic Matter (POM) than Stations 3 and 5. Station 3 for example has 3.29% Particulate Organic Matter (POM) which is less than half the amount of Particulate Organic Matter (POM) found in Station 1 or Station 2. There is very little textural difference between the sediments obtained from the above mentioned sets of sampling stations. (Figures 5.1 and 5.2.)

5.3 PHI SKEWNESS, SORTING AND KURTOSIS

Table 5.1.4 is a description of particle distribution at 4 of the sediment core sampling stations.

TABLE 5.1.4 PARTICLE SIZE DISTRIBUTION AT 4 SELECTED SAMPLING STATIONS IN RONDEVLEI (MEASURED ON THE PHI SCALE)

Description of distribution	Station 1	Station 2	Station 3	Station 5
phi skewness	-0.23	-0.12	0.11	0.26
phi sorting	1.01	1.39	1.21	1.23
phi kurtosis	1.18	0.78	0.75	1.06

Negative skewness at Stations 1 and 2 represent a coarse tail while positive skewness of Stations 3 and 5 represent a fine tail. Stations 3 and 5 have a great amount of fine material, particularly Station 5. This is representative of zones of accumulation of fine material carried in suspension. Stations 1 and 2 show the presence of coarse material, a matter which would be expected in these canals as they experience a higher gradient of flow from the lake (Station 5) in which flow gradient is minimal.

In all stations the material is poorly sorted. Values lie between 1.00 and 2.00, an indication of a poorly sorted distribution (Chakela, Q. Pers. Comm.). Values of phi kurtosis fall between 0.67 and 1.18. This shows both mesokurtic kurtosis which is a normal distribution and platykurtic kurtosis (flatter than a normal distribution). This kind of kurtosis is a further indication of poorly sorted material.

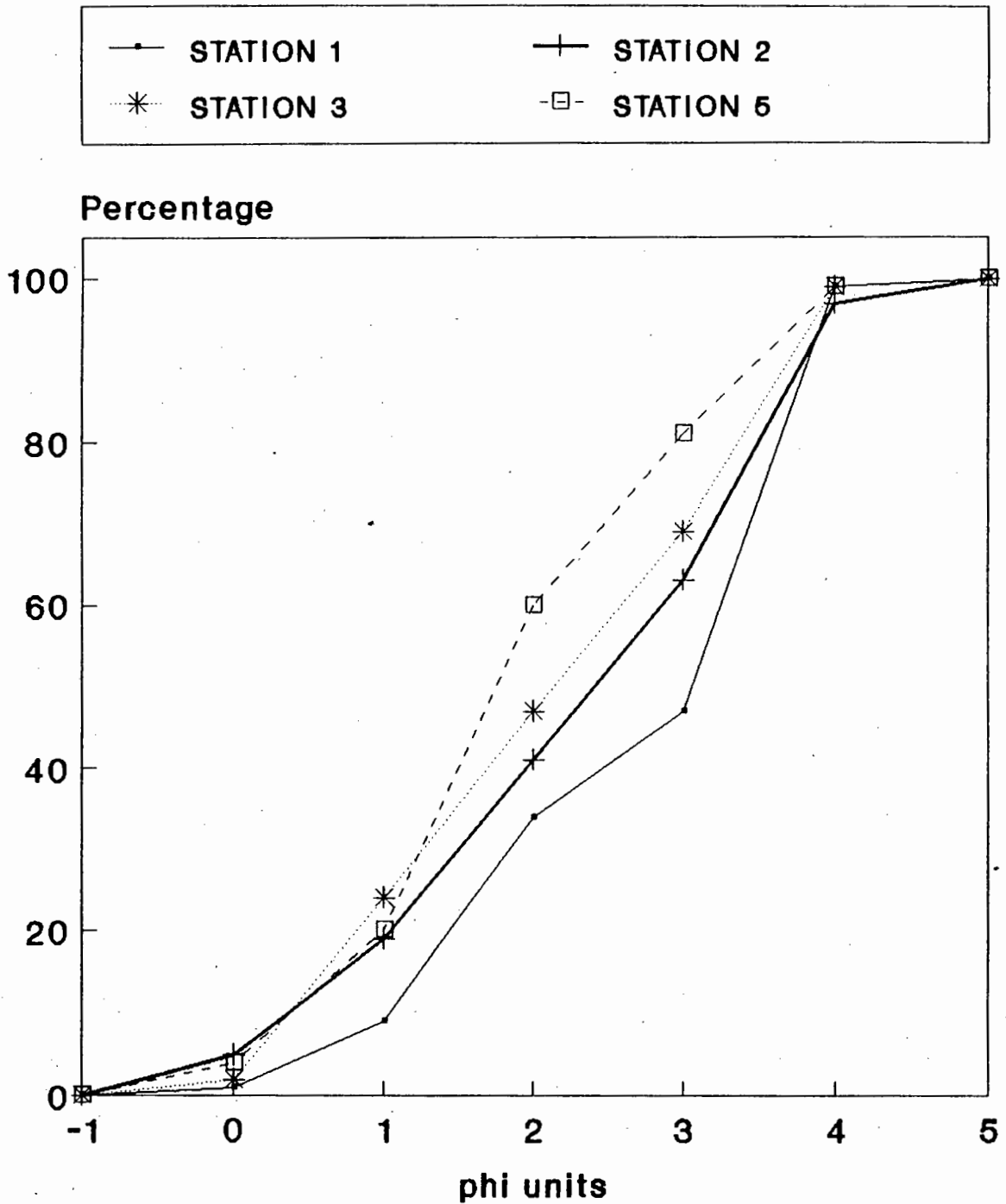
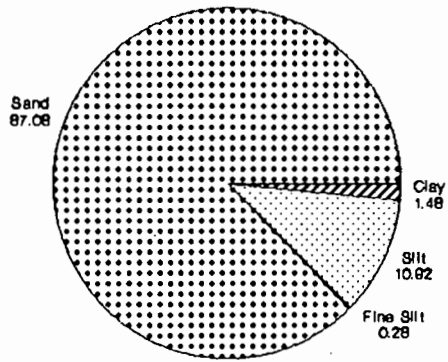
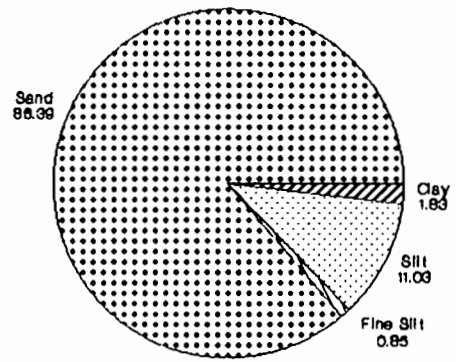


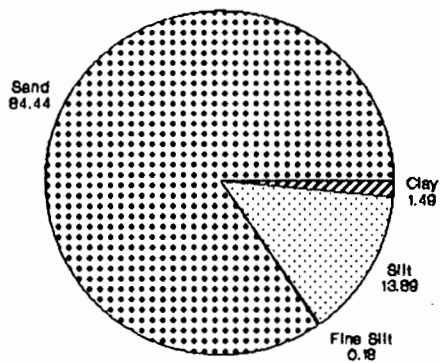
Figure 5.1 Sediment particle size distribution.



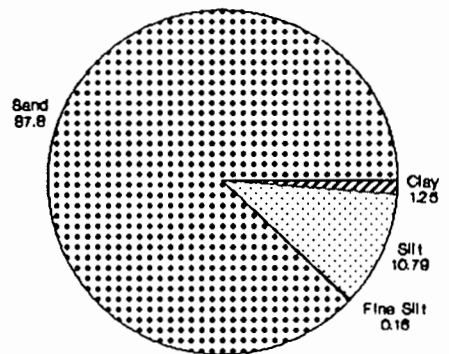
STATION 1



STATION 2



STATION 3



STATION 5

Figure 5.2 Textural classes

CHAPTER 6

DISTRIBUTION OF PHOSPHORUS AND SOME OF ITS SPECIES IN THE SURFICIAL SEDIMENTS

Analysis of trapped sediments revealed high values of Particulate Organic Matter (POM) as well as phosphorus in the sediments of the five stations studied. On account of this, I decided to do a single analysis of phosphorus distribution in the sediments. It is necessary to do this kind of analysis seasonally in order to evaluate seasonal changes for modelling purposes. It is not easy, however, to monitor seasonal changes because sediment analysis of this nature is time-consuming.

Stations 1, 2, 3 and 5 were chosen for this study because of the availability of information relating to the limnological characteristics of the overlying water at these stations. Apart from their accessibility, these stations present a broad diversity of sediments due to their varying environmental conditions (see Chapter 2). Station 5A, the mudflats was included in order to increase the diversity of environments studied. (Figure 2.4.)

Tables 6.1.1 and 6.1.2 represent a summary of descriptive statistics for phosphorus and its fractions as well as for Particulate Organic Matter (POM) from each of the sediment fractions. 5 cores, each divided into 8 fractions of sediments were taken from 5 stations (Figure 5.1) at Rondevlei in March 1988. Figures 6.1, 6.2, 6.3, 6.4 and 6.5 represent values of some different fractions of phosphorus, that is, inorganic, organic and adsorbed fractions, distributed vertically over 5 stations. Of the 5 stations monitored, the mudflats (Station 5A) had the highest mean total content of phosphorus ($243.91 \mu\text{g g}^{-1}$), the bulk of which was organically bound. The

other stations with high Total Phosphorus (TP) values were Stations 1 and 2. The organically bound fraction was also higher than the inorganic fraction for Station 1. The reverse is true for Station 2 where the inorganic fraction was approximately twice as great as the organically bound species.

Except for Station 1 most of the phosphorus was found in the uppermost layer, that is the first 20mm of the sediment. At Station 1, the bulk of Total Phosphorus (TP) was between 60mm and 80mm depth (Figure 6.1). A definite decrease with increasing depth occurred at Stations 2 and 3. For other stations there were some fluctuations, particularly for Stations 5 and 5A where high values were recorded at depths between 120mm and 140mm, and 140mm and 160mm respectively. Although the overall mean values of Inorganic Phosphorus (IP) and Organic Phosphorus (OP) were approximately the same, spatial variation was very distinct. Furthermore, Inorganic Phosphorus (IP) and Adsorbed Phosphorus (AP) generally reflected values for Total Phosphorus (TP). Organically bound phosphorus fluctuated fairly unpredictably. Station 2 had the highest quantities of Inorganic Phosphorus (IP) (Figure 6.2) and Station 5 exhibited a value higher for Inorganic Phosphorus (IP) than Organic Phosphorus (OP). For all stations there was a drop in phosphorus level between 80mm and 100mm.

Figures 6.8, 6.9, 6.10 and 6.11 reflect a spatial pattern of phosphorus and each of its representative fractions. A set of data used in these figures is the same as the one presented in the preceding paragraphs. However, a display of data in these figures gives a clear indication of the horizontal distribution of each phosphorus fraction in the sampled area of the lake. High values of Total Phosphorus (TP) have been recorded in certain areas. A discussion relating to this issue will be found in the next chapter.

Percentage Particulate Organic Matter (POM) of the sediment core fraction varies with depth, (Figure 6.6). No relationship appears to exist between Particulate Organic Matter (POM) content and distribution of phosphorus. Highest values of Total Phosphorus recorded for Station 2 at 0-20mm depth contained the highest concentration of Inorganic Phosphorus (IP). At the same time minimum values of Particulate Organic Matter (POM) were recorded for this station. Furthermore minimum values of Particulate Organic Matter (POM) were recorded for Station 5A where the highest values of Adsorbed Phosphorus (AP) were recorded.

Generally, high values of phosphorus and its fractions were obtained at 60mm-80mm depth. pH of sediment at this level was between 7.5 and 7.8 (Figure 6.7).

TABLE 6.1.1 MEAN VALUES OF PHOSPHORUS AND SOME OF ITS FRACTIONS IN THE SURFACE SEDIMENTS IN RONDEVLEI. n=40.

Variable	Arithmetic mean	Range	SD
TP $\mu\text{g/g}^{-1}$	141.47	481.25	126.18
OP $\mu\text{g/g}^{-1}$	70.49	456.87	88.25
IP $\mu\text{g/g}^{-1}$	70.97	292.75	67.92
AP $\mu\text{g/g}^{-1}$	20.77	54	14.01
POM. $\mu\text{g/g}^{-1}$	4.89	4.34	1.41

- TP - Total Phosphorus
- OP - Organic Phosphorus
- IP - Inorganic Phosphorus
- AP - Adsorbed Phosphorus
- POM - Particulate Organic Matter from sediment cores
- SD - Standard deviation from the mean.

TABLE 6.1.2 MEAN VALUES OF PHOSPHORUS AND SOME OF ITS FRACTIONS FOR SEDIMENT CORE, PER STATION. n=8.

Variable			Station 1	Station 2	Station 3	Station 4	Station 5
(a)	TP $\mu\text{g g}^{-1}$	Mean	177.19	154.80	82.91	48.53	243.91
		Range	456.25	390.62	143.75	62.50	343.75
		SD	160.26	116.67	58.60	22.65	134.15
(b)	OP $\mu\text{g g}^{-1}$	Mean	108.19	51.95	44.97	22.78	124.53
		Range	459.75	123.37	95.75	41.50	270.00
		SD	151.58	50.08	33.98	15.80	91.91
(c)	IP $\mu\text{g g}^{-1}$	Mean	69.00	102.81	37.94	25.75	119.38
		Range	122.50	271.00	70.25	52.00	244.00
		SD	51.60	85.41	28.45	16.53	85.09
(d)	AP $\mu\text{g g}^{-1}$	Mean	23.88	22.50	16.59	7.31	33.64
		Range	36.50	32.50	21.35	11.00	53.00
		SD	12.57	10.44	8.67	3.65	17.53
(e)	POM $\mu\text{g g}^{-1}$	Mean	7.27	6.13	2.57	4.87	3.29
		Range	4.34	7.22	6.41	18.91	8.35
		SD	1.41	2.44	2.61	7.11	2.78

The correlation matrix tables 6.1.3 and 6.1.4 represent a summary of the relationship between phosphorus fractions and Total Sediment Phosphorus (TSP). Phosphorus fractions have been correlated between themselves as well as between selected properties of sediment, that is pH, and Particulate Organic Matter (POM).

TABLE 6.1.3 CORRELATION MATRIX SHOWING THE RELATIONSHIP BETWEEN TOTAL SEDIMENT PHOSPHORUS (TSP), RELATED FRACTIONS AND OTHER SEDIMENT PROPERTIES

	IP	OP	AD	TP	pH	POM
IP	*	*	0.76	0.74	0.32	*
OP	*	*	*	0.85	*	*
AP	*	*	*	0.52	0.42	*
TP	*	*	*	*	0.33	*
pH	*	*	*	*	*	*
POM	*	*	*	*	*	*

n=42

p < 0.05

IP - Inorganic Phosphorus
 OP - Organic Phosphorus
 AP - Adsorbed Phosphorus
 TP - Total Phosphorus
 pH - Phosphorus
 POM - Particulate Organic Matter

Results indicate a strong correlation between Total Phosphorus (TP) and Organic Phosphorus (OP), $r = 0.85$ at $p < 0.05$. Furthermore there is a strong correlation between Total Phosphorus (TP) and Inorganic Phosphorus (IP) at $r = 0.74$ at $p < 0.05$. Inorganic Phosphorus (IP) is related to Adsorbed Phosphorus (AP) at $r = 0.76$ at $p < 0.05$

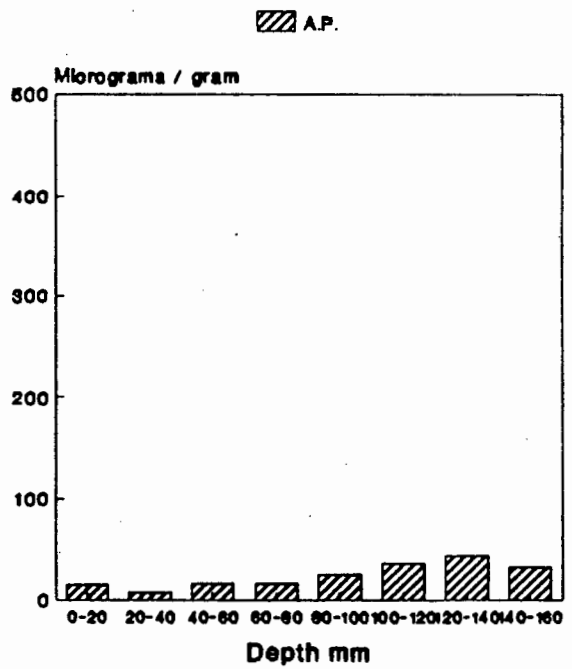
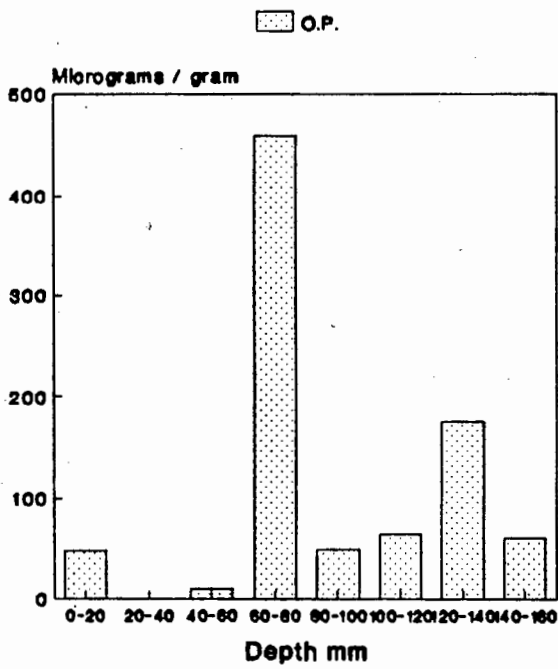
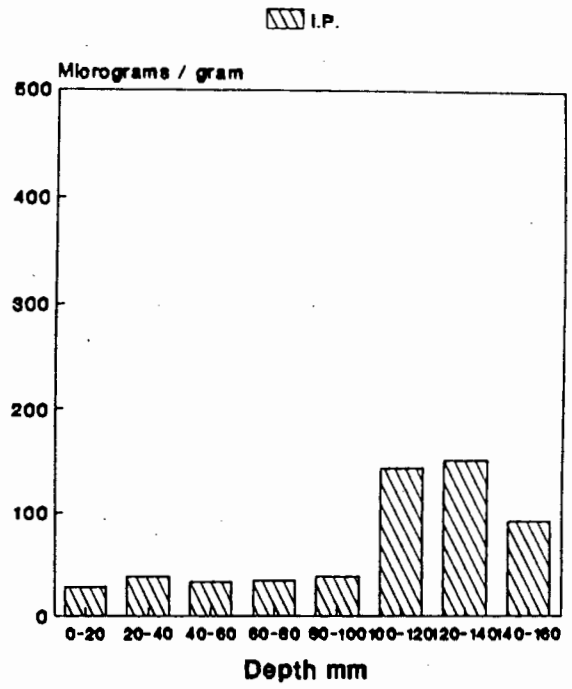
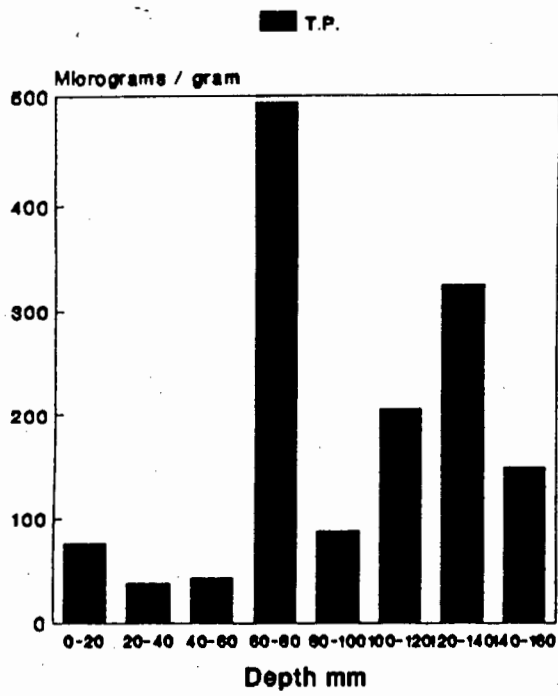


Figure 6.1 Station 1 - Phosphorus

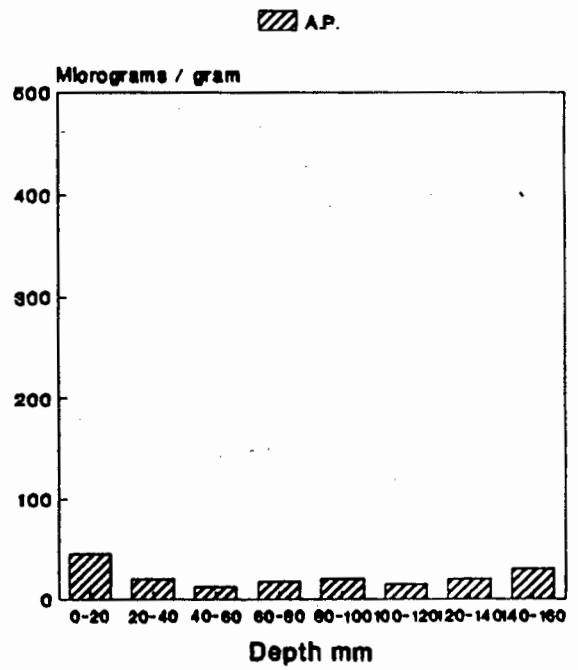
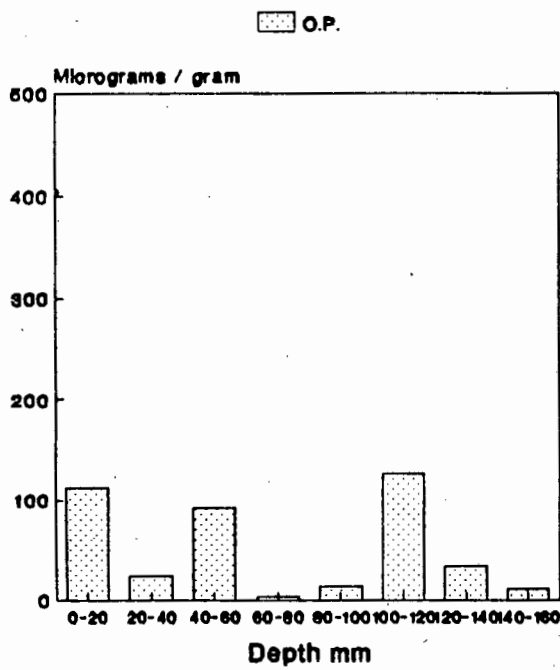
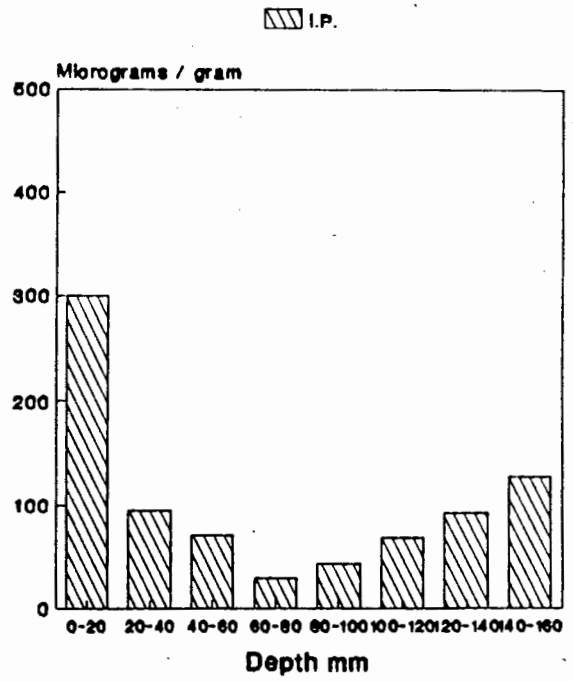
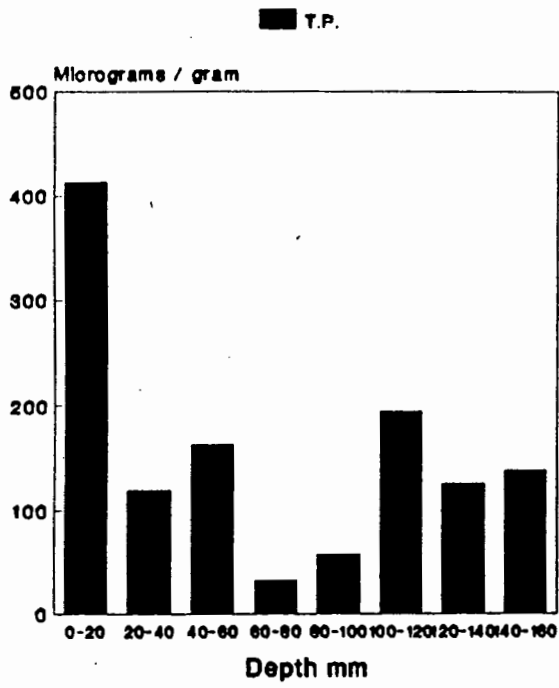


Figure 6.2 Station 2 - Phosphorus

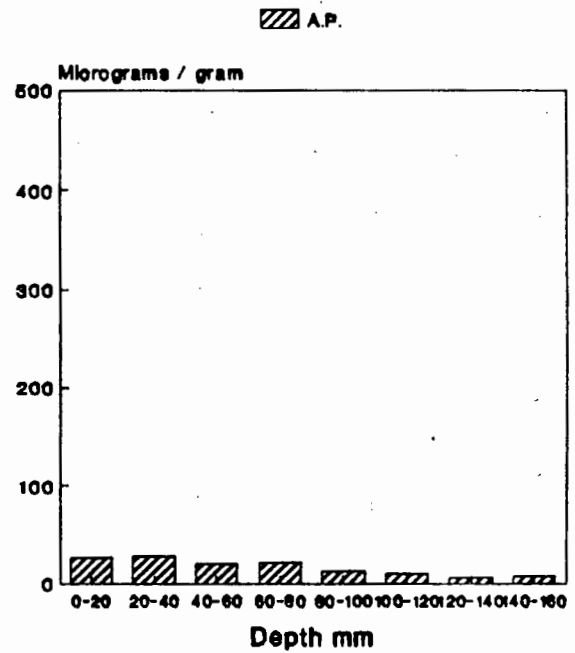
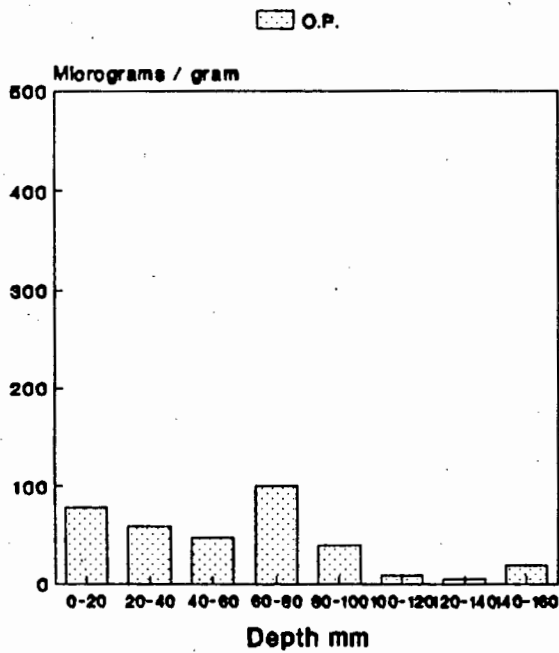
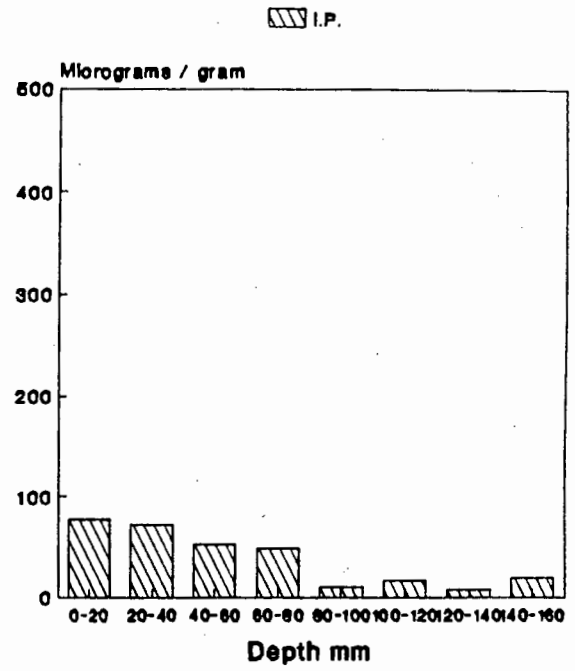
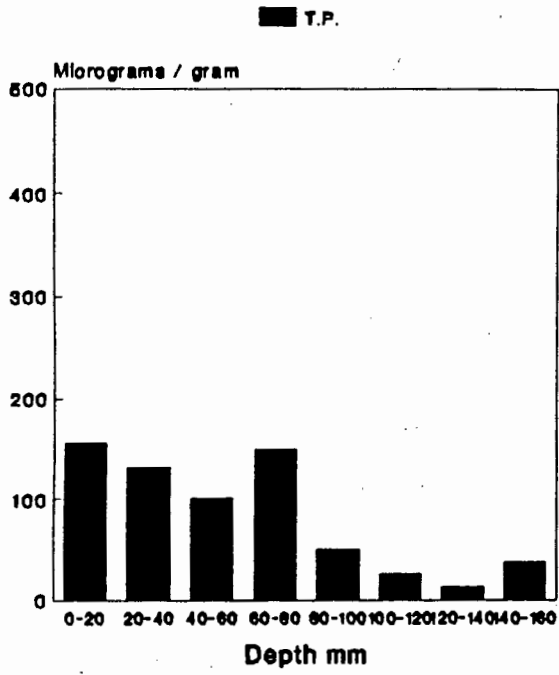


Figure 6.3 Station 3 - Phosphorus

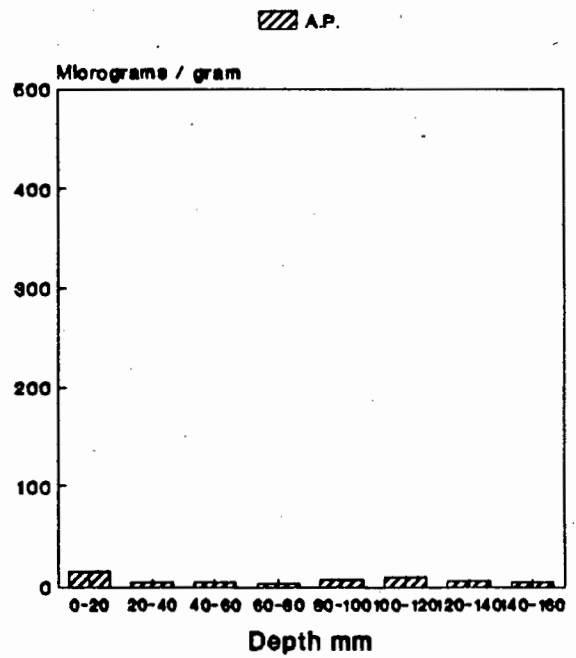
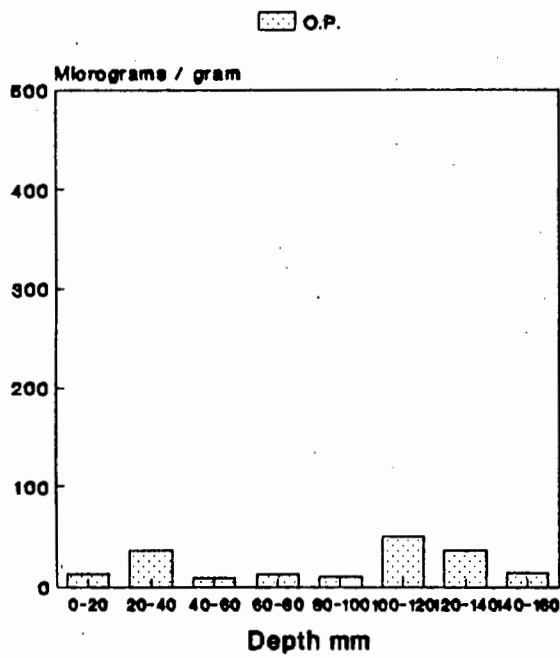
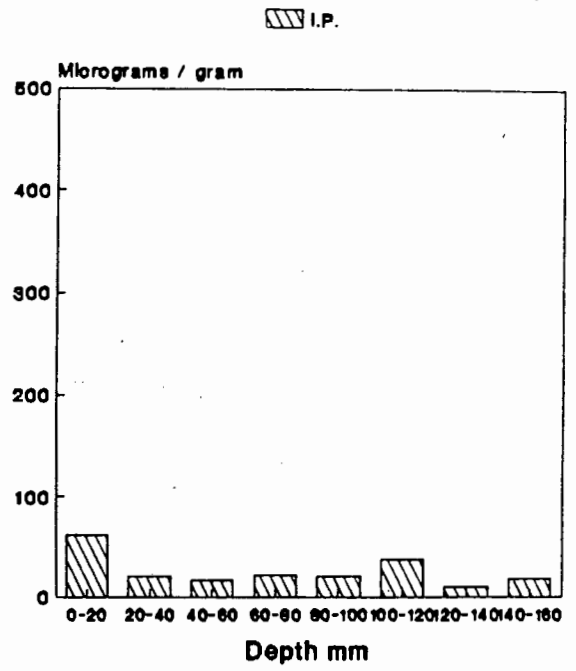
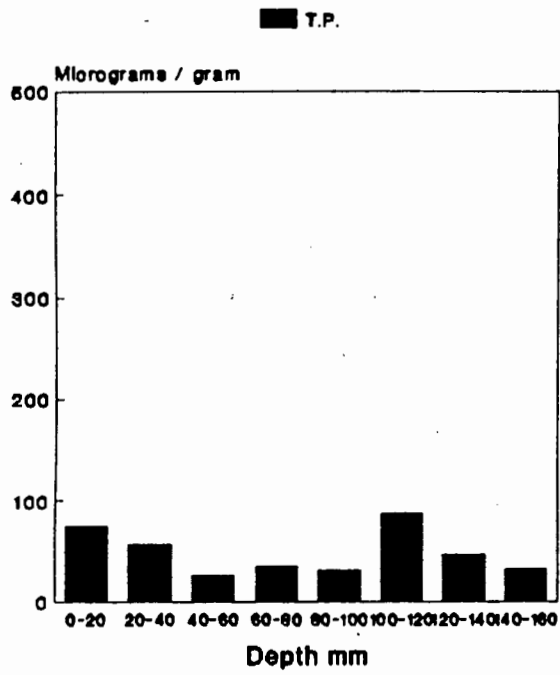


Figure 6.4 Station 5 - Phosphorus

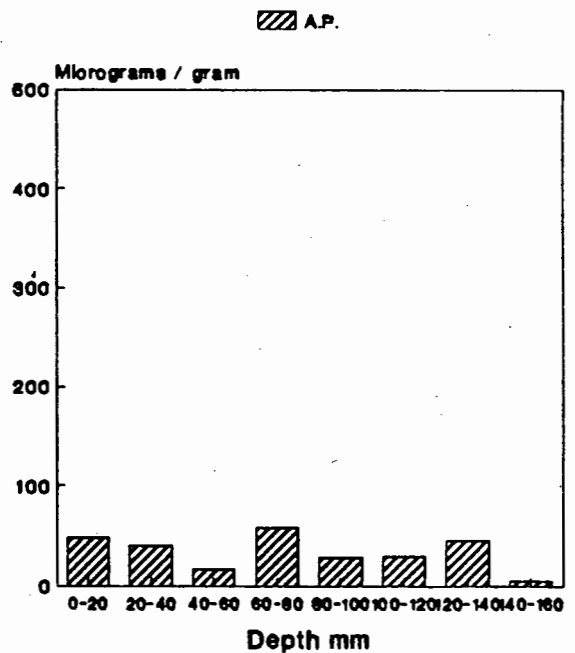
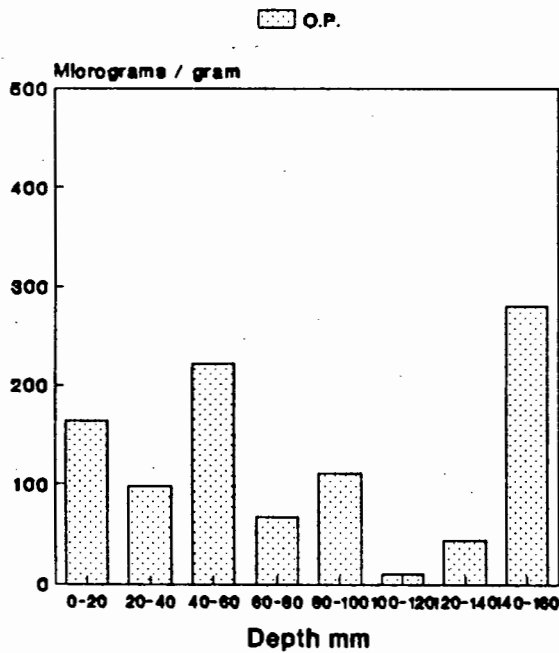
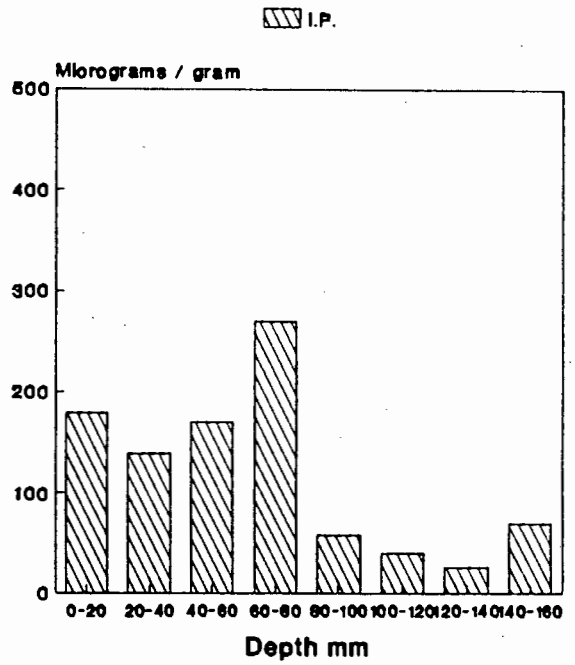
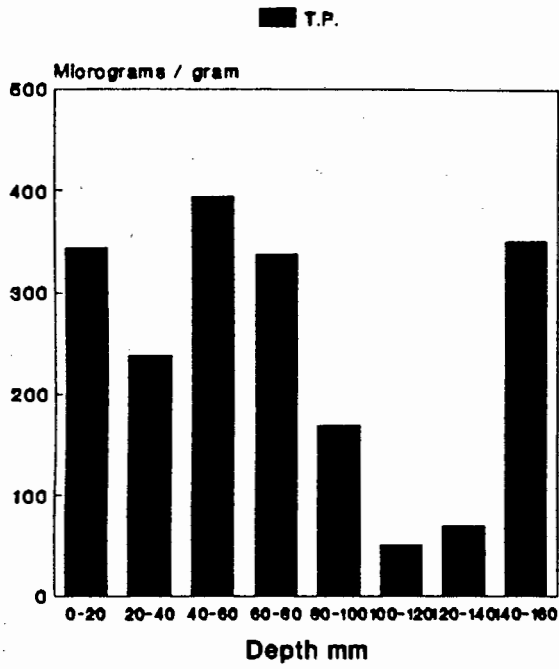


Figure 6.5 Station 5A - Phosphorus

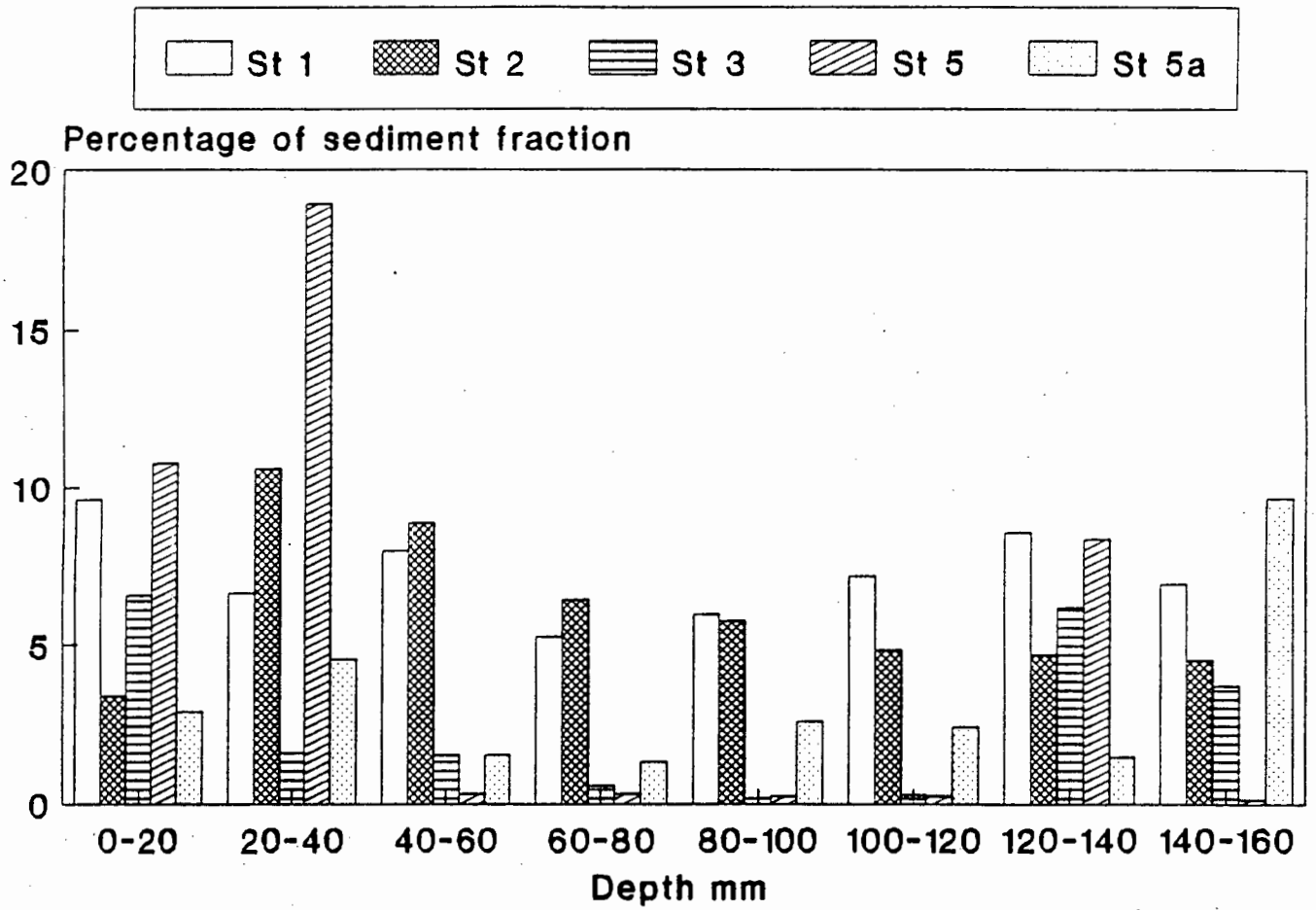


Figure 6.6 Sediment particulate organic matter

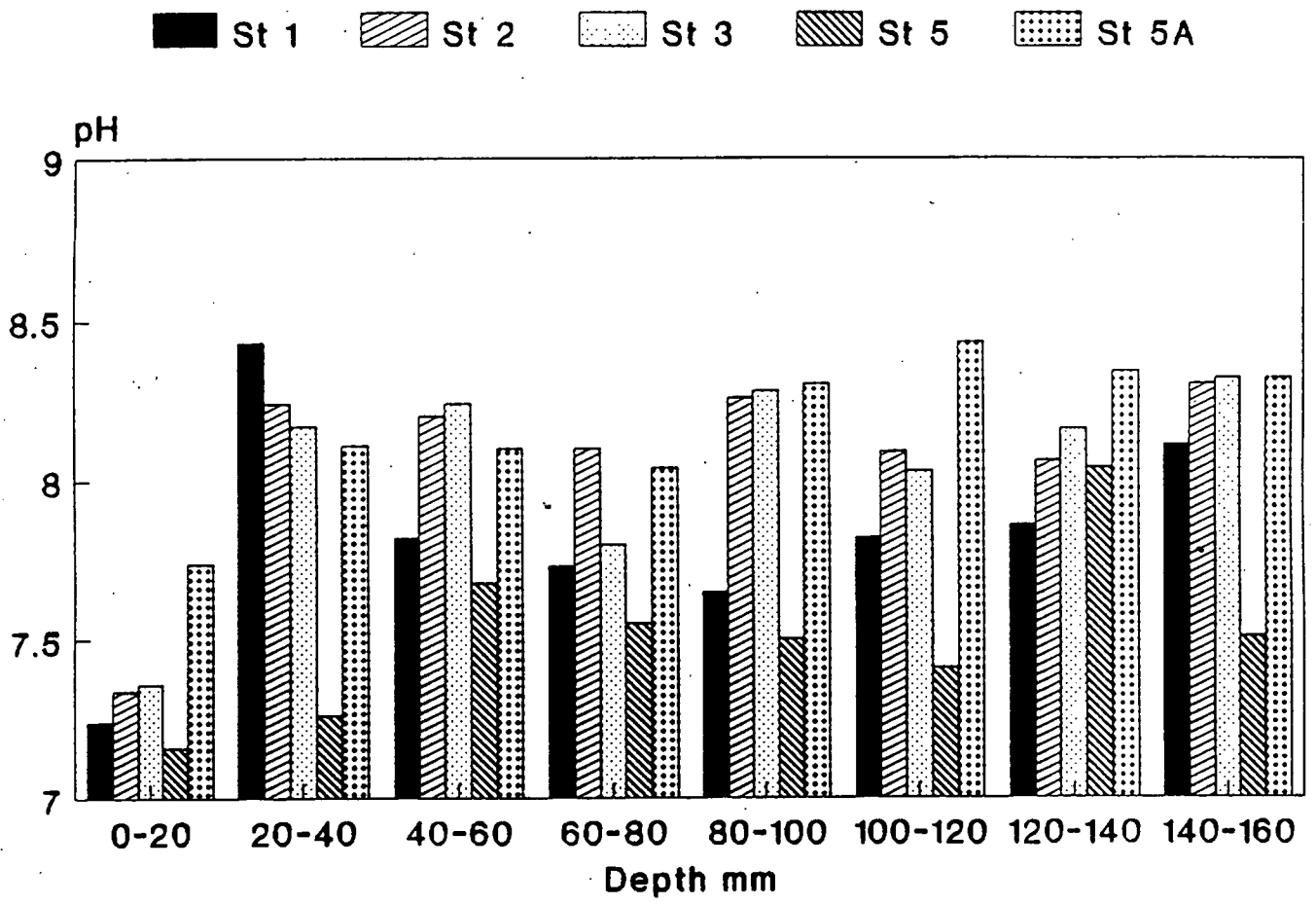


Figure 6.7 Sediment pH

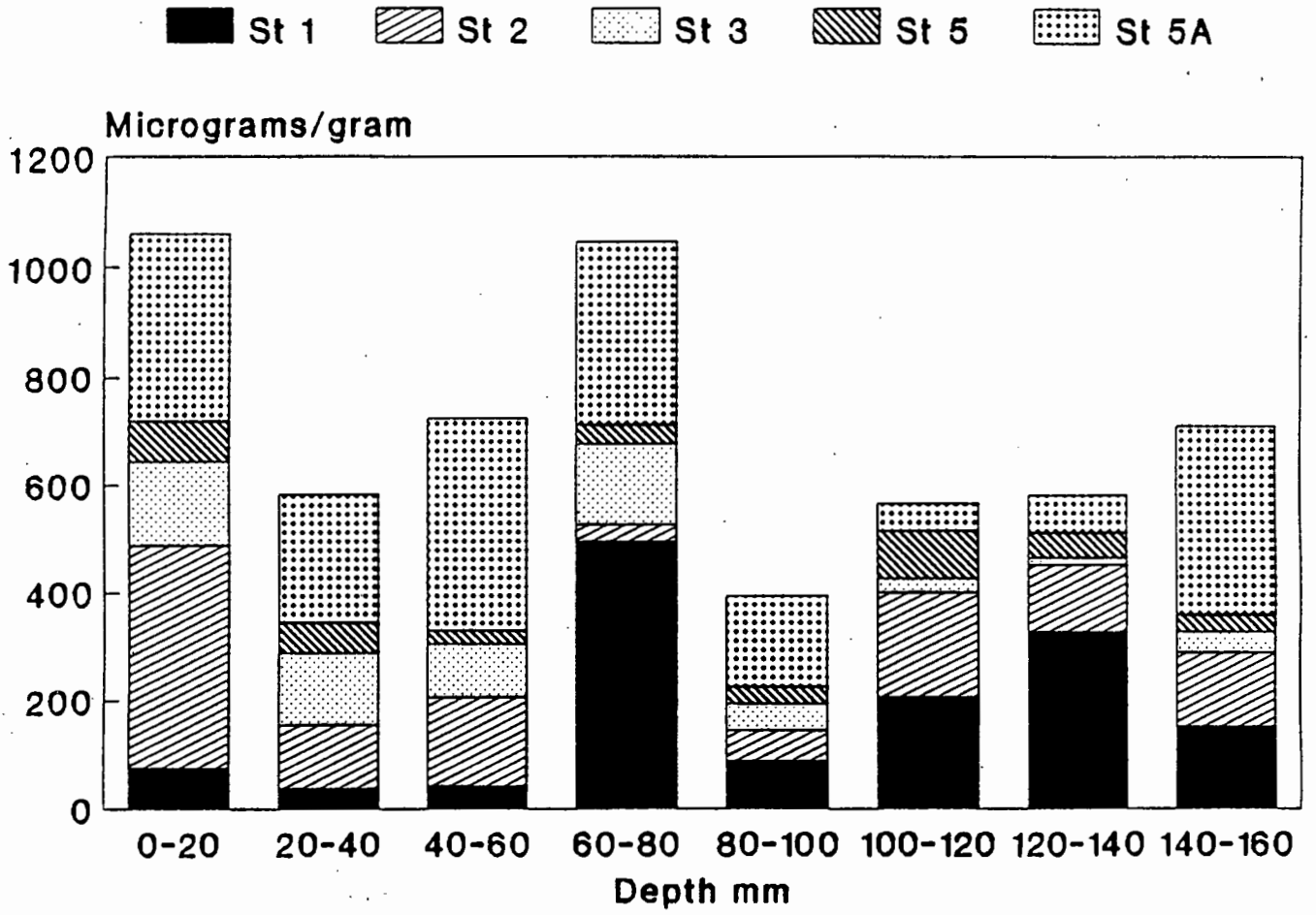


Figure 6.8 Total Phosphorus

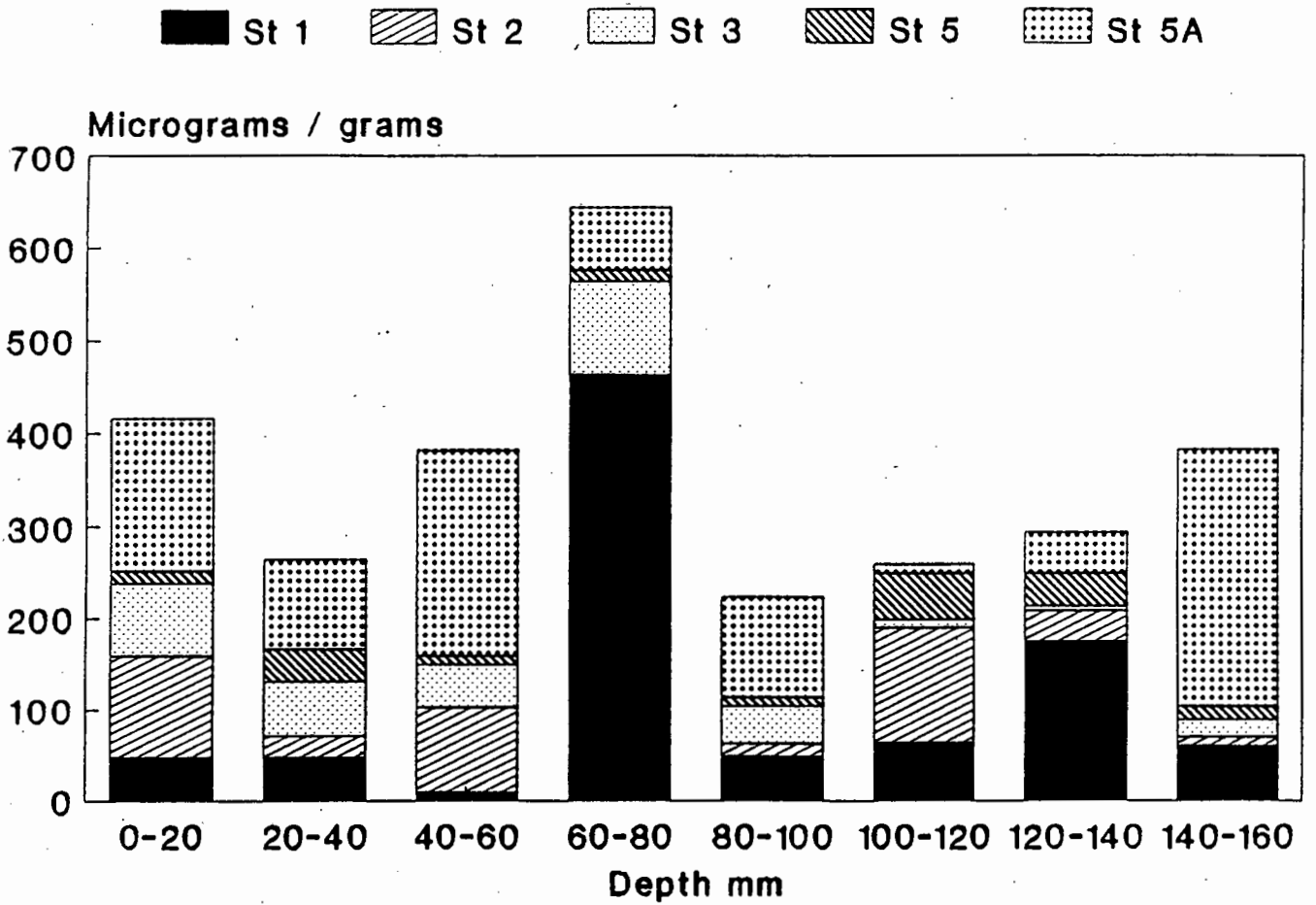


Figure 6.9 Organic Phosphorus

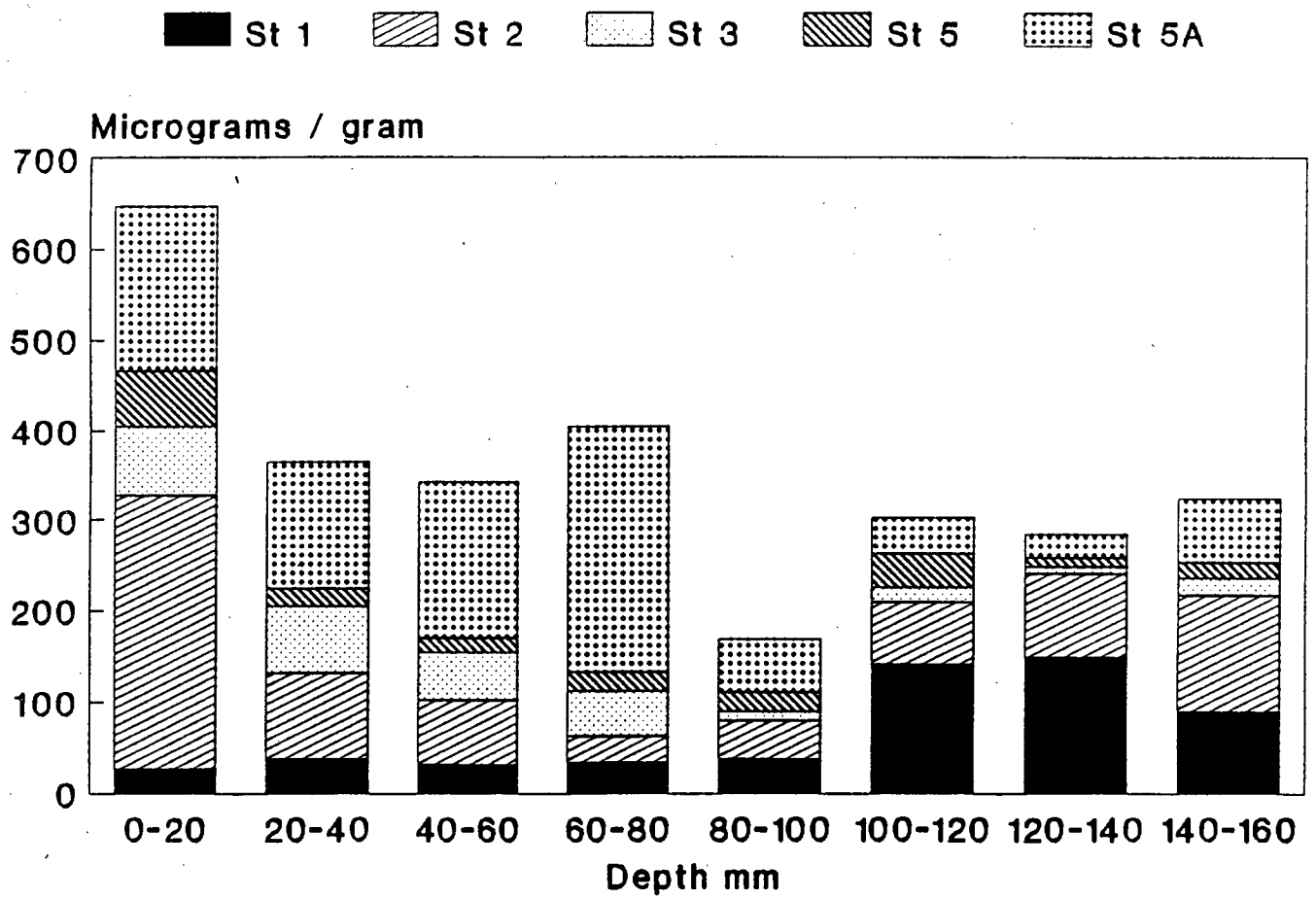


Figure 6.10 Inorganic phosphorus

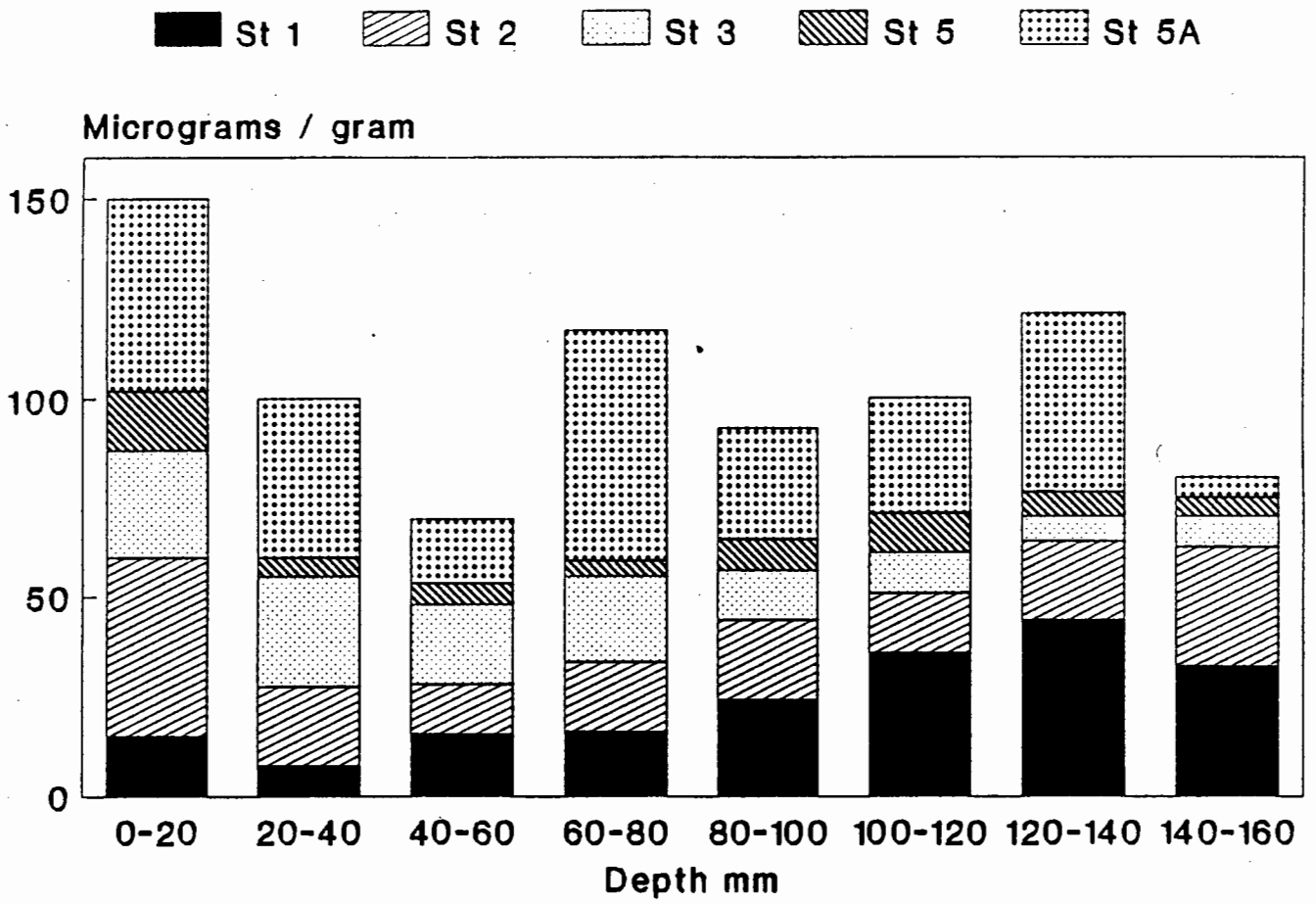


Figure 6.11 Adsorbed phosphorus

CHAPTER 7

DISCUSSION

7.1 LIMNOLOGICAL CHARACTERISTICS

7.1.1 TEMPERATURE

On account of shallowness and winds which blow over the whole lake, there is entire mixing of the water. No vertical temperature stratification was observed in Rondevlei. Although there were no observations made in relation to vertical temperature stratification, according to Gardiner A.C. (1988), Rondevlei falls "outside a strict category of polymitic lakes". As expected a seasonal pattern is shown in Figure 4.1. Spatial and temporal patterns reflect diurnal as well as seasonal variations in water temperature. A maximum reading of 27°C was recorded in Station 5 during early afternoon hours. Readings taken from the same station during early hours of the day amounted to 23°C. These differences are caused by aspect as well as length of the exposure of water to heat energy. It is, however, necessary to note that spot temperature readings like these give a mere indication of the variations that occur.

Cloudiness is another factor that played an important role in influencing temperatures. A minimum temperature of 9°C was recorded in Station 4 during a cloudy winter morning (Figure 4.1). After cloud cover disappeared, readings between 12°C and 13°C were recorded on the same day for the same station and other neighbouring stations.

Although there is no vertical temperature stratification in Rondevlei, fluctuations in water levels have a great influence on spatial temperature variations. This is particularly common in summer when the water level is low over the whole lake (Figure 4.2) and when the weather is calm. During this time of the year horizontal temperature stratification is common. Temperature of the on-shore water is generally higher than temperature of the off-shore water. According to Gardiner A.C. (1988), variability of the maximum temperatures is a result of differences in depth, as well as differences in sampling time. He observed rapid heating and cooling of the surface in temporarily sheltered parts of the vlei during summer and autumn. Since the lake water never gets very hot and never freezes, one would agree with Gardiner A.C. (1988) that Rondevlei falls under a category of subtropical lakes.

7.1.2 CONDUCTIVITY

With a mean of 163.81 mSm^{-1} , a maximum value of 741.60 mSm^{-1} and a minimum value of 74.26 mSm^{-1} , Rondevlei falls under a class of moderately saline lakes (Talling and Talling 1965). Time and space variations are considerable. A value of 741.60 mSm^{-1} was recorded during the high flow winter season in Station 3 (Figure 4.7). At the same time, a value of 114.13 mSm^{-1} was obtained in Station 1. Although conductivity changes very little with variations in concentrations of organic matter, the high value for Station 3 may be attributed to leaching of ions from flooded vegetation and other elements which have accumulated in the channel during a dry period. Furthermore a high concentration of conducting ions would be expected in this non-perennial channel, owing to excessive evaporation, and atmospheric

fallouts. The only time that the water flows in this channel is during the peak-flow winter season. Storm water which flows in this channel is usually full of salts. During the time this stormwater flows, all the material that accumulated in the channel during the dry season of the year, flushes into the lake, thereby enriching the water with salts.

The bulk of the water flowing down the channels, particularly through the Princessvlei canal, has a diluting effect. Because of channel water from Princessvlei, and because of additional amounts of rainwater, values of conductivity as low as 114.13 mSm^{-1} have been recorded downstream from Princessvlei canal. One would conclude from these observations that conductivities in Rondevlei do not only vary seasonally, but they also depend on the effects of the catchment characteristics of rainfall and waterflow.

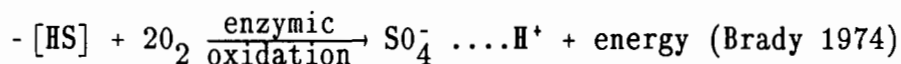
7.1.3 pH

As shown in Figure 4.4, pH of the water in Rondevlei is fairly high, with a mean of 8.20 and a range of 1.55. A slight increase of pH from late summer to autumn was noted. A maximum value of 9 was recorded in autumn, and a minimum value of 7.45 was recorded during the winter season. A significant correlation between pH and properties of water like oxygen and Total Suspended Sediment (TSS) has been presented in Table 4.1.2.

A high rate of primary production in summer and autumn (Gardiner A.C. 1988) results in excessive utilization of CO_2 . During the process of photosynthesis, removal of CO_2 shifts the reaction of $\text{CO}_2 \rightleftharpoons \text{HCO}_3^- \rightleftharpoons \text{CO}_3^{2-}$ towards CO_3^{2-} ; this results in a higher pH. Furthermore during fragmentation and decomposition of organic matter, pH increases (Foth 1978). Positive and negative ions leached from these organic substances, associate with H^+ and OH^-

ions which remain in a dissociated form in water, following the reaction $\text{H}_2\text{O} \rightleftharpoons \text{H}^+ + \text{OH}^-$. The association of these ions results in the increase in OH^- ions. $\text{A}^+ + \text{OH}^- \rightleftharpoons \text{AOH}^-$ if OH^- is already in excess in water, and $\text{Z}^- + \text{H}^+ \rightleftharpoons \text{HZ}$ if H^+ ions are in excess in water, where A^+ and Z^- are ions released in water. An increase in OH^- ions will result in the increase of pH above 7. (Faber 1978.)

Discharge of acids leached from Table Mountain sandstone and podsols of pH < 4 (Witkowski and Mitchell 1987; Gardiner A.C. 1988), as well as humic substance have a dilution effect, particularly during highflow rainy seasons. Stations 1, 2 and 3 (Figure 4.3) experience this discharge of acid-rich water. The effect of acids released during decomposition of organic matter, is of significant importance. Oxidation reactions for example



result in additional pools of H^+ ions. Although there is no quantitative data relating to oxidation processes taking place in Rondevlei, as far back as 1932 Hutchinson et al. remarked on the smell of H_2S in the thick bottom mud of Rondevlei. In 1988 Gardiner A.C. reported the same observation. There is the possibility, therefore, that oxidation processes are of considerable importance in Rondevlei.

Results of this investigation confirm that Rondevlei has a high pH regime observed by Gardiner A.C. (1988) who found a mean of 8.60, a maximum of 10.05 and a minimum of 8.15. Increase in photosynthetic activities of phytoplankton algae result in an increase in pH. Removal of these algal communities, will, of course, bring about a decrease in demand of CO_2 , and a consequent decrease in the production of bicarbonate ion which is a major

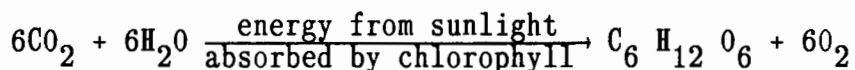
contributor to high pH.

7.1.4 OXYGEN

Diurnal variations of O_2 were not monitored since the aim of recording O_2 levels was merely to check the aerobic status of the lake. According to these records, dissolved oxygen concentrations remained fairly high throughout the lake, maintaining a mean value of $8.5 \text{ mg}/\ell^{-1}$ (Figure 4.5). A maximum concentration of $14.00 \text{ mg}/\ell^{-1}$ was recorded in late spring and a minimum value of $5.4 \text{ mg}/\ell^{-1}$ was recorded during the winter season. In percentage saturation, levels of oxygen fluctuated above the South African general standard of 75%.

Two main factors which contribute to high concentrations of oxygen in Rondevlei are the frequent mixing of the water column and the high photosynthetic activity of the local phytoplankton algal communities (Gardiner A.C. 1988).

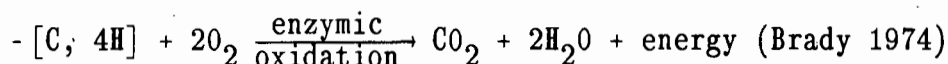
Factors such as wind, shallowness and lack of temperature stratification encourage mixing. When vertical mixing occurs, minerals are recirculated rapidly and made available to the phytoplankton communities which inhabit a highly favourable, and chemically stable, environment. The photosynthetic activity of the phytoplankton enriches the water with a supply of oxygen that is given off during the process of photosynthesis. The overall photosynthetic reaction presented by MacKean (1969),



results in an increase in oxygen concentration. The dependence of oxygen

solubility on temperature is greatly overshadowed by phytoplankton activity. Large algal communities forming patches of green surface scum are common in summer, a period of low flows and minimum water levels. Photosynthetic activity of these algae result in high oxygen outputs of remarkable spatial and temporal variation.

Algal decay involves oxidation processes in which oxygen is consumed. Oxidation of organic compounds, for example carbon-hydrogen containing compounds



results in high utilization of oxygen.

The process of decomposition is an ongoing process. The combined influence of this process with other processes in the lake distort expected seasonality of oxygen and pH, as well as of other chemical constituents of the water. In spite of all the oxygen-depleting and -releasing processes taking place, a seasonal trend has been observed for Stations 1 and 2. An increase in water level results in reduction in turbulence and mixing. This brings about fluctuations in oxygen concentrations which correspond to fluctuations in water level. It is difficult to say exactly why Stations 1 and 2 maintain a seasonal trend of oxygen levels. It is possible that high primary production experienced at other stations, particularly at Stations 4 and 5 is responsible for the fluctuations in oxygen levels. This high primary production is reflected in the values of Total Suspended Solids (TSS) and Particulate Organic Matter (POM). (Figures 4.4 and 4.11.)

7.1.5 MACRONUTRIENTS

(a) Calcium

Results show a decrease in concentration of calcium during late summer and autumn (Figure 4.8). These findings are very similar to those of Gardiner A.C. (1988), whose samples were, however, drawn from different areas of the lake. Both submergent and emergent vegetation attain peak growth and maturity in summer and autumn. Calcium is a cell wall component and plays an important role in the structure and permeability of membranes of plants (Foth 1978). It is therefore expected that there will be a high utilization of calcium during the summer and autumn seasons of the year.

During winter and very early spring, absorption of calcium by plants is low. Seasonal die-back of *Typha* and *Potamogeton* adds to the existing PO_4 which forms a compound with calcium. Reaction processes are also quite low because of low temperature conditions. Reaction rates decreased with a decrease in temperature. Furthermore, during this time of the year, death, fragmentation and decomposition of plants is high due to flooding. As a result, all these levels of calcium tend to rise during winter and spring.

Although calcium is not immediately released into the sediment, carbon dioxide is one of the immediate products of decomposition. The reaction of carbon dioxide in the sediment produces carbonic acids (H_2CO_3), and bicarbonates of calcium and other bases (Brady 1974). Dissolution of these acids increase concentrations of calcium in the water column.

An important feature which makes a large contribution to the existing levels of calcium in Rondevlei is its bedrock geology and mineralogy. Hydrolysis of limestone and calcareous sands plays a significant role in

determining quantities of calcium in the water column. Although dissolution of Ca CO_3 may take place optimally in summer and autumn, due to favourable temperature conditions, processes of precipitation and complexation occur at a high rate during this time of the year, since other ions that form complexes with calcium, such as phosphorus, are also in excess. These processes are slow in spring and winter. Furthermore, photosynthetic processes are also slowed down by low winter temperatures. Less carbon dioxide is utilized by plants, hence more of it reacts with other chemical constituents in the water column and results in bicarbonates of calcium and other bases. (Weisz and Fuller 1962.)

No correlation has been found between calcium and other chemical constituents which I have studied in Rondevlei. Gardiner A.C. (1988) studied this system, and his findings were similar to mine. Further studies on the relationship between this ion and organic as well as inorganic compounds would throw further light on the behaviour of this element in Rondevlei.

(b) Phosphorus

Seasonal trends of Soluble Reactive Phosphorus (SRP) in the water column are shown on Figure 4.9. The highest values were recorded during late autumn to midwinter. Variations of Soluble Reactive Phosphorus (SRP) correspond to those of Total Dissolved Solids (TDS). This may be attributed to a common cause of variation, e.g. there might be environmental variables which influence similarity in variation of these two parameters, for example, flushing from the catchment.

Phosphorus is an essential nutrient in the growth of living cells. Nearly two percent of phosphorus dry weight is found in the cytoplasm. Spring

and summer are periods of maximum growth of phytoplankton and macrophytes, as indicated earlier (Foth 1978, Gardiner A.C. 1988). Uptake of this nutrient by aquatic plants has been confirmed by Stake (1968). Perhaps the lowest reading recorded during spring at Station 5A, which is dominated by reeds of *Typha capensis*, could serve as evidence of uptake by plants. Seasonal variations in loading capacity of wetlands have been investigated by Harrison et al. (1960) and Sloey et al. (1978). According to their observations, when plants cease to grow in winter, there is a consequent drop in the rate of removal of nutrients such as Phosphorus.

Although biological activity, which contributes to the loading capacity due to breakdown of organic material, is reduced in winter (Howard-Williams 1985), reduction in phosphorus uptake and loading by allogenic inputs leave a considerable amount in the system. As far as allogenic inputs are concerned, catchment characteristics play an important role. Two examples from this study are a peak value of phosphorus recorded at Station 2 during mid-summer and a very low value recorded at Station 1 during a peakflow season. The former is a typical example of point discharge of waste water mixed with water from a discrete, summer rain storm. According to Snoeyink et al. (1980), a typical concentration of phosphates found in fresh raw domestic wastewater is "5 mg/litre" orthophosphate as phosphorus. Therefore a high value recorded at Station 2 is significant of discharge of waste water.

On the other hand, the low value recorded at Station 1 implies dilution by water from a nutrient-poor source. Station 1 is on Princessvlei canal which carries storm water from Princessvlei to Rondevlei. From the observed concentration one would come to a conclusion that this water from Princessvlei has low phosphorus concentration, hence a dilution effect in Rondevlei.

In spite of dilutions by water from Princessvlei, it is evident that a

considerable amount of Soluble Reactive Phosphorus (SRP) is flushed into the lake through the canals that discharge water from Rondevlei catchment (Figure 4.3). Simulated mean annual discharge (calculated over a period of 6 years) into Rondevlei is 6.75×10^9 litres of water. This water is responsible for the transportation of 2.46×10^6 mmol Soluble Reactive Phosphorus (SRP) per annum of $0.001 \mu\text{mol}/\ell/\text{day}$ (mean phosphorus values calculated during a sampling period in). The mean outflow through the weir during peak flows amounts to 1.74×10^9 litres of water. Soluble Reactive Phosphorus (SRP) amounting to 1.27×10^5 mmol per annum or $0.0002 \mu\text{mol}/\ell/\text{day}$ is transported by this water out of the vlei through the weir, during peak water flows. This means that a balance of 2.34×10^6 mmol Soluble Reactive Phosphorus (SRP) is retained in the lake per annum. This amounts to $0.0008 \mu\text{mol}/\ell$ of Soluble Reactive Phosphorus (SRP) per day.

It is unlikely that these phosphorus quantities added to the existing amounts (e.g. $0.0005 \mu\text{mol}/\ell$ Soluble Reactive Phosphorus (SRP) in the lake) remain in a soluble form. This is a matter that depends on the concentration of phosphorus in the sediments. Further details relating to sediment phosphorus quantities in Rondevlei and the ability of sediments to transport and to retain phosphorus will be dealt with in the next section.

7.2 SEDIMENT CHARACTERISTICS

7.2.1 SEDIMENT ACCUMULATION

The main contributors of autochthonous material to sediment in Rondevlei are emergent and submerged vegetation, including phytoplankton, and different types of weeds (Chapter 1). Detritus from these plants makes a fair

contribution to the food of invertebrates and different micro-organisms. Feeding by these organisms enhances fragmentation and sedimentation (i.e. accumulation of matter on the sediments) and their faecal pellets, as well as their bodies (when they complete their life cycles), increase the bulk of the bottom sediment (Rogers and Breen 1982, 1983). Springtime sedimentation rates appear to have been highest when compared to those of other seasons of the year.

Results indicate that another possible source of particulate matter is allochthonous material. During summer and autumn, non-perennial canals are choked with terrestrial weeds that have very short life cycles. Senescence and death of these plants results in accumulation of organic debris in the canals. The first winter rains flood this vegetation and later on, during periods of heavy rains and flood, these organic materials are flushed into the lake where they settle to the bottom. Other sources of allochthonous material include suspended sediments that originate from Rondevlei catchment (Figure 2.2), as well as atmospheric fallouts. Stormwater is a major transporting agent of total suspended solids (Chapter 4).

According to the results of this study there is a considerable amount of sediment accumulating in Rondevlei. Station 4 exhibits the highest values of total solids in $\text{g/m}^2/\text{day}$, i.e. mean is $169.19 \text{ g/m}^2/\text{day}$. Station 5 also has very high quantities of accumulating material when compared to other stations. The canals have lower quantities of trapped solids, although their values of percentage Particulate Organic Matter (POM) are higher than those of the lake. Station 4 does not only have the highest value of accumulating solids, but it also exhibits the highest percentage organic matter when compared to other stations (Table 5.1.2). From this observation it is clear that Particulate Organic Matter (POM) is a major source of accreting sediments in the lake. It

is also evident from this study that sedimentation rates vary from station to station, a matter which depends on the environmental conditions existing at each station.

Total Particulate Phosphorus (TPP) measured in trapped sediments followed a different pattern from that of accumulating sediments, and Particulate Organic Matter (POM). Various factors which account for this difference will be discussed in the following sections.

7.2.2 PHOSPHORUS LOADING AND RETENTION

The highest mean particulate phosphorus in the sediment traps $15.9 \mu\text{g/g}^{-1}$ was recorded during the summer season, while the lowest mean value $10.7 \mu\text{g/g}^{-1}$ of phosphorus was recorded in spring. A maximum value of $20.3 \mu\text{g/g}^{-1}$ was obtained for Station 5 and a minimum value of $10.0 \mu\text{g/g}^{-1}$ for Station 2 during summer time of the year (Table 5.1.1). Various factors account for this variation in time and space. Temperature is one of these factors.

Summer is a period of high temperature conditions, and Mark (1959) found that a rise in temperature intensifies the leaching of phosphorus from the sediments. According to Bailey G.W. (1968), the amount of phosphorus taken up by sediment is proportional to the concentration of phosphorus initially present. It is therefore necessary to realize that high temperature conditions encourage regeneration of phosphorus from the sediment and a result of this is high adsorption on to sediment particles. In other words, high dissolution and adsorption occur at the same time, if the system is to remain in equilibrium (Nichols 1983; Rogers et al. 1985). Thus phosphorus that wells up from bottom sediments through desorption processes that occur as a

result of equilibrium shift, does not remain in solution, but immediately adsorbs onto suspended particulate matter. According to White et al (1984) natural systems like Rondevlei exhibit change. Like other environmental systems, which exchange matter with their surroundings, Rondevlei is maintained in a dynamic steady state by a throughput of matter and energy. In this case, equilibrium tends towards phosphorus adsorption.

Furthermore, leaching of organic compounds as a result of fragmentation of senescing and dead plants has been documented in Howard-Williams and Junk (1968). According to investigations by Rogers and Breen (1982), leaching of organic compounds from submerged plants is slow, but greater than would be expected in the case of emergent plants. In Rondevlei, spring and summer phytoplankton productivity is very high (Gardiner A.C. 1988). During these seasons, suspended sediment is very rich in Particulate Organic Matter (POM) (Table 5.1.1). It is therefore not surprising to have high values of phosphorus during this highly productive period of the year (Table 5.1). Spring values, however, may not be as high as summer values. The reason for this is a nutritional demand by aquatic plants. Stake (1968), Sloe et al. (1978) and Rogers et al. (1985) have found that aquatic plants have a great capacity for absorbing phosphorus. Phytoplankton blooms as well as aquatic macrophytes in Rondevlei are both responsible for the loss of phosphorus observed during the spring season. Although adsorption of phosphorus on to aquatic sediments has been observed by Bailey G.W. (1968), Correll et al. (1975) and Twinch and Breen (1982), they also found that absorption by aquatic macrophytes is very important.

A low mean value of particulate phosphorus for Station 4 provides scope for research on retention of phosphorus in wetland ecosystems. Station 4 is located at the outlet of the lake (the weir). Low values of organic solids

and total particulate phosphorus at this station are indicative of flushing from sediments over the wall of the weir. As it has been stated in the preceding section, there is a considerable amount of phosphorus that is transported out of the lake, by flowing water during peak flows.

The second reason is the dilution effect of catchment water. A low concentration of phosphorus observed during the spring season has aroused suspicion not only of nutrient demands of phytoplankton blooms and other macrophytes, but also of dilution effects due to nutrient-poor floodwater which flows down Rondevlei Catchment during winter and spring. Although there is no evidence that water flowing out of Princessvlei is nutrient poor, the results of this study indicate that water flowing from Princessvlei into Rondevlei is low in nutrients, and therefore dilutes Rondevlei water, resulting in lower quantities of nutrients in Rondevlei. Levels of Soluble Reactive Phosphorus (SRP) from Princessvlei canal (Figure 4.9) fall between the maximum and minimum values for rain water, that is 1.3×10^{-4} and 4×10^{-5} mmol (Delny Britton. Pers. Comm.).

Floodwater flowing over Table Mountain sandstone, and nutrient-poor sands, carries in suspension sand and silt onto which particulate phosphorus from stormwater, and from various other sources, is adsorbed. Due to a large bulk of suspended sediment, and a large volume of water, concentrations of adsorbed phosphorus remain very low in winter (Figures 4.2 and 4.4). During summer and autumn, water levels drop drastically, thereby decreasing the dilution effect. Particulate phosphorus levels increase during this time of the year as a result of high dissolution and precipitation as a result of the increase in temperature, and therefore of reaction processes. Lack of large amounts of water and phosphorus-poor sediments are other factors which contribute to the increase in quantities of particulate phosphorus during the

warm summer season.

7.2.3 BEHAVIOUR OF PHOSPHORUS FRACTIONS IN RONDEVLEI SEDIMENTS

Of the three fractions of phosphorus studied in Rondevlei sediments, adsorbed phosphorus is of the lowest concentration, and according to Ostrofsky (1987) this is the fraction that is most likely to contribute to internal loading of phosphorus. He states that iron-bound and loosely sorbed phosphorus tend to occur in lakes with a lot of sedimentary iron, while iron-bound phosphorus can be released at low redox potentials, and that "loosely sorbed phosphorus includes interstitial soluble reactive phosphorus which can migrate into the overlying hypolimnetic waters". He concludes that lakes with anoxic hypolimnia and which have a lot of iron are "susceptible to internal loading".

On the whole, the results agree strongly with those obtained by Ostrofsky (1987). He worked on a broad diversity of lakes, that is, from oligotrophic to eutrophic, and from soft water to moderately alkaline lakes. His results suggest that a high concentration of adsorbed phosphorus (that which has been taken up by the soil, either through chemical or physical processes) is an indication of the presence of sedimentary iron.

Although there is a considerable quantity of iron in Rondevlei water (mean $0.72 \mu\text{mol l}^{-1}$, maximum $1.43 \mu\text{mol l}^{-1}$), Gardiner A.C. (1988) found a negative correlation between iron and Soluble Reactive Phosphorus (SRP). Furthermore, results of this investigation show that for all stations, quantities of adsorbed phosphorus are lower than those of other investigated fractions in Rondevlei (Figures 6.7, 6.8, 6.9, 6.10 and 6.11).

With deposits of limestone and calcareous sand deposits, sediments of

Rondevlei are more likely to have calcium-bound phosphorus. Witkowski and Mitchell (1987) studied limestone-derived soils of lowland fynbos and Fernwood soils of the Strandveld, and found that these soils have high calcium-bound phosphorus fractions. They also found that mountain fynbos soils, which cover most of Rondevlei catchment, have high iron-bound phosphorus. Rondevlei is also underlain by Cape granite, and Witkowski and Mitchell (1987) have noticed that granite-derived soils are richer than sandstone derived soils in phosphorus content, while both soils have iron bound phosphorus. However, the figures obtained for adsorbed phosphorus support the observation that calcium-bound phosphorus predominates iron-bound phosphorus in Rondevlei.

With its rich diversity of sediments, Rondevlei presents a wide scope for future quantitative analysis of phosphorus fractions. The kind of research needed will determine the degree of concentration and availability of each phosphorus fraction in the varying sediments. At present, one can only say that a high pH value (Figure 6.7) of sediments indicates the absence of excess hydrous oxides of aluminium and iron. This means that the fraction of Total Inorganic Phosphorus (TIP) present in sediment can only fall in a category of calcium phosphates.

7.2.4 RELATIONSHIP BETWEEN PHOSPHORUS AND OTHER PROPERTIES OF SEDIMENTS IN RONDEVLEI

The importance of the organic phosphorus fraction is noted by the strongest correlation between total phosphorus and organic phosphorus (Figure 6.2). However no correlation exists between organic matter and organic phosphorus. This contrasts sharply with the findings of Williams *et al.* (1976) and those of Ostrofsky (1987). Both workers conducted their

investigations in the lakes of eastern North America, which exhibit different environmental conditions from Rondevlei. For example, the sediments of their study environments contain high quantities of aluminium and iron, while Rondevlei is rich in calcium deposits. This indicates differences in the sediments of the chemical composition. It is possible that there are other properties of sediments which are more important than organic matter in Rondevlei. In this case, the relationship between organic matter and phosphorus content of the soil is overridden by the activities of these other properties. However, further investigations are necessary to verify this observation. Bailey G.W. (1968) has stated that soils have different abilities to fix phosphorus. Therefore the results conform to the expectation that phosphorus and its relative species may be expected to vary from soil to soil. Environmental conditions of temperature, redox potential, organic matter content etc. (Chapter 1.3) play a major role in determining type and quantities of phosphorus in the soil. Rondevlei sediments are no exception to this rule.

7.2.5 DYNAMICS OF PHOSPHORUS IN RONDEVLEI

Results of the present study conform to the findings of Nicholas (1983), who found that phosphorus does not move far into the sediments. Most of it remains in the surficial layer of sediments. Indeed, for most stations in Rondevlei, phosphorus is highly concentrated in the first 20mm of the sediment column. For Station 3, observations agree with those of Williams et al. (1976), Hosomi et al. (1982) who found that phosphorus decreased in concentration with depth. Both investigators worked on fresh water lakes. The same observations were made by Joh (1983) and Yamaha and Kayama (1987)

for marine systems. Yamaha and Kayama (1987) have stated that dissolution of phosphorus occurs at the sediment water interface. According to their findings, sixty percent of soluble phosphorus is attributed to the dissolution of phosphorus precipitated in the surficial sediments. Exceptions, for example, of high concentrations of phosphorus in the bottom sediments may be expected under a natural system like Rondevlei, which was once exposed to marine influence.

According to Livingstone and Boykin (1962), who studied mud samples from Linley Pond in Connecticut U.S.A., a considerable amount of phosphate may be expected in the bottom sediments in shallow lakes which were overlain by marine water during their oligotrophic stage. Rondevlei is one example of such lakes. They postulate that total ionic activity of the water overlying the sediment plays an important role in the chemistry of the lake and they show that phosphate is inversely related to the exchange capacity of the mud. Sediments formed under oligotrophic conditions, but bathed by water of higher ionic strength, release a considerable amount of phosphate.

Rogers et al. (1985) have found wetland sediments to be sinks for phosphorus from waste water. Station 2 is a point of discharge, not only of flood water, but of stormwater. This station exhibits large amounts of inorganic phosphorus, and it is well known that inorganic polyphosphates may occur where pollution by detergents is severe. This may adsorb onto silt particles, the sedimentation of which result in high concentration of phosphorus in the bottom sediments.

Another factor which may account for precipitation of large amounts of phosphorus in sediments of Station 2 is redox potential. In comparison to other stations, low oxygen concentration was recorded for this station during the time when the samples were taken. This is a sign of the presence of

biodegradable compounds (Snoeyink et al. 1980). A considerable amount of oxygen is necessary for the aerobic degradation of these compounds, particularly during the warm season. This, of course, results in the low concentrations of oxygen in the overlying water. Phosphorus adsorbs strongly on calcium carbonate (Cole et al. 1953; de Kanel and Morse 1978), and this is a very rapid process (Rogers et al. 1985). Hence high concentrations of phosphorus may be expected in calcium carbonate-rich sediments.

A striking feature of Stations 1, 2 and 5A is the large amount of phosphorus in the sediments and the relatively low amounts adsorbed onto sediment particles. A common feature of these stations is the vegetation of emergent macrophytes that is supported by their sediments. This feature does not exist at Stations 5 and 3, which are completely barren of emergent vegetation.

Loss of phosphorus to emergent vegetation has been documented in Furners and Breen (1978), Howard-Williams and Allanson (1978) and Twinch and Ashton (1983). Plant roots absorb phosphorus from sediment pore water. According to Rogers et al. (1985), removal by plants is temporary, in that release occurs during death and decomposition of these plants. Factors which influence dynamics of phosphorus have been outlined in Chapter 3. There are several other things which may be responsible for the behaviour of phosphorus in Rondevlei. Of the factors mentioned and investigated, none seems to have a profound effect on the behaviour of this nutrient in the lake.

Individual stations monitored in Rondevlei show varying characteristics related to phosphorus and its different species. Station 1 and Station 3 have the maximum values of sedimentary phosphorus at 60-80mm depth. At both stations the bulk of phosphorus is organically bound. Station 5 has the least quantities of phosphorus when compared to other stations. Unlike the

preceding two stations, highest readings of phosphorus at this station were recorded for 100-120mm depth, and at less than 80% of phosphorus is organically bound. Station 5A exhibited the largest quantities of phosphorus, the maximum values of which were recorded at 140-160mm depth. Like other stations already mentioned, the dominant species of phosphorus at Station 5A is organic phosphorus.

Although maximum values of phosphorus were recorded at 60-80mm depth for Station 2 (as it was in the case of Stations 1 and 3), this station is exceptional because the bulk of the phosphorus is inorganic. At all stations except Station 1, inorganic phosphorus is concentrated in the uppermost layers of sediment, i.e. at 0-20mm depth. This behaviour of phosphorus conforms to the observations that have been discussed in the previous sections, i.e. that processes of dissolution and precipitation occur at sediment water interface. Migration of this nutrient to the bottom layers of sediment will depend on various processes which are taking place at different sediment layers. These processes include adsorption and desorption. There are also activities of microbial communities existing in the sedimentary environment, as well as varying sediment characteristics. It has been indicated earlier in this thesis that reversion of some of the condensed forms of phosphorus results from the activity of micro-organisms. These activities have been discussed in detail in Chapter 1. It will be interesting to investigate the extent and importance of these activities in Rondevlei.

Besides the input and output by autochthonous material, which varies from station to station, there is also input from allochthonous sources. For example, Station 2 is a point of discharge of allochthonous material. It is therefore not surprising to see large quantities of phosphorus being stored by sediments which appear to be the source of phosphorus.

Finally, the flushing out of phosphorus from some stations takes phosphorus from these stations and transfers it to other stations. This not only creates a high phosphorus gradient, but it leaves the lake with pockets of nutrient that enhance vegetation growth at different parts of the lake. The result of this is siltation and sedimentation during senescence and death of fertilized macrophyte beds. Quantities that leave the lake through the weir are smaller than those flushed into the lake. This subject has been discussed in the introductory sections of this chapter. Taking into account other sources of this nutrient like bird droppings and hippopotamus defaecation, which have not been quantified, one can see that there are many factors which govern spatial variation of sediment phosphorus in Rondevlei.

According to the findings of this study, surficial sediments in Rondevlei contained 12 times as much phosphorus as that which was found in the sediment traps. A mean value of $141.47 \mu\text{g g}^{-1}$ of Total Phosphorus (TP) was found in the surficial sediment while a mean value of $12.65 \mu\text{g/g}^{-1}$ of Total Particulate Phosphorus (TPP) was recorded for 5 stations monitored in Rondevlei. There is a considerable spatial variation for both sediment sources of phosphorus. I have already stated that there are other sources apart from the ones investigated in this experiment. For both trapped sediments and core sediments there was no relationship between Particulate Organic Matter (POM) and Sediment Total Phosphorus (STP). Previous research done on sediments in other lakes have shown contrasting results. It is important therefore to conduct further investigations in order to establish the relationship between phosphorus and other characteristics of sediments.

7.2.6 THE FUTURE OF RONDEVLEI

Thus far, we have seen the present condition of Rondevlei. An overview of this lakelet indicates that it is eutrophic. Consequences of eutrophication in Rondevlei have been noted in Gardiner A.C. (1988). The proliferation of phytoplankton communities which are dominated by blue-green algae is presently a problem in Rondevlei. Death and decomposition of these plants enhances accumulation of phosphorus rich sediments in the lake. The increase of phosphorus loads results in rapid growth of aquatic macrophytes. *Typha* and other nuisance plants are growing at an alarming rate at present. This poses a problem of accelerated siltation and a threat of impending death to this lake.

Further evidence of eutrophication is the fluctuations in oxygen level of the overlying water which has been noted in certain areas of the lake. These fluctuations in oxygen-concentration, together with high concentrations of hydrogen sulphide, witnessed by Hutchinson et al (1932) and Gardiner A.C. (1988) are consequences of eutrophication.

In spite of excessive plant growth, which results in inputs of autochthonous nutrients, Rondevlei receives stormwater which is rich in soluble phosphorus and suspended sediments. These are problems which call for immediate action by management if this nature reserve is to be saved.

Dredging of the lake, application of herbicides or any other artificial control methods should be avoided. Artificial control methods have proved to be detrimental to the life of fauna and flora in this natural environment. In the past, negative impacts (Chapter 2) have resulted from unwise manipulation of this lakelet. Although it is necessary to implement control measures in order to save Rondevlei from further acceleration of eutrophication, it is

important to consider long term benefits from the methods used as control measures.

Models which provide information predicting the response of systems like Rondevlei have been used successfully in the past. By using these models, negative impacts on the system under control have been avoided. These models provide knowledge and information relating to the problem at hand. Information relating to the cause and effect of the problem is a successful management tool to the solution of a problem.

In the case of Rondevlei, sediments both allogenic and autogenic, have been studied. In this experiment, sediments have been found to be carriers of phosphorus. As it has been stated in the introductory chapter, phosphorus is the most important nutrient associated with eutrophication, and therefore a causal indicator.

In solving an eutrophication problem of Rondevlei, models which predict the intake phosphorus concentrations from external load, for example, the phosphate budget model (OECD 1982) should be utilized. Models like this cannot be used in isolation, especially in aquatic systems where both allocthonous and autochthonous sources of phosphorus are involved. In addition to these, sediment phosphorus models which describe phosphorus and oxygen conditions in lake sediments should be adopted. The latter type of models include a sediment phosphorus model by Meyer et al. (1978) which take into account "anaerobic, and aerobic decomposition; diffusion adsorption and chemisorption, sedimentation and resuspension". Temperature and various fractions which are part of degradable phosphorus are also important in these models.

To avoid mistakes and intensification of management problems, which has so far been experienced in Rondevlei, these models should be studied

carefully. It is only when we understand how the system works, that we can wisely improve its condition or prescribe remedies to its unsatisfactory condition. Rondevlei is not an exception to this rule.

It is therefore important to note that this study will only serve as an introduction to a multifaceted research project which should be aimed at solving the eutrophication problems of Rondevlei and other lakes which have similar problems under similar environmental conditions. Once research relating to the demands of the above mentioned models has been completed, it will be necessary to make proper adjustment evaluations, which will lead to the making of an adjustment decision model suitable for Rondevlei and similar systems. Proper adoption of a suitable model will lead to the reduction of negative effects of eutrophication which presently exist in Rondevlei. At this stage, further studies on the physical and chemical properties of sediment should be pursued to satisfy the requirements of the above mentioned models.

CHAPTER 8

SUMMARY AND CONCLUSIONS

This thesis is an initial characterization of certain aspects of water and sediment chemistry of Rondevlei. It is also an attempt to present information relating to phosphorus status of Rondevlei sediment.

Physical variables of temperature, flow, rainfall and water level as well as Total Suspended Solids (TSS) show considerable seasonal variations. While there was a drastic drop in temperature during winter, maximum rainfall, flow and waterlevel records were recorded during the winter season. With the exception of Station 2 Particulate Organic Matter (POM) concentrations rose during late summer: peak values were recorded in autumn and, for Station 2, during spring. Inorganic chemical parameters of pH, electrical conductivity, Total Dissolved Solids (TDS), and Soluble Reactive Phosphorus (SRP) exhibited high values in autumn. Low values of oxygen percentage saturation were recorded during late summer. Calcium did not vary seasonally.

Results obtained from sediment trapping revealed a high degree of temporal as well as spatial variability. Maximum flux rates were recorded to total solids and for Particulate Organic Matter (POM) during spring and minimum values during autumn. Peak values of total particulate phosphorus were noted during summer. As indicated previously, suspended sediment showed high values of phosphorus during summer time, a period of high phytoplankton productivity. Leaching of organic compounds from submerged plants may be responsible for this rise in phosphorus levels.

Since there is no correlation between total phosphorus and particulate organic matter (Table 5.1.3), one may conclude that due to temperatures

favourable for desorption and adsorption processes, phosphorus which precipitates during summer in Rondevlei may have its source in sediments. Besides the temperature of the overlying water, which is high in summer (Figure 4.1) in Rondevlei, pH values of the overlying water rise during early summer (Figure 4.6). The rise in pH is an indication of the presence of high concentrations of hydrogen ions which, act as catalysts of chemical reactions in aquatic systems. With high temperature, and an increased pH, optimum chemical reactions occur resulting in increased particulate phosphorus levels.

As noted earlier, in Rondevlei spring is a period of phytoplankton blooms. Excessive utilization by growing plants leads to the depletion of this ion. Therefore it is not surprising to see low values of phosphorus during springtime. Maximum phytoplankton productivity (observed by Gardiner A.C. 1988), is perhaps a clear evidence of mobilization of phosphorus by aquatic macrophytes. In addition to this a significant positive correlation between Total Solids (TS) and Particulate Organic Matter (POM) shows the presence of organic solids being regenerated biologically in the system.

The quantities and forms of phosphorus varied with depth in the sediment, and from place to place.

Results of distribution of phosphorus and its related species indicate variability in depth and space. This study, like previous investigations revealed a decrease in phosphorus content with increasing depth, a feature which should be expected under normal circumstances. Exceptional cases may be explained by looking at the history of the lake concerned, in this case, Rondevlei. Rondevlei is one of the lakes which have been under marine influence during certain stages of their existence. As a result of exposure to marine influence it tends to have considerable amounts of phosphorus in its bottom sediments. This makes it different from lakes which

show a decline in phosphorus content with increasing depth.

Of these forms of phosphorus investigated, inorganic phosphorus is highly concentrated in sediments found at the point of discharge of urban runoff. Runoff of urban effluents would contain sufficient Phosphorus to explain the quantities of phosphorus observed at Station 2.

Adsorbed phosphorus recorded for all stations was very low. Although Gardiner A.C. (1988) has mentioned the occurrence of anoxic condition in Rondevlei sediments, a condition which favours the presence of loosely sorbed phosphorus in lakes, no evidence of plenty of sedimentary iron in Rondevlei has been obtained. The occurrence of this condition in lakes with anoxic hypolimnia exposes such lakes to internal loading. It is quite unlikely that this situation exists in Rondevlei. As it has been pointed out earlier, sediments in Rondevlei exhibit alkaline characteristics. These characteristics, together with a low percentage of adsorbed phosphorus, is clear evidence that internal loading is not a feature of Rondevlei. Further investigations are therefore necessary in order to account for probable sources of phosphorus in the lake.

It is however clear at this stage that urban runoff is one of the possible sources of phosphorus. Finally, it is interesting to see the correspondence of phosphorus distribution with that of emergent vegetation. Although there is no quantitative data for Rondevlei to support this issue, workers like Furners and Breen 1978, Howard-Williams and Allanson (1978), Twinch and Ashton (1983) and Rogers *et al.* (1985) have shown that emergent vegetation is responsible for the disappearance of phosphorus in sediments. Further research is necessary to confirm the occurrence of this phenomena in Rondevlei.

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APPENDIX A

Preparation of Murphy & Riley solution for the determination of Phosphorus

Reagents:

Sulphuric Acid - (140ml of concentrated sulphuric acid + 860ml H₂O)

(96% or 1.84 Kg l⁻¹)

Potassium Antimonyl tartrate (0.5486 grams to 200 ml H₂O)

Sodium Molybdate (20 grams to 50l)

Ascorbic Acid and Water

To make a 500ml volume of Murphy and Riley solution, reagents were mixed in the following quantities:

Reagent	Quantity
5NH ₂ SO ₄	250ml
NH ₉ + Molyb	75ml
Pot Ant Tart	25ml
Ascorbic Acid	2.64 g
H ₂ O	150ml

Standards were prepared by using potassium dihydrogen phosphate.