THE ARTIFICIAL RECHARGE OF URBAN STORMWATER RUNOFF IN THE ATLANTIS COASTAL AQUIFER

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by

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PREFACE

The investigation described in this thesis was carried out by the author in the employment of the Division of Water Technology of CSIR. Professor Denis Hughes and Dr. Alex Weaver supervised the preparation of the thesis. The investigation formed part of the overall Atlantis Groundwater Research Programme managed by Dr Gideon Tredoux. The author joined the Research Programme in September 1987 and assumed responsibility for the research covered in this thesis. The initial fieldwork prior to this date was thus carried out by other members of staff under Dr Tredoux supervision.

This study represents original work by the author and has not been submitted in any form to another University. Where assistance has been given by others it is duly acknowledged.

SYNOPSIS

The thesis covers the investigation of the stormwater runoff and artificial recharge components of the Atlantis Water Resource Management Scheme in the Southwestern Cape. The objective of the study was to obtain an in-depth knowledge of the process of artificial recharge of urban stormwater runoff, in order to identify the most efficient recharge management strategy for the Atlantis aquifer. To achieve the objective it was necessary to first study the existing knowledge on urban stormwater hydrology and artificial recharge by spreading, and to create a conceptual model of what might be expected. The study area was then investigated to examine how closely the actual situation was reflected by the conceptual model, enabling recommendations to be made for the sound management of the system.

The stormwater runoff component was found to differ from most urban hydrological studies as a result of its large baseflow component. The sandy nature of the catchment, small percentage area of effective impervious surface, and high groundwater table resulted in the baseflow constituting more than 40% of the total stormwater runoff and accounting for over 60% of the pollution load. The "first flush" effect established as a major source of pollution in other studies, was found to be of minor significance in this study area. The overall stormwater quality (excluding the noxious industrial baseflow) was found acceptable for artificial recharge within the study area, although the baseflow from the industrial sub-catchments showed the potential for being a major source of pollution in the future.

The treated wastewater used for artificial recharge prior to 1987 was found to be unacceptable for recharge purposes. The treated industrial effluent should under no circumstances be recharged up-gradient of the Witzand well field. The treated domestic effluent although of a poorer quality than the resident Witzand well field groundwater could be recharged in order to boost recharge volumes and form a buffer against further intrusion by the poor quality groundwater from the Brakkefontein area. This would however only be acceptable if strict water quality control is maintained and recharge does not take place west of the present basin.

The recharge basin was found to be well situated with respect to influencing the Witzand wellfield and maintaining a groundwater buffer against poor quality groundwater flow from the northeast towards the central area of the wellfield. Unfortunately the surrounding low-lying topography and sandy retaining walls have resulted in return flow and raised groundwater-levels. The raised groundwater mound does not comply with the conceptual model and together with the sandy nature of the unsaturated zone resulted in less effective purification during infiltration. The practice of letting large portions of the basin floor dry-out during summer was shown to be beneficial and the periodic cleaning of the deeper portions of the basin essential.

The artificially recharged water was found to have influenced the upper portion of the aquifer well beyond the West Coast Road. The study of groundwater quality being a good method for tracing artificially recharged water. The groundwater quality has improved as a result of artificial recharge since the removal of treated wastewater from the recharge basin. The groundwater was found to be very responsive to the slightest changes in recharge basin water quality or/and quantity. Management of the recharge basin therefore had to be very much of a compromise between qualitative and quantitative approaches. The present approach of recharging all the stormwater runoff throughout the year providing the most efficient compromise under the present conditions.

The study revealed that the most efficient recharge management strategy would be the recharge of treated domestic sewage effluent in the present recharge basin and all residential stormwater runoff plus industrial "stormflow" stormwater runoff in a new recharge basin located northwest of the present basin. Strict water quality control must be maintained on the water discharged into the basins and an annual wet/dry cycle implemented within the basins to boost infiltration. The entire system should continue being monitored to safe guard the groundwater resource from pollution and over exploitation.

Footnote:- *For compatibility with computer printouts decimal points are used in the format of real numbers in tables, etc.*

A "Cape hydrological year" (March - February) was used as this coincided with the seasonal rainfall pattern and recharge cycles experienced in the study area.

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CHAPTER 1

1. INTRODUCTION

The research presented in this thesis forms part of a larger ongoing research project on groundwater resource management of a coastal aquifer. This is a CSIR project undertaken by the Groundwater Programme of the Division of Water Technology. The findings of the research are used by the Western Cape Regional Services Council (WCRSC) for development and management of the southern West Coast Region. This report concentrates on one component of the research undertaken since 1986.

1.1 General Background

Exploration of the primary aquifers of the south-western Cape was initiated in the late 1960's. The investigations were related to the development of groundwater supplies and the evaluation of aquifers as potential storage areas and natural purification systems for surface waters and treated waste waters. Attention was initially focused on the Cape Flats and Atlantis aquifer units, with the first hydrogeological investigation in the Atlantis area in 1972 by the Geological Survey (Vandoolaeghe, 1984). A number of springs that existed in the Silwerstroom area were identified as surface outlets of the Atlantis aquifer. This suggested that a cheap source of plentiful water was immediately available for the planned industrial township of Atlantis. It had been planned to bring surface water for the town from the Misverstand Weir on the Berg River near Moorreesburg, some 50 km away. As a temporary measure the Silwerstroom spring was dammed and provided between 35 and 55 $L.s^{-1}$ of potable water (Van der Merwe, 1980). Further exploration involved an extensive drilling programme which ultimately led to the development of the Silwerstroom and Witzand wellfields. The initial investigations showed that the aquifer was of such an extent, that with proper utilisation, it could, for a considerable period of time, provide the total water supply for Atlantis. The Atlantis Water Resource Management Scheme thus came into being to exploit and ensure the most efficient use of this coastal aquifer.

1.2 Atlantis Water Resource Management Scheme (AWRMS)

Atlantis is a national growth point situated some 50 km north of Cape Town on the somewhat bleak and relatively undeveloped West Coast (Figure 1). Development began in 1976, with an envisaged population of 334 000 people (DWA, White Paper, WPQ-1976) by the turn of the century. The population constitutes primarily working-class people who find employment in local industry, which is attracted to the town through State decentralisation incentives. Today the town has a population of over 70 000 and an industrial component of some 140 factories with 13 000 employers (WCRSC, personal communication). The area set aside for development covers approximately 130 km^2 and consists essentially of sand dunes which are to a large extent stabilized by vegetation.

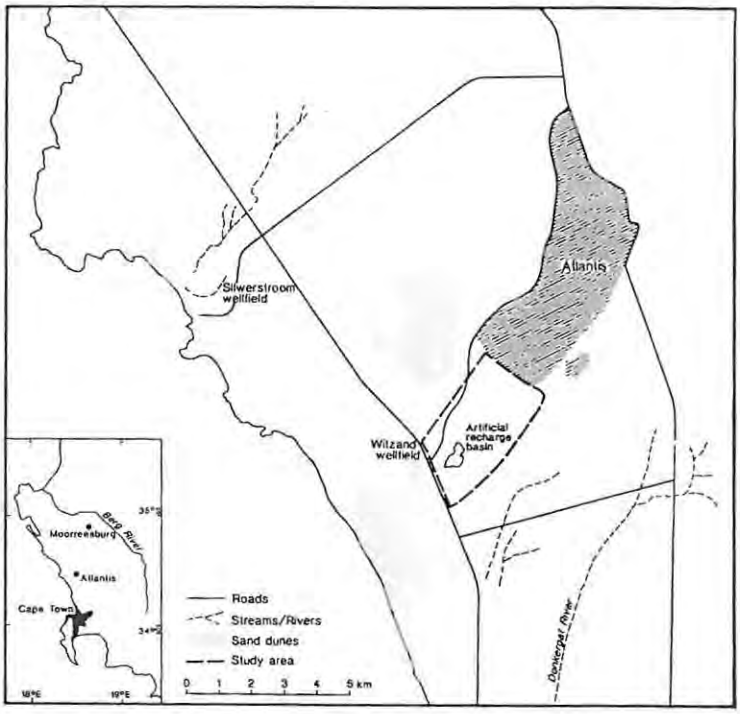


Figure 1 Location plan

The increasing degree of urbanisation has resulted in an increase in town water supply from 0.43×10^6 m^3 in 1977 to 4.57×10^6 m^3 in 1990. It thus became necessary to establish the Atlantis Water Resource Management Scheme (AWRMS) in order to safeguard the groundwater resources, as these at present form the sole source of water supply. The AWRMS has been designed in such a way that water extracted from the aquifer once used in Atlantis, is collected and artificially recharged to supplement the natural recharge of the aquifer. Figure 2 gives a three-dimensional representation of the scheme and the different components of the AWRMS are illustrated in Figure 3.

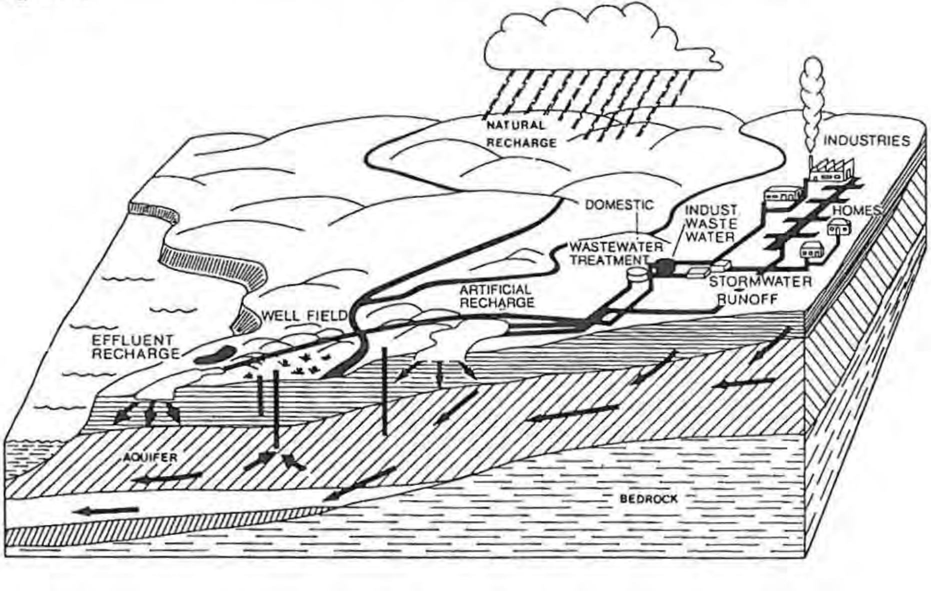


Figure 2 A three-dimensional representation of the Atlantis Water Resource Management Scheme [diagram by A. du Toit, CSIR]

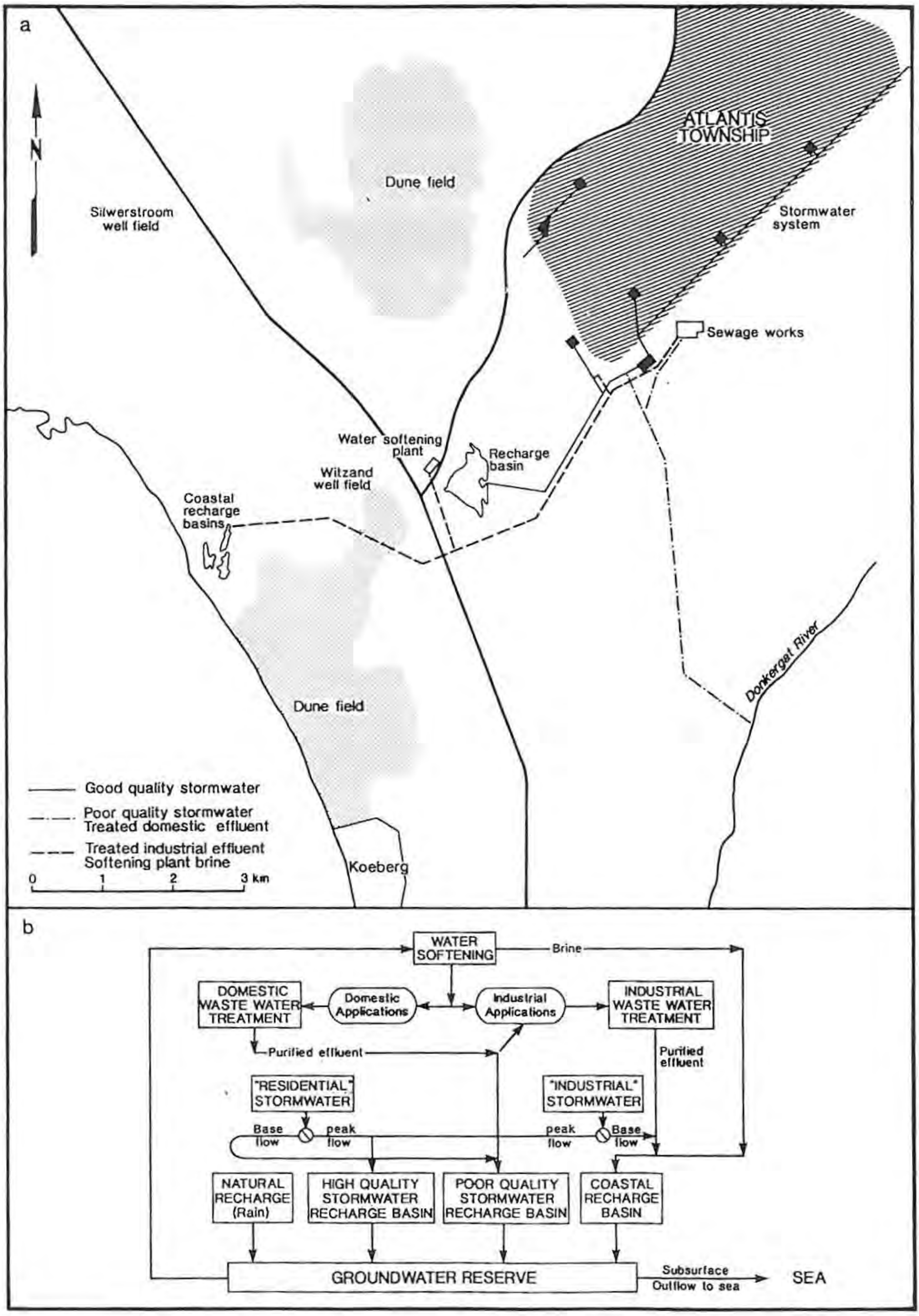


Figure 3 Atlantis water resource management scheme:

a) the present components

b) the conceptual plan

The different components may be summarised as follows:

a) Natural recharge of the aquifer by way of precipitation. The areas of mobile dune fields have been identified by Tredoux and Tworeck (1984) as the primary/major source areas of natural recharge.

b) Groundwater extraction in two well fields. These include the pumping boreholes, pump stations, pipe networks, reservoirs and an ion exchange water softening plant.

c) An urban stormwater reticulation system containing underground pipes and eleven detention basins.

d) Twin sewerage reticulation for the residential and industrial areas and corresponding parallel waste water treatment works.

e) Outfall pipelines and diversion mechanisms for disposing of the treated wastewater, urban stormwater runoff and water softening plant brines to either the Donkergat River or recharge basins.

f) An artificial recharge basin for good quality water and a groundwater quality monitoring network.

g) Coastal recharge basins for the disposal of poor quality water, with a groundwater pollution monitoring network.

1.3 Previous work

The Atlantis area was first mapped geologically by Houghton (1933) and subsequently by several members of the South African Geological Survey in order to produce standard 1 : 50 000 geological maps. The most recent work was that of Rogers (1980) who undertook a detailed investigation of the Cenozoic sediments. The first hydrogeological investigation was in 1972 by members of the Geological Survey and was followed by a number of other regional investigations (Noble, 1976; Smit, 1976; Vegter *et al.*, 1976; Kok, 1977). The drilling operations were undertaken by the Department of Water Affairs. Van der Merwe (1980) produced the first comprehensive report on the Atlantis aquifer and this remains the most definitive research on the area. Several Department of Water Affairs reports have subsequently been produced (Bredenkamp & Vandoolaeghe, 1982; Vandoolaeghe & Bertram, 1983; Bertram *et al.*, 1984), but all deal with extensions to the two existing well fields.

During the 1980's the Institute for Groundwater Studies (University of OFS) undertook a groundwater modelling exercise using data from the Atlantis aquifer. The objective was to develop a preliminary mathematical model which could describe groundwater flow in the aquifer (Müller & Botha, 1986). The most recent reports (Fleisher, 1990 and Weaver, 1989) deal with the latest extensions to the Witzand wellfield and water balances for the wellfield.

The CSIR involvement began in late 1982 and initially concentrated on water quality monitoring with regard to artificial recharge. This involved the establishment of a monitoring network and the collection of field data for the development of a groundwater database. The nature of groundwater studies requires that field data be collected over a reasonably long period of time and thus no detailed analysis of the data has as yet been undertaken. The subject of artificial recharge has been briefly touched on at conferences by Tredoux and Tworeck (1984), Tredoux (1987) and Tredoux *et al.* (1988). The monitoring system and database have been revised on an annual basis by Wright *et al.* (1988), Wright (1989a/b/c) and Wright (1990) in order to refine the system and formulate management decisions.

1.4 Problem statement

A great deal of research has been done on the Atlantis Aquifer. Most of this was of a regional nature or concerned specifically with production well fields, and to date no comprehensive study has been made of the artificial recharge system and its related components. The establishment and management of the artificial recharge system was undertaken using knowledge and expertise gained elsewhere, with the result that many of the management decisions were based on a "trial and error" strategy. Although the monitoring network was initiated as far back as 1983, it is only now that the data base is large enough to permit an in-depth study of this component.

The fact that groundwater is to remain the sole source of water supply until beyond the year 2000 makes it imperative that all components of the AWRMS are managed as efficiently as possible to ensure the long term reliability of the water supply. There is thus an urgent need to fully research the stormwater runoff and artificial recharge components in order to develop a sound management strategy.

CHAPTER 2

2. THE NATURE OF STORMWATER RUNOFF QUALITY AND ARTIFICIAL RECHARGE

Most aquifers are naturally recharged by infiltrating rainwater and/or surface water. In the case of an unconfined aquifer, such as the Atlantis coastal aquifer, the groundwater level will fluctuate with the amount of recharge in relation to the outflow from the aquifer. It is thus advantageous if the aquifer can be artificially recharged in order to augment the natural recharge, especially in areas of poor natural recharge, but high groundwater abstraction.

Artificial recharge may be defined as "the process whereby water infiltrates from works or is induced artificially to infiltrate the ground from a body of water or injection well in quantities, and commonly at rates, in excess of natural infiltration" (Ineson, 1970, pp.1). Artificial recharge has a wide application and the principal benefits may be classified into two categories : relief of overdraft (depleted groundwater supplies) and access to more groundwater by using groundwater basins as cyclic storage and distribution systems (Espina, 1980). The two main methods of artificial recharge are by infiltration/spreading basins and injection wells. Infiltration basins are the more common method and are both cheap to construct and operate (Brown and Signor, 1974). This method is ideal for highly permeable, unconfined, alluvial aquifers. Injection wells are more suitable in the case of deep, confined aquifers. This review is only concerned with the recharge/infiltration spreading basin method as the Atlantis aquifer is an unconfined, sandy aquifer.

Artificial recharge schemes are found in many areas of the world and make use of river water, stormwater and treated waste water. The use of waste water often comes under severe public criticism, but these aesthetic objections and prejudices occur largely due to mis- or lack of information (Todd, 1959; Buros, 1976; Driscoll, 1986). The water used in the City of London, for example, has during several past droughts passed through five sewage treatment plants (Blackburn, 1978). The ever increasing world population and improving living conditions are placing greater demands on the existing water supplies. The once off use of water is fast becoming unacceptable and the reuse of waste water and stormwater runoff a necessity (Dean and Lund, 1981).

The reuse of stormwater runoff and treated waste water is now a relatively common practice throughout the world (Seaburn, 1970; Bouwer & Chaney 1974; Idelovitch *et al.*, 1980; Ho *et al.*, 1981; Crook *et al.*, 1990). The normal urban uses of water do not really alter the structure of the water, but just add both dissolved and suspended impurities. However obnoxious these impurities may seem they generally amount, by weight, to less than 0.01 percent of the total waste water (Buros, 1976). Most of the pollutants, that is excluding industrial pollutants, can be removed by relatively simple physical, biological and chemical means.

2.1 The use of treated waste water for artificial recharge

In waste water effluents the organic and bacteriological constituents are added to the original water, whereas the inorganics largely reflect the mineral composition of the source water (Chang & Page, 1979). Groundwater naturally contains only small amounts of dissolved organic substances (e.g. humic and fulvic acids) and minor amounts of trace elements. The organic compounds added to the water in urban catchments are both of a natural and synthetic nature and are decomposed by two processes:

a) aerobic metabolisms where the end products include CO_2, H_2O, NO_3^-, SO_4^{-2} and microbial cells; and
b) anaerobic metabolisms which are slower and initially form acids, alcohols, amines and mercaptans, before resulting in products such as CH_4, H_2, NH_4^+, H_2S CO_2 and H_2O (Bouwer and Chaney, 1974).

Processes and technologies therefore exist for the efficient treatment of the average urban waste water.

The industrial age has, however, unfortunately added over 2 million more man-made organic compounds to the list of possible pollutants in waste water (Freeze & Cherry, 1979). Many of these compounds are resistant to biological degradation and are toxic at very low concentrations. The danger substances are those which are relatively soluble, nonvolatile and refractory. Clearly adsorption cannot cope with the excessive concentrations of the modern industrial environment. Thus, some characteristics of waste water may limit its acceptability for artificial recharge by infiltration. The AWRC (1982) regard the level of pretreatment received, the concentration of toxic wastes, the salinity and suspended solids, biochemical oxygen demand (BOD) and temperatures as the main characteristics to be considered if waste water is to be reused.

Secondary treated waste water is generally acceptable for recharge by infiltration from spreading basins. More than 98% of the inorganic constituents in treated effluent are in a dissolved form, while trace metals are either as colloidal solids or dissolved solids. The micro-organisms and viruses appear as particulates (Chen *et al.*, 1974). Ideally tertiary treated waste water should be used but the high costs involved at present make this impractical. In many cases the purification during recharge attains the same result as tertiary treatment. The presence of toxic contaminants in waste water means that treated waste water can be grouped into

a) effluents, like domestic sewage, which contain only minor amounts of innocuous industrial effluent;
b) nocuous effluents, like industrial waste water, which contains toxic material.

The former group is suitable for consideration for recharge and the latter group is totally unacceptable (that is for recharge of a groundwater resource used for drinking water).

The potential that treated waste water offers for artificial recharge schemes is illustrated by the Whittier Narrows Reclamation Plant in California. In 1977 the plant provided more than 8.6 x $10^6 m^3$ p.a. of tertiary treated water for recharge purposes. This is the equivalent of the annual water demand of approximately 9 000 families (Driscoll, 1986).

2.2 The Use of Urban Stormwater Runoff for Artificial Recharge

2.2.1 Urban stormwater as a potential source of recharge water

Under natural conditions a percentage of all precipitation infiltrates and becomes groundwater thus recharging the aquifer (Figure 4). When urbanization takes place many of the natural hydrological processes are streamlined resulting in reduced natural recharge within the catchment. Precipitation, that previously infiltrated, is now caught by buildings, roads, walkways, etc., and channelled via drainage systems away from the catchment. Urbanization thus, not only produces larger volumes of surface runoff, but concentrates the runoff more rapidly (Overton & Meadows, 1976; Douglas, 1983; Simpson & Stone, 1988).

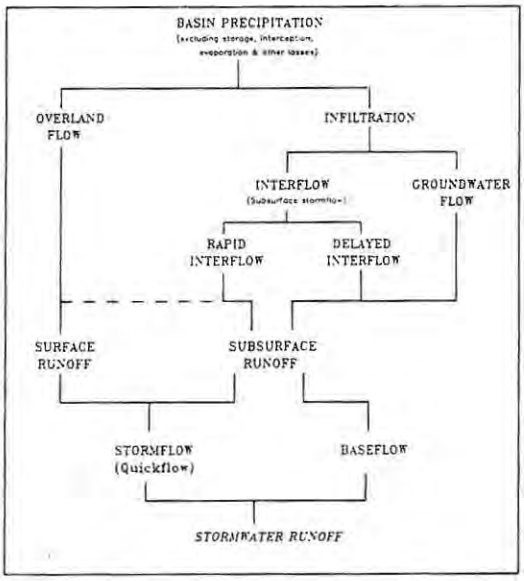


Figure 4 Diagrammatic Representation of the Runoff Process (after Ward, 1975, p. 239)

Although urbanization reduces the infiltration spatially, by collecting the stormwater runoff, it boosts the potential for infiltration at selected sites (Lerner, 1990). Instead of rapidly removing this increased volume of water from a catchment, once collected and concentrated it can be transferred to the most suitable site and artificially recharged into the aquifer. Urban stormwater therefore offers a readily available source of substantial volumes of water for recharge.

2.2.2 Stormwater quality

Apart from peak flows, urbanization also affects the stormwater runoff quality. The high concentration of population, commerce and industry in urban areas results in large scale production of waste material and pollutants. Precipitation and the resultant runoff loosen, suspend and then transport the pollutants within the stormwater discharge. Thus although stormwater is not a pollutant, it serves as a vector for the pollutants. The range of pollutants may vary greatly and includes those demanding oxygen, nutrients, solids fractions, heavy metals, bacteria, hydrocarbons and pesticides (Weatherbe & Novak, 1977). Research in North America has indicated that approximately half of the 129 listed U S Environmental Protection Agencies priority pollutants have been detected in urban stormwater runoff. These include a number of mutagenic substances with a potential for entering the biological food chain (Field, 1985).

Not only is urban stormwater runoff capable of containing a wide range of pollutants, but it is also known to have high concentrations of these pollutants. For example, Cordery (1977) found that in comparison with raw sewage, the stormwater from a sandy urban catchment in Sydney contained the equivalent of 60% of the suspended solids, 7% of the BOD, 19% of the phosphate and 5% of the ammonia. The fact that raw sewage is treated, whereas stormwater is not, can therefore often mean that stormwater is more polluted than treated sewage effluent. Similar results have been obtained by Field & Fan (1981), Field & Turkeltaub (1981) and Gutteridge *et al.*, (1981). Both Weatherbe & Novak (1977) and Qureshi & Dutka (1979) have shown that microbiologically, stormwater runoff may be more contaminated than dilute raw sewage. A recent study along the False Bay coastline has shown that urban stormwater outfalls contribute far greater microbiological pollution than the sewage effluent outfalls originating in the same urban area (Augoustinos & Kfir, 1990).

The pollution potential of stormwater runoff is not just by way of the high concentration of specific pollutants/constituents but also from the resultant effect caused by the interaction between different constituents. An example is the detrimental effect which increased concentrations of heavy metals have on the decomposition of organic matter. Heavy metals are a form of toxicity to the bacteria and reduce their decomposition activities. The large volumes discharged by stormwater systems also result in a shock loading effect in the receiving water body.

The concentration of pollutants may be relatively consistent during baseflow conditions but varies dramatically during storm events (rainfall event). At the beginning of a storm event those pollutant particles lying loose on impervious surfaces are quickly suspended and transported by the incipient overland flow. This results in a "first flush" effect when the volume of stormwater is still relatively minimal but the concentration of pollutants is very high. The concentration then decreases until the peak flows resulting from the storm event scour/remove the compacted particles in the catchment (Mance & Harman, 1978; Hoffman *et al.*, 1982; Simpson, 1986; Hvitved-Jacobson *et al.*, 1987). An Australian study by Cordery (1977) suggested that most of the pollution is removed from the catchment by the first 10 to 20 mm of rain, provided fairly high intensities occur. Continued rain there after removes only minor amounts of pollutants.

These findings suggest a relationship between pollutant load and the antecedent dry period. One school of thought (Sartor *et al.*, 1974; Weatherbe & Novak, 1977; Randall, *et al.*, 1978; Urbonas & Tucket, 1980; Colwill *et al.*, 1984; Simpson, 1986) believes that pollutant build-up on land surfaces and the subsequent washing off of these pollutants is related in some way to the duration of the dry period preceding the storm event. Another school (Whipple, *et al.*, 1977; Mance & Harman, 1978; Bedient *et al.*, 1980) believes the length of the antecedent dry period and the magnitude of the previous storm event have little effect on the mass of pollutants discharged. It is rather the characteristics of the current storm event that has a dominant influence. Barkdoll *et al.*, (1977) suggest that the similarity in shape between hydrographs and pollutographs indicates that flow is the dominant factor influencing pollution loads.

The presence of the first flush effect has been well established by urban hydrologists. Helsel *et al.*, (1979) for example, found that in the United States 90% of all storm events analysed in commercial catchments showed a first flush effect, with a 80% rate for residential catchments. The first flush does not however necessarily include all pollutants. Microbial populations in fact do not reflect a first flush effect, but rather increase with flows and then remain at high concentrations for long periods after the flow has once again subsided (Qureshi & Dutka, 1979; Wright, 1990).

2.2.3 Pollution sources

The source of pollutants carried by stormwater runoff may be either specific - a point source - or diffuse - a non-point source. A survey undertaken by Wanielista (1979) indicated that 80% of the time urban stormwater quality is determined by non-point source pollution. Simpson (1986) grouped the sources into three main categories, namely, atmospheric fallout, erosion of the catchment, and materials imported from outside the catchment.

The atmosphere acts as a pollutant source both as dry weather fall out and rainfall washout. Simpson & Hemens (1978) ascribed 51% of the suspended solids, 35% of the phosphorus, 80% of the nitrogen and 43% of the lead found in stormwater runoff in a Natal urban catchment to atmospheric deposition. Other studies by Halverson *et al.* (1984), Ebbert & Wagner (1987) and Ng (1987) have confirmed that precipitation is a source of both nitrogen and phosphorus, while Green *et al.* (1986) found a strong correlation between lightning activity and nitrate levels. These studies established that most atmospheric pollutants are washed out at the beginning of rainfall events and thus the amount of rain and intensity thereof, has little bearing on the amount of pollution.

Research in both the United Kingdom (Ellis & Dochinger, 1978) and the United States (Randal *et al.*, 1978; Gutteridge *et al.*, 1981) found that although the source of atmospheric pollutants may be site specific, the fallout/washout is relatively uniform over metropolitan areas. Heaney and Sullivan (1971) estimated that approximately 70% of the material found on street surfaces in Chicago could be attributed to atmospheric fallout.

The role of motor vehicles as a source of pollutants has been well established (Bardoll *et al.*, 1977; Goettle, 1978). Exhaust emissions contribute lead to atmospheric fallout, while wear-products that collect on the road surface contribute both metals and hydrocarbons (Wigington *et al.*, 1983). The importance of vehicle omission to atmospheric fallout was demonstrated in a West German town by Goettle (1978). All traffic was prohibited for a period of days and it resulted in an 85% reduction in concentrations of lead, carbon monoxide and nitrous oxides. Much of the pollution found on roads is of a fine nature and almost 90% is found within 0.3 metres of the kerb (Gutteridge *et al.*, 1981). It is these pollutants found near the kerb in catchpits of the road drainage system that contribute to the first flush effect (Mance & Harman, 1978).

The landuse practised in a catchment is important as it not only affects the erosion potential, but also determines the types of materials imported into the catchment. The pollution loads from industrial and commercial catchments appear to produce the greatest concentrations of pollutants (Overton & Meadows, 1976; Polls & Lanyon, 1980; Gutteridge *et al.*, 1981). Industry serves as a major polluter by way of leaching from open stockpiles of raw materials, finished products and process wastes; accidental spillage and leakage; and illegal flushing. The pollutants include oils, lubricants, toxic material and heavy metals. Commercial areas generally have the highest degree of imperviousness and produce pollutants such as lead, rubber compounds, oil and suspended solids.

Residential catchments are largely responsible for providing organics, bacteria and nutrients to the stormwater runoff. These originate from litter, plant material, and human and animal excreta. The most important organic elements are carbon, hydrogen, oxygen and nitrogen which through the action of aerobic bacteria produce carbon dioxide, water and nitrate. The process depletes the stormwater oxygen content and provides energy for increased bacterial growth (Overton & Meadows, 1976). Nutrients such as nitrogen and phosphorus which cause eutrophication in the receiving water body also originate from fertilizers used in gardens, parks and sport fields. Pesticides are another major pollutant which originate from gardening practices.

Gutteridge *et al.* (1981) found that there appears to be no difference between old and newly developed residential catchments, but rather that the quantities of pollutants produced vary according to the economic standard of the suburb. These findings are a confirmation of a study by Charachlis *et al.* (1978) which found that a low income suburb in Houston produced substantially more pollution than an adjacent middle class suburb. What is important is whether new construction is taking place in a catchment. Ellis (1976) found that in catchments where construction is taking place or soil erosion is rife, the suspended sediment contains substantial clay which acts as excellent sorbents for trace metals. Suspended solids such as concrete, ash, brick and aggregate components are also highly absorbent and may pick up aerosol metal ions, oil, grease and detergents and accumulate them in benthal sludges.

There are thus numerous diffuse pollution sources in an urban catchment other than the obvious point sources. All the sources ultimately contribute to the accumulation of pollutants on the catchment surface from where they are removed by the first flush of stormwater. Unlike point sources this type of pollution is difficult to control especially in developing nations where standards are often primitive in comparison to the highly developed nations of Europe and North America.

2.2.4 *Stormwater purification*

The polluted nature of urban stormwater runoff emphasises the need for its treatment. Unfortunately the large volumes of runoff during storms make it economically unrealistic to treat stormwater. One method of reducing the pollution load other than isolating the point sources and perhaps implementing more frequent sweeping of the streets, is by allowing the pollutants to settle out in detention basins. A study by Martin & Millar (1987) showed that during periods of baseflow, a detention basin reduced suspended constituent loads by the settling out of the heavier suspended particles. The pond reduced many of the metals and nutrients, but proved inefficient with the major ions. During stormevents the turbulent inlet discharge was found to scour the pond bottom, resuspending bottom sediment and so reducing pond efficiency. It has been further shown by Hvitved-Jacobsen *et al.* (1987) that best results are obtained with detention basins that contain reeds and rushes. Research in the United Kingdom has shown that reed bed treatment systems reduce BOD and suspended solids concentrations, but are ineffectual in the removal of nitrogen species and phosphate (Cooper *et al.* 1990). Although Green *et al.* (1986) warn of the potential pollution risk when placing highly polluted stormwater runoff in detention basins in the urban environment, it remains the most practical method of reducing pollution loads in stormwater runoff.

2.3 The Process of Artificial Recharge

The artificial recharge of the groundwater by means of infiltration/spreading basins appears fairly straightforward. Any surplus water is merely put into a basin and allowed to infiltrate into the unconfined aquifer. In reality the process involves many complex hydraulic and chemical processes that, if not fully understood and monitored, can result in both the pollution of the aquifer and over utilization of the groundwater resource. Artificial recharge schemes are therefore thoroughly researched and carefully monitored to ensure that they always meet the set requirements. A set of basic guidelines for the establishment of an artificial recharge scheme are provided in Appendix A.

2.3.1 The groundwater mound

The recharge process involves the growth of a groundwater mound beneath the spreading basin. The areal extent of the mound and its rate of growth depends on a number of factors.

a) The stratigraphic configuration of the subsurface formations may lead to perched water tables which could cause early saturation and reduced infiltration rates. In most cases the reason for retarded infiltration is located at surface level. Where there is a semi-pervious soil layer or clogged layer at the surface underlain by a more pervious layer, there will be little to no saturation and positive pressures above the water table, where the movement of water will characteristically be vertical. If the profile above the water table is at field capacity, then slightly less water than the storage coefficient has to be added before a steady flow to the aquifer can be established. At the Ghazvin Project in Iran it was found that about 5% (by volume) of moisture had to be added to the unsaturated layers before steady flow to the underlying aquifer began (Berend, 1970).

If the semi-pervious layer is at some depth below the surface but above the aquifer, then the uppermost layers may become saturated with unsaturated conditions occurring below the semi-pervious layer. Near the centre of the basin, the flow will be nearly vertical and one-dimensional, whereas near to the edge, there will be significant lateral flow which will increase the area of the limiting layer involved in this infiltration process (Figure 5).

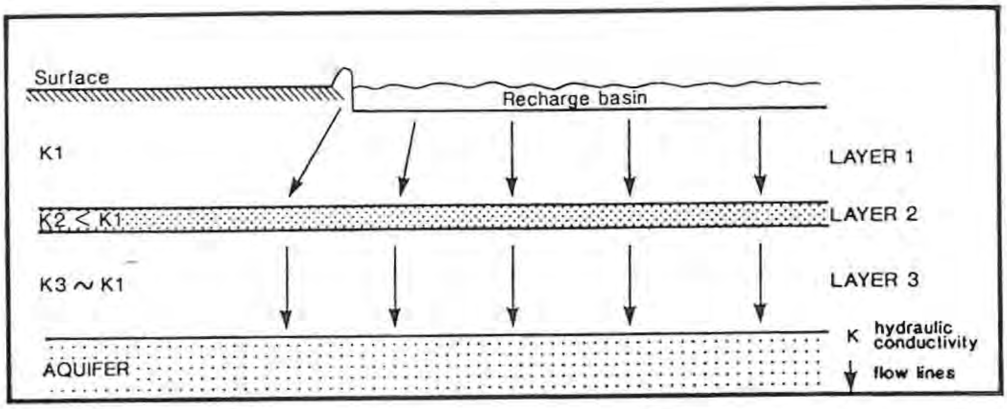


Figure 5 Percolation through an Underground Limiting Layer
(after Berend, 1970)

Changes in the recharge basin water level will have very little effect on the seepage rate per unit area of the limiting layer but may drastically change the flooded area of the limiting layer and so the total seepage discharge. The relative share of lateral flow will increase as the flooded surface of the recharge basin decreases. The phreatic level of the horizontal seepage wedge will be virtually a straight line and its position can be predicted if the layers and hydraulic conductivities are known (Berend, 1970).

Mathematical models for determining the dimensions of the groundwater mound have been produced by a number of researchers (Bouwer, 1962; Hantush, 1967; Marino, 1975) but all have limitations. The models neglect unsaturated flow, utilize the Dupuit-Forchheimer theory of unconfined flow, and assume a recharge rate that is constant in time and space. Rubin (1968) and Jeppsan & Nelson (1970) provided a more accurate approach by considering the complete saturated-unsaturated system, but by doing so, vastly increased the complexity of the calculations. Unfortunately, practical research has shown that much of the theoretic analysis has little relevance in real situations (Freeze and Cherry, 1979).

b) The distance between the initial groundwater table and basin floor should ideally be at least 3 metres to permit longer periods of infiltration and slower development of fully saturated and anaerobic conditions (Berend, 1970; AWRC, 1982). This is not as important if there is high horizontal hydraulic conductivity which allows more rapid lateral flow and thus a lower mounding level. The water table in the surrounding area should not be allowed to rise to within 1.5 metres of the surface as this could result in water loss by evaporation and increased salinity in the soil. If the surrounding area is of low lying topography it may allow partially "treated" recharge water to escape from the system and flow as surface water towards the production boreholes (AWRC, 1982).

c) The aquifer (saturated zone) thickness, porosity and areal extent determine the available storage capacity and the retention time. The aquifer should be such that the system can both store and transmit all the recharged water. It is the porosity and hydraulic conductivity of the aquifer that influence the rate of movement and therefore the retention time of the water.

As water is recharged, so the mound develops until a boundary is reached. This boundary is either a lateral control (horizontal direction) or a potential control (vertical direction). If there is no lateral control and a potential control is reached, then the height of the mound remains constant and spreading in a horizontal direction theoretically becomes infinite (Blair, 1970). If the lateral control is a discharge point, then discharge begins and increases until flow equals that of the inflow of the basin and natural groundwater flow. If the lateral control is an impermeable boundary, it will result in a "damming" effect.

Dispersion, that is the mixing and spreading of the recharged water, is caused by velocity variations within the media pores and by molecular diffusion. Diffusion is defined by Freeze and Cherry (1979) as the process whereby ionic or molecular constituents move under the influence of their kinetic activity in the direction of their concentration gradient. It does not require any bulk hydraulic movement of the solution. Diffusion only stops when concentration gradients disappear. When the infiltration rate is relatively high, the major mechanism is mechanical dispersion or spreading and molecular diffusion is negligible.

The porosity not only controls the velocity of movement and volume of water that infiltrates, but also the volume of air available for oxidation. The greater the porosity the greater the treatment potential. Gas accumulation in the sands was also found to be responsible for decreasing the infiltration capacity at the Veluwe artificial recharge scheme in the Netherlands (Zoeteman *et al.*, 1975). The gas accumulation was caused by small differences in temperature and a pressure drop just under the infiltration surface in combination with oversaturation of the water with air.

d) The management of the recharge basin obviously plays an important role in determining the infiltration rate. If the optimum water depth is not maintained it can lead to a decrease in the amount of water recharged. Although increased water depth in the basin results in greater hydraulic head and higher infiltration rates (Espina, 1980) it can result in increased hydraulic impedance of the clogging layer on the basin floor. If the water depth is too shallow, any wave action in the basin may stir up the sediment on the basin floor and seal pores which would otherwise remain open. The shallow water can also result in increased evaporation with a resultant increase in salt concentrations. This is especially true for hot dry climates such as is experienced in Southern Africa.

2.3.2 *Clogging*

Clogging of the soil/sand beneath the recharge basin affects both the rate of infiltration and the quality of the infiltrating water. Clogging occurs both on the surface of the basin floor and at depth and is caused by physical processes, biological reactions and chemical reactions. Most surface water has algae growing in it if the water is stagnant. The algal growth can with time result in a reduction in the influence of the sun on the water and on drying will form an algal mat on the basin floor. The amount of growth in the recharge basin depends largely on the concentration and total input of plant nutrients such as phosphorus compounds (Zoeteman *et al.*, 1975). Although visually important this form of clogging is not a major problem as when the basin refills, so the dry algal mat once more becomes buoyant (Blair, 1970).

The major form of physical clogging is due to the deposition and filtering of suspended solids. Suspended matter in the recharge basin settles out to either form an impervious clay film on the basin floor or blocks the soil/sand pores (Blair, 1970; Bouwer & Chaney, 1974). Initially only the larger suspended solids are trapped but as these form a restriction in the "pore neck", so finer particles are held back until a clogged layer develops. If the restricting layer is not compacted and biological clogging does not take place, the resistance should increase in proportion to the suspended solids added (Rice, 1974). The initial soil texture is important as a well sorted soil allows deeper penetration before physical clogging takes place. Furthermore, Bouwer and Chaney (1974) found that recharge water with a high sodium content tends to deflocculate colloidal soil particles and thereby hinder water passage.

Clogging due to suspended matter also occurs at depth. Both attractive molecular forces and repulsive electrostatic forces exist between the grains of sand and suspended particles as the water infiltrates down. The higher the concentration of suspended particles, the lower the repulsive forces. The attraction of suspended particles onto the grains, forms domes on top of the grains, thus enlarging the surface area with little increased restriction to flow. At the same time larger particles are bridging over the gaps and trap other particles. As deposition continues the flow paths between grains are straightened and reduced in size so particles are now swept through without adhering to the grains. The "straining efficiency" thus decreases and suspended material may be transferred to greater depths where it can cause clogging (Blair, 1970).

Berend (1970) suggests that although the deposition/settling of suspended material is important, it is filtering which is the more effective process, per unit amount of suspended matter, in sealing the basin floor. Once a restricting layer has been formed it automatically initiates filtering, especially if compaction takes place. This is especially true in the more porous sandy terrains. All matter larger than the soil pore size become trapped in the filter mat and active colonies of predatory micro-organisms and bacteria develop. These result in most of the bacteria and micro-organisms being removed in the upper 1 to 2 metres of soil (Hofkes and Visscher, 1986). This growth of bacterial flora within the upper filter zone of the basin floor is far more important than visual algal growth on the surface. The bacteria activity provides an additional cleaning process which eliminates much of the suspended organic matter contained in the infiltrating water. The development of the micro-organisms does, however, lead to clogging of the strata. So as more biological clogging takes place, so the filtration capacity increases and smaller and smaller particles are captured, thus decreasing the absorption capacity.

A further process is chemical clogging caused by decreasing permeability as a result of the chemical interaction between dissolved chemical constituents and compounds in the water and the soil/sand which results in a decrease in pore size. The interaction may cause the precipitation of calcium carbonate, other calcium and magnesium salts, and ferric or manganic compounds (Blair, 1970; Rice, 1974). In some waters the presence of algae can result in the precipitation of calcium carbonate while bacteria can cause the precipitation of iron salts (Fetter and Holzmacher, 1974). If clays are present these may swell as a result of ion exchange (Blair, 1970; AWRC, 1982). Chemical clogging becomes especially significant when the recharge water has a high sodium concentration.

Research has indicted that it is advisable to follow a management strategy of allowing the basin to dry out after recharge cycles (Berend, 1970; Blair, 1970; Bouwer & Chaney, 1974; Espina, 1980; Crook *et al.*, 1990). The periodic drying of the basin floor effectively restores the infiltration rate by causing the decomposition of the clogged layer. The basin should be allowed to dry naturally with minimal mechanical cleaning as this can lead to compaction and the creation of an impervious layer just below the depth of treatment. The wet/dry cycles also provide a management tool for controlling the growth of the groundwater mound and conditions in the unsaturated zone.

There is no hard and fast rule on the ideal length of wet and dry cycles. At an artificial recharge operation near Newman, Western Australia, Foo *et al.* (1989) found that by operating in a wet - dry mode it resulted in higher infiltration rates for only a few days. Although extended dry periods were expected to reduce the regional water table it was not enough to significantly improve recharge rates. The slight gain in the initial recharge period was more than offset by losses from storage due to evaporation. When continuous recharge was practised it led to a greater degree of clogging but this was overcome by lightly scraping the basin floor. This contrasts with Montebello Forebay in Los Angeles County where it was found the 21-day cycles were most effective (Crook *et al.*, 1990).

Blair (1970) provides a rough guide to the absorption capacity of a basin, that is, the volume of water absorbed per unit of surface area in a given time:

coarse textured soil = 0.6 - 4.0 m^3/m^2/day,
medium textured soil = 0.6 - 1.3 m^3/m^2/day,
fine textured soil = < 0.4 m^3/m^2/day/.

The oxygen which enters the pore spaces during the dry cycle does so by means of diffusion and mass flow. Mass flow may account for as much as 40 % of the entering oxygen. Lance *et al.* (1973) found that at Flushing Meadows in California most of the oxygen entered within 3 days of recharge being stopped. This suggests that dry cycles should not necessarily be lengthy but rather more frequent.

A certain degree of clogging of the soil/sand beneath a recharge basin is unavoidable and is to some extent, advantageous for the filtering effect it has. Careful management is required in order to obtain the best compromise between infiltration and filtration. The wet/dry recharge cycles provide a valuable tool towards obtaining this management objective, but have to be adapted for each specific site.

2.3.3 *Physical and chemical water quality changes during filtration*

An infiltration basin is in many ways similar in operation to a slow sand filter, but without a piped under-drain. Bianchi (1970's) believes that undisturbed sand is a far more efficient filter than any sand filtration system. Natural sands have a certain amount of clay and cementing agents, which are the products of weathering and biodegradation of vegetation, which produces varying degrees of intergrain-bonding and thus greatly increases the sands adsorptive properties. This increases a natural sands filtering capacity and efficiency over that of a washed sand. The smaller grain size also enhances mechanical filtering.

The artificial recharge process is thus not only a case of "topping up the groundwater reservoir" but also one of water purification. Artificial recharge schemes in Holland have shown that the condition of the soil beneath the basin is the single most important factor influencing water quality changes in the infiltrating water. The presence of peat, for example, increases the content of organic constituents, phosphate and ammonia (Haasnoot & Leeflang, 1970). The amount of clay present in the soil determines both the cation exchange capacity and the adsorptive capacity (Schmidt & Clements, 1977). The purification/change in water quality takes place by means of a number of processes, namely, filtration, dilution, physico-chemical and biological processes. These are often inter-dependent and it is thus difficult to study each process in isolation. The processes take place in the recharge basin, at the basin surface, in the unsaturated zone and in the saturated zone. The unsaturated zone is the most important area with regard to purification of infiltrating water (AWRC, 1982; Hofkes & Visscher, 1986).

Filtration actions are responsible for removing the majority of the suspended material. This leads to an improvement in water quality but a reduction in intrinsic permeability and reduced infiltration rates (discussed in section 2.2.3). Very small algae tend to penetrate into a porous basin floor whereas larger algae and bacteria tend to form a surface mat. This surface mat in turn tends to strain out other suspended solids thus increasing the surface mat and decreasing infiltration rates. Filtration is considered the major process whereby micro-organisms and particulate organic materials are removed (Millar & Blair, 1970; Chang & Page, 1979; Roberts, 1980; Hofkes & Wisscher, 1986).

Biological activity within the filter mat adds to the degradation of organic material and is responsible for reducing the smell and improving the taste of infiltrating poor quality water (Winquist & Marelius, 1970). The finer bacteria that pass through the filter mat results in a build-up below the surface. The survival of the bacteria in the subsurface environment is influenced by soil moisture content, temperature, pH and availability of nutrients and oxygen (Gerba *et al.*, 1975). It has been shown that bacteria die-off occurs very rapidly after infiltration and generally occurs in the upper 1 to 2 metres (Blair, 1970; Winquist & Marelius, 1970; AWRC, 1982; Hofkes & Visscher, 1986). Where micro-organisms have been found to move over distances, the movement has been associated with macropores as found in gravels, coarse textured soils, structured clay soils, fractured rock and limestones. Tredoux *et al.* (1980) found that in some sands *E.Coli I* survived for distances of up to 27 metres. Although quickly retained once beneath the surface, the micro-organisms do not immediately die-off but continue to multiply during the acclimatization period (Bouwer & Chaney, 1974; Idelovitch *et al.*, 1980).

During the biological degradation of the organic material in the filter mat, amounts of oxygen are consumed and this results in the liberation of carbon dioxide. Diurnal variations are important as the biogenic production of oxygen depends on the intensity of light (Frank, 1970). The presence of oxygen is very important for soil bacteria to be able to play an active purifying role in the unsaturated zone. At depths of 1 m all the available oxygen may be exhausted resulting in an increase in dissolved carbon dioxide (Blair, 1970). Hydrogen transfer is the essential reaction in bacterial metabolism and dehydrogenation may occur with O_2 (oxidation), NO_3^- (denitrification), SO_4^{2-} (sulphate reduction) and CO_2 (methane fermentation). If the organic material penetrates down to depths where there is no free oxygen, the nitrates may assume the role of hydrogen acceptors (Baars, 1957; Roberts, 1980). It is desirable for total die-off to be achieved in the unsaturated zone as once the bacteria has gained entrance to the aquifer (saturated zone) the survival distance is vastly increased.

The fate of viruses remains an unknown factor. Some viruses do get removed in the biomass by phagocytes and also become adsorbed or exchanged on clays and minerals. The probability of removal improves with decreasing pH and increasing TDS (Drewry & Liassen, 1968; AWRC, 1982). Other factors influencing the removal of viruses include soil texture, type of virus, infiltration rate and presence of organic matter (Gerba *et al.*, 1975; Jansons *et al.*, 1989). It is, however, still uncertain whether the fixation by adsorption and exchange is permanent as these reactions are reversible if conditions are changed (i.e. the ionic environment). Hurst *et al.* (1980) goes as far as to suggest that soils with a high virus adsorption capacity favour virus survival.

A study by Bouwer *et al.* (1974) at Flushing Meadows, indicated that calcareous sands could remove all viruses after a passage of only 0.25 m. Studies such as that by Fildier (1983), as summarized in Table 1, suggest that a retention time of six months is adequate for a reasonable safety margin for both bacteria and viruses.

Table 1 Survival time for pathogenic bacteria and viruses in underground formations

Bacteria/Viruses/Parasites	Survival Time
Faecal coliforms	6 days
Entamoeba histolytica	8 days
Entero virus	12 days
Cyst of *Ascaris*	6 months

From Fildier (1983)

The removal of nitrogen during infiltration illustrates the importance of oxygen, the interrelationship between the processes and the management potential which the processes provide. Nitrogen is found most abundantly in the nitrate and ammonium form in recharge water. When the recharge water begins to infiltrate the ammonium ions are adsorbed by the soil, while nitrate ions in the soil are denitrified and leached by the infiltrating water. The extent to which ammonium ions are adsorbed to the soil depends on the soil type and composition and on the concentration of ammonium ions and other cations (Ho *et al.*, 1981). When infiltration ceases, the adsorbed ammonium ions are nitrified to nitrate ions. It has been established (Cochet *et al.*, 1990) that almost all the ammonium discharged into the soil system can be biologically oxidized to nitrate within a few centimetres of travel through an aerobic unit.

The nitrification and denitrification processes are carried out by micro-organisms and suitable conditions must prevail for their existence and growth. If high levels of NH_4 are present, it may result in the nitrification process being stopped at the nitrate stage, while the micro-organisms are unable to function at temperatures below 5.5°C and above 40.5°C (Cochet *et al.*, 1990). As the dissolved oxygen content of the infiltrating water decreases due to oxidation processes, so conditions become more favourable for denitrification. The longer the anaerobic conditions persist, the greater the degree of denitrification. The corresponding decrease in infiltration and leaching results in larger numbers of ions remaining in the soil occupying adsorption sites and in so doing reducing the adsorption capacity available for the next period of recharge (Ho *et al.*, 1981). This illustrates the necessity of advocating a wetting/drying recharge strategy as it allows for the alternating flow of water and air into the pores of the soil, and so ensuring completion of the nitrogen removal process. Both nitrification and denitrification may thus be achieved in the same profile.

Thus by way of careful recharge management, water with high nitrogen concentrations, such as treated sewage effluent (where ammonium is the most common form of nitrogen), may be effectively purified (Blair, 1970; Bouwer *et al.*, 1974; Bouwer, 1976; Lance & Whisler, 1976). During prolonged recharge all the free oxygen in the sands pore spaces is used up due to nitrogenous and carbonaceous oxygen demand. The organic nitrogen in the water can then not be converted and remains in the ammonium form. The ammonium ions are adsorbed to the cation exchange complex clay and organic matter. Just before the cation exchange complex is saturated with ammonium, the recharge is stopped. This once again allows oxygen into the soil and allows the absorbed ammonium to be converted to nitrate by nitrifying bacteria. That water which has infiltrated deeper into the anaerobic zone, is denitrified to give nitrogen gas and oxides of nitrogen which are lost to the atmosphere. That nitrate which is not denitrified, is leached/flushed out by the new pulse of infiltrating recharge water and produces a nitrate peak which enters the aquifer. If insufficient oxygen enters the soil between recharge periods, it will not result in total nitrification of the ammonium. This will mean reduced adsorption of ammonium during the next recharge period and higher concentrations of ammonium in the recharge water reaching the aquifer. The following equations represent the full sequence of events:

Aerobic conditions	Ammonification:	organic nitrogen $\rightarrow NH_3 \rightarrow NH_4$
	Nitrification:	$NH_3 + 3O \rightarrow HNO_2 + H_2O$
		$HNO_2 + O \rightarrow HNO_3$
Nearly anaerobic	Denitrification:	$8H + HNO_3 \rightarrow NH_3 + 3H_2O$
Anaerobic conditions	Denitrification:	$1OH + 2HNO_3 \rightarrow N_2 + 6H_2O$

Dissolved constituents in the infiltrating water may in fact be immobilised by a number of chemical processes such as, cation exchange, precipitation and adsorption, oxidation, complexation and chelation (Chang & Page, 1979). Cation exchange is the most predominant exchange reaction, with the most important being those involving monovalent and divalent cations such as Na^+- Ca^{2+}, Na^+- Mg^{2+},K^+- Ca^{2+} and K^+- Mg^{2+}. The differing hydrated radii of ions such as Na^+ and Ca^{2+} means that the replacement of Ca^{2+} with two Na^+ ions causes an increase in crystal lattice size and thus a decease in permeability (Freeze & Cherry, 1979). The cation exchange reactions are fairly easily reversible.

Adsorption and precipitation reactions are difficult to distinguish and appear more effective with trace organic substances, trace metals and phosphorus compounds. Anions such as carbonate, hydroxide, sulphite and phosphate may form rather insoluble compounds with trace metals, which once precipitated may be removed by filtration. The covalent bonding-induced adsorption is a reaction which is not easily reversible. The most likely site for organic constituents to be adsorbed to is positively charged edges of clay minerals. The adsorbed organic compounds may then be removed by microbial decomposition as well as by chemical and photochemical decomposition and volatilization (Chang & Page, 1979).

Adsorption and precipitation are the main mechanisms for the removal of phosphorus and fluorides. Phosphorus which occurs as ortho-phosphate can be almost completely removed under suitable conditions. In acidic soils the phosphate is adsorbed by iron and aluminium oxides, while in calcareous sands it is removed by the precipitation of calcium phosphate compounds (AWRC, 1982). Fluoride is adsorbed to a number of components, but especially to hydrous aluminium oxides, and may be precipitated as fluoroapatite and fluorite.

Although the fixation on to clay minerals may take place during the recharge phase, it is only after oxygenation during the drying out phase that the fixations become permanent. Calcite, limonite, clay and silica coatings on grains or cement are responsible for much of the heavy metal fixation (AWRC, 1982). The amount of clay in the sand not only determines the cation exchange capacity, but also the adsorptive capacity. Clay-loam or sandy-loam soils are thus ideal for recharge as they combine good treatment capacity due to the clay content and have acceptable infiltration rates.

The final phase in the recharge process is the mixing and dilution of the recharge water with the groundwater in the saturated zone (aquifer). If the volume of recharged water is small in comparison to the regional groundwater flow, then the quality requirements of the recharge water may be relaxed as it will be diluted by the groundwater. The groundwater quality determines the norm against which possible contamination levels are measured. Schmidt and Clements (1977) warn that mixing should not be taken for granted as groundwater flow is generally of a laminar nature and thus not conducive to mixing and diffusion of the artificially recharged water.

2.4 A conceptual model

The discussion in the preceding sections has emphasised the fact that artifical recharge by means of spreading involves a compromise between obtaining maximum infiltration and maximum water purification. The success of artificial recharge thus depends on the correct physical characteristics of the site, the correct quality recharge water, and sound recharge management procedures. Seldom is it possible in real life to achieve the perfect compromise.

If, however, all these conditions could be met in a homogeneous unconfined aquifer, the infiltration process should appear as illustrated in Figure 6.

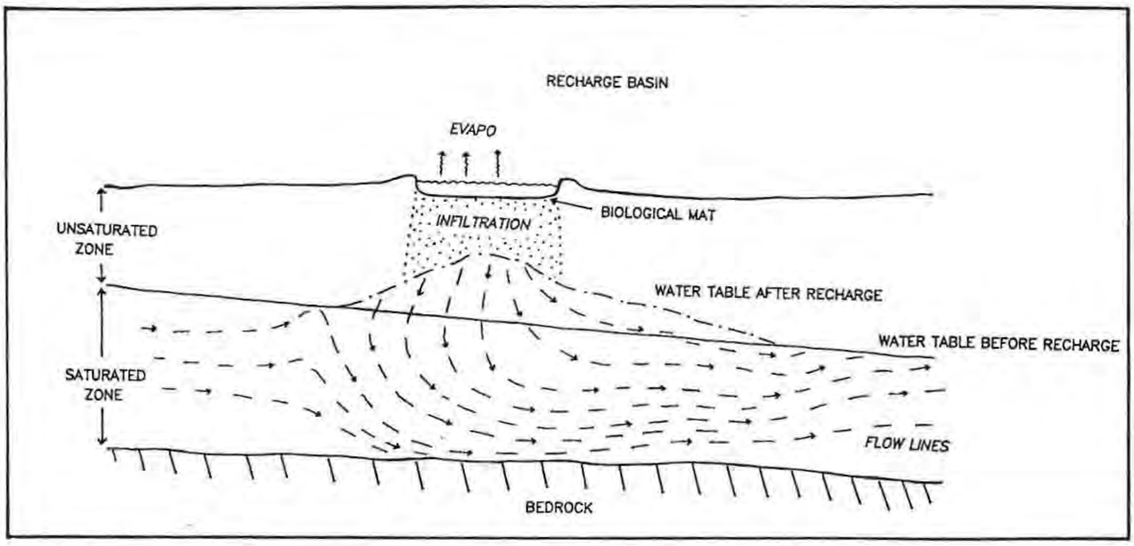


Figure 6 Schematic cross-section showing infiltration into a homogeneous aquifer

The infiltration is vertical with the groundwater mound never rising to within 1.5 m from the surface. Once the infiltration water reaches the saturated zone it mixes with the natural groundwater in the aquifer and with distance down gradient from the basin becomes completely dispersed. The water in the basin is maintained at such a level as to minimize evaporation and a possible resultant increase in salts in the water. The hydraulic gradient allows for the maximum transfer of water to the extraction point (well field). The expected water quality changes due to infiltration through the unsaturated zone are:

- TOTAL DISSOLVED SOLIDS (TDS)
  The concentration of TDS will probably increase due to some evaporation in the basin and as a result of ion exchange and mineral hydrolysis in the subsurface;

- SODIUM
  Sodium concentrations could increase (or decrease) due to ion exchange processes. It generally increases due to calcium and potassium exchange for sodium;

- POTASSIUM

  Potassium concentrations will be reduced by ion exchange processes and adsorption to clay material if present;

- CALCIUM

  Calcium concentrations normally decrease, but may increase as a result of ion exchange and due to dissolution if the pH of the water is low;

- MAGNESIUM

  Magnesium concentrations will probably decrease and only increase if the recharged water is sodium rich;

- SULPHATES

  Sulphate concentrations may be reduced by biological action to sulphides including hydrogensulphide, where highly anaerobic conditions prevail. Additional sulphate may be released through the oxidation of iron sulphide if oxygen is available and through precipitation as gypsum;

- CHLORIDE

  Chloride is not removed during infiltration and thus serves as a means of tracing recharged water in the subsurface environment provided the background groundwater chloride concentration is sufficiently different;

- AMMONIA NITROGEN

  Ammonia and organic forms of nitrogen are initially removed by adsorption and ion exchange processes before being converted to nitrate during periods of aerobic conditions. Thus under ideal recharge conditions, ammonia is completely depleted;

- NITRATE

  Nitrate concentrations may be reduced by as much as 50 to 60%, although total denitrification has been found to occur. Nitrate is normally removed in the unsaturated zone;

- PHOSPHORUS

  Phosphorus in the form of orthophosphate can be almost totally removed from the recharged water. In acid soils the phosphate is removed by adsorption and in calcareous sands/soils by precipitation. The removal is non-reversible and dependent on the soil texture, cation exchange capacity and calcium content;

- FLUORIDE

  Fluoride concentrations may be reduced by the process of precipitation;

- BORON

  Boron may be reduced through the process of adsorption but remains unaffected in sandy and gravely soils;

- IRON AND MANGANESE

  Both iron and manganese concentrations may increase as they are dissolved from the soil matrix. Alkaline soils and aerobic conditions counter this process. Iron may also precipitate on the basin floor;

- HEAVY METALS

  Heavy metals may be removed under aerobic and alkaline conditions by the precipitation of oxides and by co-precipitation. This removal may however, only be temporary;

- COLOUR, TURBIDITY AND SUSPENDED SOLIDS

  Suspended solids concentration will be reduced by filtering and biological degradation, while colour and turbidity are reduced during the processes of adsorption and biological oxidation;

- BIOCHEMICAL OXYGEN DEMAND (BOD) AND TOTAL ORGANIC CARBON (TOC)

  Both the BOD and TOC will be greatly reduced by the combined action of filtering and biodegradation. Not all organic compounds are, however, removed;

- MICROBIOLOGICAL ORGANISMS

  Filtration and sedimentation greatly reduce the concentration of microbiological organisms with some adsorption taking place at depth. The concentrations may be completely reduced given sufficient retention time;

- VIRUSES

  Viruses are removed by adsorption and exchange processes but are not necessarily inactivated by these processes.

The recharged water will thus be treated by way of filtration; microbiological oxidation and reduction; chemical reaction; adsorption; ion exchange; and dilution to reduce or remove many of the water quality variables. It is, however inevitable that some refractory organics, viruses, and heavy metals and possibly nitrates may enter and remain in the aquifer for unknown periods of time. Chapters 6 and 7 examine how closely the Atlantis artificial recharge scheme fits the conceptual model described in this section.

CHAPTER 3

3. DESCRIPTION OF THE STUDY AREA

3.1 Location

The study area is located within the Atlantis Coastal Aquifer and covers an area of approximately 40 km^2. It includes the Atlantis urban area and that area to the south-east of the north/south Atlantis feeder road (Dassenberg Drive), as far south as the Witzand wellfield (Figure 1). It thus includes all the area directly connected with the urban stormwater runoff and artificial recharge components of the AWRMS (Figure 3). The boundary between the artificial recharge zone and the Witzand wellfield is an arbitrary line which for this study has been taken as the West Coast Road (R27). Although the study area is restricted to a certain portion of the aquifer, it should not be seen in isolation from the remainder of the aquifer.

3.2 Topography and Drainage

The study area traverses the three main topographical features found in the Atlantis area, namely the featureless coastal plains, the interior plateau, and the intermediately stepped "escarpment" zone. The Atlantis urban area is located on a flat interior plateau which varies between 120 and 200 metres above sea level. The natural drainage is in a south-easterly direction towards the Brakkefontein streams (Figure 7). The surface runoff is intermittent and only takes place during significant rainfall events and for very brief periods thereafter. The relief drops dramatically to form a steep slope in the area between Atlantis township and the artificial recharge basin, the recharge basin being situated on the innermost edge of the coastal plain at 60 metres above sea level. The coastal plain consists of low vegetated sand dunes with several natural depressions. The vegetation throughout the study area is coastal fynbos which has been invaded by rooikrans (*Acacia cyclops*).

3.3 Climate

The study area has a Mediterranean climate with a long dry summer and wet winter. Temperatures are relatively moderate with a mean of 23.2°C in summer and 11.8°C in winter. The first major rainfall event occurs in March but the true rainy season only begins in May and ends in early October (Figure 8 and Appendix B). The area experiences approximately 88 rain days per annum and had an annual average of 493 mm for the study period. The cloudless skies and prevailing south-easterly wind during summer result in high evaporation rates.

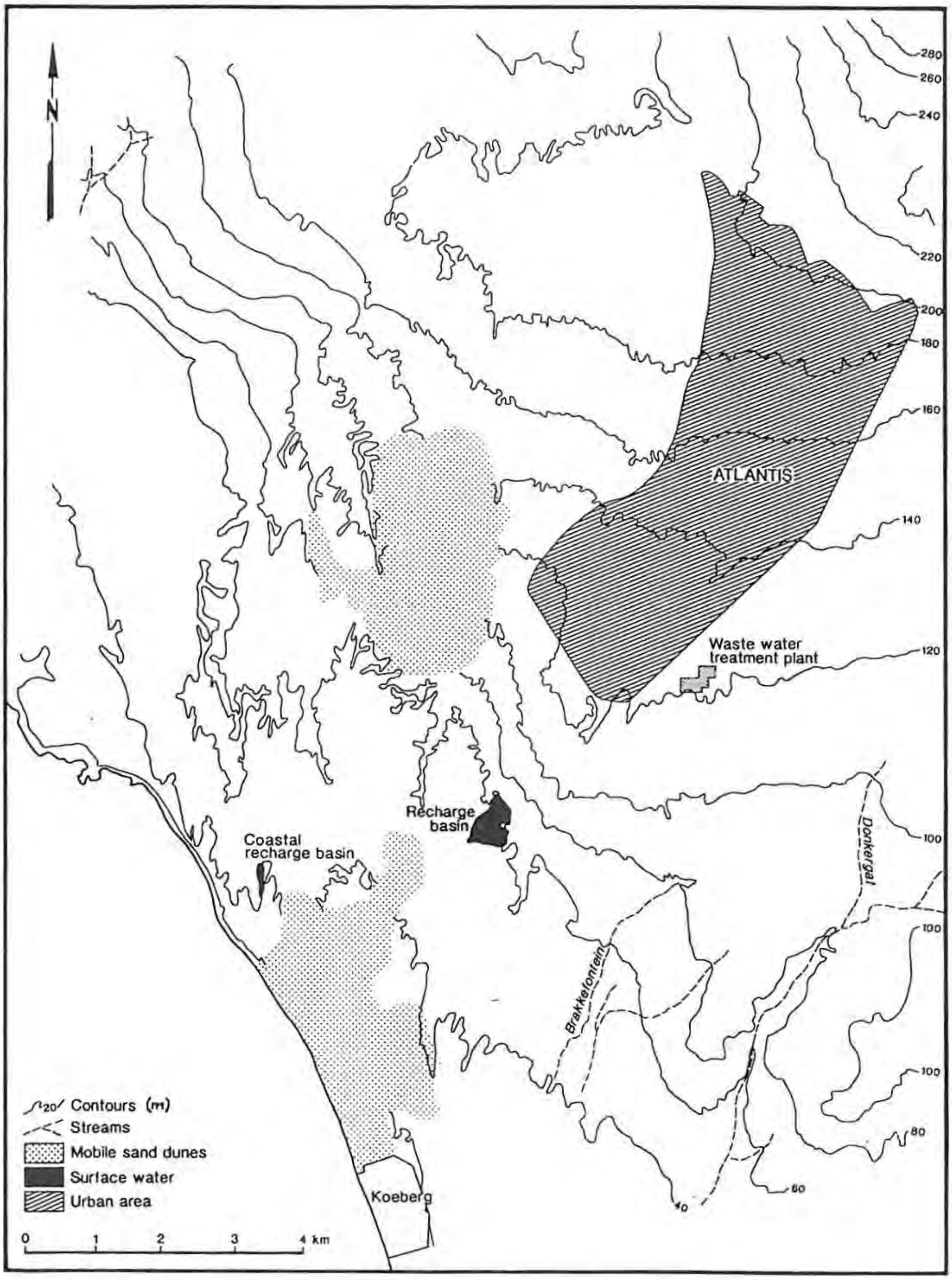


Figure 7 Relief map of the study area

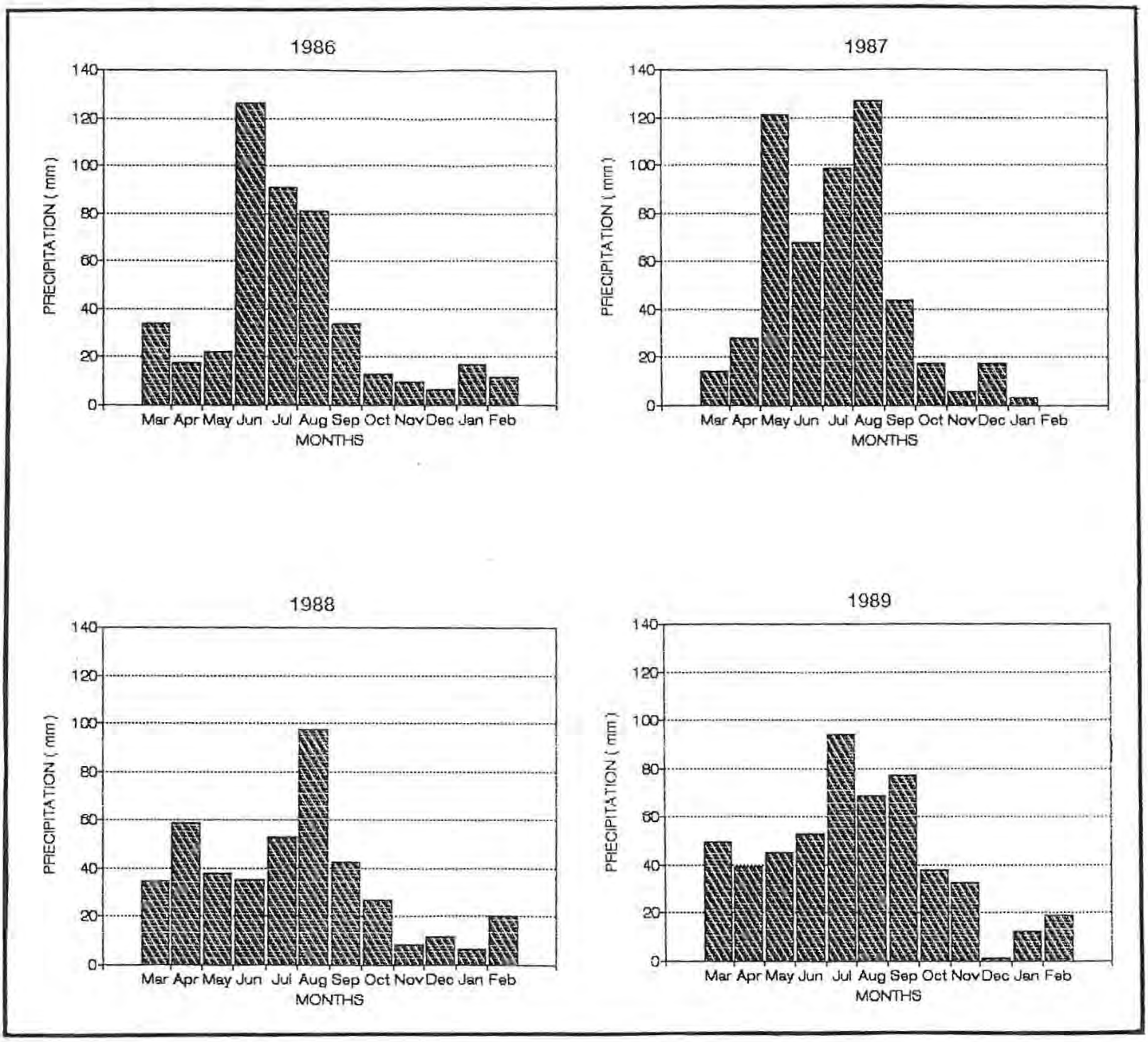


Figure 8 Monthly rainfall totals: 1986 - 1989

3.4 Geology

The geology in the Atlantis area is summarized in Table 2 and schematically depicted in Figure 9. Only the Tygerberg, Springfontein and Langebaan Limestone Formations occur in the study area. The Tygerberg Formation consists of phyllitic shales and graywacke which weather to produce substantial thicknesses of yellow or grey clay. The Cenozoic sediments of the Springfontein and Langebaan Limestone Formations are aeolian in origin. The Springfontein Member is a moderately well-sorted quartzose, fine to medium sand, while the Mamre Member which is peaty and muddy, is considered the inland equivalent. The upper calcareous sands of the Langebaan Formation consist mainly of semi-consolidated, shelly, calcareous sand which contain a calcrete horizon ascribed to seasonal fluctuation of the water table causing dissolution and subsequent reprecipitation of calcium carbonate (Rogers, 1980).

The Cenozoic sediments are relatively thin in the Atlantis urban area and consist of the Langebaan Limestone Formation and Mamre Member, overlying the Malmesbury shales. To the south of Atlantis the Mamre Member goes through a facies change to become the Springfontein Member, and the thickness of the Langebaan Limestone Formation may be as much as 30 metres in the vicinity of the West Coast Road (R27).

3.5 Hydrogeology

The unconsolidated Cenozoic sediments overlying the Malmesbury Group rocks form the primary coastal aquifer. Although the Malmesbury Group does contain groundwater, there is very little evidence of water being exchanged between the bedrock and the overlying sediments. The upper weathered Malmesbury shales form an impervious clay layer hindering any exchange of groundwater. The bedrock topography plays an important role in the aquifer as it is responsible for forming five compartments or sub-units (Van der Merwe, 1980). The compartment boundaries are bedrock highs which restrict the general groundwater flow. It is suggested that the Atlantis urban area is isolated from the artificial recharge basin and Witzand wellfield by one of these compartment boundaries.

Groundwater levels are relatively shallow and may be as little as 3 metres below surface during spring. Very little is known about the hydraulic parameters of the groundwater system in the study area and the only available data is for three boreholes in the central zone of the Atlantis township. Average hydraulic conductivity values of 25 $m.day^{-1}$ and storativity values of 0.05 were recorded by Bredenkamp and Vandoolaeghe (1981). The Langebaan Limestone Formation contains lenses of calcareous and argillaceous material that in areas restrict the vertical movement of groundwater. This is especially true for the area to the immediate north of the artificial recharge basin.

The groundwater quality varies throughout the aquifer (Fleisher, 1990) including that portion within the study area. Groundwater in the urban area is generally, of a poorer quality to that found in the artificial recharge zone. The groundwater also displays hydrochemical stratification within the aquifer.

Table 2 A summary of the geology in the Atlantis area

GROUP	FORMATION	MEMBER
Recent	Witzand	[mobile dunes]
Bredasdorp	Langebaan limestone	
	Springfontein	Springfontein
	Varswater	Duynefontein Silwerstroom
Malmesbury	Tygerberg	
Cape granite	Darling pluton	

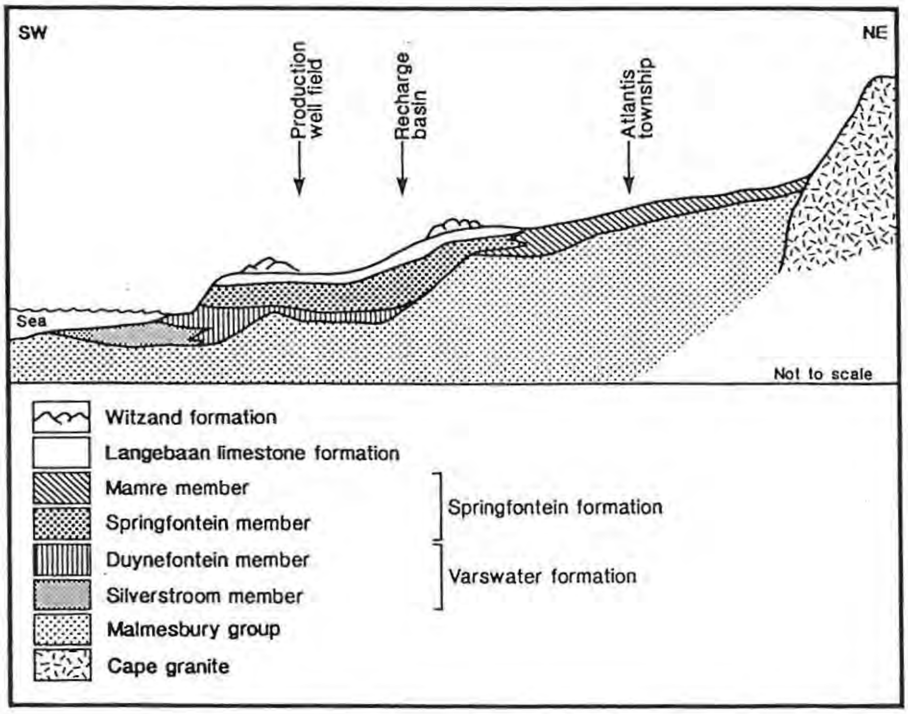


Figure 9 Schematic cross-section of the geology in the southern portion of Atlantis aquifer

3.6 Urban Development

The existing town of Atlantis was planned as two separate sections (Plate 1). The northern section consisting of four residential sub-catchments, one of which contains a small shopping complex. The southern section contains the industrial and commercial activities (Table 3) and is divided into five industrial sub-catchments and one noxious industrial sub-catchment. The noxious industrial area is zoned for those industries that produce very poor quality waste water.

Table 3 A summary of the range and relative importance of different industrial and commercial enterprises in Atlantis

Type of Industry	The number of specific industries as a % of the total number of industries
Iron & steel related	28
Textile & leather related	32
Rubber & plastic products	10
Wood & paper products	6
Chemical products	4
Ceramics/cement/bricks	4
Electronics	3
Food & beverages	2
Printing works	1
Transport related	1
Commercial enterprises	9

Survey undertaken February 1988

It is generally accepted that urban development results in an increase in the percentage of impervious surface as a result of buildings, roads, and paved areas. Stephenson *et al.* (1986) produced a general set of values for the percentage imperviousness that may be expected for the various landuse types in Southern Africa (Table 4). The generalized values are however not applicable to the study area. An exercise to calculate the pervious/impervious ratio in the Atlantis urban catchment provided the data summarized in Table 5.

Table 4 Values of percentage impervious surface recommended for use in Southern African conditions

Land Use	Percentage Imperviousness
Rural	0 - 6
Light density residential	6 - 15
Medium density residential	10 - 25
Light commercial/industrial	20 - 45
Commercial/industrial/downtown	65 - 100

[From Stephenson *et al.* (1986) Table 7.3, p 87]

Table 5 Percentage impervious surface in the Atlantis urban area

Sector	% Imperviousness	% Effective imperviousness
Residential	33	<5
Industrial	15	8

It is immediately clear that in Atlantis the industrial area has a smaller percentage imperviousness which contradicts the findings of Stephenson *et al.* (1986). This is as a result of the largely undeveloped nature of the industrial zone in comparison to the residential zone (Plate 1). The "effective imperviousness" is a more meaningful parameter in the study area and relates only to that area which contributes directly to overland flow. Huber *et al.* (1982) state that where impervious areas are not connected to the drainage system, these areas should not be considered impervious. This is particularly valid in Atlantis where downpipes from the roofs drain onto grass or sand surrounding the building. This is not only in the residential area but also in the industrial areas as is evident in Plate 2. The roads and compacted sidewalks are the only true impervious areas in Atlantis which contribute directly to surface runoff. The urban area has approximately 145 km of tarred road, which accounts for a total impervious area of approximately 1.2 km^2.

An important concept in the urban development was the development of separate stormwater and wastewater (sewage) reticulation systems. At the request of the senior WCRSC Engineer the developers went a step further by designing separate wastewater systems for the residential and industrial zones. Thus permitting additional management options in the AWRMS.

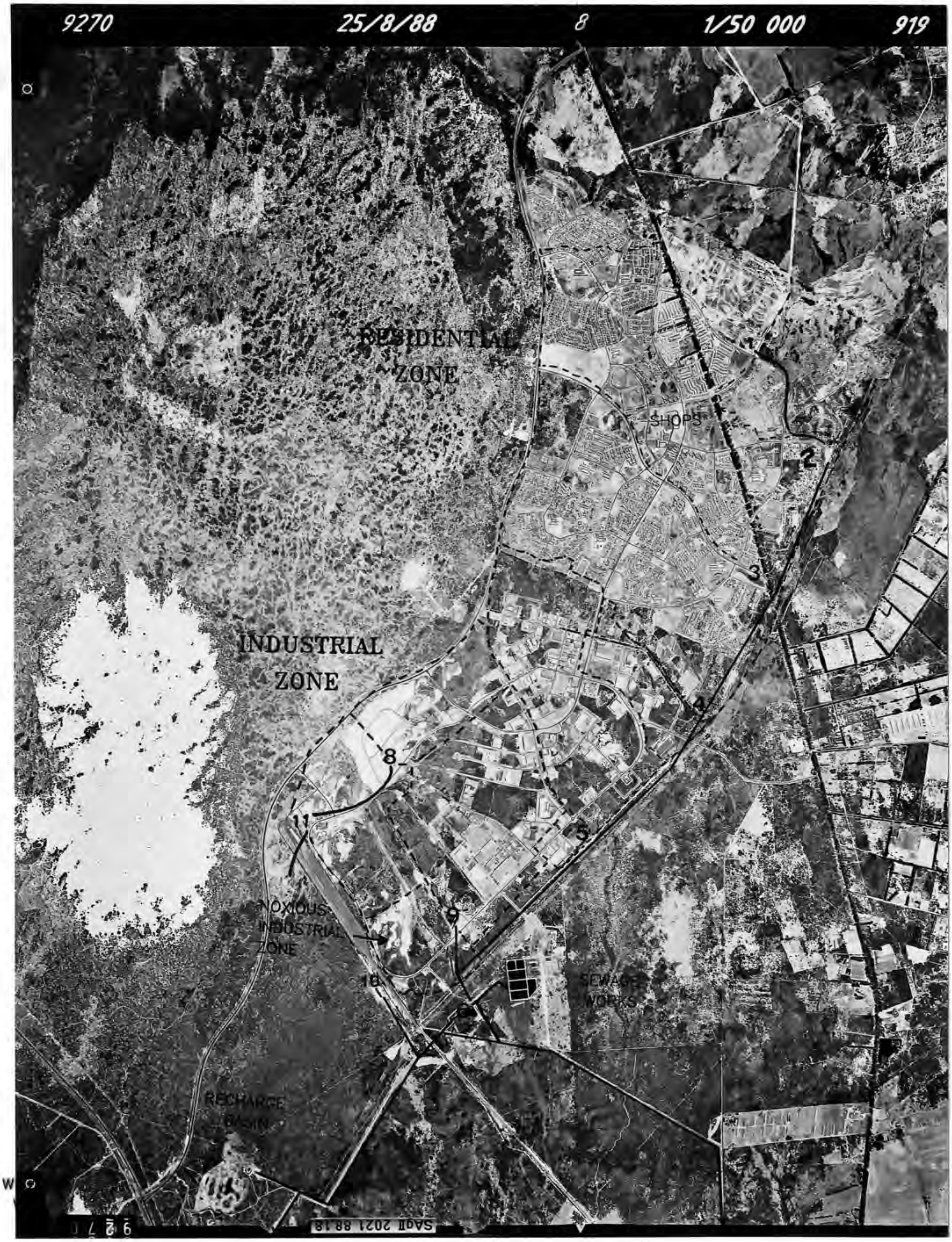


Plate 1 Areal view of study area

(a)

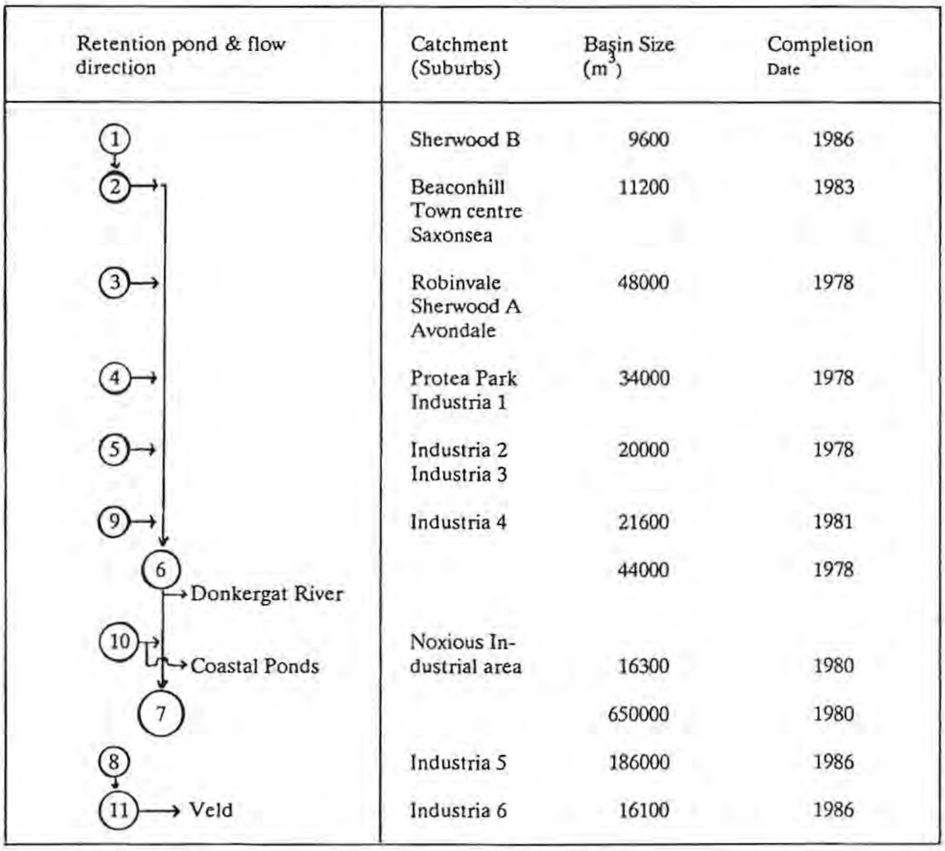
(b)

Plate 2 Typical examples of (a) the residential, and (b) the industrial areas

3.7 The stormwater system and artificial recharge basin

The initial stormwater runoff system was designed to collect and dispose of all urban stormwater as cost effectively as possible, without polluting the environment. It was only once the potential for artificially recharging the coastal aquifer was realised, that full consideration was given to the water quality aspects of the system. The system has thus over the years been modified to reflect the changing management philosophies.

The existing urban stormwater system covers approximately twenty square kilometres of urbanised catchment. It consists of an integrated system of underground stormwater pipes which collects and conveys stormwater runoff from ten urban catchments and discharges it into detention basins (Plate 1 overlay). The stormwater peaks are reduced by these basins and in certain strategically located basins subjected to pollution reduction features. Thereafter most of the stormwater is conveyed in a trunk outfall pipe system to the artificial recharge area where a retention basin has been constructed to recharge the aquifer. Figure 10 illustrates the stormwater system and summarizes a few of the more important details.



Retention pond & flow direction	Catchment (Suburbs)	Basin Size (m^3)	Completion Date
①	Sherwood B	9600	1986
②	Beaconhill Town centre Saxonsea	11200	1983
③	Robinvale Sherwood A Avondale	48000	1978
④	Protea Park Industria 1	34000	1978
⑤	Industria 2 Industria 3	20000	1978
⑨	Industria 4	21600	1981
⑥ → Donkergat River		44000	1978
⑩ → Coastal Ponds	Noxious Industrial area	16300	1980
⑦		650000	1980
⑧	Industria 5	186000	1986
⑪ → Veld	Industria 6	16100	1986

Figure 10 A diagrammatic representation of the Atlantis stormwater system

The detention basins in the residential zone (basins 1 - 4) are designed to reduce peak flows. The basins have large diameter inflow pipes (1 metre) and small diameter outflow pipes (0.3 metres) causing any peak flows to overflow into the basin causing a delayed release into the main stormwater outfall pipe (Plate 3a). The detention basins in the industrial zone (basins 5, 9 & 10) also include pollution reduction features such as reed beds (Plate 3b). Detention basin 6 (Plate 3c) is subdivided so that the stormwater first flows into a desilting area before filtering through a large area of reed beds. The desilting area is periodically dredged and reduces silting-up of the final retention basin/artificial recharge basin (Basin 7). Basin 6 may also act as a mixing basin for the stormwater and treated domestic effluent if the additional water is required for recharge in basin 7.

The stormwater runoff system has several other special features which facilitate the efficient management of the scheme. A sluice system in operation along the trunk outfall pipe to the south of basin 6 enables the polluted and more saline baseflow to be diverted to the Donkergat River and thus away from the artificial recharge basin. Basin 10 has a built-in diversion system which ensures that all baseflow is diverted to the coastal recharge basins and only peak flows enter the artificial recharge basin (Basin 7). The system is illustrated in Figure 3.

Detention basins 8 and 11 are located in undeveloped industrial catchments and at present receive negligible quantities of stormwater runoff. Basin 8 drains into basin 11 which in turn discharges into the vegetated dunes to the south of the railway station. The railway station and adjoining shunting yards represent the largest semi-impervious area in Atlantis and the resultant stormwater runoff drains along the railway line in a south-easterly direction. This water has no bearing on the stormwater runoff system and flows towards the natural depression on the farm Brakkefontein, to the east of the artificial recharge basin.

The final stormwater basin (Basin 7) to the south of Atlantis serves as a retention/ infiltration/ recharge basin. What was initially designed as "the easiest and most economical way of disposing of urban stormwater discharge" (Liebenberg & Stander, 1976) has become a vital component of the AWRMS. The retention basin was created by constructing two relatively short sections of earth "retaining wall" between the sand dunes some 500 m up gradient of the Witzand well field. When filled to capacity the basin holds 650 000 m^3 and covers an area of 27 ha. The sandy nature of the retaining walls and dunes results in substantial seepage once the water level is above 58 mamsl and large areas of shallow surface water form in the depressions to the south and south-west of the basin.

The stormwater discharge initially enters a small stilling basin before flowing over a flow gauging weir and into the main retention basin. The stilling basin is periodically cleaned to remove any sediment and organic material that may settle on the basin floor. The size of the stilling basin in comparison to the main retention basin is well illustrated in Plate 1. At the time at which the photograph was taken, the main basin contained a mere 47 000 m^3 of water and only the deeper portions of the basin were covered by water.

(a)

(b)

(c)

Plate 3: Examples of the stormwater detention basins:
(a) A residential basin; (b) an industrial basin (c) Basin 6

CHAPTER 4

4. METHODOLOGY

4.1 Research framework

The study is concerned with the artificial recharge of the coastal aquifer in the area north east of Witzand wellfield (Figure 1). Research is concentrated on the artificial recharge and stormwater runoff components of the AWRMS, with the objective of:

(a) establishing the quality and quantity of stormwater runoff and wastewater originating in the Atlantis urban catchment;
(b) identifying that water acceptable for artificial recharge into the aquifer up-gradient of Witzand wellfield;
(c) verifying that the present artificial recharge basin is hydrogeologically isolated from the urban area;
(d) establishing the efficiency/effectiveness of the past recharge management strategies in the light of accepted artificial recharge practices;
(e) determining the most efficient artificial recharge management strategy for the AWRMS.

4.2 Hypotheses

The validity of the following hypotheses will be investigated in this study:

(a) The "first flush" effect commonly found in stormwater runoff is of minor importance in the study area;
(b) The residential stormwater runoff and treated wastewater is of an acceptable quality for artificial recharge;
(c) The artificial recharge area is hydrogeologically isolated from the Atlantis urban area;
(d) The recharge water may be traced using chemical variables and does not immediately disperse vertically throughout the aquifer;
(e) The most efficient recharge management strategy is a compromise between obtaining maximum infiltration and maximum water purification.

4.3 Study approach

The given study objectives indicate that the main emphasis is on water quality management which involves efforts to control the physical, chemical and biological characteristics of water. One of the most unusual characteristics of water is its ability to dissolve a greater range of substances than any other liquid (Driscoll, 1986). This coupled with the random nature of water quality makes water quality monitoring a complex exercise (Fetter, 1980; Ward and Loftis, 1986). It was therefore necessary in 1987 to re-evaluate the existing approach and use a systems perspective.

This involved considering monitoring purposes and monitoring activities, as outlined by Sanders and Ward (1988) in the Colorado State University short course "Design of water quality monitoring networks". The sequence followed is summarized in Figure 11. This approach avoids the common practice of gathering data for an entire "shopping list" of variables with the variable coverage being expanded or reduced in response to availability of funding and resources.

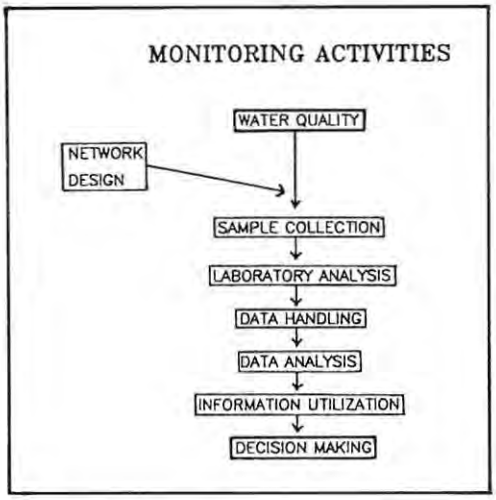


Figure 11 The monitoring system based on the operational activities involved in the flow of information through a monitoring system (After Sanders *et al.*, 1983)

4.4 Network design

Network design has received considerable research attention since the early 1970's (Montgomery & Hart, 1974; Beckers & Chamberlain, 1974; Kazmann, 1981; Sanders *et al.*, 1983). This information was used in determining sample locations, frequency and water quality variables to be measured in the study area, especially since 1986. It was obviously not practical to study all the hundreds or thousands of potential chemical compounds in water, physical water quality variables and various biological species. For example, more than 450 chemical compounds have been identified as important in water quality problems (Sanders *et al.*, 1983). It was therefore necessary to apply a hierachical ranking system to identify those water quality variables at the top, which have aggregated effects of all the other water quality variables. Table 6 provides a summary of water quality variables used in other monitoring networks and those selected for this study. Some variables are more important in surface water quality than in groundwater quality.

A number of sampling stations were established within the stormwater runoff system to monitor the water quality on a routine basis. The location of the various stations and the sampling frequency during the final year of the study are summarized in Figure 12. All the sampling stations were along the main stormwater outfall pipe and either sampled the main discharge of stormwater (PO2B,

Table 6 Water quality variables analysed for in other water quality management systems

Variables	Sanders *et al* (1983)	USEPA Nightingale (1989)	US Geol. Survey German (1989)	Aust. Water Resource Council (1982)	Pinetown Study Simpson (1986)	Johannesburg Green *et al* (1986)	Present Study
Physical	temperature	EC	EC	EC	EC	EC	EC
	EC		turbidity	turbidity	suspended solids	suspended solids	
	suspended sediment		colour	suspended solids			
	colour						
Inorganic major ions	calcium	calcium	calcium	calcium			calcium
	magnesium	magnesium	magnesium	magnesium			magnesium
	sodium	sodium	sodium	sodium			sodium
	potassium	potassium	potassium	potassium			potassium
	bicarbonate	bicarbonate		bicarbonate		bicarbonate	
	alkalinity		alkalinity				alkalinity
	sulphate	sulphate	sulphate	sulphate	sulphate	sulphate	sulphate
	chloride	chloride	chloride	chloride	chloride	chloride	chloride
	fluoride			fluoride			
	silica						
	pH	pH				pH	pH
Trace metals	zinc		zinc	zinc	zinc		zinc
	arsenic		arsenic				
	lead		lead	lead	lead		lead
	nickel						
	iron		iron	iron	iron		iron
	manganese		manganese	manganese	manganese		manganese
	mercury		mercury	mercury			
	antimony						
	cobalt						
	chromium		chromium		chromium		chromium
	cadmium		cadmium	cadmium	cadmium		cadmium
	copper		copper		copper		copper
			silver				
			barium	boron			
Organic	pesticides						
	cyanide compounds						
	TOC			TOC			
	DOC			DOC			DOC
	COD				COD		
Nutrients	nitrogen	nitrate	nitrogen	nitrogen	nitrate	nitrate	nitrate
	ammonia						ammonia
	phosphorus	phosphate	phosphorus	phosphorus	phosphate		orthophosphate
	BOD			BOD			
Micro-biological	total coliform						total coliform
	faecal coliform						faecal coliform
	faecal streptococci		*E. coli*		faecal streptococci		
							coliphages

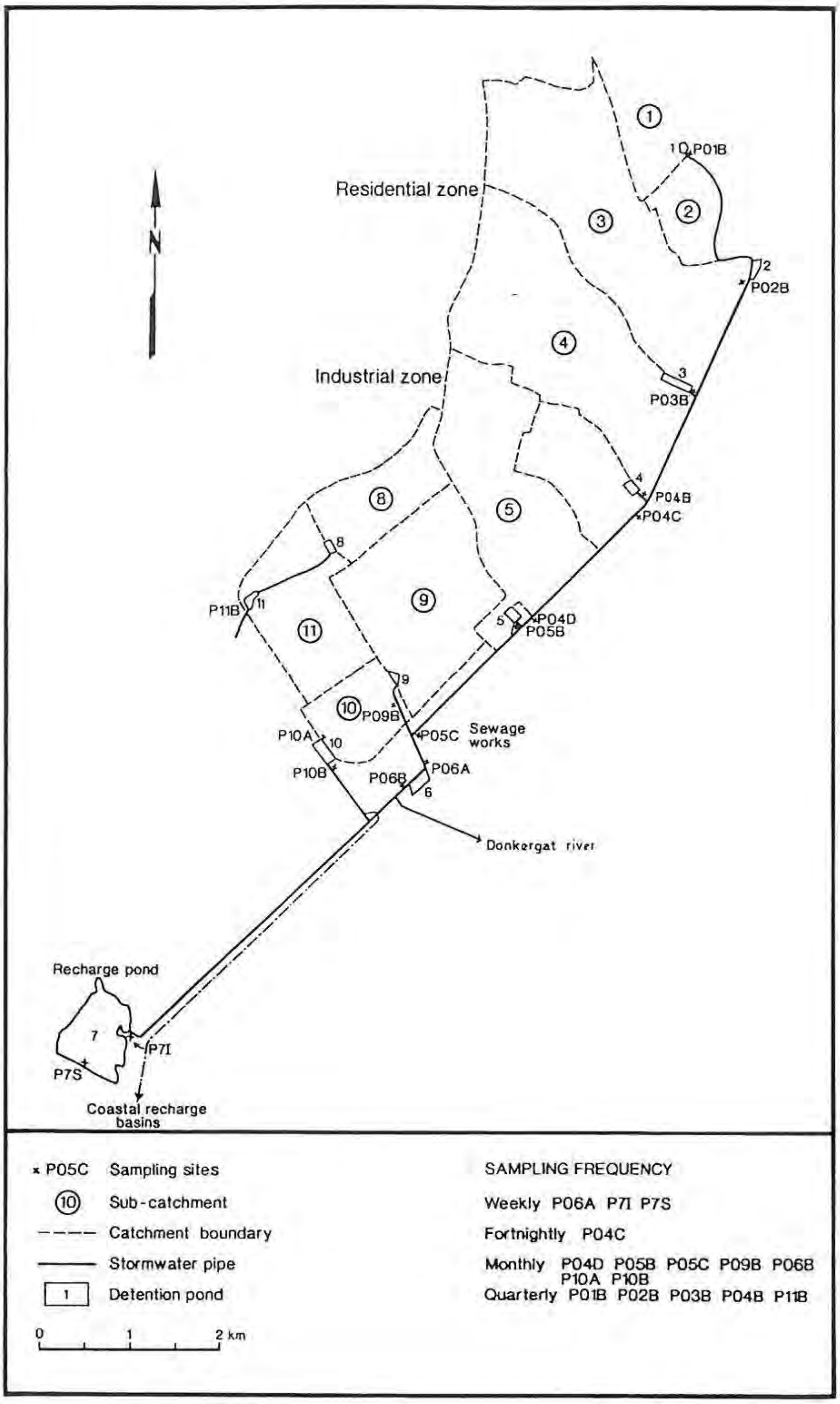


Figure 12 The stormwater runoff sampling programme

PO4C, PO4D, PO5C) or subcatchment discharges connecting to the main outfall pipe (PO1B, PO3B, PO4B, PO5B, PO9B). The sampling points were within the stormwater pipe and thus at least 2 metres below surface with access via manholes.

Sample site PO6A was located at the point where the stormwater outfall pipe enters basin 6 and measured the total stormwater quality originating in the urbanized area except for the noxious industrial water. Site PO6B measured the water quality as it leaves basin 6 and enters the final stretch of outfall pipe before the recharge basin. Sample site P7I was located at the point where the stormwater outfall discharges into the basin 7 settling basin. Sample site P7S was selected as a representative site for the recharge basin water and is opposite the waterlevel recording station.

A storm event monitoring site was established in a specially constructed manhole 100 m upstream of basin 6. At this point the stormwater outfall pipe is at a depth of more than 3 metres and the roof of the pipe was removed to allow easy access. The chamber (2 m x 2 m x 3 m) above the pipe was large enough to accommodate two automatic water quality samplers and a flow gauging system (Plate 4). The flow gauging system consisted of a standard Stevens float gauge housed in a 165 mm diameter stilling tube and a horizontal chart recorder.

A second, older, flow gauging station was situated between the stilling pond and the main retention basin (pond 7). The station consisted of a rectangular measuring weir with a pressure bladder water level recorder (Plate 5). The system was fully automatic and provided a digital read-out as well as a continuous record on a circular chart recorder. During 1989 a second flow gauging system, namely, an Ott float operated, horizontal drum water level recorder, was installed at the same station. The flow gauging system was established with the aid of the Directorate Hydrology, Department of Water Affairs (DWA). The DWA staff re-surveyed the weir structure and developed a series of stage-discharge and stage-velocity tables.

During the study period a number of flow gauging exercises were undertaken over the entire stormwater system. These attempts at obtaining flow data for the various sub-catchments coincided with water quality sampling runs in order to determine pollutant loads. The gauging was done using a Braystoke miniature current flow meter, and in the case of very low discharges, a bucket and stop watch. The large diameter (300 mm to 1500 mm) of the stormwater pipes and low discharges (baseflow conditions) made flow gauging very difficult and standard flow gauging equipment designed for sewers could not be used (CSIR, Division of Building Technology, personal communication, 1989).

Although many flow gauging structures are available (Muller, 1987; Leupold & Stevens Inc., 1987; Shaw, 1983) none were built in to the original stormwater runoff network. Subsequent inclusion of such structures within the completed stormwater system were not justified as both the nature of the stormwater system with its underground pipes and the actual AWRMS management requirements did not warrant the costs involved. Those flow gauging stations which were later established, concentrate on the total stormwater runoff and merely address the minimum requirements of the AWRMS.

Plate 4 The Pond 6 "manhole" monitoring site showing the flow gauging system and automatic water quality sampler

Plate 5 The flow gauging station situated between the stilling pond and the main retention basin (Pond 7)

An important component of the monitoring network was that which concerned the collection of data for the artificial recharge basin water balance. The flow into the basin (pond 7) was measured at the "weir" flow gauging station already described. The water level within the recharge basin itself was measured on a weekly chart recorder installed on the southern wall of the basin and connected via a stilling tube to the deepest portion of the basin. Measurements were also made manually from gauge plates in the basin, on a weekly basis, the water level data then being used to calculate volumes.

Meteorological data, such as rainfall, evaporation, temperature, wind speed and direction, were collected at a first order weather station at the Atlantis wastewater treatment plant and from Koeberg weather station. Rainfall was also recorded by a Casella natural-siphon chart recorder rain gauge situated at the water softening plant (Figure 3).

The groundwater monitoring network was concentrated around the artificial recharge facility and in a down gradient position towards the Witzand well field (Figure 3). The artificial recharge basin (Pond 7) was completed in 1980 but it was only in late 1983 that the first observation points were established. The observation points were established to monitor both groundwater levels and groundwater quality. Initially the network consisted of seventeen piezometers and four boreholes (DWA exploration holes), but in 1986 a further twenty piezometers were installed with the assistance of the Directorate of Geohydrology, DWA. Problems were, however, encountered in penetrating clay and calcrete layers and the piezometers often did not reach the required depth. In 1987 a private drilling contractor was employed to extend the monitoring network and by the beginning of the 1987 rainy season the monitoring network consisted of sixty observation points (Figure 13). At the end of 1988 it became necessary to drill a further eighteen observation holes. These were necessary for completing the network, replacing existing non-functional observation points and monitoring the possible influence of more saline groundwater from the surrounding aquifer.

Most observation sites had two boreholes to monitor the groundwater at both a shallow (10m) and deeper level (20m). Several of the shallow boreholes were in fact well points, having been jetted in using water and a drilling mud (REVERT). All the monitoring points were constructed with 50mm diameter PVC casing and slotted Boode screens and will for the sake of convenience be referred to as boreholes whether drilled or jetted.

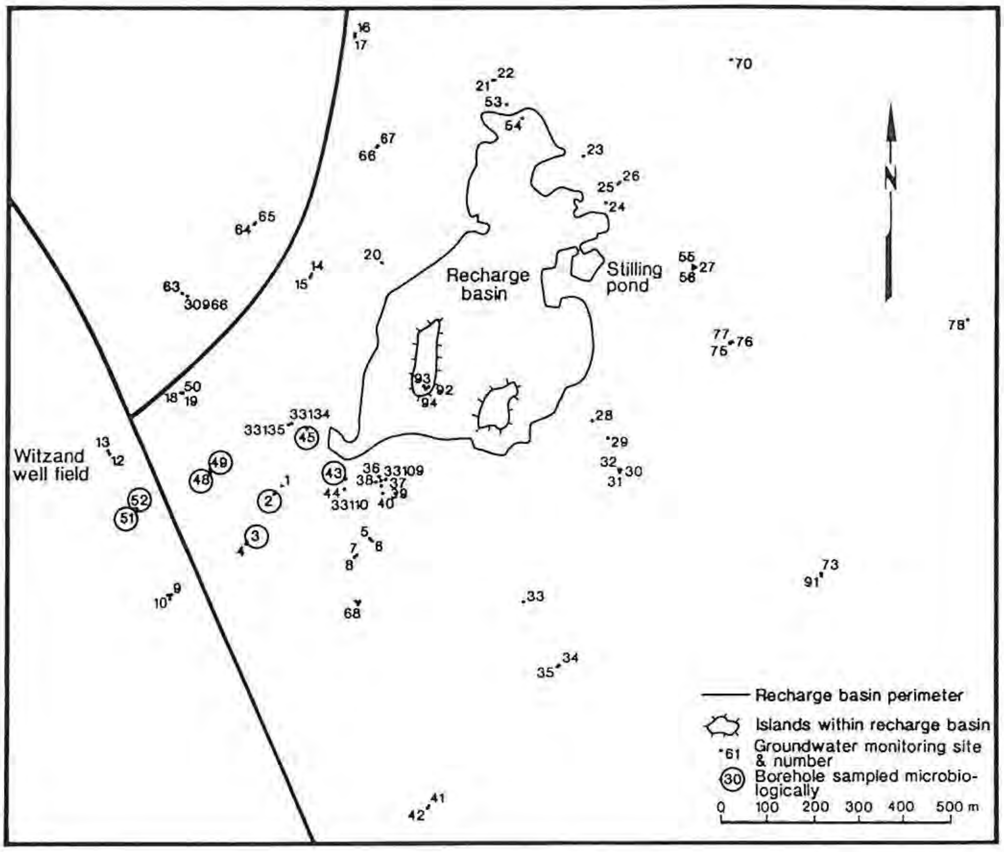


Figure 13 Borehole location plan in the vicinity of the artificial recharge basin (Pond 7)

4.5 Sample collection

Sample collection involved both making discharge/volumetric measurements and collecting water quality samples. Quality control was vigorously applied during sample collection activities as sampling is recognised as one of the most error prone sections of any monitoring programme. Analytical results are only as good as the samples they are testing. Many guidelines for sampling and sample preservation are available and in this study those proposed by Kempster & Smith (1985), Muller (1987) and Scott (1989a) were used.

The sampling of stormwater runoff quality involved taking a grab sample in midstream and filling three plastic 250 mL sample bottles. The sampling frequency is shown in Figure 12. The sampling of storm events was done with the aid of automatic samplers. A sampler designed to collect 48 samples in one cycle, was programed to collect a grab sample every four hours. A second sampler, a a Manning S-4400 portable discrete sampler, was used to collect 24 samples at increasing time intervals during storm events. The sampler was connected to the flow gauging apparatus and was triggered off as soon as stormwater levels rose in the outfall pipe. The sample interval was initially brief to ensure maximum data acquisition during the early stages of the hydrograph. Thus being able to monitor any "first flush" effect that may be present.

Sampling the groundwater quality variables involved a more complex procedure. Groundwater quality is relatively constant with time because of the low rate of groundwater flow and thus sampling frequency could be lower than with stormwater runoff. The actual act of sampling, however, was more time consuming and required more preparation. The borehole had first to be purged of its stagnant water before a sample could be taken. The stagnant water was not representative of the aquifer as a whole and the hydraulic properties, geology and construction details had to be considered for each individual borehole in order to decide on purging times and rates. The temperature, pH, and EC of the water was monitored regularly during purging and sampling only began once the EC had stabilized. Garrett (1988) found that for many monitoring wells, field parameters stabilize after three well volumes have been purged. During the present study it was found that when using the Division of Water Technology 3-stage submersible electric centrifugal pump, the shallow boreholes had to be purged for about eleven minutes at the rate of $0.17\ L.s^{-1}$. Care had to be taken as if purging rates exceed development rates the borehole could suffer physical change. Both submersible and air lift pumps were used for sampling boreholes during the study.

All samples were collected in plastic bottles. New bottles were used whenever possible, especially when sampling for trace and heavy metals. When old bottles were used, these were first washed with 10 per cent HCl, rinsed with tap water and finally rinsed with distilled water. In the field, the bottle was again rinsed twice with the water to be sampled. Care was taken to ensure that no air remained in the bottle once the sample had been collected, as exposure of the groundwater to atmospheric oxygen and loss of carbon dioxide could effect the water chemistry enough to initiate changes in the equilibrium. In the case of microbiological sampling the bottles were glass and sterilized in the laboratory before sampling. The bottle was not rinsed in the field, but filled directly from the source, allowing for a small air space between the sample and cap. Care was taken not to ever touch the neck or lip of the bottle or the thread of the cap. Once collected the sample was immediately stored in a "cool box" and transported to the laboratory within six hours. The microbiological sampling was confined to a series of boreholes between the artificial recharge basin and the wellfield (Figure 13) and was done every six months.

No special sampling procedures such as filtering in the field were required for the major ions and nutrients, whereas samples to be analysed for trace metals were both filtered and acidified in the field. The filtration was to remove any iron particles that may flake-off the casing or remain from drilling operations. The samples were acidified using nitric acid to ensure that the metals remain in solution.

The measuring of water quantity variables was done on a continuous and routine basis. The gauging stations with chart recorders, which contained water depth trends, were visited weekly to change the charts. Other measurements taken during flow gauging exercises were velocities (using the miniature current flow meter), pipe gradients, pipe diameters and depth of water level.

Groundwater levels within the boreholes were measured on a monthly basis with the aid of an electrical drop line. The four DWA boreholes equipped with Ott water level floats and horizontal chart recorders were checked on a monthly basis.

Several other forms of field data had to be collected during the study. Much of this work was done from aerial photographs, followed by field surveys. Two examples being "landuse type" data and percentage impervious surface in the catchment. The surveying of monitoring sites and artificial recharge basin geometry was undertaken by members of the WCRSC Survey Section.

4.6 Laboratory analysis

Laboratory analysis is a complex and specialized activity as it involves the analysis for many water quality variables with several alternative procedures. It also includes operational procedures such as the handling and flow of samples in the laboratory, quality control and the recording of analytical results. This part of the study was undertaken by the Analytical Services Programme staff of the Division of Water Technology, CSIR.

The water quality variables analysed included physical variables (temperature, electrical conductance, turbidity and pH), inorganic chemical variables (major ions and trace metals), organic chemical variables (dissolved organic carbon), nutrients (forms of nitrogen and phosphorus) and microbiological variables. The physical variables were determined in the field as they are unstable and change with time. All other variables were analysed in the laboratory using the methods recommended by Standard Methods for the Examination of Water and Wastewater (APHA, 1985).

The analysis of trace metals is relatively expensive and therefore only selected elements were done and only when considered necessary. The great number of man-made organic compounds and high analytical costs meant that none were included in this study. As carbon serves as a key element in natural organic compounds it was used as an indicator variable and total concentrations of dissolved organic carbon (DOC) were monitored. Dissolved organic carbon as carbon was determined by automated infrared carbon dioxide measurement following potassium persulphate and ultra-violet digestion (CSIR, 1974).

Microbiological indicator organisms were analysed for as water may act as the transmitting medium for a wide variety of disease-causing organisms which generally originate from human waste (Cabelli *et al.*, 1983; Borrego *et al.*, 1990). The pathogenic micro-organisms, however, appear intermittently in natural waters at low concentrations and present techniques available for the selective recovery and enumeration are complex and costly. It is therefore standard practice to analyse for other micro-organisms which share the same habitats. A number of researchers (Bonde, 1974; Kenard & Valentine, 1974; Grabow *et al.*, 1984; Borrego *et al.*, 1990) have confirmed this correlation between indicator organisms and the presence of pathogens. Indicator micro-organisms selected in the present study were total coliforms, faecal coliforms faecal *streptococci* and coliphages. The total coliforms, faecal coliforms, and faecal *streptococci* were analysed per 100mL using the membrane filter technique (APHA, 1985) with dehydrated mEndo agar bes, mFC agar and *mEnterococcus* agar respectively. A modified double-layer-agar method (Grabow *et al.*, 1984) was used for plaque assays of coliphages. Total coliforms and coliphages were counted after incubation for 16 hours at 37°C. Faecal coliforms were counted after incubation for 16 hours at 45°C. Faecal *streptococci* were incubated for 48 hours at 45°C.

Quality control was ensured in a number of ways. Duplicate samples were taken in the field without informing the laboratory staff and proved a highly successful method of checking on the laboratory staff. The laboratory itself used control samples taken from a large quantity of stabilized water collected periodically from the study area. A further quality control was the fact that the laboratory consistently rated in the top two in the South African Inter-laboratory Comparison Studies [Smith 1991].

Another component of this activity was the calculation of stormwater runoff velocities and discharges from the field measurements. The velocity area method (Herschy, 1978; Shaw, 1983) was employed using the Manning Equation. The shallow water depth and relatively small wetted surface made the 0.6 depth and mid-section methods the most appropriate for the study (Herschy, 1978; Muller, 1987). The results were cross-checked using the Crimp Bruges Tables and Diagrams (Bruges, 1969).

4.7 Data handling

Data handling consisted of the aquisition and collection of all required water quality data. Much of the data could be transferred directly from the CSIR laboratories, but other data, such as meteorological, survey, wastewater quality and pond level records had to be obtained from the relevant WCRSC departments. Besides data on water quality there are many other types of information that are necessary in water quality management (Flemal *et al.*, 1979). Once the data was received it then had to be sorted, evaluated and verified for accuracy. Wherever possible this was done while loading the data in the data base. The data base was created on a Hewlett Packard 9000 series 310 computer. The data was stored in a matrix format with routines and programmes being written in Basic.

4.8 Data analysis

Data handling and data analysis are closely linked as data analysis often requires the rapid manipulation of large amounts of data. The multiplicity of variables which determine water quality, and the broad spectrum of management requirements combine to create a formidable obstacle in obtaining precise information from the data base (Sanders *et al.*, 1983). There are a great number of techniques which may be used to analyse water quality data and in this study efforts were concentrated on the more general techniques, as these are most often used for coarse scale (time and/or space) analysis of water quality conditions (Hirsch *et al.*, 1982; Smith *et al.*, 1982; Sanders *et al.*, 1983).

The fundamental difference in the nature of surface- and ground-water meant that the stormwater runoff data was analysed differently to the groundwater data. Figure 14 provides a flow chart for the stormwater runoff data analysis.

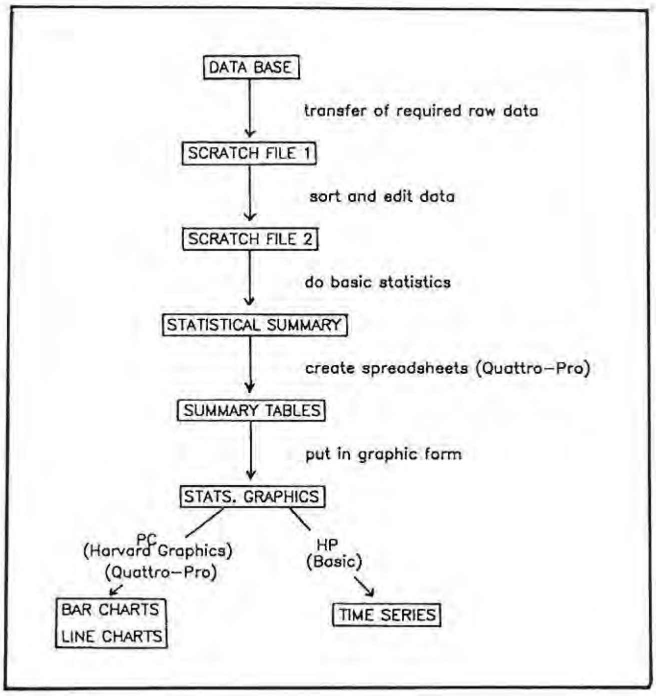
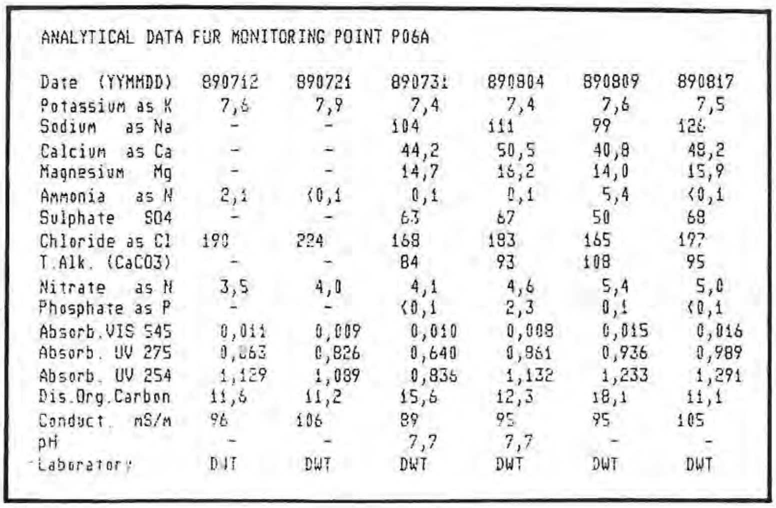


Figure 14 Flow chart for the data analysis of stormwater quality data

Once the necessary data file (Table 7) was in the required format (Scratch file 1) it was edited to only include data representative of baseflow conditions (Scratch file 2). The summary tables only contained those statistical parameters considered relevant and not the entire statistical summary (Table 8). Bar/line charts and time series plots were considered the most appropriate means of presentation.

Table 7 An example of stormwater runoff data format in the data base


ANALYTICAL DATA FUR MONITORING POINT P06A

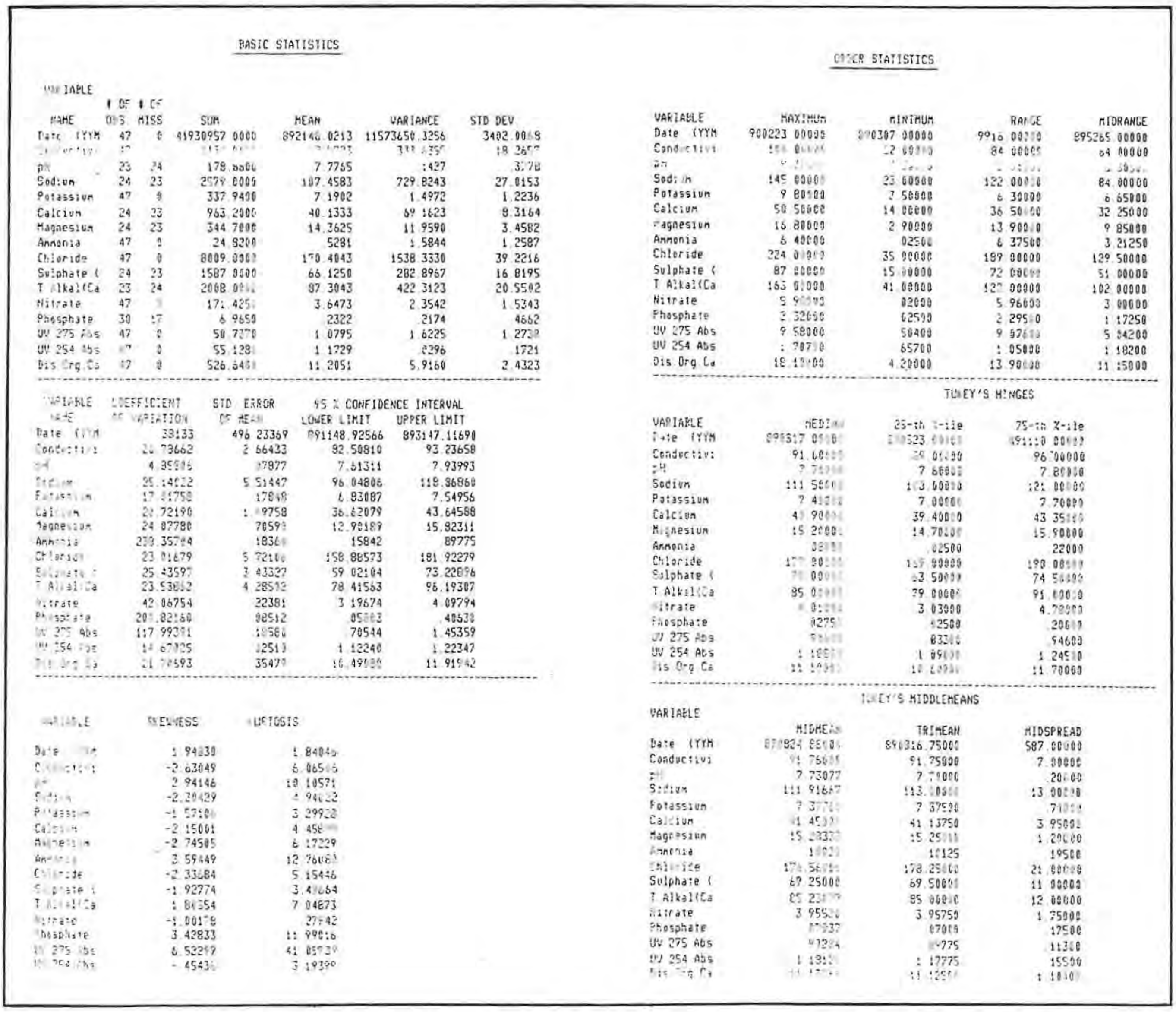
Date (YYMMDD)	890712	890721	890731	890804	890809	890817
Potassium as K	7,6	7,9	7,4	7,4	7,6	7,5
Sodium as Na	-	-	104	111	99	126
Calcium as Ca	-	-	44,2	50,5	40,8	48,2
Magnesium Mg	-	-	14,7	16,2	14,0	15,9
Ammonia as N	2,1	<0,1	0,1	0,1	5,4	<0,1
Sulphate SO4	-	-	63	67	50	68
Chloride as Cl	190	224	168	183	165	177
T.Alk. (CaCO3)	-	-	84	93	108	95
Nitrate as N	3,5	4,0	4,1	4,6	5,4	5,0
Phosphate as P	-	-	<0,1	2,3	0,1	<0,1
Absorb.VIS 545	0,011	0,009	0,010	0,008	0,015	0,016
Absorb. UV 275	0,863	0,826	0,640	0,861	0,936	0,989
Absorb. UV 254	1,129	1,089	0,836	1,132	1,233	1,291
Dis.Org.Carbon	11,6	11,2	15,6	12,3	18,1	11,1
Conduct. mS/m	96	106	89	95	95	105
pH	-	-	7,7	7,7	-	-
Laboratory	DWT	DWT	DWT	DWT	DWT	DWT

4.9 Information utilization

This is the final activity and involved the interpretation of information extracted from the data during data analysis activities. It included determining the format in which the interpreted information would be presented/reported.

The activity was undertaken in a number of phases. The first phase was a literature study on all aspects of artificial recharge and urban stormwater hydrology including all previous work done in the Atlantis aquifer. The second phase concentrated on urban stormwater runoff and any other wastewater leaving the Atlantis urban catchment. This is reported in Chapter 5. A third phase looked at the concept and present state of artificial recharge in the study area and are dealt with in Chapters 6 and 7. A final phase involved an investigation of the hydrogeological isolation of the artificial recharge zone from the Atlantis urban area and constitutes Chapter 8.

Table 8 An example of the summary statistics obtained on the stormwater runoff data



```
                              BASIC STATISTICS

 VARIABLE
            # OF  # OF
   NAME     OBS.  MISS        SUM             MEAN          VARIANCE      STD DEV
 Date  (YYM  47     0  41930957.0000    892146.0213   11573650.3256    3402.0068
 Conductivi  47           [illegible]    [illegible]     [illegible]     18.2657
 pH          23    24      178.8600         7.7765          .1427         .3778
 Sodium      24    23     2579.0000       107.4583       729.8243       27.0153
 Potassium   47     0      337.9400         7.1902         1.4972        1.2236
 Calcium     24    23      963.2000        40.1333        69.1623        8.3164
 Magnesium   24    23      344.7000        14.3625        11.9590        3.4582
 Ammonia     47     0       24.8200          .5281         1.5844        1.2587
 Chloride    47     0     8009.0000       170.4043      1538.3330       39.2216
 Sulphate (  24    23     1587.0000        66.1250       282.8967       16.8195
 T Alkal(Ca  23    24     2008.0000        87.3043       422.3123       20.5502
 Nitrate     47     0      171.4251         3.6473         2.3542        1.5343
 Phosphate   30    17        6.9650          .2322          .2174         .4662
 UV 275 Abs  47     0       50.7370         1.0795         1.6225        1.2738
 UV 254 Abs  47     0       55.1281         1.1729          .0296         .1721
 Dis Org Ca  47     0      526.6461        11.2051         5.9160        2.4323
---------------------------------------------------------------------------------
 VARIABLE   COEFFICIENT     STD  ERROR      95 % CONFIDENCE INTERVAL
   NAME     OF VARIATION    OF MEAN       LOWER LIMIT    UPPER LIMIT
 Date  (YYM       .38133     496.23369   891148.92566   893147.11690
 Conductivi     20.78662       2.66433       82.50810       93.23658
 pH              4.85986        .07877        7.61311        7.93993
 Sodium         25.14022       5.51447       96.04806      118.86860
 Potassium      17.01758        .17848        6.83087        7.54956
 Calcium        20.72190       1.69758       36.62079       43.64588
 Magnesium      24.07780        .70593       12.90189       15.82311
 Ammonia       238.35784        .18360         .15842         .89775
 Chloride       23.01679       5.72106      158.88573      181.92279
 Sulphate (     25.43597       3.43327       59.02184       73.22896
 T Alkal(Ca     23.53862       4.28512       78.41563       96.19307
 Nitrate        42.06754        .22381        3.19674        4.09794
 Phosphate     200.82160        .08512         .05083         .40530
 UV 275 Abs    117.99391        .18586         .70544        1.45359
 UV 254 Abs     14.67025        .02510        1.12240        1.22347
 Dis Org Ca     21.70593        .35479       10.49080       11.91942
---------------------------------------------------------------------------------

 VARIABLE          SKEWNESS        KURTOSIS

 Date  (YYM         1.94830         1.84046
 Conductivi        -2.63049         6.06546
 pH                 2.94146        10.10571
 Sodium            -2.20429         4.94022
 Potassium         -1.57106         3.29928
 Calcium           -2.15001         4.458[illegible]
 Magnesium         -2.74505         6.17229
 Ammonia            3.59449        12.76063
 Chloride          -2.33684         5.15446
 Sulphate (        -1.92774         3.49664
 T Alkal(Ca         1.84354         7.04873
 Nitrate           -1.00178          .27942
 Phosphate          3.42833        11.99016
 UV 275 Abs         6.52299        41.05939
 UV 254 Abs         -.45431         3.19390
```

```
                              OTHER STATISTICS

 VARIABLE          MAXIMUM          MINIMUM            RANGE        MIDRANGE
 Date  (YYM   900223.00000     890307.00000       9916.00000    895265.00000
 Conductivi    [illegible]         22.00000         84.00000        64.00000
 pH            [illegible]      [illegible]      [illegible]     [illegible]
 Sodium          145.00000         23.00000        122.00000        84.00000
 Potassium         9.80000          3.50000          6.30000         6.65000
 Calcium          50.50000         14.00000         36.50000        32.25000
 Magnesium        16.80000          2.90000         13.90000         9.85000
 Ammonia           6.40000           .02500          6.37500         3.21250
 Chloride        224.00000         35.00000        189.00000       129.50000
 Sulphate (       87.00000         15.00000         72.00000        51.00000
 T Alkal(Ca      163.00000         41.00000        122.00000       102.00000
 Nitrate           5.98000           .02000          5.96000         3.00000
 Phosphate         2.32000           .02500          2.29500         1.17250
 UV 275 Abs        9.58000           .50400          9.07600         5.04200
 UV 254 Abs        1.70700           .65700          1.05000         1.18200
 Dis Org Ca       18.10000          4.20000         13.90000        11.15000
---------------------------------------------------------------------------------
                                      TUKEY'S HINGES

 VARIABLE              MEDIAN       25-th %-ile      75-th %-ile
 Date  (YYM      890517.00000     890323.00000     891110.00000
 Conductivi          91.00000         89.00000         96.00000
 pH                   7.75000          7.60000          7.80000
 Sodium             111.50000        103.00000        121.00000
 Potassium            7.41000          7.00000          7.70000
 Calcium             40.90000         39.40000         43.35000
 Magnesium           15.20000         14.70000         15.90000
 Ammonia          [illegible]           .02500           .22000
 Chloride           177.00000        169.00000        190.00000
 Sulphate (          70.00000         63.50000         74.50000
 T Alkal(Ca          85.00000         79.00000         91.00000
 Nitrate              4.01000          3.03000          4.78000
 Phosphate             .02750           .02500           .20000
 UV 275 Abs       [illegible]           .83300           .94600
 UV 254 Abs           1.10000          1.09000          1.24500
 Dis Org Ca       [illegible]      [illegible]         11.70000
---------------------------------------------------------------------------------
                        TUKEY'S MIDDLEMEANS
 VARIABLE
                      MIDMEAN          TRIMEAN        MIDSPREAD
 Date  (YYM      890824.85000     890316.75000        587.00000
 Conductivi          91.76000         91.75000          7.00000
 pH                   7.73077          7.79000           .20000
 Sodium             111.91667        113.00000         18.00000
 Potassium        [illegible]          7.37500           .70000
 Calcium          [illegible]         41.13750          3.95000
 Magnesium        [illegible]         15.25000          1.20000
 Ammonia          [illegible]           .10125           .19500
 Chloride         [illegible]        178.25000         21.00000
 Sulphate (          69.25000         69.50000         11.00000
 T Alkal(Ca       [illegible]         85.00000         12.00000
 Nitrate          [illegible]          3.95750          1.75000
 Phosphate        [illegible]           .07000           .17500
 UV 275 Abs       [illegible]      [illegible]           .11300
 UV 254 Abs       [illegible]          1.17775           .15500
 Dis Org Ca       [illegible]      [illegible]          1.10000
```

CHAPTER 5

5. STORMWATER RUNOFF

Urban stormwater runoff from Atlantis township constitutes an important component of the Atlantis Water Resource Management Scheme (AWRMS). Under normal circumstances stormwater runoff is basically an engineering problem, with the objective of collecting and disposing of the stormwater as safely and cost effectively as possible. In Atlantis, however, as much water as possible has to be reused and even the unused water has to be correctly disposed of to ensure that the groundwater resources are not polluted.

In Atlantis it is therefore necessary to have a thorough knowledge of both the quality and quantity of all the water being discharged from the urban area in order to be able to fully utilize this limited resource. An extensive stormwater monitoring programme has been operational for a number of years and data has been collected on stormwater quality and quantity variables. This chapter deals with urban stormwater runoff data collected between 1986 and 1989.

5.1 General

The Atlantis stormwater drainage network covers an area of approximately 20 km^2 and drains both residential and industrial areas. The stormwater system intersects the groundwater table and drains groundwater from the aquifer throughout the year. The stormwater runoff thus has two distinct components, namely, stormflow and baseflow. The highly seasonal nature of the rain results in large volumes of stormwater runoff during winter and low, but consistent flows during summer, giving a linear relationship between rainfall and runoff. During summer (October to April) the stormwater runoff consists almost entirely of baseflow which results largely from groundwater flow. In winter (May to September) the rainfall results in overland flow and interflow which provides the stormflow component and increases the baseflow by way of delayed interflow.

The fact that Atlantis only has in the order of 88 rain-days per annum means that although stormflow accounts for as much as 60% of the volume of stormwater runoff, it is concentrated into less than 20% of the year. Baseflow thus plays an important role in the stormwater runoff. The origin and composition of the stormwater runoff is therefore likely to result in stormwater quality variation, both spatially and in time.

5.2 Stormwater quality

The stormwater quality was monitored over the entire urban catchment at a number of strategically located sites (Figure 12). The network, sampling programme, data base and methods of data evaluation are discussed in Chapter 4. Statistical summaries of the data are given in Appendix C and presented graphically in Appendices D, E and F.

The fact that Atlantis stormwater runoff comprises two distinct components, namely stormflow and baseflow, is clearly reflected in the water quality. Table 9 provides a comparison between typical stormflow and baseflow water quality and illustrates this point within the different subcatchments. The stormflow is consistently of a better quality (except for metals) than that of the baseflow and appears relatively uniform throughout the catchment. This is probably a reflection of the fact that it is basically only the roads which contribute to the overland flow and cause washoff or scouring of the catchment. In the majority of the catchment the rain infiltrates and enters the stormwater system as rapid interflow and is thus filtered by the sand. The average stormflow water quality originating in the catchment (P06A in Table 9) is thus of a good quality. This is anomalous when compared to the findings of other urban stormwater such as Cordery (1977), Field & Fan (1981), Field & Turkeltaub (1981) and Gutteridge *et al.* (1981).

As a general rule a rainfall event of as little as 2.5 mm, of short duration (<10 minutes), resulted in the stormwater salinity (EC) dropping to below 35 $mS.m^{-1}$. A rainfall or storm event is defined as a period of continuous precipitation without a break lasting more than 3 hours (Simpson & Kemp, 1982). It was often difficult to clearly delineate storm events in the study area as the frontal systems which dominate the Cape winters, may result in up to 2 weeks of almost continuous drizzle and mist. Yet even during the wettest months of the year much of the runoff is baseflow and thus of a poorer water quality (Figure 15).

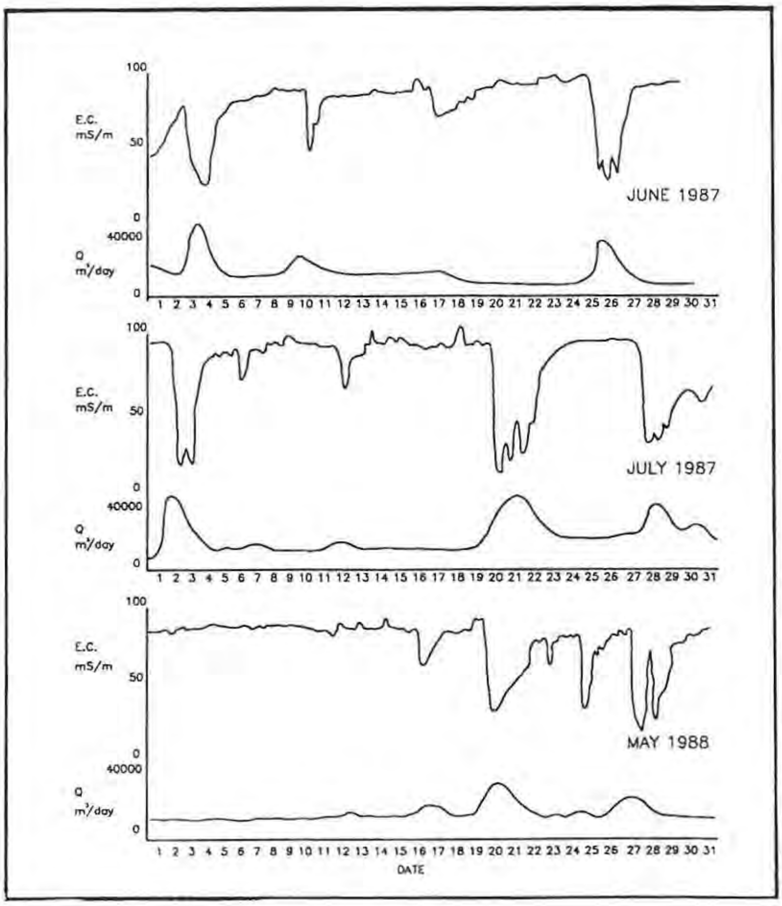


Figure 15 Hydrographs of stormwater discharge and salinity trends.

Table 9 A comparison between typical stormflow and baseflow water quality

DETERMINANT	P 01B		P 02B		P 03C		P 04B		P 04C		P 05B		P 09B		P 06A		P 7In		P 7S		P 10A		P 10B	
	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE	STORM	BASE
Potassium (K)	1.4	3.8	1.7	5.4	4.2	8.4	3.4	7.4	3.5	7.7	2.3	5.4	1.5	1.1	2.5	7.4	3.4	6.7	5.3	7.4	3.3		8.0	13.3
Sodium (Na)	25	41	29	71	32	105	32	97	30	98	19	141	18	173	23	108	34	89	69	82	41		390	651
Calcium (Ca)	10.4	23.7	12.3	29.4	21.1	40.9	20.1	37.9	19.8	38.4	13.1	47.2	9.3	53.7	14.9	38.5	18.3	32.7	35.1	26.7	16.8		146.9	155
Magnesium (Mg)	3.5	5.1	4.5	11.2	5.3	14.1	5.1	14	4.9	13.8	2.2	15.8	2.3	18.3	3.4	14.7	5.1	11.2	10.6	10.4	3.5		47.8	67.7
Ammonia as N	<0.05	<0.05	<0.05	0.090	<0.05	0.420	0.070	0.090	0.070	0.110	<0.05	0.150	<0.05	0.060	<0.05	0.080	0.160	0.110	<0.05	0.140	0.580		0.060	0.990
Cadmium (Cd)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01		<0.01	<0.01
Copper (Cu)	<0.01	0.010	<0.01	<0.01	0.010	<0.01	0.010	<0.01	0.010	<0.01	0.040	0.012	0.010	<0.01	0.010	<0.01	<0.01	<0.01	0.010	<0.01	0.010		0.010	0.010
Chromium (Cr)	<0.02	<0.01	<0.02	<0.01	0.030	<0.01	<0.02	<0.01	<0.02	0.020	0.040	0.018	<0.02	0.013	<0.02	0.015	<0.02	0.013	<0.02	<0.01	<0.02		<0.02	0.022
Manganese (Mn)	0.020	<0.01	0.030	<0.01	0.030	<0.01	0.020	<0.01	0.020	<0.01	0.020	<0.01	0.110	<0.01	0.040	<0.01	0.030	<0.01	<0.01	0.011	0.070		0.030	0.019
Iron (Fe)	0.860	0.254	1.580	0.367	2.110	0.139	1.530	0.235	1.690	0.346	1.320	0.223	1.420	0.188	1.630	0.288	1.470	0.396	0.160	0.190	2.670		0.150	0.334
Nickel (Ni)	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	0.010	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02		<0.02	0.016
Lead (Pb)	0.030	0.030	0.040	0.031	0.040	0.029	0.050	0.026	0.050	0.031	0.070	0.023	0.050	0.020	0.050	0.020	0.040	0.021	<0.02	0.021	0.050		0.020	0.021
Zinc (Zn)	0.013	<0.01	0.024	<0.01	0.038	0.012	0.039	<0.01	0.046	0.019	0.385	0.088	0.276	0.019	0.159	0.023	0.080	0.015	0.011	0.012	0.149		<0.01	<0.01
Sulphate (SO4)	8	22	11	42	17	56	25	63	20	61	10	83	10	84	14	71	22	56	44	51	24		197	257
Chloride (Cl)	35	59	46	104	47	178	51	156	47	158	32	207	25	250	37	169	52	141	111	128	68		679	1171
T.Alkal (CaCO3)	40	62	37	78	61	77	43	75	50	75	28	118	25	162	36	77	45	74	84	67	34		266	229
Nitrate as N	0.26	3.07	0.75	4.66	1.50	6.27	2.05	4.05	1.67	5.12	0.36	1.46	0.18	0.06	0.82	4.87	1.41	1.43	2.06	0.34	0.56		<0.05	0.23
Phosphate as P	<0.05	<0.05	<0.05	<0.05	0.12	0.10	0.09	<0.05	0.09	0.05	<0.05	0.10	<0.05	<0.05	<0.05	0.36	<0.05	0.06	0.06	0.13	0.19		0.09	0.14
UV 545 Abs.	0.020	0.012	0.022	0.020	0.025	0.008	0.017	0.012	0.018	0.010	0.010	0.011	0.017	0.014	0.019	0.011	0.016	0.016	0.014	0.017	0.060		0.018	0.022
UV 275 Abs.	0.790	0.832	0.960	0.996	0.971	0.658	0.596	0.971	0.730	0.863	0.284	1.013	0.285	1.208	0.509	0.854	0.580	0.997	0.874	1.086	0.959		1.754	2.164
UV 254 Abs.	1.002	1.081	1.211	1.263	1.223	0.864	0.766	1.271	0.925	1.128	0.374	1.342	0.363	1.594	0.650	1.122	0.744	1.296	1.125	1.409	1.190		2.361	2.918
Dis.Org.Carbon	6.3	8.7	7.2	9.3	9.2	7.5	5.5	10.6	7.3	9.4	3.8	14.3	3.5	16.9	4.7	11.0	6	10.7	10.3	12.3	6.9		11.9	33.3
Conductivity	22	38	26	60	33	86	33	80	31	80	20	103	17	118	24	85	33	71	63	64	32		290	405
pHs (20deg C)	8.9	8.4	8.9	8.2	8.5	8.1	8.6	8.1	8.6	8.1	9.0	7.9	9.2	7.7	8.8	8.1	8.7	8.2	8.1	8.3	8.8		7.1	7.1
TDS (Calc)	141	240	166	384	211	550	208	512	198	512	128	659	106	755	150	544	208	454	403	410	205		1856	2592
HARDNESS (CaCO3)	40	80	49	120	75	160	71	152	70	153	42	183	33	209	51	156	67	128	131	109	56		564	666
% Balance	2.20	2.64	0.65	1.86	1.01	2.12	2.43	1.11	2.00	0.95	1.87	0.74	2.67	2.61	1.55	1.90	0.28	1.77	1.67	1.51	3.75		0.52	2.3
CATIONS meq\L	1.93	3.49	2.31	5.61	2.98	8.02	2.90	7.45	2.81	7.51	1.74	9.95	1.45	11.73	2.09	8.02	2.91	6.6	5.78	5.96	3.04		28.45	42.02
ANIONS meq\L	1.98	3.58	2.33	5.72	3.01	8.19	2.97	7.53	2.87	7.58	1.70	10.03	1.42	12.04	2.12	8.17	2.92	6.72	5.87	6.05	3.15		28.6	42.99

Units : mg.L^{-1} [EC in ms.m^{-1}]

Storm events were monitored on a continuous basis during two rainy seasons in order to study any possible first flush effect. Although a first flush effect was detected confirming the earlier findings of researchers such as Mance & Harman (1978), Hoffman *et al.* (1982), Simpson (1986), Hvitved-Jacobson et al. (1987), it was of relatively minor concern. The hydrographs in Appendix F illustrate how during storm events the water quality (in this case depicted by salinity) of the first flush effect remains lower than the baseflow. Only once during the 1988 rainy season was the salinity higher than the baseflow and in this case the volume of water during the first flush was very small in comparison with the remaining peak flow. These results are similar to those of Cordery (1977) for a sandy urban catchment in Sydney. The nutrients and major ions had very similar trends to the salinity as depicted in the hydrographs. The organics, as depicted by DOC, often exhibited the more characteristic "first flush" effect. The concentrations were however rather erratic and although periods of peak flow resulted in a corresponding rise in organic concentrations no general trend could be identified. Some of the highest concentrations were recorded during periods of baseflow.

The fact that stormflow basically only occurs during the winter months and is in most respects of superior quality suggests that there may be a seasonal trend in the stormwater runoff quality. This seasonal trend can be detected in the total stormwater runoff (P06A) water quality variable concentrations. Figure 16 shows the chloride trend and the arrows highlight the seasonal increase in concentration. The seasonal trend is in fact reflected in the baseflow which suggests that the water quality is a result of a large component of rapid interflow during winter and predominantly delayed interflow in summer.

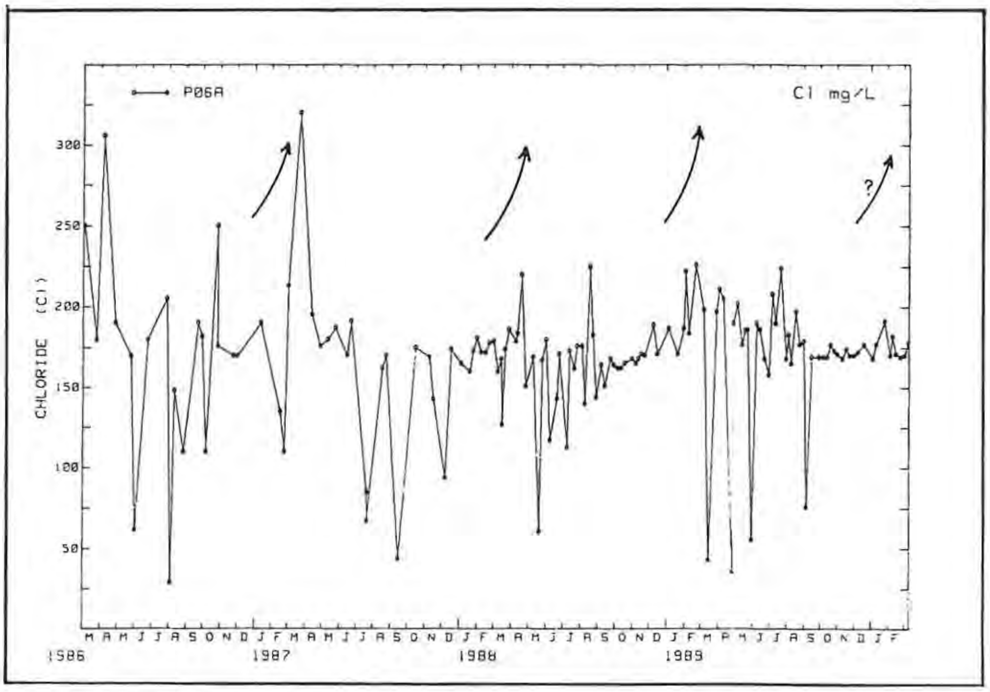


Figure 16 P06A Chloride concentration showing a vague seasonal trend

The seasonal trend seen in the nitrate concentrations of the total stormwater runoff is anomalous compared to the other water quality variables. The concentration increases during the rainy season yet is not related to storm events as these in fact result in very low concentrations (Figure 17). This trend was probably due to the rising groundwater levels during the rainy season, resulting in increasing nitrification and due to its mobility, being rapidly transported into the stormwater runoff.

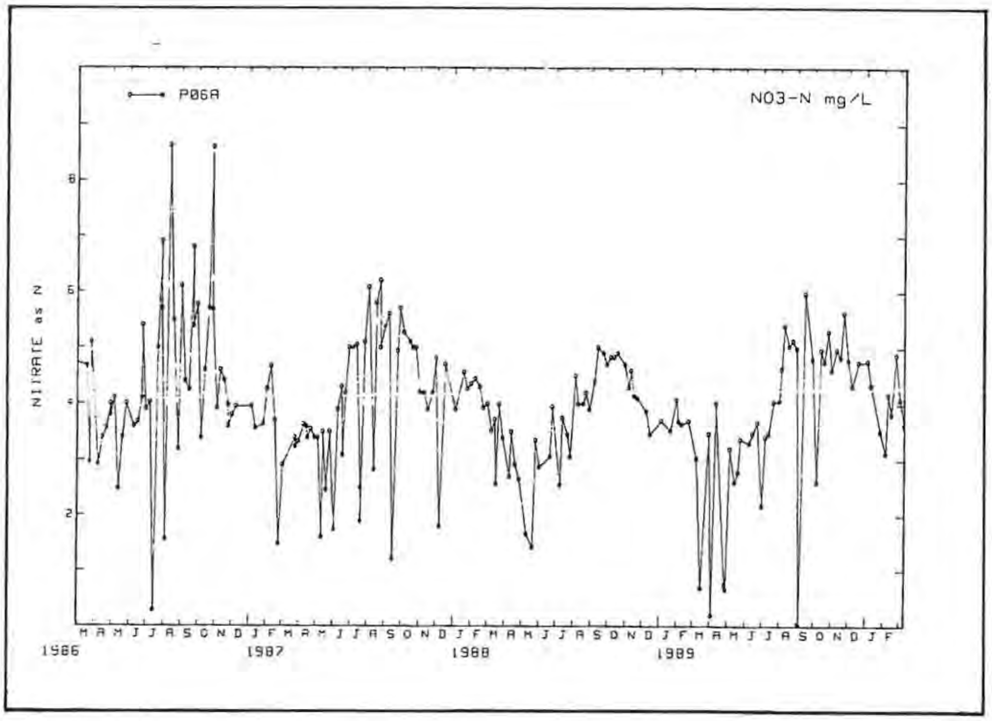


Figure 17 Total stormwater runoff nitrate trend

Because of the importance of the baseflow component to the overall stormwater runoff it was studied in isolation. The baseflow water quality analysis (Appendixes C, D & E) indicate a marked spatial variation within the catchment. The salinity, as measured by electrical conductivity (Figure 18) illustrates this spatial variation well and has a similar trend to the other water quality variables. The stepped appearance coincides with urban zones within the catchment suggesting that the type of landuse/urbanization is a controlling factor in stormwater quality. Stations P1 and P2 represent the newer more upmarket residential suburbs, while P3 and P4 represent stormwater originating in the older, central residential suburbs that have lower income groups and higher population densities. The slightly higher concentrations in P3 is possibly a reflection of the presence of the central shopping area. The salinity in the remaining three stations again coincides remarkably well with the different industrial zones: P5 representing the light industrial and commercial zones; P9 the heavier industrial zone; and P10 the noxious industrial zone.

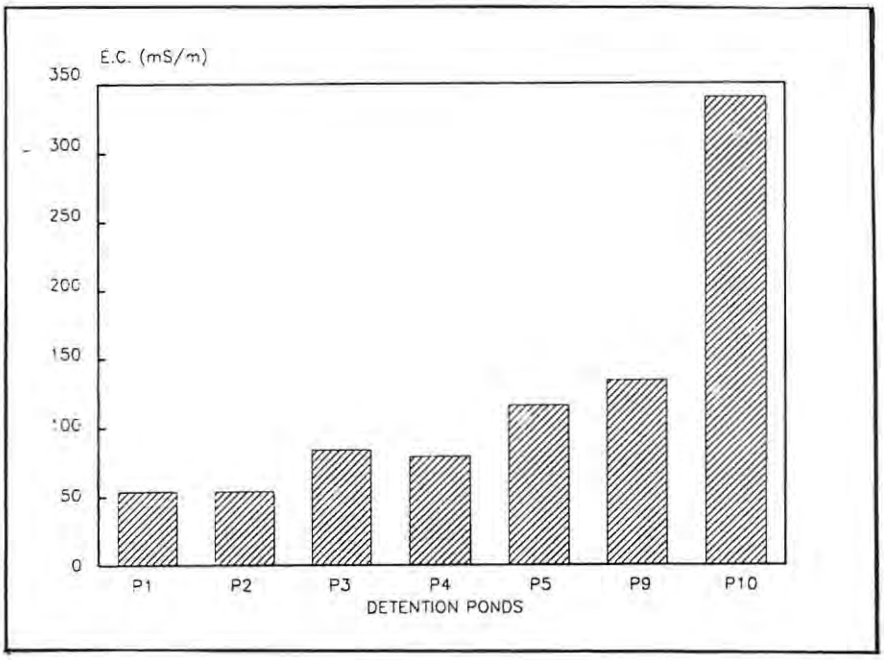


Figure 18 The average salinity in the different stormwater basins

A further factor that may influence the spatial variation is the resident groundwater quality. The importance of groundwater to the baseflow component of the stormwater runoff has already been stressed (Chapter 2). Very little data is available on the groundwater quality within the urban area, but that which is available (Table 10) indicates a definite spatial variation. The EC trend is, for example, identical to that depicted in Figure 18. A fairly close correlation can be seen with salinity, major ions and dissolved organic carbon. The dissolved organic carbon (Appendix D7) concentration in the groundwater was caused by peat horizons in the Mamre member of the Springfontein Formation. In the area around the noxious industrial pond (P10) the peat forms a compact organic unit more than a metre in thickness.

The effects of urbanization and human activity is the dominant factor influencing stormwater runoff quality. Both the potassium and ammonia trends reflect human contamination. The potassium concentrations are well above normal groundwater levels and appear to increase with increased population density. The low living standards and cultural background combine to result in human and domestic animal excreta forming a major source of pollution. Although the entire area is serviced by waterborne sewerage, there still appears to be a lot of outdoor ablution taking place.

Table 10 Groundwater quality trends in the Atlantis urban catchment

DETERMINANT	ATLANTIS URBAN AREA		
	NORTH	CENTRE	SOUTH
Potassium	3.8	0.9	2.4
Sodium	41	182	285
Calcium	24	35	109
Magnesium	5	24	29
Ammonia	0.0	1.0	0.4
Chloride	135	330	492
Sulphate	22	45	46
T. Alkalinity	65	85	285
Nitrate	3.0	0.0	0.0
pH		6.5	6.9
EC	64	126	210

UNITS = $mg.L^{-1}$, except EC = $mS.m^{-1}$

The effects of construction work as a catalyst for the transfer of pollutants (Ellis, 1976) was also identified in the study area. The stormwater runoff quality at basin 1 in the new residential suburbs improved as soon as the major period of construction ended after 1987. The high concentrations were not due to a single pollution episode but occurred throughout the wet season. The lower concentrations recorded at station P2 being due to dilution by the additional stormwater runoff added from sub-catchment 2.

The nitrate concentration (Appendix D5) highlights the residential catchments as a source area. The contrast between the residential and industrial areas indicates that atmospheric fallout is not the major source of nitrate as found in other studies (Halverson *et al.*, 1984; Simpson, 1986; Ebbert & Wagner, 1987; and Ng, 1987). A follow-up investigation in the basin 3 catchment traced the pollution to the site of an old stock pen. It is thus thought that the major source of nitrate and possibly to a lesser extent, potassium, is the manure which accumulated in stock pens used by the farmers in this area before urban development took place. The decreasing trend seen during the study period indicates that the source is slowly being depleted. The increase seen during 1989 in the central and southern area of Atlantis may, however, be related to increased washoff as these areas have a greater component of overland flow, especially as above average rainfall was received during 1989.

The stormwater runoff from the industrial catchments is not only of a poorer quality than the residential catchments, but also experiences greater fluctuations in quality as a result of industrial spills, leakages and illegal flushing. The salinity range, for example, during 1989 was 897 $mS.m^{-1}$ in the Pond 5 catchment and 18 $mS.m^{-1}$ in the total residential stormwater runoff (Appendix C). The examples given in Table 11 illustrate the danger which the industrial stormwater could pose to the overall stormwater quality. This is especially true in the case of metals and other toxic constituents used in industries such as textiles (dyes), printing works, chemical industry and plating works (Overton & Meadows, 1976).

Table 11 Examples of the stormwater runoff quality during spillages in the industrial catchment

Determinants	P5 Industrial Area		P9 Industrial Area		P10 Industrial Area	
	Normal	Spillage	Normal	Spillage	Normal	Spillage
Potassium as K	5.2	29.5	4.2	12.9	11.7	42.7
Sodium as Na	163	1255	184	212	544	
Calcium as Ca	62.5	39.1	68.0	71.0	142.3	
Magnesium as Mg	19.8	0.8	24.6	21.7	60.6	
Ammonia as N_4	<0.1	0.4	0.1	0.4	0.3	416.5
Sulphate as SO^4	83	327	128	127	256	
Chloride as Cl	236	231	264	299	950	504
T.Alk. ($CaCO_3$)	107	2284	161	167	179	
Nitrate as N	<0.1	0.4	1.5	8.3	<0.1	<0.1
Phosphate as P	0.1	0.6	0.1	4.5	<0.1	13.7
Absorb. UV 545	0.034	0.093	0.013	0.045	0.021	0.070
Absorb. UV 275	1.229	3.369	1.256	1.381	2.006	4.091
Absorb. UV 254	1.581	4.222	1.675	1.769	2.672	4.148
Dis. Org. Carbon	36.5	92.5	19.3	17.7	30.9	802.0
Conduct. mS/m	118	1000	142	154	370	485
pH	7.0	12.2	8.1	7.7		

Normal = The average water quality under normal (general) conditions during the period prior to the respective spillage. If not specified units = $mg.L^{-1}$

Fortunately the volumes of stormwater runoff (during baseflow conditions) discharged from the industrial catchments remain small and these areas thus have minimal effect on the overall stormwater quality. Figure 19 illustrates the relatively minor effect which the Pond 5 industrial catchment had on the overall stormwater runoff salinity (P04D is before addition of pond 5 water and P05C after). During times of major spills/illegal flushing, the pollutants are not always removed by the pollution control features in the respective detention basins and are detected in the stormwater runoff entering the final retention basin (Pond 7).

All the industrial stormwater detention basins have pollution reduction features but these appear to be of limited value. The stormwater entrance and exit points at Pond 6 were monitored for a year in order to gauge the basin's effectiveness in reducing pollution. Unfortunately it was

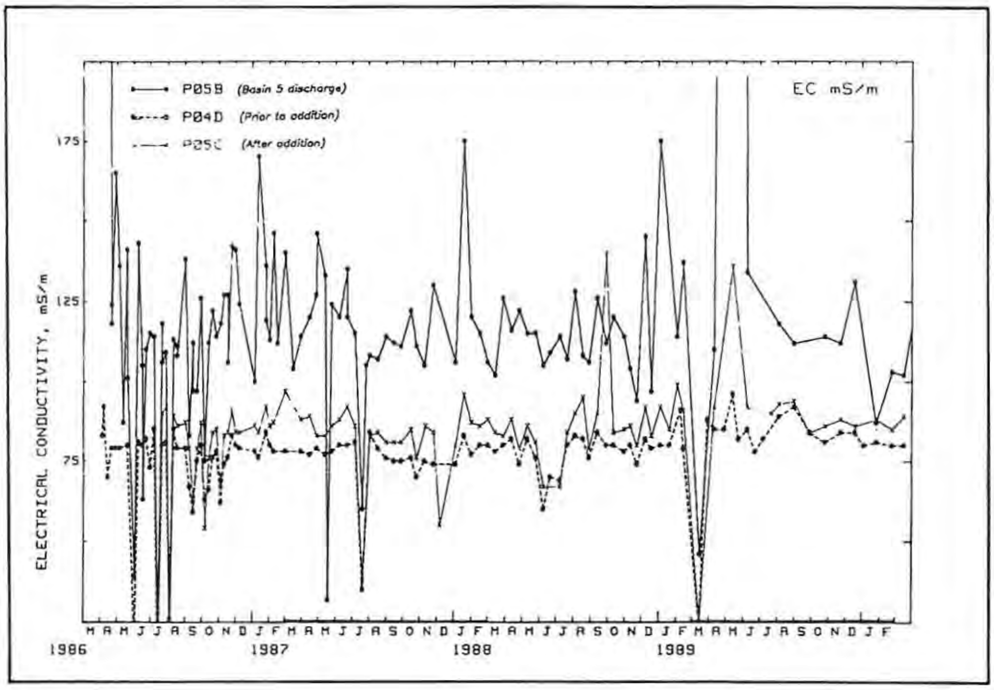


Figure 19 Stormwater salinity (EC) trends illustrating the effect which Basin 5 (Industrial catchment) has on the overall stormwater runoff salinity.

difficult to assess the residence time. During periods of baseflow, the residence time was probably several days whereas during storm events it was hours. Table 12 gives a few examples of water quality at the entrance and exit points of basin 6 during 1988. The 28 March, 31 October, 23 November and 20 January results are examples of prolonged periods of baseflow conditions and indicates that the reed beds help reduce the ammonia, nitrate and phosphate concentrations. This confirms the findings of the study by Martin & Müller (1987) in the USA. The 25 May and 8 June illustrate the "time delay" in the basin as the catchment experienced a storm event two days prior to sampling. The outlet water still contained a large component of stormflow and therefore had better quality water. The 26 April and 13 September are examples of the autumn and spring transition period between dominantly baseflow conditions and the winter stormflow conditions. The 8 July and 29 August represent samples collected during a period of stormflow and suggests that during periods of peak flow the basin continued to act as a pollution reduction facility. This is, however, by no means conclusive and requires an in depth investigation before any firm conclusion may be made. It is also not clear how much of a scouring effect there is within the detention basins at the start of storm events, especially in Basins 5 and 9.

Table 12 A comparison between stormwater quality flowing in and out of Basin 6 during 1988

DETERMINANT	28 MAR		26 APR		25 MAY		8 JUN		8 JUL		29 AUG		13 SEPT		31 OCT		23 NOV		20 JAN	
	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET	INLET	OUTLET
Potassium (K)	7.2	7.3	6.9	7.8	7.5	6.3	6.5	4.2	5.6	5.2	7.6	6.0	8.0	9.0	8.0	6.8	7.3	7.5	6.8	7.6
Sodium (Na)	112	114	93	103	104	83	77	44	71	56	88	68	100	124	105	107	110	112	107	114
Calcium (Ca)	40.7	42.9	39.0	40.4	39.5	33.3	34.4	22.4	33.5	26.1	44.4	35.8	46.8	52.2	40.5	41.3	40.2	41.1	37.8	39.9
Magnesium (Mg)	15.3	16.2	14.0	10.6	15.7	12.4	10.8	6.8	10.3	8.1	13.4	10.2	15.3	14.0	15.5	15.5	15.1	15.6	15.2	15.9
Ammonia as N	0.6	0.1	0.1	0.6	0.1	0.2	3.8	0.0	0.3	0.1	0.4	0.1	0.1	0.3	0.1	0.1	0.1	<0.1	0.3	0.2
Sulphate (SO4)	57	59	53	57	57	46	48	25	40	33	49	38	60	71	63	63	59	60	63	69
Chloride (Cl)	186	183	151	156	167	137	117	73	113	87	144	109	151	181	168	167	170	175	171	185
T.Alkal (CaCO3)	85	94	81	101	81	75	99	54	66	58	96	84		116	82	92	82	94	80	89
Nitrate as N	3.4	2.0	2.7	1.7	3.4	1.9	<0.1	1.2	2.6	1.5	3.9	2.6	5.2	4.9	4.7	3.1	4.1	2.6	3.5	1.5
Phosphate as P	0.1	<0.1	0.0	0.5	<0.1	<0.1	1.0	0.1	0.6	0.4	<0.1	<0.1	<0.1	0.6	0.1	0.1	<0.1	<0.1	0.1	<0.1
UV 545 Abs.	0.012	0.007	0.013	0.017	0.010	0.009	0.028	0.006	0.014	0.012	0.025	0.017	0.012	0.024	0.015	0.015	0.011	0.014	0.007	0.009
UV 275 Abs.	0.814	0.840	0.885	0.812	0.868	0.754	0.880	0.529	0.649	0.635	0.961	0.875	0.988	1.011	0.933	0.957	0.912	0.950	0.826	0.890
UV 254 Abs.	1.072	1.110	1.154	1.049	1.144	1.000	1.119	0.690	0.851	0.827	1.251	1.136	1.286	1.300	1.218	1.252	1.193	1.235	1.092	1.170
Dis.Org.Carbon	9.7	11.7	11.9	11.8	11	10	12.1	5.8	10	8.6	13.2	11.6	12.2	13.6	11.2	11.7	11.6	12.4	11.3	11.8
Conductivity	90	91	79	82	84	70	66	41	62	50	78	62	90	102	86	88	84	84	87	92
pHs (20deg C)	8.0	7.6	7.8	7.4	7.8	7.3	7.3	7.8	7.5	7.5	7.8	7.2	7.5	7.0	8.3	7.9	7.8	7.3	8.3	7.9

Units : mg.L^{-1} (EC = mS.m^{-1})

The water entering the stormwater system from the noxious industrial stormwater basin (basin 10) is of particularly poor quality (Appendix C12). Pond 10 intersects the groundwater seepage as the pond receives no stormwater baseflow. A comparison between the pond water quality and that in the surrounding boreholes (Table 13) confirms this fact. The groundwater in the surrounding area is of poor quality and varies substantially between boreholes. The quality and variation are due to the peat content in the sands. The base of Pond 10 in fact intersects a compact peat horizon which is more than a metre in thickness and is probably responsible for the high sulphate and dissolved organic carbon concentrations. The stormwater runoff input into Pond 10 (P10A) is of reasonable quality except for ammonia and iron (Table 9). Unfortunately the volume of stormwater runoff is not sufficient to dilute the Pond 10 water to an acceptable level (see "P10B Storm" in Table 9).

Table 13 A comparison of water quality in Basin 10 and the surrounding boreholes

DETERMINANT	BASIN10	BH71 150 m	BH72 100 m	BH95 200 m *
Potassium (K)	9.3	3.2	12.6	2.4
Sodium (Na)	544	821	159	285
Calcium (Ca)	143	260	136	109
Magnesium (Mg)	61	103	23	29
Ammonia as N	0.2	0.5	0.1	0.4
Sulphate (S04)	247	146	72	46
Chloride (Cl)	950	1745	364	492
T.Alkal (CaCO3)	188	220	214	285
Nitrate as N	0.0	0.0	0.2	0.0
Phosphate as P	0.0	0.0	0.1	0.1
UV 275 Abs.	1.740	1.091	0.605	1.579
UV 254 Abs.	2.410	1.513	0.813	2.098
Dis.Org.Carbon	23.9	13.9	11.1	25.4
pHs (20deg C)	8.1	6.9	7.1	6.9
Conductivity	370	585	165	210

* Distance from basin

Units : $mg.L^{-1}$ ($EC = mS.m^{-1}$)

5.3 Stormwater quantities

The measurement of stormwater discharges from the catchment formed an important part of the study. Two flow gauging stations were in operation at the beginning of the study (discussed in section 4.4) and several years of data were available. When this field data was screened and verified it was found to contain gross inaccuracies. A series of flow measurements were made over a period of one year using the current flow meter, in an attempt to establish a stage-discharge relationship and a correction factor. The quality of the field data improved dramatically with the introduction of a new flow gauging station at the end point of the stormwater system.

Table 14 summarizes the daily stormwater runoff discharges for one year and illustrates the seasonal variation. Not only does the stormwater contain large components of stormflow during winter but also larger volumes of baseflow. The increased baseflow results from interflow which is to a large extent absent during summer. Average baseflow values range from 2160 m.^{3}day^{-1} (25 L.s^{-1}) in summer to 4752 m.^{3}day^{-1} (55 L.s^{-1}) during the wettest winter month. During 1989 the study area, received above average rainfall and stormflow accounted for 56% of the stormwater runoff discharged from the catchment. Stormflow, however, only contributed to the overall stormwater runoff during 18% of the year.

Table 14 Stormwater runoff volumes discharged from Atlantis during 1989

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1	9840	2160	2160	14800	4752	15630	6318	4925	2938	3154	2592	2837
2	1860	2160	2160	5760	11230	7200	6221	3917	2765	3024	2592	2592
3	1814	2160	2160	3880	4520	4970	59153	3715	2765	3024	2592	2332
4	1814	2160	2160	3880	15760	4750	31379	16348	2765	2894	2592	2074
5	1814	2160	2160	3880	5630	4750	23796	6548	2765	2842	2160	1900
6	1814	2160	2160	3880	4752	4750	13230	4709	2765	2768	4964	1814
7	1814	2160	2160	3880	4752	4750	11151	4666	2765	2686	2506	1814
9	1814	2160	2160	3760	4550	5310	10022	7474	2678	2580	2160	1814
10	1814	2160	14350	3760	9630	5184	9310	6739	2592	2530	2160	1814
11	1814	2260	7210	3700	13010	4957	8240	6739	2592	2478	2160	1814
12	8710	2260	3800	3700	6330	17807	7020	6529	2592	2428	2160	1814
13	30920	2260	3024	3680	4752	5000	6480	6113	2592	2374	2160	1814
14	6370	2160	3024	3640	5530	9148	6394	5303	2592	2322	2160	1814
15	1814	2160	3024	3640	9640	31709	6221	7614	2592	2270	2160	1814
16	1814	2160	3024	3640	54320	21530	5638	4666	2506	2218	2160	1814
17	1814	2160	45530	3640	12980	6048	8397	4406	47287	2160	2160	1814
18	1814	13400	6460	3640	9870	5962	17978	4018	16531	2160	19283	1814
19	1814	14600	3880	3640	4970	5781	8402	3888	5238	5014	10076	4374
20	1814	53240	3880	3640	4750	6613	10422	3880	5045	3168	2371	24433
21	1814	8760	5913	4450	4750	5216	7135	3880	4125	3182	2160	2794
22	1814	3000	3680	3880	4750	4953	6480	4455	3802	3024	2355	1952
23	1814	2160	3680	8670	4750	4925	6194	4115	3715	2765	2419	1678
24	1814	2160	3680	4030	8925	7767	5373	3880	3715	3195	2419	1883
25	1814	2160	3680	46500	59230	8428	4925	3880	3715	2659	2419	1685
26	1814	2160	3680	18460	22640	30913	4925	4158	3715	2592	2419	1681
27	1814	2160	3680	7130	6330	45539	4925	9470	3715	2592	2290	1814
28	1814	2160	3680	6330	4750	8062	4825	3751	3355	2592	2160	1814
29	11470	2160	3680	9870	4750	16400	5913	3586	3283	2592	2160	
30	9280	2160	5940	13850	4750	7916	4957	3586	3283	2592	2160	
31	3500		12450		5370	7031		3302		2592	3618	
TOTAL	123672	147300	170389	210970	327273	323749	321892	188282	153553	85105	100037	79425

TOTAL FOR YEAR 2231647

CAPE HYDROLOGICAL YEAR : March - February

UNITS = cu metres

The flow gauging exercises periodically undertaken throughout the stormwater system were not as successful as was hoped. The problems experienced and reasons for the erratic results are detailed in Section 3.2. The results do, however, provide a reasonably accurate estimate of the relative discharge from the different sub-catchments (Table 15).

Table 15 Average discharges from the different sub-catchments as a percentage of the total stormwater baseflow component

SUB-CATCHMENT	DISCHARGE as a % of total baseflow
Basin 1	2
Basin 2	8
Basin 3	32
Basin 4	40
Basin 5	14
Basin 6	4

The large volume of stormwater runoff discharged during storm events makes flow gauging in underground stormwater pipes both dangerous and near impossible. It was, however, observed that the flow from the upper catchments (Basins 1 and 2) did not increase proportionally as much as the other sub-catchments. The volumes of total stormwater runoff are within the ranges predicted by the engineers who planned the system (Bishop, personal communication, 1989).

5.4 Pollutant Loads

One of the most useful sets of data in water quality monitoring is pollutant loads as these combine the water quality data set with the water quantity variables. The difficulties experienced in accurately measuring the water quantity variables in the stormwater system made the calculation of pollution loads more difficult. Table 16 provides average pollutant loads for several sub-catchments during summer baseflow conditions. Average values were used for both the water quality variables and the water quantity variables, and the loads represent the cumulative loads per day.

Table 16 illustrates how, although the industrial stormwater runoff (Basins 5 & 9) had higher concentrations than the residential stormwater runoff (Basins 3 & 4 and Upper Res), their pollutant loads were lower. As a general rule the industrial base flow component is diluted by the residential stormwater runoff and does not pose a serious threat to the overall stormwater quality. A threat does however exist during those times that spills, leakages and illegal flushing take place (see Table 11).

During storm events the addition of the stormflow component greatly reduces the overall concentration of the pollutants, but due to the great volumes of water involved, result in larger pollutant loads. This is illustrated by the example given in Table 17. This may appear rather confusing and lead to the impression that the stormflow component is the major source of pollution. When, however, the baseflow and stormflow components are examined on an annual basis (Table 18) it is seen that the baseflow remains the dominant component, accounting for 61% of the total annual salt load in Pond 7.

Table 16 Average stormwater runoff loads for selected sub-catchments during 1989

DETERMINANT	UPPER RES.		POND 3		POND 4		POND 5		POND 9		TOTAL STMWATER	
	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load	Conc	Load
Potasium	5.4	1.2	8.4	6.0	7.4	6.9	5.4	1.4	1.1	0.1	7.4	16.1
Sodium (Na)	71	15.3	105	74.8	97	90.1	141	36.5	173	7.5	108	233.3
Calcium (Ca)	29.4	6.3	40.9	29.1	37.9	35.2	47.2	12.2	53.7	2.3	38.5	83.2
Magnesium(Mg)	11.2	2.4	14.1	10.0	14	13	15.8	4.1	18.3	0.8	14.7	31.7
Ammonia as N	0.090	0.0	0.420	0.3	0.090	0.1	0.150	0.0	0.060	0.0	0.080	0.2
Iron (Fe)	0.367	0.1	0.139	0.1	0.235	0.2	0.223	0.1	0.188	0.0	0.288	0.6
Sulphate (S04)	42	9.1	56	39.9	63	58.5	83	21.5	84	3.6	71	153.4
Chloride (CL)	104	22.5	178	126.9	156	144.9	207	53.6	250	10.8	169	365.0
T.Alkal(CaC03)	78	16.8	77	54.9	75	69.7	118	30.6	162	7.0	77	166.3
Nitrate as N	4.66	1.0	6.27	4.5	4.05	3.8	1.46	0.4	0.06	0.0	4.87	10.5
Phosphate as P	<0.05		0.10		<0.05		0.10		<0.05		0.36	
Dis.Org.Carbon	9.3	2.0	7.5	5.3	10.6	9.8	14.3	3.7	16.9	0.7	11.0	23.8
TDS (Calc)	384	82.9	550	392.0	512	475.5	659	170.8	755	32.6	544	1175.0

CALCULATIONS DONE USING : average baseflow concentrations
average baseflow discharge volumes

UNITS : concentrations = $mg.L^{-1}$
loads = $kg.day^{-1}$

Table 17 A comparison between typical stormwater runoff pollutant loads ($kg.h^{-1}$) during stormflow and baseflow conditions

DETERMINANT	POLLUTANT LOADS ($kg.h^{-1}$) BASEFLOW	STORMFLOW
Potassium (K)	0.9	9.4
Sodium (Na)	11.6	93.8
Calcium (Ca)	4.2	50.5
Magnesium (Mg)	1.4	14.1
Ammonia as N	0.01	0.44
Iron (Fe)	0.05	4.05
Sulphate (SO_4)	7.3	60.7
Chloride (Cl)	18.3	143.5
T. alkal. ($CaCO_3$)	9.6	124.2
Nitrate as N	0.2	3.89
DOC	1.4	16.6
TDS	59.0	574.1

Discharge values: Baseflow 35 $L.s^{-1}$
Stormflow 766 $L.s^{-1}$

Baseflow data = average values
Stormflow data = as measured at Pond 7 on 8/10/1990

Table 18 Stormwater runoff salt loads during 1989

MONTH	BASEFLOW DISCHARGE cu. metre	%	BASEFLOW LOADS tons	%	STORMFLOW DISCHARGE cu. metre	%	STORMFLOW LOADS tons	%	TOTAL FLOW DISCHARGE cu. metre	TOTAL FLOW LOADS tons
MAR	49680	38	28.6	55	81550	62	23.5	45	131230	52.1
APR	57300	39	33.0	56	90000	61	25.9	44	147300	58.9
MAY*	72536	43	41.8	60	97853	57	28.2	40	170389	70.0
JUN*	85930	41	49.5	58	125040	59	36.0	42	210970	85.5
JUL*	93708	29	54.0	44	233565	71	67.3	56	327273	121.3
AUG*	103467	32	59.6	48	220282	68	63.4	52	323749	123.0
SEPT*	109546	34	59.6	49	212346	66	61.2	51	321892	120.8
OCT	126968	67	73.1	80	61314	33	17.1	20	188282	90.8
NOV	89735	58	51.7	74	63818	42	18.4	26	153553	70.1
DEC	80091	94	46.1	97	5014	6	1.4	3	85105	47.5
JAN	65714	66	37.9	79	34323	34	9.9	21	100037	47.8
FEB	54992	69	31.7	82	24433	31	7.0	18	79425	38.7
TOTAL	989667	44	566.6	61	1249538	56	359.9	39	2239205	926.5

Salt = as determined in TDS

% = as a percentage of the monthly total

* = winter months

TOTAL SALT LOAD : Winter = 508 tons
: Summer = 406 tons

5.5 Wastewater

The parallel, but separate stormwater/sewer system in Atlantis allows for the secondary treatment of the poorer quality wastewater. Thus although raw sewage is generally of a poor water quality, once treated, it can compare favourably with stormwater runoff quality (Cordery, 1977; Field & Fan, 1981; Field & Turkeltaub, 1981; and Gutteridge *et al.*, 1981). The further separation of industrial and domestic wastewater in Atlantis provides additional opportunities for obtaining treated effluent of acceptable quality. Table 19 summarizes a few of the water quality variables in the Atlantis wastewater, both before and after treatment.

Table 19 Atlantis wastewater treatment works : typical analysis

		Wesfleur Domestic WWTW		Wesfleur Industrial WWTW	
		Influent	Effluent	Influent	Effluent
COD	mg.L^{-1}	1040	70	889	96
BOD	mg.L^{-1}	393	9	354	11
Ammonia nitrogen as N	mg.L^{-1}	68	1.6	51	2.4
Oxidised nitrogen as N	mg.L^{-1}	-	19.7	-	8.0
Total nitrogen as N	mg.L^{-1}	91	25.9	79	14.3
Suspended solids	mg.L^{-1}	466	18	239	10
Dissolved solids	mg.L^{-1}	896	832	1132	1009
Total phosphorus as P	mg.L^{-1}	20.4	13	13.7	5.1
Conductivity	mS.m^{-1}	151	118	174	148
Flow measured	MLday^{-1}	2.5	-	3.9	-

Although the water quality of the effluent fulfils the Department of Water Affairs permit criteria, it is not necessarily acceptable for artificial recharge in the aquifer. The industrial effluent should, for example, never be used for artificial recharge of an aquifer that is being exploited for town water supply. This is because any wastewater from an industrial catchment is prone to pollution by a great number of pollutants, many of which remain unaffected by treatment in wastewater treatment plants. Each year the industrial sector develops and synthesizes new chemicals and no amount of treatment could remove the many chemicals which find their way into the waste water.

Factories in Atlantis are not permitted by the WCRSC to dispose of softening waste liquors or dyebath liquors into the sewerage system and have to use special disposal contractors. The high cost of this special effluent disposal as against the relatively low fine for polluting the system makes the dumping/flushing of effluents into the sewerage and stormwater systems rather attractive. This appears a fairly common occurrence and several companies have been caught and prosecuted.

5.6 Concluding remarks

The stormwater runoff from the Atlantis urban catchment was found to have two distinctive components, namely baseflow and stormflow. The sandy nature of the catchment and low income type of urban development result in interflow, especially rapid interflow, constituting a large portion of the stormflow. The baseflow component contributes substantial quantities of discharge throughout the year as a result of the large component of groundwater being drained from the underlying primary coastal aquifer. The study area does thus not have as large a seasonal variation in stormwater runoff volumes as might be expected for a South African catchment with highly seasonal rainfall. The five winter months (rainy season) are in fact responsible for approximately 60% of the annual stormwater runoff.

The stormwater runoff has very definite spatial quality variations which reflect both land use and groundwater quality. Different industrial and construction activities act as distinct point sources and pose the greatest threat to the stormwater runoff quality. The seasonal trend reflected by a number of water quality variables is linked directly to the stormflow/baseflow ratio within the stormwater runoff. The first flush effect is present in the catchment but is of little importance due to the high salinity of the baseflow. The lack of importance is a reflection of the large amount of rapid interflow compared to overland flow in the stormflow component.

The total stormwater runoff, as monitored during the study period, was of an acceptable quality for purposes of artificial recharge of a sandy unconfined aquifer. The industrial stormwater runoff poses the greatest threat to the water quality, as it has a relatively high background salinity and is becoming increasingly susceptible to spills, leakages and illegal flushing.

The domestic effluent, although containing relatively high concentrations of nutrients, does not generally contain the large number of chemical and synthetic pollutants found in industrial effluent. This water if correctly treated and monitored with regard to water quality can constitute an additional source of recharge water.

CHAPTER 6

6. THE ARTIFICIAL RECHARGE BASIN

The artificial recharge system in Atlantis has developed over a period of some 14 years and changed from what was initially an engineering solution for the disposal of treated wastewater and storm-water to what is today a fully fledged artificial recharge system. Thus when the recharge basin (Pond 7) was designed and completed in 1980, its main purpose was for the infiltration of as much water as possible. It was only when the full potential of recharge for the purpose of supplementing groundwater supplies at the Witzand well field was realised that water quality became the overriding control factor.

Plate 6 shows the areal extent of the recharge basin and stilling basin, and their location with respect to the Atlantis urban area, Witzand well field and coast.

PLATE 6 The artificial recharge basin as seen from the coast with Witzand well field in the foreground and Atlantis township and sewage works in the background (upper left corner).

The present artificial recharge system is therefore the result of a number of changes made over a period of ten years. As the management strategy changed, so structural changes were made to the system. This study covers the crucial period of change since 1986 when attempts were made to establish the best compromise between obtaining maximum infiltration and maximum water purification.

6.1 Available water for recharge

Three sources of water are available from the Atlantis urban catchment for recharge purposes, namely, stormwater runoff, groundwater, and treated wastewater. The stormwater system collects both stormwater runoff and groundwater drainage, while the dual sewerage system divides the wastewater into industrial and domestic components. Figure 20 provides some idea of the volumes and water quality of each component available for recharge.

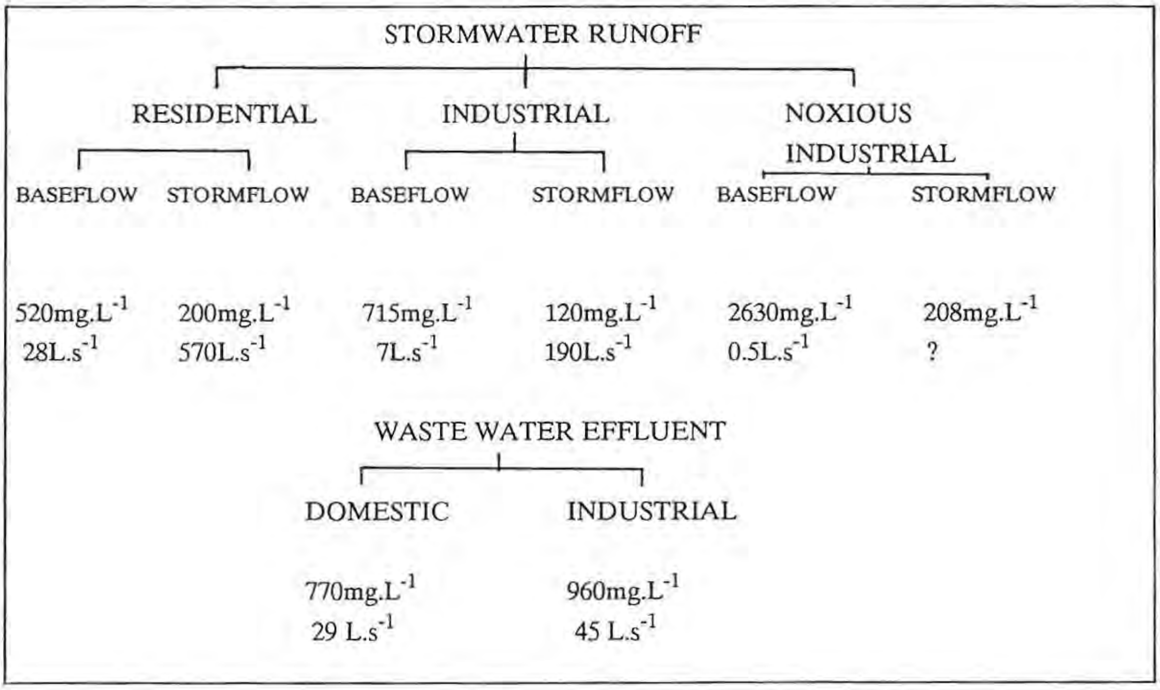


Figure 20 Different types of water available for recharge. (Average TDS values and estimated discharge volumes are given to enable a relative comparison to be made).

The wastewater and baseflow discharge volumes are relatively constant although the baseflow does have a seasonal fluctuation. The stormflow discharge volumes however fluctuate greatly and the values used in Figure 20 are for a typical winter rainfall event and should only be used for comparitive purposes. From a water quality perspective it is clear that both the noxious industrial baseflow and the industrial effluent should not be considered suitable for recharge of an aquifer used for drinking water supply. The remaining components may be combined to provide a number of different recharge options (Table 20).

Table 20 Possible recharge options using treated wastewater and stormwater runoff from the Atlantis urban catchment

No	RECHARGE OPTION	VOLUME* as %	TDS LOAD $t.yr^{-1}$
1	All treated wastewater effluent and all stormwater runoff	100	2991
2	Treated domestic effluent and all stormwater runoff	69	1630
3	All stormwater runoff	49	926
4	All residential stormwater runoff and industrial stormflow	45	813
5	All stormflow (domestic and industrial)	27	360
6	Only residential stormwater runoff	37	694
7	Treated domestic effluent and residential stormwater runoff and industrial stormflow	65	1517
8	Treated domestic effluent (winter only) and residential stormwater runoff and industrial stormflow	53	1106

* Volume given as a % of the total volume (4.5×10^6 $m.^3yr^{-1}$) of wastewater & stormwater discharging from the urban catchment [using 1989 data].

In Table 20 the "volume column" indicates the percentage volume each option represents of the total quantity of water discharged from the urban catchment. In this case the 1989 discharge volumes and salt concentrations were used to calculate loads. The expected volumes of water and pollutant loads for the various recharge options illustrate how the recharge management strategy is a compromise between obtaining quantity and quality. Although the addition of domestic effluent to the stormwater runoff increases the volume of water by some 41% it also boosts the TDS by more than 75%. Similarly the additional volume of water gained by including the industrial baseflow to the residential stormwater runoff and industrial stormflow hardly warrants the increased TDS load. This is especially true when considering the added risk of industrial spills/flushing which the industrial baseflow poses. It would thus appear as if recharge option 4 offers the best compromise or option 7 if the aquifer is able to cope with the added pollutant load. In order to determine the best option that is acceptable, it is necessary to establish what volumes of water need to be extracted and the groundwater quality of the aquifer in the vicinity of the production well field.

6.2 Groundwater requirements

The Witzand well field represents the point at which the natural and artificially recharged groundwater is extracted from the aquifer. Ideally the rate of extraction should not exceed the rate of recharge (natural and artificial) and the water quality should not deteriorate as a result of artificial recharge. The graph in Figure 21 clearly illustrates the increasing groundwater extraction as a result of growing urban demand. The natural recharge of the system has been estimated by Fleisher (1990) to be 4 x $10^6 m^3$ per annum, which is less than that which is being abstracted. It is therefore essential that the artificial recharge be greater than 1.5 x $10^6 m^3$ per annum to avoid groundwater mining. The artificial recharge component will have to increase if future demands are to be met as the natural recharge will remain relatively constant.

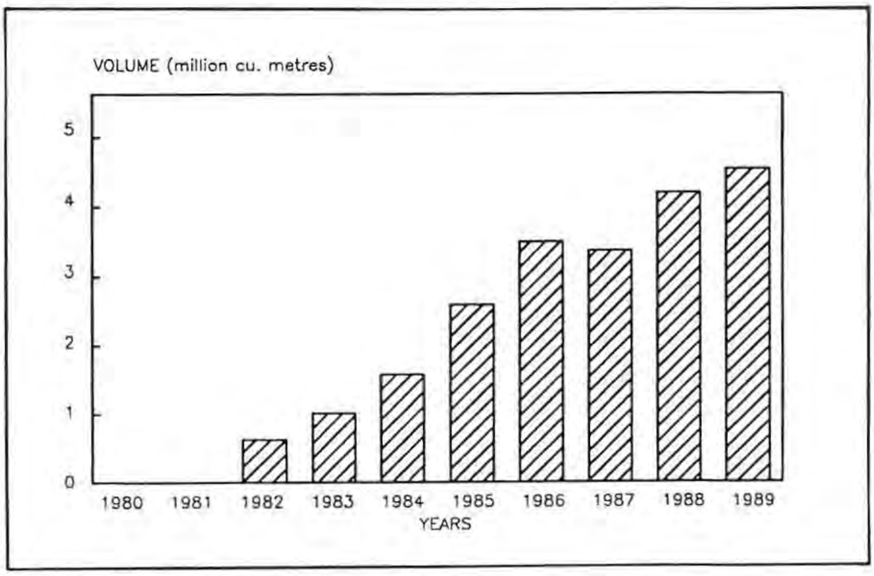


Figure 21 Witzand well field annual production totals

The groundwater quality in the vicinity of the well field varies from north to south with more saline water in the south. There is also a small, but gradual decline in water quality with time. Potassium is the only water quality variable which appears to have decreased in concentration since 1987. Table 21 contains a water quality comparison between different types of water available for recharge and the Witzand well field groundwater quality. Using the groundwater quality in the well field as a datum for what is acceptable, taking into consideration that purification takes place during artificial recharge, it appears that the treated domestic effluent is of too poor a quality to be recharged. The stormwater runoff appears acceptable except for the magnesium concentration which is slightly too high considering that concentration may increase during the recharge process.

Table 21 A water quality comparison between Witzand well field groundwater and available recharge water

Determinand	Stormwater Runoff		Domestic Sewage Effluent	Witzand Well Field	
	Residential	Res. & Ind. Effluent		North	South
Potassium (K)	7.8	7.4	26.1	1.6	2.2
Sodium (Na)	98	113	226	65	116
Calcium (Ca)	39	42	45	98	91
Magnesium (Mg)	14	15	13	9	13
Ammonia (N)	0.1	0.1	1.6	< 0.1	< 0.1
Sulphate (SO_4)	56	71	114	30	60
Chloride (Cl)	161	177	298	119	190
T.Alk. ($CaCO_3$)	79	85	133	222	201
Nitrate (N)	4.3	4.1	3.7	0.5	0.3
Phosphate (P)	0.0	0.0	13	0.0	0.0
DOC	10.3	11.2	12.4	8.6	8.2
pH	7.8	7.7	9.3	7.5	7.6
EC ($mS.m^{-1}$)	84	92	118	86	108

Units = $mg.L^{-1}$

6.3 Existing recharge management strategies

In March 1986 (the beginning of the period on which the study is based) the artificial recharge basin was receiving all the urban stormwater runoff and treated wastewater. This entailed relatively large volumes of water and by mid-July 1986 the recharge basin was in danger of overflowing with possible structural damage to the walls of the basin. Water thus had to be syphoned out of the basin during both July and August. The syphoned water formed a large body of shallow water to the south of the basin and resulted in overland flow across the West Coast Road. The overland flow which included return flow and direct seepage through the basin walls reached the edge of the Witzand well field.

In November 1986 a diversion pipeline was constructed from the sewage works to the Donkergat River. This was as a result of a change in recharge management strategy towards a more water quality orientated approach, and allowed for the diversion of all treated wastewater from the recharge basin. In November/December 1987 the diversion pipeline was also connected to the main stormwater outfall pipeline (Figure 2). This allowed for the diversion of all the stormwater runoff away from the recharge basin during baseflow conditions.

The management strategy during 1987 therefore resulted in a substantial reduction in recharge input volumes. The exceptionally high rainfall experienced in 1987 resulted in larger stormwater runoff volumes and better water quality and would have compensated for much of the diverted water. Unfortunately large quantities of this stormflow was lost along the outfall pipeline to the north east of the basin. The contractors, Basil Starke, required water for construction purposes and pumped water from a manhole along the outfall pipeline. In order to obtain sufficient water, sand bags were used to dam up water inside the pipeline. Unfortunately, when the rains began, it resulted in a total blockage and the collapse of the manhole. The pipeline could not be repaired until after the rainy season and this led to the continual loss of a substantial volume of water which should have flowed into the recharge basin.

The water quality orientated management strategy and below average rainfall during 1988 resulted in a greatly reduced volume of water. All stormwater runoff baseflow was diverted into the Donkergat River until mid-April and once again from 4 November 1988. Thus only stormflow and the slightly less saline winter baseflow was allowed into the recharge basin. This policy allowed the recharge basin to dry out completely by mid-January 1989. The recharge basin floor as a whole was found to contain very little "filter mat" material. It was only in the deeper areas (below the 56 m contour) of the main basin (Figure 22) that a proper filter mat had formed. Plate 7 shows how on drying the compacted filter mat shrunk and formed 15 cm deep cracks/crevices. Once completely dry, the mat of organic and suspended material became extremely light and was easily removed by grading. The dry period extended for more than 1.5 months allowing the strong south-easterly winds to blow away any fine material on the basin floor.

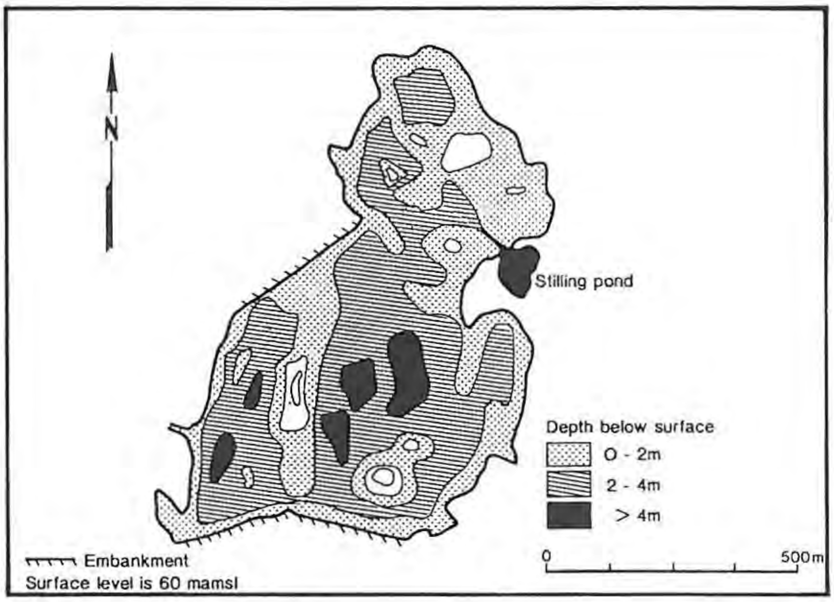


Figure 22 Bathymetry of the artificial recharge basin

Plate 7 The filter mat which formed on the deepest portion of the basin floor. On drying 15 cm deep cracks/crevices formed

The opportunity was also taken to do double-ring infiltrometer tests within the basin. No hydraulic conductivity (K) data is available for the recharge basin prior to recharge operations. A hydraulic conductivity value was also obtained in the undisturbed area surrounding the basin in order to get some idea of what the original basin hydraulic conductivity may have been before recharge began. The hydraulic conductivity values were found to be within the range expected for unconsolidated clean sand (Scott, 1989b). The lower hydraulic conductivities in the deeper portions of the basin reflect the invariable decline which occurs with time as a result of a build-up of suspended material and microbiological growth (Figure 23).

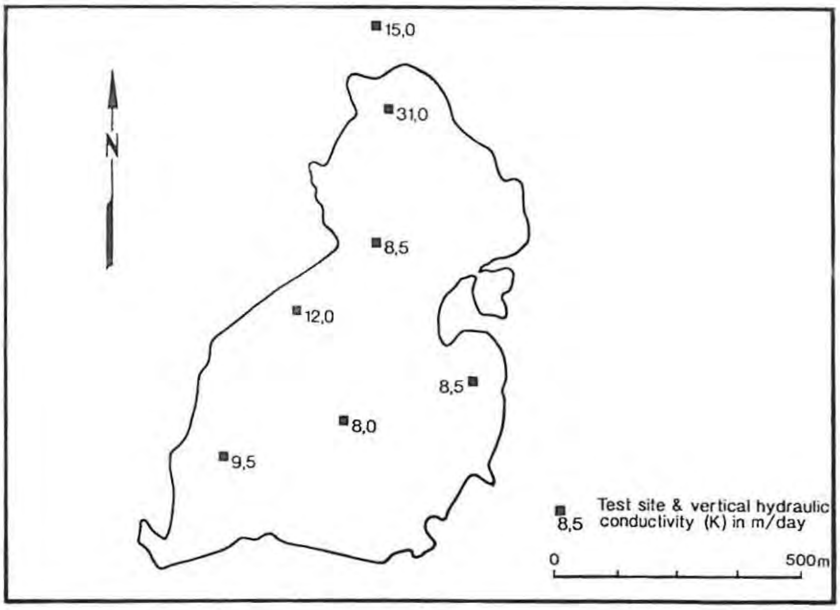


Figure 23 Results from the infiltrometer tests undertaken in the artificial recharge basin (after Scott, 1989b)

The increased demand for water during the 1988/89 summer season led to increased production in the Witzand well field and a decision to increase the volumes of water artificially recharged by including treated domestic effluent. The latter decision was unfortunately a rather hasty decision with all the relevant facts not having been fully considered. The treated wastewater being recharged was not only of domestic origin, but contained a component of industrial effluent which from a water quality point of view, is unacceptable for recharge. A certain percentage of industrial sewage was being treated in the domestic wastewater plant as volumes of domestic sewage were too small to allow for the efficient running of the treatment plant. The decision was finally overruled at the end of May 1989 after which only stormwater runoff was recharged. To offset the loss in recharge volumes, it was decided not to divert the stormwater baseflow to the Donkergat River during the dry summer months.

6.4 Water balance

Meteorologic and volumetric measurements were made throughout the study period for the purpose of determining water balances for the artificial recharge basin. The main components of the water balance are inputs (stormwater runoff and wastewater; precipitation), storage (basin water levels/volumes), and outputs (evaporation; infiltration).

The meteorological data (precipitation and evaporation) were obtained from the Wesfleur Wastewater Treatment Plant weather station. The daily rainfall totals are summarized in Appendix B. The value for direct precipitation into the basin was determined using the relevant recharge basin surface area and precipitation (only storms in excess of 5 mm were taken into consideration). The amount of evaporation from the recharge basin was determined using Symons Tank data and a conversion factor supplied by the Department of Water Affairs. The stormwater runoff and wastewater volumes discharged into the basin are summarized in Appendix G. The 1986 discharge volumes are corrected values as much of the original field data was inaccurate. The corrected data was carefully correlated with the rainfall/runoff relationship established during 1988 and 1989. The recharge basin storage volumes were obtained from the basin water level measurements.

The annual water balances for the recharge basin are summarized in Appendix H and are graphically illustrated in Figures 24, 25, 26 & 27. In the 1986 water balance (Figure 24) the values for July and August had to be estimated as an unknown quantity of water was syphoned out of the basin. The water balances accurately reflect the different management strategies as described in Section 6.3. The changes with time are shown in Figure 28 and clearly reflect the decreased volumes of water discharged into the basin during 1988. The trend for 1989 is anomalous as although larger volumes of water were once again discharged into the basin, the volume of water in the basin remained the same as 1988.

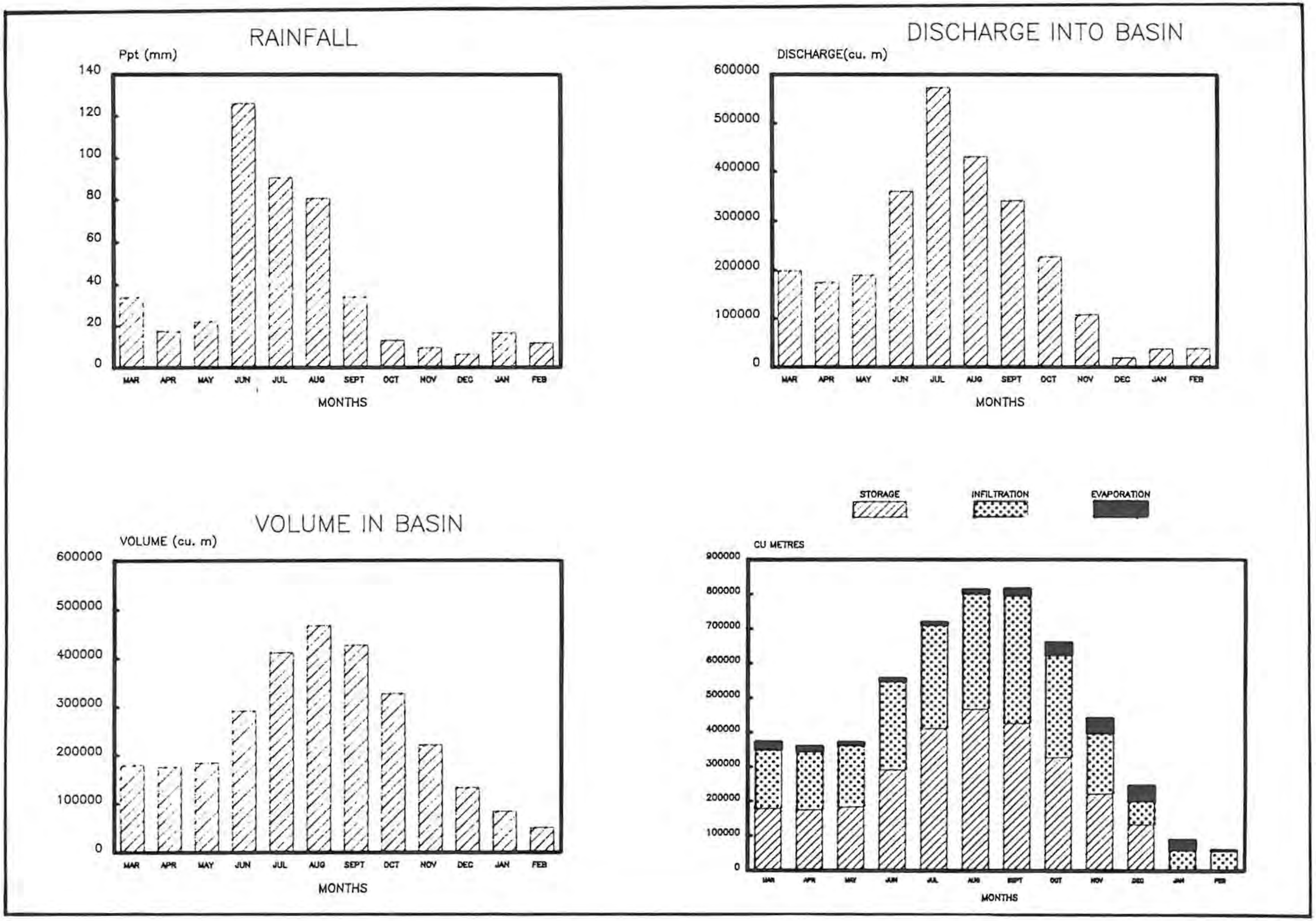


Figure 24 1986 Waterbalance for the artificial recharge basin

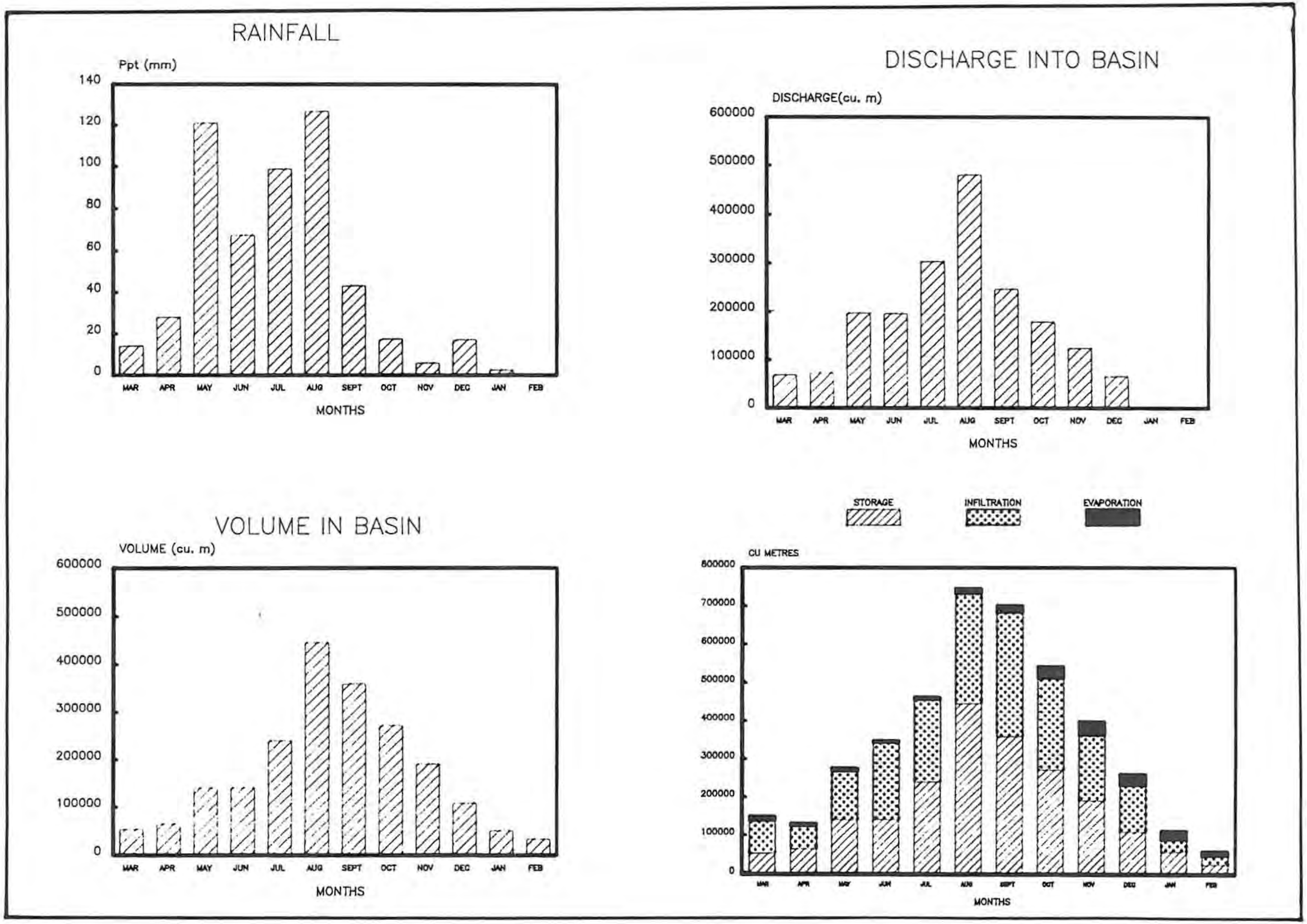


Figure 25 1987 Waterbalance for the artificial recharge basin

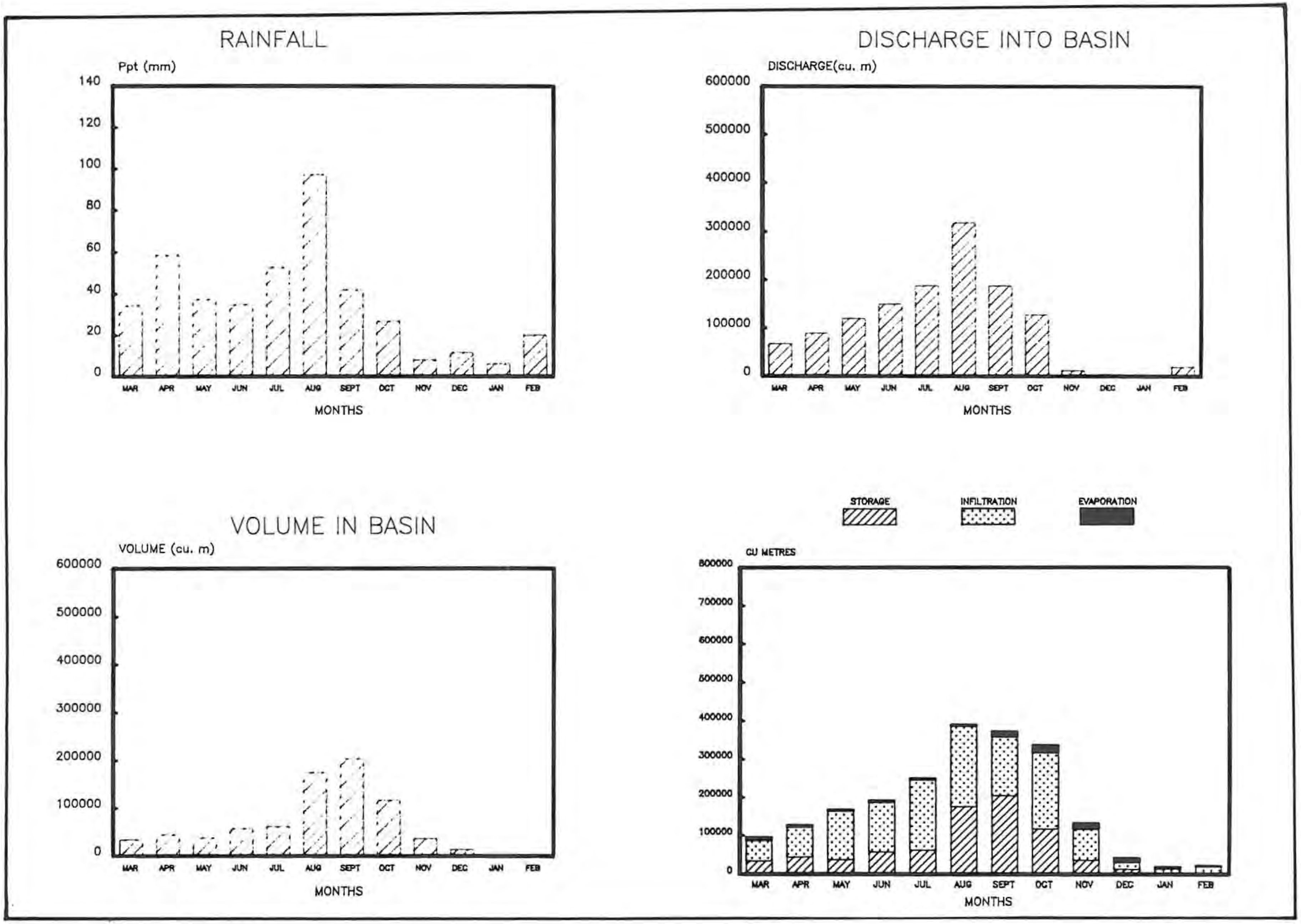


Figure 26 1988 Waterbalance for the artificial recharge basin

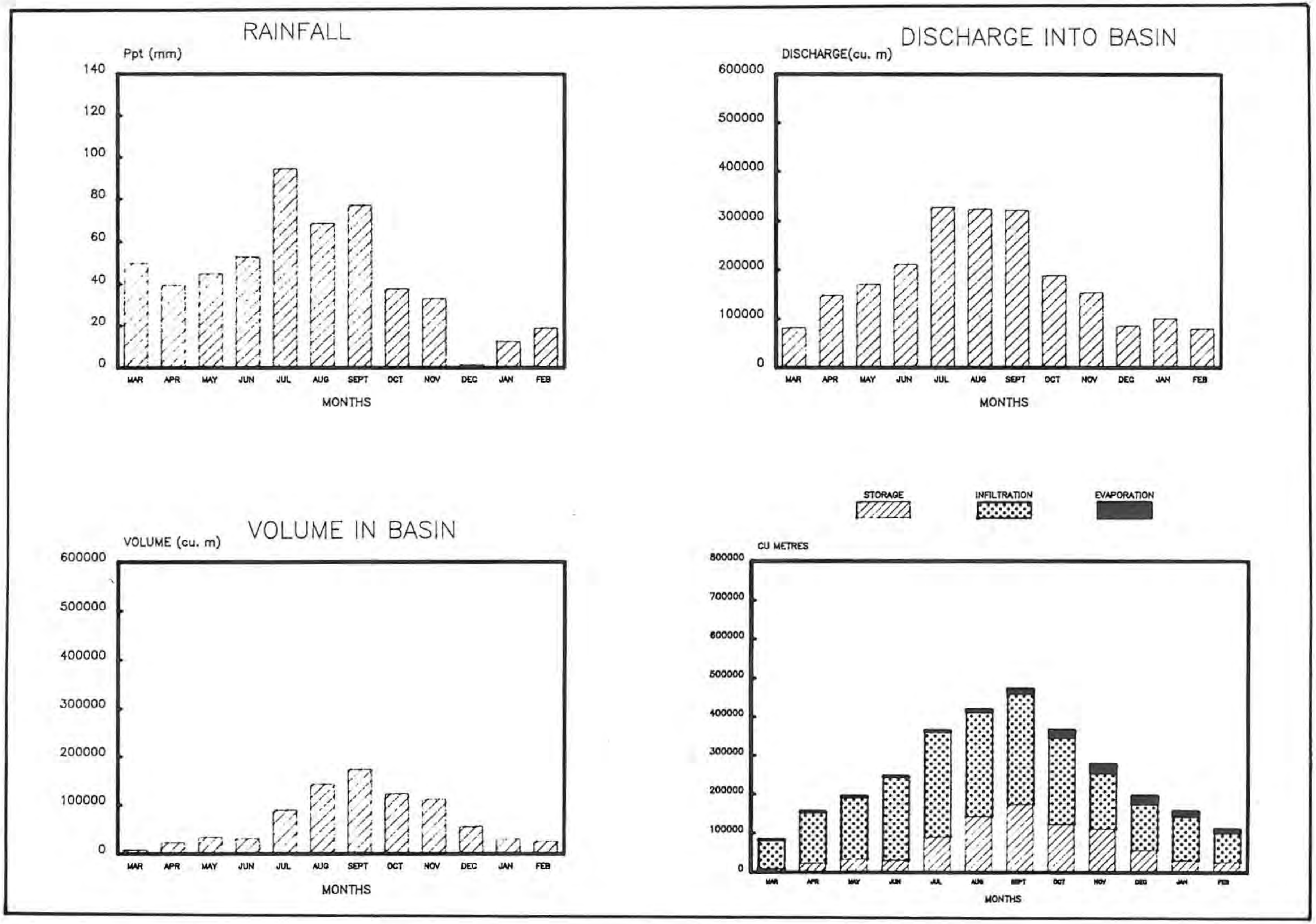


Figure 27 1989 Waterbalance for the artificial recharge basin

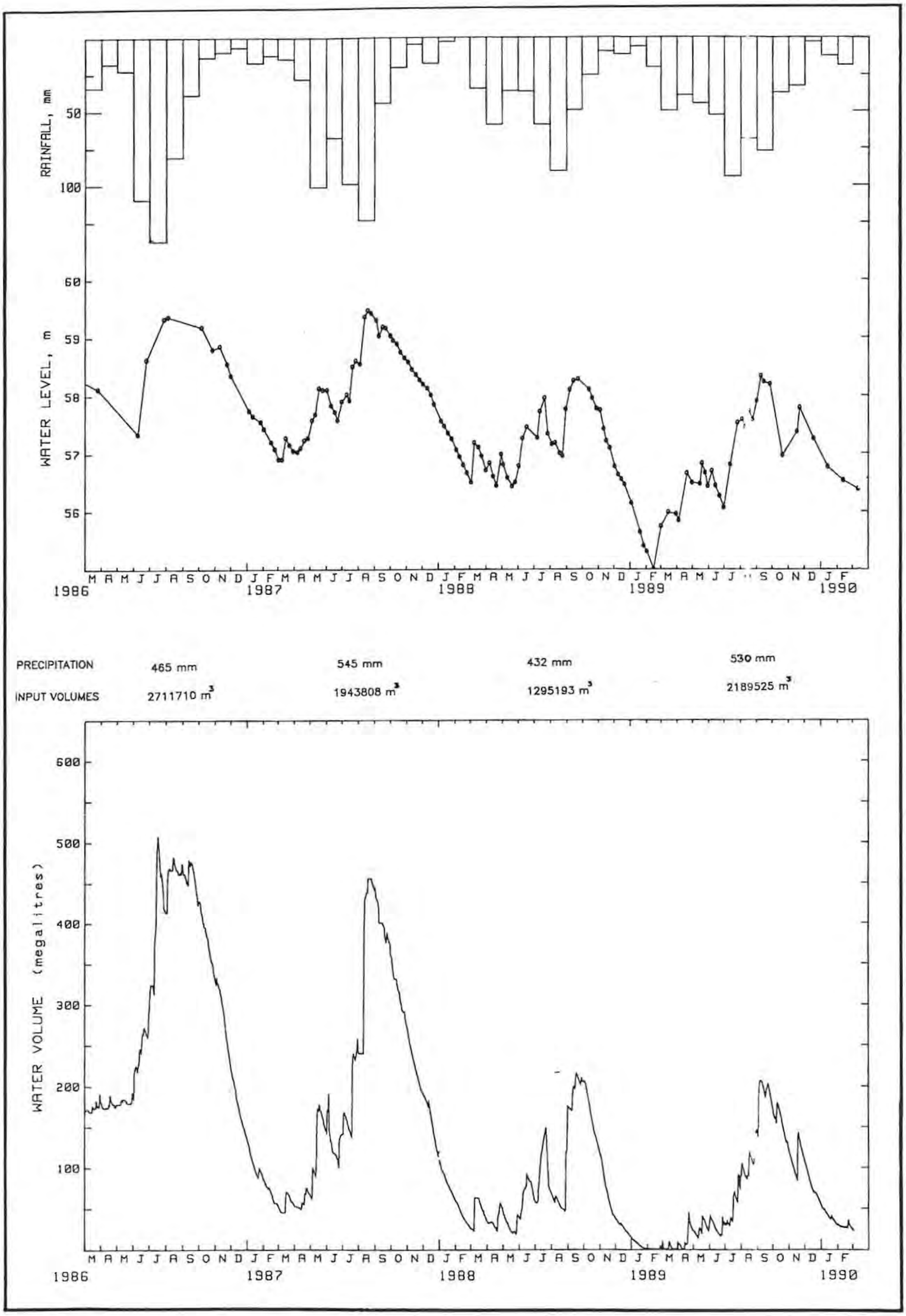


Figure 28 Volumetric trends in the Artificial recharge basin

This behaviour can be attributed to the implementation of a wet/dry cycle. During the summer of 1988/89 the pond was allowed to dry out and was cleaned, thus allowing greater infiltration once the rains began. Figure 29 provides a more detailed comparison for the years 1988 and 1989 and the infiltration figures confirm that at the beginning of the 1989 recharge cycle a large percentage of the water infiltrated leaving very little in surface storage. It was only by July/August 1989 that there had been sufficient recharge to result in a large enough groundwater mound to slow down infiltration substantially.

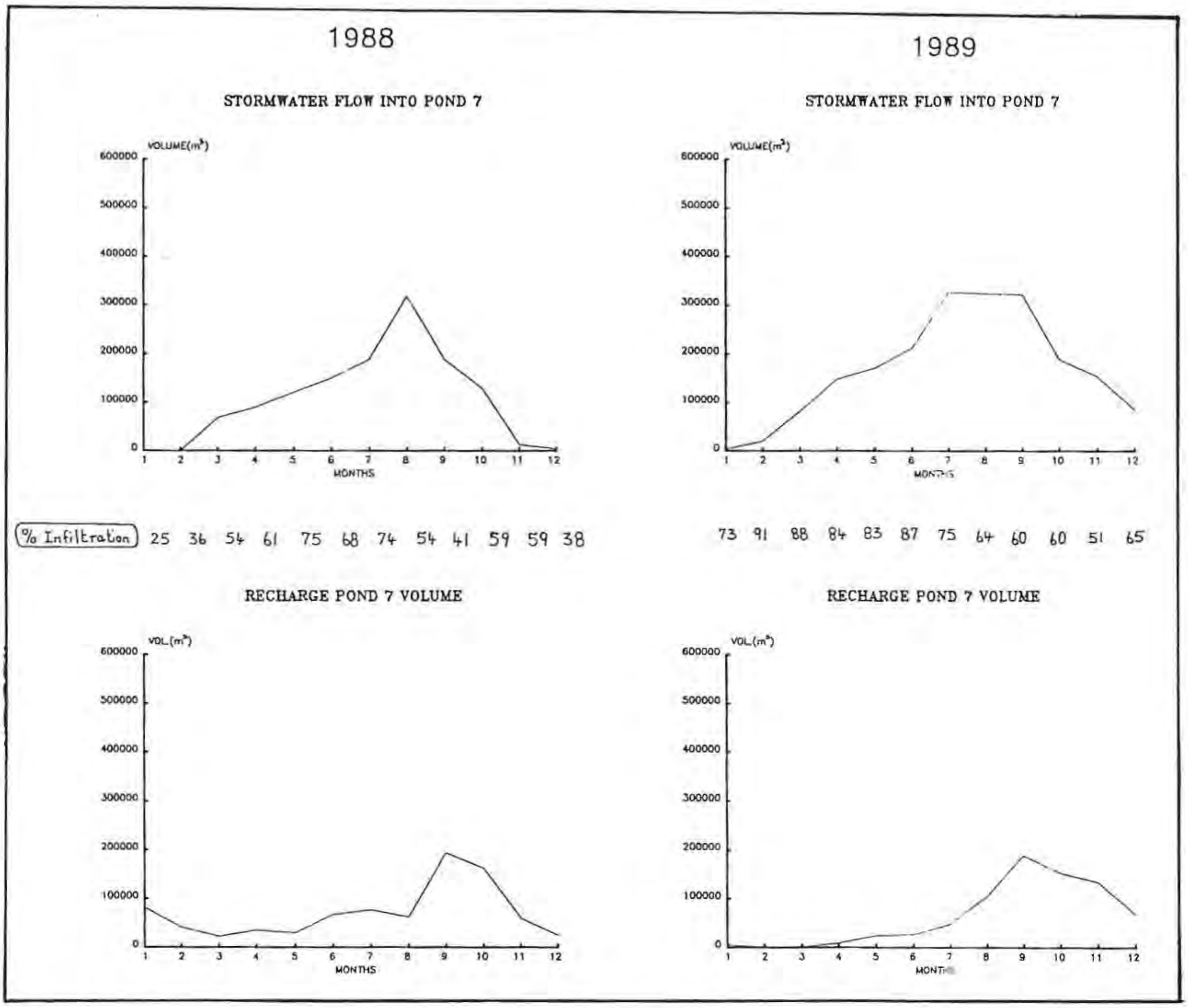


Figure 29 A comparison between the 1988 and 1989 recharge basin water balances

6.5 Water quality

The recharge basin water quality was monitored at a single sampling point on the southern edge of the basin (described in Chapter 4). An investigation using a portable electrical conductivity meter confirmed that the designated monitoring point was representative of the main portion of the basin. A statistical summary of the water quality variables is given in Appendix C14, and the trends with time are illustrated in a series of graphs in Appendix I.

Two distinct trends may be seen in the water quality during the study period. A seasonal trend is well defined by the salts and major cations and is closely related to the volumes of recharge water introduced to the basin (Figure 30 shows the salinity trend). At the beginning of winter large volumes of good quality stormflow are introduced into the basin and concentrations within the basin decrease dramatically. Concentrations remain low during the remainder of winter, but as volumes decrease in spring so the ratio of stormflow to baseflow water in the basin decreases and concentrations rise. The very high concentrations reached during December 1988 reflect the total drying-up of the basin and the effect of evaporation on the diminishing pool of water. This was especially the case with ammonia and sulphate. There is a direct correlation between concentration of salinity and major cations and volume of water in the basin.

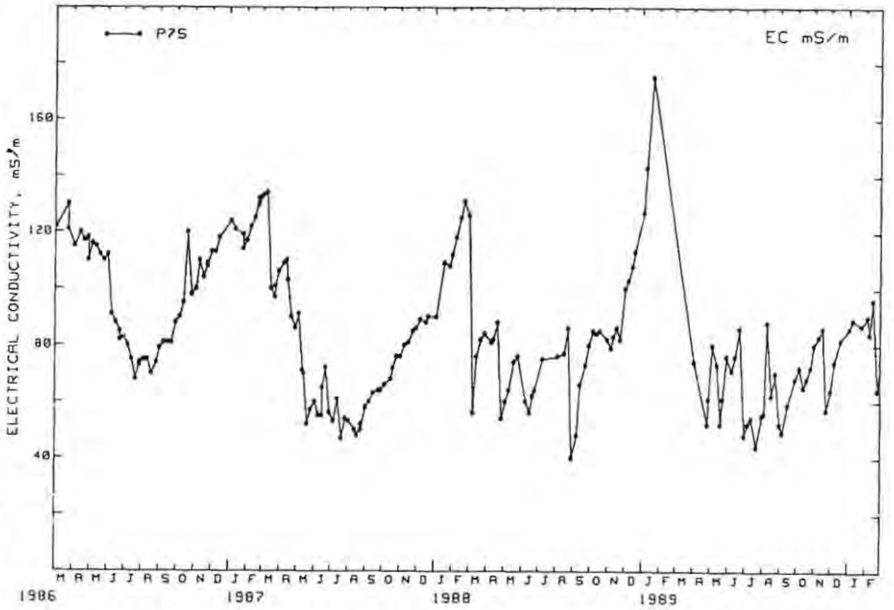


Figure 30 The salinity trend in the artificial recharge basin as depicted by Electrical Conductivity

There is also an overall improvement in water quality. Not only has the seasonal range/variation in water quality decreased, but the median has decreased with time. This is especially true since the removal of treated sewage effluent in late 1986. The reintroduction of treated wastewater in early 1989 is clearly indicated in the basin inflow potassium trend (Figure 31). The effect is also seen within the basin itself, but is not as dramatic due to dilution. The nitrate and phosphate trends highlight the improvement in water quality since the removal of treated wastewater in 1986. The nitrate trend as expected, is unlike the other water quality variables, increasing in concentration as the volume of water increases and decreasing rapidly as the stormflow into the basin ceases in September.

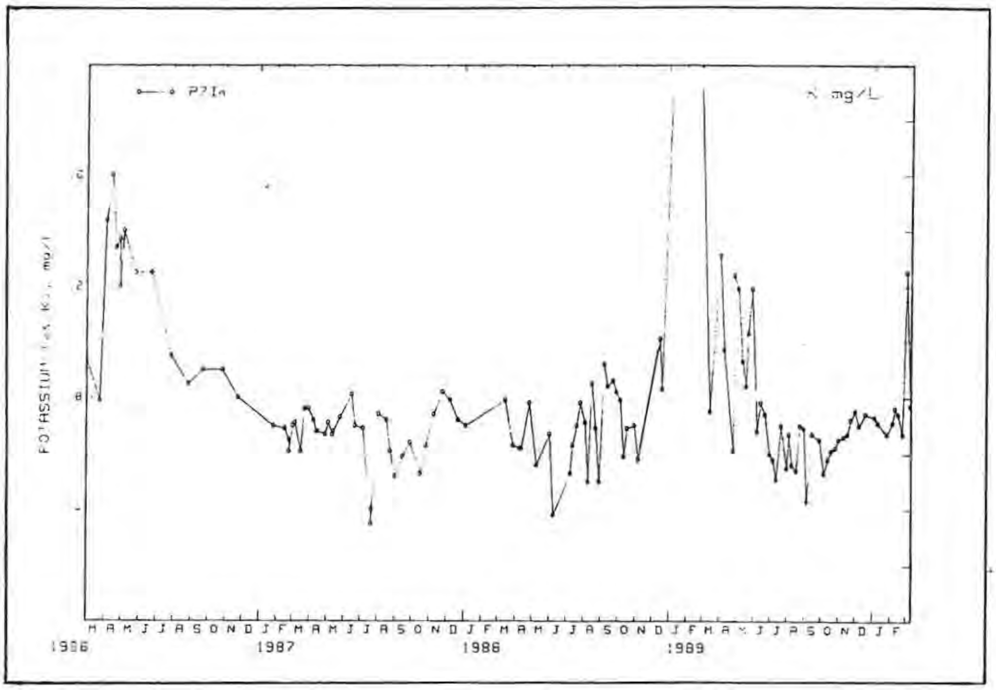


Figure 31 The potassium trend for the water discharged into the artificial recharge basin

6.6 Concluding remarks

Since 1986 the management of the artificial recharge basin has changed slightly each year, affecting both the quality and quantity of the water. During 1986 the basin received the maximum volumes of available water, whereas 1988 saw the basin receive a minimum quantity of water, but the best quality water. The 1989 management was a compromise between quality and quantity as larger volumes of water were required in the aquifer. Unfortunately the attempt at including treated wastewater had to be abandoned as it created too great a compromise with regard to water quality. The addition of stormwater baseflow during the summer months appears to have alleviated the problem for the immediate future. The treated domestic sewage effluent will in future have to be recharged but only when the water quality is acceptable and a second recharge basin is available. The practice of letting large portions of the basin dry out during late summer is beneficial and the periodic cleaning of the deeper portions of the basin essential. Unfortunately the low-lying surrounding topography, seepage through the basin retaining walls and return flow, lead to large expanses of shallow surface water between the basin and the southern portion of Witzand well field. This leads to both a "short circuiting" of the purification system and increased evaporation with resultant build-up of salts in the sand.

CHAPTER 7

7. AQUIFER RESPONSE TO ARTIFICIAL RECHARGE

The preceding chapters have examined the concept of artificial recharge, the water available for recharge, the recharge facility and management thereof. This chapter examines the response of the aquifer receiving water body to the artificial recharge, in order to test the conceptual model outlined in earlier chapters.

The natural groundwater flow in this sector of the aquifer is in a southwesterly direction with a relatively steep gradient in the area to the immediate south of Atlantis township (Van der Merwe, 1980; Müller and Botha, 1986). The effect of the artificial recharge basin is therefore superimposed on this existing regional trend. The above average rainfall during the 1980's resulted in substantial natural recharge and a general rise in groundwater levels. The amount of influence that may be attributed to the artificially recharged water is determined to a large extent by the management of both the recharge basin and production well field.

The groundwater response to the artificial recharge was studied by examining both the water quality and water level changes. The fact that large areas of surface water occurred outside of the recharge basin, especially prior to 1988, had to be taken into consideration. Figure 32 shows the extent of this surface water and its location relative to the groundwater monitoring points, and production boreholes.

7.1 Groundwater levels

Groundwater levels were first measured on a regular basis in 1985, in the area to the immediate south west of the recharge basin. By 1987 the groundwater monitoring network had been extended substantially and a regional groundwater level picture could be obtained. Figure 33 shows the changing trend in groundwater levels during the study period. The March water levels were selected as these represent the final dry month before the winter rains and new recharge cycle began. In the vicinity of the Witzand well field the groundwater level dropped by 3 metres before stabilizing slightly during 1989/90. There however appears to be a further lowering of the water level in the central area where a concentration of production boreholes occurs (Figure 32). At the southwestern corner of the recharge basin the water level also dropped by 3 metres but regained a metre during 1989/90. To the northeast (up gradient) of the basin the groundwater levels were more stable with the higher levels during 1987/88 being a result of above average rainfall and thus natural recharge.

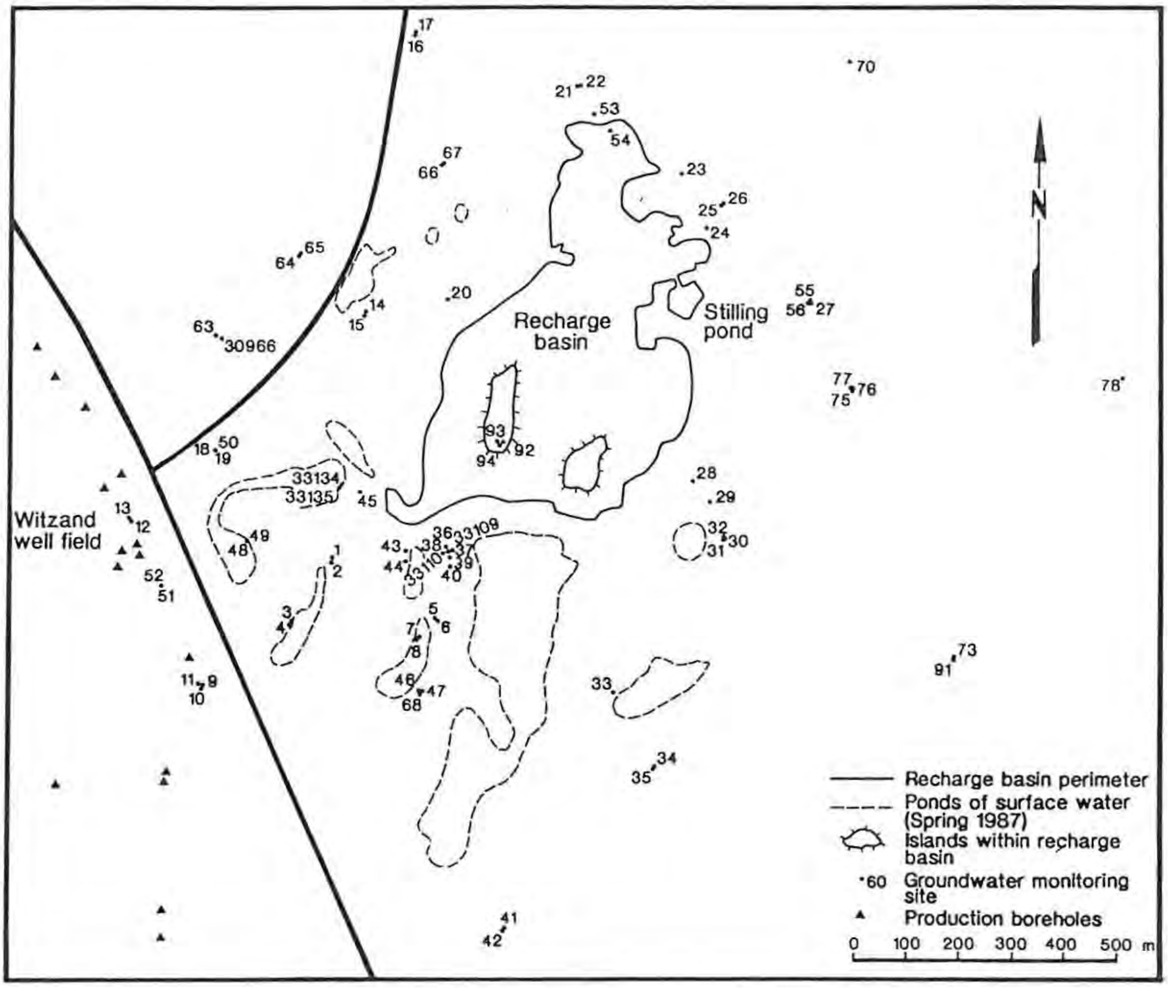


Figure 32 The groundwater monitoring sites in the vicinity of the artificial recharge basin and area covered by surface water from seepage and syphoning during 1986/87

The influence of the artificial recharge mound diminished gradually down gradient of the basin, but rapidly, upgradient of the basin. The hydrographs in Figure 34 represent three boreholes in a direct line between the recharge basin and the production well field and show the decreasing influence with distance from the basin. The influence also decreased with time reflecting the smaller volumes of recharge water during 1988. The increased volumes of recharged water during 1989 appear to have stabilized or at least slowed the earlier decreasing groundwater level trend. Similar trends may be seen in a down gradient arc from the west (borehole 20) to the east (borehole 28). A comparison of the curves in Figure 34 show that during 1987 there was a delay in the groundwater response between the recharge basin and edge of the production well field (a distance of ~500 m) of approximately 45 days. During 1988 the reduced volumes meant that groundwater levels never increased on the edge of the well field, but merely stabilized. During 1989 the groundwater levels once again rose but only after a delay of four months from when artificial recharge began.

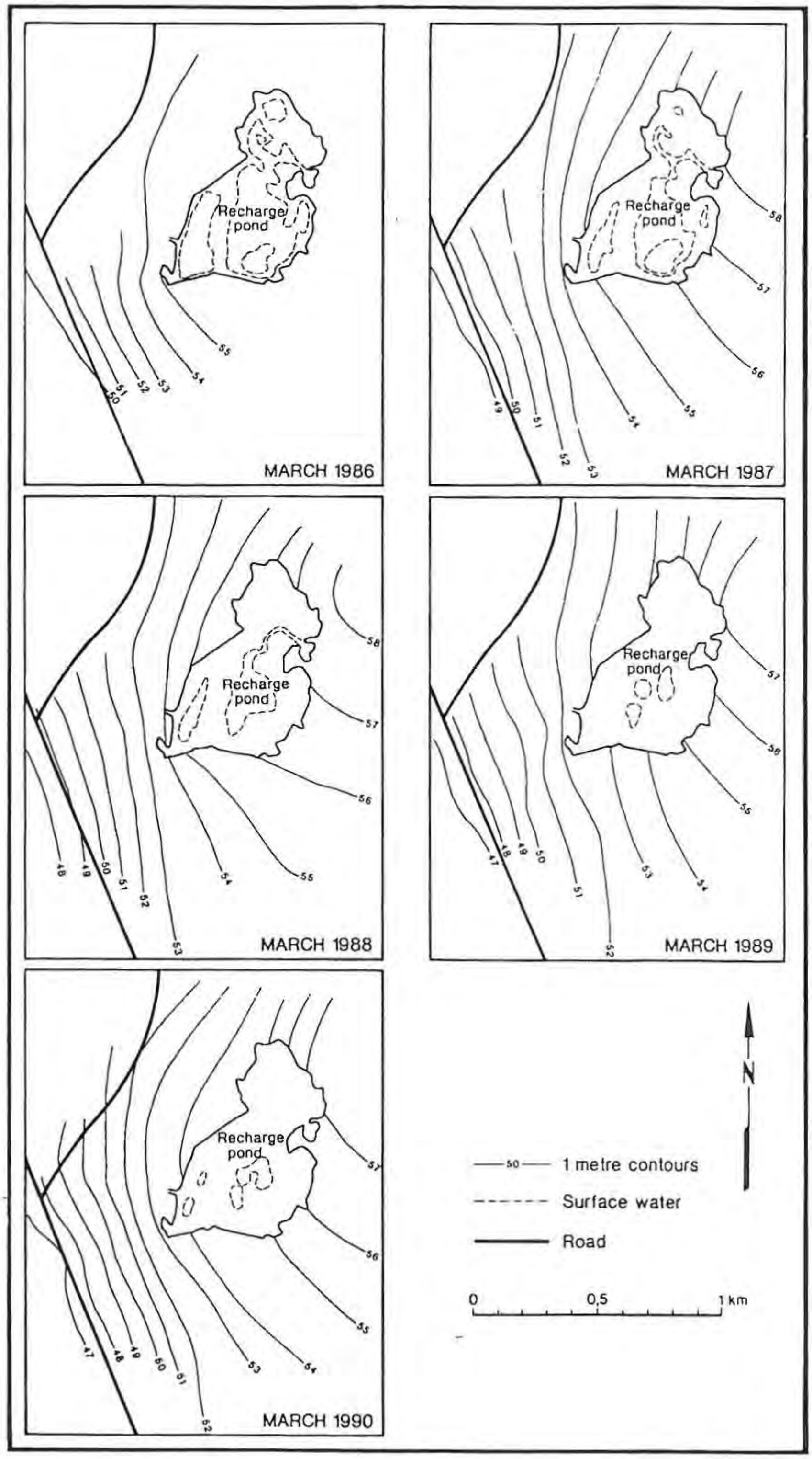


Figure 33 A series of groundwater level contour plans for the month of March 1986 - 1990

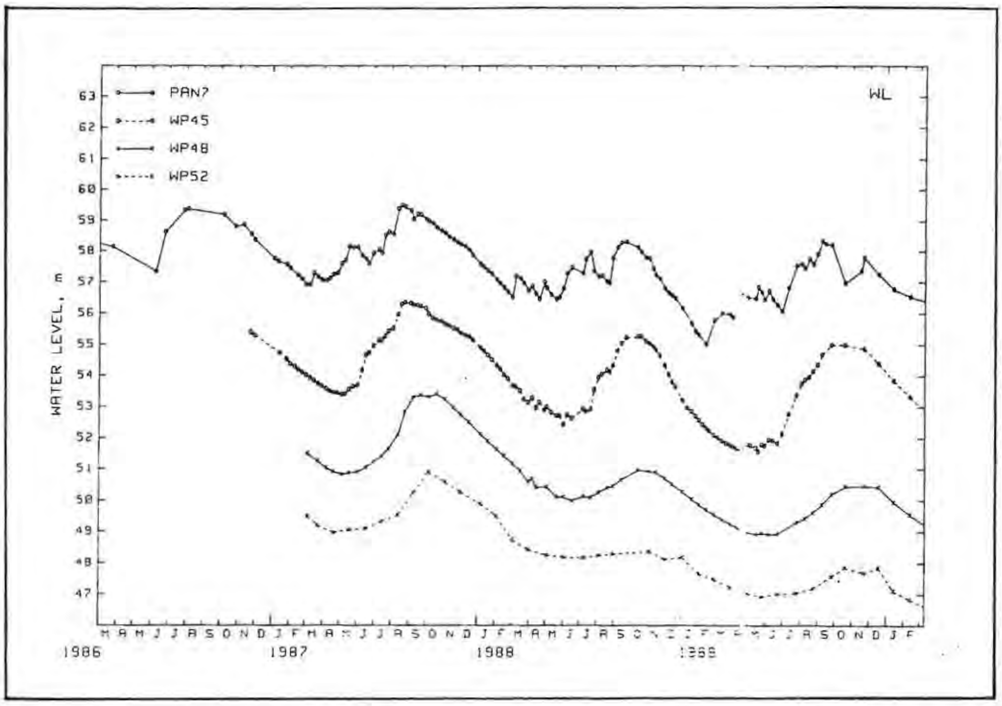


Figure 34 Hydrographs from a series of boreholes located in a direct line between the artificial recharge basin and production well field

The major area of influence was in a direction toward the production well field. The hydrographs in Figure 35 illustrate just how localized the effect of the artificial recharge mound was. Borehole 42, about 800 m south of the basin, has a hydrograph which deviates from the general trend reflecting the influence of natural rather than artificial recharge water. Upgradient of the recharge basin its influence was very limited causing a slight hydraulic barrier which resulted in the natural groundwater flow being diverted around the basin area.

The groundwater level monitoring has thus shown that the artificial recharge water had a very localised effect on the hydraulic gradient and merely reinforced the existing regional gradient which was in a southwesterly direction. The recharge mound was therefore not round, but rather elongated in a southwesterly direction. Thus conforming to the predicted flow lines as shown in the conceptual model (Figure 6). The increased production in the well field can be expected to further lower the groundwater levels and increase the effective influence of artificially recharged water.

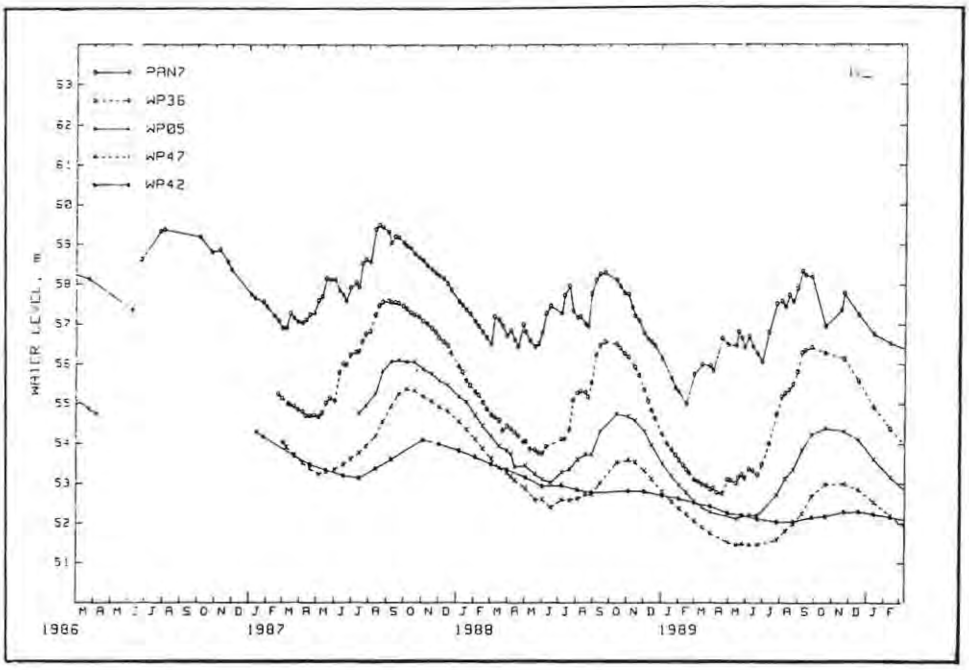


Figure 35 Hydrographs from a series of boreholes to the south of the recharge basin

7.2 Groundwater quality

The groundwater quality monitoring involved 75 boreholes and the analysis of up to 18 different water quality variables. This provided a substantial data base, and effective regional coverage since the beginning of 1987. For the purposes of this study it was not necessary to examine all 18 variables in detail and only 3 are dealt with in this discussion. Potassium was selected as it is found in low concentrations in natural groundwater, but relatively high concentrations in waste-water, especially sewage effluent. It is also a good example of those cations that are subject to ion exchange or adsorption in the presence of clay minerals. Chloride on the other hand was selected because it does not enter into any significant reactions and is transported advectively by the water. Finally, electrical conductivity (EC) was selected as it is a cheap and easy method of obtaining an indication of total salinity. Salinity is a crucial parameter in any coastal aquifer and has added importance in the Atlantis aquifer because of the high background concentrations in certain areas.

Groundwater quality time-series graphs of potassium, chloride and electrical conductivity were studied for all the boreholes surrounding the recharge basin (Figure 32). Two examples of the time-series graphs and accompanying explantation are illustrated in Appendix J. Each borehole was studied in isolation and the information gained used to establish an understanding of the regional (study area) aquifer response to artificial recharge.

7.2.1 Identification of artificial recharge influence

It was shown in Chapter 6 that the different management strategies implemented during the study period resulted in a distinct recharge water quality signature. As predicted in the conceptual model and suggested by Nightingale and Bianchi (1973) in a similar study in the USA, the influence of artificial recharge can be detected in the groundwater quality. The time-series graph in Figure 36 is representative of the area immediately down gradient of the basin and illustrates this point.

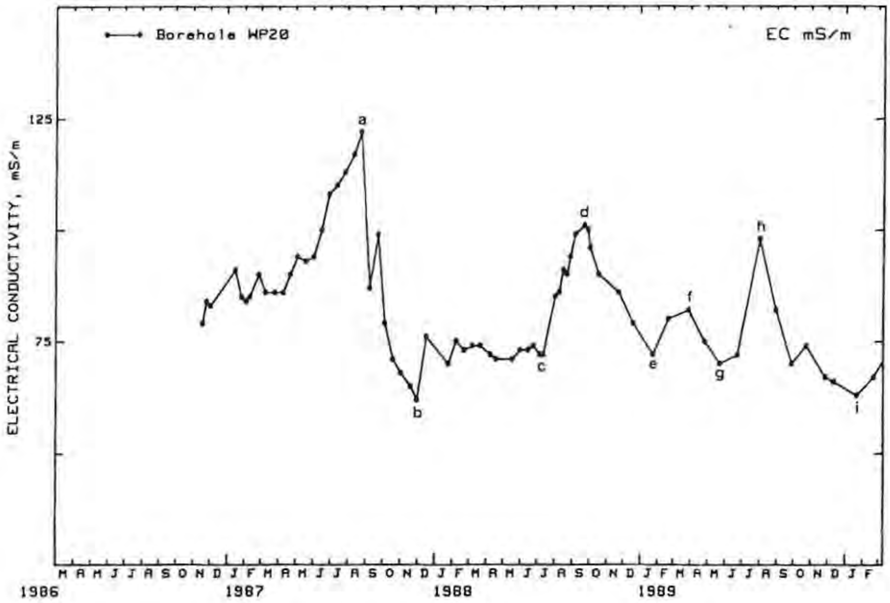


Figure 36 The groundwater quality trend (as depicted by EC) in borehole 20 showing the influence of artificial recharge water

Point (a) represents the stage at which the main pulse of artificially recharged water arrived at the borehole. The recharged water was of a better quality than that of the resident groundwater and caused a dramatic improvement in groundwater quality. This trend continued [points (a) to (b)] throughout the main period of recharge and reflects the rainy season when the recharge basin received large volumes of stormwater runoff. With the decreasing volumes of recharge water and mainly baseflow stormwater quality, the groundwater quality stabilized (point b) and then remained fairly consistent [points (b) to (c)]. The reduced rate of infiltration during this period allowed for the immobilization of dissolved constituents by way of physical and chemical processes. Many of the boreholes in fact experienced a gradual deterioration in groundwater quality as conditions returned to their existing state. With the start of the next rainy season volumes of water in the basin rapidly increased resulting in a renewed recharge cycle. The surge of fresh recharge water acted as a piston to displace the existing poorer quality recharge water that had already infiltrated ahead of it. The new surge of fresh water leached out those ions retained/ immobilized in the sand after the previous recharge cycle. This concentration of the poorer quality "tail-end" water from the previous recharge cycle produced the abrupt deterioration between points (c) and (d). Point (d) once again representing the stage at which the main surge of fresh recharge water arrived at the borehole. The entire cycle is then repeated on an annual basis. The reduced volumes and generally better quality water recharged during 1988 resulted in both point (d) being lower than (a) and slope (d-e) being gentler. The anomalous peak (e-f-g) was a direct result of the drying out and cleaning of the basin, thus allowing for increased infiltration as soon as the stormwater baseflow component was once again discharged into the basin. The increased volumes of recharge water during 1989 resulted in point (i) being of better quality than the previous year (point e) and similar to point (b).

The groundwater quality adjacent to the basin can thus clearly be linked to the management of the recharge basin. The pulses of recharge water result in distinct groundwater quality fluctuations which vary according to the volume of water recharged. The quality of the recharged water influenced the final groundwater quality. In Figure 36 the groundwater quality showed a permanent improvement after the 1987 recharge cycle as a result of the removal of the treated sewage effluent.

7.2.2 *Extent of influence*

The groundwater quality response to artificial recharge is not uniform throughout the aquifer. In the conceptual model it was envisaged that certain ions, such as potassium, would to a large extent be retained in the upper layers and concentrations would thus decrease with depth and distance from the recharge source. Other more mobile ions, such as chloride, would have a greater radius of influence. The extent to which this occurred would depend very much on the hydrogeology. There is clear evidence that hydrochemical stratification existed in the aquifer prior to artificial recharge. The groundwater quality trends shown in Figure 37 represent different depths within the aquifer at a site not affected by artificial recharge. The groundwater quality clearly varies with depth. Any artificially recharged water would therefore be infiltrating into an already hydrochemically stratified sand unit.

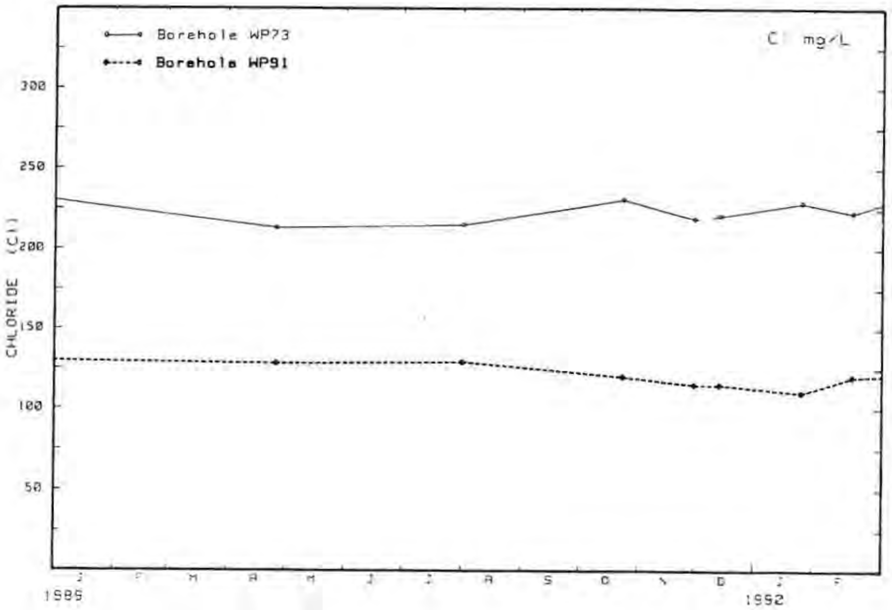


Figure 37 Chloride trends within the groundwater (WP73 = 27.5 m, WP91 = 17 m) at a site northeast of the artificial recharge basin

Those boreholes found to be influenced by artificially recharged water did in fact show different hydrochemical trends with depth. Figure 38 shows 2 sets of boreholes that sample depths of ~10 m (WP15 & 17) and ~20 m (WP14 & 16) below surface. The pair of boreholes in Figure 38(a) are closest to the basin and although both levels were influenced by artificially recharged water it was the upper level which was more responsive. At the lower level the response was more gradual with indications that with time a more uniform groundwater quality may occur as a result of the continuous recharge of water. The pair of boreholes illustrated in Figure 38(b) are located further from the recharge basin and the potassium concentration indicates how artificially recharged water only affects the upper portion of the aquifer and creates hydrochemical stratification.

The areal extent of the influence from artificial recharge on groundwater quality is shown in Figure 39. The greatest degree of influence was experienced immediately down gradient of the basin. The influence decreased with distance from the basin, but could still be identified on the edge of the Witzand well field. The presence of artificially recharged water became apparent in several of the production boreholes as early as 1986. In the vicinity of the production well field the influence of the artificially recharged water was masked by effects from pumpage. The characteristic recharge trends could not be identified and the influence was reflected in the long term water quality trends.

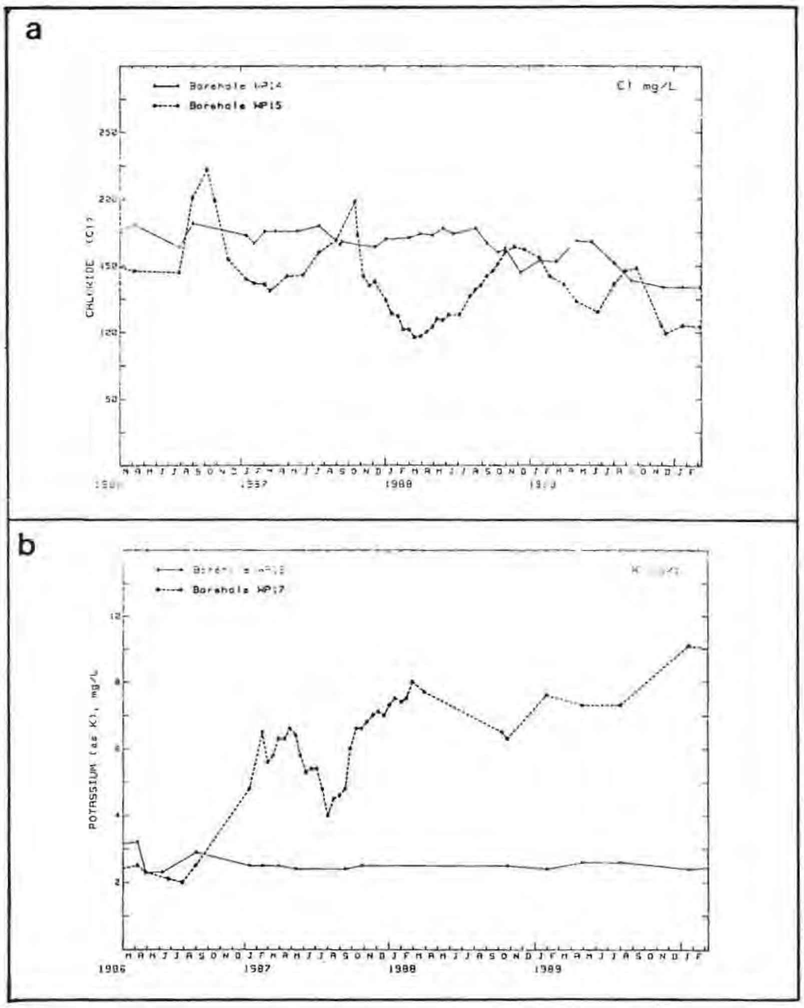


Figure 38 Water quality trends in 2 pairs of boreholes showing the different aquifer response to artificial recharge at shallow and deep levels within the aquifer

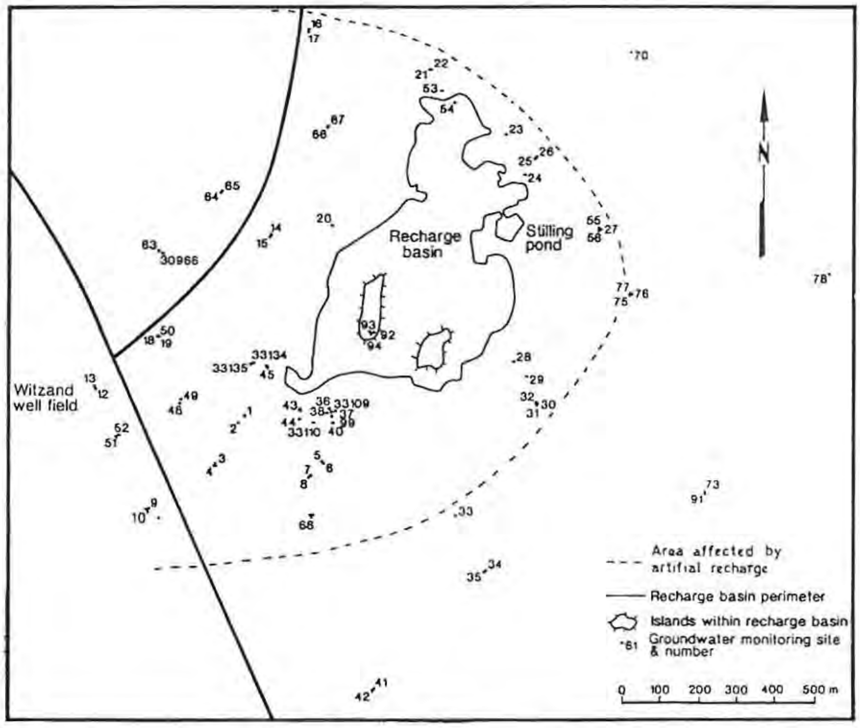


Figure 39 Plan indicating the areal extent of the influence of artificially recharged water on groundwater quality

The decreasing influence with distance from the recharge site is well illustrated in Figure 40. Both boreholes are shallow and directly down gradient of the basin although borehole 15 is 120 metres further away. The electrical conductivity trends are very similar, but delayed in time and more subdued in the furthest borehole. At shallow depths there was a fair amount of uniformity to the west and southwest of the basin for a distance of at least 200 m. At depth however the influence is not as uniform as other factors appear to affect the groundwater movement.

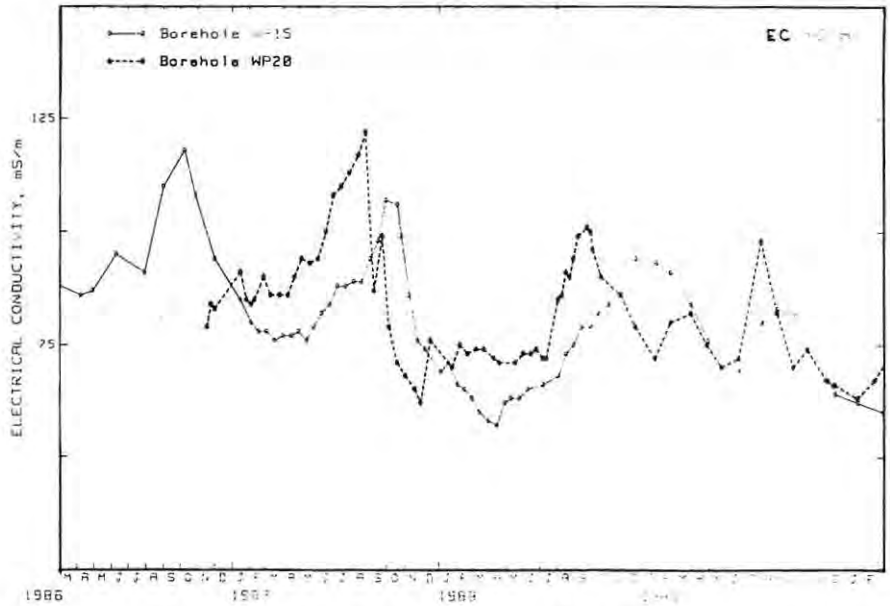
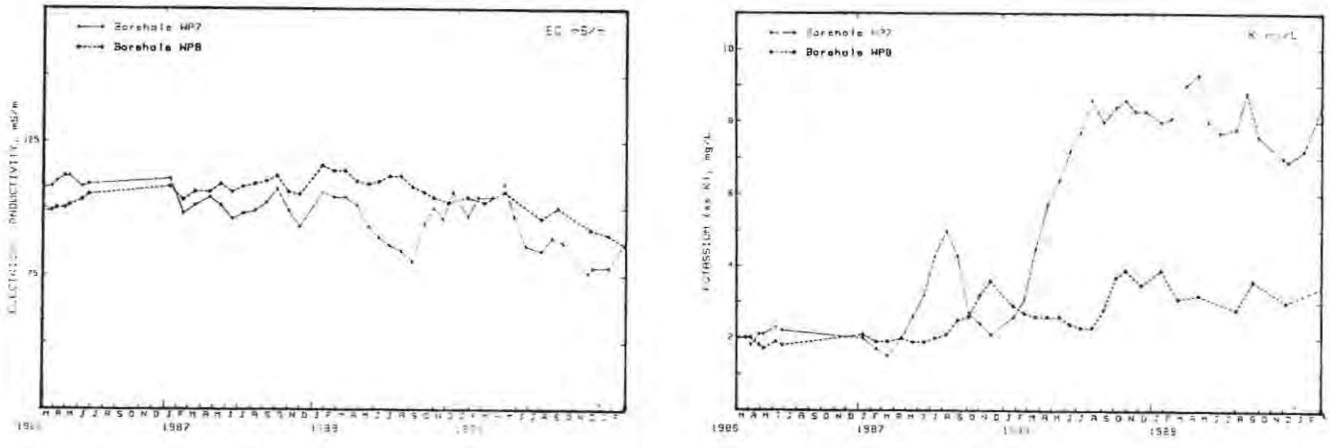


Figure 40 Electrical conductivity trends in two shallow boreholes 80 m and 200 m down gradient of the recharge basin

The influence of the artificially recharged water was very limited in the area upgradient of the basin. The potassium concentrations indicate no influence except at shallow levels directly north of the basin and in close proximity to it (boreholes 23, 24 & 25). The influence having decreased since the removal of treated sewage effluent from the basin and natural recharge from precipitation in the surrounding area now seems the dominant influencing factor. The influence of the artificially recharged water on the side of the basin was also limited. Boreholes 300 m to the southeast of the basin (boreholes 34 & 35) appeared unaffected. The groundwater quality in this area was either influenced by other surface water (caused by a break in the outfall pipe line) or natural recharge from the Brakkefontein area to the north east. The low potassium concentration and gradual increase in salinity and chloride during the abnormally wet 1980's suggests that the highly brackish groundwater from Brakkefontein is now having more of an influence than before.

7.2.3 *Influence from seepage and/or siphoned water*

There is evidence to suggest that seepage to the south of the recharge basin and siphoned water (1985 & 1986) have influenced the groundwater quality in the areas to the south of the basin. It is generally seen in those boreholes located in natural depressions/pans which during 1985/86 and much of 1987 contained surface water. Boreholes 7 & 8 (Figure 41) are an example. Up until 1987 the groundwater quality in the two boreholes (11.5 m and 22 m depth) was relatively similar, but once the surface water disappeared so the true groundwater quality responses began to be reflected.



a

b

Figure 41 Groundwater quality trends in boreholes 7 and 8: (a) Electrical conductivity (b) Potassium

It is interesting to note that the water quality of the seepage water immediately south of the basin was in most cases an improvement on that found in the recharge basin and conformed to expectations of the conceptual model. This change in water quality took place during approximately 50 metres of subsurface flow (Table 22). As previously stated surface water originating from the stormwater outfall pipe in the vicinity of borehole 33 also affected the groundwater quality.

Table 22 A water quality comparison between the recharge basin water and the seepage water ponded to the immediate south of the basin

Determinand	Recharge Basin	Seepage water	% Change
K	6.9	4.1	-40
Na	113	85	-25
Ca	31	41	+34
Mg	14.2	11.5	-6
NH_4-N	0.14	<0.05	-71
SO_4	58	47	-20
Cl	179	131	-27
Alk($CaCO_3$)	79	106	+34
NO_x-N	<0.05	<0.05	-
P	0.15	<0.05	-73
DOC	12.3	11.2	-9
EC	85	74	-13
TDS (calc)	544	474	-13
Cd	<0.02	<0.02	-
Cu	<0.02	<0.02	-
Fe	0.09	0.08	-11
Pb	<0.02	<0.02	-
Zn	<0.02	<0.02	-

Units: $mg.L^{-1}$

7.2.4 Determination of advection rates

Advection may be defined as the process by which solutes are transported by the bulk motion of the flowing groundwater (Freeze & Cherry, 1979). Measurements were made at those boreholes at which distinct recharge peaks/pulses could be identified and linked to specific recharge basin trends. The emptying and cleaning of the basin during 1988/1989 made it difficult to obtain a rate for 1989 and values are therefore given for 2 years (Table 23). As a rough guide, it appears that for the area to the immediate southwest of the recharge basin a rate of 25 to 30 metres per month for 1987 and 16 metres per month for 1988 was applicable. The rates are a reflection of the gradient which result from the different volumes of recharge water during this period. These rates do however represent very coarse measurements, computer modelling being required for more accurate values.

Table 23 Advection rates for artificially recharged water as measured from groundwater quality response

Borehole	Distance from Basin (~ metres)	Time in Months 1987	1988
15	200	5.5	5.5
45	100	3.5	7
36	70	3.5	6
34	80	4	6
2	200	8	8
5	200	4	4
18	400	7	7

A similar exercise was carried out between adjacent shallow boreholes with the results from two pairs of boreholes given in Table 24. The reduced rates since 1987 illustrates the effect of reduced recharge basin volumes and resultant reduced gradients.

Table 24 Advection rates for artificially recharged water as measured between adjacent boreholes

Boreholes	Distance between Holes (~ metres)	Time in Months		
		1987	1988	1989
36 & 40	25	1.5 - 2	1	1 - 1.5
43 & 44	20	2	1	1

7.2.5 *Microbiological contamination*

Biannual sampling of a series of eight boreholes located between the artificial recharge basin and Witzand well field (Figure 13) showed that there was no microbiological contamination of the groundwater at all. Although the recharge basin contained micro-organisms:

faecal coliform	: 1.46×10^4 per 100 mL
faecal streptococci	: 8.00×10^3 per 100 mL
coliphage	: 3.70×10^2 per 10 mL

none were ever detected in the boreholes (shallow and deep) around the basin.

7.3 Concluding remarks

The monitoring of the aquifer response to artificial recharge in the area surrounding the recharge basin has shown that:

- any changes in quality and quantity of water infiltrated in the artificial recharge basin have a direct affect on the surrounding groundwater
- recharge cycles can be identified in both groundwater levels and groundwater quality responses
- the removal of treated sewage effluent from the recharge basin resulted in a dramatic improvement in groundwater quality, but the reduced volumes led to a reduction of the groundwater mound and more subdued groundwater quality fluctuations
- the areas both upgradient and adjacent to the recharge basin have as a result of decreased artificial recharge become more prone to the influence of natural recharge
- the artificial recharge mound serves as a buffer to more saline groundwater from Brakkefontein (flow originating from the sewage works and industrial areas) which could otherwise eventually have been drawn into the central portion of the well field
- increased production in the Witzand well field is influencing both groundwater levels and water quality in the area between the well field and recharge basin
- the artificially recharged water poses no threat to the water quality of the production well field and town water supply
- the reduced volumes of water discharged into the basin and aeration of large portions of the basin floor during late summer promoted rapid initial infiltration
- the sandy nature of the recharge basin retaining walls and low-lying topography south of the basin results in seepage and large ponds of partially "treated" recharge water in close proximity to production boreholes
- the groundwater mound beneath the recharge basin rose to above the base level of the basin and resulted in permanent ponds of water in those areas below the 55 metre contour

It can be concluded from these observations that in several respects the artificial recharge system at Atlantis differs from the conceptual model. Chemical processes are not as effective during infiltration as expected. This is largely due to the nature of the sands underlying the basin and lack of a substantial unsaturated zone. The infiltrating water is also inclined to follow more gently sloping flowlines as the horizontal vector was found to be greater than expected. The increased lateral flow results in less mixing and greater hydrochemical stratification. The lack of mixing and diffusion with depth confirm the ideas put forward by Schmidt and Clements (1977). Seepage/siphoning of water from the recharge basin should be minimized as this causes a "short circuiting" effect minimizing many of processes described in the conceptual model.

The increasing groundwater abstraction in the Witzand well field will undoubtly influence the aquifer response to the existing artificial recharge process and further deviations from the conceptual model will occur. It is however necessary to verify that no unforeseen poor quality recharge is taking place up gradient of the artificial recharge zone.

CHAPTER 8

8. THE HYDROGEOLOGICAL ISOLATION OF THE ARTIFICIAL RECHARGE ZONE FROM THE URBAN AREA

The Atlantis waste water treatment plant was sited in an area believed to be hydrogeologically isolated from the Witzand well field and artificial recharge zone (Van der Merwe, 1980). Figure 42 shows the location of the urban area, waste water treatment plant, artificial recharge basin and hydrogeological divides in the aquifer. The presence of the hydrogeological divide to the south-west of Atlantis is crucial to the efficient operation of the AWRMS, as the groundwater quality in the southern portion of the urban area and around the waste water treatment plant is of a poor quality.

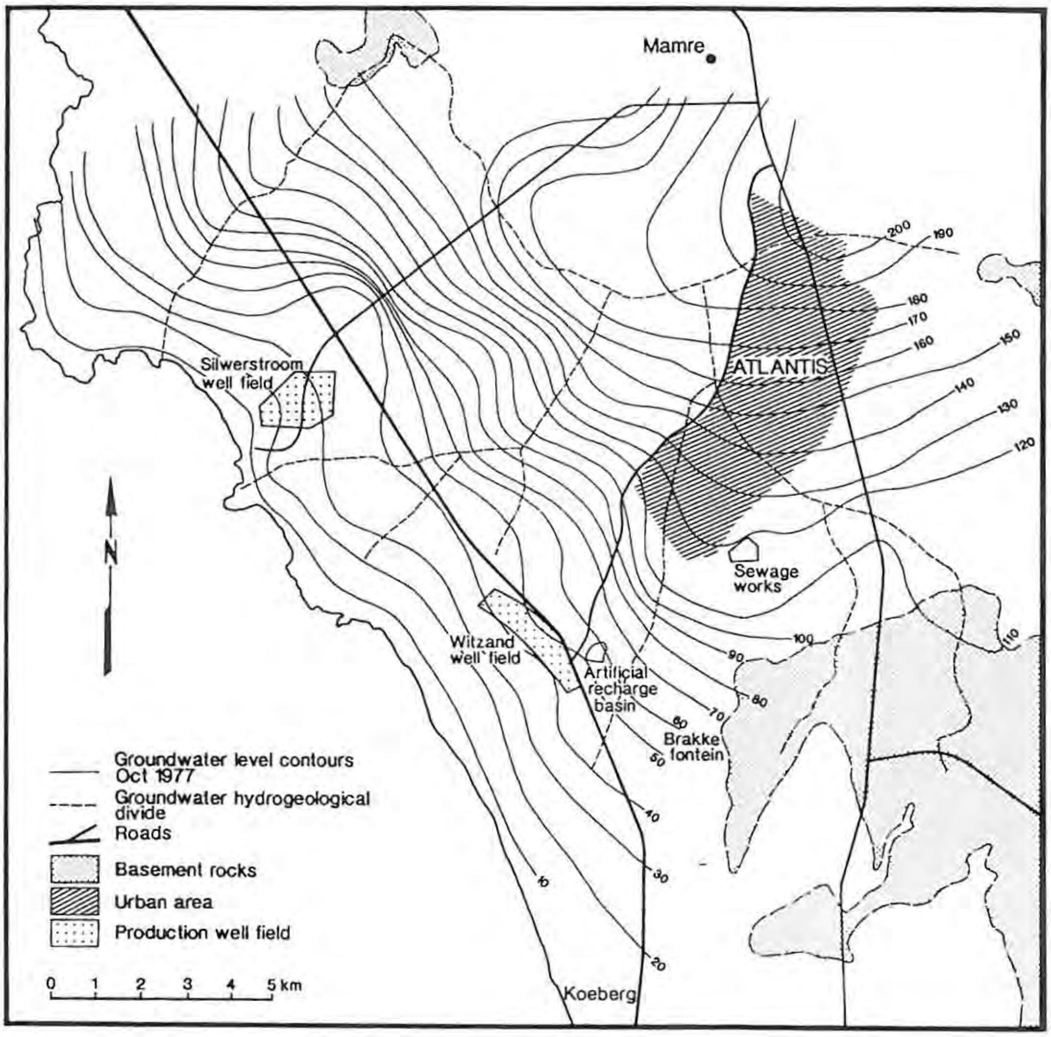


Figure 42 Groundwater level contour plan: Oct. 1977

(From Van der Merwe, 1980)

The precise location of the divide between Atlantis township and the recharge basin has never been clearly defined and the recent modelling undertaken by Müller and Botha (1986) suggested that although groundwater initially flows in a south-southeasterly direction it could swing in a southerly direction towards the recharge basin (Figure 43). This is of some concern as Müller and Botha had access to an additional 21 groundwater monitoring points which were not available to the earlier researchers.

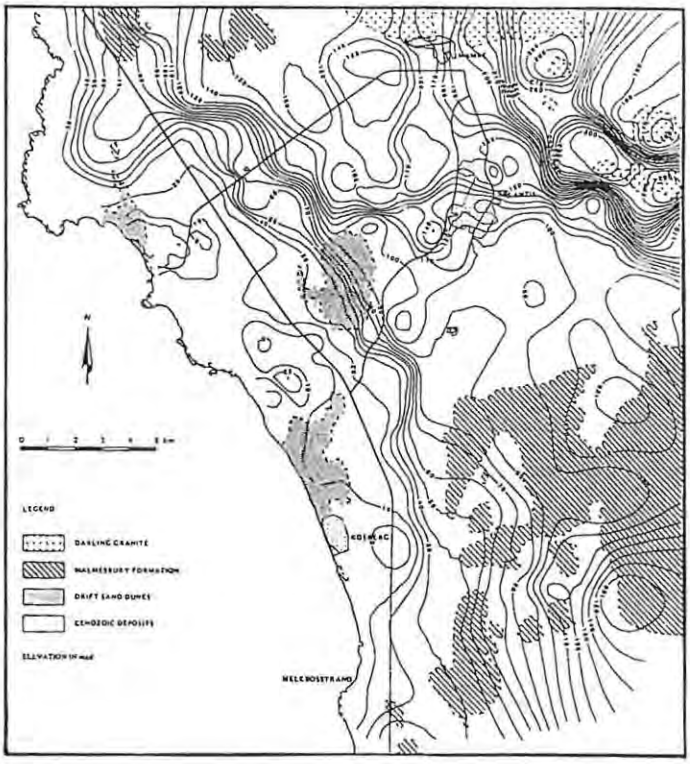


Figure 43 Bedrock elevation plan
(After Müller & Botha, 1986)

8.1 Study approach

It was thus concluded that although research had been done on a regional scale, the evidence was not conclusive and the presence of the hydrogeological divide had to be confirmed. With this in mind, ten small diameter boreholes were drilled, groundwater levels and quality monitored, and geophysical surveys (resistivity soundings) undertaken (Figure 44). The data collected was used to ascertain whether or not groundwater from the pond 10 and pond 6 area flows in a south-westerly direction towards pond 7 (the artificial recharge basin).

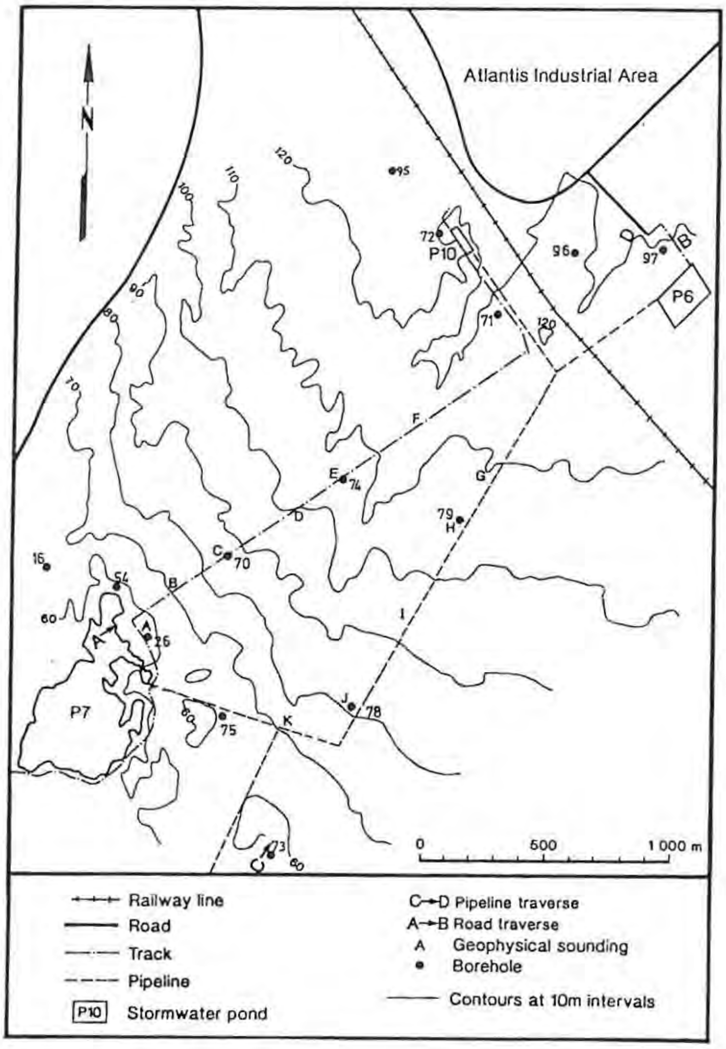


Figure 44 Plan showing a) the relief and infrastructure, and
b) location of boreholes and geophysical soundings

8.2 Discussion of results

The boreholes provided information on both the lithology of the sand units and the depth to bedrock. Figure 45 summarizes the most important geological data from the borehole logs. In all cases the boreholes intersected a 0.5 to 4 m thick transition zone between the sand units and the underlying weathered Malmesbury Shales. The weathered Malmesbury consisted of yellow and grey clay, which in areas extends to great depths. The clay is identical to that quarried in the nearby brickworks. This clay is considered impervious and thus for hydrogeological purposes the basement of the aquifer. The boreholes in the northern sector (71, 72, 95, 96 & 97) had sand to depths greater than 10 metres and with very distinct peat horizons. The central boreholes (74 & 79) had minor peat and between 6 and 7 metres of sand (including the transition zone). Boreholes 70 and 78

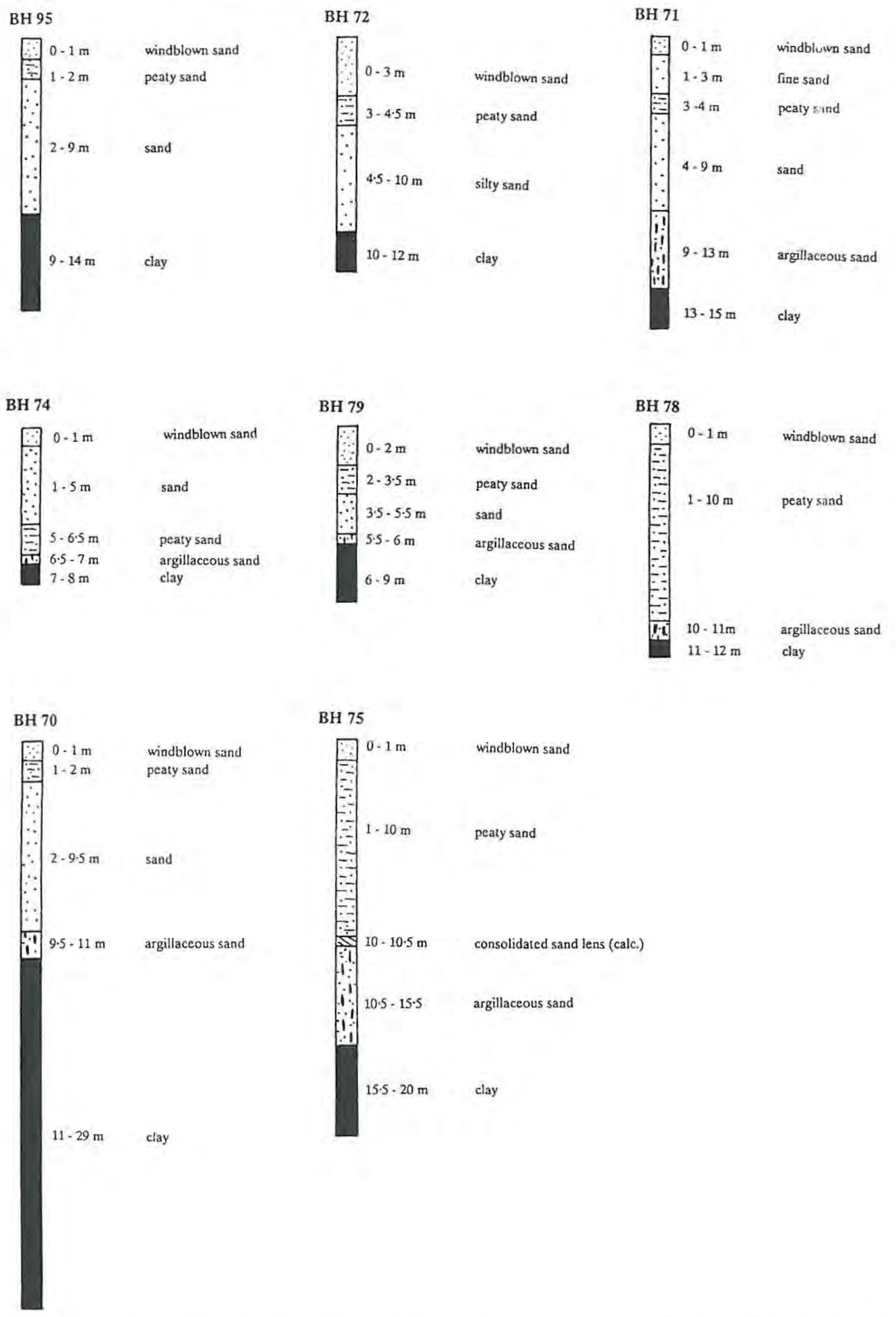


Figure 45 Geological borehole logs

intersected 10 metres of sand which then rapidly increased in thickness in a south-westerly direction. Unfortunately no geological logs are available for the shallow (< 20 m) boreholes around pond 7. Borehole 92 was drilled to 31 metres in sand before drilling had to cease due to continued loss of circulation (drilling mud), while borehole 73 intersected 27 metres of sand. It is however known that boreholes 26 and 54 contain an argillaceous lense at shallow depths (<10 metres) (Hon, pers. comm., 1989).

A total of 12 resistivity soundings were done using the Schlümberger method (Van Zyl, 1977; McNeill, 1980). The soundings were done next to boreholes for calibration purposes and between boreholes in an attempt to supplement the borehole data (Figure 44). The detailed results are summarized in Appendix K and compared to the borehole data in Table 25.

Table 25 Depth to bedrock : A comparison between geophysical results and geological data from boreholes and maps

SOUNDING SITE	DEPTH TO CLAY UNIT (m)			
	GEOLOGICAL		RESISTIVITY	
	ACTUAL	INFERRED		
A		+25	5.1	
B		+20	6.5	
C/BH 70	11			
D			10	
E/BH 74	7		6.9	
F			6.1	
G			7.1	
H/BH 79	6		5.2	5.6*
I			7.7	
J/BH 78	10		4.5/15.6	9.8*
K		+15	16	

*Unpublished sounding by MEYER & DUVENHAGE (EMATEK, CSIR)

Site A & B - the soundings gave false interpretations as geological extrapolation from boreholes 26 and 54 suggest thicknesses of sand in excess of 20 metres. The incorrect geophysical interpretation is probably due to a shallow lense of argillaceous material which was intersected in the boreholes. In borehole 54 the lens in fact forms an impervious barrier to the artificially recharged water.

Site C - this sounding proved unsuccessful and thick bush, plus the fence, unfortunately hindered any further (different traverse orientations) soundings. The borehole however confirmed the presence of the basement high

Site D - the sounding proved highly successful and correlated well with two adjacent boreholes (70 & 74). This site also confirmed the presence of the basement high

Site E - this site gave the most accurate correlation between the resistivity sounding and borehole data

Site F - a very similar sounding curve was obtained to that at site E and the geophysical interpretation was accepted. Once north of this site the depth to bedrock once again increased as observed in boreholes 71 and 72

Site G - the sounding curve was very difficult to interpret and only made sense when treated as a 5-layer curve. Not a very high degree of confidence was placed in this interpretation

Site H - as with the sounding at site G, the interpretation included a thin, non-continuous conductive layer (~10 Ohm.m) at a relatively shallow depth. Meyer & Duvenhage (1989) encounted the same layer, in other parts of the aquifer

Site I - the sounding gave a simple 3-layer curve and the interpretation correlated well with the adjacent boreholes 78 & 79

Site J - neither the E-W or N-S traverse could be correlated with borehole 78. The problem may in some way be related to the nearby pipeline although this is difficult to accept as it is a cement pipe. It is probably just a coincidence that the average of the two readings (4.5 and 15.6) equals the actual depth as measured in the borehole

Site K - the increased depth to bedrock suggested by the sounding appears slightly deeper than expected, but is not out of place in relation to the surrounding boreholes and topography.

The geophysical results support the earlier findings of Botha and Bekker (1977), Botha and Thompson (1977) and Meyer and Duvenhage (1989) that geophysical methods should not be used in the Atlantis area other than to supplement other hydrogeological methods of investigation. The extremely dry conditions of the sands were found to be a major hindrance when using geoelectrical sounding techniques and interpretation of the soundings was further complicated by the presence of thin clay and/or calcrete lenses. The information gained from the borehole logs and geophysical soundings was used to produce the bedrock elevation contour plan shown in Figure 46. The contours confirm the presence of a high to the southwest of pond 10 and that groundwater drainage from the pond 6 and 10 area should be in a southeasterly direction.

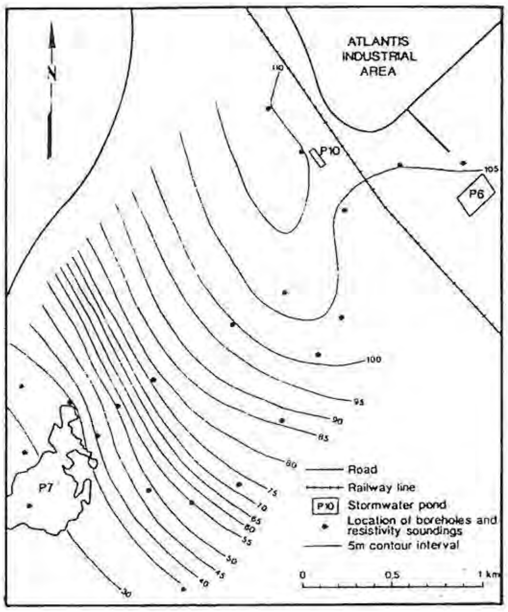
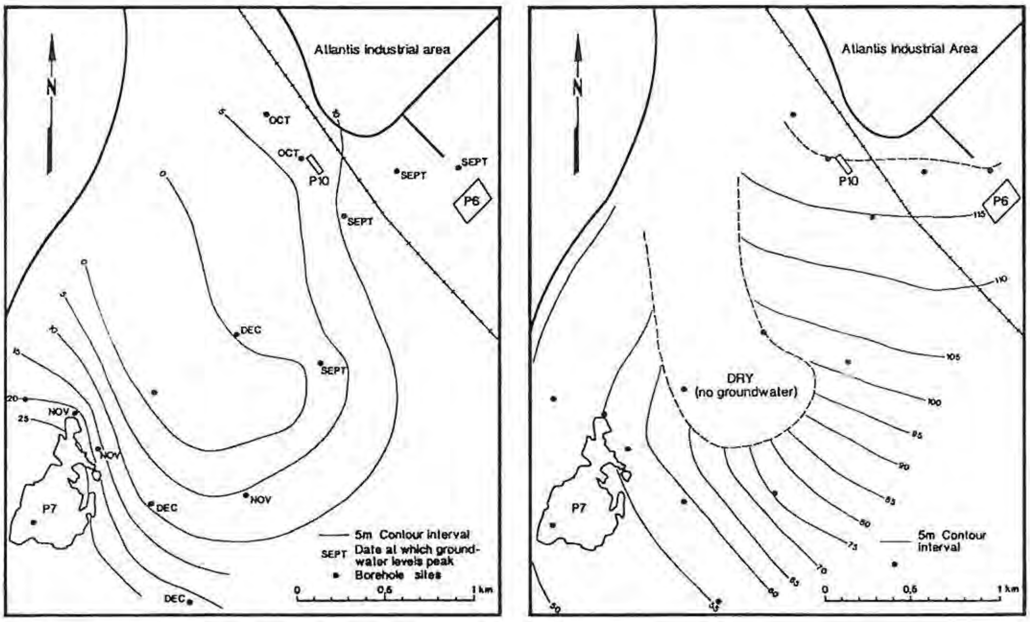


Figure 46 Contour plan showing bedrock elevations

Groundwater levels were measured on a monthly basis and showed a seasonal variation of between 0.2 m and 0.5 m. Borehole 70 remains dry throughout the year, while borehole 74 was dry during the autumn and early winter. Borehole 74 in fact yielded insufficient water for water quality sampling purposes. Both the low and/or absence of a watertable in the central area (BH 70, 74 & 79), and polarized nature of "time of peak groundwater levels" indicates the presence of a basement high or groundwater compartment boundary (Figure 47a). The water level contour plan (Figure 47b) shows a steep water level gradient in the south-east suggesting minimal groundwater flow.



(a) (b)

Figure 47 Contour plans of : a) saturated sand thickness;
b) groundwater levels in March 1990

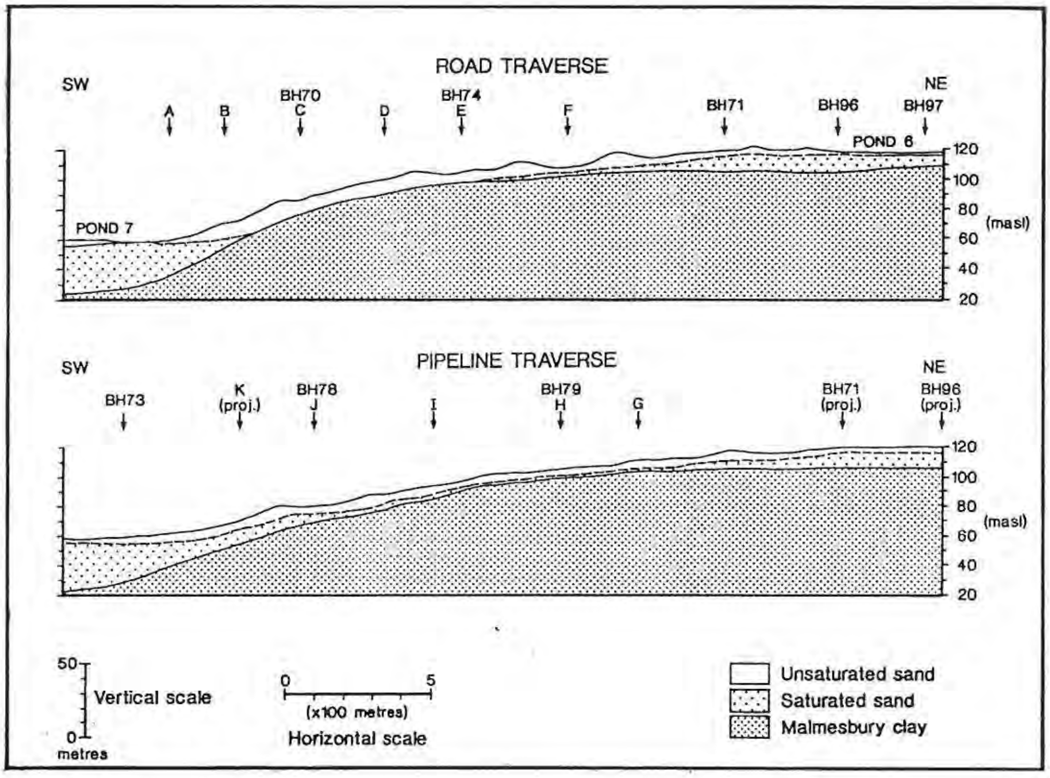


Figure 48 Hydrogeological cross-sections

The borehole, resistivity and water level data were combined to produce the cross-sections shown in Figure 48. The sections clearly illustrate the reduced sand thickness in the central area and varying aquifer thickness. In the southwest around the recharge basin the aquifer (saturated sand) is at its thickest (~25 m), whereas in the north around ponds 6 and 10 it is less than half this thickness. There is no possibility of groundwater movement from the north-east to the south-west in the area north-northeast of pond 7 and very little, if any, in the area of the pipeline traverse (GHIJ). The field surveys thus confirm the presence of a hydrogeological divide and suggest that it becomes less prominent in a south-easterly direction (towards BH 78 & 79).

The groundwater quality was sampled on a monthly basis and Table 26 summarizes the median values for each borehole. The water quality data indicates the poorer quality water that occurs in the area around pond 10 and the affect which the artificially recharged water has on the area to the immediate north of the basin. Both the potassium and total alkalinity concentrations are high near ponds 10 and 7 and low between the two areas (BH 78 & 79). The lack of sufficient water in BH 74 made sampling impossible. The high ammonia, phosphate and dissolved organic carbon characteristic of the northern area is not found further south, towards the recharge basin. The salinity and related parameters again show a distinct zonation although there is a suggestion that borehole 79 may be affected by the more saline northern groundwater. The groundwater quality does thus not provide conclusive evidence of a hydrogeological divide, but provides substantial evidence that there is very little, if any, movement of poor quality water from the industrial area to the artificial recharge zone.

Table 26 A summary of the groundwater quality up gradient of the recharge basin

DETERMINANT	SAMPLE POINT											
	BH97	BH96	BH95	BH72	BH71	BH79	BH78	BH75	BH54	BH16	BH73	BH41
Potassium (K)	1.1	1.3	2.4	12.6	3.2	0.5	0.9	1.8	2.1	2.5	1.5	1.5
Sodium (Na)	98	107	285	159	821	126	93	81	128	101	165	114
Calcium (Ca)	19	30	109	136	260	57	41	58	114	118	37	21
Magnesium (Mg)	11	15	29	23	103	21	13	10	29	15	12	10
Ammonia as N	0.2	0.6	0.4	0.1	0.5	0.1	0.1	0.2	0.2	0.1	0.0	0.0
Sulphate (SO_4)	26	130	46	72	146	116	43	23	55	32	83	26
Chloride (CI)	175	140	492	364	1745	234	187	140	275	212	221	161
T.Alkal($CaCO_3$)	37	49	285	214	220	80	56	149	258	244	81	89
Nitrate as N	0.02	0.02	0.02	0.19	0.02	0.03	0.03	0.03	0.03	0.02	6.05	0.03
Phosphate as P	0.26	0.19	0.14	0.06	0.02	0.03	0.03	0.03	0.03	0.02	0.03	0.03
UV 275 Abs.	0.947	0.978	1.579	0.605	1.091	1.711	0.512	0.183	0.215	0.058	0.382	0.615
UV 254 Abs.	1.214	1.287	2.098	0.813	1.513	2.165	0.666	0.240	0.267	0.073	0.510	0.790
Dis.Org.Carbon	8.1	9.3	25.4	11.1	13.9	14.4	6.6	4.4	6.1	4.7	6.3	8.6
pH	6.2	6.4	6.9	7.1	6.9	6.7	6.7	7.1	6.0	7.4	6.5	6.6
Conductivity	71	82	210	165	585	110	81	76	145	118	109	77

Median values in MgL^{-1} (EC in mS.m^{-1})

8.3 Concluding remarks

A number of different approaches were taken, namely, drilling, geophysical surveys, groundwater level monitoring and groundwater quality analysis, in order to establish whether the artificial recharge zone is hydrogeologically separated/isolated from the southern portion of Atlantis township. No one approach was conclusive, but when considered together, provided a formidable argument for there being a hydrogeological divide between the urban area and the artificial recharge basin. The hydrogeological divide appears to become less prominent in the area to the east-northeast of the recharge basin. Field evidence suggests that the poor quality groundwater originating in the southern industrial and wastewater treatment area drains in a southerly direction and is funnelled through the Brakkefontein vlei area before swinging southwest towards the southern portion of Witzand well field and Koeberg Power Station.

The study has also confirmed that although resistivity soundings provide valuable information they must be used in conjunction with borehole data. Further geophysical investigations are necessary in order to establish the most successful technique for this area.

CHAPTER 9

9. HYPOTHESIS TESTING AND RECOMMENDATIONS

The Atlantis Water Resource Management Scheme has been in operation for over a decade and has over the years become a relatively sophisticated water supply scheme. During this time a considerable amount of work has been undertaken resulting in a great number of technical reports and two MSc theses (from the Van der Merwe (1980) and Müller and Botha (1986) studies). Two components of the AWRMS however remained largely unstudied, namely, the stormwater runoff and artificial recharge systems. The present study had the clear objective of addressing this short-fall in the overall research programme. Five specific aims were identified in order to establish a research framework (Section 4.1) and led to the formulation of a set of hypotheses. The hypotheses are re-examined in this chapter inorder to assertain whether the objective of the study was met. This forming the conclusion to the study.

9.1 Hypothesis testing

Each of the five hypotheses stated in Section 4.2 (restated below) is examined in the context of the result obtained and accepted or rejected accordingly.

Hypothesis a - The "first flush" effect commonly found in stormwater runoff is of minor importance in the study area.

Storm event monitoring of the urban stormwater runoff showed that a "first flush" effect was present in the study area (Section 5.2). The nature of the stormwater runoff, however, resulted in the water quality during the first flush being generally of a better quality than the normal baseflow. The volumes of water during the first flush period were also insignificant in comparison to the peak flows and thus any pollutant load quickly became diluted. Although the organics showed a first flush effect the concentrations almost immediately continued to rise as discharge volumes increased on the leading limb of the hydrograph. Concentrations remained high well after the peak flows. Therefore unlike other stormwater studies (Mance & Harman, 1978; Hoffman *et al.*, 1982; Simpson, 1986; Hvitved-Jacobsen *et al.*, 1987) the "first flush" effect was found to be an insignificant contributor to the pollution load. Hypothesis (a) is therefore accepted.

Hypothesis b - The residential stormwater runoff and treated wastewater is of an acceptable quality for artificial recharge.

The acceptability of water for artificial recharge should be determined to a large extent by the water quality of the receiving groundwater body/aquifer. Ideally the artificial recharge process should not result in a deterioration of groundwater quality. Both the stormwater runoff and wastewater effluent were investigated with this philosophy in mind. The study showed that neither sources of water were uniform in quality and not only consisted of different components of water, but varied spatially and with time (Figure 20). From a water quality perspective it is clear that both the noxious industrial baseflow and industrial effluent should not be considered suitable for recharge. Although the industrial stormwater baseflow is at present diluted by the larger component of residential stormwater, it in fact, is not suitable for recharge because of the pollution risk posed by industrial spills/flushing.

A comparison between the residential stormwater runoff, treated domestic wastewater and groundwater in the vicinity of the wellfield (extraction point) indicates that only the residential stormwater runoff is acceptable for recharge (Table 21). When considering only the water quality aspect of artificial recharge, the treated domestic wastewater is unacceptable for recharge immediately upgradient of the Witzand wellfield. The dramatic improvement in groundwater quality since the removal of treated wastewater from the recharge basin in 1987 supports this conclusion (Section 7.2).

Hypothesis (b) can therefore not be accepted in its entirety. The treated domestic wastewater could only be acceptable if other influencing factors, of more importance than direct groundwater quality responses, are taken into account. These will however be discussed under hypothesis (e).

Hypothesis c - The artificial recharge area is hydrogeologically isolated from the Atlantis area.

An investigation involving drilling, resistivity surveys and groundwater level and quality monitoring confirmed the presence of a basement high in the area between the artificial recharge basin and the noxious industrial stormwater pond (P10). No evidence could be found of significant groundwater flow over the basement high. The basement high appeared less prominent in an easterly direction with evidence of saline groundwater flow from Brakkefontein moving towards the southern portion of the Witzand wellfields (Section 8.3). The artificial recharge basin was not affected by this saline water as the groundwater mound caused by recharge formed a buffer. The influence of the Brakkefontein groundwater (originating in the southern part of Atlantis and sewage works) was detected in the southeastern most monitoring sites (boreholes 34, 35, 41 & 42).

The artificial recharge basin is therefore at present isolated from the poorer quality groundwater flow originating in the Atlantis urban area. The hydrogeological divide in the form of a bedrock high is however not as extensive as previously thought and does not from a compartment boundary to the east of the recharge basin. The hypothesis is accepted with the following proviso. Any future decrease in artificial recharge and increase in groundwater extraction in Witzand wellfield could result in some influence on the southeastern periphery of the artificial recharge basin by the poor quality Brakkefontein groundwater.

Hypothesis d - The recharged water may be traced using chemical variables and does not immediately disperse vertically throughout the aquifer.

The groundwater quality monitoring around the recharge basin clearly indicated the presence of artificially recharged water (Section 7.2). There is a direct correlation between the groundwater quality trends and that of the water in the artificial recharge basin. The fact that variables such as potassium could be traced over substantial distances suggests that the purification processes during infiltration were not as effective as expected. This could be due to the low clay content of the sands and the fact that for much of the year the groundwater mound intersects portions (below 55 mamsl) of the basin floor. Where clay is present, for example boreholes 54 and 75, the potassium is effectively removed. The infiltrating water does not immediately disperse vertically throughout the aquifer. Boreholes 92, 93 & 94 in the centre of the basin indicate no sign of influence from the recharge water at depth. Down gradient of the basin the deeper levels are only gradually being affected by recharge water and it is only on the edge of the wellfield that mixing, caused by the production boreholes, results in a homogeneous water quality. Chemical variables could therefore be used to trace the movement of artificially recharged water within the upper portion of the aquifer. Hypothesis (d) is therefore accepted with reservations.

Hypothesis e - The most efficient recharge management strategy is a compromise between obtaining maximum infiltration and maximum water purification.

The literature study (Chapter 2) suggested that the methods of recharge required to obtain maximum infiltration inevitably lead to reduced purification during infiltration and visa versa. The management strategy for a recharge basin is thus a compromise between maximum infiltration and purification, the balance of which depends on local requirements. The different recharge management strategies implemented during the study and the resultant groundwater responses showed that such a balance existed in the study area. The different components of the balance were however slightly different from what was expected.

It was found that because of several factors, for example the nature of the sand and limited unsaturated zone, the purification process during infiltration was not as effective as expected. Thus the most efficient method of improving the resultant recharged water quality was by controlling the quality of the water discharged into the basin. In order to accomplish this however it meant reducing the volumes of water discharged into the basin and therefore available for infiltration. A compromise thus had to be sought between the volume and quality of water recharged (Table 20). During 1988 the water quality aspect was favoured with a resultant decrease in volumes. It immediately became clear that recharge volume was the dominant fact in the balance in order to counteract the influence of saline groundwater flow from the northeast and dropping groundwater levels as a result of increased abstraction.

The most efficient recharge management was found to be a compromise which favoured maximum infiltration as implemented in 1989/90. Infiltration was further boosted by allowing a large portion of the basin to dry out during late summer/autumn. Hypothesis (e) is therefore accepted.

9.2 Recommendations

The present approach of artificially recharging all the stormwater runoff throughout the year provides the most efficient compromise under the existing conditions. Several recommendations may however be made for the future management of the system.

1. A second artificial recharge basin should be established to the northwest of the present basin. This should be done in accordance with the guidelines given in Appendix A.

2. The existing artificial recharge basin should be used for the recharge of treated domestic effluent in order to form a buffer against any possible inflow of groundwater from the northeast towards the Witzand wellfield. Strict quality control must be maintained at the wastewater treatment plant to ensure that water quality requirements are adhered to and any unacceptable water is immediately diverted away from the recharge basin.

3. The proposed new artificial recharge basin be used for the recharge of urban stormwater runoff. This water should remain at a quality acceptable to the northern portion of Witzand wellfield.

4. The noxious industrial stormwater and baseflow from the industrial sub-catchments should be removed from the system and diverted to the Donkergat River or coastal recharge basins.

5. The artificial recharge basins be allowed to dry out at least once a year. The deeper portions of the basin should be periodically (5 years for stormwater) cleaned. The groundwater mound should not be allowed to rise to within 1.5 m of the ground surface, both inside and outside the basin.

6. The Witzand compartment (that portion of the aquifer draining towards the Witzand wellfield area) should be considered from an holistic approach. Groundwater modelling being used to produce a waterbalance for the unit.

7. Geohydrological monitoring of the unit be maintained in order to provide data for the waterbalance model and ensure the long term protection of the aquifer from pollution and over exploitation.

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APPENDIX A

BASIC GUIDELINES FOR ESTABLISHING AN ARTIFICIAL RECHARGE SCHEME

Basic guidelines for establishing an artificial recharge scheme

1. *General*

In Chapter 2 some of the problems and complexities of the artificial recharge process have been outlined. It is clear that poor planning, implementation and management of an artificial recharge scheme can have serious long-term implications. It is therefore recommended that a careful procedure for evaluation be adopted. The following basic guideline are based on those recommended by the Australian Water Resource Council (AWRC, 1982).

2. *Feasibility study*

As many aspects as possible associated with the economic and physical facets of the scheme and all suitable alternative schemes should be considered.

- Water resource requirements
  Establish the current and future water supply requirements/demands
  Determine potential of existing groundwater source.

- Possible sources of recharge water
  Identify possible sources of water for recharge
  Cost and benefits of using water for other purposes.

- Availability of aquifer for recharge
  Establish if there is an exploitable aquifer

- Alternative sources of water
  Identify alternative sources of water
  Do an economic comparison.

3. *Site selection*

Once shown to be feasible, it is necessary to select a site and design the recharge system. The major points to consider for site selection are:

- Aquifer hydrogeology
  Establishing the aquifer properties, permeability and porosity
  Determine groundwater levels and flow directions
  Determine the background groundwater quality.

- Recharge zone
  Define the most practical zone in which recharge can take place
  Establish maximum feasible distance from source of recharge water
  Establish minimum feasible distance from extraction point (wellfield).

- Proximity to existing and future development
  Ensure safe distance from developed area
  If necessary, design buffer zone.

- Surface characteristics
  Select area wit suitable to photography
  Damage to existing vegetation and environment
  Engineering cost comparison
  Route for transportation of recharge water.

- Recharge water
  Establish expected water quality
  Establish expected input volumes

- Contingency plan
  Establish contingency methods for disposal of recharge water in case of emergencies
  Pollution control measures.

- Future effects and land use
  Suitability of area should recharge operations cease
  Environmental impact study.

- Climatic effects
  Establish precipitation and evaporation rates
  Establish amount of wind and direction.

- Conceptual model
  Develop a conceptual model of system
  Attempt to mathematically model effect of recharge on aquifer.

4. *Establishment*

To undertake the design and construction of the artificial recharge system at the selected area.

- Pilot study
  If necessary undertake a pilot study in the selected area to examine on a small scale in the field the performance of the proposed ultimate recharge scheme.

- Recharge basin
  Construct spreading basin
  Construct monitoring network.

- Feed system
  Construct water conveyance system to recharge basin
  Construct contingency diversion system
  Construct water quality monitoring system.

- Monitoring network
  Establish a groundwater monitoring network
  Design a monitoring programme.

- Commission system

5. *Recharge management*

The operational techniques for an aquifer recharge scheme using waste water or stormwater involves a compromise between infiltration rate maintenance and the treatment effect.

- Maintenance of physical system
  Flooding and drying cycles.

- Monitoring of recharge system
  Data collection
  Laboratory analysis
  Data handling
  Data analysis
  Information utilization.

- Modelling of system
  Water balance
  Hydrochemistry.

- Management decisions

APPENDIX B

DAILY RAINFALL TOTALS
1986 - 1989

ATLANTIS DAILY RAINFALL TOTALS : 1986

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1				6.7	6.0					6.0	0.5	0.1
2				17.2	1.5				8.0			
3				1.2	2.0	24.0			1.3			0.7
4				4.4		11.3						
5						2.3	2.5	3.0		0.6	3.0	
6						1.1	0.6	0.7				
7					7.5		1.5					
8		0.7	5.0		2.5		0.5					
9		1.0	0.4	7.5		1.0		2.0				6.0
10			0.2	2.5	27.0	3.0	13.3					
11			4.5	6.0			2.5					
12				8.0	0.8			7.0				
13		0.4	1.8		3.5	15.0						
14		3.0	0.4		12.0	8.2	3.5					
15	7.4				1.0	0.3	6.8					
16				16.0	5.0							
17		7.0		2.9	3.0							
18		0.5		0.6								
19				2.9								0.2
20				7.0								
21							3.0				8.0	
22	10.0				14.0						5.0	5.0
23	0.9		0.8		0.9							
24					4.0							
25						0.5						
26		0.1				3.5						
27	1.2		2.0						0.5		0.5	
28	0.5		7.0	27.5		3.8						
29	14.0	5.0	0.3	0.4		6.8		0.6				
30				15.5								
31												
TOTAL	34.0	17.7	22.4	126.3	90.7	80.8	34.2	13.3	9.8	6.6	17.0	12.0

TOTAL FOR YEAR 464.8

CAPE HYDROLOGICAL YEAR = March - February

UNITS = millimetres

ATLANTIS DAILY RAINFALL TOTALS : 1987

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1				9.5	6.5							
2				2.8	20.0							
3				2.6		3.1						
4			23.0	8.5								
5			2.0		1.1						0.3	
6			1.9							1.4		
7		0.6								2.6		
8								1.2				
9				6.5		9.0				2.7		
10					1.5	50.0		7.0		8.1		
11			12.0			15.5	2.8					
12			8.2			4.0	10.5					
13		10.0	44.0									
14	14.4	1.8	0.5	0.6		3.7	2.5		1.6			
15			2.7	2.6		8.5	2.5		2.0			
16			5.5	1.7								
17			0.6	1.4								
18			0.8		31.0	14.5	0.6		0.8			
19		9.5			18.0				1.7			
20					1.7						2.5	
21						0.8	4.3			0.9		
22		6.3				6.3	9.0					
23				11.5			7.0					
24				18.5			1.8	3.8				
25				1.6	5.7					1.6		
26					5.5							
27					8.0							
28								5.7				
29												
30						8.0	2.4					
31			20.0			3.5						
TOTAL	14.4	28.2	121.2	67.8	99.0	126.9	43.4	17.7	6.1	17.3	2.8	0.0

TOTAL FOR YEAR 544.8

CAPE HYDROLOGICAL YEAR = March - February

UNITS = millimetres

ATLANTIS DAILY RAINFALL TOTALS : 1988

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1				0.5								1.0
2				3.8	0.1				6.7			0.6
3		2.5			0.9							
4		15.5			3.0							
5		2.0		9.7	7.0						0.5	
6		1.3		4.3	0.2	1.5						
7	32.0				18.8	12.5						
8	0.4				4.8				1.5			
9							9.5	17.0		3.4		
10				3.0			10.3	1.2		2.8		
11	0.3			0.6								
12	0.3			0.3	2.7							
13	0.2			8.0								
14												
15							12.0					
16								1.0				
17			0.9		1.5							
18	1.3		1.2	2.5	0.4							
19		0.7	6.8	2.4	1.0		0.2			2.2		
20		13.0	0.3		12.5					0.5		
21		5.0	0.7					0.5				
22		0.6	0.2					0.5				
23		9.3	2.8							0.3		
24		8.4	5.8					0.4		2.5		13.8
25		0.5	17.5				4.6					
26						12.5	2.3					
27						28.0		2.5				
28						3.8		2.5				4.8
29						2.5	3.3					
30						29.5						
31			1.5			7.0		1.4			5.8	
TOTAL	34.5	58.8	37.7	35.1	52.9	97.3	42.2	27.0	8.2	11.7	6.3	20.2

TOTAL FOR YEAR 431.9

CAPE HYDROLOGICAL YEAR = March - February UNITS = millimetres

ATLANTIS DAILY RAINFALL TOTALS : 1989

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1	4.6			7.2		11.2						
2				1.0	6.0		2.2			0.5		
3							33.0					
4					8.4		14.7	9.5		0.6		
5							3.5					
6											1.5	
7								0.4				
8								17.5				
9						1.3						
10			8.3		6.4	1.2						
11			4.5		7.3							
12	4.0		0.6			5.7					7.3	
13	18.6										1.5	
14	1.3				1.4	1.9		3.8				
15					5.0	9.5	0.1					0.5
16					21.0	1.9						1.0
17			19.6		3.0		10.8		33.0			
18					2.5		4.0					
19		9.0				0.8	2.0					9.8
20		9.0				1.0	3.7					7.5
21		21.4	3.0	1.5								
22								1.0				
23				4.5								
24					4.5	2.5						
25				22.0	25.2	0.1						
26				2.8	3.5	18.5		4.6				
27				0.9		3.0		0.8				
28				0.9		4.0	3.0					
29	13.5			4.9		6.0						
30	7.8		3.5	7.0		0.1					1.4	
31			5.4								0.8	
					0.1							
TOTAL	49.8	39.4	44.9	52.7	94.2	68.7	77.0	37.6	33.0	1.1	12.5	18.8

TOTAL FOR YEAR 529.7

CAPE HYDROLOGICAL YEAR = March - February UNITS = millimetres

APPENDIX C

A SUMMARY OF STORMWATER RUNOFF QUALITY FOR EACH SAMPLE POINT

C1 - P01B
C2 - P02B
C3 - P03C
C4 - P04B
C5 - P04C
C6 - P04D
C7 - P05B
C8 - P05C
C9 - P09B
C10 - P10B
C11 - P06A
C12 - P06B
C13 - P7in
C14 - P7s

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P018

			1986						1987						1988						1989			
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD.DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)							5.6	4.1	22.0	8.7	7.3	9	4.4	3.3	4.9	4.3	0.6	7	3.2	2.5	3.8	3.2	0.6	4
Sodium (Na)							66	64	88	70	10.0	5	59	54	67	60	6.0	4	54	41	78	57	16.4	4
Calcium (Ca)							32	25	33	30	3.1	5	26	22	28	25	2.8	4	22	20	26	22	2.8	4
Magnesium (Mg)							8	1	10	7	3.6	5	8	7	9	8	0.9	4	8	5	11	7.8	2.3	4
Ammonia as N							0.3	0.2	0.8	0.3	0.2	9	0.1	0.0	0.4	0.1	0.1	7	0.1	0.0	0.2	0.1	0.1	4
Sulphate (SO4)							30	26	39	32	5.2	6	20	18	22	20	1.8	4	22	20	27	23	2.9	4
Chloride (Cl)							104	92	117	104	10.1	6	97	78	184	106	36.5	7	81	59	135	89	34.0	4
T.Alkal (CaCO3)							80	73	88	80	5.9	6	78	64	85	76	10.2	4	62	60	65	62	2.2	4
Nitrate as N							3.3	2.1	6.4	3.9	1.6	9	3.2	1.1	5.2	2.9	1.4	7	2.9	1.9	3.2	2.7	0.6	4
Phosphate as P							0.03	0.03	0.05	0.09	0.01	7	0.03	0.03	0.03	0.03	0.00	7	0.02	0.02	0.03	0.03	0.00	4
UV 275 Abs.							1.84	0.76	2.30	1.75	0.61	9	1.64	0.43	1.86	1.44	0.49	7	1.16	0.83	1.66	1.21	0.36	4
UV 254 Abs.							2.39	0.97	2.95	2.24	0.77	9	2.12	0.67	2.35	1.87	0.58	7	1.50	1.08	2.12	1.55	0.45	4
Dis.Org.Carbon							18.9	10.3	21.9	17.6	4.0	8	15.5	8.1	18.0	14.8	3.3	7	11.6	8.7	14.4	11.6	2.4	4
pH							8.4	7.6	11.3	8.8	1.3	9	8.2	7.6	8.6	8.2	0.3	7	7.8	7.8	7.9	7.9	0.1	2
Conductivity							56	52	67	56	4.4	9	54	45	100	59	18.9	7	44	38	64	48	11.8	4

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P02B

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)							5.3	3.9	10.3	6.1	2.3	10	4.5	3.8	10.1	5.6	2.2	7	4.6	3.0	5.5	4.4	1.2	4
Sodium (Na)							64	60	70	64	3.7	6	57	46	78	59	11.7	5	48	34	71	50	16.9	4
Calcium (Ca)							30	24	45	31	7.5	6	24	21	33	26	4.6	5	23	16	29	23	5.8	4
Magnesium (Mg)							10	7	10	9	1.4	6	10	7	11	10	1.7	5	8	6	11	8	2.7	4
Ammonia as N							0.0	0.0	0.1	0.1	0.1	10	0.1	0.2	21.8	3.2	8.2	7	0.1	0.1	3.7	0.9	1.8	4
Sulphate (SO4)							31	24	40	32	4.9	7	23	17	36	26	8.1	5	25	15	42	27	12.2	4
Chloride (Cl)							91	89	108	96	7.8	7	89	77	118	91	13.6	7	72	60	104	77	19.9	4
T.Alkal (CaCO3)							73	69	112	79	15.1	7	68	54	181	87	52.8	5	63	44	79	62	19.1	4
Nitrate as N							4.4	3.4	6.8	4.6	1.0	10	4.1	0.1	6.1	4.0	2.3	7	3.1	1.5	4.8	3.1	1.8	4
Phosphate as P							0.03	0.03	0.05	0.03	0.01	8	0.03	0.03	1.61	0.30	0.60	7	0.03	0.03	0.44	0.13	0.21	4
UV 275 Abs.							1.64	0.46	2.29	1.51	0.68	10	1.16	0.93	1.55	1.23	0.24	7	0.88	0.68	1.05	0.87	0.18	4
UV 254 Abs.							2.09	0.61	2.87	1.93	0.85	10	1.64	1.21	2.02	1.61	0.30	7	1.12	0.97	1.34	1.14	0.19	4
Dis.Org.Carbon							16.3	7.9	20.8	14.6	4.2	9	12.5	9.2	21.2	13.4	4.0	7	7.7	6.0	9.6	7.8	1.9	4
pH							8.2	7.4	9.9	8.3	0.7	10	7.6	7.3	8.2	7.6	0.4	7	7.6	7.5	7.8	7.6	0.2	2
Conductivity							53	50	64	54	4.0	10	52	42	78	54	11.4	7	45	35	60	46	12.9	4

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P03C

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)	8.6	4.3	16.3	10.4	4.4	7	9.0	2.8	13.9	9.1	2.9	10	9.5	8.2	12.9	9.7	1.6	7	8.9	7.7	10.1	8.9	1.1	4
Sodium (Na)	84	75	95	85	9.6	4	88	77	104	91	9.9	6	102	90	111	101	8.6	4	108	97	113	106	6.9	4
Calcium (Ca)							46	31	58	46	10.0	6	43	41	56	46	6.8	4	45	41	56	47	6.8	4
Magnesium (Mg)							14	12	14	14	0.8	6	14	14	15	14	0.3	4	15	13	16	15	1.4	4
Ammonia as N	0.1	0.0	0.1	0.1	0.0	8	0.4	0.0	1.6	0.6	0.6	10	0.2	0.0	10.3	2.1	3.8	7	0.3	0.1	3.3	0.9	1.6	4
Sulphate (SO4)	48	36	52	46	6.9	4	46	36	53	45	5.2	8	44	39	58	46	8.3	4	53	49	56	53	3.1	4
Chloride (Cl)	128	114	164	134	19.2	6	150	120	172	150	17.3	8	174	152	182	171	11.1	7	174	166	185	175	8.5	4
T.Alkal (CaCO3)	110	63	185	117	51.1	4	108	53	175	109	37.1	8	84	77	151	99	35.0	4	95	74	117	95	22.9	4
Nitrate as N							7.2	1.2	12.3	7.1	3.1	10	5.3	3.8	6.2	4.9	0.9	7	5.9	4.6	6.4	5.7	0.8	4
Phosphate as P	0.10	0.00	0.40	0.14	0.12	7	0.10	0.00	1.60	0.30	0.50	9	0.10	0.03	1.80	0.60	0.78	7	0.10	0.02	0.40	0.20	0.2	4
UV 275 Abs.	1.14	0.58	1.67	1.13	0.47	4	0.82	0.48	1.06	0.78	0.23	8	0.76	0.70	0.94	0.77	0.08	7	0.81	0.66	0.93	0.80	0.15	4
UV 254 Abs.	1.49	0.76	2.16	1.47	0.60	4	1.07	0.63	1.39	1.02	0.30	8	1.01	0.92	1.22	1.03	0.10	7	1.06	0.86	1.22	1.05	0.19	4
Dis.Org.Carbon							9.6	5.8	12.4	9.3	2.4	7	10.0	8.9	11.9	10.1	0.9	7	9.2	7.5	12.1	9.5	2.2	4
pH	8.2	8.1	8.3	8.2	0.1	3	7.8	7.3	8.6	7.8	0.5	10	7.4	7.0	8.0	7.5	0.4	7	7.7	7.6	7.8	7.7	0.1	2
Conductivity	78	75	80	78	1.7	7	80	66	90	78	6.8	10	89	80	94	88	4.5	7	91	85	100	92	7.4	4

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P04B

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)	7.4	6.3	8.4	7.3	0.6	13	7.7	6.6	8.8	7.8	0.6	13	7.7	7.2	8.8	7.8	0.5	7	7.6	7.4	7.8	7.6	0.2	4
Sodium (Na)	93	83	101	92	5.3	11	94	80	100	93	5.3	11	96	93	100	96	3.3	4	98	94	99	97	2.2	4
Calcium (Ca)							35	34	41	36	2.4	6	34	33	35	34	0.7	4	39	37	47	40	4.4	4
Magnesium (Mg)							15	15	16	15	0.6	6	15	14	16	15	0.7	4	14	14	15	14	0.7	4
Ammonia as N	0.1	0.0	0.6	0.2	0.2	14	0.1	0.0	4.6	0.6	1.3	13	0.0	0.0	0.1	0.1	0.0	7	0.1	0.1	0.2	0.1	0.0	4
Sulphate (SO4)	58	54	74	60	5.8	11	57	47	64	57	4.8	11	50	49	55	51	2.9	4	63	61	65	63	1.7	4
Chloride (Cl)	155	140	170	156	9.2	13	158	140	165	155	9.2	11	163	150	169	161	6.3	7	162	152	170	162	8.9	4
T.Alkal (CaCO3)	65	60	74	65	4.6	11	70	58	88	71	7.5	11	65	64	69	66	2.2	4	76	66	79	74	5.7	4
Nitrate as N							5	1.7	6.8	4.9	1.7	13	3.8	3.0	5.3	4.1	0.9	7	4.5	3.2	4.9	4.3	0.8	4
Phosphate as P	0.05	0.03	0.78	0.16	0.22	13	0.05	0.03	0.25	0.06	0.06	12	0.03	0.03	0.03	0.03	0.00	7	0.03	0.03	0.05	0.03	0.00	4
UV 275 Abs.	0.96	0.94	0.99	0.96	0.02	3	0.93	0.81	1.04	0.93	0.08	8	0.88	0.78	0.89	0.85	0.05	7	0.94	0.81	1.01	0.93	0.09	4
UV 254 Abs.	1.26	1.24	1.29	1.26	0.03	3	1.22	1.07	1.37	1.21	0.10	8	1.15	1.05	1.18	1.14	0.05	7	1.24	1.06	1.32	1.21	0.11	4
Dis.Org.Carbon							10.2	8.3	11.2	9.9	1.1	7	10.3	9.6	10.7	10.2	0.3	7	10.6	9.2	10.9	10.3	0.8	4
pH	7.8	7	7.9	7.6	0.3	10	7.8	6.9	8.2	7.7	0.3	13	8.0	7.2	8.5	7.8	0.5	7	7.7	7.6	7.9	7.7	0.2	2
Conductivity	79	72	84	79	3.1	13	79	69	80	78	3.2	13	80	73	81	79	2.9	7	82	80	89	83	3.8	4

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P04C

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)																			7.7	6.7	9.2	7.8	0.6	18
Sodium (Na)																			98	94	112	99	4.4	13
Calcium (Ca)																			40	37	49	41	4.0	13
Magnesium (Mg)																			14	13	16	14	0.7	13
Ammonia as N																			0.1	0.0	8.9	0.6	2.1	18
Sulphate (SO4)																			58	51	74	59	6.3	13
Chloride (Cl)																			159	149	187	161	10.5	18
T.Alkal (CaCO3)																			77	70	120	82	14.0	13
Nitrate as N																			5.1	0.0	6.9	4.7	1.7	18
Phosphate as P																			0.03	0.03	1.36	0.13	0.35	14
UV 275 Abs.																			0.87	0.80	1.05	0.89	0.07	18
UV 254 Abs.																			1.13	1.05	1.37	1.16	0.09	18
Dis.Org.Carbon																			10.4	9.1	12.3	10.5	0.9	18
pH																			7.7	7.5	8.0	7.7	0.2	9
Conductivity																			84	78	99	85	5.1	18

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P04D

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)	7.5	6.2	9.4	7.5	0.8	36	7.8	6.9	11.4	7.9	0.9	22	7.8	6.2	8.8	7.7	0.6	26	7.8	6.8	10.1	7.9	0.8	17
Sodium (Na)							94	86	97	93	3.9	7	92	68	99	90	7.8	15	98	95	130	101	9.1	13
Calcium (Ca)							38	34	42	38	2.5	7	38	31	45	38	3.5	15	39	37	49	40	3.8	13
Magnesium (Mg)							15	13	15	15	0.5	7	14	9	15	14	1.4	15	14	13	16	14	0.6	13
Ammonia as N	0.1	0.0	7.7	0.6	1.6	36	0.1	0.0	3.6	0.4	0.8	22	0.1	0.0	3.2	0.5	0.8	26	0.1	0.0	8.9	0.7	2.2	17
Sulphate (SO4)							50	44	58	51	5.1	8	48	37	52	47	4.2	16	56	51	71	57	5.6	13
Chloride (Cl)	150	114	201	152	25.7	7	152	135	165	152	8.6	9	152	107	190	153	15.3	26	161	149	179	163	9.7	17
T.Alkal (CaCO3)							83	71	96	84	7.8	8	79	63	97	79	9.3	15	76	71	180	86	29.1	13
Nitrate as N	4.6	3.3	9.6	4.9	1.3	36	4.9	3.4	6.6	5.0	0.9	22	4.2	0.0	5.8	3.9	1.5	26	4.3	0.8	6.9	4.3	1.6	17
Phosphate as P	0.1	0.0	1.6	0.1	0.3	35	0.1	0.0	0.8	0.1	0.2	17	0.02	0.02	1.31	0.14	0.29	26	0.03	0.03	0.36	0.07	0.09	17
UV 275 Abs.	0.88	0.79	1.16	0.90	0.1	36	0.91	0.67	1.13	0.93	0.14	22	0.85	0.70	1.37	0.87	0.13	26	0.86	0.75	1.10	0.87	0.09	17
UV 254 Abs.	1.15	1.04	1.58	1.18	0.1	36	1.18	0.88	1.47	1.21	0.17	22	1.11	0.91	1.84	1.14	0.19	26	1.12	0.99	1.43	1.14	0.11	17
Dis.Org.Carbon							9.9	7.9	12.7	10.1	1.3	11	10.5	9.1	24.5	11.3	3.1	26	10.3	8.7	13.6	10.3	1.1	17
pH	8.0	7.6	8.3	7.9	0.2	15	8.1	7.6	8.3	8.1	0.2	22	7.8	7.4	8.5	7.9	0.3	24	7.8	7.6	9.1	7.9	0.5	8
Conductivity	79	59	92	77	6.9	36	78	70	84	78	3.2	22	80	60	91	78	5.8	26	84	78	96	84	4.6	17

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT :   P05B

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)	6.5	3.0	50.0	7.8	7.1	42	5.4	4.1	11.1	6.1	1.9	26	5.3	3.6	17.7	5.9	2.8	25	5.4	4.7	29.5	7.9	8.1	9
Sodium (Na)	150	100	592	212	154.1	9	158	137	244	165	28.7	13	147	120	187	151	19.2	14	161	139	1255	282	365	9
Calcium (Ca)							60	40	119	65	23.8	9	56	44	81	56	9.4	14	47	39	63	49	6.7	9
Magnesium (Mg)							19	11	21	18	3.3	9	17	14	20	17	1.9	14	18	1	21	16	6.2	9
Ammonia as N	0.1	0.0	1.3	0.3	0.3	43	0.1	0.0	0.6	0.1	0.2	26	0.1	0.0	12.4	0.9	2.5	25	0.1	0.0	0.4	0.1	0.1	9
Sulphate (SO4)	69	58	125	76	20.6	9	82	53	99	77	14.6	13	81	63	114	87	17.6	15	83	73	327	116	80.5	9
Chloride (Cl)	265	170	1188	377	276	15	263	190	397	273	62.2	14	217	176	301	220	32.4	25	230	207	278	234	25.4	9
T.Alkal (CaCO3)	133	70	175	127	33.8	10	128	105	186	135	20.5	13	132	109	186	134	23.8	14	118	107	2284	358	722.0	9
Nitrate as N							1.2	0.1	2.3	1.2	0.7	26	0.9	0.0	3.6	0.9	0.7	25	1.5	0.0	2.8	1.3	0.9	9
Phosphate as P	0.1	0.0	0.9	0.2	0.2	41	0.1	0.0	0.6	0.1	0.2	21	0.03	0.03	5.23	0.29	1.04	25	0.1	0.0	21.0	2.5	6.90	9
UV 275 Abs.	1.29	0.28	1.81	1.27	0.36	33	1.22	0.84	1.60	1.21	0.17	22	1.12	0.56	3.66	1.19	0.57	25	1.23	1.01	3.37	1.52	0.76	9
UV 254 Abs.	1.70	0.35	2.37	1.66	0.47	33	1.62	1.15	2.11	1.61	0.23	22	1.49	0.86	4.15	1.54	0.63	25	1.61	1.34	4.22	1.97	0.92	9
Dis.Org.Carbon							14.7	9.2	42.0	16.3	8.8	11	17.5	10.9	48.0	18.4	7.6	25	15.7	14.3	92.5	27.1	25.5	9
pH	7.3	5.5	8.0	7.3	0.6	23	7.7	7.1	10.2	7.8	0.6	26	7.7	7.4	8.3	7.8	0.3	23	7.5	7.0	12.3	8.4	2.2	5
Conductivity	122	100	620	156	106.2	43	118	104	175	121	15.8	26	114	94	175	117	16.9	25	114	103	1000	215	295	9

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P05C

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)	7.5	6.9	9.8	7.6	0.6	22	7.5	6.9	9.8	7.6	0.6	22	7.5	3.9	8.6	7.4	0.9	23	7.7	7.0	10.5	7.8	0.9	12
Sodium (Na)							105	97	112	104	6.2	8	102	90	179	108	23.2	12	106	97	237	119	39.6	11
Calcium (Ca)							41	35	47	41	4.0	8	39	36	67	42	8.4	12	40	27	49	41	5.9	11
Magnesium (Mg)							16	15	17	15	0.7	8	15	14	24	15	2.9	12	15	4	16	14	3.5	11
Ammonia as N	0.1	0.0	3.4	0.3	0.7	22	0.1	0.0	3.4	0.3	0.7	22	0.1	0.0	1.9	0.3	0.4	23	0.1	0.0	6.1	0.7	1.7	12
Sulphate (SO4)							59	53	68	60	5.3	8	59	48	112	62	16.5	12	68	59	85	68	7.6	11
Chloride (Cl)	173	155	208	176	16.7	9	173	155	208	176	16.7	9	167	143	284	174	27.8	23	173	153	188	172	9.9	12
T.Alkal (CaCO3)							86	75	91	85	6.2	8	79	66	162	87	25.1	12	82	74	285	100	61.6	11
Nitrate as N	4.7	3.4	8.1	4.8	1.2	22	4.7	3.4	8.1	4.8	1.2	22	3.9	0.5	5.1	3.8	0.9	23	4.7	2.7	6.4	4.4	1	12
Phosphate as P	0.1	0.0	0.3	0.1	0.1	17	0.1	0.0	0.3	0.1	0.1	17	0.03	0.02	0.11	0.03	0.02	23	0.07	0.03	2.74	0.35	0.80	11
UV 275 Abs.	0.94	0.69	1.16	0.96	0.13	22	0.94	0.70	1.16	0.95	0.13	22	0.88	0.78	1.38	0.92	0.14	23	0.89	0.81	1.11	0.91	0.08	12
UV 254 Abs.	1.23	0.92	1.50	1.25	0.16	22	1.23	0.92	1.50	1.25	0.16	22	1.16	1.02	1.86	1.21	0.19	23	1.17	1.06	1.43	1.19	0.11	12
Dis.Org.Carbon							10.5	8.3	12.3	10.4	0.9	10	11.6	9.6	17.9	12.1	2.0	23	11.3	9.4	22.0	12.0	3.3	12
pH	8.0	7.5	8.3	7.9	0.2	22	8.0	7.5	8.3	7.9	0.2	22	7.9	7.5	8.5	7.9	0.2	21	7.9	7.6	10.9	8.3	1.3	6
Conductivity	86	76	97	86	4.9	22	86	76	97	86	4.9	22	86	79	140	89	12.3	23	89	84	136	93	13.9	12

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P09B

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)	1.3	0.2	3.3	1.4	0.7	33	3.4	1.6	6.9	3.6	1.5	21	4.5	2.9	8.6	4.9	1.7	18	3.6	1.1	12.9	4.1	3.0	12
Sodium (Na)	220	214	226	220	8.8	2	233	156	297	225	51.1	7	217	171	247	216	22.8	10	235	173	261	224	32.2	12
Calcium (Ca)	78	77	79	78	1.4	2	77	48	93	72	17.6	7	76	59	134	80	22.1	10	74	54	80	73	7.4	12
Magnesium (Mg)	33	32	34	33	1.3	2	31	21	33	29	5.2	7	26	22	32	27	3.4	10	25	18	30	26	3.5	12
Ammonia as N	0.1	0.0	0.8	0.1	0.1	33	0.1	0.0	1.9	0.2	0.4	21	0.1	0.0	0.4	0.1	0.1	18	0.0	0.0	0.4	0.1	0.1	12
Sulphate (SO4)	174	168	180	174	8.5	6	119	48	161	110	37.6	8	141	96	148	131	18.2	10	138	84	167	136	20.6	12
Chloride (Cl)	334	318	371	340	18.8	2	338	208	450	323	77.2	9	326	194	465	320	59.2	18	325	250	381	319	43.0	12
T.Alkal (CaCO3)	200	199	201	200	1.4	2	208	142	299	202	49.6	8	176	146	242	181	31.6	10	181	161	213	183	19.4	12
Nitrate as N	0.3	0.0	1.4	0.5	0.4	33	0.1	0.1	3.5	0.3	0.7	21	0.2	0.0	1.4	0.4	0.4	18	1.3	0.1	8.3	1.7	2.2	12
Phosphate as P	0.05	0.01	0.18	0.05	0.04	32	0.03	0.02	0.09	0.03	0.02	16	0.04	0.03	0.70	0.12	0.18	18	0.03	0.03	4.50	0.40	1.29	12
UV 275 Abs.	1.64	1.13	1.93	1.61	0.20	31	1.58	0.84	2.13	1.53	0.31	21	1.46	1.24	1.64	1.46	0.12	18	1.40	1.21	1.58	1.39	0.10	12
UV 254 Abs.	2.17	1.51	2.55	2.14	0.26	31	2.09	1.11	2.81	2.02	0.41	21	1.99	1.66	2.16	1.94	0.15	18	1.82	1.59	2.09	1.84	0.14	12
Dis.Org.Carbon	7.2	6.6	17.2	9.2	4.5	5	15.3	12.0	45.0	18.4	9.6	10	19.3	16.7	23.8	19.5	1.7	18	17.7	14.3	24.7	18.1	2.5	12
pH	7.8	7.6	7.9	7.8	0.1	13	7.9	7.3	8.1	7.8	0.2	21	8.0	7.5	9.0	8.1	0.4	17	7.8	7.7	8.1	7.9	0.2	7
Conductivity	160	106	178	153	19.4	33	154	97	200	148	27.6	21	163	133	199	162	16.6	18	165	118	185	160	19.3	12

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P10B

	1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS
Potassium (K)	8.9	2.6	42.7	11.6	8.4	26	9.3	5.1	16.5	9.8	3.4	13
Sodium (Na)	445	205	673	465	127.4	18	544	431	783	569	99.1	13
Calcium (Ca)	159	96	183	153	27.4	18	143	136	165	146	9.3	13
Magnesium (Mg)	55	26	77	55	14.3	18	61	50	73	61	7.6	13
Ammonia as N	0.2	0.0	416.5	26.9	89.5	26	0.2	0.0	2.4	0.4	0.7	13
Sulphate (SO4)	185	88	221	178	37.2	18	247	220	268	246	13.3	13
Chloride (Cl)	832	253	1244	815	246.2	26	950	785	1342	1020	166.8	13
T.Alkal (CaCO3)	239	90	406	238	74.9	18	188	151	245	191	25.7	13
Nitrate as N	0.1	0.0	0.1	0.0	0.0	26	0.0	0.0	0.4	0.1	0.1	13
Phosphate as P	0.03	0.00	13.70	0.95	2.96	26	0.03	0.03	0.64	0.12	0.19	13
UV 275 Abs.	1.69	0.30	4.24	1.81	0.86	26	1.74	1.40	2.57	1.82	0.34	13
UV 254 Abs.	2.31	0.76	4.26	2.48	0.83	26	2.41	1.9	3.37	2.45	0.44	13
Dis.Org.Carbon	23.4	9.5	802.0	64.1	160.2	26	23.9	9.3	35.3	23.8	8.1	13
pH	7.6	7.3	9.4	7.9	0.6	21	8.1	7.5	8.6	8.1	0.4	8
Conductivity	340	118	485	336	87.8	26	370	315	465	378	46	13

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P06A

DETERMINANT	1986						1987						1988						1989					
	MEDIAN	MIN.	MAX.	MEAN	S. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	S. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	S. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	S. DEV	OBS.
Potassium (K)	7.2	5.3	13.0	7.4	1.3	42	7.4	6.3	8.3	7.4	0.4	44	7.5	6.3	9.3	7.5	0.5	40	7.4	6.6	9.8	7.5	0.6	43
Sodium (Na)	124	97	180	127	26.7	10	108	93	208	112	25.4	12	107	82	136	108	12.0	25	113	99	145	115	10.0	22
Calcium (Ca)							41	36	46	41	2.7	12	41	33	48	41	3.0	25	42	38	51	42	3.5	22
Magnesium (Mg)							16	14	19	16	1.3	12	15	12	18	15	1.2	25	15	14	17	15	0.8	22
Ammonia as N	0.1	0.0	6.1	0.6	1.2	43	0.1	0.0	15.0	0.6	2.3	44	0.1	0.0	3.1	0.4	0.6	40	0.1	0.0	6.4	0.6	1.3	43
Sulphate (SO4)	69	57	98	72	12.4	10	63	54	79	65	7.9	18	61	49	82	62	6.7	26	71	50	87	71	8.3	22
Chloride (Cl)	181	135	305	193	42.5	16	175	160	320	184	34.2	20	171	127	226	176	19.8	40	177	158	224	181	14.7	43
T.Alkal (CaCO3)	95	80	155	101	24.5	11	88	70	135	90	14.8	18	83	65	113	85	9.7	24	85	74	163	89	18.3	22
Nitrate as N							4.3	1.6	6.2	4.4	0.9	44	3.8	1.7	5.0	3.8	0.7	40	4.1	0.2	5.9	3.9	1.2	43
Phosphate as P	0.10	0.02	4.10	0.42	0.83	41	0.05	0.02	0.40	0.08	0.08	34	0.03	0.01	0.40	0.06	0.07	40	0.00	0.03	2.32	0.24	0.48	28
UV 275 Abs.	0.94	0.79	1.17	0.96	0.09	32	0.94	0.73	1.33	0.98	0.13	39	0.89	0.74	1.20	0.91	0.08	40	0.92	0.64	9.58	1.10	1.33	43
UV 254 Abs.	1.23	1.06	1.59	1.26	0.12	32	1.23	0.96	1.69	1.28	0.17	39	1.17	0.98	1.62	1.19	0.11	40	1.21	0.84	1.49	1.19	0.11	43
Dis.Org.Carbon							10.8	8.6	13.0	10.8	1.02	15	11.5	9.7	17.5	11.8	1.7	40	11.2	8.8	18.1	11.6	1.9	43
pH	7.8	7.5	8.2	7.8	0.2	22	7.9	6.7	8.3	7.9	0.3	42	7.8	7.4	8.3	7.8	0.2	36	7.7	7.3	9.3	7.8	0.4	21
Conductivity	90	77	132	93	10.5	43	88	80	135	89	8.9	44	90	70	108	90	7.3	40	92	83	106	93	5.4	43

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P06B

	1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS
Potassium (K)	7.5	6.3	9.0	7.3	0.7	21	6.8	5.5	9.6	7.2	1.3	11
Sodium (Na)	111	92	124	110	7.3	16	109	76	129	106	13.6	11
Calcium (Ca)	41	38	52	42	3.4	16	42	34	45	41	3.3	11
Magnesium (Mg)	16	11	17	15	1.6	16	15	10	17	14	2.2	11
Ammonia as N	0.1	0.0	0.7	0.2	0.2	21	0.1	0.0	1.1	0.2	0.3	11
Sulphate (SO4)	63	49	71	63	6.1	16	63	46	78	63	8.9	11
Chloride (Cl)	176	150	188	175	9.9	21	168	130	208	168	19.8	11
T.Alkal (CaCO3)	92	85	116	94	7.8	16	89	68	99	88	8.8	11
Nitrate as N	2.2	0.9	4.9	2.3	0.9	21	3.0	1.7	4.2	2.9	0.9	11
Phosphate as P	0.03	0.03	0.60	0.10	0.18	21	0.05	0.03	1.44	0.19	0.42	11
UV 275 Abs.	0.94	0.81	1.09	0.93	0.07	21	0.89	0.70	1.05	0.89	0.11	11
UV 254 Abs.	1.24	1.05	1.43	1.22	0.08	21	1.16	0.91	1.36	1.17	0.14	11
Dis.Org.Carbon	11.7	10.8	13.9	11.8	0.78	21	9.9	9.2	12.6	10.5	1.2	11
pH	7.5	7.0	8.2	7.5	0.3	20	7.5	7.3	8.1	7.5	0.3	7
Conductivity	90	77	102	89	4.9	21	89	66	102	87	8.8	11

A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

SAMPLE POINT : P7In

	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)	12.3	6.9	16.0	11.3	2.9	14	7.2	6.1	8.2	7.1	0.5	26	7.8	5.6	37.3	8.9	6.6	21	7.1	5.8	13.1	7.8	1.9	31
Sodium (Na)	155	135	180	152	15.4	9	118	80	144	116	20	12	144	100	506	204	122.9	14	114	95	152	120	16.3	16
Calcium (Ca)							44	35	46	43	3.9	7	50	40	124	69	30.7	14	42	39	45	42	1.8	16
Magnesium (Mg)							18	14	19	17	2.4	7	19	11	57	24	13.8	14	15	14	17	15	0.9	16
Ammonia as N	0.1	0.0	1.6	0.2	0.4	15	0.1	0.0	0.5	0.1	0.1	26	0.3	0.0	310.0	15.8	67.5	21	0.1	0.0	0.9	0.1	0.2	31
Sulphate (SO4)	83	64	100	85	11.2	9	68	54	79	68	8.5	12	77	56	164	92	36.7	15	69	58	84	71	8.5	16
Chloride (Cl)	212	180	270	218	26.1	10	199	140	274	200	39.1	13	188	153	896	280	200.3	21	178	155	237	183	18.8	31
T.Alkal (CaCO3)	131	93	155	127	17.7	10	86	75	109	89	11	12	132	90	1188	213	295.5	13	93	81	99	93	4.7	16
Nitrate as N							2.0	0.1	5.3	2.5	1.6	26	2.1	0.0	4.9	2.5	1.5	21	2.9	0.6	4.5	2.9	0.9	30
Phosphate as P	2.98	0.05	5.80	2.68	1.61	14	0.05	0.03	0.88	0.09	0.18	23	0.05	0.03	9.20	0.64	1.98	21	0.00	0.01	3.14	0.26	0.72	19
UV 275 Abs.	1.05	0.99	1.08	1.05	0.03	6	1.02	0.78	1.31	1.03	0.15	21	1.02	0.84	4.06	1.32	0.74	21	0.96	0.76	86.00	3.69	15.28	31
UV 254 Abs.	1.34	1.26	1.39	1.33	0.04	6	1.34	1.03	1.71	1.34	0.18	21	1.34	1.09	4.15	1.68	0.77	21	1.25	0.98	1.61	1.23	0.12	31
Dis.Org.Carbon							12.1	9.3	14.6	11.8	1.6	8	12.7	11.2	698.0	46.9	149.0	21	11.3	9.5	14.1	11.4	1.1	31
pH	7.9	7.7	8.5	7.9	0.2	9	8.1	7.4	9.7	8.3	0.7	25	7.9	7.4	8.9	8.1	0.5	18	7.8	7.3	8.2	7.8	0.2	15
Conductivity	118	105	128	117	7.4	15	93	74	119	94	10.4	26	96	81	410	143	89.9	21	91	83	110	93	6.6	31

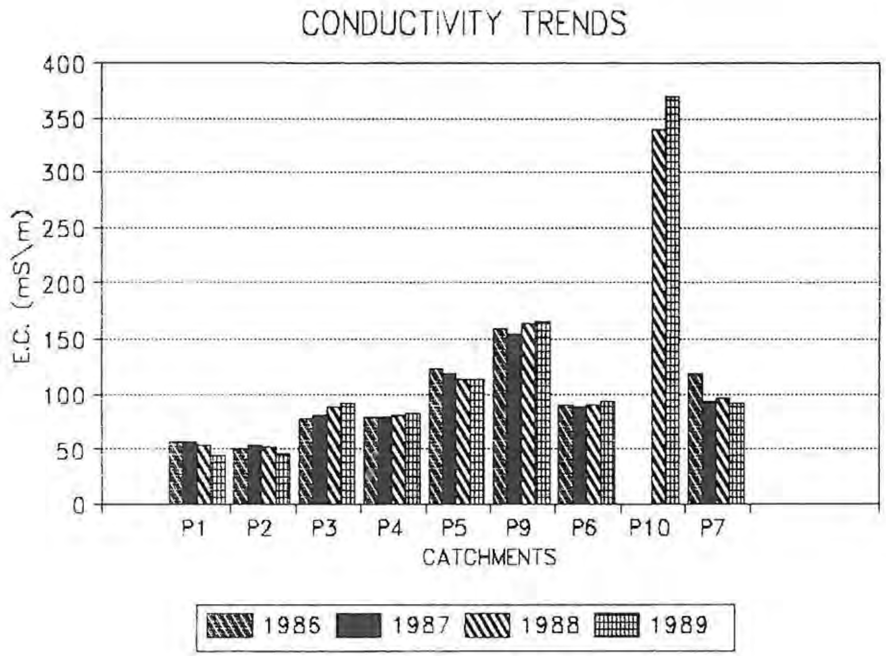
A STATISTICAL SUMMARY OF STORMWATER RUNOFF QUALITY

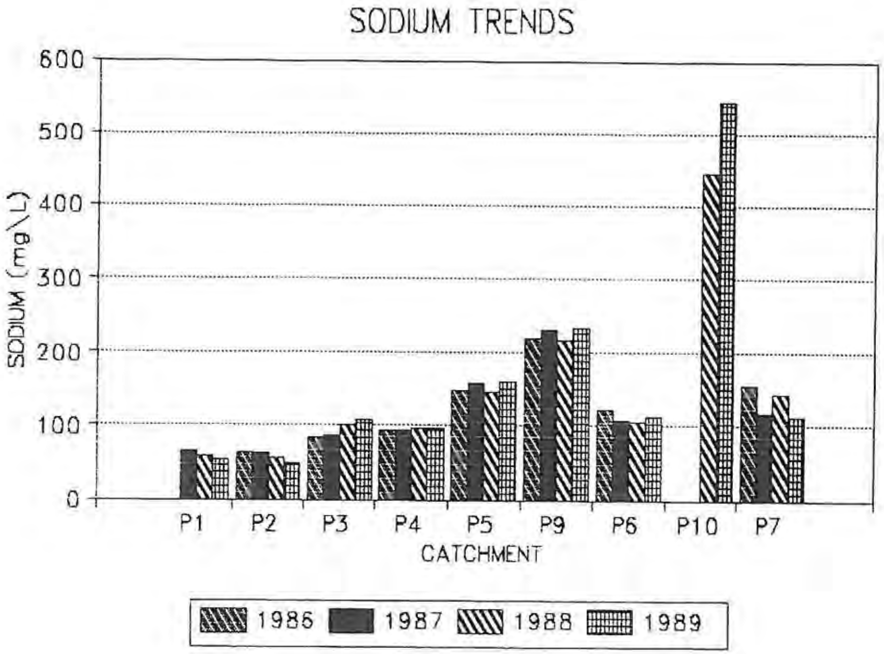
SAMPLE POINT : P7S

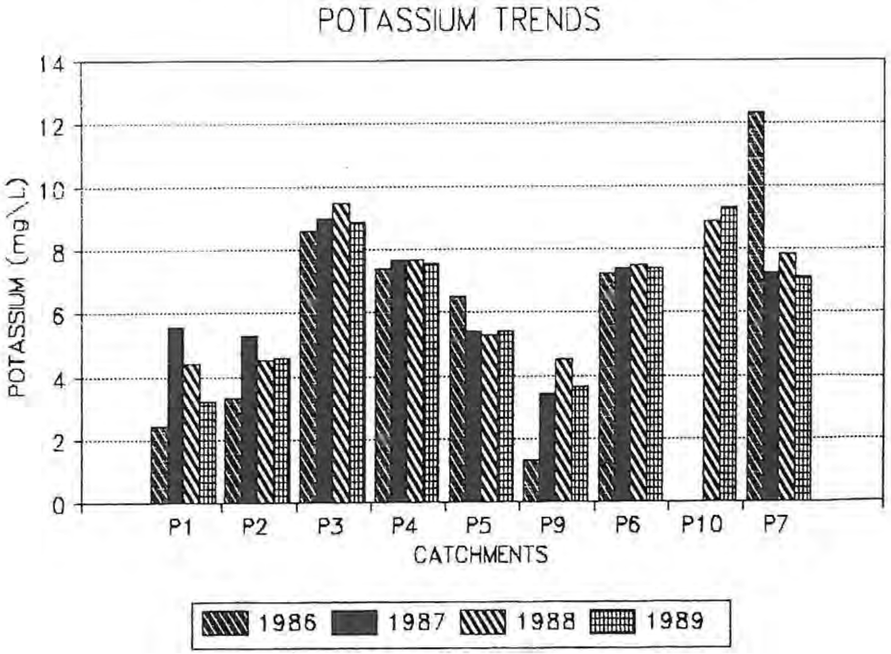
	1986						1987						1988						1989					
DETERMINANT	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.	MEDIAN	MIN.	MAX.	MEAN	STD. DEV	OBS.
Potassium (K)	10.9	6.5	15.4	10.7	2.6	53	6.7	4.3	13.6	7.4	2.4	56	6.9	4.2	13.3	7.1	1.7	38	6.7	4.6	10.0	6.7	1.3	42
Sodium (Na)	145	90	185	137	35.5	12	99	51	168	99	38.5	21	90	42	165	94	28.9	23	84	57	128	85	21.3	22
Calcium (Ca)							46	28	65	45	10.7	15	43	24	57	43	8.7	23	33	23	41	33	4.6	22
Magnesium (Mg)							14	8	18	13	3.2	15	12	6	20	12	2.9	23	10	6	16	11	2.7	22
Ammonia as N	0.2	0.0	1.6	0.3	0.3	54	0.1	0.0	0.6	0.1	0.1	56	0.1	0.2	0.8	0.2	0.2	38	0.1	0.0	0.4	0.1	0.1	42
Sulphate (SO4)	73	46	100	73	16.2	12	54	32	69	51	10.2	24	50	26	68	49	9.2	24	53	36	72	51	10.9	22
Chloride (Cl)	202	125	266	196	44.6	21	173	84	283	173	55.7	32	149	67	270	147	41.1	38	130	75	211	133	35.2	42
T.Alkal (CaCO3)	135	90	173	133	23.7	13	112	60	182	112	36.5	23	105	59	148	105	23.8	24	80	65	100	81	10.9	21
Nitrate as N							0.6	0.0	2.8	0.8	0.8	56	0.3	0.2	2.3	0.6	0.7	38	1.2	0.0	3.9	1.1	0.8	42
Phosphate as P	1.58	0.05	5.30	1.52	0.88	51	0.36	0.05	1.28	0.43	0.32	44	0.11	0.20	0.49	0.17	0.15	38	0.06	0.00	0.90	0.14	0.22	26
UV 275 Abs.	0.99	0.72	1.61	1.01	0.22	41	1.00	0.63	1.69	1.03	0.30	50	0.94	0.59	1.76	0.98	0.27	38	0.89	0.56	1.19	0.87	0.19	42
UV 254 Abs.	1.27	0.91	2.11	1.31	0.30	41	1.31	0.82	2.28	1.35	0.42	50	1.22	0.76	2.37	1.29	0.37	38	1.14	0.72	1.58	1.14	0.24	42
Dis.Org.Carbon							14.4	6.5	29.0	15.6	6.5	21	12.6	6.9	26.7	12.8	3.9	38	10.4	5.9	16.7	10.7	2.9	42
pH	9.3	7.7	11.1	9.2	0.8	30	8.6	4.9	10.3	8.6	0.9	54	9.2	7.5	9.9	8.9	0.7	33	7.9	7.5	9.7	8.3	0.8	20
Conductivity	109	68	132	101	18.8	54	74	47	134	79	24.7	56	80	40	126	78	17.6	38	71	44	96	69	13.8	42

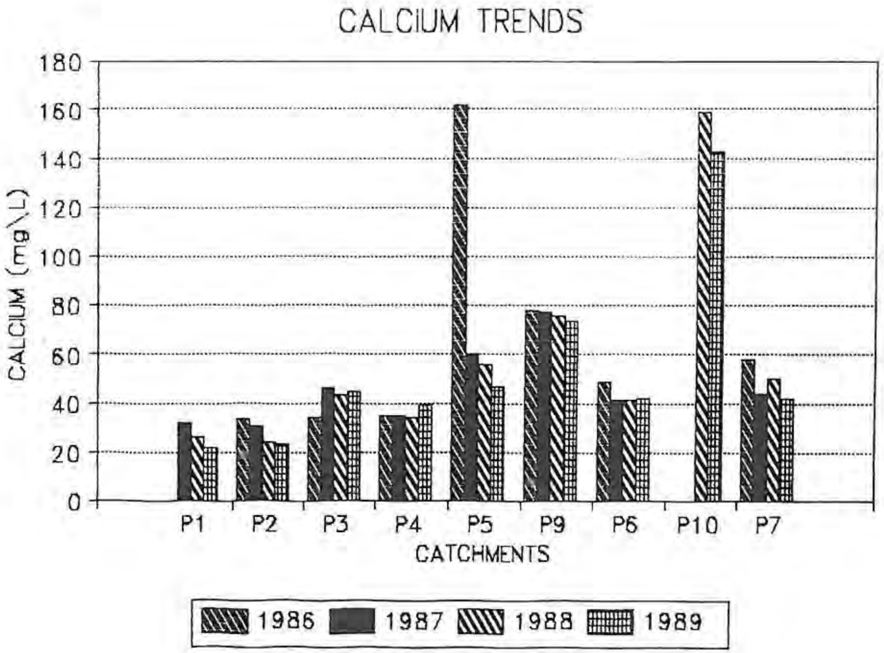
APPENDIX D

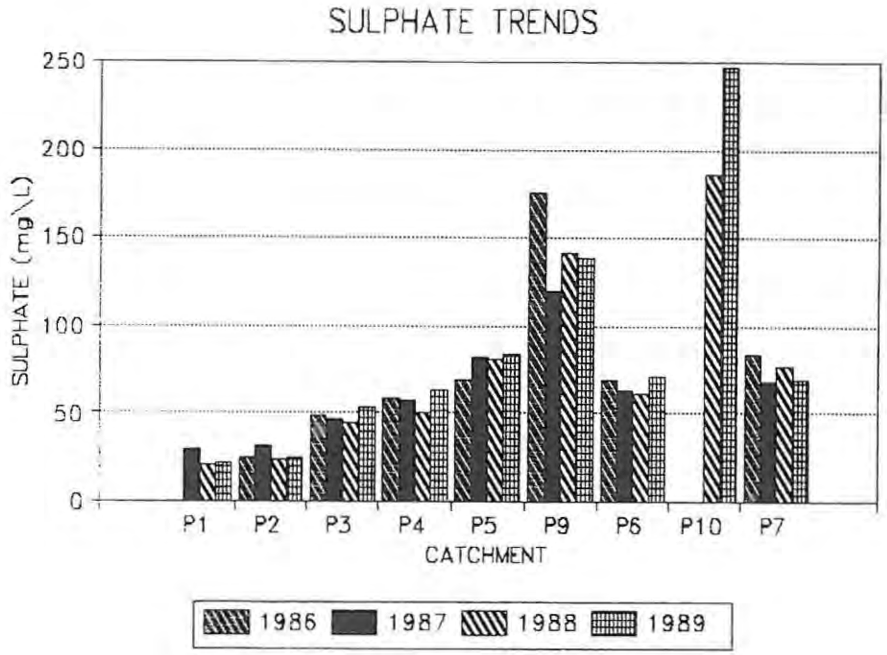
BAR GRAPHS SUMMARIZING THE STORMWATER RUNOFF QUALITY

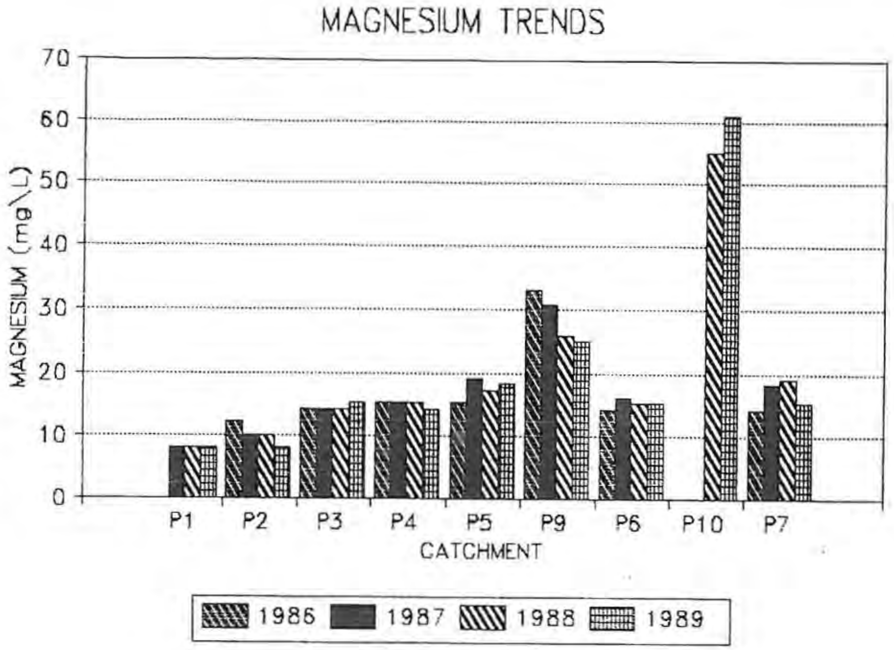

CONDUCTIVITY TRENDS

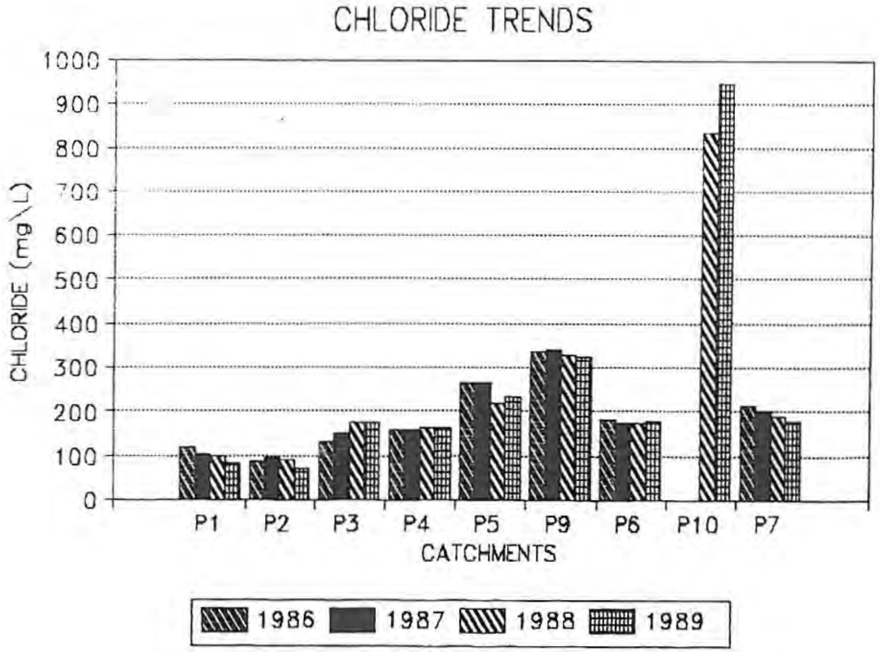

SODIUM TRENDS

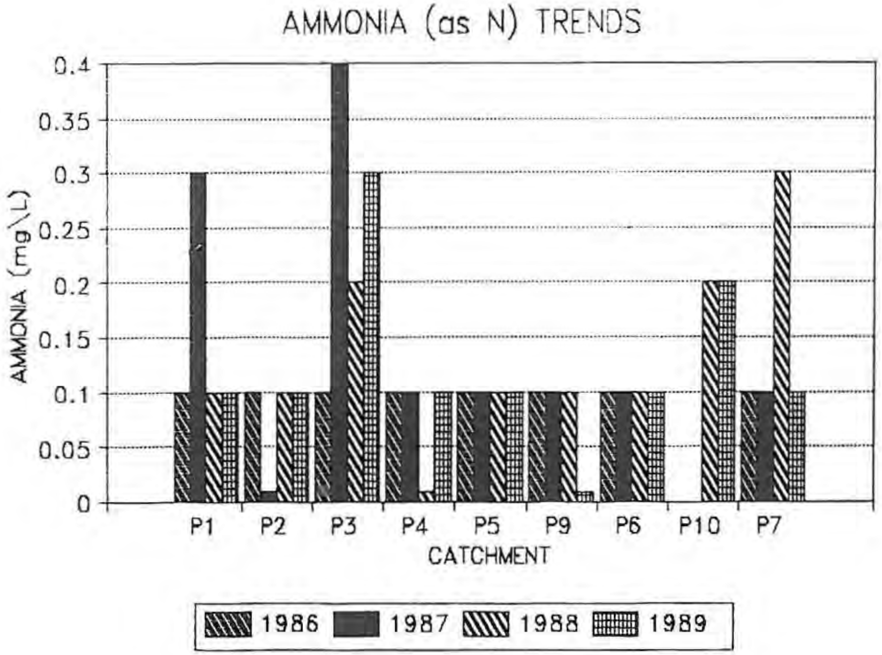

POTASSIUM TRENDS


CALCIUM TRENDS

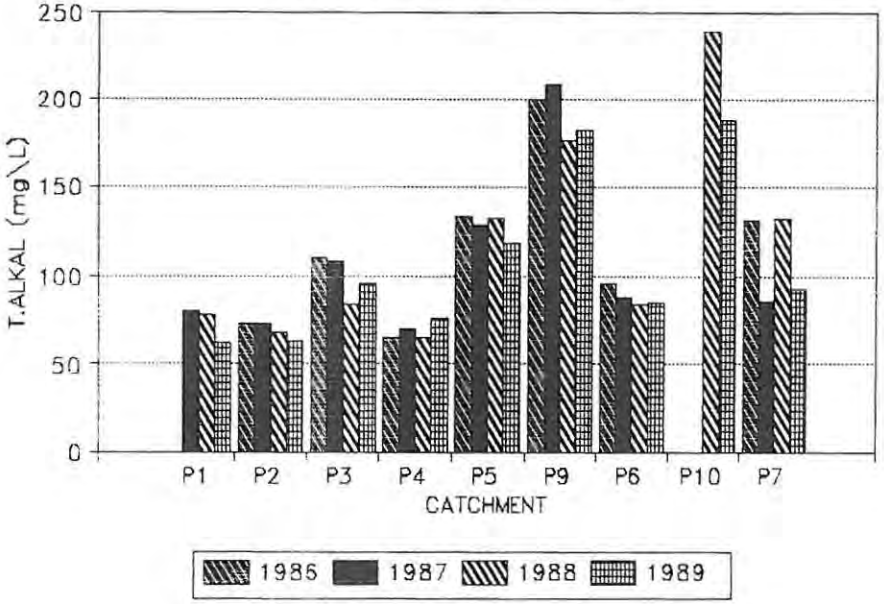

SULPHATE TRENDS


MAGNESIUM TRENDS

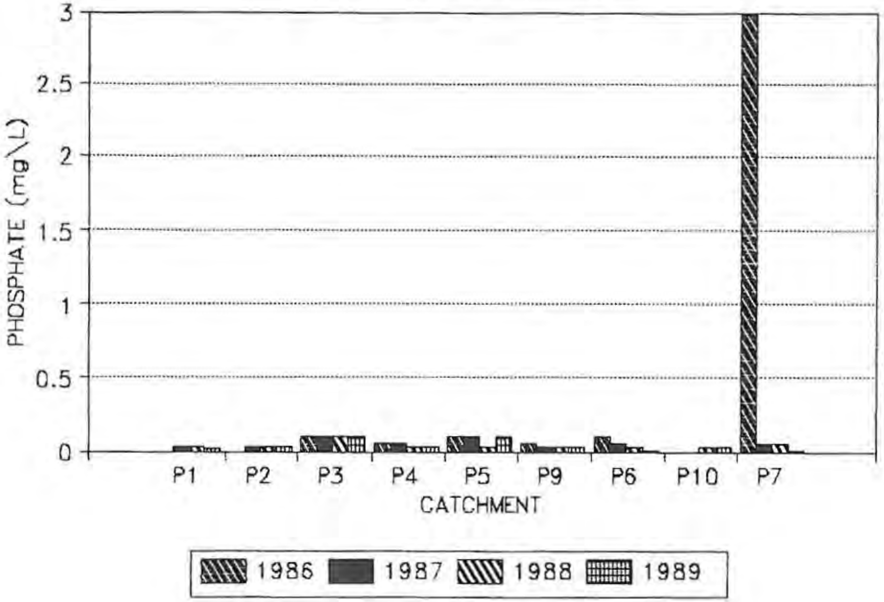

CHLORIDE TRENDS


AMMONIA (as N) TRENDS

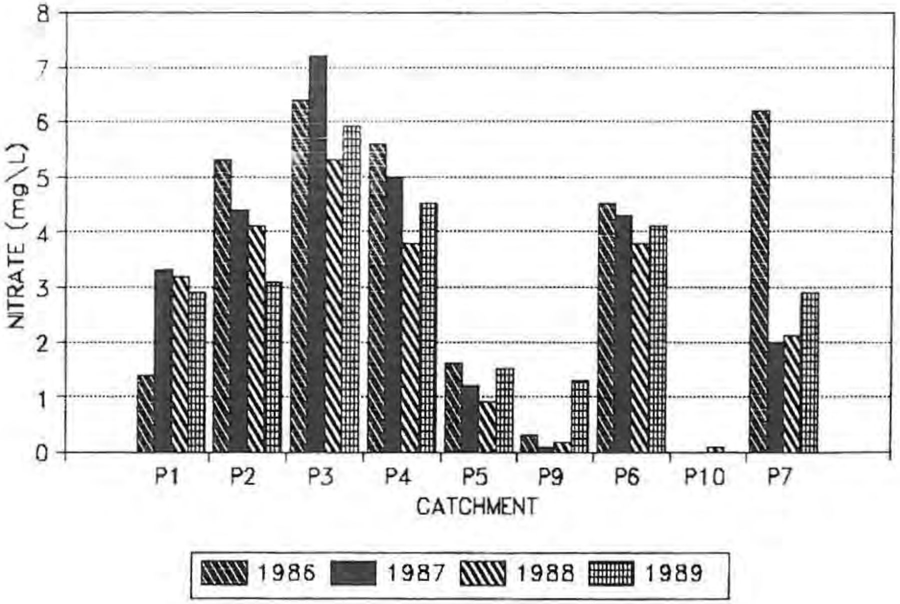
TOTAL ALKALINITY TRENDS



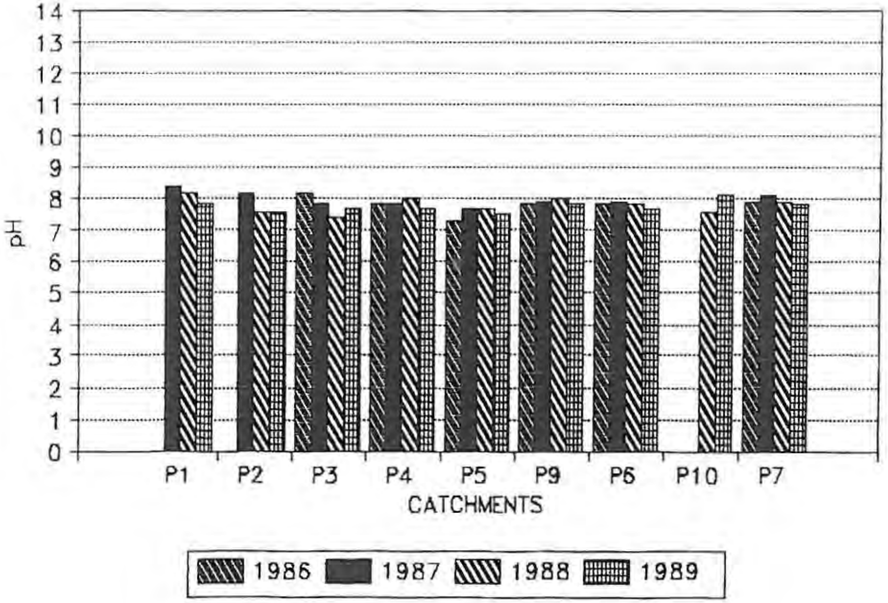
PHOSPHATE TRENDS

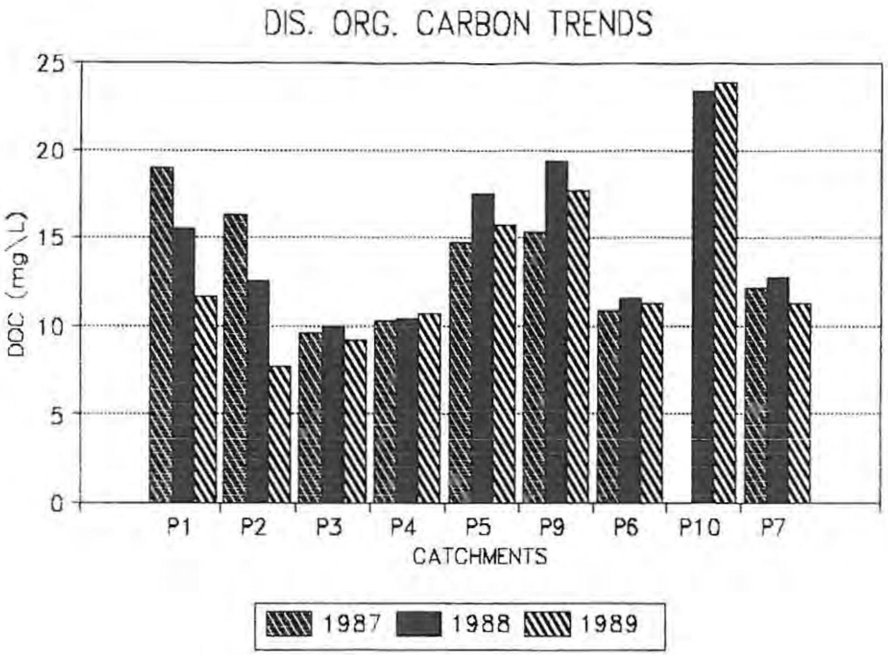


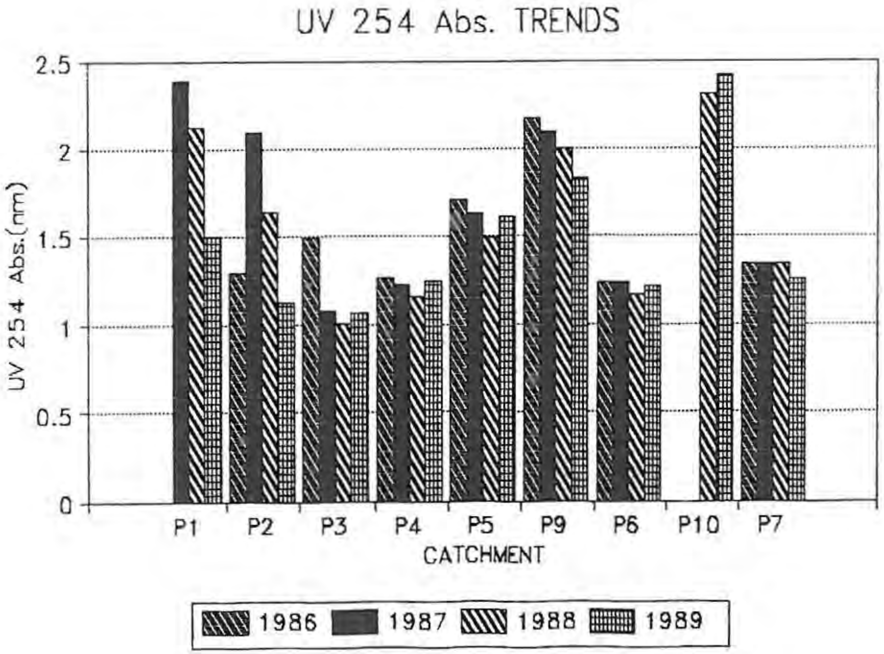
NITRATE (as N) TRENDS



pH TRENDS




DIS. ORG. CARBON TRENDS
DOC (mg\L)
0
5
10
15
20
25
P1
P2
P3
P4
P5
P9
P6
P10
P7
CATCHMENTS
1987
1988
1989


UV 254 Abs. TRENDS
UV 254 Abs.(nm)
0
0.5
1
1.5
2
2.5
P1
P2
P3
P4
P5
P9
P6
P10
P7
CATCHMENT
1986
1987
1988
1989

APPENDIX E

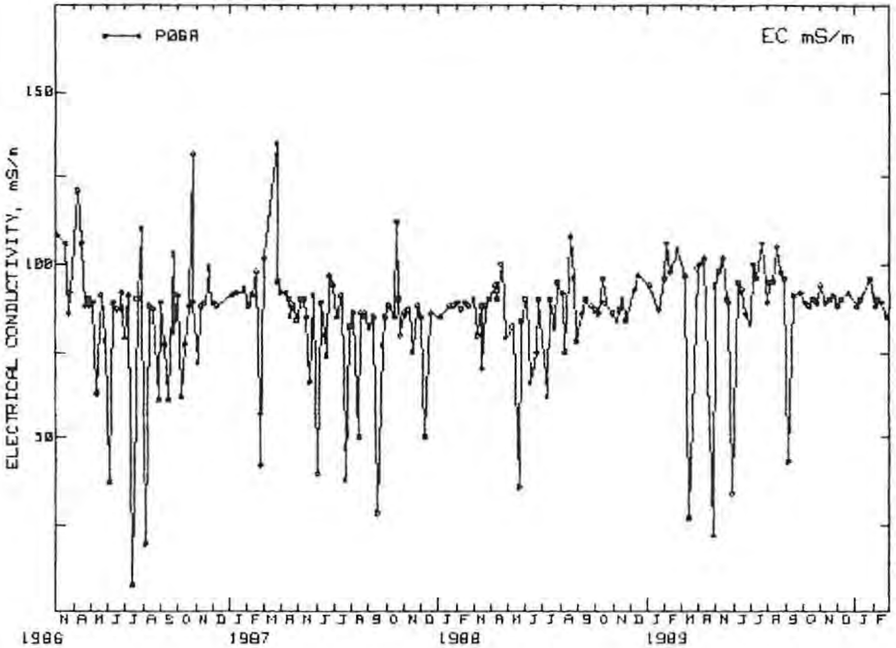
TIME-SERIES PLOTS FOR STORMWATER RUNOFF QUALITY VARIABLES ENTERING POND 6

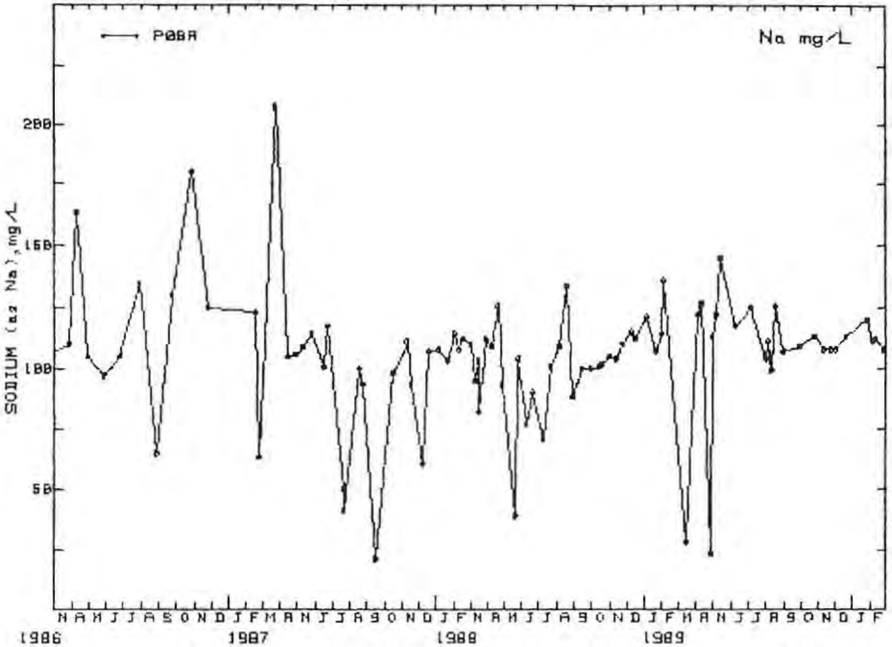
E1 - EC, K, Na, Cl

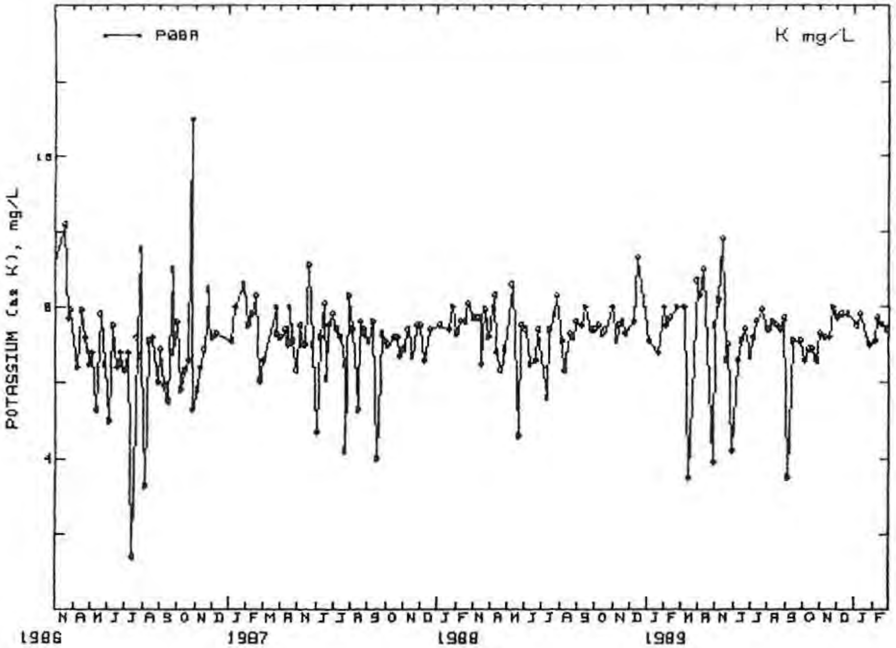
E2 - Ca, Mg, SO_4, T.Alk as $CaCo_3$

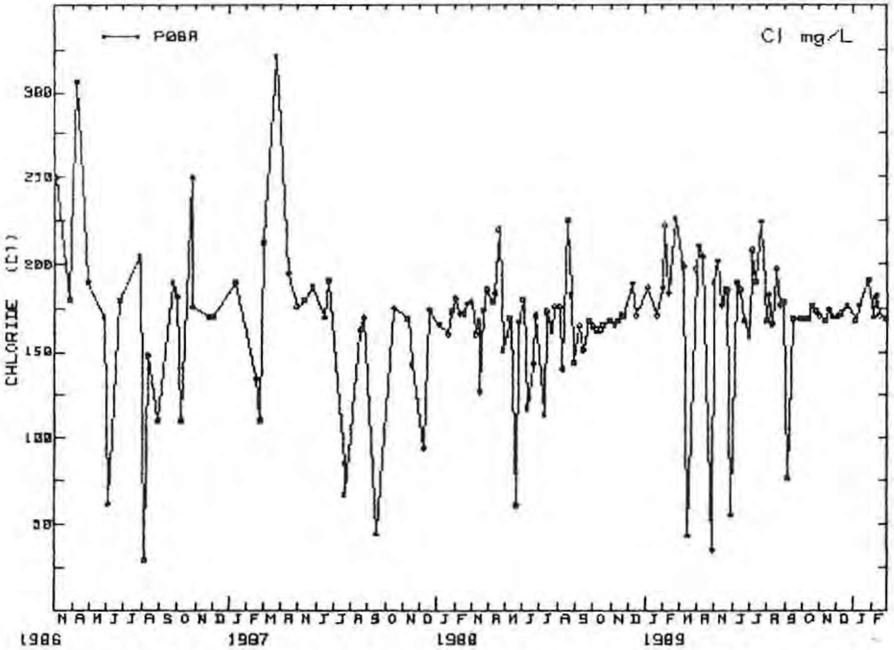
E3 - NH_4 as N,NO_x as N, PO_4 as P, pH

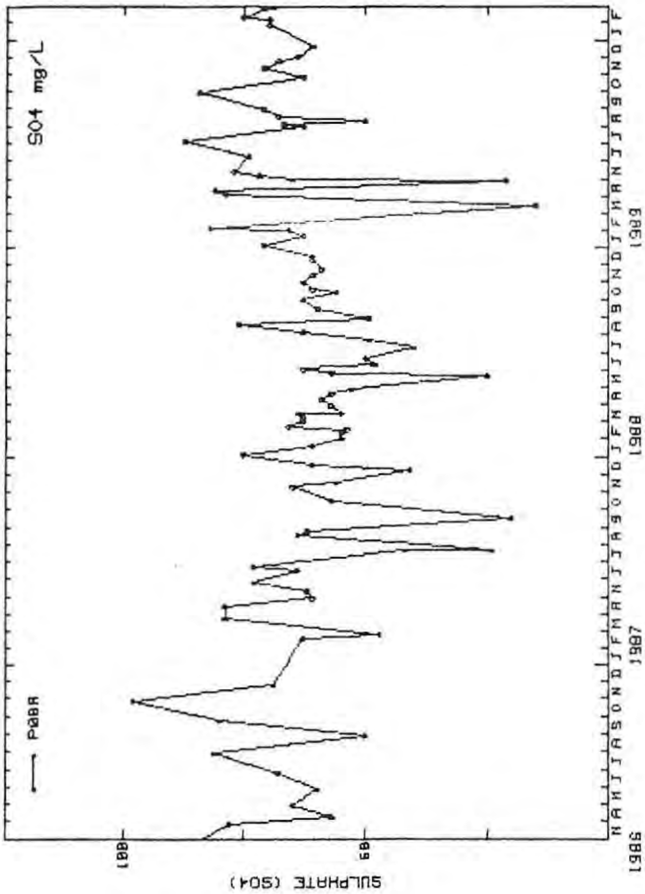
E4 - DOC, UV 254 Abs.

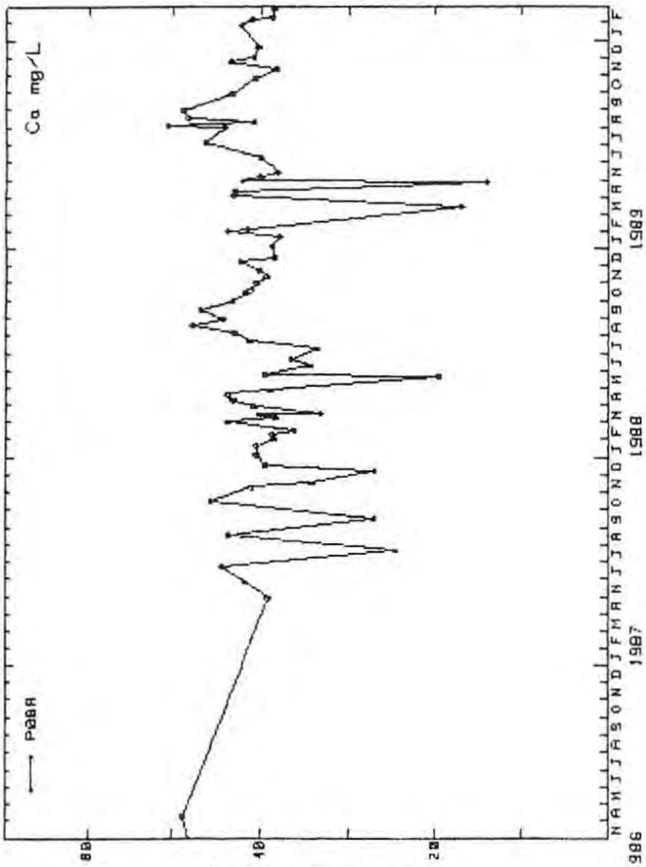

P08A
EC mS/m
ELECTRICAL CONDUCTIVITY, mS/m
150
100
50
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

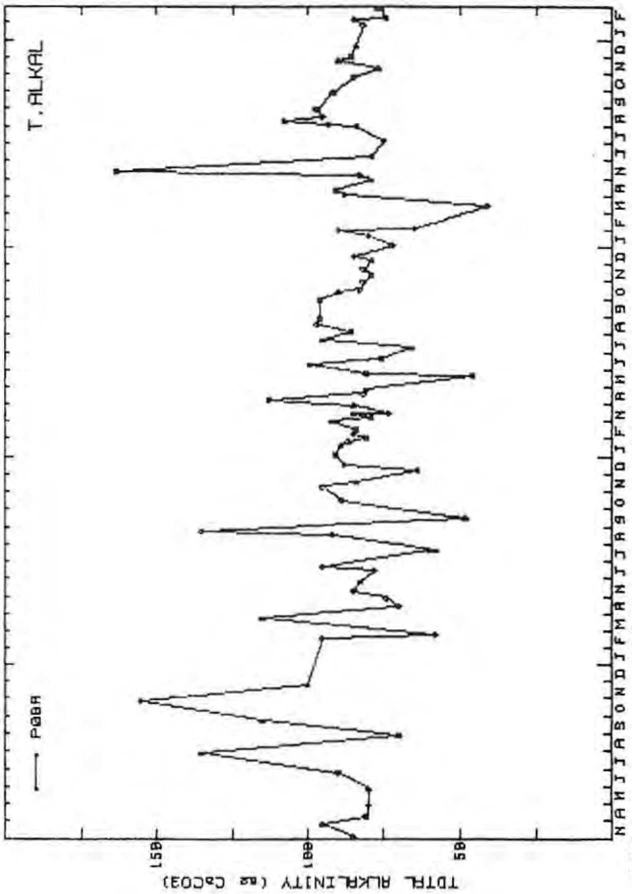

P08A
Na mg/L
SODIUM (as Na),mg/L
200
150
100
50
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

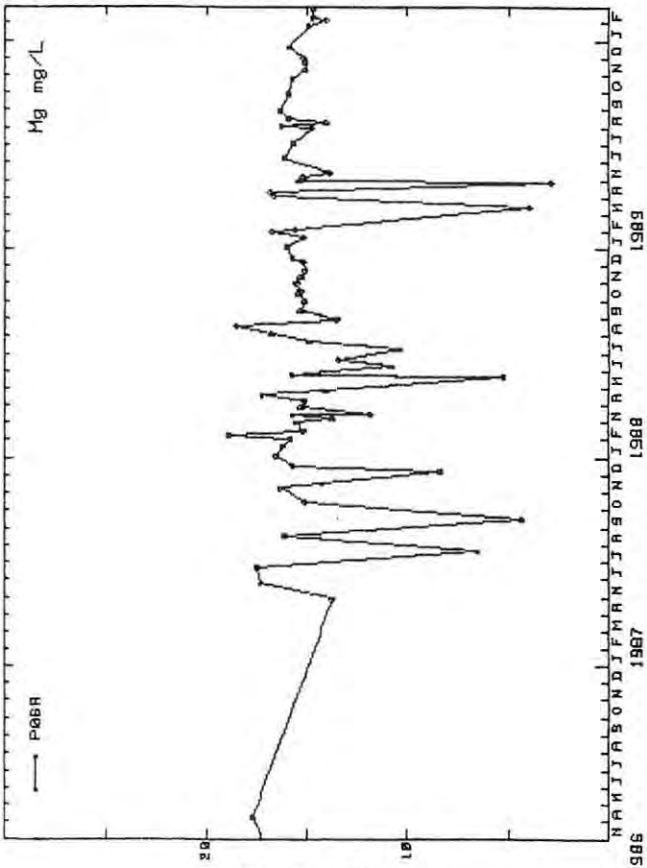

P08A
K mg/L
POTASSIUM (as K), mg/L
10
8
4
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

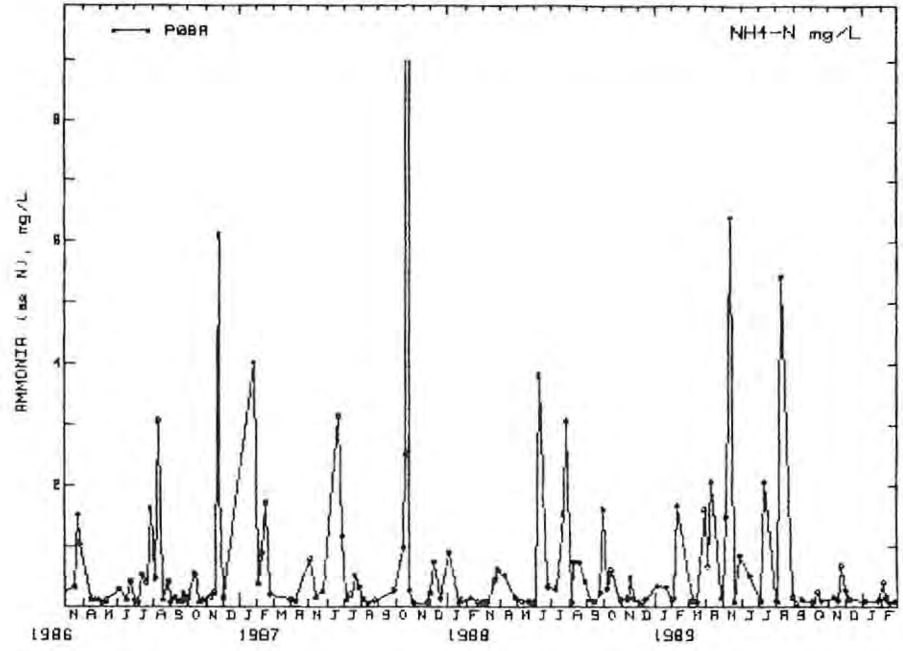

P08A
Cl mg/L
CHLORIDE (Cl)
300
250
200
150
100
50
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

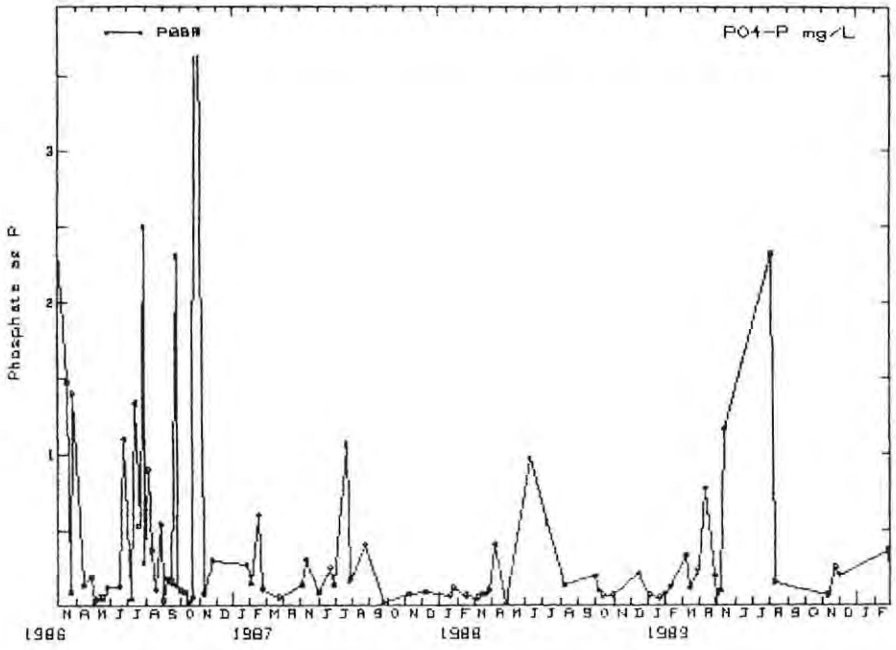

SO4 mg/L
P08A
SULPHATE (SO4)
100
50
N A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

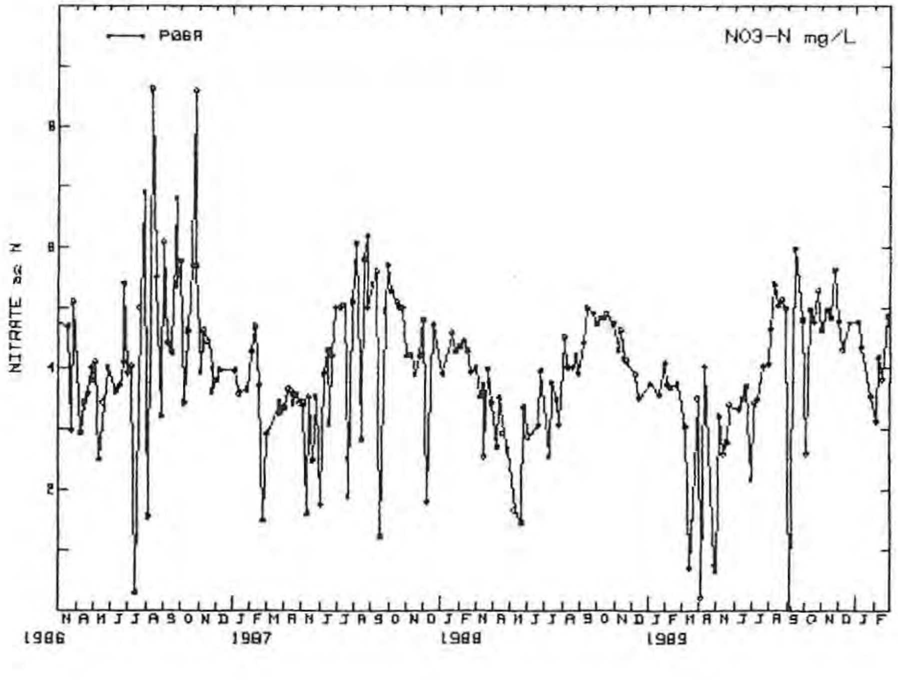

Ca mg/L
P08A
CALCIUM (as Ca), mg/L
60
40
20
N A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

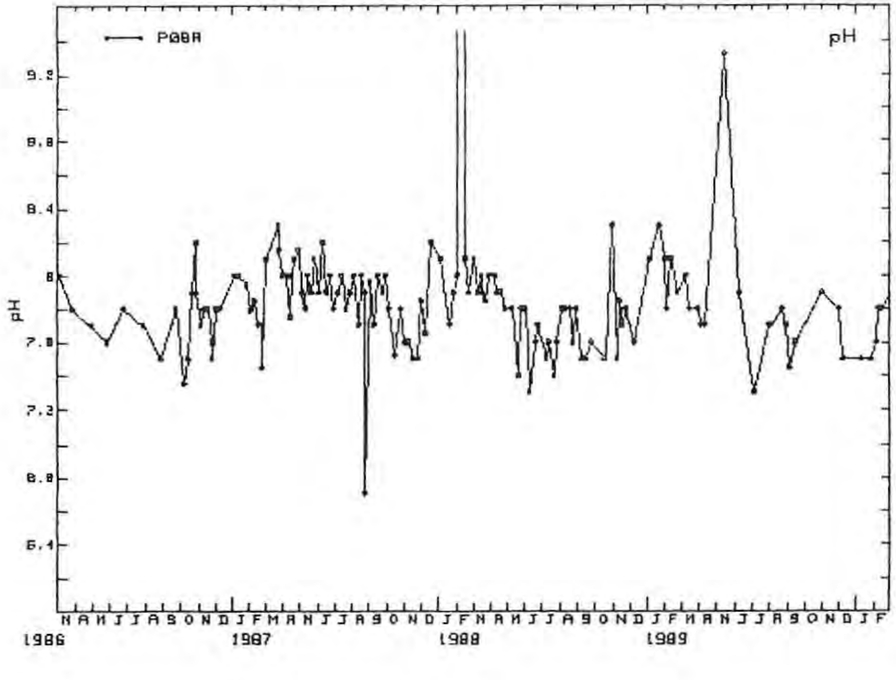

T.ALKAL
P08A
TOTAL ALKALINITY (as CaCO3)
150
100
50
N A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989


Mg mg/L
P08A
MAGNESIUM (as Mg), mg/L
20
10
N A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989


P08A
NH4-N mg/L
AMMONIA (as N), mg/L
2
4
6
8
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989


P08A
PO4-P mg/L
Phosphate as P
1
2
3
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989


P08A
NO3-N mg/L
NITRATE as N
2
4
6
8
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989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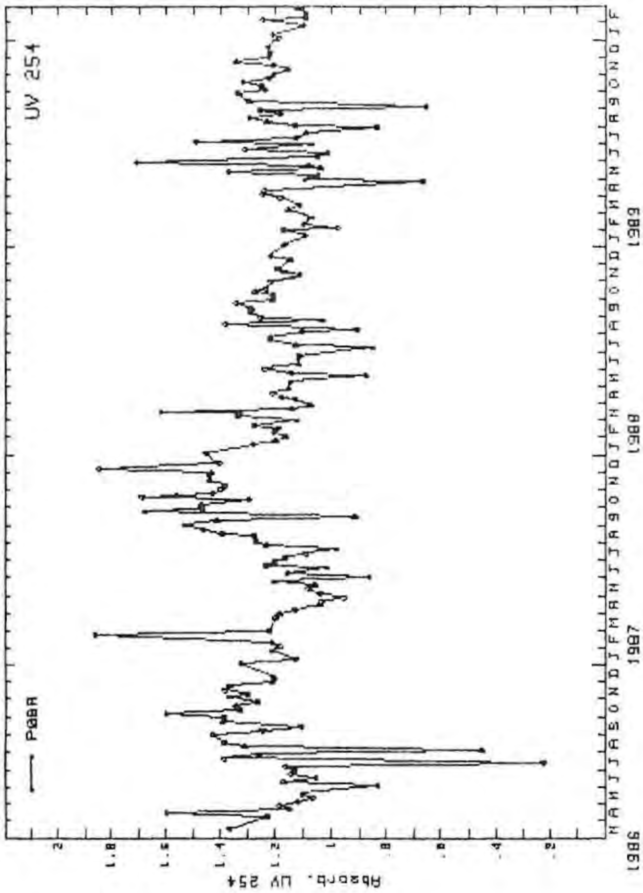
pH
pH
6.4
6.8
7.2
7.6
8
8.4
8.8
9.2
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989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P8BA
Absorb. UV 254
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1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
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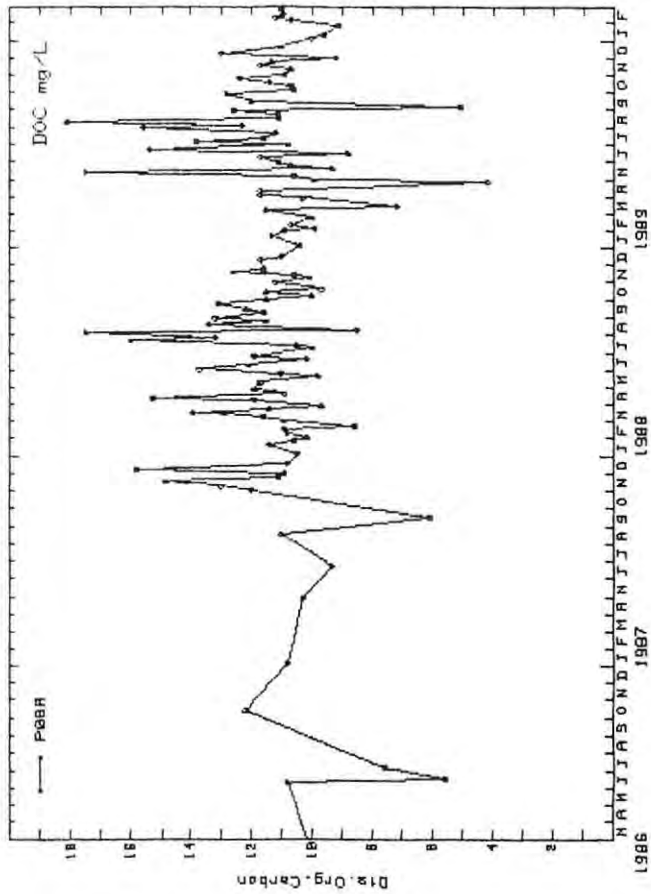
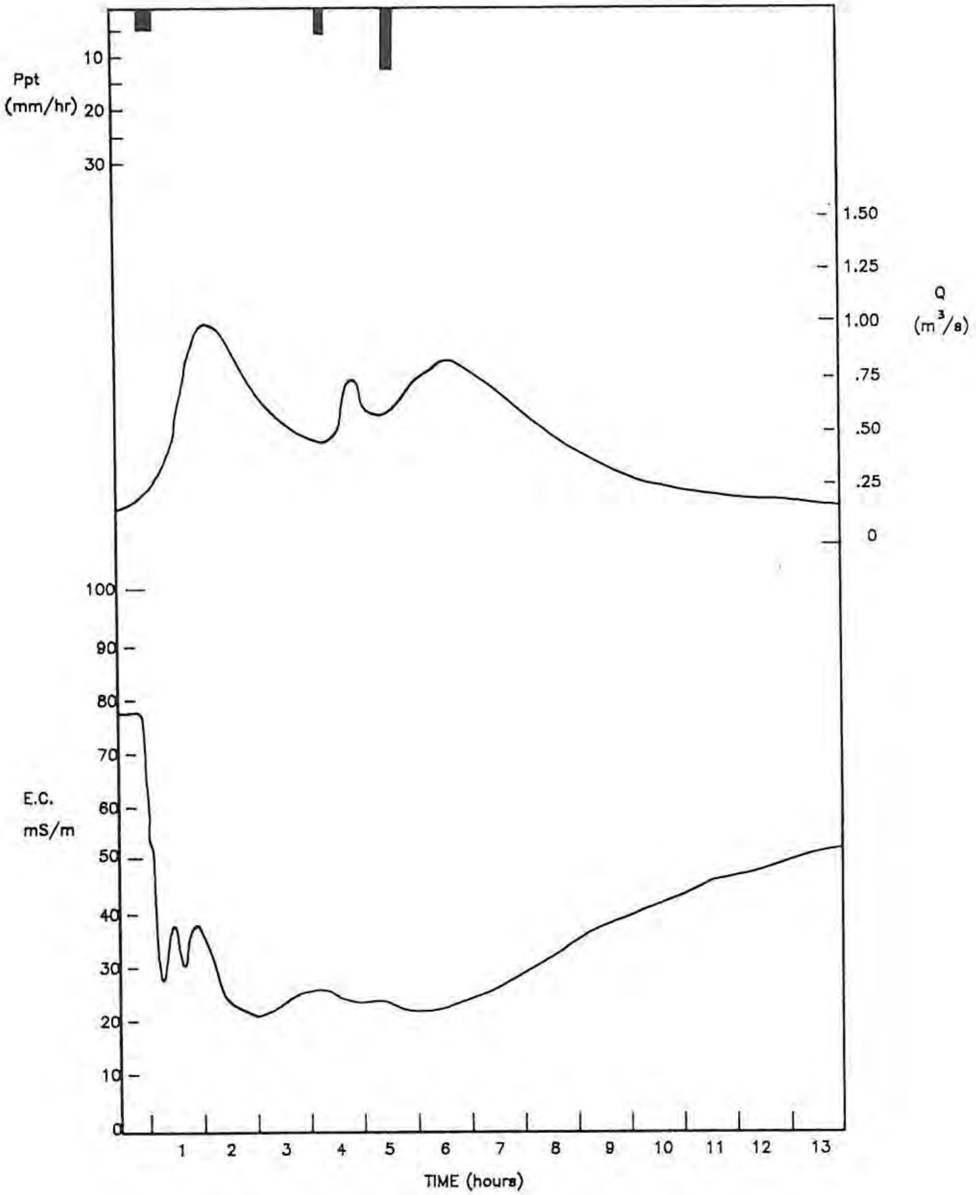
1986
1987
1988
1989

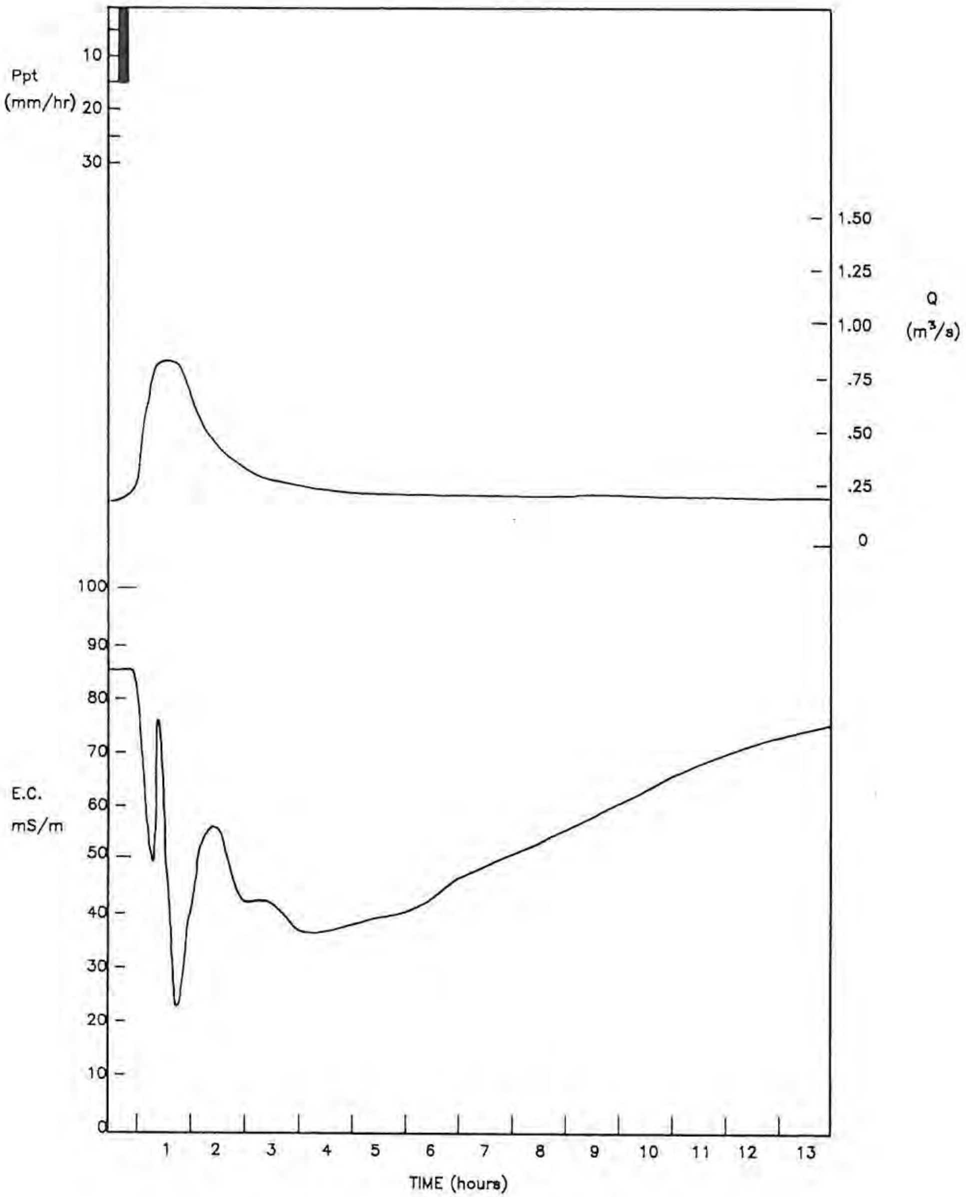

DOC mg/L
P8BA
Dis.Org.Carbon
18
16
14
12
10
8
6
4
2
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

APPENDIX F

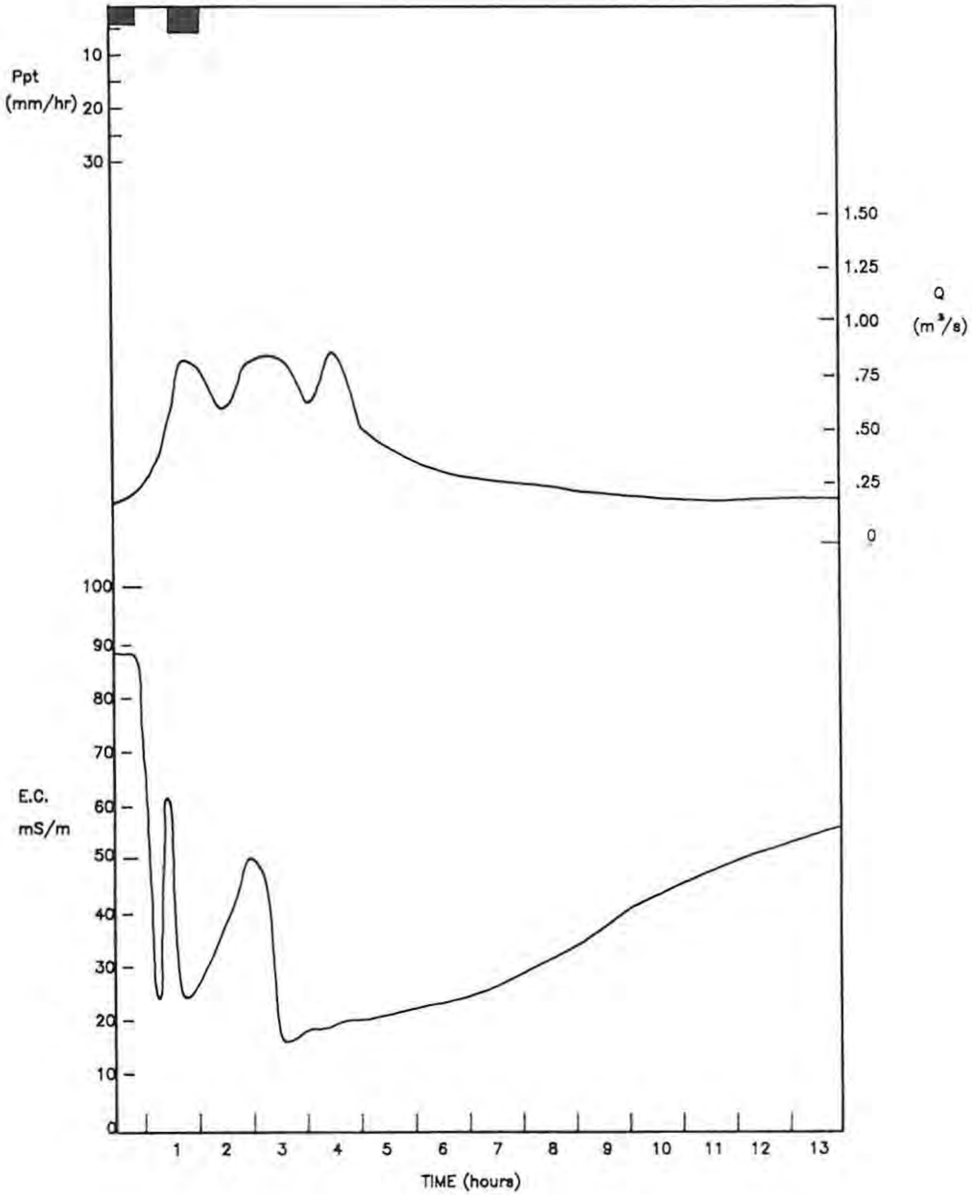
HYDROGRAPHS FOR SELECTED STORM EVENTS



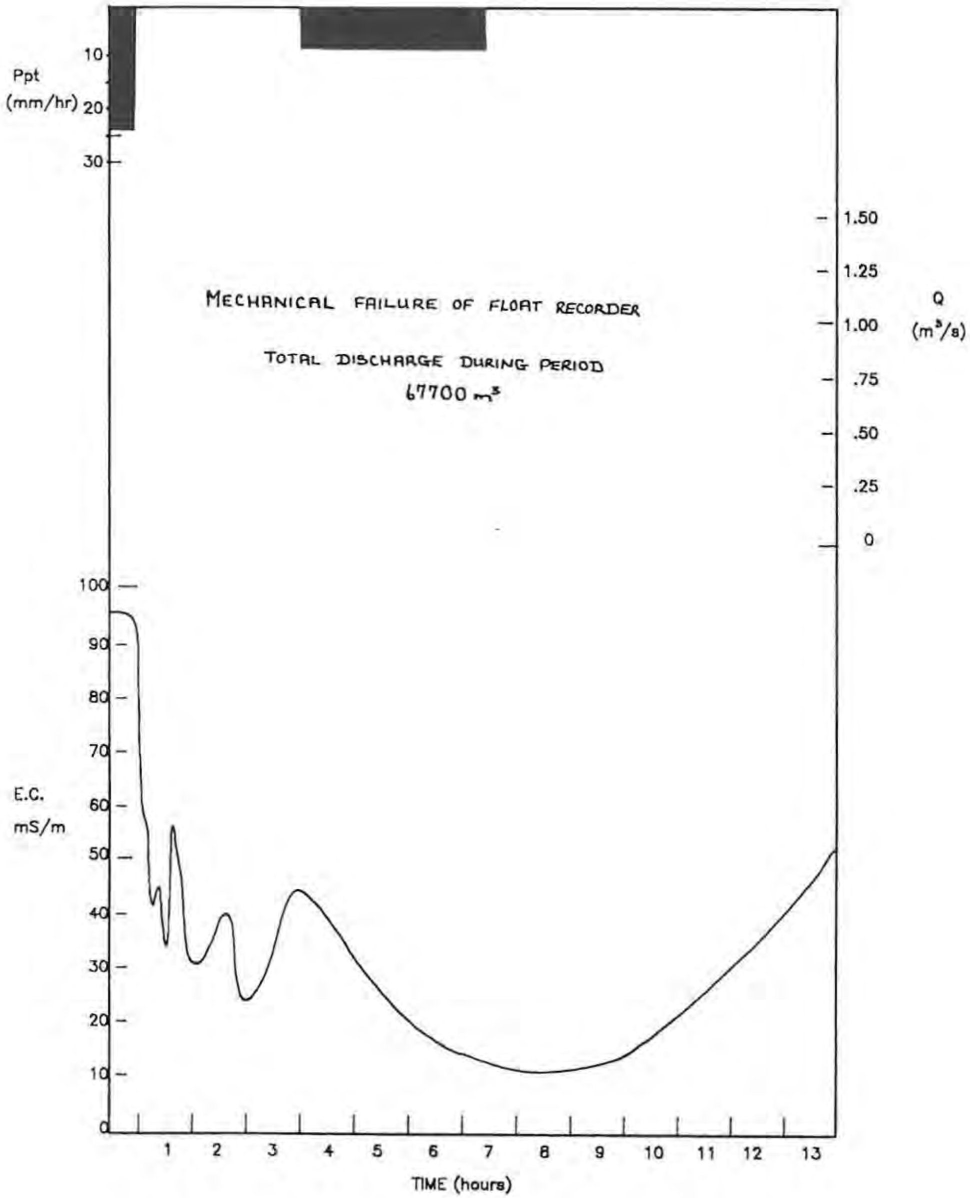
STORM HYDROGRAPH 24/04/88



STORM HYDROGRAPH 23/05/88



STORM HYDROGRAPH 3/06/88



MECHANICAL FAILURE OF FLOAT RECORDER

TOTAL DISCHARGE DURING PERIOD
67700 m³

STORM HYDROGRAPH 27/08/88

APPENDIX G

DAILY STORMWATER RUNOFF DISCHARGE ENTERING THE ARTIFICIAL RECHARGE BASIN

ATLANTIS STORMWATER RUNOFF & WASTEWATER VOLUMES ENTERING THE ARTIFICIAL RECHARGE BASIN : 1986

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1	4500	4500	6000	5140	15720	11590	10650	8690	5000	1000	760	640
2	5000	4500	5000	8240	19140	6940	10360	7730	4410	570	670	660
3	5000	4500	5000	35700	17450	5160	10970	7570	9090	660	640	660
4	6500	4500	5000	10240	15630	17300	10780	8530	14070	650	520	680
5	5000	4500	5000	12390	13520	33380	10430	10000	9000	650	3650	630
6	5000	4500	5000	8560	14610	18850	11360	9500	5500	670	630	790
7	5000	6000	5000	7250	18980	18400	9970	9040	5300	620	650	520
8	4500	6500	9500	5870	6390	15280	8130	7680	5000	670	670	660
9	4500	5000	6500	5260	2160	11510	12150	7570	4900	640	640	7960
10	5000	5000	6000	12470	11660	9430	11160	10700	4700	650	660	690
11	5000	5000	11000	12070	48550	15390	18340	9310	4500	650	610	630
12	5000	5000	6000	10730	21250	9670	25780	7150	5490	640	660	620
13	5000	7000	8000	18590	12230	8380	12570	12210	3770	640	660	660
14	5000	10000	6500	7790	15930	13910	11400	6390	2630	620	640	670
15	12000	6000	5000	5950	74040	42260	12250	8880	2960	690	630	640
16	6500	5000	5000	6350	25410	16320	18630	6930	2380	680	650	680
17	5000	15000	5000	16590	21990	13610	9940	7460	2840	630	670	1450
18	5000	6500	4500	17650	24030	11140	12480	8020	2440	670	610	1510
19	5000	5500	4500	9730	18900	11100	12440	7420	1030	650	660	2200
20	5000	5000	5000	8110	17230	10570	11260	4200	670	700	1080	1110
21	5000	5000	5000	16180	13990	10040	8470	8020	660	690	9040	910
22	5000	5000	5000	6800	14330	9090	10730	5690	1150	580	7260	1300
23	15000	5000	6500	6490	25070	10290	9530	6050	1470	650	660	4260
24	6000	5000	5000	7260	15420	10840	10280	6270	1970	630	710	930
25	5000	5000	5000	7120	14770	11180	8850	5320	2170	650	670	760
26	6500	4500	5000	1220	15380	10990	8450	5320	1370	670	610	750
27	5000	5000	5000	7620	11750	13830	8900	5370	1420	680	650	1180
28	7500	5000	5000	49500	12330	11670	8690	5350	1330	630	640	5700
29	25000	5000	6120	21250	12100	10960	8310	5370	850	610	620	
30	6500	12000	16000	12200	11990	22000	8260	5480	1400	670	630	
31	5000		9000		12010	10640		5130		640	610	
TOTAL	200000	176000	191120	360320	573960	431720	342020	228350	109470	20440	38460	39850

TOTAL FOR YEAR : 2711710

DONKERGAT DIVERSION INSTALLED : 20/11/86
DONKERGAT DIVERSION CONNECTED : 2/12/86

UNITS = cu. metres

CAPE HYDROLOGICAL YEAR = March - February

ATLANTIS STORMWATER RUNOFF & WASTEWATER VOLUMES ENTERING THE ARTIFICIAL RECHARGE BASIN : 1987

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1	1040	1840	1530	12180	3840	7220	19980	7350	3900	2710		
2	1080	1470	1420	12690	6430	6230	9360	5940	3560	3010		
3	1140	1580	1320	6490	33960	5490	9260	5400	4980	2860		
4	1310	1320	1550	4030	7610	6840	8410	5340	5180	2880		
5	1620	1550	26800	25080	4300	6850	8200	4560	4140	3140		
6	1510	1570	8520	6670	5860	5490	7360	5020	3740	2950		
7	2020	1310	5790	3570	4420	5300	7770	4940	3560	3000		
8	2150	1870	2160	3650	4240	4940	7150	4620	3640	8040		
9	1810	1570	1760	3490	4310	4840	6790	4930	3420	3010		
10	1770	1520	1710	7840	4230	8830	2200	7890	3390	14350		
11	2170	[illegible]	1570	5540	5910	72240	10700	4860	3440	6300		
12	1840	1490	16400	3270	3770	88280	7040	14350	3610	6140		
13	1970	1330	11490	3410	4130	26050	19030	5040	3550	1060		
14	2380	5130	36130	3090	3690	14960	8050	4970	3540	210		
15	19680	6570	9090	2550	3360	13760	11300	4720	3290	1580		
16	2060	1490	7420	3420	3590	17110	6290	5550	7310			
17	1710	1480	12000	7850	3740	13050	8130	6740	3330			
18	1770	1720	5740	5780	3960	11610	2030	4140	6440	310		
19	1640	1320	6690	2850	36680	27510	1690	4990	8650	380		
20	1620	11890	4310	3010	33090	11980	1650	4590	10730	380	1850	
21	1720	2050	4090	2710	18160	11610	1710	4630	5700	1360		
22	1360	1410	3870	2040	9470	11390	7070	4760	3420	1410		
23	1140	8970	4220	1570	9230	16590	18290	4550	2460			
24	1110	2700	3010	3920	8540	13430	11560	4680	2660			
25	1920	1750	2920	29350	8430	9090	15040	4550	2880	2030		
26	1540	1470	2630	12760	11150	10070	7430	7220	2740			
27	2220	1630	2430	5800	13030	9910	5850	4890	2740			
28	1580	1530	3310	4970	11260	10610	6330	4430	2980			
29	1250	1520	2960	3210	17160	10290	5890	11940	2920			
30	1360	1540	2740	4010	8710	8330	5990	6120	2800			
31	1150		2430		7720	10740		5220				
TOTAL	69660	74170	198010	196800	303980	480640	247550	179190	124850	67110	1850	0

TOTAL FOR YEAR : 1943810

DONKERGAT DIVERSION SLUICE INSTALLED : 14/12/87

UNITS = cu. metres

CAPE HYDROLOGICAL YEAR = March - February

ATLANTIS STORMWATER RUNOFF & WASTEWATER VOLUMES ENTERING THE ARTIFICIAL RECHARGE BASIN : 1988

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1			1710	4460	3740	3740	13600	3000	3000			2400
2			1910	3880	3740	3740	4550	2800	2550			960
3		1330	[illegible]	7270	3740	3740	3850	2565	4980			
4		11460	1910	3030	3970	3740	3850	2565	1200			
5		4860	1910	3020	5470	3740	3850	2565				
6		1330	1910	11890	13320	4750	3850	2565				
7	47150	760	1910	7830	3890	15630	3850	2565				
8	11600	740	[illegible]	3750	43600	4750	16553	2565	980			
9	3500	710	1910	3650	7060	4370	18980	41230		1030		
10	1960		[illegible]	3030	3880	4370	8452	7110		1600		
11	860		[illegible]	6480	3880	4370	3860	2560				
12	860		1910	3380	5890	4370	3860	2560				
13	740		1920	3860	3890	4370	3850	2560				
14	730	890	1710	14350	3890	4370	3850	2560				
15		1940	1910	5670	3890	4370	21239	2560				
16		1940	1940	7860	3880	4370	7186	3740				
17		1940	[illegible]	3120	4870	4370	3560	2560				
18	970	1940	[illegible]	3120	3870	4370	3560	2560		860		
19		1930	[illegible]	5430	4320	4340	3860	2560				
20		11470	[illegible]	6970	14620	4340	3860	2560				
21		7540	[illegible]	3760	4800	4340	3860	2870				
22		2650	2060	3760	3860	4340	3860	3000				
23		12630	4750	3760	3860	4340	3860	2560				
24		10450	2160	3760	3860	4340	3860	2770		630		9470
25		3980	9890	3760	3860	4340	9130	2560				2130
26		1940	29310	3760	3860	16300	4780	2560				
27		1940	9890	3760	3860	61150	3560	3980				
28		1940	3020	3760	3840	24860	3560	4120				5200
29		1940	3020	3740	3840	6750	8660	2560				
30		1940	3020	3740	3800	54800	3530	2560				
31			3020		3800	36930		2560			3650	
TOTAL	68370	90190	120890	150610	188650	318700	188730	128410	12710	4120	3650	20160

TOTAL FOR YEAR : 1295190

DONKERGAT DIVERSION CLOSED : 14/04/88
DONKERGAT DIVERSION OPENED : 4/11/88

UNITS = cu. metres

CAPE HYDROLOGICAL YEAR = March - February

ATLANTIS STORMWATER RUNOFF & WASTEWATER VOLUMES ENTERING THE ARTIFICIAL RECHARGE BASIN : 1989

DATE	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC	JAN	FEB
1	9840	2160	2160	14800	4760	15630	6320	4920	2940	3150	2590	2840
2	1460	2160	2160	5760	11230	7200	6220	3920	2760	3020	2590	2590
3		2160	2160	3880	4520	4970	59150	3710	2760	3020	2590	2330
4		2160	2160	3880	15760	4750	31380	16350	2760	2890	2590	2070
5		2160	2160	3890	5630	4750	23800	6550	2770	2840	2160	1900
6		2160	2160	3880	4750	4750	13230	4710	2770	2770	4960	1830
7		2160	2160	3890	4750	4750	11150	4670	2760	2690	2510	1820
8		2160	2160	3760	4550	4750	10370	28020	2770	2630	2290	1810
9		2160	2160	3760	4550	5310	10020	7470	2680	2580	2170	1810
10		2160	14350	3760	9630	5180	9310	6740	2600	2530	2160	1810
11		2260	7210	3700	13010	4960	9240	6740	2590	2480	2160	1820
12	8710	2260	3800	3700	6330	17810	7020	6530	2590	2430	2160	1820
13	30920	2260	3040	3680	4750	5000	6480	6110	2590	2380	2160	1820
14	6370	2160	3020	3640	5530	9150	6390	5300	2590	2320	2160	1810
15		2160	3020	3640	9640	31710	6230	7610	2590	2270	2160	1810
16		2160	3020	3640	54320	21530	5640	4670	2510	2220	2160	1820
17		2160	45530	3640	12980	6050	8390	4410	47290	2160	2160	1810
18		13400	6460	3640	9870	5960	17980	4020	16530	2160	19280	1810
19		14600	3880	3640	4970	5780	8400	3890	5240	5010	10080	4370
20		53240	3880	3640	4750	6610	10420	3880	5050	3170	2370	24430
21		8760	5910	4450	4750	5220	7130	3880	4120	3180	2160	2790
22		3000	3680	3880	4750	4950	6480	4450	3800	3020	2350	1950
23		2160	3680	8670	4750	4920	6190	4110	3720	2760	2420	1680
24		2160	3680	4030	8920	7770	5370	3880	3720	3190	2420	1880
25		2160	3680	46500	59230	8430	4930	3880	3710	2660	2420	1690
26		2160	3680	18460	22640	30910	4930	4160	3710	2600	2420	1680
27		2160	3680	7130	6330	45540	4920	9470	3720	2590	2290	1820
28		2160	3680	6330	4750	8060	4930	3750	3350	2600	2160	1810
29	11470	2160	3680	9870	4750	16400	5910	3590	3280	2590	2160	
30	9280	2160	5940	13850	4750	7920	4960	3590	3280	2600	2160	
31	3500		12450		5370	7030		3300		2590	3620	
TOTAL	81550	147300	170390	210970	327270	323750	321890	188280	153550	85100	100040	79430

TOTAL FOR YEAR : 2189520

DONKERGAT DIVERSION CLOSED : 31/03/89

CAPE HYDROLOGICAL YEAR : March - February

UNITS = cu. metres

APPENDIX H

ARTIFICIAL RECHARGE BASIN ANNUAL WATER BALANCE

WATER BALANCE FOR THE ARTIFICIAL RECHARGE BASIN : 1986

MONTH	BASIN VOLUME (Start)	INPUT VOLUME Direct Ppt.	Stormwater	TOTAL VOLUME (Basin)	BASIN VOLUME (End)	DEFICIT TOTAL	EVAPO.	INFILTRAT.
MAR	168030	4650	200000	372680	180861	191819	22537	169282
APR	180861	1800	176000	358661	177601	181060	14161	166899
MAY	177601	2400	191120	371121	185817	185304	7877	177427
JUN	185817	9540	369720	555677	292793	262884	6797	256087
JUL	292793	31394	573960	898147	412574	485573	6806	298767 ‡
AUG	412574	18207	431720	852501	468247	394254	20365	373889 ‡
SEPT	468247	4872	342020	815139	427555	387584	18484	369100
OCT	427555	1662	228350	657567	328400	329167	33875	295292
NOV	328400	1600	109470	439470	222715	216755	42289	174466
DEC	222715	960	20440	244115	134270	109845	43792	66053
JAN	134270	1365	38460	174095	85655	88440	28077	60363
FEB	85655	688	39850	126193	52513	73680	149	58731

TOTAL INPUT : DIRECT Ppt. = 79138
STORMWATER = 2711710

VOLUME IN BASIN
START 168030
END 52513

TOTAL OUTPUT : EVAPORATION = 250009
INFILTRATION = 2426356

UNITS = cu. metres
EVAPO.= Symons Tank

‡ Estimated value as water was syphoned out to avoid structural damage to the wall
An estimated 230 000 cu. metres of water was lost.

WATER BALANCE FOR THE ARTIFICIAL RECHARGE BASIN : 1987

MONTH	BASIN VOLUME (Start)	INPUT VOLUME Direct Ppt.	Stormwater	TOTAL VOLUME (Basin)	BASIN VOLUME (End)	DEFICIT TOTAL	EVAPO.	INFILTRAT.
MAR	52513		69660	122173	54509	67664	11294	56370
APR	54509	1693	74170	130372	65680	64692	6784	57908
MAY	65680	11980	198010	275670	141212	134458	7439	127019
JUN	141212	9810	196800	347822	141542	206280	5205	201075
JUL	141542	16238	303980	461810	240041	221769	6355	215414
AUG	240041	24567	480640	745244	445555	299689	13508	286181
SEPT	445555	7418	247550	700523	359275	341248	18320	322928
OCT	359275	2400	179190	540865	272006	268859	30740	238119
NOV	272006		124850	396856	191182	205674	35551	170123
DEC	191182	1200	67110	259492	109033	150459	29481	120978
JAN	109033		1850	110883	59069	51814	22863	28951
FEB	59069			59069	25205	33864	12098	21766

TOTAL INPUT : DIRECT Ppt = 75352
STORMWATER = 1943810

VOLUME IN BASIN
START 52513
END 25205

TOTAL OUTPUT : EVAPORATION = 199638
INFILTRATION = 1846832

UNITS = cu. metres
EVAPO.= Symons Tank

WATER BALANCE FOR THE ARTIFICIAL RECHARGE BASIN : 1988

MONTH	BASIN VOLUME (Start)	INPUT VOLUME Direct Ppt.	INPUT VOLUME Stormwater	TOTAL VOLUME (Basin)	BASIN VOLUME (End)	DEFICIT TOTAL	DEFICIT EVAPO.	DEFICIT INFILTRAT.
MAR	25205	2016	68370	95591	34706	60885	7869	53016
APR	34706	2390	90190	127286	45506	81780	4232	77548
MAY	45506	1035	120890	167431	38821	128610	2603	126007
JUN	38821	1640	150610	191071	58342	132729	3013	129716
JUL	58342	2678	188650	249670	62837	186833	3128	183705
AUG	62837	8381	318700	389916	176314	213602	3532	210070
SEPT	176314	6675	188730	371719	204993	166726	13241	153485
OCT	204993	2550	128410	335953	117580	218373	18974	199399
NOV	117580	1000	12710	131290	37246	94044	14736	79308
DEC	37246		4120	41366	14623	26743	9934	16809
JAN	14623		3650	18273	1243	17030	2832	14198
FEB	1243	58	20160	21461	1072	20389	208	20181

TOTAL INPUT : DIRECT Ppt = 28423
STORMWATER = 1295190

TOTAL OUTPUT : EVAPORATION = 84302
INFILTRATION = 1263442

VOLUME IN BASIN
START = 25205
END = 1072

UNITS = cu. metres
EVAPO.= Symons Tank

WATER BALANCE FOR THE ARTIFICIAL RECHARGE BASIN : 1989

MONTH	BASIN VOLUME (Start)	INPUT VOLUME Direct Ppt.	INPUT VOLUME Stormwater	TOTAL VOLUME (Basin)	BASIN VOLUME (End)	DEFICIT TOTAL	DEFICIT EVAPO.	DEFICIT INFILTRAT.
MAR	1072	445	81550	83067	8000	75067	689	74378
APR	8000		147300	155300	22457	132843	1605	131238
MAY	22457	1437	170390	194284	33233	161051	1962	159089
JUN	33233	1877	210970	246080	30403	215677	1224	214453
JUL	30403	6739	327270	364412	89039	275373	2029	273345
AUG	89039	5523	323750	418310	141542	276768	5539	271230
SEPT	141542	8945	321890	472277	173106	299171	12068	287103
OCT	173106	4602	188280	365988	122102	243886	20339	223547
NOV	122102	1323	153550	276975	110228	166747	23210	143537
DEC	110228		85100	195328	55522	139806	20326	119490
JAN	55522	137	100040	155699	29947	125752	12654	113098
FEB	29947	375	79430	109752	25205	84547	8448	76099

TOTAL INPUT : DIRECT Ppt = 31303
STORMWATER = 2189520

TOTAL OUTPUT : EVAPORATION = 110091
INFILTRATION = 2086607

VOLUME IN BASIN
START = 1072
END = 25205

UNITS = cu. metres
EVAPO.= Symons Tank

APPENDIX I

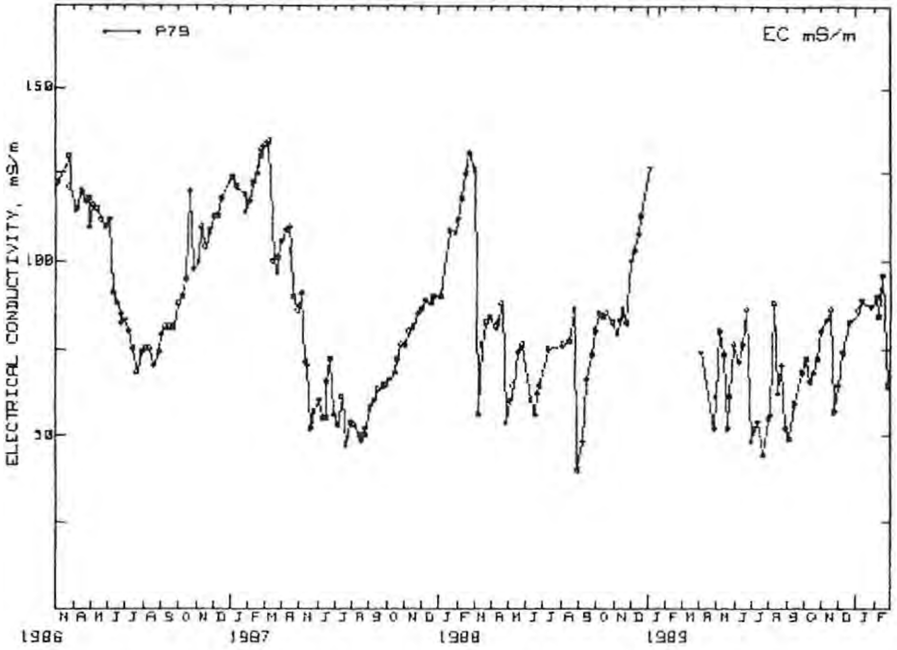
WATER QUALITY TRENDS IN THE ARTIFICIAL RECHARGE BASIN

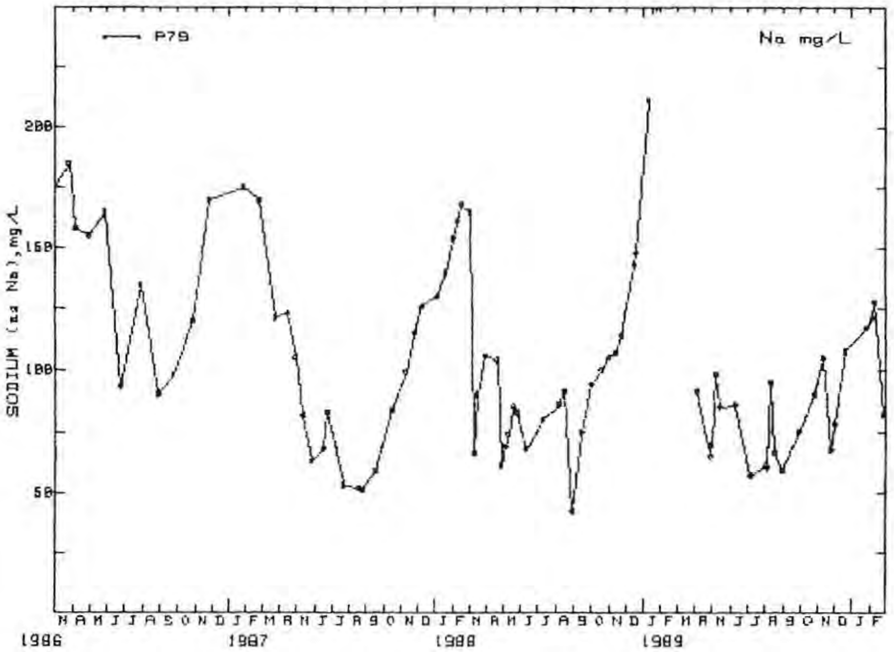
I_1 - EC, K, Na, Cl

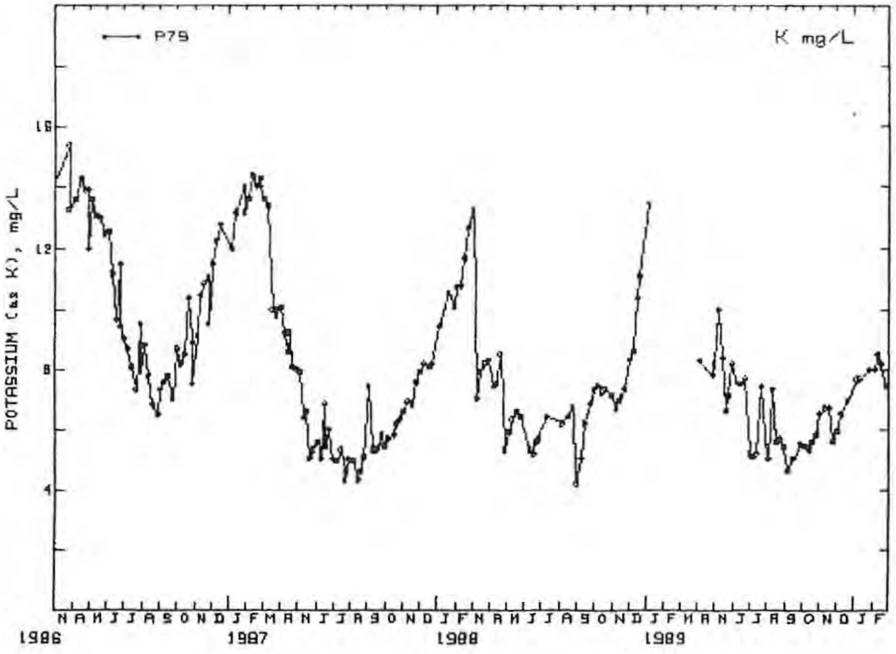
I_2 - Ca, Mg, SO_4, T. Alk as $CaCO_3$

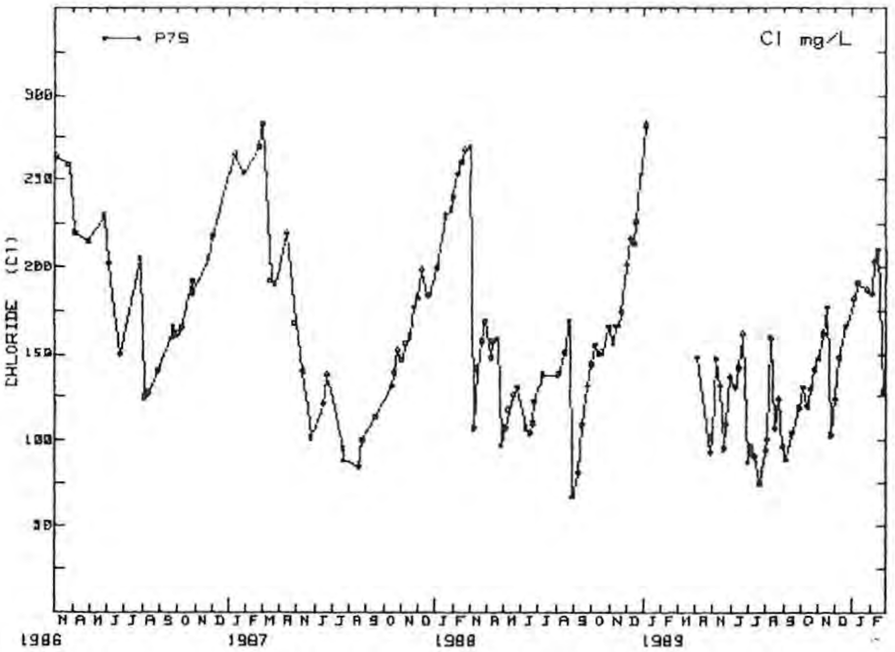
I_3 - NH_4 as N, NO_x as N,
PO_4 as P, pH

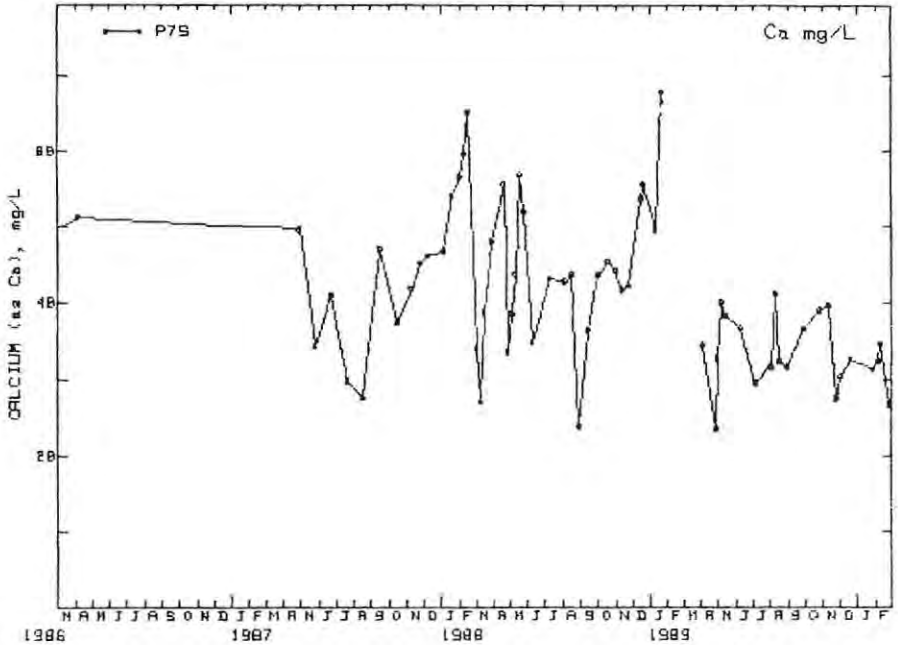
I_4 - DOC, UV 254 Abs.

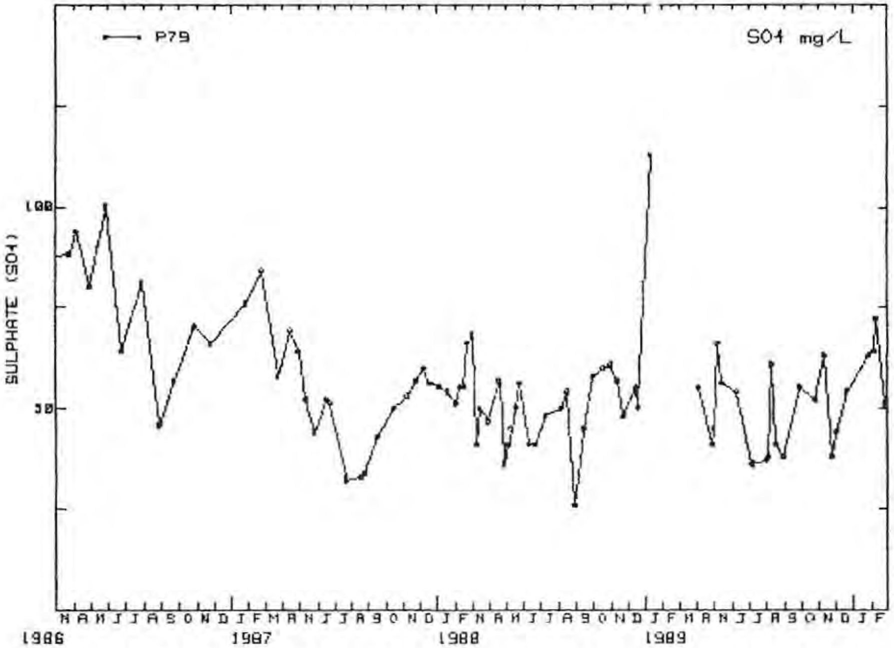

P79
EC mS/m
ELECTRICAL CONDUCTIVITY, mS/m
150
100
50
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

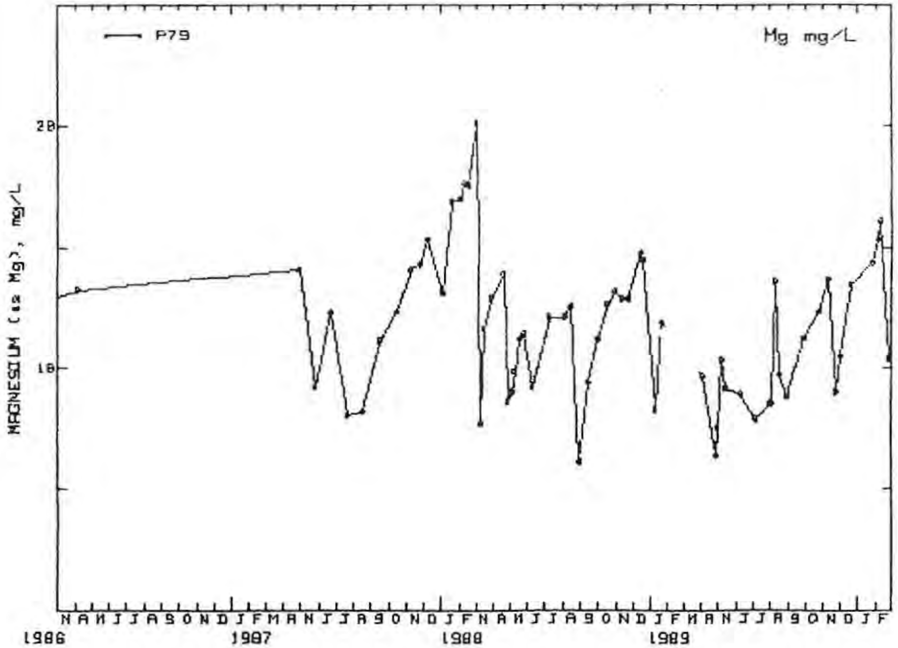

P79
Na mg/L
SODIUM (as Na), mg/L
200
150
100
50
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

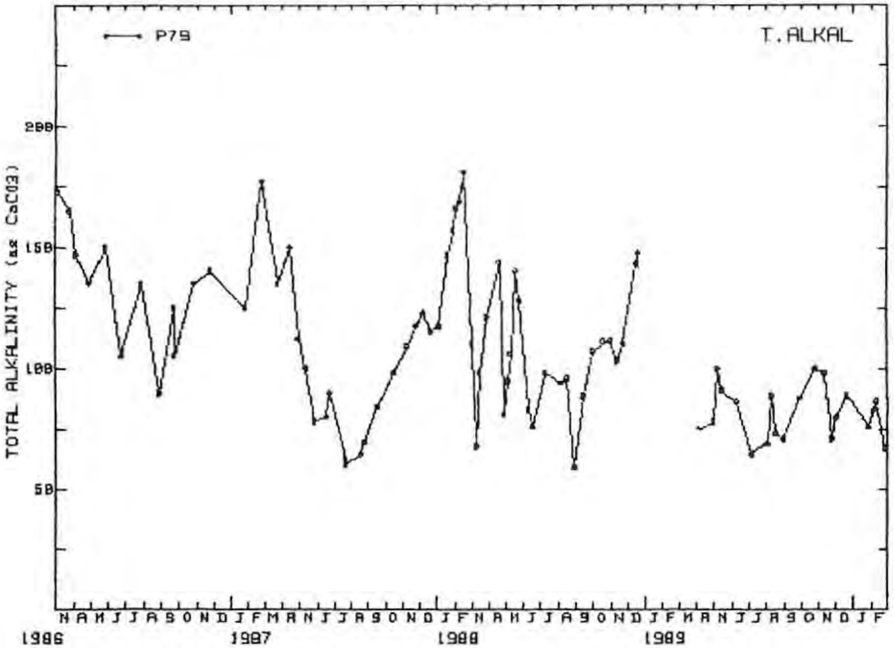

P79
K mg/L
POTASSIUM (as K), mg/L
16
12
8
4
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

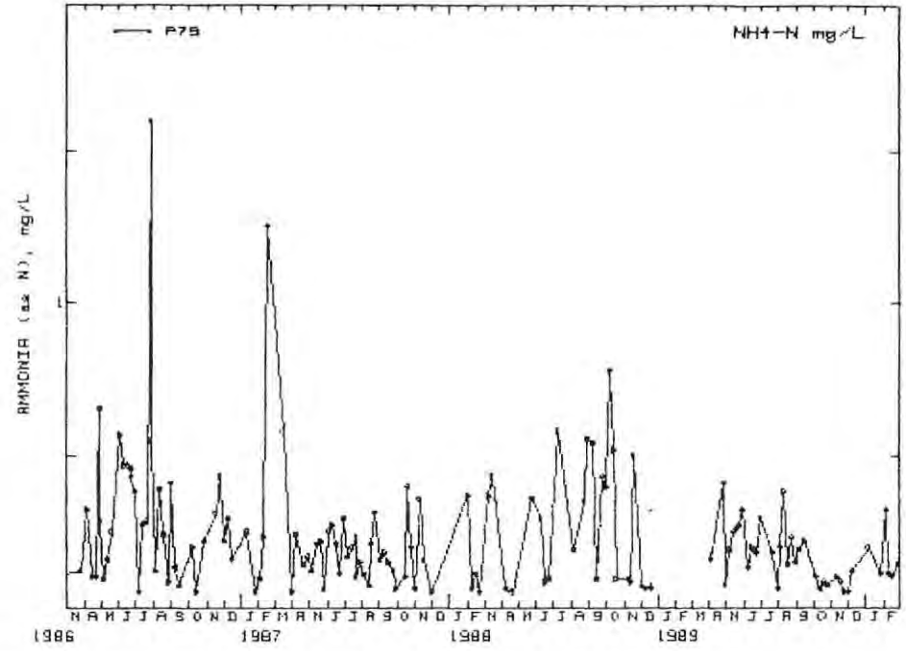

P79
Cl mg/L
CHLORIDE (Cl)
300
250
200
150
100
50
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

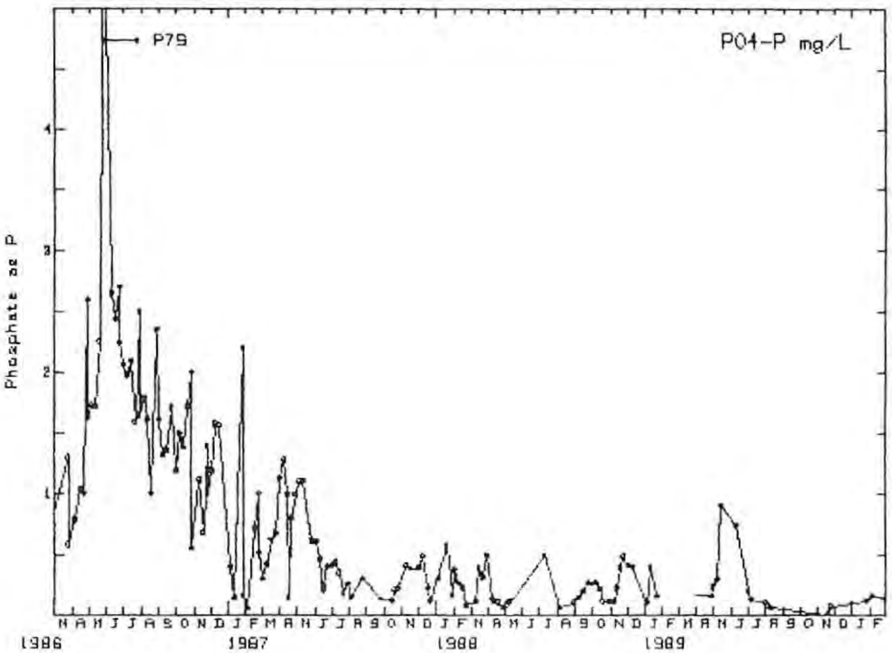

P79
Ca mg/L
CALCIUM (as Ca), mg/L
60
40
20
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

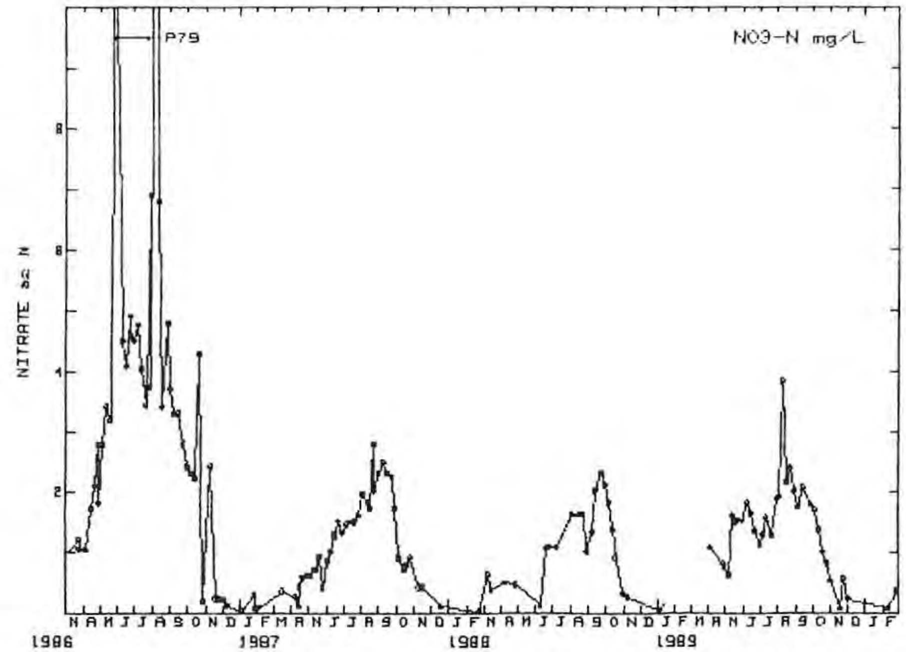

P79
SO4 mg/L
SULPHATE (SO4)
100
50
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

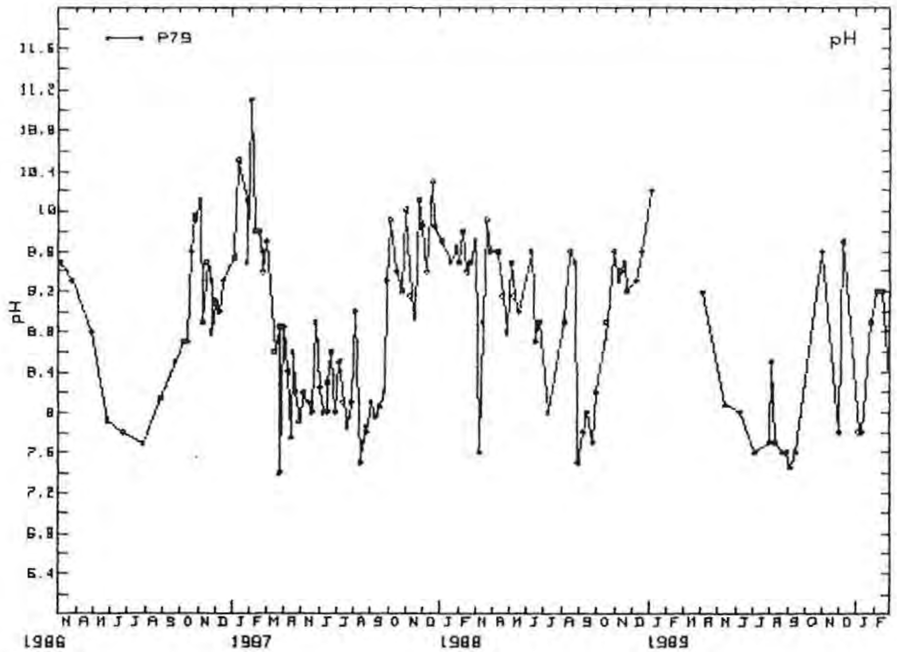

P79
Mg mg/L
MAGNESIUM (as Mg), mg/L
20
10
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

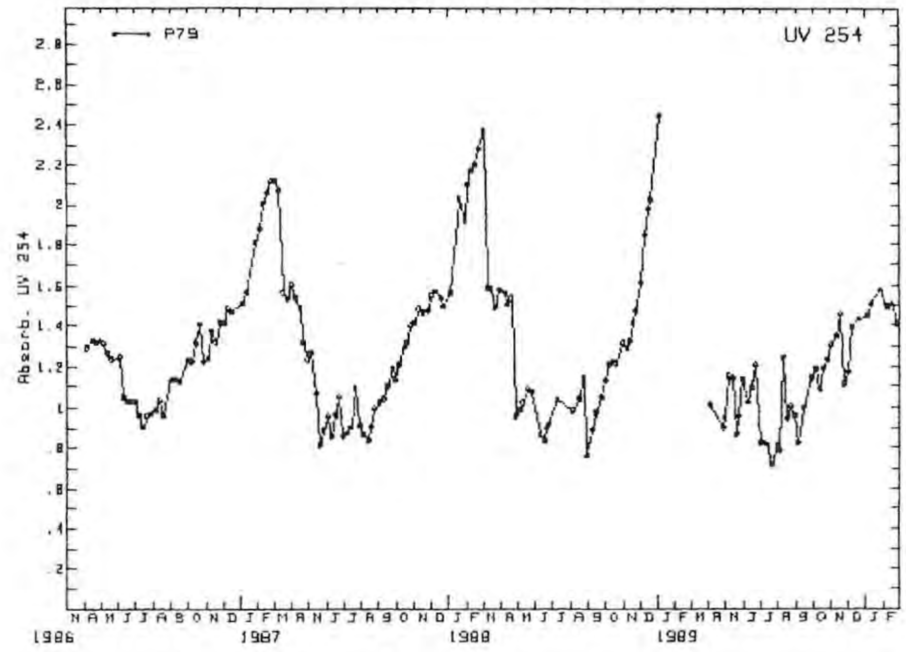

P79
T.ALKAL
TOTAL ALKALINITY (as CaCO3)
200
150
100
50
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

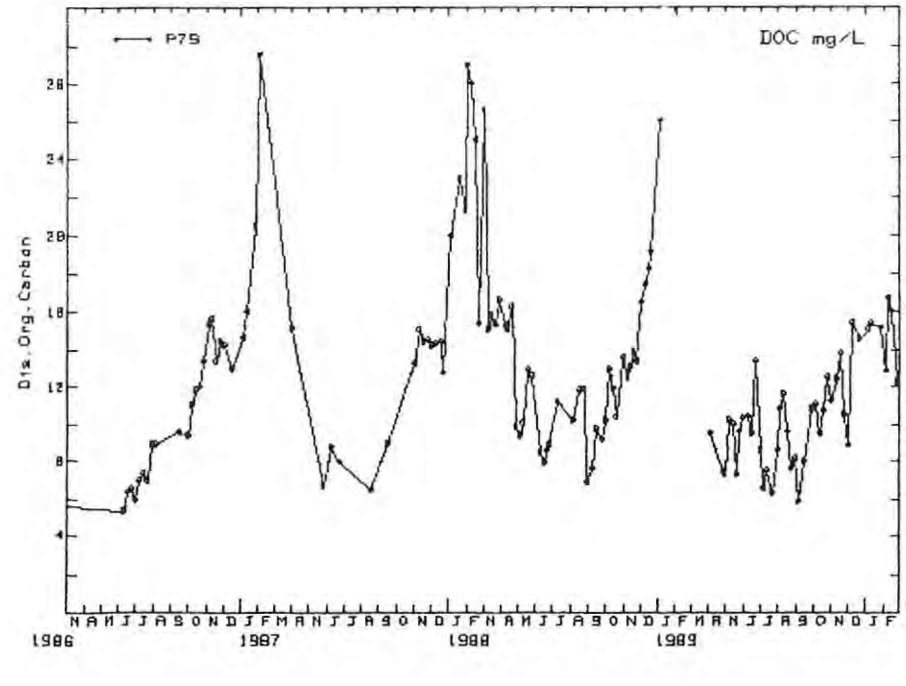

P79
NH4-N mg/L
AMMONIA (as N), mg/L
1
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989


P79
PO4-P mg/L
Phosphate as P
1
2
3
4
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989


P79
NO3-N mg/L
NITRATE as N
2
4
6
8
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

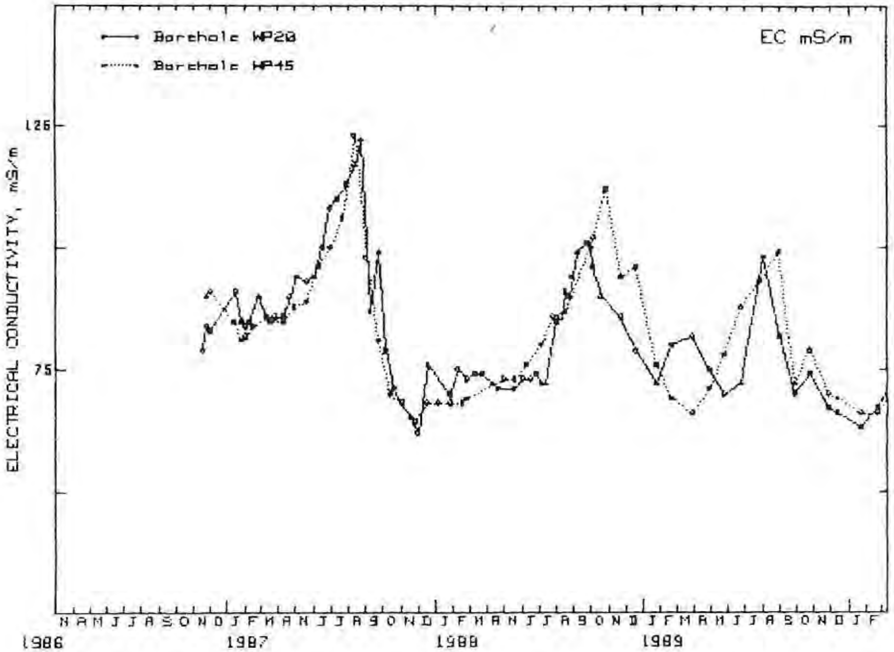

P79
pH
pH
11.6
11.2
10.8
10.4
10
9.6
9.2
8.8
8.4
8
7.6
7.2
6.8
6.4
M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

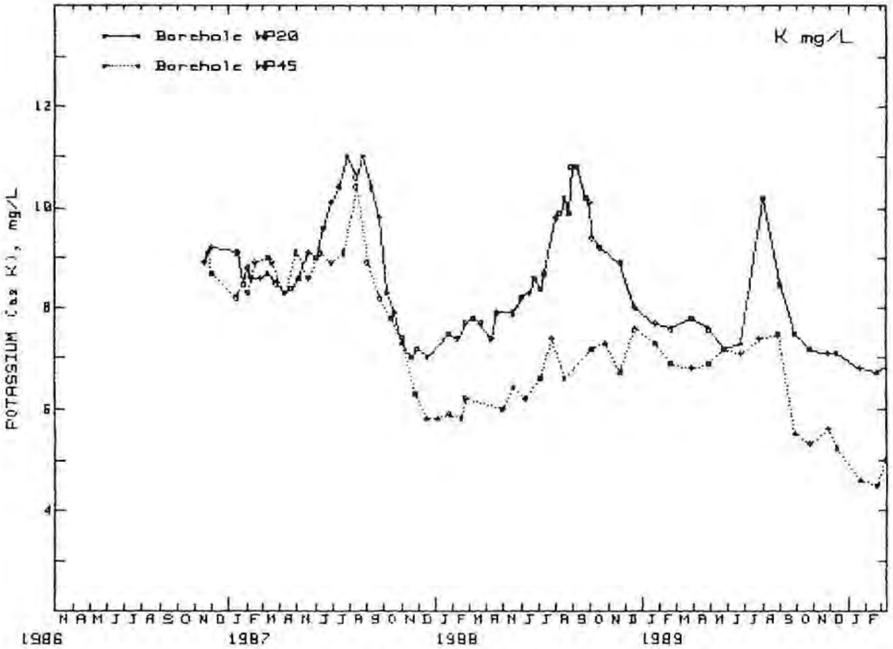

P79
UV 254
Absorb. UV 254
2.8
2.6
2.4
2.2
2
1.8
1.6
1.4
1.2
1
.8
.6
.4
.2
N A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989


P79
DOC mg/L
Dis.Org.Carbon
28
24
20
16
12
8
4
N A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F
1986
1987
1988
1989

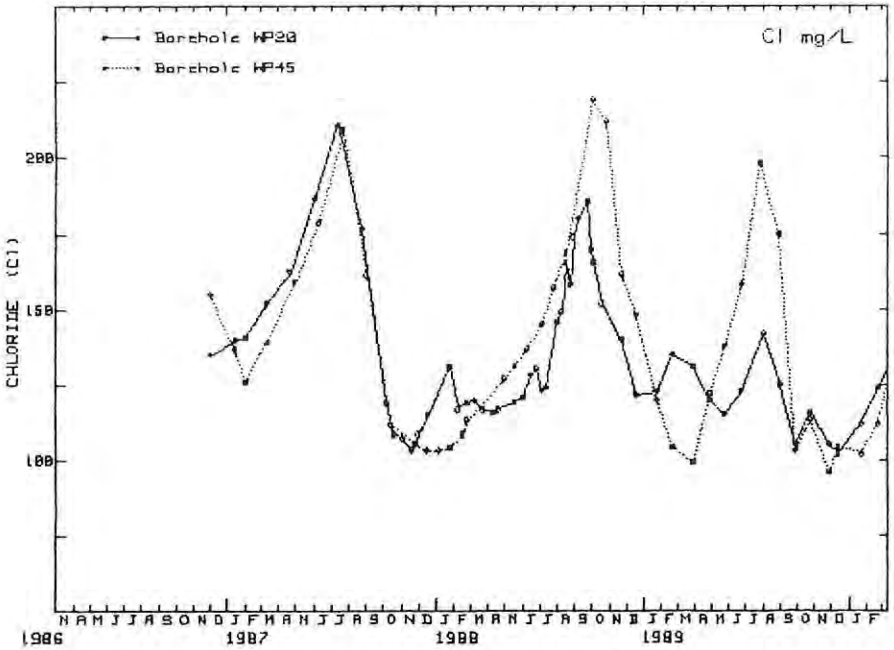
APPENDIX J

GROUNDWATER QUALITY TRENDS AROUND THE ARTIFICIAL RECHARGE BASIN



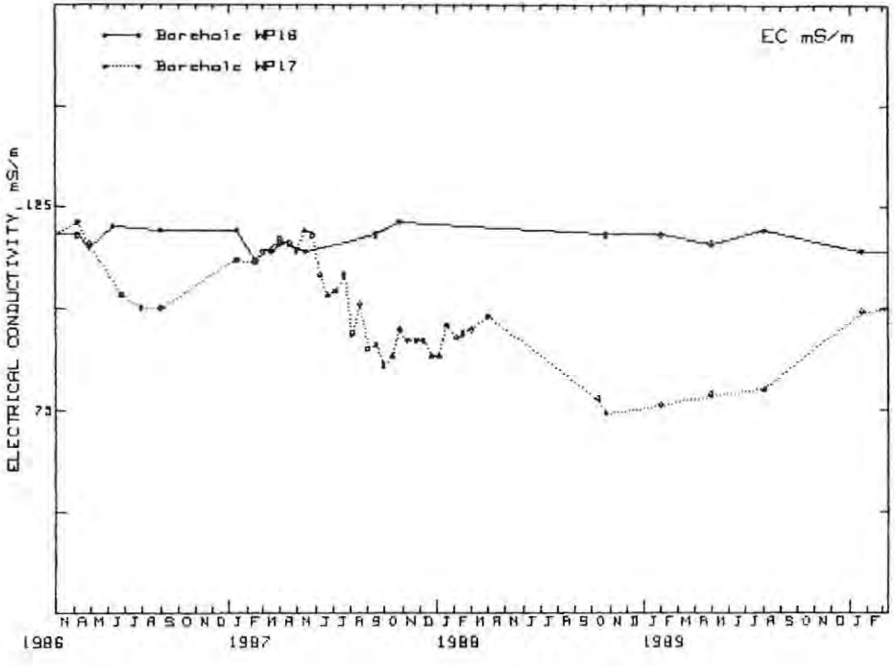


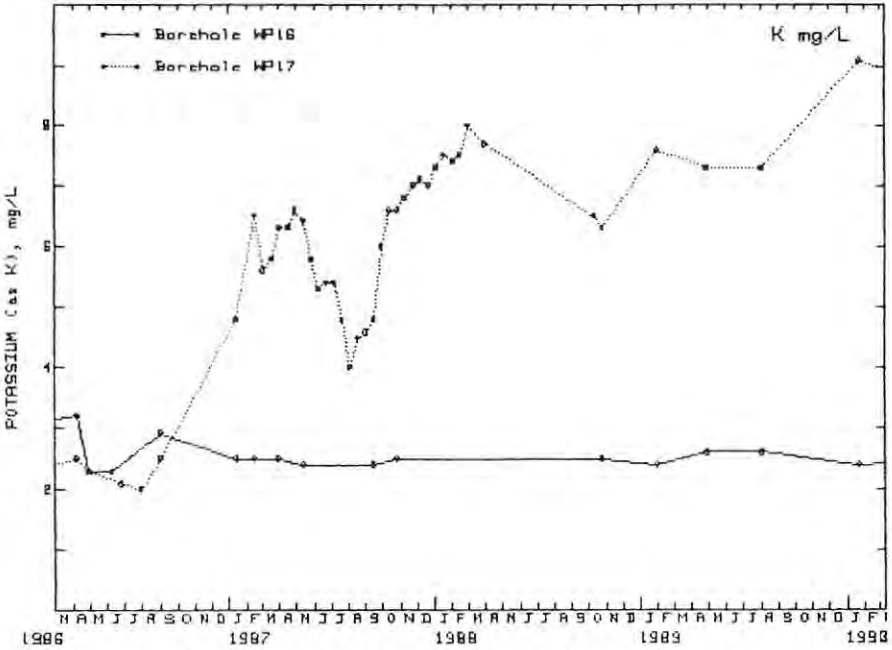
BOREHOLES: 20 [12 m] 45 [9.5 m]

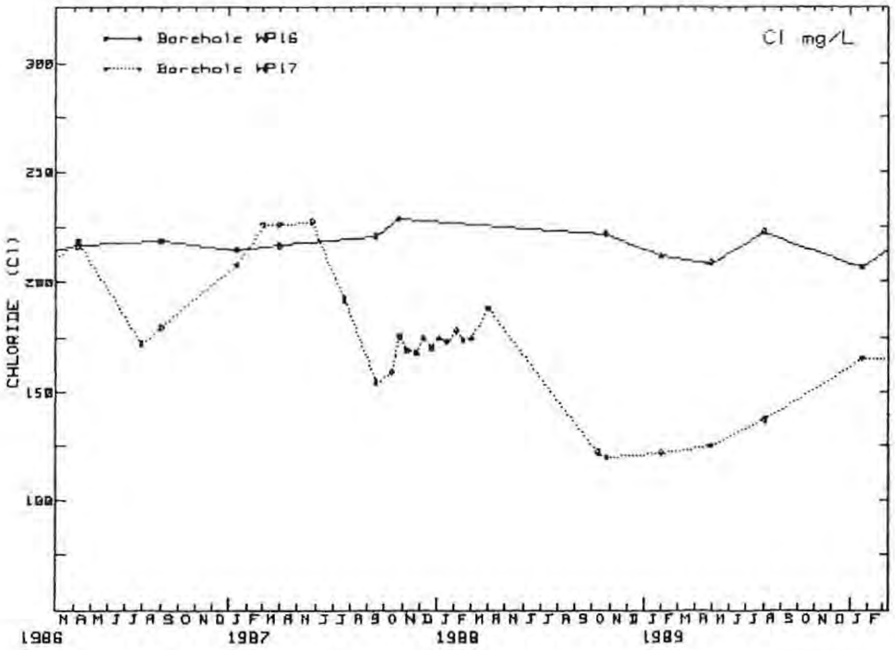


Both boreholes are shallow and about 50 m down gradient of the recharge basin with the result that their water quality trends are accurate reflections of the recharge basin management. The discontinuation of the artificial recharge of treated sewage effluent in 1987 is reflected in the dramatic improvement in groundwater quality in both boreholes. It would appear that the present recharge strategy is resulting in a gradual improvement in the water quality [seen in small peaks each year and overall trend].

The lack of a K peak in 1988 at borehole 45 is a direct result of reduced volumes of water in the recharge basin. The reduced volumes during 1988/89 meant that the southwestern lobe of the basin closest to borehole 45 never filled with recharge water and thus infiltration took place at a greater distance from the borehole. Because of ion exchange the amount of potassium reaching the borehole was greatly reduced and hence no potassium peak and resultant abrupt decrease once the new pulse of recharge water arrived. The increased volumes in 1989/90 once again caused a decrease, but not as much as previous years due to the absence of a potassium peak which proceeds the good quality recharge surge.







BOREHOLES: 16 [20.7 m] 17 [9.5 m]

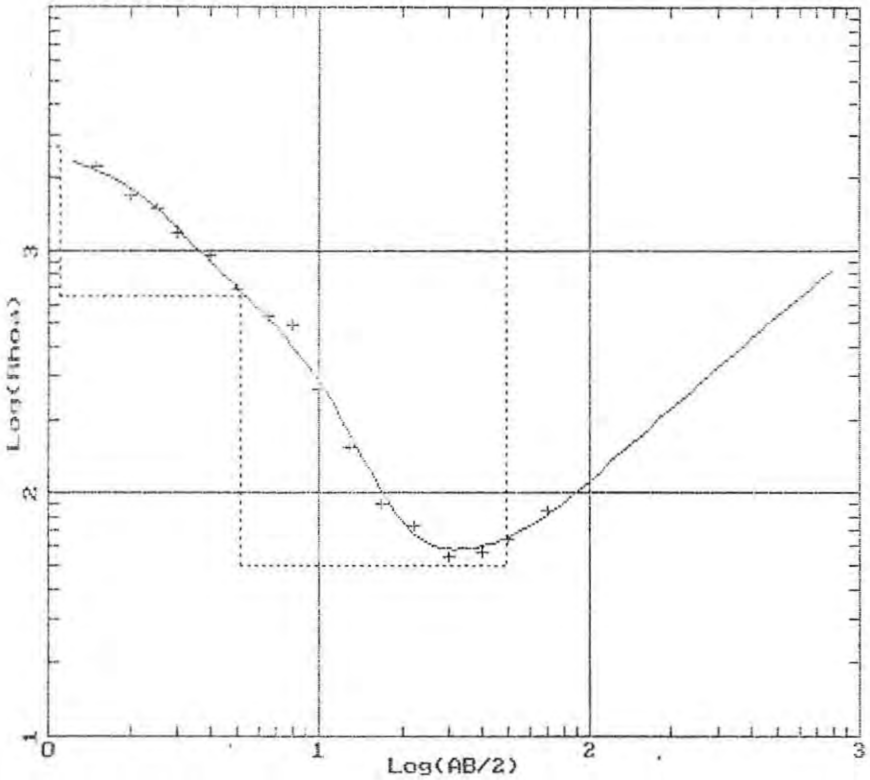
The trends clearly show the stratified nature of the groundwater quality. At shallow levels the groundwater displayed large seasonal variation, whereas at deeper levels the variation was very subdued. The large fluctuations in water quality and increasing K concentrations in borehole 17 confirm the influence of artificial recharge water. It would however appear that the groundwater quality response is about 1 year behind that of the artificial recharge basin. The vastly reduced volumes of recharge water during 1988 being reflected in the greatly reduced response during early 1989. The existing natural groundwater quality has now been completely swamped by artificial recharged water resulting in the reduced salinity and abnormally high K concentrations. The influence of artificially recharged water first having a major effect in early 1986.

At deeper levels [borehole 16] the water quality is still very much a reflection of the original groundwater quality. These levels do show a very minor influence from the artificially recharged water especially when the recharge basin was filled to capacity as was the case in 1985 and 1986. The present management strategy for the recharge basin is unlikely to influence the groundwater quality at depth in this area.

APPENDIX K

EXPLORATION RESISTIVITY SOUNDING CURVES

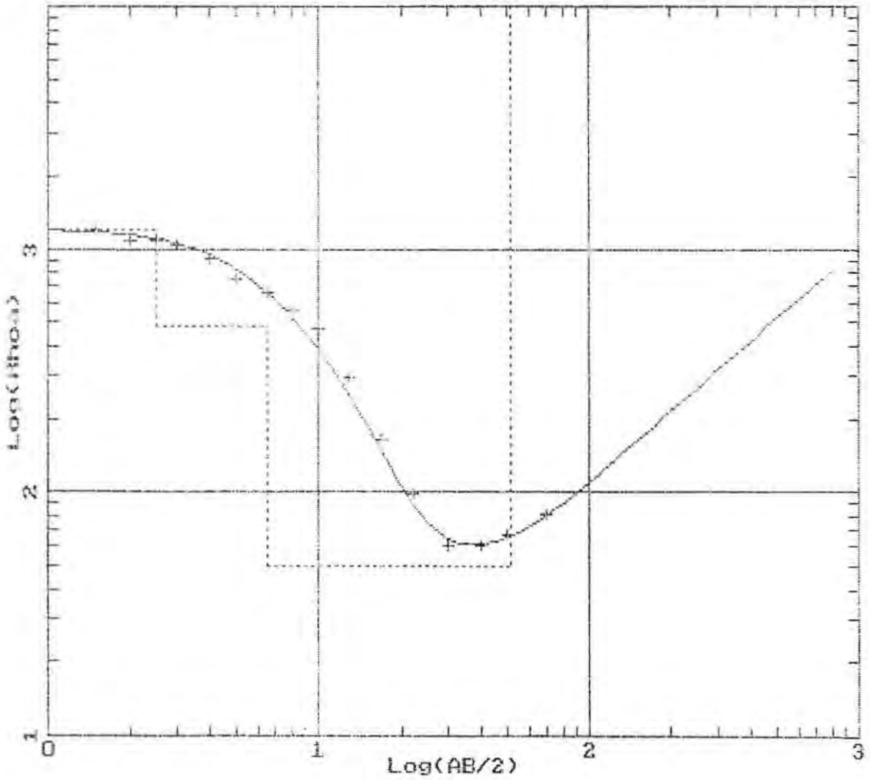
(Schlumberger method)



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	1.10	2700.00	1.10
2	4.00	650.00	5.10
3	44.00	50.00	49.10
		10000.00	

WRIGHT
ATLANTIS

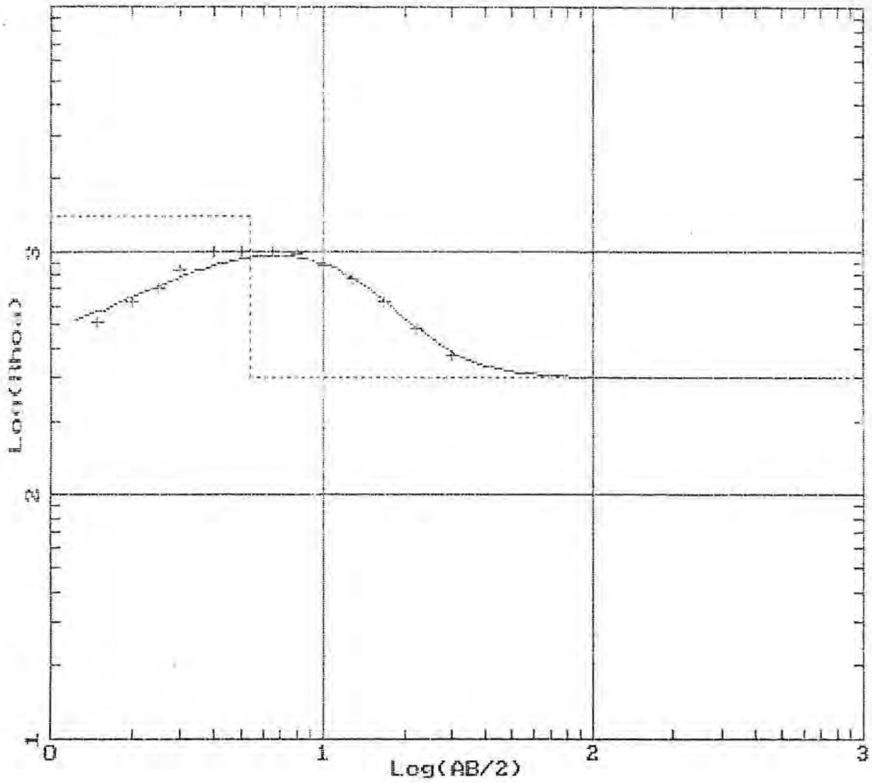
E.S. A



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	2.50	1200.00	2.50
2	4.00	480.00	6.50
3	45.00	50.00	51.50
		10000.00	

WRIGHT
ATLANTIS

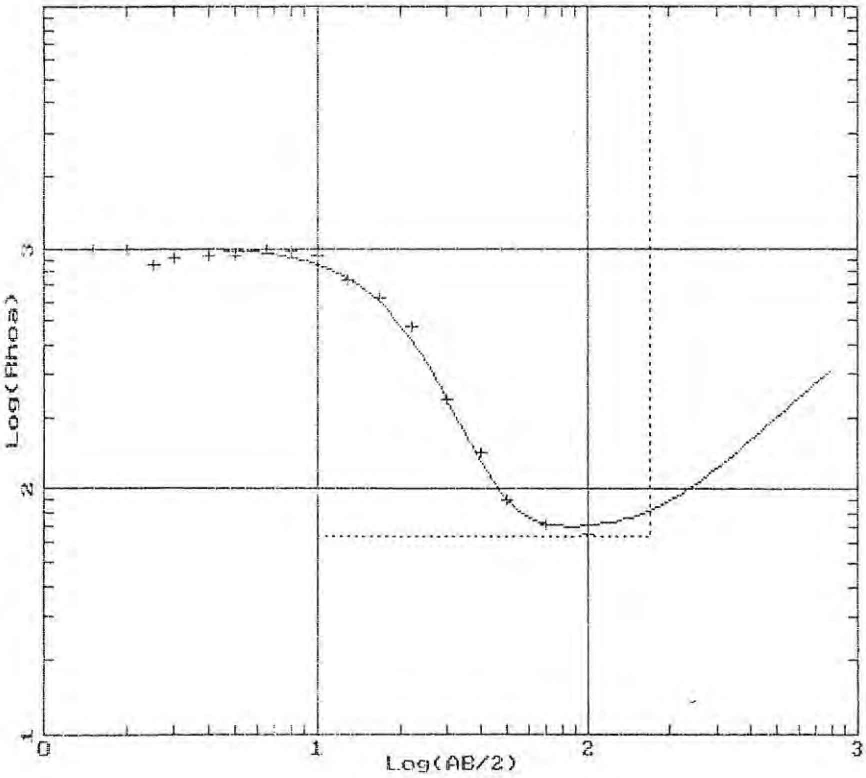
E.S. B



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	0.90	430.00	0.90
2	4.50	1400.00	5.40
		300.00	

WRIGHT
ATLANTIS

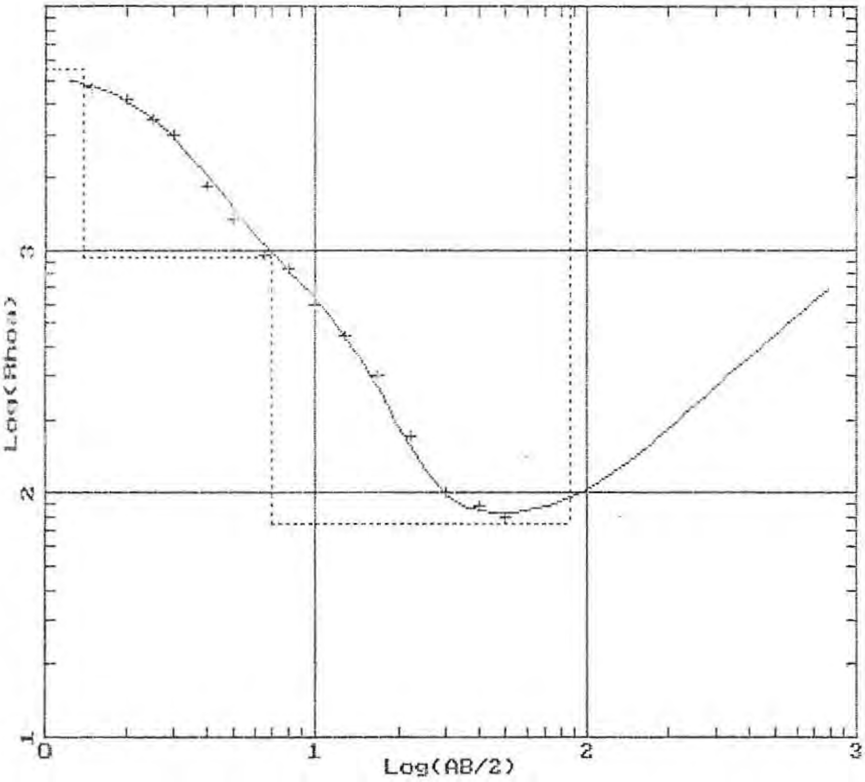
E.S. C



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	10.00	1000.00	10.00
2	160.00	65.00	170.00
		10000.00	

WRIGHT
ATLANTIS

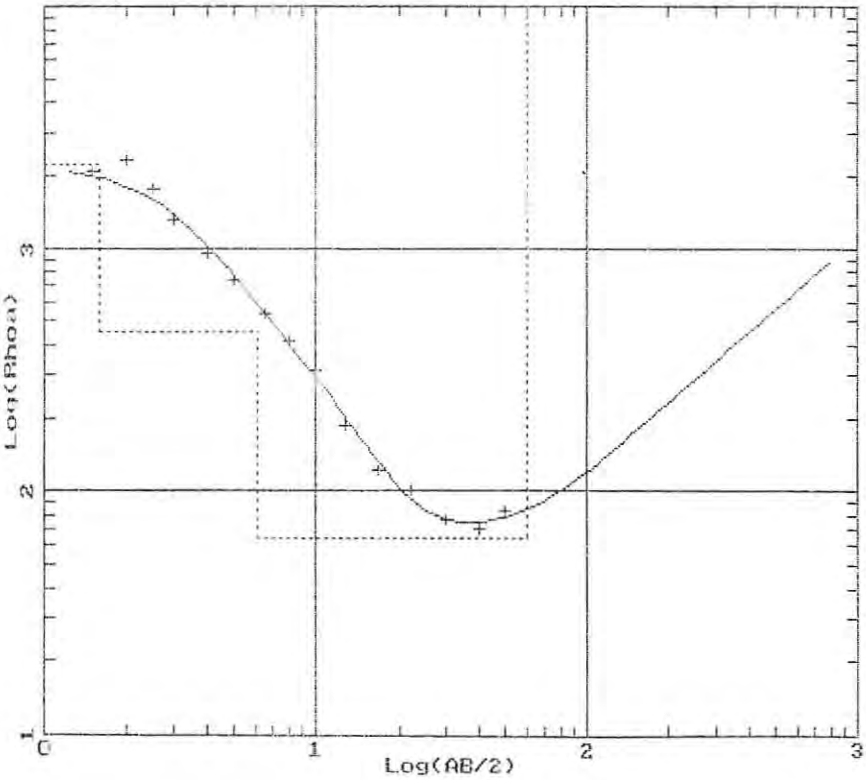
E.S. D



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	1.40	5500.00	1.40
2	5.50	930.00	6.90
3	80.00	75.00	86.90
		10000.00	

WRIGHT
ATLANTIS

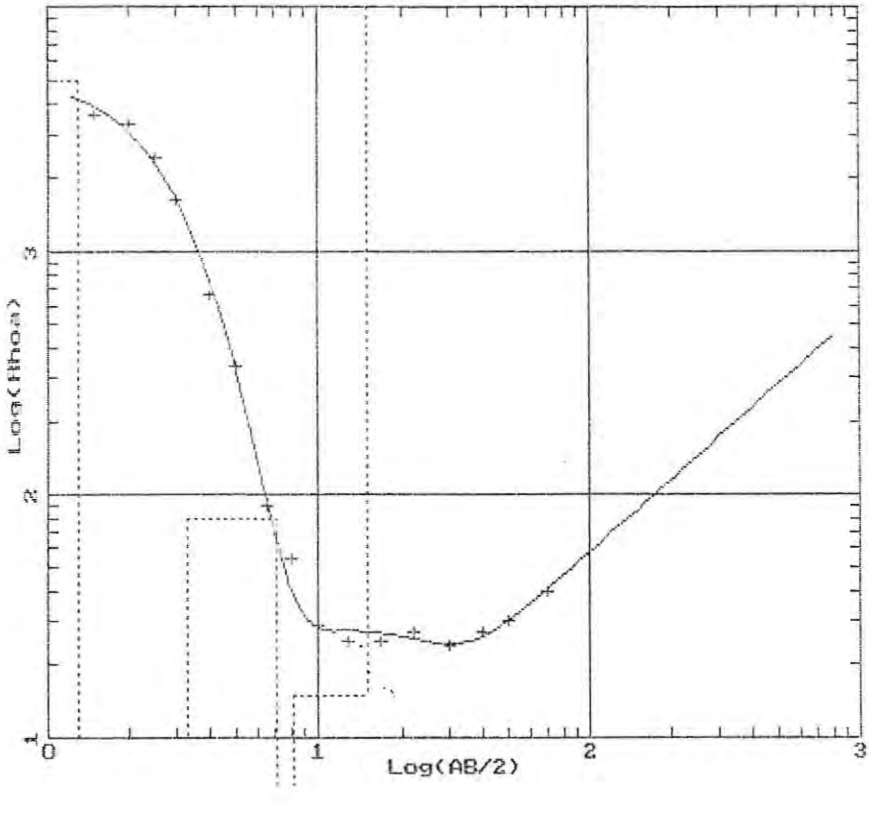
E.S. E



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	1.60	2200.00	1.60
2	4.50	450.00	6.10
3	54.00	65.00	60.10
		10000.00	

WRIGHT
ATLANTIS

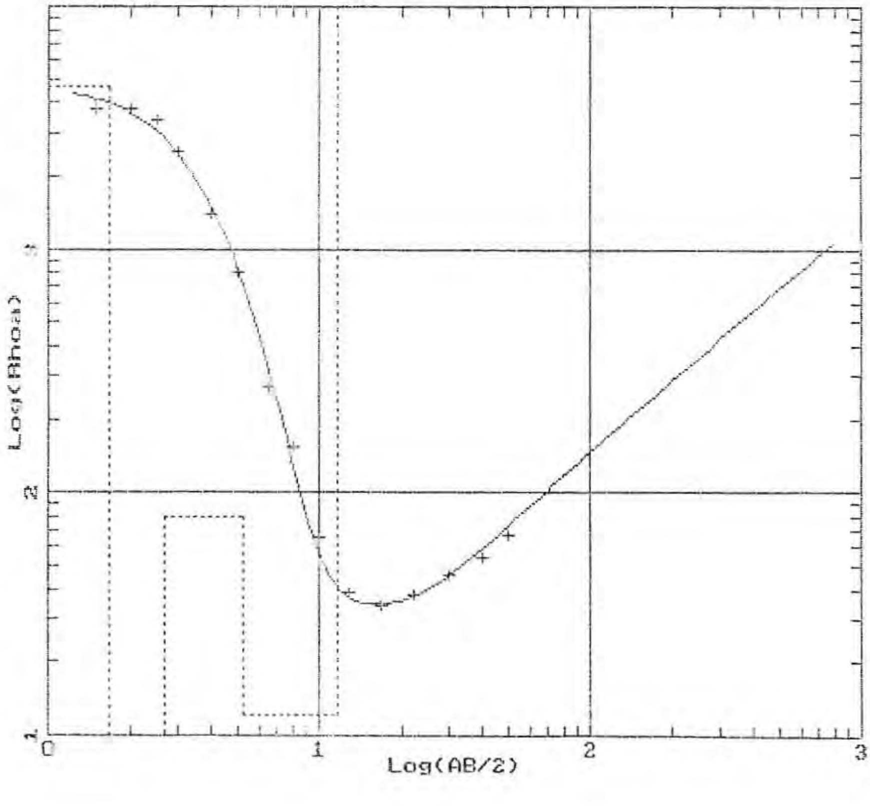
E.S. F



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	1.30	5000.00	1.30
2	2.00	10.00	3.30
3	3.80	80.00	7.10
4	1.00	1.00	8.10
5	7.00	15.00	15.10
		10000.00	

WRIGHT
ATLANTIS

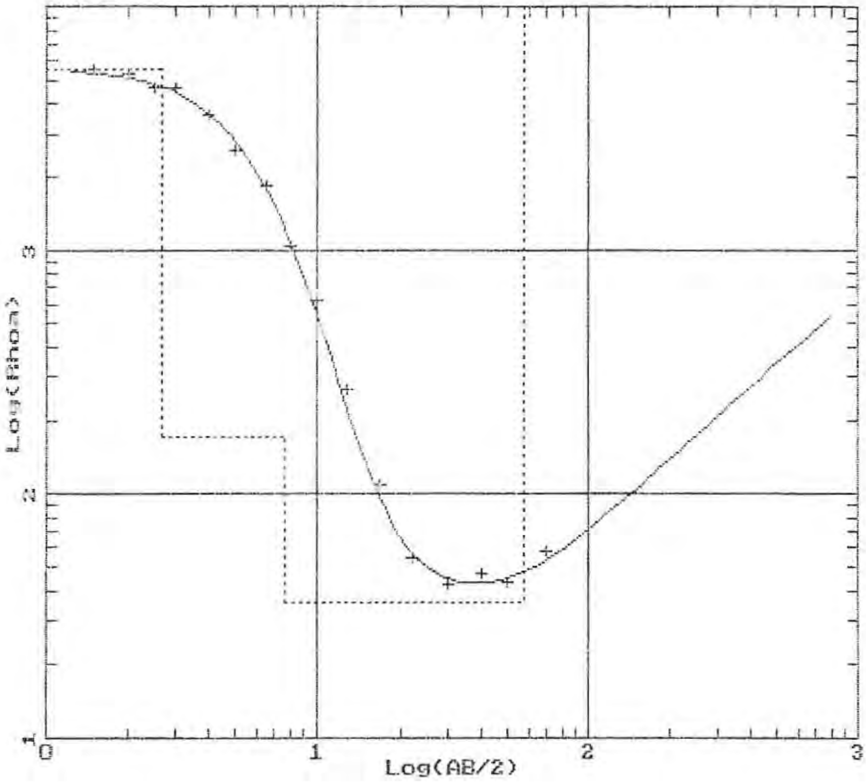
E.S. G



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	1.70	4700.00	1.70
2	1.00	10.00	2.70
3	2.50	80.00	5.20
4	6.50	12.00	11.70
		10000.00	

WRIGHT
ATLANTIS

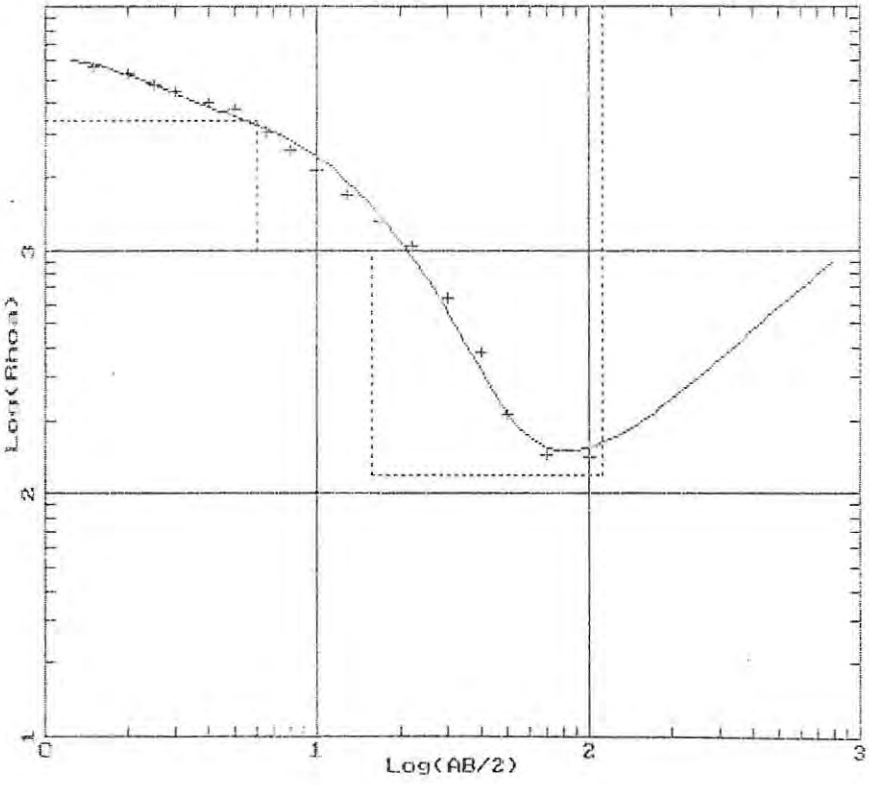
E.S. H



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	2.70	5500.00	2.70
2	5.00	170.00	7.70
3	50.00	36.00	57.70
		10000.00	

WRIGHT
ATLANTIS

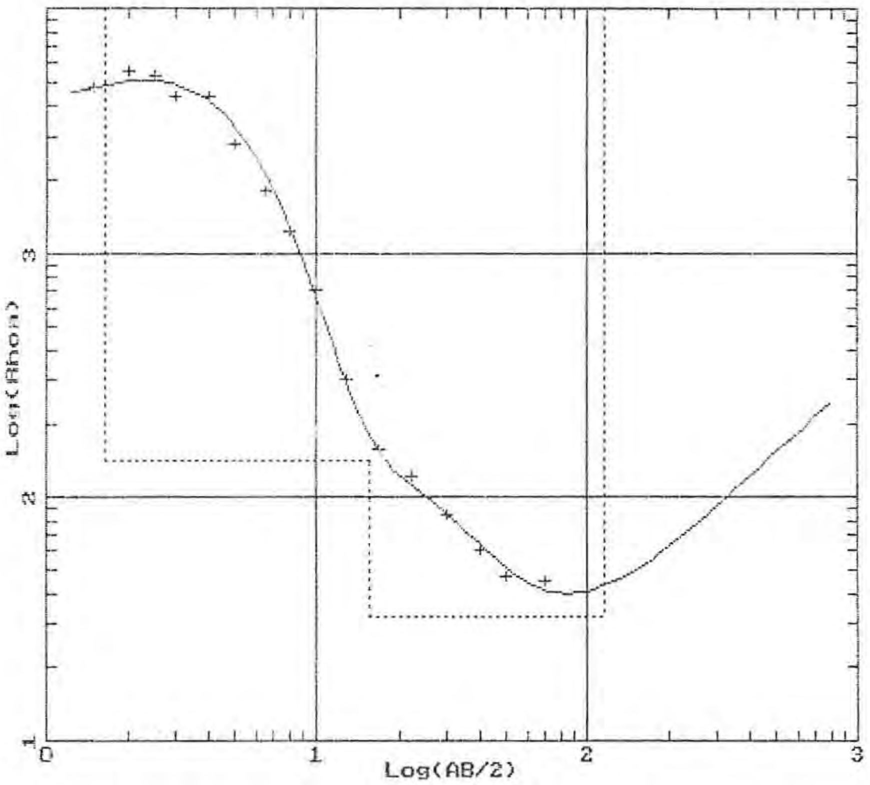
E.S. I



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	1.00	6700.00	1.00
2	5.00	3400.00	6.00
3	10.00	1000.00	16.00
4	96.00	120.00	112.00
		10000.00	

WRIGHT
ATLANTIS

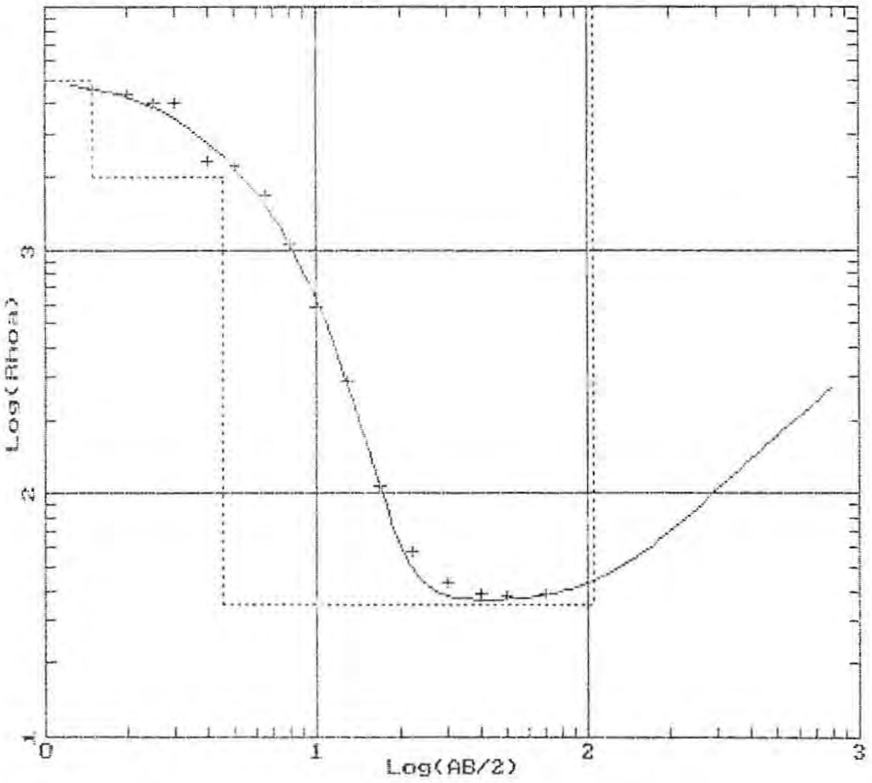
E.S. K



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	0.85	3800.00	0.85
2	0.80	15000.00	1.65
3	14.00	140.00	15.65
4	100.00	32.00	115.65
		10000.00	

WRIGHT
ATLANTIS

E.S. J



n	Thick-ness (m)	Resis-tivity (Ohm.m)	Depth (m)
1	1.50	5000.00	1.50
2	3.00	2000.00	4.50
3	100.00	35.00	104.50
		10000.00	

WRIGHT
ATLANTIS

E.S. J1