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FLOODING OF CENTRAL AND EAST RAND GOLD MINES:

AN INVESTIGATION INTO CONTROLS OVER THE INFLOW RATE, WATER QUALITY AND THE PREDICTED IMPACTS OF FLOODED MINES

Report to the
WATER RESEARCH COMMISSION
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Flooding of Central and East Rand Gold Mines:

An investigation into controls over the inflow rate, water quality and the predicted impacts of flooded mines.

Report prepared for

Water Research Commission

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Catchment Water Quality Deterioration as a Result of Water-Level Recovery in Abandoned Gold Mines on the Eastern and Central Witwatersrand

The steering committee who directed the project consisted of the following persons:

Mr A.G. Reynders	Water Research Commission (Chairman)
Mr H.M. du Plessis	Water Research Commission
Mr P. Smit	Water Research Commission (Committee Secretary)
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Due to personnel Changes during the course of the project the following alternate members were appointed by the respective organisations:

Mr van Zyl	Directorate Water Quality Management DWA&F
Mr J.I Rademeyer	DWA&F
Mr M Simonic	Directorate Geohydrology DWA&F
Mr A Frits	Water Research Commission (Committee Secretary)

The results of this project are due to willing co-operation from many institutions and the specialists who work for those institutions. The investigator was given permission to enter their property, interview their staff and obtain water samples on surface and underground. Often reports, maps, records and results were made available and usually freely copied. The co-operation of many people who work for the following institutions is therefore gratefully acknowledged.

Anglo American library services
Boksburg Municipality
Consolidated Modderfontein
Department of Water Affairs and Forestry
Genmin, including Grootvlei Mine
Germiston Municipality
Gold Fields of South Africa, Oberholzer research section
Government Mining Engineer
JCI library services
Johannesburg Municipality
Nigel Gold Mining Company

Primrose Gold Mining Co.
Rand Mines
Rand Water Board.
Roodepoort Municipality
Springs Municipality
University of the Witwatersrand: Geology, Shonland Research Centre and Botany Departments.
Village Main Reef Mines

Many people in the area were approached for samples from their private boreholes, most co-operated willingly.

J.R. Scott (Researcher)

Disclaimer

Much of the information used in this investigation was sourced from numerous investigators. Thus water sampling and chemical analyses have not all been performed by the same laboratory under the same conditions. Most of the results are not based on regularly monitored values thus represent a once-off picture, long term monitored values based on many seasons of evaluation may show a different picture. As no monitoring of this situation has ever been conducted this was a *best approach* within the constraints of the project.

The situation within the investigation area is also dynamic, since gold recovery from waste dumps is removing many of the diffuse sources of pollution, the mine waste heaps. As their removal is a relatively long term process, no immediate changes will be evident and long term monitoring would be necessary to evaluate the real changes.

Units and Conversions

All co-ordinates used in figures and maps are given in metres

Flow values are given in mega litres per day = Ml/d.

If: 1 mega litre (Ml) = 1 000 cubic metre (m^3) = 1 000 000 litres (l)

Then: 1 Ml/d = 11.574 l/s

All chemical analyses of dissolved species are reported as milligrams per litre = mg/l

Salt loads are given in tons per day = t/d.

If: Load = flow × concentration

To report the load as t/d the following unit manipulation must be used:

$$(\text{Ml/day}) \times (\text{mg/l})/1000 = \text{t/d}$$

Executive Summary

1. Introduction

The Central and East Rand mining areas have been extensively mined since 1886 to depths of up to 3 500 m below surface. During the long history of mining these areas have been dewatered to allow mining operations to continue unhindered by water ingress. Up to the 1950's, each mine was responsible for their own pumping. As some mines reached the end of their working lives and were abandoned or closed, so more and more pumping was left to the remaining mines, until most of the pumping was conducted from one mine in a particular area. Because pumping from these points kept all the related mines dry, some operations were able to mine without pumping. Thus those mines that continued to pump were granted state assistance for their pumping costs.

Until June 1991, dewatering on the East Rand was achieved from S.A. Lands and Exploration (Sallies) No. 1 Shaft, with smaller volumes pumped from Grootvlei Mines No 3 and 4 shafts. On the Central Rand dewatering has continued until the present from East Rand Proprietary Mines (ERPM) Hercules and SW vertical shafts and at Durban Roodepoort Deep (DRD) from No. 5 Shaft.

Mining in this area cannot continue indefinitely and at some time either due to economic constraints or to the ore being totally depleted, all mining will stop. At that time there will be no further reason to dewater the underground excavations and, if the results were environmentally acceptable, pumping could stop and the pumping costs would be saved, this future eventuality gave rise to this project. Thus if mining stops, and at the same time dewatering stops allowing the mine excavations to flood, what will the results be?

The objectives of the investigation were therefore:

- Investigate the rate of water-table recovery in the abandoned gold mines of the Eastern and Central Witwatersrand; upon cessation of pumping from these mines.
- Investigation into processes affecting the quality of the water in these mines and prediction of the likely water quality in fully recovered mines.
- Quantification of possible seepages from these mines upon full recovery of the water table.
- Evaluation of the overall impact on possible further deterioration of the surface water quality in the catchments.

2. Physical Description

The Central and East Rand Mining areas are two of the nine distinct gold mining areas (goldfields) that have developed in the greater Witwatersrand Basin, these are shown in Figure 1.

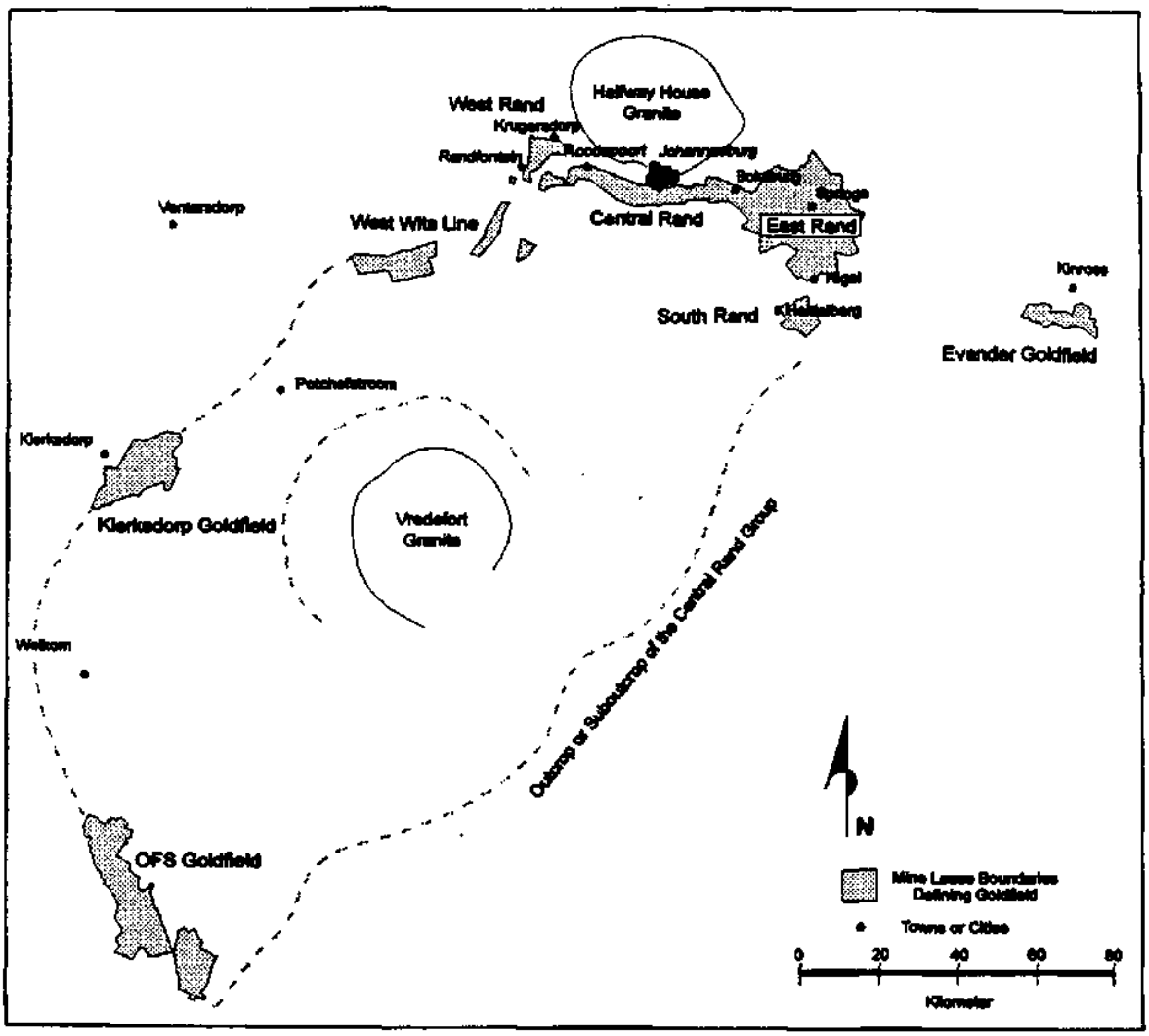

Figure 1 Map of the Witwatersrand Basin

On the Central Rand the first mines developed because the gold bearing reefs are well exposed, extensions were easily traced into the East Rand area where the reefs have a shallow basin-like structure. These reasons: early discovery and initial mining development on the Central Rand and the shallow nature of the East Rand reefs have led to both areas being mined to the limit of profitability and most of the mines are now inactive.

3. Methodology

The Investigation was conducted by studying historical records of mining development, investigating records kept by the mines and the Department of Water Affairs as well as taking stream, groundwater and mine water samples to get a picture of the conditions that prevailed at the time of investigation.

4. Recovery

There are many variables that govern water recovery in the mines. They are dependant on the history of mining, for example, such factors as ownership changes, mining techniques and level of expertise attained by the company, have a bearing on the recovery. Many of the factors differ from mining company to mining company. Mining has not stopped everywhere thus, some of the variables, such as mined out volume, are presently changing in space and time. Many of the factors that influence the underground volume cannot be determined. This means that a detailed study of some of the aspects can be very confusing and defining parameters for modelling is extremely difficult, or so full of assumptions that the model results are meaningless.

4.1. Mechanisms of Recovery

Observation of the underground inflows leads to the following classification:

Rapid Flows. These flows cascade rapidly downgradient in preferred channels, such as incline shafts, to meet the rising mine water body. There is little further degradation of this type of water, it retains its recharge identity. Some of these inflows are closely related to rainfall events as their flow increases soon after such events.

Diffuse Flows. Slow drips and trickles occur anywhere mine openings intersect water bearing geological structures. This water may move through stopes, dam up against ore heaps left in the stopes or haulages. It collects in some places forming stagnant pools. Because of its travel path this water degrades in the mine. The diffuse drips and trickles combine forming flows, collect in drains and become larger flows eventually joining the other water flowing rapidly to the deep flooded regions.

The nature of the underground flow can be related to the sources of recharge.

Four sources of recharge are active:

Direct recharge from rainfall events to outcrop and outcrop workings. This is often facilitated by the removal of topsoil over a fairly wide area in an attempt to expose the reefs. The loose material scraped off in this way is usually placed so that runoff is controlled, this prevents erosion but also forms a holding pond which encourages recharge. Direct recharge to open surface workings contributes to the rapid inflow. Direct recharge to outcrop contributes to the diffuse inflow.

Seepage recharge. Where outcrop or outcrop workings have been covered or filled seepage through the cover or fill material, which may be very permeable, takes place.

Surface water losses. Surface streams and dams may flow over outcrop or outcrop workings, or be located above mine workings and loose water to the underground openings, these contribute to the rapid flow. Many streams flow in geological structure-controlled valleys and losses via the structure to subsurface workings are possible. For example via dike or fracture zones, thus contributing to the diffuse flow.

Groundwater on the Central Rand contributes a baseflow to the recovery. On the East Rand most of the mining area is overlain by dolomites and dolomitic groundwater contributes the bulk of the inflow. Groundwater losses are predominantly via geological structures, such as dikes or fissure zones. Groundwater contributes a diffuse, continuous, steady flow to the underground workings.

On the Central Rand, Witwatersrand Supergroup sediments outcrop. A large proportion (minimum of one third) of the water entering the subsurface is derived from direct recharge, seepage recharge and surface water losses. The remaining baseflow (up to two thirds) is derived from groundwater losses. The catchment area in which the reef outcrops occur has sufficient recharge to provide the groundwater contribution without an extensive cone of dewatering around the workings being evident.

On the East Rand, Witwatersrand Supergroup sediments are covered by younger rocks over most of the area, very little outcrop occurs. Direct recharge occurs during exceptional rainfall and forms an insignificant contribution to the total recharge. Most of the recharge is derived from groundwater losses, predominantly from the Transvaal Supergroup dolomites which overly approximately one third of the investigation area. Recharge to the dolomite from within and outside the investigation area and from the swampy stream system of the Blesbok Spruit is sufficient to provide the bulk of the mine inflow. This aquifer acts as a capacitor, attenuating seasonal fluctuations in the system.

4.2. Rate of Recovery

The rate of recovery is governed by the volume of the excavations and the water inflow rate. The time of recovery can be derived from an elementary relationship:

$$\text{Time} = \frac{\text{Mined out Volume}}{\text{Inflow Rate}} \frac{D^3}{D^3 / T}$$

4.2.1. Volume of the Excavations

Variables which affect the volume of rock removed include the following:

Differential mining and mining intensity, for example, on the East Rand some areas were mined predominantly for pay shoots, this led to patchy discontinuous mined-out areas, while others areas were mined out completely.

Number of reefs mined, in the Central Rand up to six reefs were mined, predominantly in the western parts, toward the east fewer and thinner reefs were mined until on the East Rand predominantly one reef was mined.

Efficiency of scale and economics, some mines due to poor early planning closed down prematurely so that considerable volumes of mineable reef were left, while adjacent mines with perhaps better planning and more efficient management and mining techniques were able to mine to greater depths with higher extraction proportions.

Stratigraphy and structural geology were not as well appreciated by all parties in the earlier stages of mining. When mining went off-reef due to a geology related problem, if a solution was not easily found, large blocks were left unmined.

Backfilling. During active mining, waste rock was packed into haulages and stopes, this saved dump space on surface (land was expensive) and added support to the mine workings. In recent times, slimes, from the reworking of dumps, have been backfilled by gravity feeding into the underground workings.

Stope closure and collapse. This is related to various rock mechanics factors including: dip of the reef, fracture density and orientation, competency and weathering resistance of the overlying strata, depth of mining and the amount of support left or introduced. The latter, in spite of being engineered is very variable. For example, in some places rock supports were left unmined or backfilling of waste rock added support. Wooden supports or packs were placed more regularly where problems were expected, thus providing more predictable support. Originally teak supports were used, but even this hard wood has collapsed due to the humid and acid atmosphere and now offers no support.

From the above description it can be understood that determining the volume of mine excavations could never be precise. A further complication is the partial filling by water that occurs in all mining areas.

Two methods were used to estimate the mined out volume.

1. Volume = stope area × stope height

The area affected by stoping can be measured from the mine shareholder plans. The stope height could vary from 0.5 m to more than 2 m, although the accepted limit for the working height is 0.8 m. Thus volumes were calculated using stope heights of 0.5 and 0.8 m. Other mine excavations, such as haulages and crosscuts, make up approximately 15% of the volume.

2. $$\text{Volume} = \frac{\text{Tonnage}}{\text{Density}}$$

The total tonnage of rock that was milled at each of the mines has been recorded by the Chamber of Mines since it's inception in 1887. The tonnage conversion to volume was calculated using a density of 2.75, which is the value used on the mines for density related calculations.

The tonnage milled was predominantly ore, off-reef tonnage was usually not sent to the plant for milling. Thus 15% off reef development must be added.

4.2.2. Inflow Rate

Due to the diffuse, multiple source, nature of the inflows to the workings and the inaccessibility of many of the old areas, flow gauging of the incoming water was not possible.

The mines kept accurate records of the volume of water that was pumped from the workings. These records were required by the mine for engineering planning and cost accounting since pumping costs form a large proportion of the mines working costs. The records were also required by the Department of Water Affairs for the mine's water consumption permit and by the Department of Mineral and Energy Affairs to determine the pumping subsidy that was to be paid.

During periods when stable underground water levels were maintained an equilibrium existed between inflowing and pumped water volumes, since no dewatering nor storage was taking place. During such periods, the pumping record, will give the best available estimate of the rate of water inflow to the mines.

On the **East Rand** stable water levels were maintained from 1988 until pumping stopped in 1991. The pumping records for this period shows that

An average of 53 Ml/day were pumped from Sallies No. 1 shaft and 11.5 Ml/day were pumped from the Kimberley Reef at Grootvlei No. 3 and 4 shafts.

Thus, over a period of almost 3 years when the water level was maintained at 1606 mbd the average extraction from the system was **64.5** Ml/day.

On the **Central Rand** water levels have been stable in the central and eastern sections since 1977. While in the west stable water levels have been maintained since 1990. The pumping records show that:

- ERPM (Based on 12 years of data)

At Hercules shaft water collecting on ERPM is pumped to dewater the mine, thus 16.02 Ml/day is pumped, but 8.93 Ml/day of this water is service water, originating from RWB water and ice, which is used to cool the workings. Thus, 7.09 Ml/day is made on ERPM

At SW Vertical Shaft pumping maintains the water level at 1083 mbd in the central mines (CMR to Simmer and Jack), and 1170 mbd in Rose deep. These mines are defunct so no service water is added but some slime is disposed underground. Thus 16.58 Ml/day are pumped but 2.74 Ml/day slime is disposed, so 13.84 Ml/day is made in the central mines.

- DRD (Based on 2 years of data)

At DRD water is derived from the eastern neighbour Rand Leases and from DRD. Pumping maintains the water level at 2380 mbd in DRD and 1200 mbd in Rand Leases. About 18.06 Ml/day is pumped from DRD, made up of 4.74 Ml/day from Rand Leases, 10.23 Ml/day is from DRD and 3.09 Ml/day service water, thus 14.97 Ml/day is made on the western mines.

Thus almost **36** Ml/day is made daily in the Central Rand mines.

4.2.3. Predicted Recovery Times

		Mined Vol. (km^3)	Inflow Rate (m^3/day)	Time to fill (years)
	Max.	283.7		22.90
Central Rand	Min	224.5	35900	18.13
	Min (Unreliable)	84.1		6.88
	Max.	304.4		13
East Rand	Min	207.1	64500	9
	Extrapolated			14

On the East Rand the recovery has been monitored since pumping stopped in June 1991, thus the observed recovery trend could be used to help predict the times of recovery. The times given for the East Rand ignore the fact that three years of recovery are already completed, thus the times should be reduced by 3 years.

The wide range given for the Central Rand includes, area measurement from mine plans, which underestimates the area due to the scattered nature of the workings on many different reefs. In addition some mines were not measured because there are no maps available but volumes were inferred from the lease areas. Thus this volume is considered to be unreliable.

5. Discharge

5.1. Discharge Points

The mine excavations, in solid crystalline rock, introduce porosity to an otherwise impervious rock sequence. Thus the mine openings and the surrounding mining induced fracture systems form tabular, porous zones within impervious rocks. The hydraulic properties of these tabular zones will be the same as those described for confined aquifers:

- The aquifer is a permeable body which is bound above and below by impervious material, the usual example would be a fairly clean washed sand bound by clay layers.
- The aquifer has a recharge area where the rocks are exposed or unconfined.
- The water in the aquifer is under pressure, the pressure head of the supposed recharge area.
- Water will rise in a borehole drilled into such an aquifer to a level termed the piezometric* surface.
- When the ground surface is lower than the piezometric surface, a borehole drilled at such a point would be free flowing. Such boreholes are often referred to as artesian boreholes.

The *mine openings are defined as* **mine aquifers**, *because due to fracturing,* closure and water filling, they can no longer be viewed as stopes or haulages. And while they appear to have confined aquifer relationships, the characteristics have not been proven.

The mine aquifers of the Central and East Rand are partly dewatered. When all pumping stops and the mine aquifers are allowed to fill, piezometric surfaces will be definable for the aquifers. Vertical shafts which intersect the aquifer are equivalent to boreholes drilled into a confined aquifer, they can therefore be considered to be piezometers where the piezometric surface could be measured. Shafts with collar elevations lower than the piezometric surface will become discharge points, equivalent to artesian boreholes, from the mine aquifer.

The mining induced porosity is such that the mine aquifers are highly transmissive zones and once filled, water will move preferentially via the most transmissive route, following the path of least resistance. Thus even when fully recovered, the water will move through the mine aquifers without recharging the surrounding, low permeability rock. The shafts connected to the mine aquifers are therefore the potential discharge points and not geological structures such as faults or dike zones which have much lower transmissivity.

Thus identifying shafts with potential to become discharge points involves predicting what the piezometric surface would be and comparing shaft elevations

* A piezometric surface is defined as an imaginary surface representing the total head of groundwater in a confined aquifer. It is shown by the level to which water will rise in a well.

with that surface. All shafts with elevations below the predicted piezometric surface have potential to become discharge points.

Piezometric surfaces are assumed to be the elevation of the major inflows (recharge points) to the system.

5.1.1. Central Rand

Historical evidence has shown that the main inflows are occurring at the outflow from Florida Lake, in the vicinity of Village Main Reef Mines, and at the Knights and Waverley mines. The surface elevation§ of these points ranges between 1670 and 1720 m above mean sea level (mams). The measured average groundwater level in these areas is 15 m below surface, the piezometric level would be similar to, or slightly lower than, this level. Thus for identifying potential outflow shafts a level of 1660 mams has been used.

Using this level South East and Far East Vertical shafts have the greatest potential to flow, being 59 and 54 m below the proposed piezometric surface. This is some 10 to 15 m lower than the next nearest shaft, Hercules shaft. The South East Shaft is the most probable shaft based on the elevation determination used in this investigation. It is located adjacent to Cinderella Dam on a headwater stream of the Elsburg Spruit.

All the mines on the Central Rand are interconnected at some level. It would be possible to isolate DRD by plugging present connections which exist at 14 level 580 m below surface. By doing this DRD will fill up in isolation from the rest of the system and the discharge points will be either old incline shafts in the Klip River Valley or DRD No. 6 shaft. Some advantage may be derived from this approach, due to the outflow volume being shared by two catchments. The water quality at DRD may also be better than the overall quality at one outflow point.

5.1.2. East Rand

Precise locations of the inflow points, in this area, are not known, thus predicting a piezometric level for the mine aquifer is difficult. Major inflows were recorded in the vicinity of Consolidated Modderfontein and East Geduld thus if the piezometric surface is related to the type of shallow inflow observed at Cons. Modder No. 8 shaft, where the surface elevation is 1623 mams, the inflow depth is 50 m below surface then the piezometric surface would be 1573 mams.

Using this level, Nigel No. 3 shaft is 24 m below the proposed piezometric surface, this is 9 m lower than the next nearest shaft elevations. The outflow at this point is dependant on interconnectedness between Sub Nigel and Vogelstruisbult Mines. If the interconnection is blocked then Marivale 4 or 7 shafts, which are 8 and 9 m respectively below the proposed piezometric surface,

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§ All surface elevations have been measured from 1: 10 000 orthophoto maps. More precise elevation surveying may be necessary to properly differentiate between points where elevations are similar.

could form outflow points. Appropriate monitoring at selected shafts will provide early warning of the state of the connection between Sub Nigel and Vogelstruisbult.

5.2. Discharge Volume

5.2.1. Central Rand

The discharge volume will be similar to the pumped volume minus service water, ice and waste disposal. This is because recharge of the surrounding secondary aquifers will be confined to areas around shafts, especially if the shaft linings have broken down, this means that there will be little reduction in volume. Thus if decanting is allowed to take place a steady state will develop with the recharge volume equal to the discharge volume. Thus some 34 Ml/day will discharge from the identified outflow shaft, made up of a groundwater baseflow of 24 Ml/day and a seasonally variable component of some 10 Ml/day.

Constructed compartmentalisation at DRD would allow 8 Ml/day to discharge at DRD and reduce the volume at South East Shaft to 26 Ml/day.

5.2.2. East Rand

The volume of water emanating at Nigel No 3 shaft will be less than the present inflow volume. This will be due to the recovery rate slowing down from the base of the dolomites (550 mbd), due to some of the inflows from the dolomites being cut off. This will particularly apply to the last 100 to 140 m of water rise.

When the water level reaches the main inflow level, estimated to be 25 to 27 m below surface at East Geduld, equilibrium will be established. At this point the outflow rate at the decant shafts will be equal to the inflow rate from the dolomites. The volume should be of a similar order of magnitude to the river flow rate before mining and effluent disposal altered the surface and groundwater flow situation in this area. This estimate assumes that the main flow in the river, prior to mining, was derived from groundwater.

The flow rate can therefore be estimated from Mellor's (1921) observations that the swamps dried up in winter, the dry period lasting for about half of the year. This means that the flow rate will be lower than the total effluent disposal to the river, which is able to keep the river flowing year round. If the total effluent disposal is 65 Ml/day from Herold (1990), then the outflow at Nigel will be less than this figure, probably half (based on the half year dry period) i.e. 33 Ml/day.

More precise estimation of the flow rate is not possible because:

- No hydraulic records were kept during mining activity
- Lack of information on groundwater conditions in the area
- The inaccessibility of the underground workings for direct observation.

6. Water Quality

6.1. Factors affecting the quality of the rising water.

One of the major factors contributing to water degradation is the reaction of water with sulphide minerals, producing the so called *Acid Rock Drainage*. The Witwatersrand Supergroup sediments contain varying proportions of sulphide minerals, the predominant sulphide being pyrite (FeS_2). In many of the gold bearing reefs this mineral may form up to three percent (by mass) of the rock.

Mining of the Witwatersrand Supergroup sediments has produced: On surface; rock piles, sand and slime dumps. Underground; backfilled rock piles and spoil heaps in stopes and haulages. These all contain pyrite which, in the broken and crushed rock, is now exposed to air and water and oxidises. Due to this oxidation the rocks and accumulations have characteristic red and yellow staining and discoloration from secondary iron oxide minerals and mineraloids. The acid content of water that passes through such accumulations increases.

Thus the reactivity of the water increases, and in its passage, it reacts with other minerals, either to generate more acid or to neutralise the existing acid. The total dissolved solids (TDS) content of the water rises. The water may be characterised by one or more of the following: Low pH, high TDS, high sulphate (SO_4) content, or high heavy metal content (particularly Fe, Mn, Ni or Co).

Due to the variable nature of the recharge sources and to the many different places where acid formation can occur, water degradation is diffuse and no one source can be identified as a major contributor to the overall degradation of the water. Surface degradation and subsurface degradation both contribute to the overall lowered water quality.

1. Surface Degradation

- Surface water through intimate interaction with mine wastes takes on a very similar identity to the water found in the mines.
- Groundwater which is affected by seepage from mine waste heaps has the same chemical identity as the water in the mines.
- Reef outcrop areas that have not been mined nor developed in any way were found to have acid water draining from them.

These water sources contribute to water flowing into the mine cavities. The mine waste heaps are often located above shallow surface workings and reef outcrop and are thus in hydraulic communication with the deep mine cavities. Seepage may be lost vertically to the mine openings or may contaminate surface water streams which flow between the mine wastes, these streams loose* water on flowing over surface workings and outcrop.

- The area is highly industrialised and densely populated thus the surface streams carry a wide variety of effluent in addition to mine waste-derived seepage, their quality can vary within tens of metres. None of the streams are in pristine condition. These streams loosing to the subsurface contribute a diffuse pollution load.

Incipient water chemistry classification work suggests that mine water is closely related to surface water types. Study of the Boron content of the different water types also shows this relationship, surface water and mine water containing high Boron while groundwater samples contain little or no boron. Boron is an element used in hard detergents and is common in waste-water streams.

2. Subsurface degradation

A proportion of the water recharging the mines arrives from a number of widely distributed small drips, trickles and seeps, most are via geological structures.

- This water has passed through different geological horizons where mineral water interactions will have caused further degradation from what may have started on surface. Water on the East Rand is buffered by dolomitic water, thus the pH drop is not as pronounced as it is on the Central Rand. Seepage recharge in this area rarely enters the mines directly, but first via the Karoo or dolomites where reactions (predominantly neutralisation in the dolomite) can change the chemistry of this source of poor quality water.

- Other Mining. On the East Rand, shallow, underground coal mining has taken place in many areas. Many of these old coal mines are flooded and contribute seepage to the gold mine workings below. The groundwater in the vicinity of such coal mines shows increased sulphates.

- In the mines these diverse flows pass through a variety of conditions, such as backfilled waste rock, loose ore in stopes and haulages that has never been removed and fine material that has collected in travelling ways. These materials are pyrite bearing, thus the flows are exposed to pyrite in many of their courses. The mines are open to air circulation and even in abandoned sections, natural air circulation, due to up-draught shafts, ensures that there is enough oxygen for oxidation of the pyrite. In addition the warm, humid, underground conditions, encourage bacterial development. Bacteria catalyse the oxidation of the pyrite increasing the rate of this acid forming reaction. Thus the water further deteriorates on its passage underground by reaction with sulphide minerals and mixing with stagnant water lying in disused mine openings.

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*The term loose is in use in the mining industry, the process is similar to seepage or percolation, the trems commonly used in geohydrology relating to vertical (steep hydraulic gradient) movement of water into the subsurface. Loose is distinct from these terms, in that, certain characteristics such as, flow rate, potential flow volumes and leaching characteristics, are very different from what may be expected under natural conditions due to the underground excavations generating channel flow conditions and dewatering creating steep hydraulic gradients for kilometres underground.

When an equilibrium is reached between inflowing and outflowing water the water level in the mines will be within the region of the deepest surface workings which penetrated the oxidised zone. In this zone pyrite had already been oxidised in antiquity. Thus with much of the subsurface flooded, anoxic conditions will prevent, or slow down, continued degradation. The non-flooded region will contain little unoxidised pyrite, thus subsurface degradation will be naturally minimised. At this stage the degradation process will predominantly be controlled by surface sources.

Surface sources are dynamic and some are being removed by recovery of the mine waste heaps, others can be controlled by legislation and policing.

> The water flowing from the dolomites has a high buffer capacity which acts against pH lowering caused by pyrite oxidation, thus pH rarely goes below 5. Sulphates and other salts in solution give the water an unacceptably high TDS, much of this is derived from surface pollution sources.

6.2. Predict quality in filled mines.

Because of the many variables governing water inflow to the mines, the large number of points where degradation can occur and the number of indeterminable factors, using a model to generate the final water quality is not possible.

The water quality in the filled mines is predicted from samples taken of dammed underground water and rising water in the mined basins. This is the best basis for prediction since conditions in these basins are similar to what they will be on full recovery. Water collecting in stagnant pools in underground workings is often isolated from the recharge water and may be degraded to a much greater extent thus having very low pH and high TDS. Water in actively filling areas is more dynamic and has not degraded to the same extent.

The most contaminated mine water has a high density of about 1.02, this will ensure that the worst water is trapped in the deepest parts of the mine aquifer.

Water in the Kimberley Reef basin should show the maximum level of degradation that will be reached on the East Rand, since typical Kimberley Reef ore has a higher pyrite content than Main Reef ore. Thus representative samples from the Kimberley Reef basin could be used as indicators of the typical water quality that may be expected.

7. Management

Management of this system must aim to reduce the influence of mine water recovery on the natural environment.

7.1. Possible Influences of Mine Water Recovery

A number of possible influences were proposed at the beginning of this study while others have become evident from the study:

- Springs re-emerging in the Blesbok Spruit river system that will inundate low lying areas and destabilise mine waste heaps.
- Increase in subsurface instability and seismic activity.
- Recharge of local aquifers by mine water. On the East Rand, it was suggested, that such recharge would promote instability in the dolomites.
- Negative impacts on the natural environment around the discharge points.
- Water quality deterioration.
- Negative impacts on water users downstream of the discharge points.
- Water inrushes into ERPM from the filled East Rand mining basin.

7.2. Significance of the Impacts

- This study has shown that the re-emergence of springs in the Blesbok Spruit will not significantly alter the volume of water in the river.
- Mine stability will increase rather than decrease.
- Recharge of local aquifers.

  On the Central Rand the groundwater is held in secondary aquifers which are intimately associated with the mine aquifers in the reef outcrop zone only. The secondary aquifers loose water to the mine aquifers in this zone. As long as water is allowed to decant a hydraulic gradient will remain from the secondary aquifers to the mine aquifer. Thus there will be continued movement of water from the secondary aquifers into the mine aquifers. Proper monitoring of water levels to ensure that gradient reversals do not take place will be necessary to provide warning of any reversals that may occur. Aquifers may be recharged by mine water at the decant points depending on the condition of the shaft linings.

  On the East Rand the dolomitic aquifer will be recharged by mine water. This will be a problem if there is significant water movement through the dolomite since the mine water will dissolve the dolomite. Such water movement will be controlled by water level gradients in the dolomite. Understanding and evaluation of these were not part of this project, but this aspect should be evaluated as a priority.

- Surface discharge

  The most significant impact of the recovered mine water will be where it discharges into surface stream systems. On full recovery water will be discharged from the East Rand mines into the Blesbok Spruit and from the Central Rand mines into the Elsburg Spruit. Both of these streams are already affected by Acid Mine Drainage derived from seepage from mine waste heaps.

Neutralised and clarified mine water is also disposed of into the upper reaches of the Elsburg Spruit.

Large flows of poor quality mine water will have a negative impact on both of these streams, affecting both the biota and the downstream water users. Thus some form of control or purification will be necessary.

7.3. Impact Reduction

7.3.1. Removal of Surface Sources

Seepage inflows and surface water quality could improve with time due to:

- Reworking and removal of some of the mine waste heaps.
- The termination of mine water disposal when mining stops.
- Better stream management, controlling pollution inputs and stream flow in the vicinity of mine dumps.

Thus with time, and perhaps added control measures, the quality of water recharging the dolomites could improve.

Better effluent clean up which is being investigated by some of the industries on the East Rand should ensure that some of the river water has a better quality and hence losses from the river system to the mines will be of improved quality.

7.3.2. Treatment of Discharge Water

One of the options that has been proposed for control of the outflowing water has been continued pumping of mine water from shallower than mining depth. For example on the East Rand a pumping depth, from within the mine, at the base of the dolomites has been proposed. This method retains the hydraulic conditions between the mine aquifers and the surrounding shallower aquifers, the pumped volume would be the same as when mine dewatering remained active. This approach would reduce pumping costs due to the lower lift required, but pump operation and maintenance will continue indefinitely. The pumped volume would remain high and pre-pumping and post-pumping water treatment would be required. Good water will continue to be drawn into the system to be pumped out as bad water.

The discharging water whether pumped or allowed to emanate naturally will be of poor quality and some permanent treatment plant would be required to control pH (particularly the Central Rand) and remove dissolved solids from the water before discharge to a river system. This is a costly long term option. Chemical techniques to purify the outflowing water are capital intensive, require skilled personnel for operation and supervision. Such a system may have to operate indefinitely thus maintenance and upgrading will also become problems. The disposal of wastes and sludges generated by such processes will also transfer the problem to some other point.

7.3.3. Inflow Control

In many instances, reasonable quality groundwater or surface water enters the mine aquifer system where it becomes contaminated in the recharge area by reaction, mixing or further degradation in the mines. Thus inflow control must be introduced. Two forms of control are possible:

- Surface water losing sites must be controlled
- Groundwater losses must be minimised

Surface water losing sites must be positively identified, by stream gauging. The surface losses must then be minimised, where possible, by blocking surface sinks at appropriate places, and canalising streams where they flow over reef outcrop. This method is used on the West Rand to prevent pumped water from re-entering the mines.

Prevention of groundwater losses to the mines where degradation starts or continues would be a good control measure. This could be achieved by consuming groundwater in such a way that a balance is achieved between recharge and consumption which minimises the inflow to the mines. Thus reducing the volume of outflowing poor quality water. Certain precautions are required here to retain a balance so that poor quality mine water does not recharge the shallow aquifers.

For these reasons the baseflow component from groundwater must be established by monitoring and the area should be investigated hydrogeologically so that a planned groundwater development program could be used to minimise groundwater losses to the mines. This investigation has shown that groundwater quality varies in space. Optimal extraction points may be identified in poor quality groundwater areas, thus a detailed study of quality variations in the aquifers would have to be undertaken, to properly plan water use.

8. Recommended Future Work

8.1. Monitoring

The effective implementation of any of the management options require better understanding of the system. This will only be achieved by monitoring followed by further study and evaluation of the monitored data.

Monitoring and modelling of the situation would be required to note any improvement in water quality with time and to prevent contamination of presently clean groundwater due to hydraulic gradient changes.

Monitored data that is required includes

- Stream flow gauging

- Geohydrological studies including borehole census, groundwater utilisation, temporal and spatial water level studies to identify rainfall recharge relationships and water table gradients.
- Continued monitoring of mine water levels and pumping rates where applicable. To generate mine hydrograph and chemograph information.

8.2. Research Needs

Investigate the aquifer potential of the East Rand dolomitic aquifers

Evaluate the present nature of the East Rand dolomitic aquifer, whether karstic or not, and predict future karst development due to dissolution by acid mine water.

Tracer studies to identify the sources of inflow to the mines should be undertaken. Various state of the art techniques should be evaluated to find the most appropriate for routine application.

Study of rivers in this area as line sources of pollution, evaluating the recharge impact of rivers to the dolomites of the East Rand, the emergency water supply dolomites of the Klipriver Basin and structural controlled losses where rivers flow over Witwatersrand and Ventersdorp Supergroup outcrop.

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Chapter 1. Introduction

1.1 Aims

It is now 108 years since gold mining started on the Central and Eastern Witwatersrand, at the height of mining activity in the late 1940's there were thirty-nine mines operating in the area. At present most of the mines have reached the end of their profitable working life due to depth, geological complications and their primitive, poorly planned, beginnings. In spite of this the gold bearing ore has not been completely depleted and given the correct economic circumstances, it is possible, that the remaining mines may remain active for many years.

Investigations with regard to restarting mining at some of the existing but dormant mines, or opening completely new mines have been conducted whenever the gold price has prompted such interest. This interest has been shown by existing as well as new mining companies and shows that the economic mineral potential of the area has not yet been depleted.

The area is unique, in that solid rock formations were mined at relatively low grades to depths of over three kilometres. At these depths water inrushes were experienced from surface as well as from fissures and fractures up to one kilometre below surface. Thus during the working life of the mines, inflowing water had to be removed. Initially this was done by bailing, but later when pumps of the required lift became available, by pumping. The water was pumped from settling sumps, launders or dams underground. The pumping cost forming up to 10% of the mines operating costs.

As mining developed and the underground operations became interlinked, so the task of dewatering was carried by fewer mines, usually the deepest mine had to bear responsibility for all the dewatering. Initially water committees were formed, where all the benefactors contributed to the pumping costs and later as some of the members stopped participating, the state became involved, by granting subsidies or giving assistance to cover the pumping costs.

The mines kept fairly careful account of the volumes of water used underground, as well as the volumes pumped from underground. This was to divide the contributions paid by water committee members fairly, or to claim the subsidy from the State which was based on these volumes.

Unfortunately on the Central and Eastern Witwatersrand, too much water was encountered on the mines, so that mining was conducted with little concern for groundwater. It was a nuisance which had to be disposed of as cheaply as possible. Thus no studies of the sources of inflow nor of local aquifers were conducted, there was no monitoring of groundwater levels. All the exploration boreholes that were drilled on the Central and Eastern Witwatersrand record only the reef horizons. Groundwater a valuable resource, being totally ignored.

These facts while giving reliability to the volumes reported by the mines, have made evaluation of inflows and the long term results of recovery difficult.

At the time of writing only two mines were fully operational with four other mines operational but not developing new ground. Thus the present dewatering is conducted for very few beneficiaries, making the relative cost prohibitive. Within the near future all mining will stop and water will be allowed to freely flood the mine workings.

This project was initiated at the request of the Government Mining Engineer to investigate the result of the cessation of pumping in the Central and East Rand Mining areas.

The objectives of the investigation were therefore:

- Investigate the rate of water-table recovery in the abandoned gold mines of the Eastern and Central Witwatersrand, upon cessation of pumping from these mines.
- Investigation into processes affecting the quality of the water in these mines and prediction of the likely water quality in fully recovered mines.
- Quantification of possible seepages from these mines upon full recovery of the water table.
- Evaluation of the overall impact on possible further deterioration of the surface water quality in the catchments.

The original aims were paraphrased by Brown (1992) showing where the emphasis was placed from the Department of Water Affairs and Forestry's point of view. This investigation divided the points into questions that had to be answered or investigated. These breakdowns of the project aims are listed for comparison in Table 1.1.

Table 1.1 Project Aims and Method of Investigation

Original aims of the investigation	Paraphrase of original aim by DWA&F	Points investigated by this Project
Investigate the rate of water-table recovery in the abandoned gold mines of the Eastern and Central Witwatersrand, upon cessation of pumping from these mines.	Recovery Investigation of the mechanisms and rate of water-table recovery.	What are the present form of the underground openings? What is the relationship of the underground openings to the surface and near surface geology? What volume is still open underground? How and from where does water enter the mines? At what rate will the water fill the mines, how long will it take for the mines to be filled completely?
	Discharge Identify discharge points and volume.	When the mines have filled completely will the water flow out of the mines? Where will water flow out? What volume of water will flow out?
Investigation into processes affecting the quality of the water in these mines and prediction of the likely water quality in fully recovered mines.	Water Quality Identify factors affecting the quality of the rising water.	What factors affect the water quality in the mines? How and where does the inflowing water quality deteriorate? Surface Degradation Subsurface degradation
Quantification of possible seepages from these mines upon full recovery of the water table.	Predict quality in filled mines.	What will the water quality be when the mines are full and decanting?
Evaluation of the overall impact on possible further deterioration of the surface water quality in the catchments.	Impact Reduction Reduction or control of inflow/outflow water. Water table lowering methods.	What are the potential problems that may develop due to the recovered situation? Re-emergence of springs Mine instability What are the real problems that may develop due to the recovered situation? Recharge of local aquifers. Surface discharge What can be done to reduce the effects or negative environmental impact? Removal of Surface Sources Treatment of Discharge Water Inflow Control

The information from this project should be useful to:

- The Government Mining Engineer

  The results should highlight the extent and necessity of dewatering pumping so that future subsidy grants can be planned.

- The Department of Water Affairs

  Permitting dewatering pumping for new dewatering schemes

  Evaluating the effects of the cessation of pumping on the environment

  Evaluation the overall effect on the Vaal Barrage Catchment.

- The Mines

  For evaluation of potential future mining activity

  Preparing closure applications for dormant mines.

The project has been financed by the Water Research Commission. Many of the mining companies have also shown an interest in this project and have been helpful in contributing data, giving assistance and allowing access to some of their working areas.

1.2 Previous Work

No previous geohydrological investigations have dealt with this area, although the companies involved in mining have assessed the water inflow rates for the purpose of designing their pumping facilities. Numerous minutes and memoranda from technical meetings at the Chamber of Mines deal with predicted rates of water rise and other aspects pertinent to individual mining companies.

First hand observations made by miners and others at the time of shaft sinking and mine development often referred to water inflows, which, in many instances, caused major setbacks to the then developing technology of mining. Day to day events were reported in the South African Mines, Commerce and Industries, a weekly journal edited by O'Flaherty. Numerous interesting reports concerning water ingress to the mines were found in this journal dating as far back as 1903. Other first hand observations are reported by du Toit (1921), Jeppe (1946), Wërdmuller (1986) and de Jager (1986) while Dolan (1961) summarises the problems status as it was percieved at that time. Dolan predicted that because of the intrinsic ingeneuity found in this country, that when water filling of the mines actually becomes a problem, some solution would be found. That time has arrived.

On the East Rand investigations conducted by de Bruin (1991), with the aim of motivating for the establishment of a new pumping station at Grootvlei No 3 shaft, evaluated the rate of water rise in the East Rand Basin. Private correspondence between Fuller-Good (1992) and the Department of Water

Affairs, reported on an internal investigation at Gold Fields of South Africa, which covered similar ground to this investigation but related specifically to the mines in the Goldfields Group. The situation on the Central Rand was investigated by Rolfe (1991) who adequately described the water level and pumping situation up to that date.

Influences on water chemistry associated with mining activity have been investigated by Jones *et. al.* (1988), Kempe (1983) and Wittmann *et. al.* (1977). At the time of investigation by Wittmann *et. al.* (1977) economic rather than environmental issues were important and their report highlighted the situation from the point of view of recovering metals from the leachate streams. Since the 1980's environmental issues have become increasingly important, van der Merwe (1990) highlights some of the recent trends in legislation and control of acid mine drainage in South Africa.

This report is a first attempt to sinthesize the topics of the sources of water flowing into Witwatersrand mines, the resultant water level rise, expected long term results of full mines and the quality of the water in the mines. As many of the mines are defunct, shafts are blocked and working areas are inaccessable, first hand observations and measurements could usually not be made. Thus this investigation has drawn heavily on observations made by first hand observers and uses their sometimes casual, qualitative observations about these issues to build a picture of what has happened. The investigation therefore draws on evidence and clues to arrive at conclusions in a similar way to what is done in police work.

1.3 Structure of the Report

The area under investigation has been divided into the Central and East Rand mining areas, they are geographically, geologically and geohydrologically distinct. Thus because of their differences they have been dealt with separately in this report. The report is divided into two sections, Chapter 3 and it's subsections relate to the situation on the East Rand and Chapter 4 and it's subsections relate to the Central Rand. The differences between the two areas have also resulted in different outcomes from water recovery thus separate conclusions, recommendations and management plans are presented for each of the areas.

As far as possible the figures, diagrams and summary data tables have been included in the text at the relevant position. This enables the reader to refer directily to the information without unnecessary cross referencing, this approach has also kept the Appendices to a minimum.

Most of the data presented is in summary form. All the data generated by this investigation is stored on computer disk.

Chapter 2 The Witwatersrand

2.1 Introduction

Mining activity in the Central and East Rand portions of the Witwatersrand basin has been in progress for 108 years. The gold bearing reefs were exploited for 95 kilometres along strike and to depths of greater than three kilometres following a west to east arc from Roodepoort to Springs and from there along a north to south arc to Nigel. As such the area forms only a small portion of the greater Witwatersrand Basin as shown in Figure 2.1.

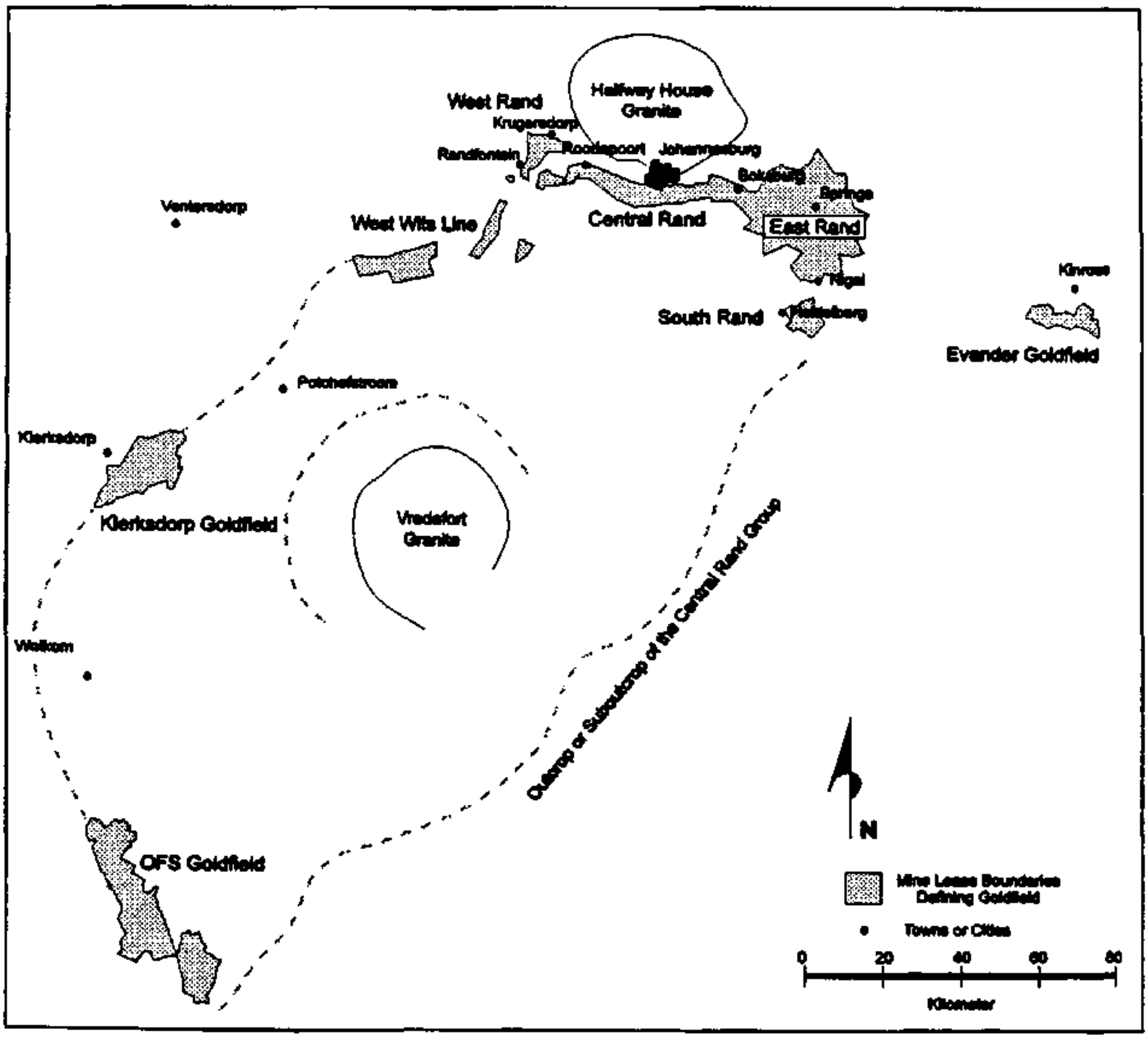


Figure 2.1 Map of the Witwatersrand Basin

During the time of mining many thousands of people have earned their living from the mines and from secondary industries which developed to supply the mines with equipment, to beneficiate the ore, and to provide for the populations requirements. In this way the mines on the Witwatersrand have shaped the economy of this country. At the time of writing many of the mines are worked out, abandoned or have closed down, but the industrial and financial centre that was established continues to dominate the economy. Large companies have been founded on this industry and have accumulated great wealth and power. Through diversification these companies have removed their dependence on the mines for their financial success.

Most mineral recovery is not a renewable process. So mine closure is the inevitable end result of starting a mine.

Mining has an enormous effect on the natural environment, so that there is always a concern about whether the damage is worth the benefits, there will always be a struggle between environmentalists and economists. One hundred years ago when this country was entering its mining age, environmental concerns were not thought about. At that time nobody could have envisaged the size or importance that gold mining would become in this country.

Many of the environmental problems could not have been dreamed about at the beginning of mining. Some of the problems have only been understood since the 1980's, so that in retrospect it is easy to be wise and say that management solutions are better than post operational remedial works (Miller *et. al.* 1988), this philosophy must be applied to new mines which should include planning for, and evaluation of, all known environmental hazards resulting from mining operations.

2.2 Causes of Acid Mine Drainage

Acidic water associated with mining activity has been a long recognised problem, in 1903 it was already referred to as if an established phenomenon concerning pumped water on the Witwatersrand, O'Flaherty (1903). The mechanisms of acid generation have been investigated and described by many authors and will not be dealt with in detail in this report. Descriptions of the processes are given by Stumm *et. al.* (1981) and Steffen *et. al* (1990). Specific descriptions of the phenomenon in South Africa are given by Jones *et. al.* (1988), Kempe (1983), Van der Merwe (1990) and Wittmann *et. al.* (1977).

The Witwatersrand Supergroup sediments contain varying proportions of sulphide minerals, the predominant sulphide being pyrite (FeS_2). In many of the gold bearing reefs this mineral may form up to three percent (by weight) of the rock, other sulphides such as pyrrhotite (FeS), arsenopyrite (FeAsS), chalcopyrite ($CuFeS_2$), galena (PbS), cobaltite ((Fe,Co)AsS) and gersdorffite (NiAsS) occur as traces.

Various textural forms of pyrite occur, some are more susceptible to weathering breakdown than others, for example the Kimberley Reef, which has a higher pyrite content than the other reefs, also has a much higher buckshot pyrite content than the other reefs. Buckshot pyrite grains usually consist of a mass of small (often less than 1 micrometer across) pyrite crystallites, each is surrounded by phyllosilicates, giving the buckshot grain a porous appearance. Because of this they have a very high surface area and are more reactive than the more dense pyrite crystals found in other reefs, thus they could enhance water quality deterioration.

Mining of the Witwatersrand Supergroup sediments has produced; on surface rock piles, sand and slime dumps, underground backfilled rock piles and spoil heaps in stopes and haulages, left by abandonment of mines. These all contain pyrite which is now exposed to air and water and oxidises. Due to this oxidation and subsequent precipitation of secondary iron oxide minerals and mineraloids the rocks and accumulations have characteristic red and yellow staining and discoloration. Water that has passed through such accumulations is characterised by lower pH, and elevated concentrations of metals in solution.

According to Stumm *et. al.* (1981), atmospheric oxidation initiates the reaction, the sulphidic component (S_2^-) in pyrite is oxidised to sulphate (SO_4^{2-}), whereby acidity (H^+) is generated and ferrous iron (Fe^{2+}) ions are released, this reaction is depicted in chemical reaction 2.1.

$$FeS_{2(s)} + \tfrac{7}{2}O_2 + H_2O \longrightarrow Fe^{2+}{}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + \underset{Acidity}{2H^+}{}_{(aq)} \quad \ldots\ldots 2.1$$

Once the reaction has been initiated ferrous iron (Fe^{2+}) is oxidised to ferric iron (Fe^{3+}), this reaction is very slow but its rate is increased by microbial catalysis. The chemical reaction is shown in 2.2.

$$Fe^{2+}{}_{(aq)} + \tfrac{1}{4}O_2 + H^+ \xrightarrow{Bacteria} Fe^{3+}{}_{(aq)} + \tfrac{1}{2}H_2O \quad \ldots\ldots 2.2$$

The ferric iron is then hydrolysed by water to form the insoluble precipitate ferrihydrite ($Fe(OH)_3$) and more acidity, shown in reaction 2.3.

$$Fe^{3+}{}_{(aq)} + 3H_2O \longrightarrow Fe(OH)_{3(s)} + 3H^+ \quad \ldots\ldots 2.3$$

Thus the oxidation of pyrite is one of the most acidic of all weathering reactions since from one mole of pyrite, four moles of acidity are released.

In addition to reacting directly with oxygen, pyrite may also be oxidised by dissolved ferric iron to produce additional Fe^{2+} and acidity. As shown in reaction 2.4.

$$FeS_{2(s)} + 14Fe^{3+} + 8H_2O \longrightarrow 15Fe^{2+}{}_{(aq)} + 2SO_4^{2-}{}_{(aq)} + \underset{Acidity}{16H^+}{}_{(aq)} \quad \ldots\ldots 2.4$$

This means that once the acid generating reactions have begun, oxygen is only necessary for the microbially catalysed oxidation of ferrous to ferric iron. Pyrite will continue to be oxidised, in the absence of oxygen by ferric iron. Thus flooding or sealing acid producing areas in the mines may not stop acid production.

The oxidation of sulphide minerals in backfilled rock piles, uncleared loose rock and ore piles in stopes and other uncleared places underground, and loose fine grained material that has washed or gravity accumulated in mine openings, generates acidity which lowers the pH of the waters flowing through the mines.

The low pH water has the ability to leach other sulphide minerals and some of the oxide minerals in the ore. The other base metal sulphides in the reef in addition to iron, contain elements such as; Ni, Pb, Cu, Co and As, while some of the leachable oxides are uranium bearing. Thus the water has a low pH, characteristic high iron and sulphate content and may also be contaminated with one or more of the heavy or transition metals and uranium or its daughter products.

The presence of precipitated iron oxides, which are evident wherever mine water accumulates or flows underground, suggests that many of the trace metals will be removed from the water since they coprecipitate readily with the iron oxides (Drever, 1982).

2.3 Conceptual Model of the Surface Situation

The conditions and influences on surface have been investigated and reported on by, Marsden (1986), Jones *et. al.* (1988), Funke (1990) and Herold (1990).

At least four investigations, studying various aspects of the surface water quality in this area, were in progress concurrently with this investigation. These were being conducted by Atomic Energy Corporation, Department of Water Affairs and Forestry, jointly by two private consultants as well as a project being conducted by the Germiston municipality in conjunction with Rand Afrikaans University. Co-operation was obtained from some of these investigators. Other, privately funded investigations are also underway at various levels in this area.

Thus for this investigation to superficially address these aspects would be inappropriate. This investigation also shows that a co-ordinated approach is essential, this will only be achieved when all the parties involved in the surface and subsurface hydrology in this area are brought together. The present individual approach is unsatisfactory as it leads to duplication.

2.4 Conceptual Model of the Subsurface Situation

Mining on the Witwatersrand has created sheet-like openings which are continuous laterally and with depth, to maximum mined depths of 3.5 km. In places the mining has followed a braided deposit of high and low gold values referred to as *pay streaks* these have given the stopes a discontinuous structure. In these cases the discontinuous sheet is joined by haulages and drives. The geological structure is that of a basin, with the rim more steeply dipping than the basin bottom, which may be horizontal. On the East Rand the maximum dip is in the order of 30 to 40° with average dip below 10°. On the Central Rand Dips of 60 to 70° can be found with average dip of about 45°.

Where the mine openings dip steeply, the forces are such that even when unsupported, they remain open. In shallow dipping areas, these may also be associated with greater depth as they occur deeper into the basin, the stopes had to be supported to prevent collapse. Cambden-Smith (1993) stated that in some of the Rand Mines deepest workings (3200 mbd) total closure takes place within 5 months. The wooden supports in old parts of mines are completely rotten and offer no support. Most of the very deep, below 1500 mbd, inactive workings can be assumed to have closed completely.

The idea of closure must be qualified using the descriptions of stope fracturing given by Venter (1969), Brand (1986), Gay et. al (1986), and Wolmerans (1986). These are shown in the following Figures 2.2 to 2.5.

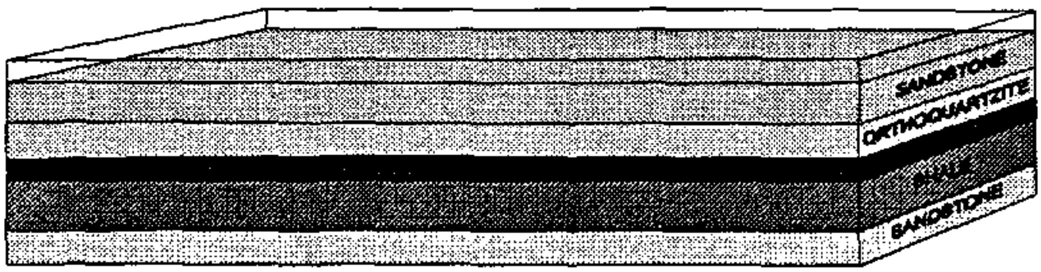


Figure 2.2 Layered sequence of Rocks containing a tabular ore body.

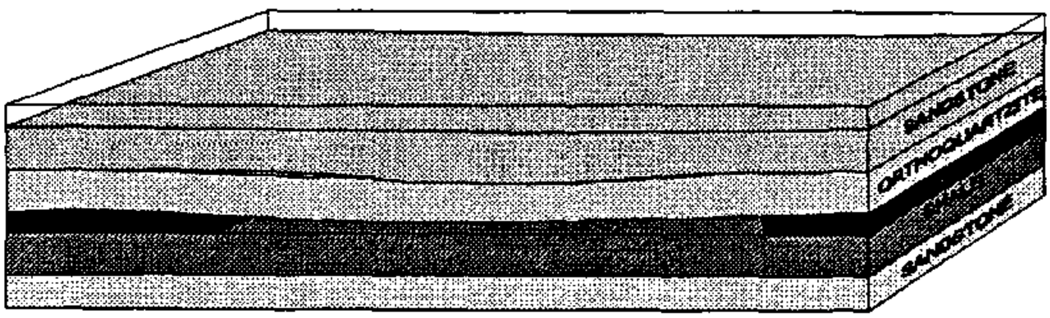


Figure 2.3 The layered sequence with a portion of the ore-body removed showing sagging of the roof rocks.

These figures although highly simplified show what happens on the Witwatersrand. A tabular ore body is removed from a layered sequence of rocks. If unsupported the overlying strata will sag into the excavation. Competent layers will fracture, while incompetent layers will deform plastically, in many cases horizontal fracturing and parting parallel to the bedding occurs between layers of different competency. Rotation around the pivot of fracturing causes tensional fractures to occur in front of the stope and immediately after it. Beyond these the fractures become compressional.

The details are shown in Figure 2.4

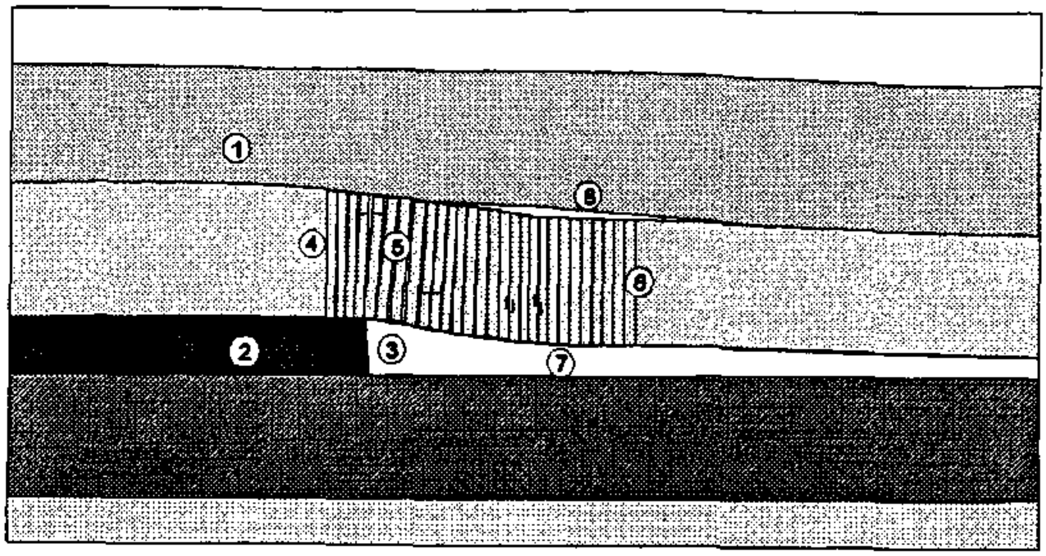


Figure 2.4 Details of fracture and Parting types around a Stope. After Venter (1969).

The numbered points in the figure can be described as follows:

1. Incompetent layers which deform plastically
2. Tabular ore body
3. Stope with ore removed
4. Tension fractures ahead of stope
5. Open tension fractures
6. Compression fractures. These fractures can be very tightly closed, this is shown by their disappearance to the right of the diagram
7. Unsupported stope with sagging roof rocks. Shear movement along fractures gives rise to sagging into the stope.
8. If the geology is layered shear movement may give rise to dilation which may cause opening of geological planes between competent and incompetent beds.

Figure 2.5 shows a more detailed picture of the fractures around a stope.

The numbered points in the figure refer to different fracture types defined by Gay *et. al.* (1986).

1, 2, 3. Extension fractures, due to pulling apart forces similar to those described by Venter (1969)

4. Bedding plane fractures, these cause roof instability
5. Shear fractures, which are mining induced normal faults.

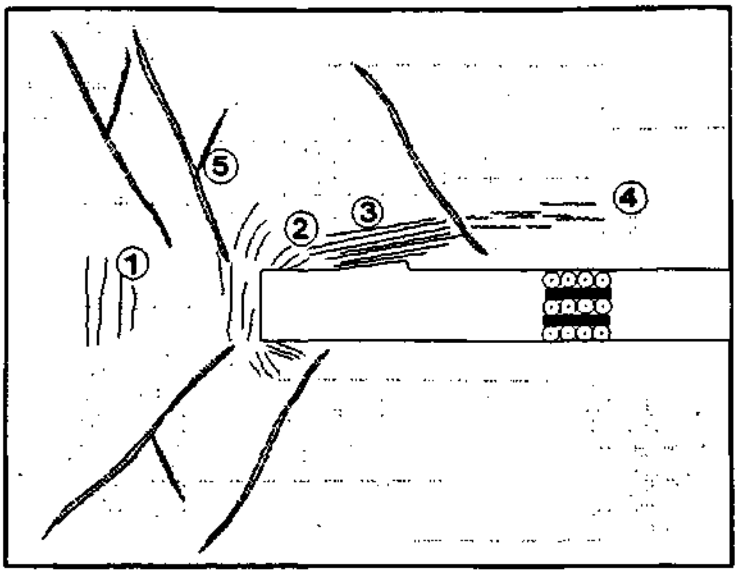


Figure 2.5 Fracturing Around a Stope after Gay *et. al.* (1986)

From this figure it is evident that horizontal fracturing causes roof instability and that fractures are relatively symmetrical around the stope. Thus fractures occur in the footwall as well as the hangingwall of the stope. Stope closure from the floor is termed baulking.

The effect of this fracturing, collapse and baulking is that the mine openings become closed. If significant roof collapse occurs then the volume of the stope will be lost. If the roof does not significantly sag (a situation that holds on the Witwatersrand), then in spite of stope closure, the hollowed out volume remains constant, being spread over a wider zone as, secondary, mine induced porosity in the originally completely solid rocks.

Thus tabular zones of porous rock have been crated within solid impervious rocks by mining. These have the structural relationships of classical confined aquifers. On the East Rand the aquifers have the form of a Basin, while on the Central Rand they are dipping tabular aquifers.

Introductory texts on groundwater such as Hamill *et. al.* (1986) give the following characteristics for confined aquifers:

- The aquifer is a permeable body which is bound above and below by impervious material, the usual example would be a fairly clean washed sand bound by clay layers.

- The aquifer has a recharge area where the rocks are exposed or unconfined.

- The water in the aquifer is under pressure, the pressure head of the supposed recharge area.

- Water will rise in a borehole drilled into such an aquifer to a level termed the peizometric level.

- When the ground surface is lower than the peizometric level, a borehole drilled at such a point would be free flowing.

These characteristics are considered to be oversimplifications, and free flowing boreholes can result from other subsurface conditions. Whether the confined aquifer conditions ever truly exist in nature may be questionable. Most groundwater texts imply, without stating, that these structural relationships hold for primary aquifers in a layered sequence of (probably unconsolidated) sediments. Thus whether these confined aquifer characteristics will become evident for the man-made, hard rock, confined aquifers of the Witwatersrand remain to be seen. For the rest of this discussion however, the mine openings will be referred to as **mine aquifers**, because for reasons discussed above they cannot be viewed as stopes or haulages and while they appear to have confined aquifer relationships, the characteristics have not been proven.

The rocks overlying the mine aquifers are different on the East and Central Rand, and will be described separately.

3.1 Introduction

3.1.1 Background

Underground water has been consistently pumped from the East Rand mining basin since the beginning of this century. From 1963 the mines received state assistance for this purpose but this was withdrawn in 1991. On 17 July 1991 pumping from underground stopped and since then water has been flooding the mines.

The water level in the flooding mine openings has been monitored from two observation points; Sallies No. 1 Shaft and Grootvlei No. 4 Shaft. Water samples were dipped from the rising water within the mines, at the same time that depth measurements were taken.

3.1.2 Method of Investigation

No previous geohydrological investigations have dealt with this area, although the companies involved in mining have assessed the water inflow rates for the purpose of designing their pumping facilities. Numerous minutes and memoranda from technical meetings at the Chamber of Mines deal with predicted rates of water rise and other aspects pertinent to individual mining companies. Mining companies also submitted monthly reports to the Department of Water Affairs and Forestry (DWA&F). This historical data concerning water quality and pumping rates has been used in this investigation together with field investigation to augment the data and for control.

The data was obtained from records kept by the relevant mines, the Government Mining Engineer, Rand Water Board and the Department of Water Affairs.

Most of the underground workings are inaccessible, thus information about the water flowing into the mines had to be obtained from monthly records submitted to the DWA&F. Consistent records were only available from June 1983 until March 1990. These included the pumped volumes which were calculated from the pump power consumption and water chemistry, which was unfortunately limited to a few select parameters. Thus, neither the reliability of the analyses nor missing parameters could be calculated. Samples were taken at 69 boreholes to establish the groundwater quality distribution and water elevations, where possible. The magnitude of this part of the investigation was contained by concentrating on boreholes located in the dolomite aquifer. Dolomite distribution was based on the most reliable geological mapping available according to Buttrick *et al.* (1992).

Rand Water Board due to their requirement to purify water from the Vaal River Barrage to drinking water quality monitor surface water quality in streams flowing into the Vaal Dam and Barrage. The results of their monitoring, as monthly averages, are published in annual reports. Four of the most recent reports, 1988 to 1991, and one earlier report, 1976, have been used to study ten sampling points on the Blesbok Spruit, five on the Riet Spruit and two other more distant points in the system. Thus a picture of the variability of the surface water quality has been obtained. An additional sixteen samples were taken during this investigation from surface water bodies in the area. Four sites on the Blesbok Spruit, located between The Grootvlei Proprietary Mines Limited (Grootvlei) and Marivale Proprietary Mines Limited (Marivale), which are regularly sampled by Grootvlei, were also included.

Since this area has a high population density, as well as being an area of intense industrial activity, the streams flowing through the area are used for effluent disposal. Effluent that is disposed of, must conform to certain standards and is monitored by the Department of Water Affairs. Companies or municipalities generating such wastes are required to regularly submit details to the DWA&F. These records were made available for this investigation.

3.2 Description of the Investigation Area

The study area is referred to as the **East Rand**, covering 768 km² and including all or portions of the municipal districts of Boksburg, Brakpan, Benoni, Springs, Nigel and Heidelberg. In mining terms the area is referred to as the **East Rand Basin.** It is geographically and geohydrologically distinct from other mined basins on the Witwatersrand. Figure 3.2.1 shows a map which locates the investigation area.

The investigation area is defined by the 2890 and 2930 km South and 70 and 40 km East, grid lines of the South African co-ordinate system.

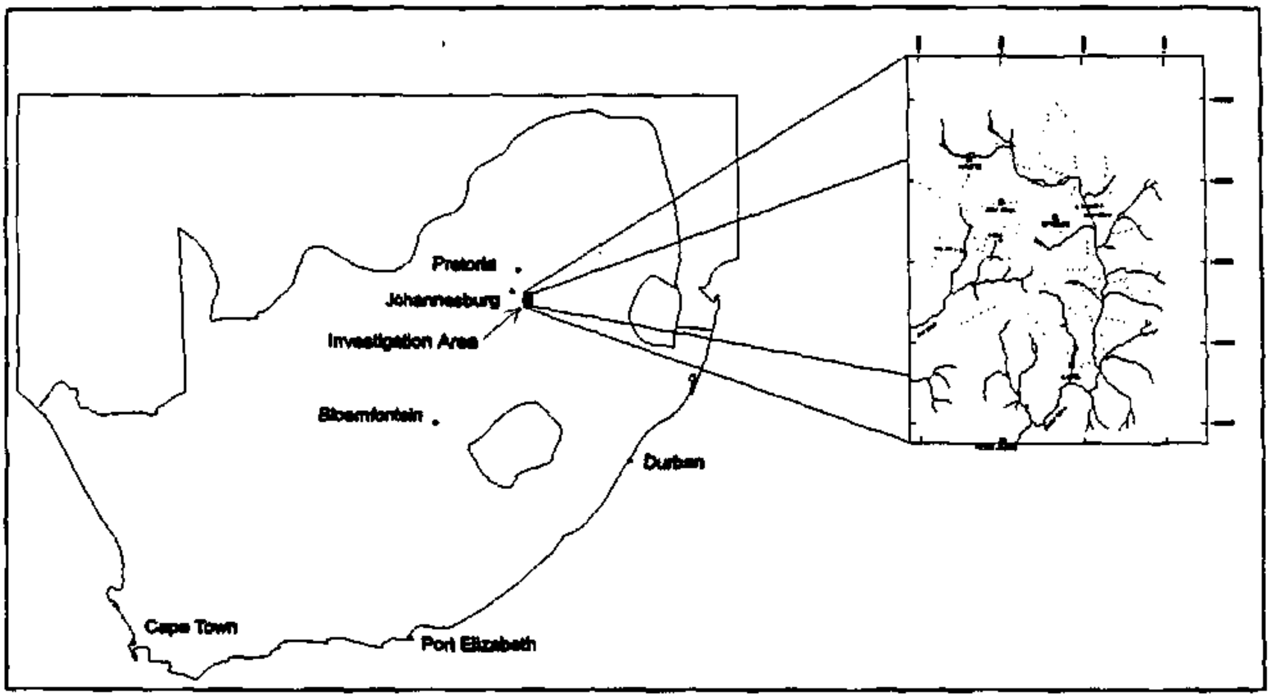


Figure 3.2.1 Location Map of the East Rand

3.2.1 Topography and Surface Hydrology

3.2.1.1 Description of the Main Streams

There are two stream systems draining this area, the Blesbok Spruit system drains the northern and eastern portions, while the Riet Spruit drains the central and western parts of the area. These streams form part of the Vaal River Barrage catchment with the Blesbok Spruit flowing into the Suikerbosrand River and the Riet Spruit joining the Klip River. The Blesbok Spruit catchment covers some 1427 km² while that of the Riet Spruit covers 820 km².

The Blesbok Spruit is the larger of the two streams and, according to the Geological map, flows over alluvium covered dolomite for much of its course through the investigation area. There are numerous small dams on the Blesbok Spruit, predominantly in the north and northwest, these were originally constructed to supply the burgeoning mining area with fresh water, before the

Vaal Dam system was developed. At present they serve as a green belt running through the area where most of the dams are used for recreation. One of these small (1,6 x 0,5 km) dams, the Cowles dam, is located on dolomite.

The Blesbok Spruit flows almost North South through the area of interest for about thirty kilometres, in this distance there is an elevation difference of only 50 m. Because of this low gradient the river is swampy for most of its course through the area. The swamps occur from Cowles Dam to beyond Marivale, a distance of 22 km (17 km on alluvium covered dolomite). The modal width of this swamp is 0,5 km. Most of this reach of the river is choked with reeds, although numerous large pools of slowly moving or standing water exist. The fall over this swampy region is 14 m, i.e. a fall of 1:1571.

The steepest gradients on the river occur South of Nigel, in this region the swamps disappear. Most of the Blesbok Spruit catchment (98.8%) occurs within this area.

The Blesbok Spruit is ephemeral, intermittent flow, at various points during the dry months, depends on effluent disposal. From Cowles dam to the swamps below Marivale the stream flows all year, in spite of high extraction by ERGO and Schoeman Farms. During periods when upstream reaches are dry, this section flows because of effluent disposal into Cowles Dam. Below the Marivale wetlands and bird sanctuary, the stream dries up for much of the year. At Heidelberg, the stream usually flows all year, with input from tributaries outside the investigation area, thus samples taken at this point are not representative of the stream section being investigated.

Although the stream and associated dams have been designated a green belt and hiking trail, most of the sites have been spoilt by the adjacent mine waste heaps, and unofficial dumping. Reclamation and the development of office parks adjacent to some of these sites, is upgrading the area. The Cowles Dam is surrounded by mine wastes and industries, it is used for industrial waste disposal, the water quality in the Blesbok Spruit deteriorates at this point. The high salt content of the water in Cowles dam forms a white precipitate on the sediment at the edge of the dam.

The Riet Spruit drains the western portions of the area and flows Westwards out of the area. Within this area this stream is made up of numerous, small, ephemeral tributaries, these have steeper gradients than are found in the Blesbok Spruit. For example, the stream from Sallies to the Western exit point drops 60 m in 10 km. The catchment in this area represents only 29.4% if the total Riet Spruit catchment. Some of the streams forming the Riet Spruit do not dry up due to recieving seepage from an active slimes dam.

River gauging occurs at two Rand Water Board sampling points in this river system. Both of these are outside the area of investigation, but scatter plots of the recorded flows are shown in Appendix 1.

To understand the variations in the surface water chemistry, the sample positions must be envisaged, these are shown in Figure 3.2.2, along with the drainage network for the area.

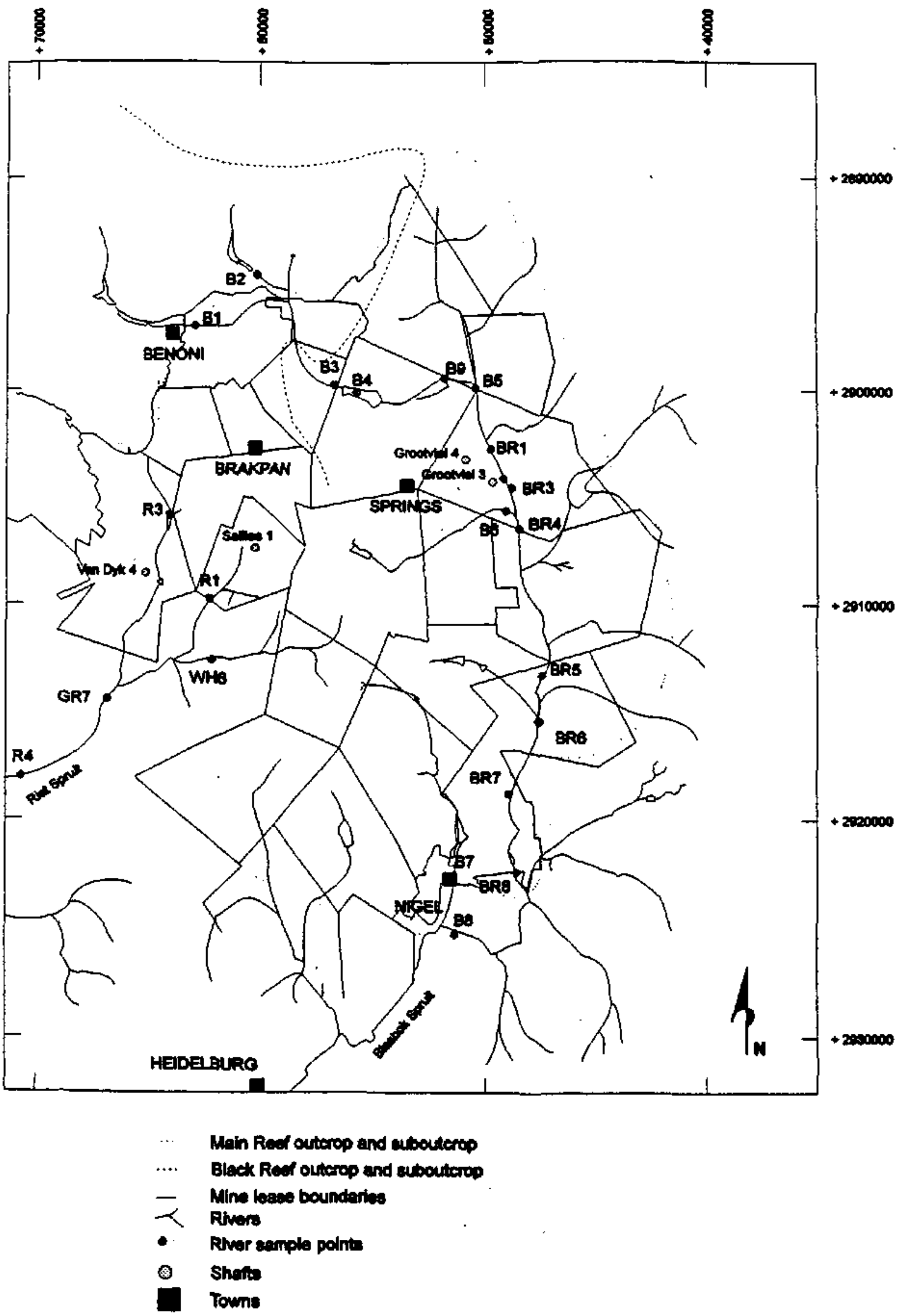


Figure 3.2.2 Location of Sample Points and Drainage Network on the East Rand.

3.2.1.2 Description of the Topography

Most of the area is flat with maximum elevation differences of 120m between the highest point at Duduza and the lowest point, the southern exit point from the area of the Blesbok Spruit.

The flat topography is also shown by the low gradients of the streams as described in the previous section.

The most prominent topographic features in this area are man made, the numerous sand and slimes dumps which have been developed. The original dumps are being reworked and two very prominent slimes dams have resulted from this reworking, in the South and the East of the area.

3.2.2 Climate

The climate in this area is temperate, highveld (Schulze, 1966), with a short cold winter and a hot summer. Rainfall occurs in summer predominantly during thunderstorms experienced from October to April.

At the Vaal Barrage rainfall recording station, located some 70 km South West of this area, records published by the Department of Water Affairs (1985), show that an average precipitation of 700 mm/year is recorded, while the average Symons pan evaporation is 1416 mm/year. Records for the Jan Smuts recording station, some 15 km North West of the area, show that the average precipitation is 732 mm/year with average Symons pan evaporation of 1765 mm/year.

Rainfall records kept by the Grootvlei Mine show an average rainfall at the mine offices of 770 mm/year.

3.2.3 Land Use and Economic Potential

Most of the area lies within 10 Km of the industrial areas associated with Springs and Brakpan and within 20 km of the large industrial areas of Benoni and Boksburg. There are also many mines, their associated villages and waste dumps scattered throughout the area. The predominant land use in the area is urban and suburban development.

The areas where agricultural land has developed are predominantly in the southern parts of the area and around the mining areas where maize and stock farming is practised. More intensive farming using irrigation water from the Blesbok Spruit is practised in some areas above President Dam, below Cowles Dam and southeast of Springs. This is fairly limited due to the lack of appropriate land adjacent to the water rich stretches of the river, most of these areas being occupied by mine waste heaps.

Mining in the area boomed during the 1940's and 1950's but many mines closed down during the 1960's. At present most of the mines are inactive, awaiting closure from the Department of Water Affairs and Forestry, some have been abandoned. The economic situation is closely associated with the depressed mining activity, with many of the former busy light industries having closed, much of the industrial premises were vacant at the beginning of the investigation. Active marketing of the area by the local authority, relatively low rentals and proximity to good infrastructure has reversed this trend during the period of investigation.

The operating Mines in the Area are Grootvlei and Consolidated Modderfontein, Grootvlei is a marginal mine, dependant on state assistance for its continued existence. The economic situation at Grootvlei has been detailed in a report by the Government Mining Engineer (1991), much of the information is confidential.

A few large industries have developed in this area, these are Sappi, Impala Platinum and Zincor, these are all effluent producing industries. The effects of this effluent disposal is monitored by consultants, whose reports are made available to the Department of Water Affairs.

3.2.4 Geology

A generalised lithostratigraphic section giving the geological succession to be expected in this area is shown in Figure 3.2.3. The average thickness of the main lithologies and economic horizons is indicated.

Wagener (1972) describes the East Rand Basin as a relatively shallow, lagoon-like extension of the main Witwatersrand Supergroup[1] Basin. The sediments making up the basin, lie unconformably on pre Witwatersrand basement rocks and have been gently folded. Thus the rocks making up the Witwatersrand Supergroup, in this area, form an asymmetrical, south-west, plunging syncline. Dips on the northern limb are in the order of 45 degrees, while those on the southern limb are in the order of 25 degrees.

In this report the outcrop[2] and suboutcrop[3] of the main reef are often referred to and shown on many of the figures, because these define the extent of the East Rand Basin. Similarly the outcrop and suboutcrop of the Black Reef defines the extent of the Dolomites. Where the outcrop of the Main or Black Reefs coincides with river courses, open reef workings at the surface may be flooded during periods of high river flow.

A geological Map showing the main geological relationships is shown in Figure 3.2.4.

[1]For convenience and reading fluidity stratigraphic nomenclature will often be referred to by name without including the stratigraphic rank except when the omission may lead to ambiguity.

[2] Outcrop means those areas where the rocks being traced, in this case Main or Black Reef, are exposed at surface. At the scale of the maps in this report this is a linear trace.

[3]By suboutcrop is meant linear features that are projected to the surface. These represent contact areas where the rocks abut against or are truncated by younger sediments.

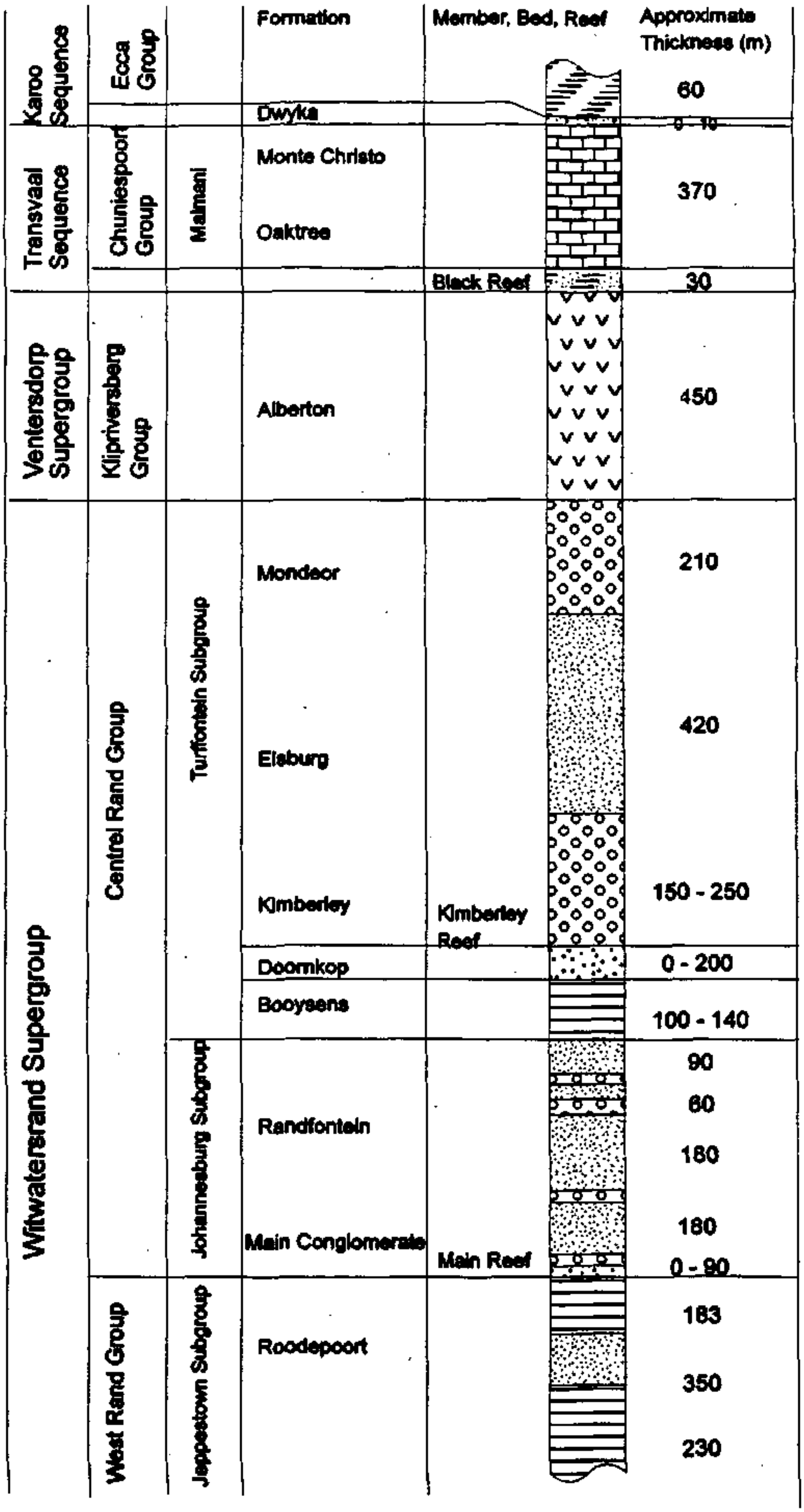


Figure 3.2.3 Lithostratigraphic Section of the East Rand Geology

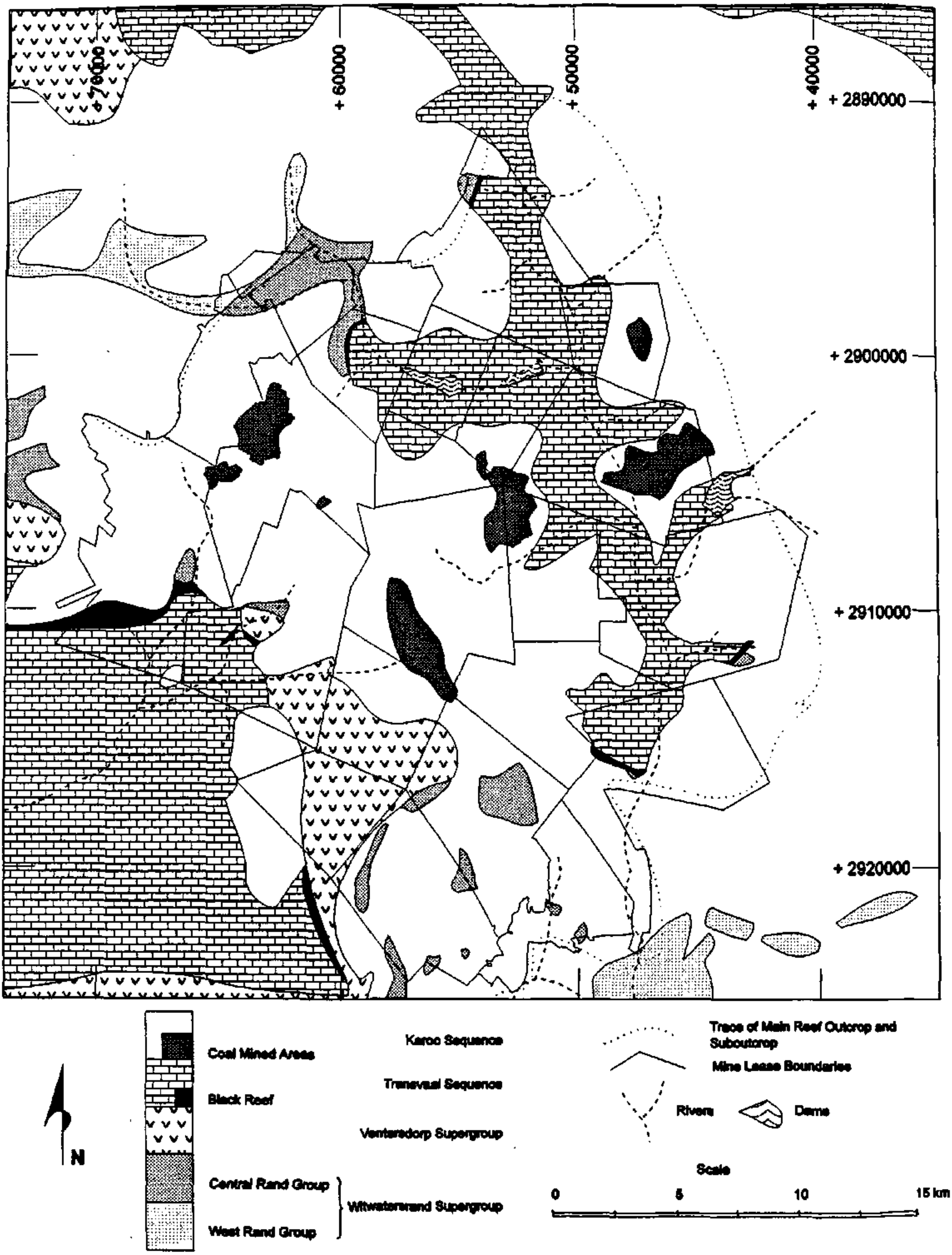


Figure 3.2.4 Simplified Geology of the East Rand after Wagener (1972).

In the Western portion of the study area the Witwatersrand sediments are overlain by rocks of the Ventersdorp Supergroup, which are in turn overlain by the Black Reef Formation and dolomites of the Malmani Subgroup of the Transvaal Sequence. A post Karoo Sequence sill has been exposed by erosion in this area.

The closure of the plunging syncline occurs in the central and eastern parts of the study area. Here Ventersdorp or Witwatersrand rocks are overlain by Ecca Group sediments of the Karoo Sequence. Further east a north-easterly plunging portion of the Transvaal basin directly overlies the Witwatersrand sediments and comprises of the Black Reef Formation and the Malmani Subgroup. Fox (1939) describes the dolomites as a wedge below the Karoo and above the Witwatersrand sediments with average dips of 5° north-east and a depth of 762 metres. In this region these older rocks are predominantly covered by sediments of the Karoo Sequence. Exceptions occur where inliers of Malmani dolomite are exposed in parts of the Blesbok Spruit flood plain.

A section, shown on the geological map as line A-B-C, highlights the vertical geological relationships in the East Rand and is given in Figure 3.2.5.

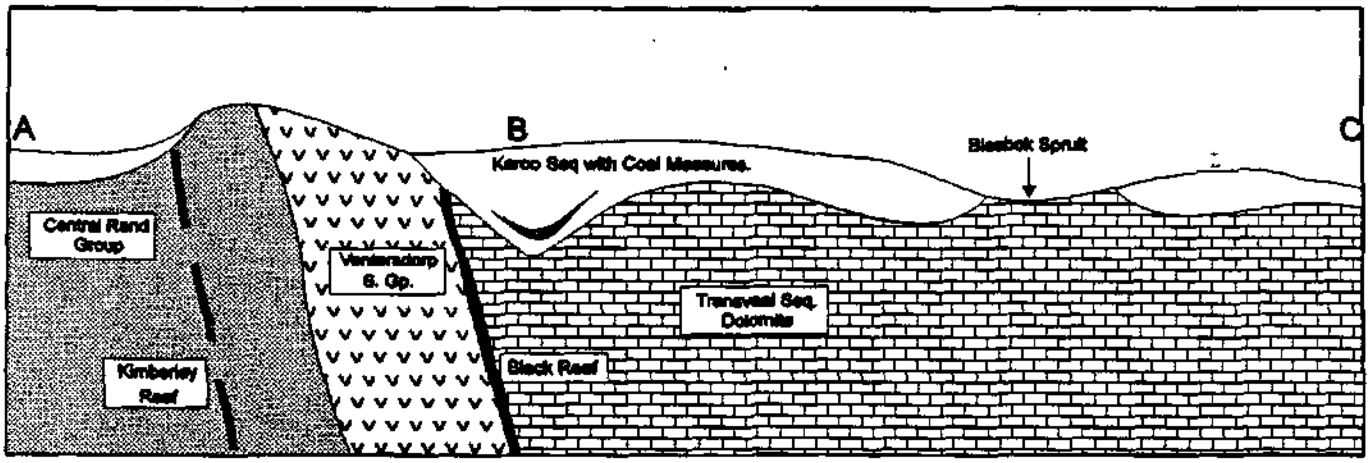


Figure 3.2.5 Geological Section From Spaarwater to Springs to East Daggafontein Mines. Vertical Exaggeration 100×.

Important factors to note from the geology are:

- The distribution of dolomite, which is an important aquifer in the area and supplies much of the water which seeps into the underground workings. Dolomite also has a neutralising or buffering effect on surface and groundwater, thus maintaining a high pH.
- The outcrop areas of Central Rand Group sediments and Black Reef sediments (the base of the dolomites), both of which are regions of surface exploration, trenching and open mining activity.
- The distribution of Karoo sediments. The lowermost sequences consist of diamictite, a very fine grained sediment of glacial origin, which could form a confining layer preventing groundwater from passing through the Karoo sediments.

To summarise:

In the West the Witwatersrand Supergroup sediments are either exposed or overlain by Ventersdorp Supergroup and lower units of the Transvaal Supergroup, with some remnants of a Karoo sill.

In the central portion of the area Witwatersrand Supergroup sediments are overlain by Karoo.

In the north-eastern and eastern sections Witwatersrand Supergroup sediments are overlain by Black Reef and dolomites which are predominantly covered by Karoo.

3.2.5 Groundwater

Two distinct dolomite aquifers occur in the study region:

- One in the northern part of the area overlies the Witwatersrand sediments, it is up to 200m thick (Briggs, 1992). A prominent set of sills occurs in this dolomite below 60m, referred to as the Green Sill. These sills have resulted in the development of a perched water table characterised by relatively shallow water levels. Major fissures occur from the dolomites into the mine workings, these are more significant in Black Reef workings since much of the off reef development is in dolomite.
- The other occurs in the south-western portion of the area, this dolomite aquifer overlies the Ventersdorp supergroup rocks which form a hydraulic barrier between it and the Witwatersrand sediments. The Witwatersrand sediments have not been mined in this area since it is a barren part of the Basin, referred to as the Boksburg Gap. These dolomites are cavernous in places with sinkhole development adjacent to the Alberton/Heidelberg road. These sinkholes are not related to mine dewatering, but, according to Brink (1979), have developed due to poor run-off control and water accumulation in borrow-pits adjacent to the paved road surface. Because this dolomitic aquifer plays little part in the inflows into the mines, most of the attention has been focused on the northern aquifer.

Frommeruze (in Venter, 1934) describes three springs in the dolomites northeast of Springs. Those on the Farms Rietvalei 195, and Olifantsfontein 196 are of significance to this study. He describes the spring as issuing from the dolomite against chert bars. "The flow of these moderately large springs was gauged at 2 cusecs each dropping to 1 cusec during prolonged drought". In SI units these flows are: 0.057 m^3/s and 0.028 m^3/s respectively. In the units more commonly used by the mines, these flows are between 2.45 and 4.8 ML/day. He also shows that small springs issue along streams and rivers where these intersect the water table, in this area these are often swampy and the issues cannot be measured. This holds for some parts of the Blesbok Spruit swamps.

Frommeruze also makes mention of the fractured condition of the dolomites as follows: "During drilling of an exploration borehole on Saltpeterkrans No 362, the Far East Rand B company encountered dolomite at 500 feet (152.4 m). The dolomite was very broken and fissured throughout and contained large amounts of water in the upper portions which flowed away and disappeared into cracks in the lower portions of the same formation."

No other mention of springs is made in this report. Springs township's name may be derived from these springs or from less significant springs that may have emanated in other places in the Blesbok Spruit valley.

3.3 Mining History

Development brought about by mining and the related population growth and construction have affected the natural conditions in the area. The mines are interconnected underground, this has altered the subsurface water flow conditions. Surface conditions have been changed by construction, excavation and waste disposal. Most of the mines are inactive, closed or abandoned, headgears have been removed, shafts are blocked and mining areas are inaccessable. Evaluating historical records has formed an important part of the project, since observations made before surface and underground changes obscured the situation, have been invaluable.

3.3.1 Coal Mining

Numerous small coal mines have been worked in this area, for example:

Table 3.3.1 Coal Mines on the East Rand

Collery Name	Date Closed	Location
Apex	1947	Brakpan
Tyne Valley	1907	
Great Eastern	1909	Springs
New Springs	1937	
Largo	1953	

These collieries have resulted in extensive areas being worked out, directly above the Witwatersrand rocks in the Brakpan area and above the dolomites in the Springs area. One section of the Largo Colliery lies under a swampy part of the Blesbok Spruit near Grootvlei No. 3 shaft.

The workings were all shallow with depths up to 50 m below surface. In some places 3 seams were mined! Such shallow workings have resulted in significant subsidence. On the Great Eastern Collieries subsidence dates back to 1907. Subsidence on the Largo Collieries, in the vicinity of the Blesbokspruit, occurred during 1932 and 1933.

Some of the subsidence has formed broad depressions, which may be permanently filled with water and appear at surface as small pans. In other places deep, vertical sided, or inverted cone shaped collapses have occurred. These are very distinct on aerial photographs, particularly in the vicinity of the Blesbokspruit near Grootvlei No. 3 shaft, where the fields are pockmarked by such collapses. Many of them contain permanent water at a similar depth to the rest water level in near-by boreholes. The subsidences appear to be related to areas within the mines where support was insufficient or rendered insufficient due to pillar robbing.

The Tyne Valley mine's southern development was curtailed by water inrushes and presumably the workings are now full of water. The Largo mine's main shaft, an incline, is full of water. This infers that the rest of the mine will also be full of water. Water production boreholes are recorded on the Largo mine plans, it is probable that they were drilled into the dolomites below the coal measures.

3.3.2 Gold Mining

Gold mining began in the area soon after the discovery of gold on the Witwatersrand in 1886, with the main period of production and development during the 1940's and 1950's. In 1955 there were 24 operating mines and 90 shafts but the fixed gold price and increasing working costs of the late 1950's and 1960's caused many of the mines to close down. The rate of mining company registration and closure is shown in Figure 3.3.1.

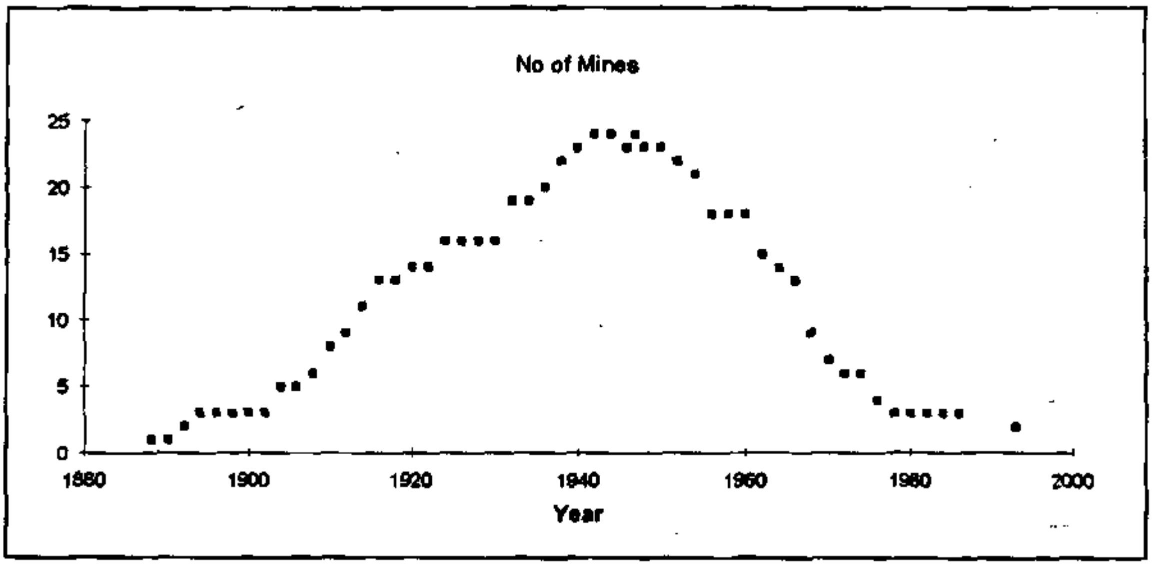


Figure 3.3.1 Plot of the Number of Mining Companies Operating on the East Rand

The main companies involved in mining in this area are shown in Figure 3.3.2. While this figure reflects past mining lease holders, these were the companies responsible for most of the underground extraction. Thus these companies will be referred to more commonly than the more recent lease holders, shown in Figure 3.3.3, many of whom are more involved in surface dump reclamation than mining. The old lease boundaries are used on many of the figures in this report, as a means of location, to relate other features, for example, rivers, to the mine lease boundarys.

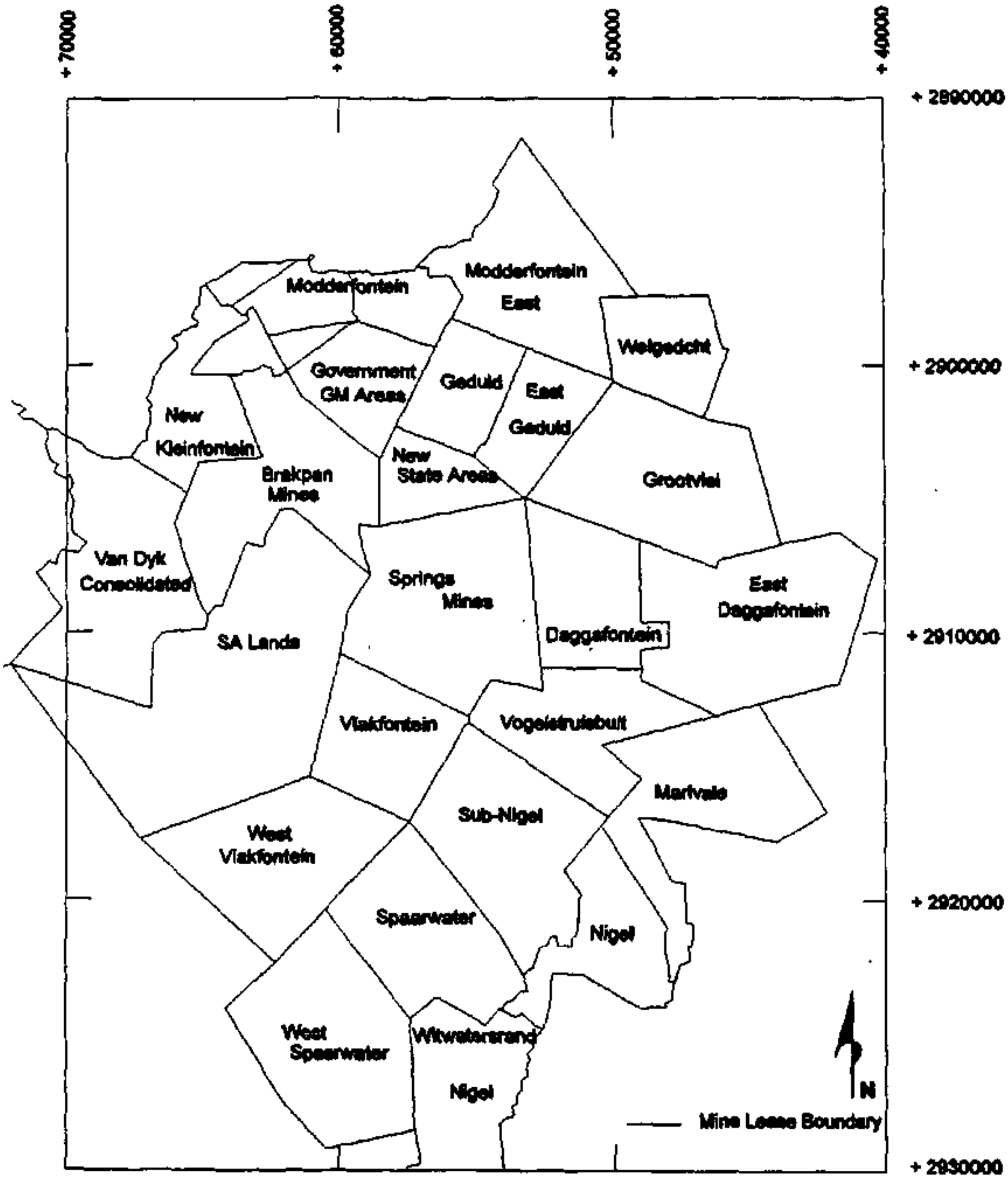


Figure 3.3.2 Mine Lease Boundaries of the 1960's.

Mining was influenced by gold price fluctuations and the devaluation of the Rand, which occurred during the 1980's. Many of the mines changed hands, new mining companies appeared and there was a resurgence of mining activity. Recent lease holders and leased boundaries, based on 1986 data, are shown in Figure 3.3.3. The faltering gold price of the late 1980's caused the demise of most of these companies and today there are only two active mines in this area:

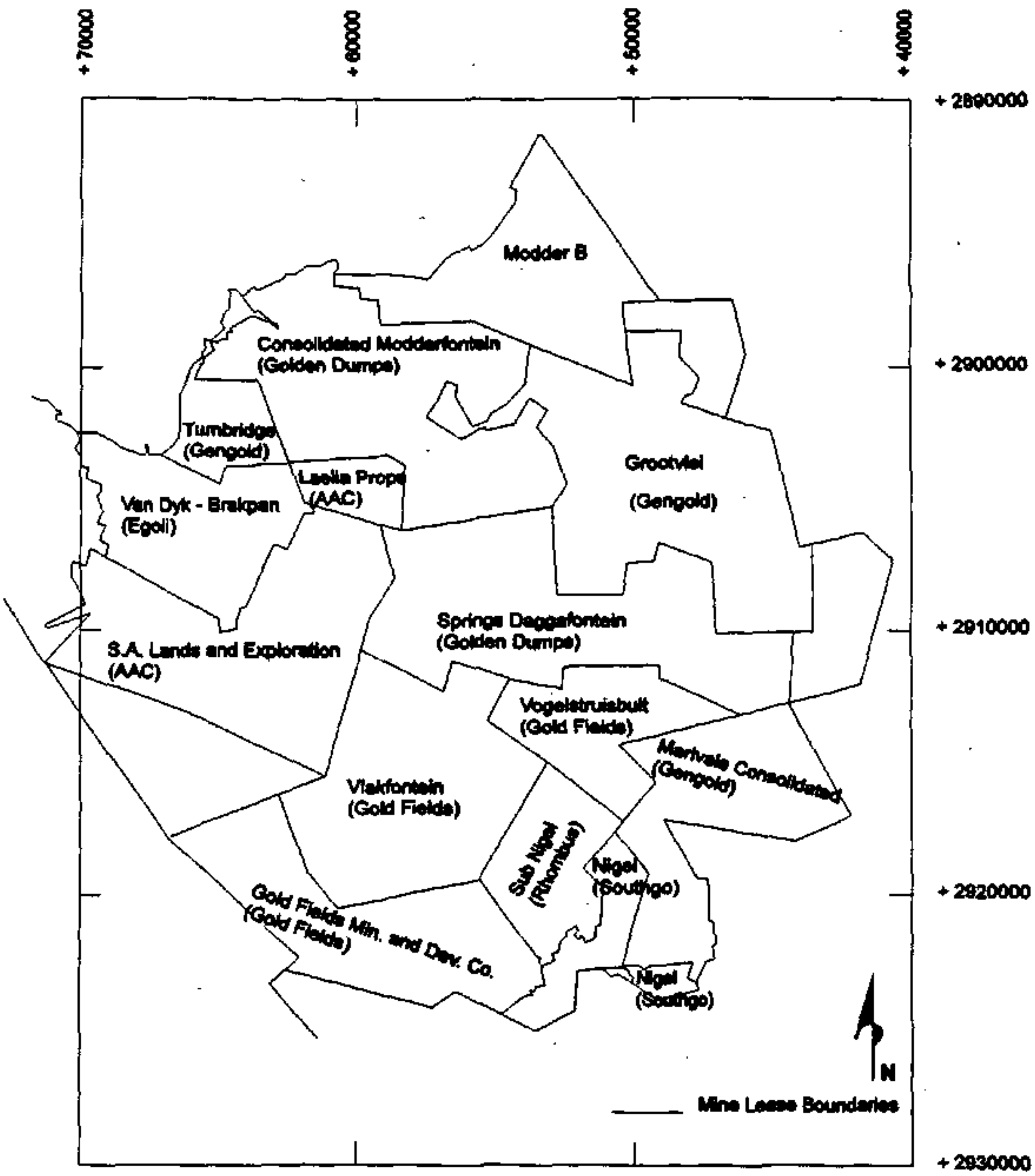


Figure 3.3.3 Mine Lease Boundaries of the 1980's.

- Grootvlei Proprietary Mines LTD with Marivale Proprietary Mines LTD operating as a section of Grootvlei.
- Consolidated Modderfontein Mines LTD (Cons Modder).

Three reefs have been mined:

Reef	Status
Black Reef	Sporadically mined
Kimberley Reef	Incipiently mined (future mining here)
Main Reef	Extensively mined (mined out)

Figure 3.3.4 shows the extent of stoping on Main Reef, which is almost mined out and has little future economic value.

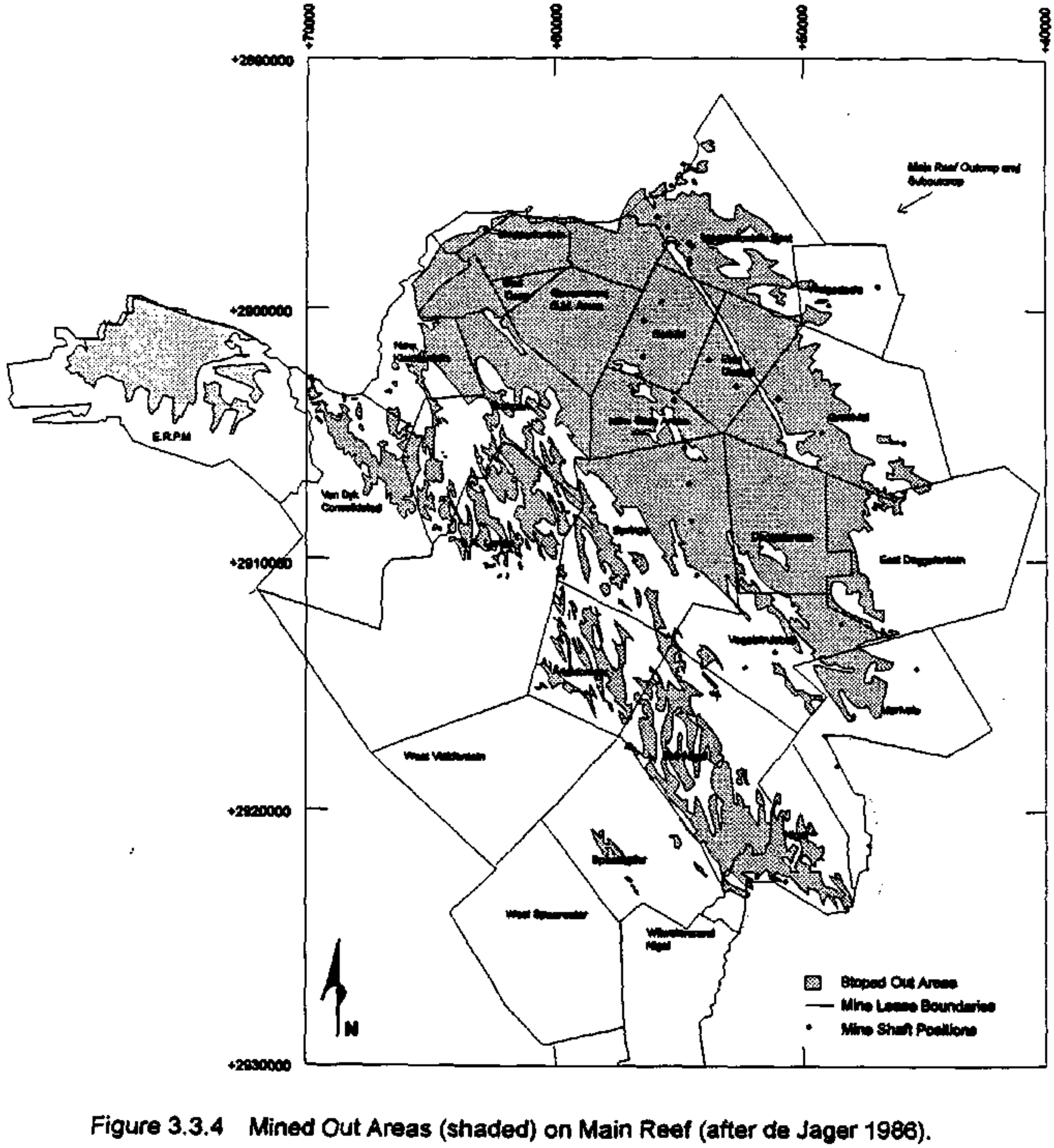


Figure 3.3.4 Mined Out Areas (shaded) on Main Reef (after de Jager 1986).

Kimberley Reef is being mined and developed, at Grootvlei an estimated mining life of 5 years is envisaged and 6 years at Cons Modder. Figure 3.3.5 shows stoped out areas on Kimberley Reef.

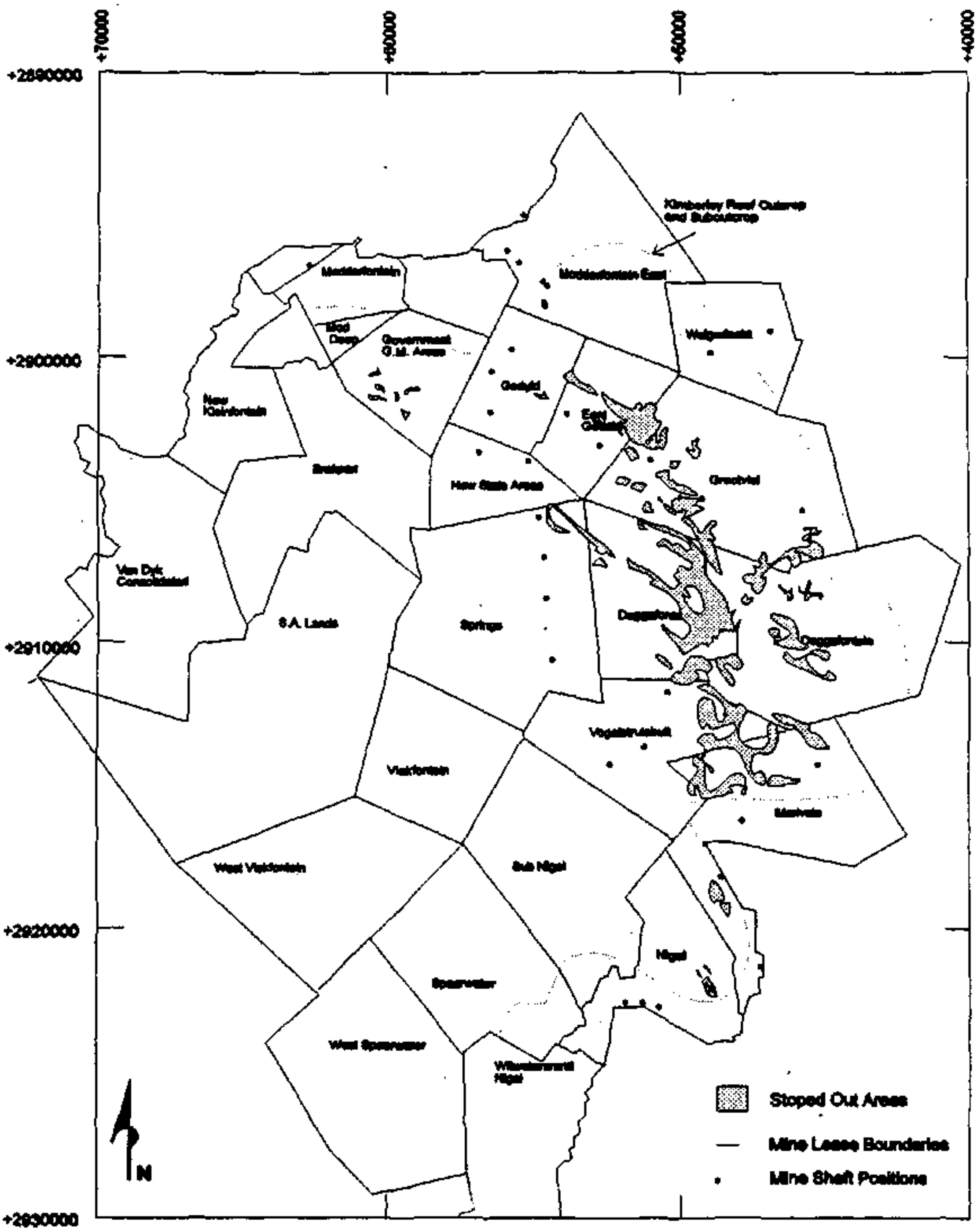


Figure 3.3.5 Mined Out Areas (shaded) on Kimberley Reef. (After de Jager 1986).

Black Reef was extensively mined on Government Gold Mining Areas and Geduld Mines and is now mined on a limited scale by Cons Modder and Grootvlei. Marivale were in the process of closing down, taking out support pillars and reclaimable scrap metal as they retreated, at the beginning of this project. The operations finally stopped on 31 July 1993.

A number of companies are reworking the numerous dumps in this area, the largest company involved in this activity being East Rand Gold and Uranium

Company (ERGO). The result of this processing has been the disappearance of some of the scattered, smaller dumps and the development of a centralized disposal approach. At present two, very large, slimes dams are accumulating in the eastern and southern parts of the study area, with a total area of 11.5 km².

The long term result of mining has been the excavation of underground basins which follow the undulations and shape of the reefs. On Main Reef basins at three different levels have developed, these are shown in Figure 3.3.6. The deepest workings in the Far East Rand Basin were developed by Vlakfontein at 2464 meters below datum (mbd)*. On the Kimberley Reef, some 600 m above Main Reef, a basin which corresponds to the East Rand Basin, has developed. This is the only basin on Kimberley Reef since considerably less mining has taken place on this reef.

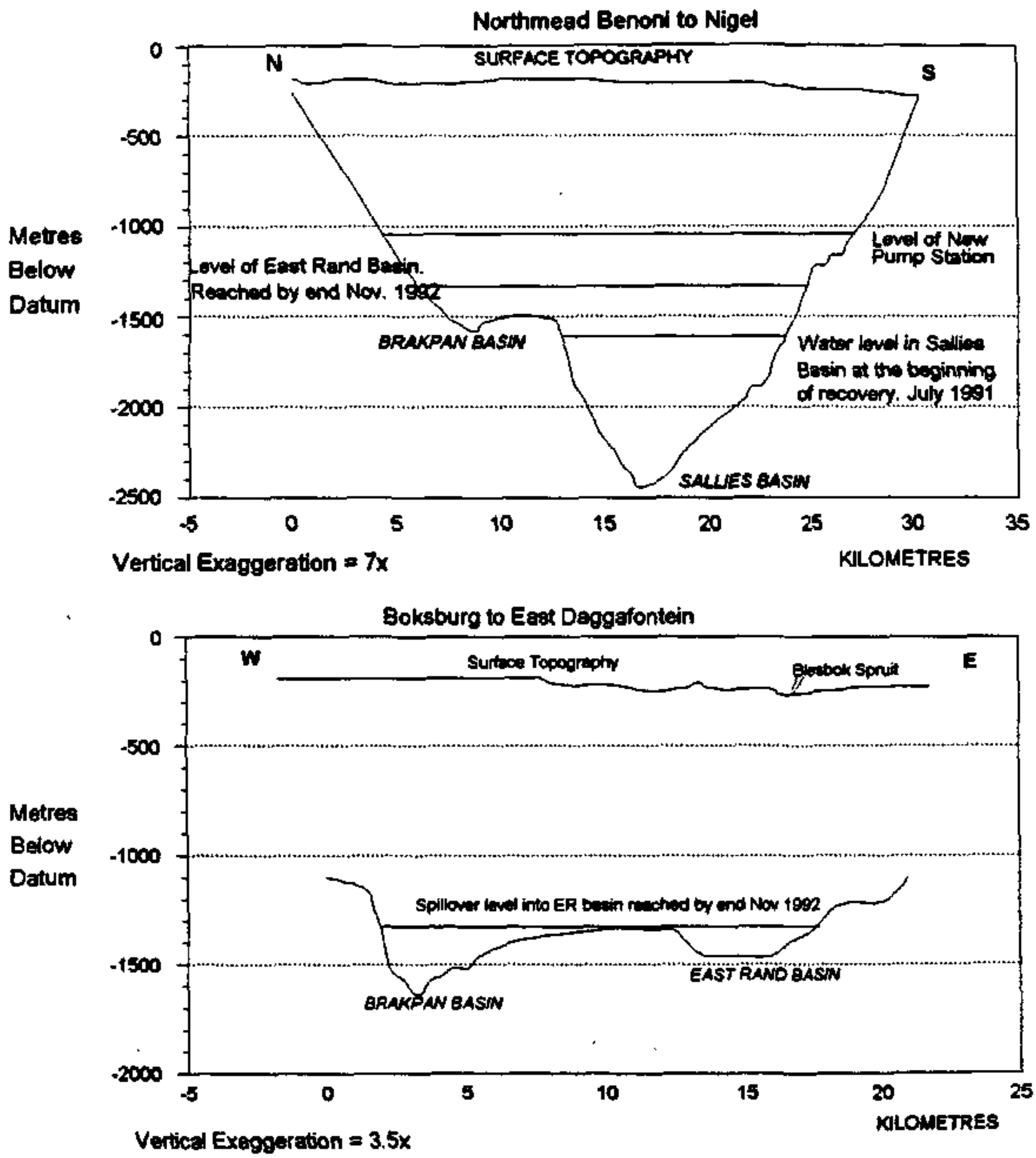


Figure 3.3.6 Sections Through Main Reef, Showing Basin Development.

* Datum = 1828.8 mams.

3.3.3 Pumping History

Records of water ingress into these mines dates back to 1909 when Grootvlei abandoned the sinking of their No. 1 shaft at 112 meters due to an estimated 10 Ml/day ingress. Further development by Grootvlei was abandoned at that stage due to lack of funds.

Most of the mines in this area have had to pump water from underground, to either dewater areas where development was intended or to keep the existing workings from flooding. The water was pumped from settling sumps, launders or dams underground at enormous cost to the mines. Dolan (1961) noted that as mining became deeper so more water had to be pumped, he quoted figures[1] which are shown in Table 3.3.2, along with more recently recorded volumes[2] and estimates[3] made by du Toit (1921), for comparison.

Table 3.3.2 Pumping Rate to Dewater East Rand Mines.

Period	Pumping Rate Ml/day
1916 to 1920[3]	38
1925 to 1931[1]	31
1952 to 1959[1]	93
1983 to 1986[2]	58.22
1987 to 1990[2]	63.65

The increase in pumped volume in the 1950's was due to the fact that the number of mining companies increased as shown in Figure 3.3.1. Along with the increase in mining companies went an increase in the volume and extent of mining, thus more water inflows were intersected.

The period of the 1950's was the time of greatest mining activity on the East Rand, when active development was taking place. Thus the mines depth was increasing. This gives the impression that the cone of influence increased as mining became deeper, drawing on a wider and thus greater source of water. When mining stops the reverse will happen in other words the rate of recharge will reduce as the mines fill up.

As mining developed and the underground operations became interlinked, so the task of dewatering was carried by fewer mines. Those mines operating in the deeper parts of the basin had to continually pump large volumes of water, while those located nearer the perimeter of the basin pumped relatively insignificant volumes. Water committees were formed, so that all the benefactors could contribute to the pumping costs. With time, as mines closed down and some of the members stopped participating, the state became involved, by granting subsidies or giving assistance to cover the pumping costs. The mines kept fairly careful account of the volumes of water used underground, and pumped from underground, because the relative contributions paid by water committee members, or amounts of subsidy recieved from the State were based on these volumes.

From the mid 1960's when many of the mines closed down, water was allowed to flood the lower workings. Pumping to dewater the reefs was left to Grootvlei, S.A. Lands and Exploration Gold Mining Company (Sallies) and Vlakfontein Gold Mining Company (Vlakfontein). The pumping costs were subsidized by the government from 1963 onward. During the 1950's Sallies was not a very wet mine, pumping only 1.8% of the water from the East Rand Basin. As the basin was developed Sallies was left to pump larger volumes, the pumping capacity at Sallies was increased repeatedly, until in 1966 most of the water from the East Rand Basin was pumped from Sallies. In 1967 a main pump station was established at Sallies No.1 shaft with Sallies, Grootvlei and Vlakfontein contributing to the capital cost and the government paying for most of the operating costs. This pump station, located at 1548 mbd, was capable of keeping the water level, in the whole basin, at 1606 mbd. The water had not reached this level at that stage and pumping was achieved in two stages using a pump station at No. 3 sub-vertical shaft and the main pump station in No. 1 shaft.

In December 1976 Sallies closed and Grootvlei took over the management and operation of the pumps. Vlakfontein closed on 4 November 1977 and their deeper workings were allowed to flood. By late 1979 the water level had reached 2170 mbd, the water level was rising at a steady rate of 0.2 meters per month as shown in Figure 3.3.7. At this time, all dewatering of the Main Reef Basin took place at Sallies No. 1 shaft, with Grootvlei pumping from the Kimberley Reef Basin at their No. 3 and 4 shafts. By the beginning of 1988 the water level was maintained at 1606 mbd.

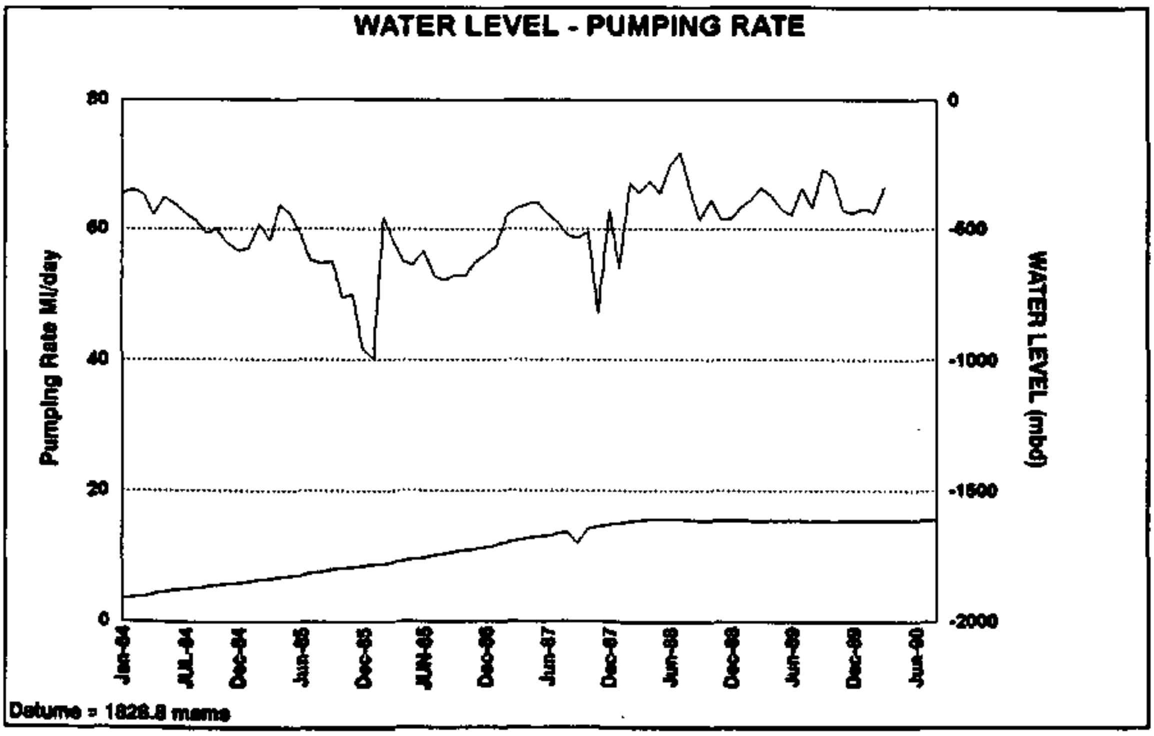


Figure 3.3.7 Water Levels and Pumping Rate at Sallies No. 1 Shaft

In 1985 the Government suspended the pumping subsidy. The Far East Rand Water Committee was formed by the existing mines in January 1986. This committee was able to persuade the government to reinstate the subsidy and the status quo was maintained until September 1990. At that time Sallies took over the pumping operation and were granted a 35% increase in subsidy. A request to increase the subsidy by a further 50% (to R1 500 000.00 per month) was considered to be unreasonable and the Government asked that alternative schemes to keep the mine workings open be investigated. Such alternatives were investigated by Grootvlei, who submitted a thorough report of their findings and proposals to the Government Mining Engineer (GME). This report forms the bulk of GME (1991).

Pumping stopped at Sallies No. 1 shaft on 27 July 1991, while Grootvlei continued to pump until the present, albeit at a reduced rate. All the water from this most recent pumping has been used in their metallurgical plant and no records have been submitted, however De Bruin (1992) has estimated the amount to be 5 Ml/day.

3.3.4 Dewatering of the Reefs

As the basins are at different levels, water flowing underground collects in one basin and cascades into a lower basin. The volumes of water flowing in this way have been estimated by Lain (1992) and are shown in Table 3.3.3.

Table 3.3.3 Pumped Water Volumes.

Water inflow Position	Volume Ml/day
Water entering the Kimberley Reef	42
Water pumped from Kimberley Reef	-22
Water flowing down shafts to East Rand and cascading to Brakpan Basins	20
Water entering the Brakpan basin directly	+37
Water cascading to Sallies Basin	57

According to these estimates a total of 79 Ml/day are pumped from the system. These flows into the mines are spatially shown in Figure 3.3.8.

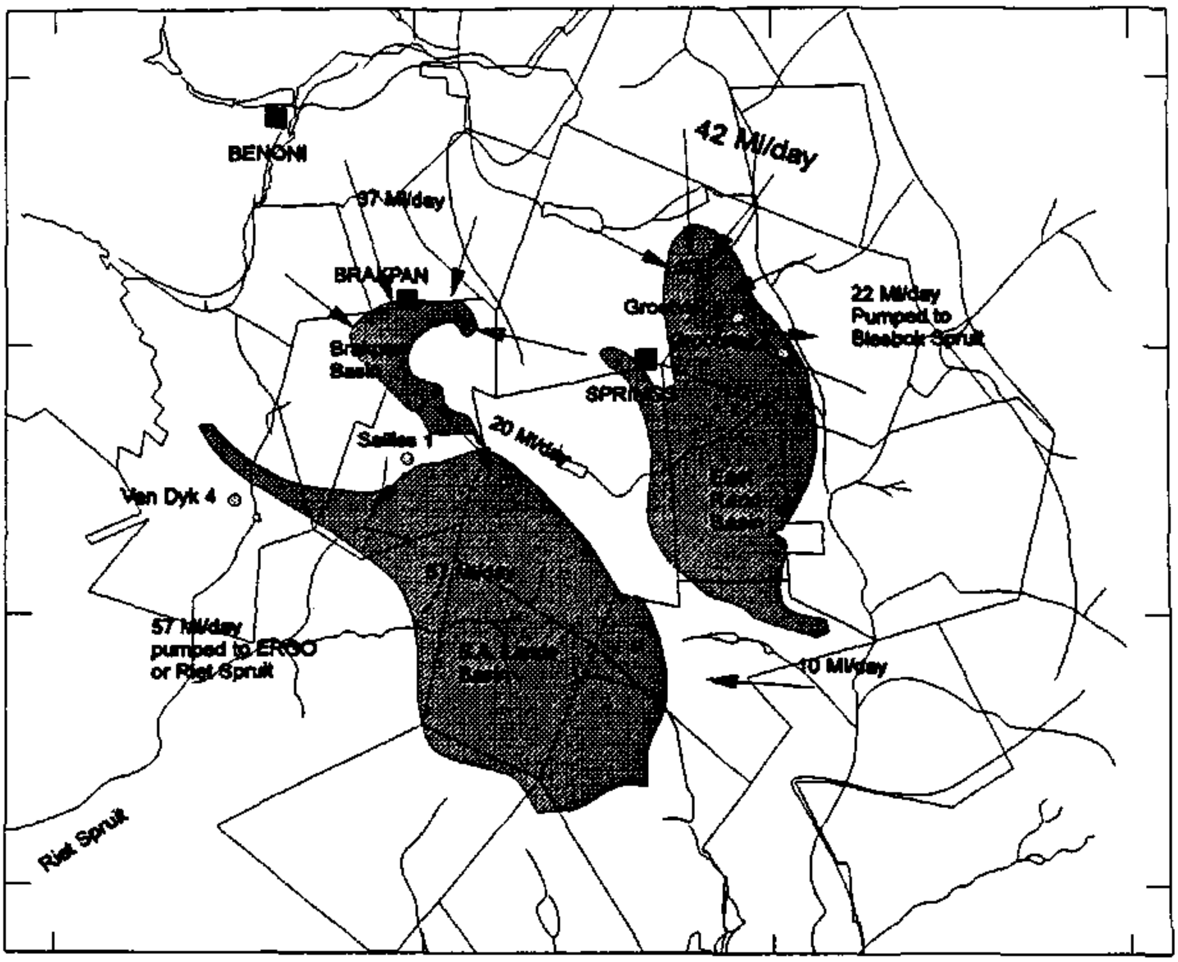


Figure 3.3.8 Water Flows Into and Out of East Rand Basins

Monthly reports giving the volume of water pumped and the chemistry of the water were submitted to the Department of Water Affairs by the company responsible for pumping. Fairly consistent records are available from 1983 to 1990. Averages calculated from these records are somewhat lower than the volumes shown above.

These records show that:

- Before 1988 when the water was still rising in the Sallies basin, **45** Ml/day were pumped from Sallies No. 1 shaft and **14** Ml/day were pumped from the Kimberley Reef at Grootvlei No. 3 and 4 shafts.
- From 1988 while the water level was constant in the Sallies basin, **53** Ml/day were pumped from Sallies No. 1 shaft and **11.5** Ml/day were pumped from the Kimberley Reef at Grootvlei No. 3 and 4 shafts.

Thus, over a period of almost 3 years when the water level was maintained at 1606 mbd the average extraction from the system was **64.5** Ml/day.

The areal extent of the basins is shown in plan in Figure 3.3.8, and Figure 3.3.9 shows the three dimensional relationship of the basins with the base of the dolomites and surface topography drawn to the same scale.

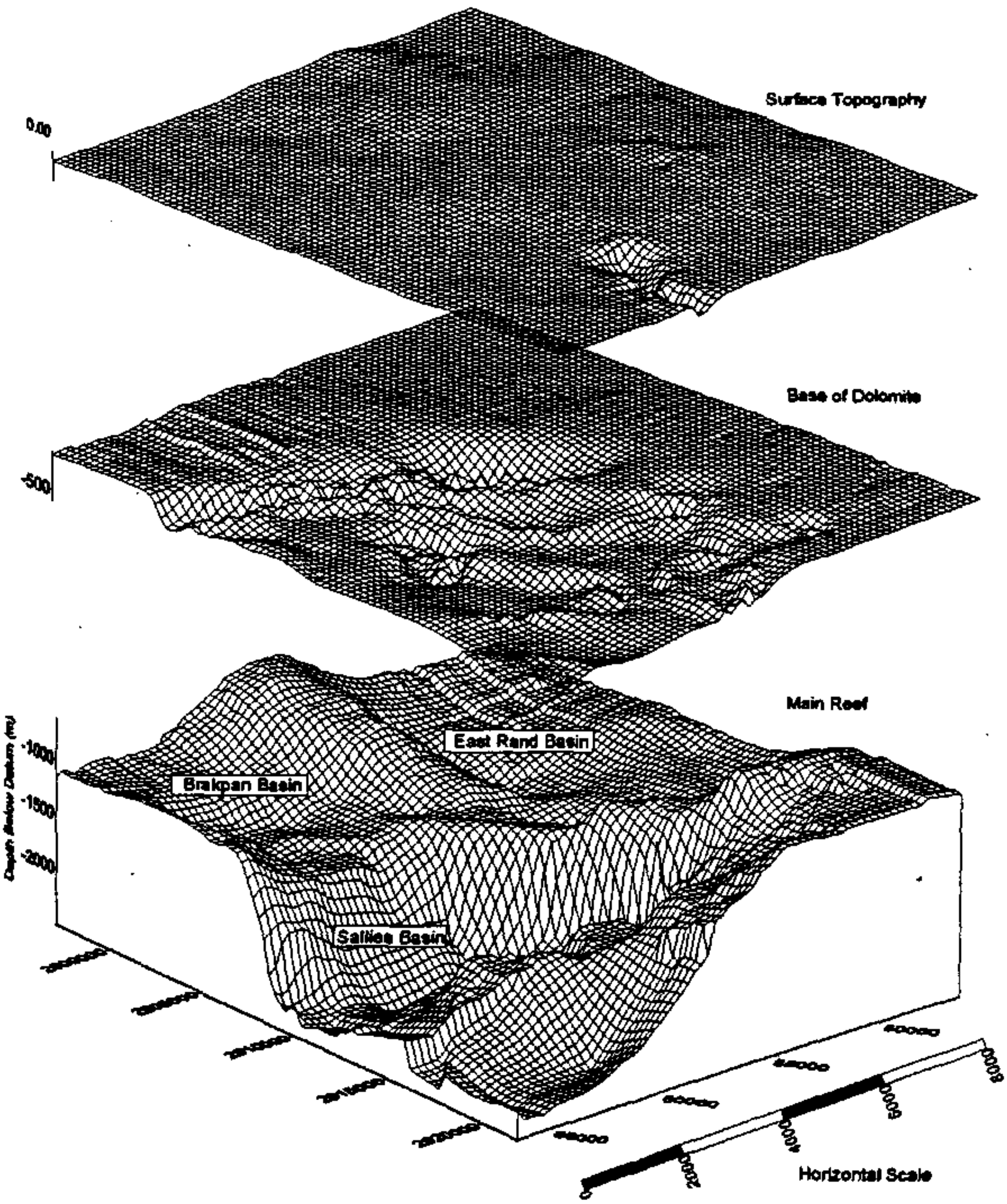


Figure 3.3.9 Three Dimensional Relationships of: Main Reef Basins, Base of the Dolomite (Black Reef) and Surface Topography.

3.4 Recovery

3.4.1 Source of the Water

3.4.1.1 Inflow Observations

At the beginning of this investigation, it was stated by Biggs (1992), that most of the inrushes to the mines were derived from the dolomites. Most of the mines in this area are inaccessable and first hand evidence for this statement could not be found. Thus a literature survey was conducted in an attempt to find out what observations had been made during mine development, the result of this survey gives indirect evidence that confirms Biggs' (1992) observations.

There is very limited outcrop of Witwatersrand sediments in this area, so direct recharge to the mine aquifer is either negligible, or limited to periods of excessive flooding along the upper reaches of the Blesbok Spruit, where outcrop does occur. For example, in 1972, following torrential rains on the East Rand, excessive inflows to the mines occurred, water flowed down outcrop workings and sinkholes in the old Black Reef workings on Government Gold Mining Areas (Anon 1988). In the clean-up operation following the flood protective burms were bulldozed into place and mine openings were blocked to prevent the recurrence of such inflows. This freak flood was the heaviest rainfall recorded in the area this centuary and it took Sallies two years to re-establish the pumping levels that they had maintained before the flood.

Direct recharge is reported to occur on Consolidated Modderfontein after heavy rainfall Griffiths (1994) while a steady source of inflow is thought to be derived from the swamps on the Blesbokspruit via a fault zone. In spite of this observation it must be noted that the Witwatersrand rocks are overlain by dolomite and that water derived from the swamps must still flow via the dolomite. The swamp area therefore forming part of the dolomite recharge.

In the discussion of the geology it was shown that most of the Witwatersrand sediments are covered by Ventersdorp Supergroup lavas, dolomites of the Transvaal Supergroup and clastic sediments of the Karoo Supergroup. The dolomites may extend from surface to more than 400m below surface as shown by du Toit (1921), Papenfus (1964) and Wagener (1972). They form a good aquifer in this area, which is exploulted for agricultural irrigation and private garden use by numerous boreholes. Water levels, measured in the dolomites during this investigation, give an average depth of 14.5 m below surface. When the Grootvlei No. 1 shaft was abandoned in 1910, due to water inrushes, it filled with water to a depth of 15 m below surface, this suggests that water levels in the dolomitic aquifer have changed little even after 80 years of mine pumping.

Du Toit (1921) claims that in most of this area the dolomites have been intruded by a post-Karoo aged sill which follows the dolomite basin morphology. This sill, an olivine dolerite, weathers rapidly when exposed in underground excavations. Many of the water inrushes, encountered during shaft sinking, were related to sills. Later investigations by Ellis (1940, 1943, 1944 and 1946), Brandt (1950), Antrobus *et. al.* (1964) and Grohmann (1988) have shown that the relationships of intrusive rocks are not as simplistic as described by du Toit (1921), but that numerous intrusives of different age and structural relationships can be identified. The relationship between sills and water inrushes is however more relevant to this investigation than the detailed classification of the intrusives, therefore du Toit's (1921) observations are significant.

Du Toit (1921), Jeppe (1946) and de Jager (1986) record that during mine development and shaft sinking most of the significant inflows encountered by the mines were derived from the dolomites. Some of the largest inflows have occurred from East Geduld No 1 shaft and at Grootvlei. Many inflows, coming directily from the dolomites occurred within the first 100 to 150 m below surface, it has been mentioned that these were often associated with sills, which occur at about that depth. Unfortunately most of the mines in this area are now inaccessable, but significant inflows were found issuing from the dolomites at Consolidated Modderfontein No 8 shaft at 30 to 50 m below surface and at Government Gold Mining areas.

Dolan (1961), lists each of the mines annual pumping rate from 1952 to 1959, an active period of mining activity when individual mines were responsible for their own dewatering. These figures are given in Table 3.4.1. If the dewatering figures are compared with the relationship to the dolomites, it can be noted that the wettest mines (those that pumped the most) are overlain by dolomite. If the shafts are related to the dolomites, as is shown by geological mapping, then twelve of the nineteen mines (about half of the area leased to mines) are overlain by dolomite and pump 85% of the water. Du Toit (1921) would include two shafts that are not directly related to the dolomites by geological mapping, if these are included then fourteen of the nineteen mines pump 92% of the water. It is interesting to note that Sallies, which is not overlain by dolomite, at that time, was the fourth driest of the nineteen mines listed.

The literature survey thus reveals that most recharge to the mine aquifer is via the Dolomites. Water inrushes take place where the mine aquifer intersects water bearing fractures or sill contacts in the dolomites, or, at deeper levels, where water bearing zones in the dolomites are connected to the mine aquifer via deep fractures or mine openings.

Table 3.4.1 Mine Pumping Relationships with Dolomitic Overburden

	Average Daily Pumping Rate (Ml/day) from East Rand Mines							
	1952	1953	1954	1955	1956	1957	1958	1959
Spaarwater	1.4	1.3	1.3	1.2	1.2	1.3	1.4	1.5
Sub Nigel	1.6	1.8	1.7	1.6	2.1	2.0	1.9	1.5
Vlakfontein	1.0	1.0	1.1	1.1	1.0	1.0	1.0	1.0
*Vogelstruisbult**	*1.7*	*1.8*	*2.0*	*2.3*	*2.4*	*1.5*	*2.4*	*2.5*
*Marivale Cons**	*2.4*	*2.0*	*1.6*	*1.2*	*1.5*	*1.8*	*1.5*	*1.5*
*East Daggafontein**	*6.5*	*6.2*	*6.5*	*7.4*	*8.0*	*6.1*	*8.1*	*7.5*
*Daggafontein**	*10.1*	*10.6*	*11.6*	*12.3*	*13.1*	*14.1*	*14.7*	*15.5*
*Springs Mines**	*3.1*	*2.9*	*2.6*	*3.1*	*2.6*	*2.4*	*2.2*	*2.1*
S.A. Lands	1.3	1.4	1.8	1.7	1.6	1.5	1.5	2.1
Van Dyk	2.0	1.8	1.6	1.5	1.7	2.0	2.1	2.1
Brakpan Mines	4.9	4.5	4.6	6.5	7.0	7.0	7.0	7.0
*Government Areas**	*15.4*	*16.2*	*16.7*	*18.7*	*21.8*	*20.2*	*18.0*	*15.4*
*Geduld**	*8.6*	*7.7*	*7.0*	*7.5*	*8.4*	*9.1*	*9.5*	*9.2*
*East Geduld**	*15.5*	*8.5*	*9.9*	*9.5*	*10.2*	*11.3*	*10.7*	*9.4*
*Grootvlei**	*6.0*	*6.7*	*6.9*	*6.1*	*6.0*	*5.4*	*5.0*	*4.4*
*Modder East**	*7.0*	*7.0*	*7.3*	*8.1*	*8.8*	*9.2*	*9.3*	*9.5*
Modder B	1.0	1.0	1.2	1.2	0.0	0.0	0.0	0.0
*New State Areas**	*0.6*	*0.5*	*0.0*	*2.3*	*0.0*	*0.0*	*0.0*	*0.0*
*Welgedacht**	*2.6*	*2.8*	*2.5*	*2.2*	*0.0*	*0.0*	*0.0*	*0.0*
Total (all mines)	92.6	85.9	88.0	95.7	97.3	95.9	96.5	92.3
Mines under Dolomite	79.4	73.1	74.6	80.8	82.7	81.1	81.5	77.1
%	85.8	85.1	84.7	84.5	85.0	84.5	84.4	83.5
Du Toit's %	92.2	91.4	91.3	92.6	92.2	91.8	91.7	91.1

3.4.1.2. Water Supply to the Dolomites

To compare the volumes pumped from the mines and the water bearing potential of the dolomites. Recharge parameters were calculated for the dolomitic terrain which outcrops in the north-eastern and south-western portions of the study area.

3.4.1.2.1. Potential Water bearing Characteristics of the Dolomite

The potential water bearing characteristics of the dolomites were calculated from relationship 3.1.

$$\text{Vol. water in dolomites} = \text{dolomite volume} \times \text{porosity} \quad \ldots\ldots\ldots \; 3.1$$

Dolomite volume was calculated from dolomite thicknesses recorded during shaft sinking and exploration drilling on the East Rand, and the dolomite area, which was determined from dolomitic exposure shown on geological maps of the area such as those of Fox (1939), Wagener (1972) and the Geological Survey (1986). The results are shown in Table 3.4.2.

Note: The volume of dolomite related to exposure is a fraction of the total dolomite in the area.

---

* Mines overlain by Dolomite are marked witha an asterisk and written in italiks.

Table 3.4.2. Volume of Dolomites.

Dolomite Information Source	Thickness (m)	Area (km²)	Volume (km³)
Wagener	423.6	109.58	46.41
Wagener and Du Toit	525.8	97.16	51.08

To calculate the potential volume of water in the dolomites, a typical, yet conservative porosity of 3% was used because there have been no hydraulic studies conducted to determine values of this nature. The average pumping from the mines can be compared with this value. The results are shown in Table 3.4.3

Table 3.4.3. Water Bearing Potential

Dolomite Information Source	Volume of water in dolomite Ml	Volume pumped from East Rand Mines Ml/year	Pumped volume as % of water in dolomite
Wagener	1 392 411.0	23 558.6	1.69
Wagener and Du Toit	1 532 419.5	23 558.6	1.54

3.4.1.2.2. Recharge Potential of the Dolomite

Recharge volumes = area × rainfall × recharge % 3.2

Area is determined from geological mapping.

Rainfall, the average annual precipitation of 710 mm, is based on monitored results from Grootvlei and appropriate Department of Water Affairs monitoring stations (DWA&F 1983).

Recharge percentage has been determined using relationships 3.3 and 3.4 which are described in the following paragraphs.

The environmental chloride method suggested by Sharma (1988) and Van Tonder *et al.* (1990) uses relationship 3.3:

$$R = P\frac{Cl_P}{Cl_G}\ {}^{mm}/_{year} \quad \text{.......................................} \quad 3.3$$

Where:

R	=	Recharge (mm/year)
P	=	Long term average annual precipitation (mm/year)
Cl_P	=	Chloride concentration of rainwater (mg/l)
Cl_G	=	Chloride concentration in groundwater (mg/l)

Using the chloride content of freshly recharged dolomitic groundwater from Welgedacht (3 mg/l), and the chloride content of rainwater from this area, given in Kafri *et al.* (1986) (0.6 mg/l), a recharge of 142 mm/year was obtained. This is 20% of the annual rainfall.

This method should be based on long term monitored values, since these are not available, the value obtained was checked using an empirical equation, equation 3.4, given by Bredenkamp (1988) for dolomitic terrain in the Western Transvaal:

$$RE_I = A(RF_I-B) \qquad 3.4$$

Where: RE_I = annual recharge

RF_I = annual precipitation

A = catchment parameter (for estimation purposes A = 0.3)

B = threshold rainfall to achieve recharge (for estimation purposes B = 313)

Using this relationship a recharge of 119 mm/year is obtained, this is 16 % of the annual average precipitation. These recharge figures are realistic given the flat topography found in this area.

The results of the recharge calculation based on relationship 3.2 are shown in Table 3.4.4.

Table 3.4.4. Recharge Potential (From rainfall only)

Dolomite Information Source	Exposed Surface Area (km^2)	% Recharge	Volume Ml/year	Volume Ml/day
1. Wagener	109.58	16	12 448.1	34.1
2. Geol. Survey Mapping	97.16	16	11 037.0	30.2
3. Whole dolomite basin being recharged	542.10	6	23 093.3	63.226
4. Total investigation area except Dol	652.84	2	9 270.4	25.4

Recharge to the exposed dolomite only, would supply some 30 Ml/day. Since dolomite covers about 30% of the investigation area additional recharge must be derived from some of the other covered regions, thus estimations for these regions, using typical recharge values have been included in the calculations. These calculations show that recharge of the same order as the long term pumping value is possible.

- Minimum recharge Ml/day (Info. source 2+4) 55.6
- Maximum recharge Ml/day (Info. source 3+4) 88.6

The volume calculated in this way, is conservative, since it assumes that recharge is derived from rainfall only. With dolomites only covering 30% of this area and the groundwater divide not clearly defined, additional recharge could also be derived from other rock units or even from outside the investigated area depending on the hydraulic gradients that may have been established by mine dewatering. In addition, the chemistry of the water shows that inputs from surface water sources also occur. If these other sources were taken into account they would increase the potential recharge volume.

These calculations show that from the given rainfall, the average mine inflow of 64,5 Ml/day, could occur without dewatering the groundwater resources of the area.

3.4.1.3 Subsurface Flow Paths

On the East Rand shallow dips on the reef suggest that stope closure can be expected, this implies that fracturing around the stopes will be relatively extensive. Kimberley Reef has been mined, particularly in the central and eastern parts of the area, so that the mine aquifer can be considered to be two parallel basin shaped bodies. The upper mine aquifer being of much smaller extent than the lower one.

The potential flow through the mines has been evaluated using mine plans held at the Government Mining Engineer. The water flow path is shown in Figure 3.4.2.

Although Pringle (1992) and Erasmus (1992) have suggested that the mines are not interconnected and Fuller-Good (1992) has stated that the water will follow a shallow path around the perimeter of the basin, the fact that pumping from Sallies No. 1 shaft dewatered the whole basin suggests that more extensive connections exist.

The mines in the northern part of the area are interconnected and there is no restriction to water movement between individual mines. In the southern region Sub Nigel and Nigel Mines are continuously connected. The mines in the central part of the basin are connected only in certain places and water flowing through this region will have to follow preferred pathways. There is no connection between Marivale, and the Nigel Mine, the connection to the lowest point at Nigel is via Vogelstruisbult to Sub Nigel at 61 level 8 haulage.

Thus it would appear that the water from Springs mines, East Daggafontein and Marivale would first have to flow into Vogelstruisbult where a connection exists (61 level 8 haulage) to Sub Nigel. Water will rise in the Sub Nigel Mine and then into the Nigel Mine to emanate at surface. Thus the limiting factor is the connection between Vogelstruisbult and Sub Nigel. If flow is restricted at this level then the water will rise at Marivale 4 or 7 shafts instead of in the Sub Nigel and Nigel Mines.

The previously mentioned investigators predicted that filling of the basin would take 45 years, this is not correct since the investigators base their estimates over a period when dewatering was still active (pre 1988). Thus their observed 2,2 m per month water rise does not take into account the corresponding removal of about 64 Ml/day by pumping at Sallies No. 1 shaft. The distinction is shown in Figure 3.4.1 where the pre-1988 non static water level can be seen.

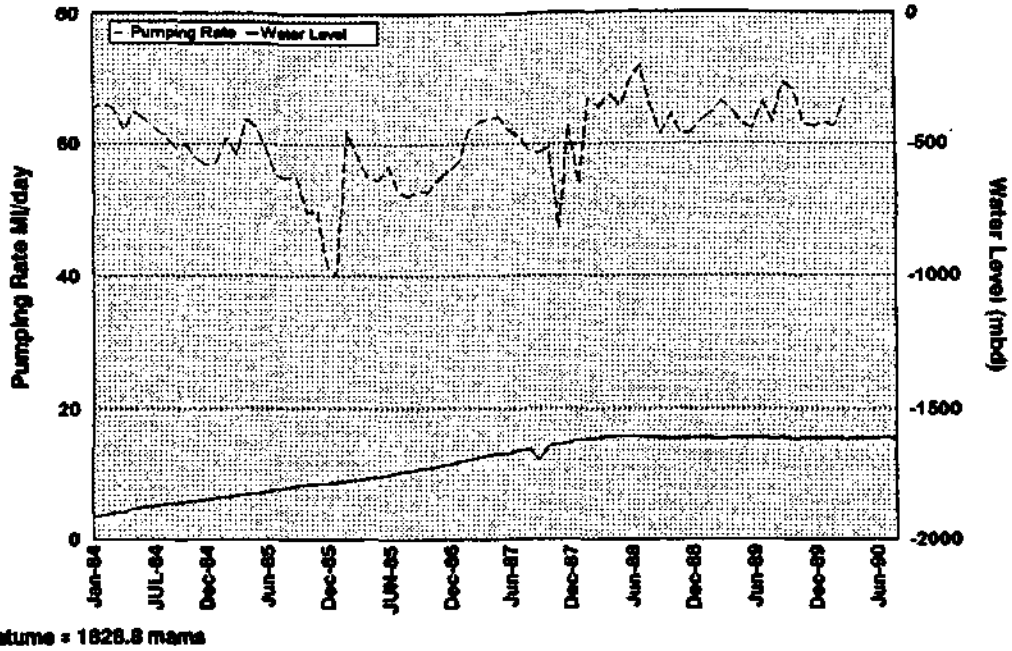


Figure 3.4.1 Water Level Rise in East Rand Basin Before Cessation of Pumping

The actual rate has been between 0.2 and 0.5 m per day or some 6 to 15 m per month. If these investigators estimations are corrected for this oversight, then, according to their other estimates, basin filling would take 6.6 years. The estimates made by this investigation show that filling will take about 15 years, of which, 3 have already passed.

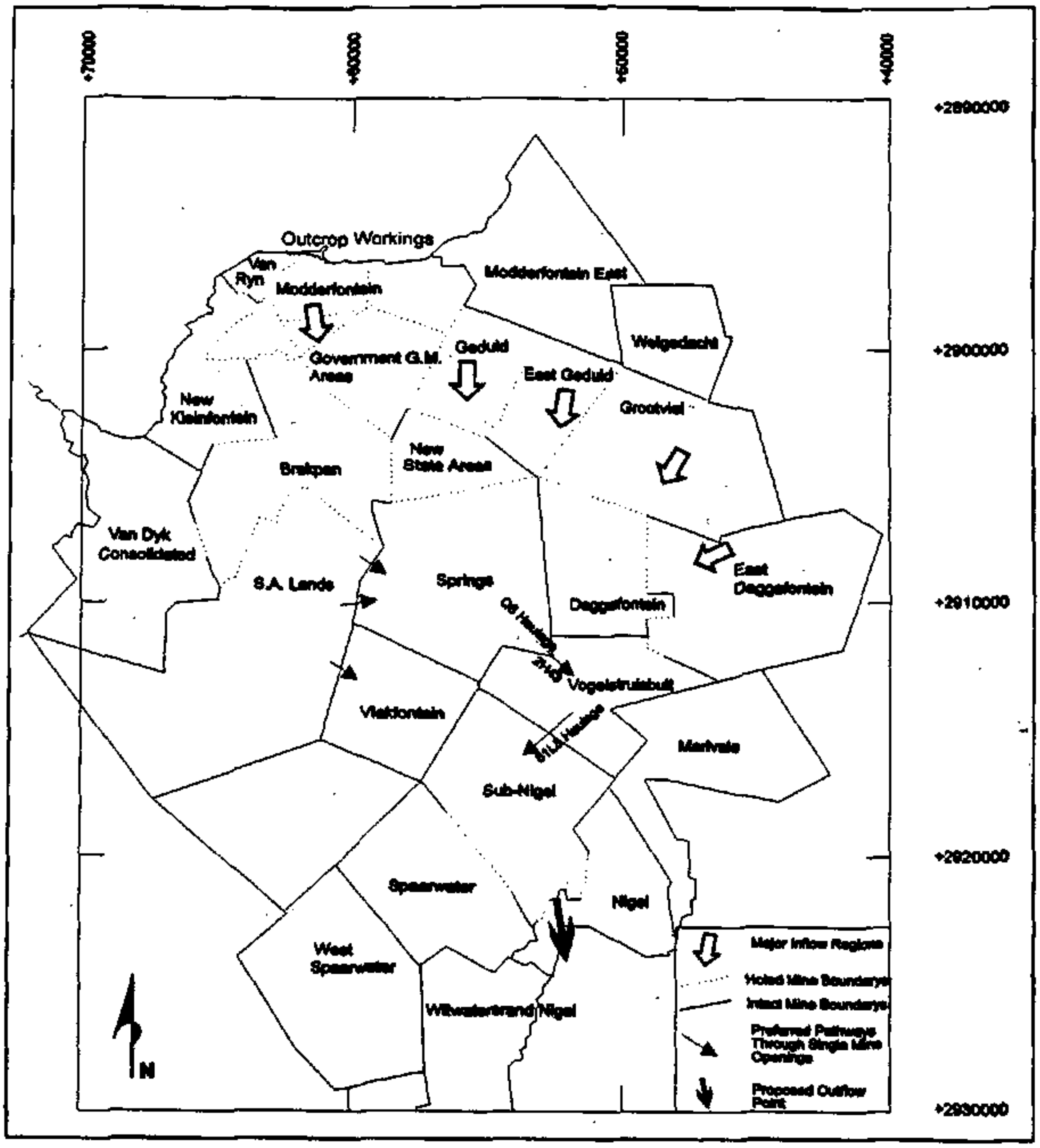


Figure 3.4.2 Breaks in Mine Boundary Pillars Allowing Water Movement.

3.4.1.4 Recovery Level and Outflow Points

The topography in this area is relatively flat and the inflow points from the dolomites are mostly below surface. Precise locations of these inflow points are not known, thus predicting a peizometric level for the mine aquifer with this lack of information is difficult. If the peizometric level is related to the type of shallow inflow observed at Cons. Modder No. 8 shaft, then the peizometric elevation could be predicted from relationship 3.5:

Peizometric level = shaft elevation - major inflow depth.................................... 3.5

Piezometric level = 1623 - 50 = 1573 mams

If these conditions are fulfilled, then those shafts with collar elevations below the predicted peizometric level will have potential to be free flowing. The shafts with this potential are listed in Table 3.4.5. If the peizometric level is lower than 50 metres, fewer of these shafts will develop the potential to be free flowing and visa versa.

Table 3.4.5 Potential Free Flowing Shafts

Shaft Name	**Shaft Elevation*** Metres above mean sea level (mams)	**Head** Metres below peizometric surface (1573 mams)
Marivale 1	1571	2
Grootvlei 3	1570	3
Marivale 5	1570	3
Marivale 4	1565	8
Marivale 7	1564	9
Sub Nigel E	1562	11
Nigel/Bultfontein	1562	11
Sub Nigel D	1560	13
Sub Nigel C	1560	13
Nigel 12	1560	13
Nigel 2	1559	14
Nigel 10	1559	14
Sub Nigel B	1558	15
Sub Nigel C.V.	1558	15
Nigel 7	1558	15
Nigel 13	1558	15
Nigel 3	1549	24

This information shows that the Nigel No 3 shaft is significantly lower than the other shafts and will therefore have the greatest potential to be free flowing.

Nigel No. 3 shaft is an inclined shaft, it has been ineffectively filled by dumped rubble and the shaft roof has collapsed but this will not affect it's potential to discharge water. It might make engineered control of the water discharge difficult.

The topographic relationships of these positions are shown in Figure 3.4.3, a three dimensional surface plot of the East Rand area.

* Measured from 1:10 000 orthophoto maps.

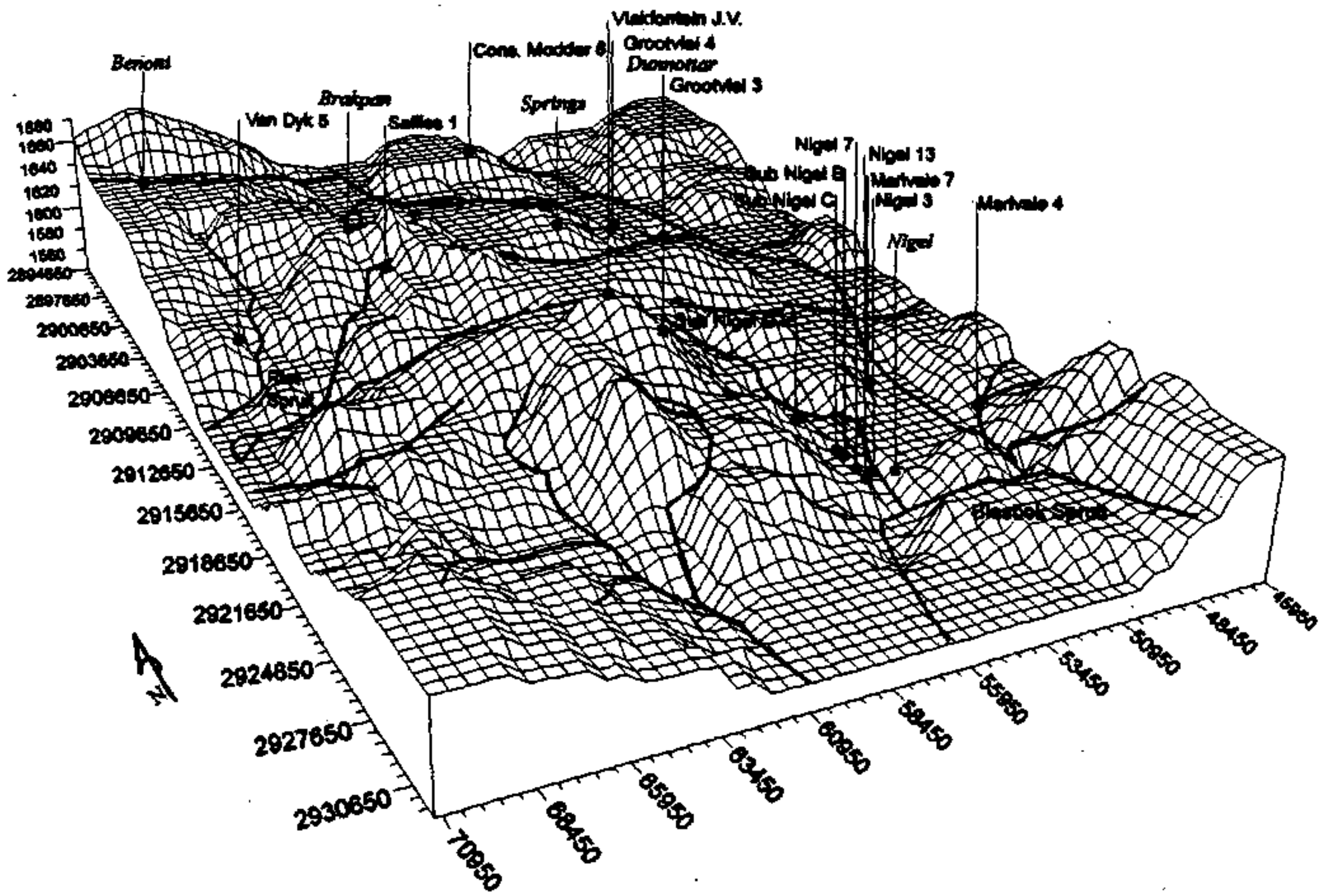


Figure 3.4.3 Three Dimensional View of East Rand Topography

3.4.1.5 Conceptual Model of Recovery

The conceptual model of subsurface flow is based on descriptions and observations made by first hand observers such as Mellor (1921) and du Toit (1921) or recorded by de Jager (1986). The conceptual model has been divided three situations depicting:

1. Pre mining conditions
2. Concurrent with mining conditions
3. Post mining conditions.

For each of these situations the envisaged conditions are described using schematic diagrams. These are shown in Figures 3.4.4 to 3.4.6 with the related explanations.

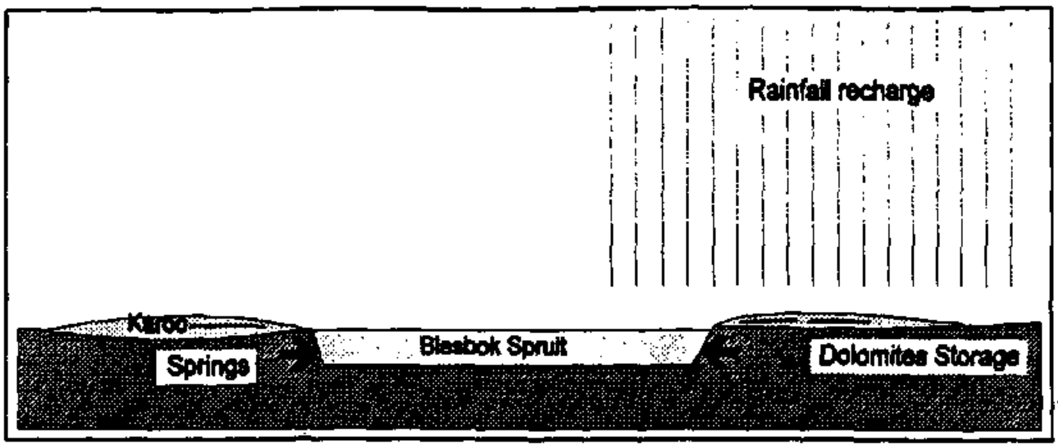


Figure 3.4.4. The Flow Situation Between The Blesbok Spruit and the Dolomites, Before Mining and Industrial Development.

1. Before mining and industrial development, Frommurze (1934) shows that springs fed the swamp area in the vicinity of Grootvlei, Mellor (1921) reports that the river was dry during winter. The springs were derived from water in the dolomites, and were controlled by topography or by water emanating along chert bands in the dolomite. Rivers which derive their water from groundwater in this way have been defined as effluent streams (Hunt, 1989) and are a surface expresion of the water table. The seasonal nature of such a stream can be related to the annual fluctuation of groundwater levels. Hamill *et. al.* (1986) describe this form of behaviour as common in streams in the Chalk of England, during the dry months when the water table is below the level of the watercourse the streams disappear.

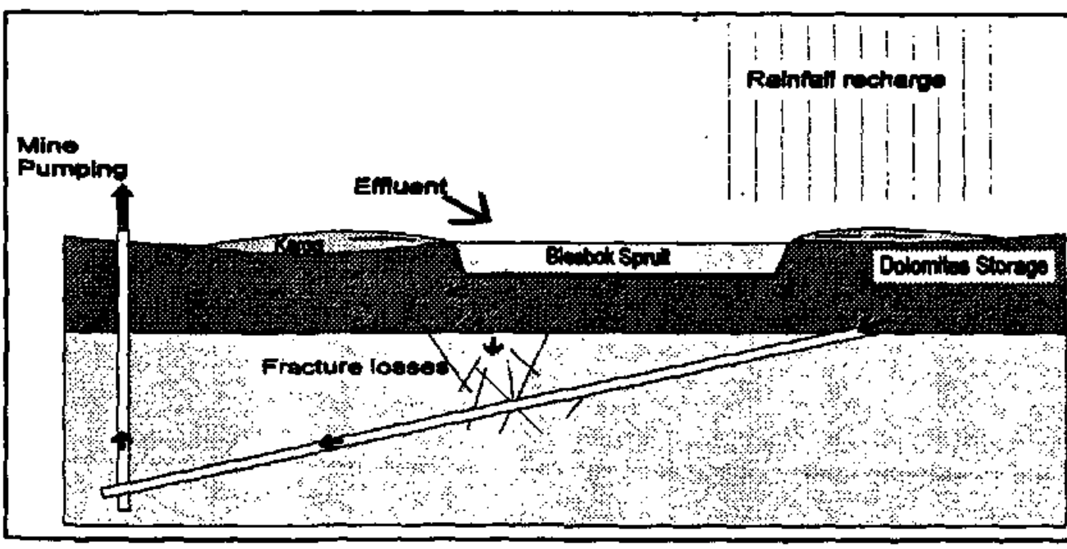


Figure 3.4.5 The Flow Situation Between The Blesbok Spruit, Dolomites, Mines and Industrial and Sewage Effluent, Since Mining and Industrial Development.

2. After mining created the mine aquifers and a downward hydraulic gradient was established due to pumping, water from the dolomites flowed downward into the underground workings, from where it was

pumped. Thus a proportion or all of the water that was available to feed the Blesbokspruit now flows underground. The schematic depicting the situation is given in Figure 3.4.5. While dewatering took place from Sallies No. 1 shaft, most of the pumped water was either discharged into, or consumed in, the Riet Spruit catchment. Smaller volumes were pumped into the Blesbok Spruit. Industrial and sewage effluent is discharged into the river. Under these conditions the river does not dry up during winter, and has been noticed to rise during dry periods.

The hydraulic situation in the Blesbok Spruit is no longer one of an effluent stream, but now one of an influent stream, water losses now occur from the stream to the subsurface. These losses plus water from the dolomitic aquifer now contribute to the inflow to the mines. The volumes of Water available from effluent disposal and from dolomitic recharge are given in Table 3.4.6. This and previous discussion on the recharge potential shows that there is an ample source of water to account for the volumes pumped from the mines. Because of this, the water levels in the dolomites are apparently unaffected.

Table 3.4.6 Effluent Discharge To Blesbokspruit River System

Effluent Disposal Point	m^3/day	Ml/day
Anchor	3772	3.772
Brakpan	*	
Daveyton	635	0.635
Rynfield	13	0.013
SAPPI Discharge	30	0.030
SAPPI Irrigation	19	0.019
Total Effluent	4469	4.469
Water from Dolomite	55599	55.599
Total	60068	**60.068**

This has provided the bulk of the water to the mine workings. Smaller amounts may have been derived from the Karoo where it overlies the mine workings and from Witwatersrand outcrop. For example, on the defunct Spaarwater mine property, there are outcrops of Witwatersrand rocks, de Jager (1994) noted significant inflows during rain storms via fractures from these outcrops.

* Brakpan Sewage works outflow is disposed of into the Jan Smuts Dam, because it is not directily discharged into the Blesbok Spruit, records do not have to be submitted to the DWA&F. However Jan Smuts Dam overflow is into the Blesbok Spruit and this source will contribute to flow in the streaam according to Herold (1990) it could be in the order of 30 Ml/day.

When the mine aquifer has been recharged, the hydraulic gradient will be such that flow from the dolomites will be reduced by flow taking place only to the shallower mine workings for example the Black Reef workings. It has been shown that these inflow points will have an elevation approximately 24 m above the elevation of the lowest shaft where water will start to decant. The shematic depiction this situation is given in Figure 3.4.6.

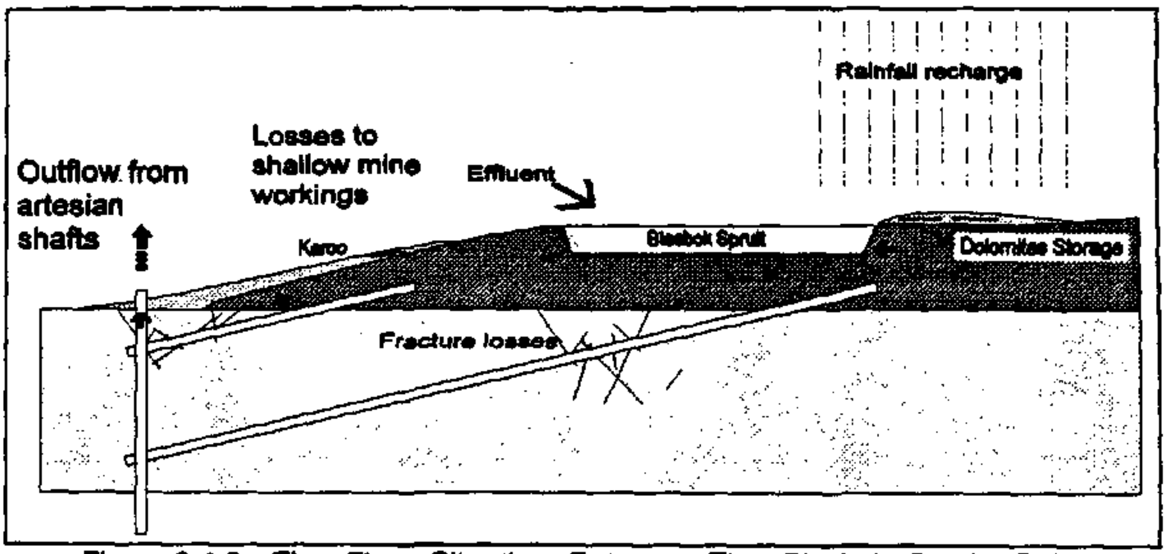


Figure 3.4.6 The Flow Situation Between The Blesbok Spruit, Dolomites, Mines and Industrial and Sewage Effluent when the Mine Aquifer has Recovered.

3. Under fully recovered conditions in the mines, the dolomites will again feed the Blesbok Spruit, flow will still take place to the mine aquifer, but it will be reduced by the lower hydraulic gradient. Due to the head difference between the main inflow positions and the potential outflow positions the water in the mine aquifer will be under pressure and will discharge from the lowest shafts connected to the system. In Figure 3.4.6 such shafts are referred to as artesian shafts.

   Under these conditions the flow in the Blesbok Spruit above the potential outflow shafts will increase, especially during the wet period since water will again be derived from the dolomites as springs. Below the artesian shafts the flow will increase by the amount flowing out of the mines if it is allowed to enter the Blesbokspruit.

3.4.2 Historical Recovery

The recovery on the East Rand, has been monitored since pumping stopped, thus a good basis for prediction has been generated by observing the response to date.

Water inflow rates are based on pumping figures.

3.4.2.1 Hydrodynamic Equations.

Sixty-four water level measurements have been taken since pumping stopped at Sallies No. 1 shaft on the 17 July 1991. At the time of writing the latest measurement had been taken on 11 August 1994, 1131 days after pumping stopped. During this period the water level has risen from 1563 to 1178 mbd., a rise of 385 meters or an average rate of 0.34 m per day.

This data is comparable to that measured during the recovery stages of a pumping test and could be analyzed using hydrodynamic principals to give aquifer parameters from which predictions could be made. Using log/normal graph paper to plot the recovery data, a plot such as Figure 3.4.7 can be generated. For most groundwater occurrences the result is a straight line. The figure shows that this measured recovery does not follow a typical straight line recovery.

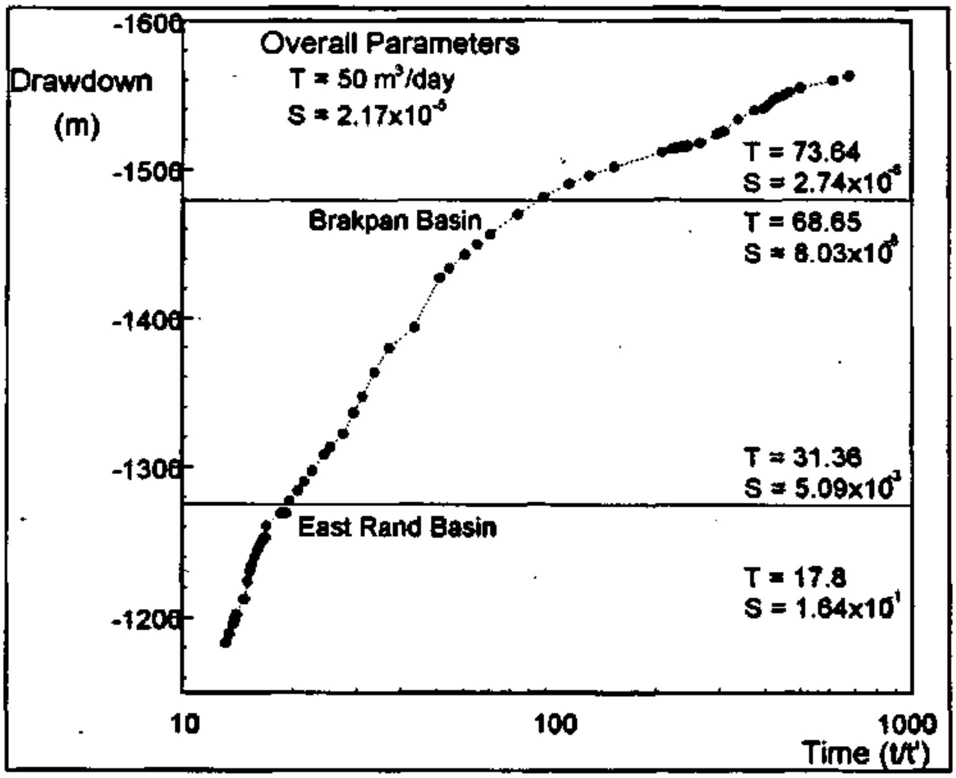


Figure 3.4.7 East Rand Theis Recovery as Measured at Sallies No. 1 Shaft.

Deviation from a straight line is due to the flow to the measuring position not fulfilling the hydrodynamic assumptions on which the recovery analysis is based. The most important of these assumptions are:

- The pumping position should be located in the middle of a horizontally infinite, saturated, porous body. The mine aquifer is not saturated. The mined volume varys with position. The recovery analysis cannot take this into account and adjusts the transmissivity and storativity, rather than taking volume changes alone, into account. Calculated parameters for different parts of the curve are shown in Figure 3.4.7.

- Flow to the extraction point should be horizontal and radial, most flow to the mine aquifer is vertically downward.

- Recharge takes place at a constant rate. The long period of recharge (three years) is such that the recharge has been affected by seasonal variations.

The most reliable portion of the recovery trend shown in Figure 3.4.7 is the recovery obtained after the East Rand Basin level was reached. Using the parameters obtained for this part of the curve (T = 17.8 m2/day and S = 0.164) and an estimated radius for the shaft of 5 m, the recovery, with an inflow of 55 Ml/day, would take 88 days. This is clearly incorrect.

Bakalowicz *et al.* (1980) have defined a function ($\underline{\aleph}$) which can be used to evaluate the suitability of using the standard hydrodynamic equations for parameter estimation:

$$\underline{\aleph} = \frac{\text{Baseflow maximum}}{\text{Transit volume of the flood event}} \qquad 3.4$$

The value $\underline{\aleph}$ varies from 0 to 1.

If:

$\underline{\aleph} \geq 0.5$	the aquifer can be analyzed using methods for porous and fissured media,
$0.2 \leq \underline{\aleph} \leq 0.4$	*the methods may not hold,*
$\underline{\aleph} \leq 0.1$	interpretations based on porous media concepts are absolutely erroneous.

Using equation 3.1, an estimate of $\underline{\aleph}$ can be made for the East Rand mine situation using the following values supplied by Grootvlei: Base flow maximum 72 Ml/day, and the volume of the flood event of 1972, 657 Ml/day, this gives:

$$\underline{\aleph} = \frac{72}{657} = 0.1095$$

This confirms the above observations about the irrelevance of using the standard geohydrological techniques. Thus, any evaluation based on the standard hydrodynamic equations is invalid and the parameters so generated are totally inappropriate.

In the mine aquifer porosity occurs as excavated open channels and as a fracture zone around the openings. Flow through these openings, except under exceptional circumstances and when the mines are completely filled, will always be unsaturated. Under these conditions the hydraulics of the flow should be analyzed in a similar way to that in channels or pipes. Thus a dynamic input-output analysis type is more appropriate. According to Ford *et* *al.* (1989) the response to a rainfall event (hydrograph) can be used to analyze the system, these authors discuss situations where outflow (spring) hydrographs are used to define system parameters. They refer to the corresponding record of water quality as a chemograph, stating that it is equally important for the evaluation of the system and can be used, for example, to define the type of recharge, whether diffuse or via a surface sink.

It is felt that for this system detailed depth measurements and sampling could give the same information as the study of a spring outflow. Techniques and equipment would have to be developed for measurement and sampling at depths of about 1 000 meters below surface. As water rises in the basin, shafts on the perimeter will become useful for water depth measurement. Some of the vertical shafts have been sealed with concrete blocks, such as Sub-Nigel B shaft, but others are open or are covered with a metal grid and could be used to monitor the water depth. The most suitable shafts for this purpose would have to be identified. From initial observations Sub-Nigel C, CV and E appear to have potential for this type of study.

3.4.2.2 Graphical Extrapolation

The measured recovery data follows a linear trend on normal graph paper, with a correlation coefficient of 0.983. This is shown in Figure 3.4.8, superimposed on which is the curve that the recovery data should have followed had it been the result of a porous continuum, i.e. the Theis recovery.

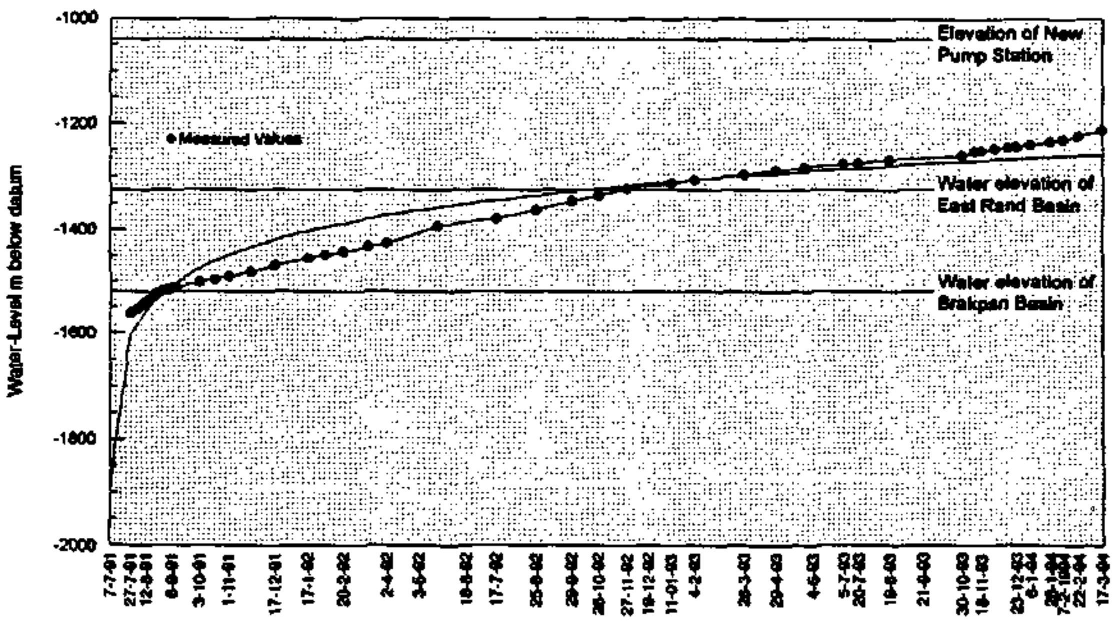


Figure 3.4.8 Straight Line Recovery vs Theis Curve

The straight line nature of this graph implies that the rate of inflow and the volume at successive depths are constant. The measured recovery trend follows a straight line with step like changes in rate at certain critical depths where the mined out volume changed.

This is consistent with recovery in a non-porous continuum and corroborates other evidence that flow is through fissures and weathered fracture zones (solution cavities) in the dolomites. Similar observations were made by Anon (1980), in a discussion on water levels rising in deep workings before the 1606 mbd. static level was reached. Such constant rate recovery lends itself to linear extrapolation and has been used to predict approximate dates at which critical water levels will be reached. These predictions have been presented in (Scott, 1992 a and b) and are shown here including the latest data as Figure 3.4.9 and 3.4.10.

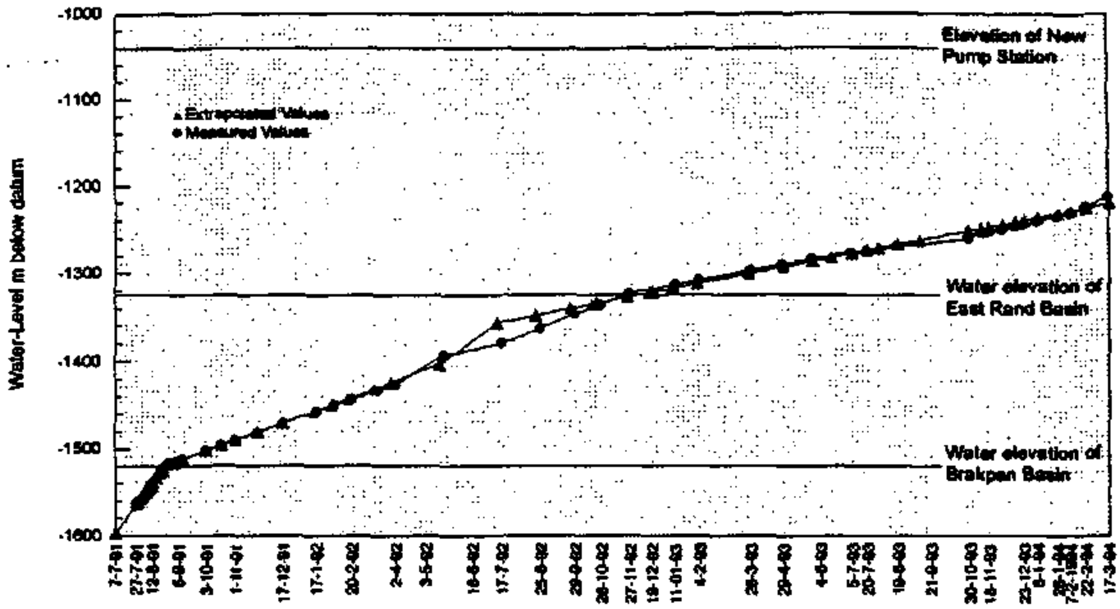


Figure 3.4.9 Measured and Predicted Recovery Trend (7-7-91 to 17-3-94)

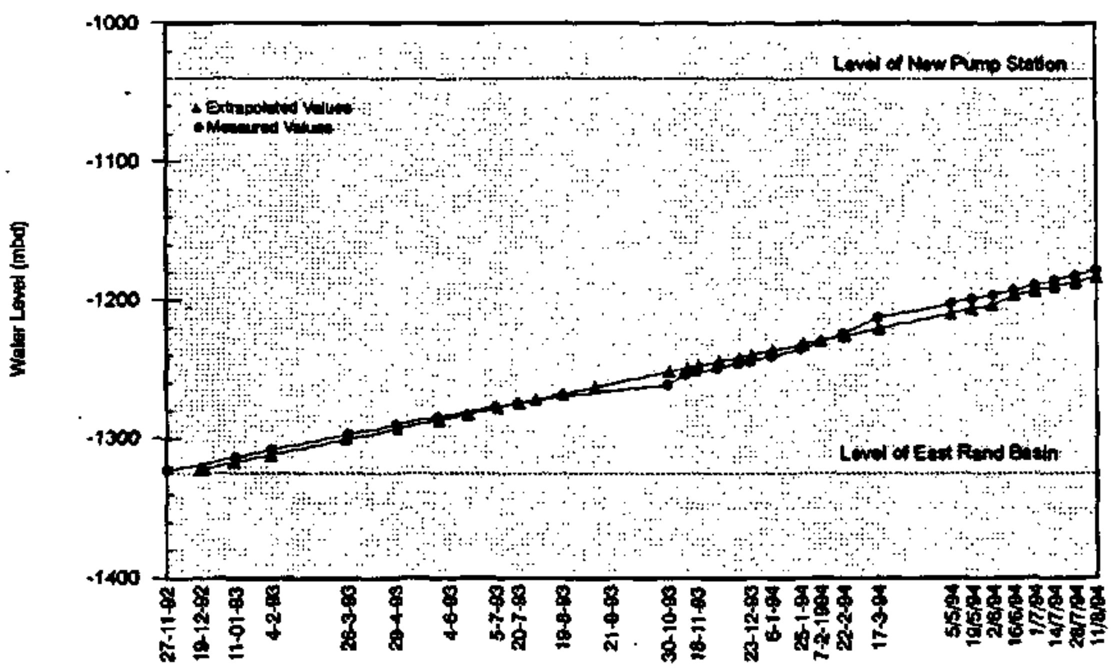


Figure 3.4.10 Measured and Predicted Recovery Trend (27-11-92 to 11-8-94)

These plots become very large when the time scale is linear, this is the reason that the data was split between Figure 3.4.9 and 3.4.10. If the data is plotted on a non-linear time scale with the spacing dictated by the frequency of observation the plot shown in Figure 3.4.11 results. On this plot the average recovery rate for successive straight sections is shown.

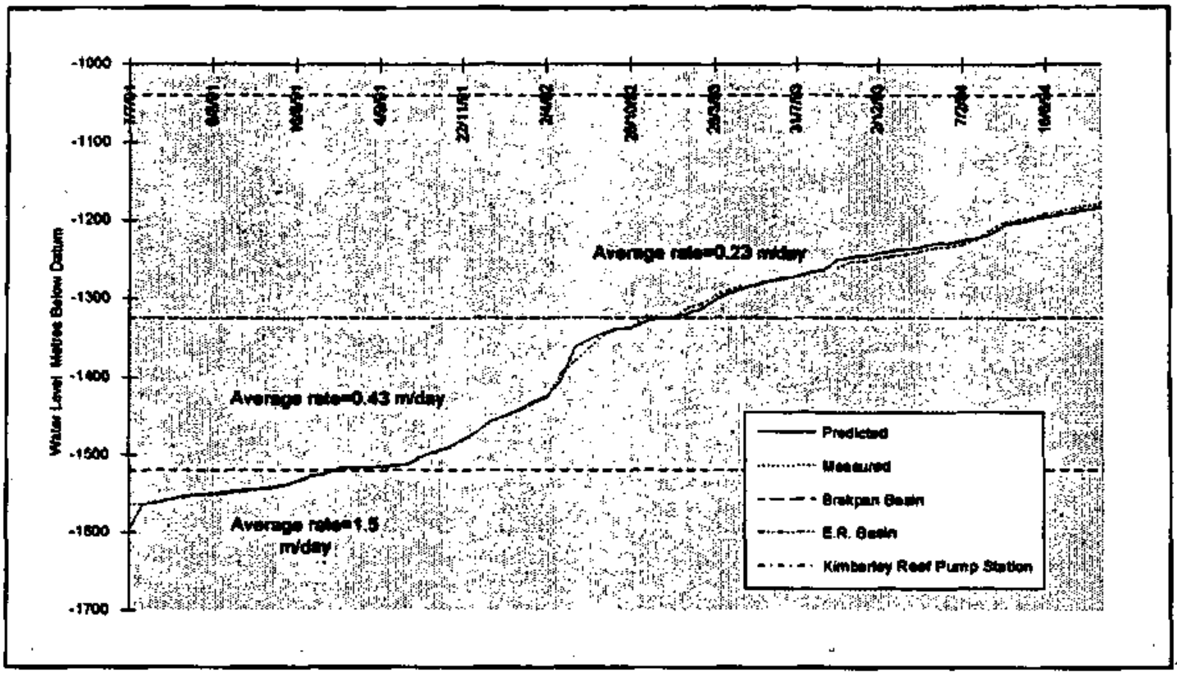


Figure 3.4.11 Measured and Predicted Recovery Trend (Non-Linear Time Scale)

Extrapolation is reasonable for short periods of time, involving relatively small volumes. It will not be accurate over a longer period when indeterminable volume changes at different mining depths and rate variations will affect the recovery rate.

3.4.2.3 Recovery Dates

The variation in mined out area can be seen from Figures 3.3.4 and 3.3.5 given in the previous section. Using areas measured from mine plans and corrected for dip angles, in conjunction with past inflow rates, average stope heights for areas already flooded could be calculated. From these values volumes could be predicted for the areas still to be flooded.

The water level has filled the workings from approximately 1600 metres below datum in June 1991 to 1200 metres below datum in June 1994, a water level rise of 400 m. Using the measured data some predictions to critical levels are shown in Table 3.4.7.

Table 3.4.7 Dates When Certain Critical Levels Will be Reached.

Date	Days Since Pumping Stopped	Water Level mbd	Description of Level
27/12/1994	1297	1150	
5/4/1996	1786	1040	New Pump Station
4/12/2001	3965	550	Base of the dolomites
16/8/2005	5389	230	Surface

The water level will reach the proposed Kimberley reef pumping station at Grootvlei No. 3 shaft at 1040 metres below datum by 1996.

The recovery levels can be related to the mined out area as shown in Figure 3.4.12.

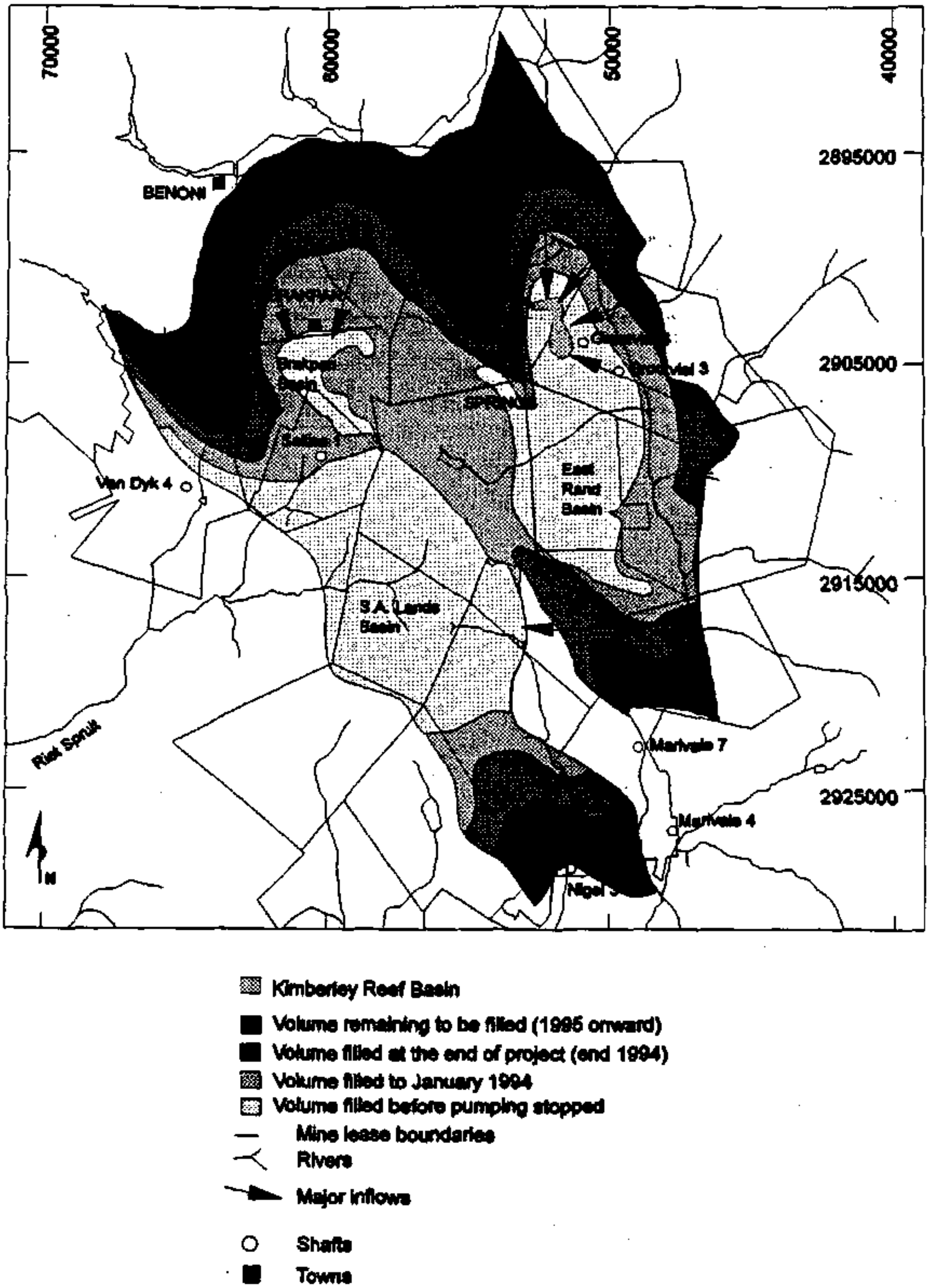


Figure 3.4.12 Water level and areas affected by water level rise

3.4.3. Mechanisms of recovery

Up to this point all inflow volumes have been assumed to be those of the average pumping rate (64,5 Ml/day) and that the majority of this water is assumed to be derived from dolomitic aquifers loosing to the dewatered workings. Direct recharge from rainfall has not been addressed. De Bruin (1991) stated that a correlation between pumping and rainfall is evident. While Griffiths (1994) states that direct recharge occurs on Consolidated Modderfontein after heavy rainfall. And de Jager (1994) noted significant inflows during rain storms via fractures from outcrop of Witwatersrand rocks on Spaarwater. Heavy flooding causes direct inflow via outcrop workings in the Blesbok Spruit valley on Government Gold Mining Areas (Anon 1988). If this is a significant contribution to the mine inflows then there should be evidence of a correlation between rainfall and either the pumping rate, or the recovery rate.

3.4.3.1. Recovery Rate

Investigation of the recovery rate shows that it is highly variable between water level measurements, particularly in the first few weeks of measurement as shown in Figure 3.4.13.

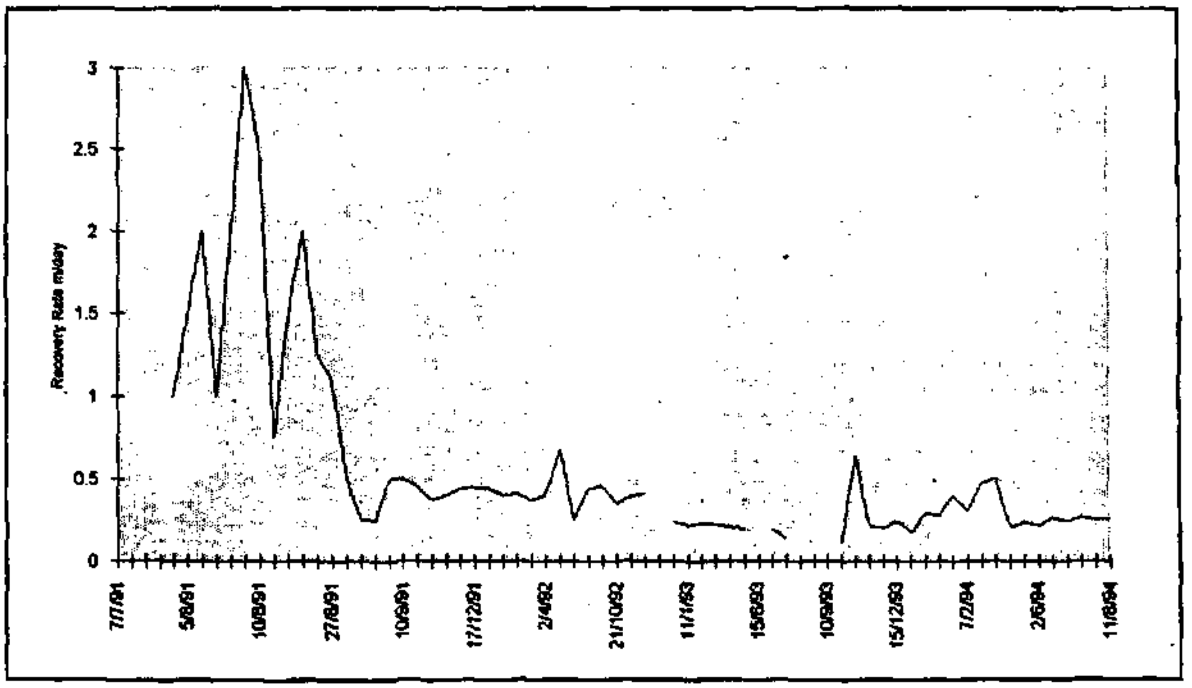


Figure 3.4.13 Recovery Rate vs Time

3.4.3.2. Pumping Rate, Recovery Rate and Rainfall Relationships

Pumping rate and rainfall data are presented in Figure 3.4.14, which is derived from the total (Sallies + Grootvlei) pumping rate and Figure 3.4.15, which compares recovery rate and rainfall.

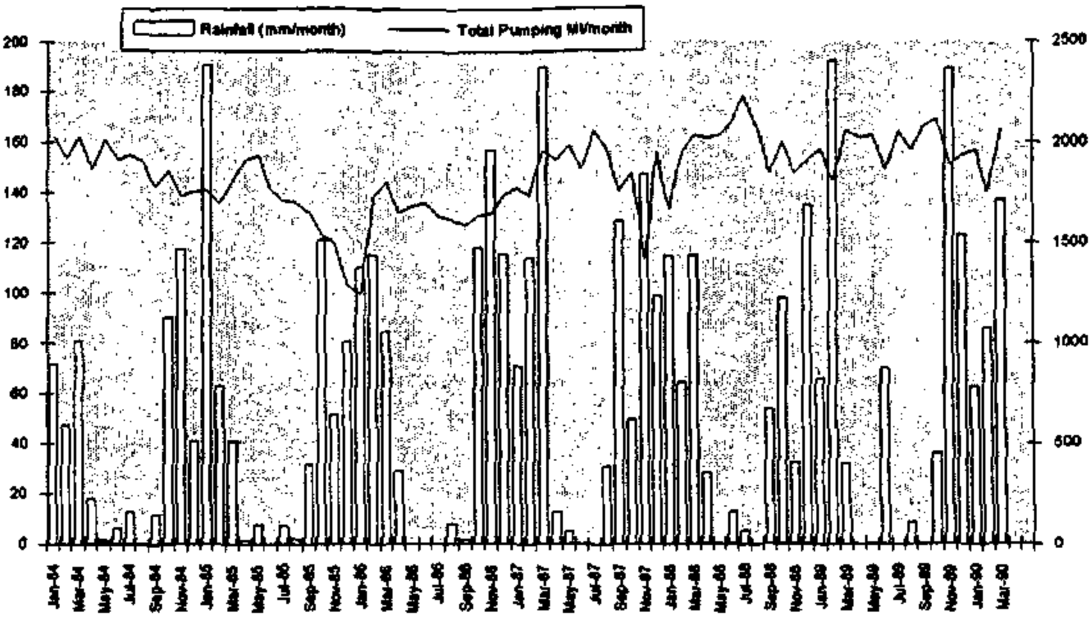


Figure 3.4.14 Total Pumping vs Rainfall

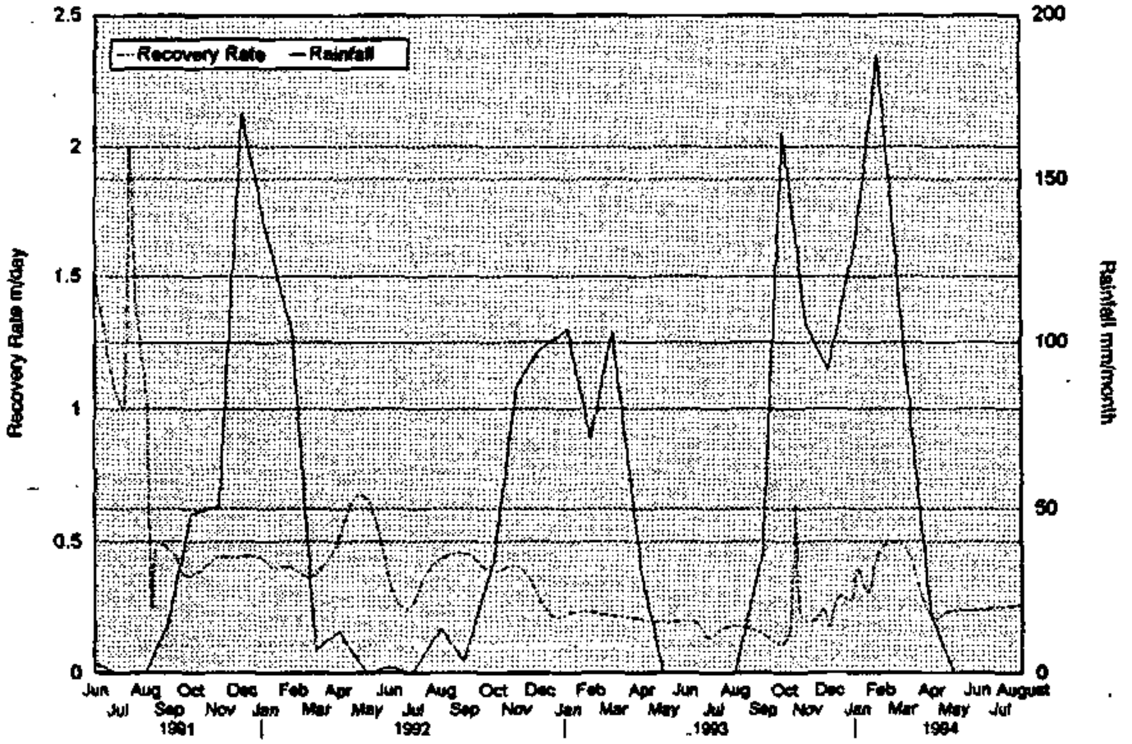


Figure 3.4.15 Recovery Rate vs Rainfall

The rainfall pumping relationship shows that there is, in some cycles, an apparent increase in pumping rate up to four months after the wet season. This suggests a lag time of 4 months for water moving through the aquifer. The recovery rate and rainfall relationship has only been monitored over three years but shows no apparent relationship.

To investigate these relationships further, scatter plots of rainfall vs pumping rate were evaluated. If there is a relationship between rainfall and pumping rate it should be linear, with increased pumping related to high rainfall periods and decreased pumping related to low rainfall periods.

The data was investigated as obtained and because of the apparent lag observed in Figure 3.4.14, using a four month moving average. The results are presented in Figures 3.4.16 and 3.4.17.

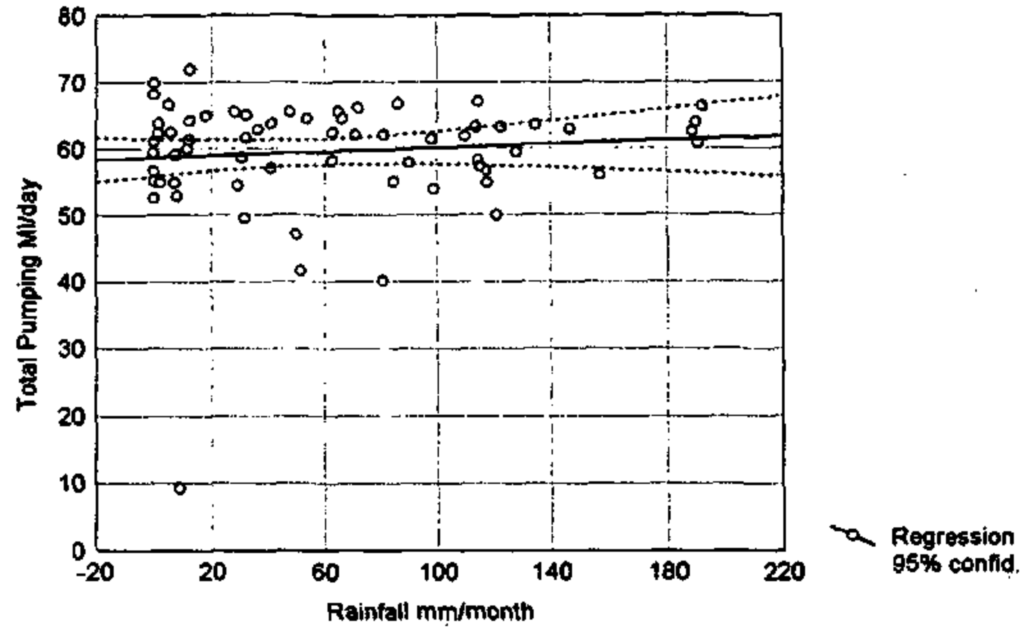


Figure 3.4.16 Scatter Plot of Rainfall and Total Pumping

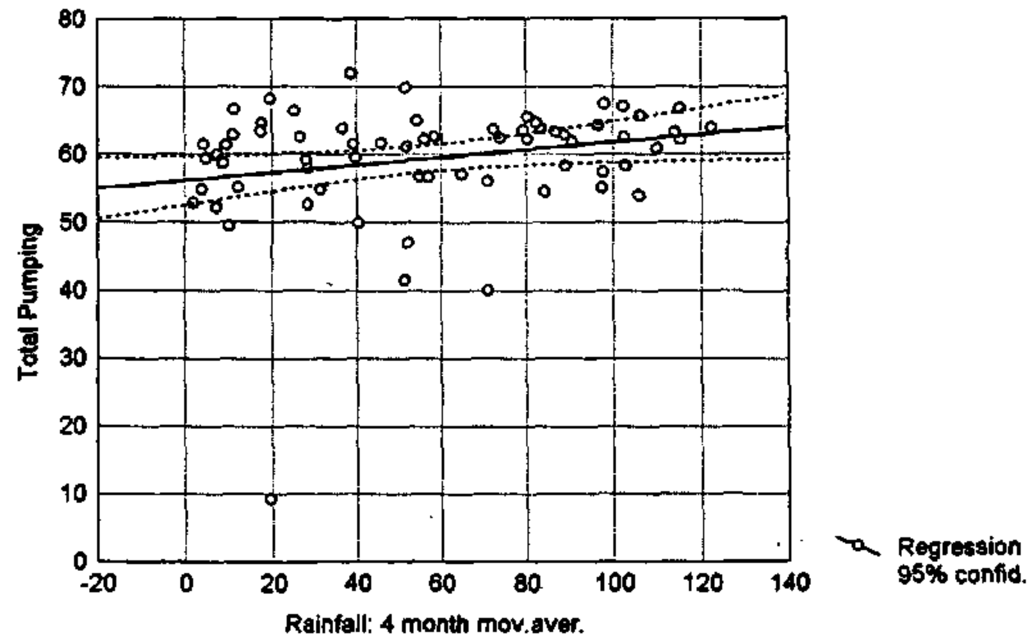


Figure 3.4.17 Scatter Plot of 4 month moving Average Rainfall and Total Pumping

Very slight adjustments in pumping rate for rainfall are suggested by the nearly horizontal regression shown by Figure 3.4.16. The broad scatter of points lends unreliability to any conclusion that may be drawn but it appears that the same pumping rate was maintained even if higher rainfall was experienced. The more pronounced gradient with the four month moving average shown in Figure 3.4.17, with the slightly better spread of data gives some confidence to the relationship between rainfall and pumping rate with a four month lag.

The actual data plot of pumping data and four month moving average rainfall, Figure 3.4.18, shows, when compared with Figure 3.4.14, that the moving average technique has some merit since there is a more obvious relationship between pumping maxima and rainfall maxima.

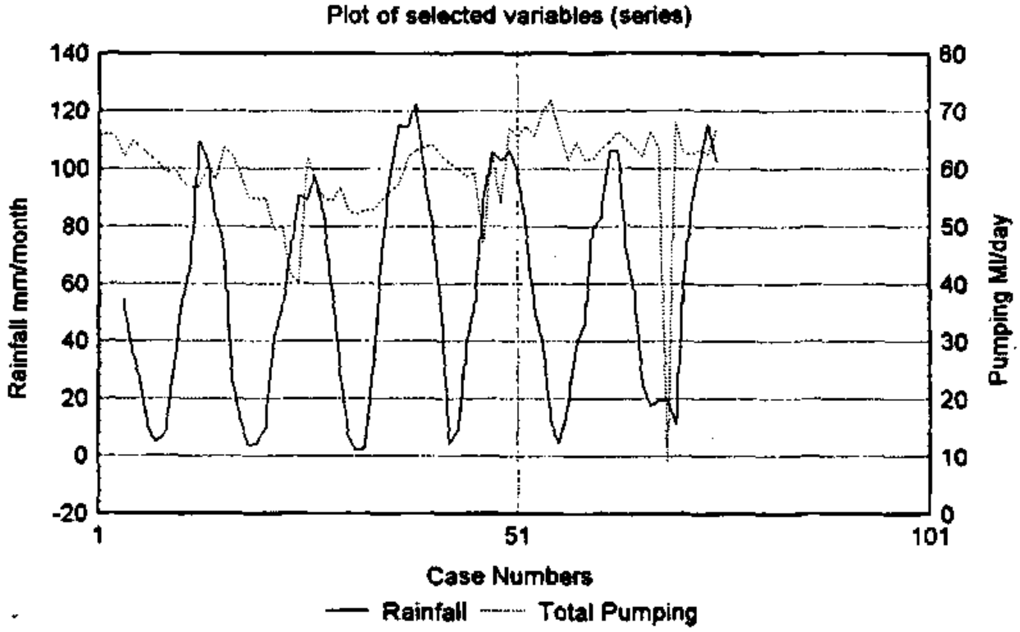


Figure 3.4.18 Total Pumping vs 4 Month Moving Average Rainfall.

Davis (1973) describes a technique called cross-correlation whereby two time series can be compared with each other. Using this technique the two series are matched against each other and at the same time a lag or time difference between the match is determined. This approach was applied to the four month moving average rainfall and pumping data. A plot showing correlation coefficient vs. match position is given in Figure 3.4.19, shows best correlations of about 0.3 at three to four months. This level of correlation is usually regarded as insignificant.

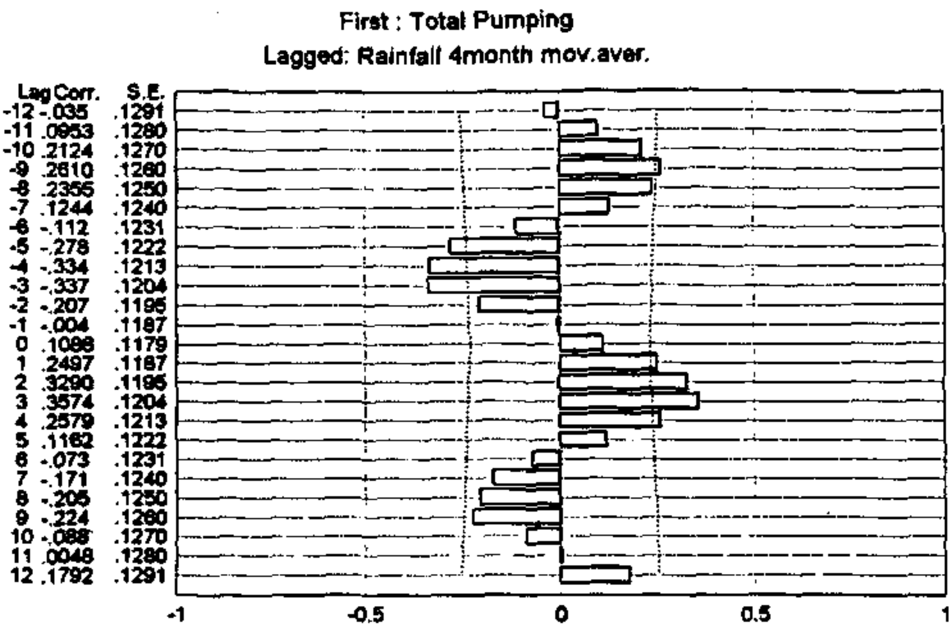


Figure 3.4.19 Correlation Coefficient vs Match Point for 4 Month Moving Average Rainfall and Pumping Rate.

Various other smoothing techniques and relationships were applied to the data including the cumulative rainfall departure method of Bredenkamp (1994). The best correlations were obtained using the moving average technique over twelve months. The results and correlation coefficient plot are given in Figures 3.4.20 and 3.4.21.

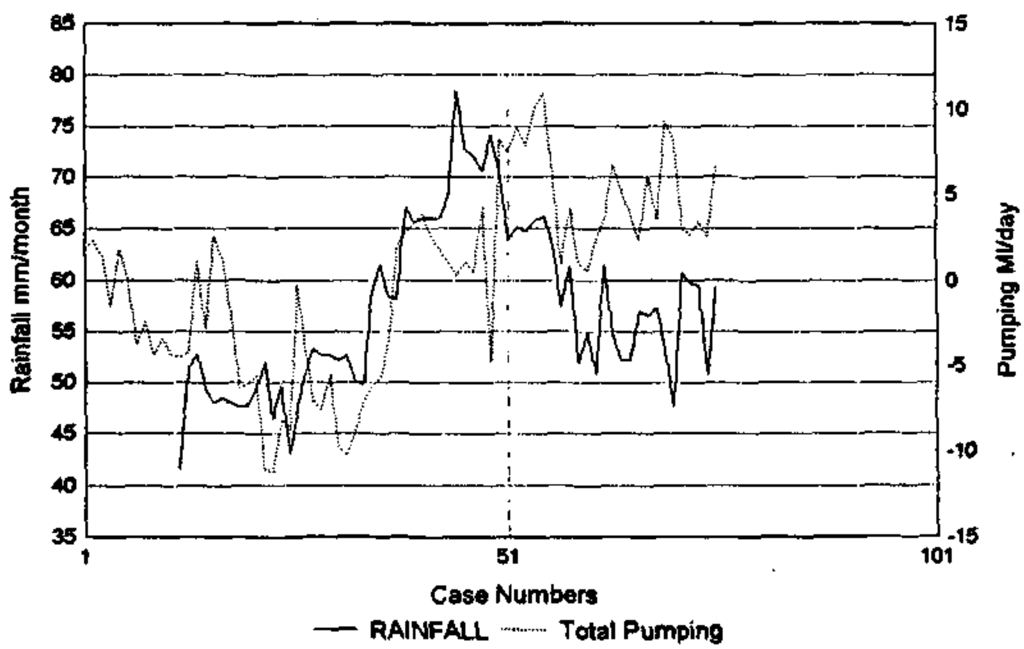


Figure 3.4.20 12 Month moving Average Rainfall vs Total Pumping

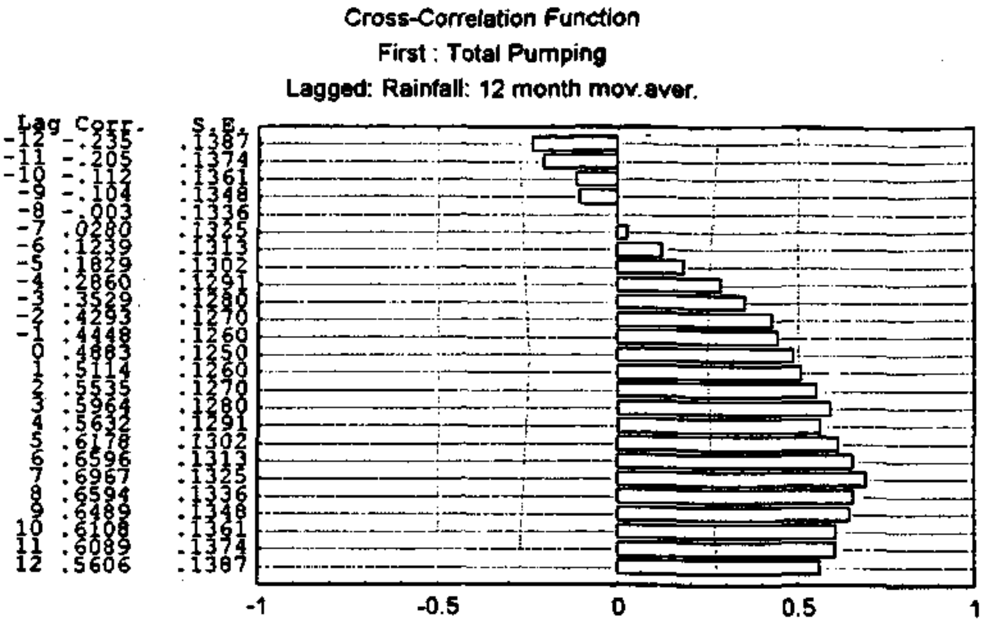


Figure 3.4.21 Correlation Coefficient vs Match Point for 12 Month Moving Average Rainfall and Pumping Rate.

The twelve month moving average analysis shows that with a lag of about 7 months a fairly significant correlation of 0.7 can be obtained.

The results of this part of the investigation show that there is a slow responce time between rainfall and pumping rate. This shows that direct recharge plays an insignificant role in the recovery of water to the underground workings. It is further evidence that the water is derived from the dolomites. Storage in the dolomites acts as a capacitor and attenuates rapid seasonal variation introducing a slow and slight responce which appears some four to seven months after the wet season.

3.4.4 Discharge volume

When the water reaches the base of the dolomites (550 mbd), some of the inflows from the dolomites will be cut off and, depending on the hydraulic gradient, mine water will begin to recharge the dolomites. This will particularly apply in the last 100 to 140 m of water rise. Some of the inflows to the mines via fractures and shafts will be cut off and the volume of water emanating at Nigel No 3 shaft will be less than the volume that has been pumped to maintain stable underground water levels.

The recovery from this point onward will follow a logarithmically decreasing recovery or a typical Theis curve, thus the recovery rate will no longer be linear. This decreasing rate will be due to the decreasing hydraulic gradient which will occur as the dolomites are recharged.

When the water level reaches the main inflow level, estimated to be 25 to 27 metres below surface at East Geduld, equilibrium will be established. At this point the outflow rate at the decant shafts will be equal to the inflow rate from the dolomites. This outflow rate will be lower than the average pumping rate which was used to dewater the mines. Predicting what this volume will be is difficult since there is no way of finding out what proportion of the inflow is derived from high elevations shuch as at Cons. Modder and what proportion is derived from deep fractures and shafts. For example the East Geduld No 1 shaft, known to have been one of the larger contributers to water inflows, is no longer accessable. However the volume should be of a similar order of magnitude to the river flow rate before mining and effluent disposal altered the surface and groundwater flow situation. This estimate assumes that the main flow in the river was derived from groundwater.

The flow rate can therefore be estimated from Mellor's observations that the swamps dried up in winter, the dry period lasting for about half of the year. This means that the flow rate will be lower than the total effluent disposal to the river, which is able to keep the river flowing year round. If the total effluent disposal is 65 Ml/day from Herold (1990), then the outflow at Nigel will be less than this figure, probably half (based on the half year dry period) i.e. 33 Ml/day.

More precise estimation of the flow rate reduction is not possible because:

- No hydraulic records were kept during mining activity
- Lack of information on groundwater conditions in the area
- The inaccessability of the underground workings for direct observation.

3.5 Water Quality

The aims of this investigation did not not allow for a detailed study of the water quality or potential pollution sources within the area of investigation. Work to this effect has been done by Herold *et al.* (1990), Jones *et al.* (1988) and Schoeman (1993). Thus the scope of the investigation did not allow for detailed monitoring. However in order to predict what the mine water quality would be, it was necessary to obtain some idea about the variation in recharge water quality, this involved studying the spatial distribution of surface and groundwater quality. Because this was not a primary aim of this investigation, many of the observations are based on limited data. More detail, including long term monitoring, would be necessary to obtain reliable results and to take the many variables that affect water quality into account, thus the results given in this document should be regarded as preliminary.

3.5.1 Surface Water

The river systems draining the investigation area have been described in Chapter 2. To understand the variations in the surface water chemistry, the sample positions must be visualized, these are shown, superimposed on the drainage network in Figure 3.2.2 on page 17.

Unfortunately no river flow measurement takes place on any of the streams in this area. River gauging on this river system occurs at two Rand Water Board sampling points downstream of the investigation area. Scatter plots of the recorded flows at these points are shown in Appendix 1.

3.5.1.1 Water Chemistry

Scatter plots of the major elements for selected sample sites are shown in Appendix 2. These show that the river samples have distinct seasonal variation and that, for the four most recent years of investigation, slightly increasing salt concentration levels have occurred. These increases are particularly significant when the corresponding increases in river flow patterns (Appendix 1), are taken into account.

Element concentrations at each sample position are shown by bar diagrams in Appendix 4. The graphs have been constructed with the upstream samples on the left and progressively downstream sample sites towards the right hand side of each chart. The following parameters have been chosen as indicators of the progressive change in water chemistry EC, Na, SO_4, Cl, Ca and alkalinity. The bar diagrams show average values, with the range being indicated, where possible, by maximum and minimum values. Widely ranging values at one point may be due to flow variations while the load remains constant. Loads, which are more important than concentrations, could not be calculated as no flow measurement takes place at any of these sample sites.

Investigation of the soils in the area by Schoeman (1993) indicates that irrigation with sodium (Na^+) levels up to 70 mg/l and chloride (Cl^-) up to 115 mg/l is acceptable on the soils in this area. The evaluation of the water chemistry shows that the Na^+ and Cl^- concentrations in the Blesbok Spruit water increase to unacceptable levels below Cowles Dam.

The charts all have a reference to the 'maximum permissible limit', a standard for **drinking water**, proposed by Kempster *et al.* (1985). This is not an attempt to define the water contamination level, but rather to introduce some standard for comparison.

The graphs show that there is a progressive increase in the concentration levels from the first sampling point at Rhynfield dam downstream to the wetlands at Marivale, with significant increases occurring at Cowles Dam. The lower reaches of the river shown by sample sites B8 and B10 have dilution from tributaries which drain agricultural areas. Sample sites B6 and B7 are located on tributaries of the Blesbok Spruit, B6 is located below a large sewage disposal site (Anchor). The tributary sampled at B7 flows through the sand and slimes disposal area used by the South East Rand Gold Holdings Limited (Southgo) and The Sub Nigel Gold Mining Company Ltd. (Sub Nigel). An active industrial area, which includes a tannery, is located upstream of the sample site. Both of these sites show higher salt concentration ranges than most other parts of the Blesbok Spruit.

Contribution from the Rietspruit system is fairly variable, three of the sample sites are taken on small tributaries and are therefore not related. GR7 is downstream of R3, and sites R4 and R5 are located on the main channel downstream of the others. Sites GR2 and GR7 are both located below a large ERGO slime dam. The high salt concentrations at these two sites suggest leachate contamination from the dump.

Effluent contribution to the river systems is summarized in Table 3.5.1. Department of Water Affairs effluent disposal records are compared with those calculated by Herold *et al.* (1990) along with an indication of the water chemistry, shown by the total dissolved solids (TDS) content.

Table 3.5.1 Effluent Discharge To Blesbok Spruit River System

SSO Report (Herold *et al.*, 1990)

Effluent Disposal Point	Ml/day	TDS	Tons/day	Tons/year
Benoni & Daveyton	30.55	632.50	19.32	7052.38
Springs & Kwa Thema	8.90	681.00	6.06	2213.25
SAPPI	22.81	1749.25	39.90	14562.51
SAPPI Irrigation	2.79	4178.50	11.68	4262.07
TOTAL	65.05		76.96	28090.20

Table 3.5.1 Continued

Department of Water Affairs Records

Effluent Disposal Point	Ml/day	TDS	Tons/day	Tons/year
Anchor	3.80	727.00	2.76	1008.35
Daveyton	0.60	517.00	0.31	113.22
Rynfield	0.01	388.00	0.00	1.77
Grundlin	12.23	3272.00	40.02	14606.04
SAPPI to Cowles Dam	0.03	1194.00	0.04	0.04
SAPPI Irrigation	0.02	3550.00	0.07	0.25
TOTAL	16.69		43.20	15729.68

There are other disposal sites whose volumes are not recorded since they do not dispose of the effluent directly into the Blesbok Spruit. These include; J.P. Marais, whose effluent is irrigated on lands adjacent to the Blesbok Spruit, McCoomb, whose discharge is consumed by SAPPI and Brakpan, which disposes into Jan Smuts Dam. It is possible that if the contribution made by these sites could be included, some of the difference between the Water Affairs records and those given by Herold *et al.* (1990) would be made up.

The high salt load contributed by Grundlin sewerage works is disposed into the Nigel Dam, there is little or no outflow from this dam, most losses being due to evaporation and groundwater losses. As this area is extensively undermined poor quality subsurface losses may enter the underground workings.

3.5.2 Groundwater

Groundwater samples were obtained from privately owned boreholes in the area. Geological maps were used to focus the sampling into areas where the boreholes were probably drilled into dolomite, occasional confirmation was obtained for this assumption from owners' records. More samples were taken in the northern half of the study area, where the dolomitic aquifer directly overlies the mine workings. There is hydraulic continuity between the dolomites and the mine workings, facilitated by fissures, particularly in Black Reef workings where much of the off reef development is in dolomite.

Groundwater quality is spatially variable, with excellent quality water being encountered in the extreme north (Welgedacht area). Water showing varying degrees of sulphate contamination is encountered in the vicinity of the Blesbok Spruit north and east of Springs and appears to be related to either coal mining or effluent disposal.

Groundwater quality of the south-western dolomite aquifer is predominantly good with the exception of areas where leachate from the large ERGO slimes dam has contaminated the water. The quality distribution in this area has been studied by the Geological and Environmental Services of the Atomic Energy Corporation, their report should highlight and better define these observations, Walton (1992).

Water classification by means of Piper and expanded Durov diagrams, following techniques described by Lloyd *et al.* (1985), has been attempted. The resultant plots are given in Appendix 4. The majority of samples plot either in a field with HCO_3^-, Mg^{2+} and Ca^{2+} dominant (Field II), described as typical of dolomitic waters by Lloyd *et al.* (1985), or in a field with no dominant cations or anions (Field V). Lloyd *et al.* (1985) state that such waters are the result of simple mixing or dissolution. With no indication of a mixing end member one must accept that dissolution is more probable. The higher SO_4^{2-} of some samples is probably due to exposure to sulphate or reaction with sulphide minerals. Occasional samples plot outside these fields, those for example, with high sodium (Field III and VI) are possibly not from the dolomitic aquifer but from the overlying Karoo, or have been contaminated by surface water. One of the samples showing high sodium and chloride was taken from a monitoring borehole at a waste disposal site, another is a deep, open subsidence into which uncontrolled dumping of predominantly solid waste has taken place.

Thus according to the Piper diagram, groundwater has followed a sulphate enrichment history. The applicability of using this form of classification is questionable since it assumes that the groundwater reacts in a natural way with a natural environment, neither of these assumptions hold in this instance due to the waste disposal practices in the area. However similar ranges, without the sulphate, extremes have been reported from other dolomitic terrain by van der Westhuizen *et al.* (1981) and Simonis (1991). Thus, some of the field indicated on the Piper diagram appears to be a natural scheme for groundwater evolution in dolomites, with the high sulphate waters representing water that has been contaminated.

The waters can be classified into distinct groupings which show that certain waters have the same ratios of elements and are therefore assumed to be related. This type of relationship holds, for example, between sea and rainwater, Raiswell *et al.* (1980). This apparent relationship is borne out in the geographical positions of the samples and implies that the water sources can be traced to near surface sources. The relationship has important implications for the study of the chemistry of the recovered water.

Bar charts of major elements showing the groundwater chemistry are given in Appendix 5. Samples which have been averaged, and plotted together were shown to be related by the Piper and expanded Durov classification studies. The charts show that most of the groundwater, including many of the samples showing some degree of contamination, would fall within the limits proposed for acceptable drinking water.

Samples from Largo (L), President Dam (PD), Strubenvale (SV) and Glen Roy (GR) show consistently higher concentrations than the other areas. It is possible that this is due to the Largo samples having been influenced by past coal mining. Glen Roy samples have been influenced by slime dam seepage. Samples from Strubenvale and President Dam have probably been influenced by a number of factors. Strubenvale is adjacent to the Grootvlei slimes and sand dumps as well as being surrounded by old coal mines. Samples labelled "President Dam" come from an area surrounded by sand and slime disposal sites from the Government Gold Mines with the old Apex Collieries to the west.

Ophori *et al.* (1989) describe techniques of evaluating the chemistry variation over a region. They show that plots of $HCO_3^{-}+CO_3^{2-}$ as a percentage of total anions can be used to indicate regions of groundwater recharge. Using the data gathered during this investigation this evaluation technique indicates that fresh water is recharging the dolomitic aquifer in the Welgedacht area.

3.5.3 Mine Water

The previous discussion on surface and ground water quality reveals that there are areas where contamination is evident. Since the mine water is derived from surface and groundwater sources, these contamination sources will influence the quality of water flowing into the mines.

Chemical information about mine water was obtained from:

- Samples taken at a number of underground seepage points
- Samples of water which has accumulated and is dammed underground
- Historical records of pumped water quality.

Water found underground comes from three possible sources:

- **Seepage water** which issues from the excavated rock at various points. Most seepages issue from closely jointed or fissured zones with collective small seepages making up the bulk of the inflow. Larger flow volumes are usually encountered in the dolomites which are related to the shallower Black Reef workings. Seepage water forms the bulk of the recharge and issues from overlying strata.

- **Surface and rain water** which enters shallow surface workings, excavations and outcropping Witwatersrand sediments. Some of these are located within the Blesbok Spruit floodplain and during high river flow water may enter such openings. One such flood has been reported as having occurred in January 1972 where an estimated 657 Ml/day entered the workings. Apart from such chance flood events in the previous chapter it was shown that this source of water forms an insignificant contribution to the mine recharge.

- **Service water**, which is made up of water used underground in drilling, cooling, humidifying and dust control, is mostly sourced from an underground collection point such as a pump station dam. Most service water originates from water already in the mine, a small proportion is derived from fresh water which is used to humidify the wooden shaft linings in old shafts.

Water collecting underground may be used and re-used as service water, but ultimately it is pumped to surface. On surface it may be used in metallurgical processing and will be disposed of with the slimes, or, if an appropriate permit exists, it may be disposed of into a river system. The chemistry of service water and pumped water should represent a mixture of waters from any of the above sources. It will always show some deterioration due to reaction with minerals in the underground environment and/or contamination during use.

The chemistry of seepage water should represent the chemistry of water recharging into the underground system before mixing or reaction in the mine openings could have an appreciable effect. Thus, this water should give an indication of the quality of the bulk of the water arriving underground.

Bar charts showing concentrations of the main elements found in mine waters are shown in Appendix 6. On these charts a distinction has been made between pumped water (P), dammed water in which mixing and reaction have taken place (D) and freshly recharging seepage water (S).

Analyses given by Bosman (1983), Kempe (1983) and Kinmont *et al.* (1986), show that sulphate contamination is often associated with coal and gold mine water. SRK (1990) refer to such water as acid rock drainage, or ARD. Unfortunately, in this area underground gold mining activity is not the only source of ARD, since defunct coal mines, numerous gold mine sand and slimes dumps and gypsum ($CaSO_4$) application to lands around Cowles Dam (Viljoen, 1992), are also sulphate contributors to the system (Scott, 1992b). For these reasons increased sulphate levels of underground waters cannot be used to show the deterioration of water in the mines, since much of the recharging water arrives with a significant sulphate content.

The chlorine and sodium content of the mine water is similar to the concentrations found in the river water. This is different from the conditions found in other Witwatersrand gold mining areas as shown by the average values given in Table 3.5.2.

Table 3.5.2 Chloride and Sodium Values for Surface and Mine Water from the East and Central Rand, and the Free State Gold Mining Areas.

	Cl^- mg/l	Na^+ mg/l
Surface above Cowles Dam	78.5	81.5
Surface below Cowles Dam	401	337
Mine East Rand	271.9	257.8
Surface Central Rand	60.6	44.8
Mine Central Rand	75.8	75.3
Surface Free State[1]	312.5	164.2
Mine Free State[2]	1657	619

The values on which these averages have been based are plotted graphically and given in Appendix 7. These plots highlight the differences between the different waters and at the same time give an indication of relationships between the waters.

The East Rand mine and surface water have similar levels of Na^+ and Cl^-, the ratio of Na^+:Cl^- is also very similar, while the concentrations and ratio for groundwater is different. This is consistent with surface water courses recharging the dolomite in the vicinity of water losses from the dolomite to the mine openings.

The Central Rand samples have low concentrations of Na^+ and Cl^-, their ratioes are not linearly defined as shown by poor correlations between the plotted points and the linear trends drawn on the plots. A Cl^- increase with fairly constant Na^+ is indicated by both surface and mine water plots, showing that there is a relationship between these waters. Surface dump leachate based on work by Wittmann *et. al.* (1976 and 1977) is consistent with the other findings.

Freeze *et al.* (1979) and Lloyd *et al.* (1985) discuss the use of environmental isotopes as tracers to relate seepage points to surface water sources. Under ideal conditions studies of this nature can be used to:

- Provide a signature of a particular groundwater type that can be related to its origin.
- Identify mixing of waters of different origins.
- Provide information about throughflow velocities and directions.
- Provide data on the underground residence time.

In this system the dolomites are a regional aquifer and as long as water is well mixed isotopic uniformity is attained. Thus, the main inflows may

[1]Data published by Coetzee (1960)
[2]Data gathered by Cogho *et. al.* (1992)

not be distinguished in this way since under these conditions surface sources loose their identity, Verhagen (1992). The sampling of underground seepages revealed distinctly different major element chemistry between samples, thus, some of the source areas and underground seepage points may be relateable to each other. More detailed work and tracing will be necessary to positively identify such relationships. Fontes (1980) shows that if surface waters have high evaporation they become enriched in heavy isotopes compared with normal groundwaters. The swamp regions may fulfill this requirement for evaporation. This form of analysis and source tracing may be an avenue for future research.

The mine water samples have been plotted on Piper and Durov diagrams for classification. These are given in Appendix 8. These diagrams show that much of the water plots in the center of the expanded Durov diagram, showing that there are no dominant anions or cations (Field V). Some of the water plots in a high sodium and sulphate or high sodium and chloride field. These are unusual since there are no sources of chloride or sodium in the mines, but high sodium and chloride water is introduced into the system by industrial effluent.

3.5.4 Relationships Between Waters

The expanded Durov classifications described previously can be used to indicate relationships between the three different water sources, thus, to complete the picture a plot of surface water has also been prepared and is given in Appendix 9. Comparison of water types is acceptable between these diagrams as long as dynamic processes between water types are not implied. Surface water is subject to rapid mixing and gaseous exchange so that the dynamics of the system are very different from those of groundwater.

Most of the surface water plots in either a SO_4^{2-} and Na^+ dominant field (Field VI), or the no cation nor anion dominant field (Field V). A few samples plot outside of these two fields showing that in some places increased chloride and sulphate levels can be found. Some of these samples are one off samples and seasonal variations can be expected. The bulk of the plots, which include long term average values from Rand Water Board sampling, give the best indication of the surface water chemistry classification.

Freshly recharged groundwater plots in field II, surface water is insignificant in this field. A considerable proportion of the groundwater samples, particularly those showing increased SO_4^{2-} levels, plot in field V. The lesser polluted portions of the Blesbok Spruit, including President dam, also plot in this field. Many of the surface and groundwater samples which plot in field V are related geographically. A large number of the underground samples also plot in field V, including the water in the Kimberley Reef basin. These relationships imply that there is some hydraulic continuity between these surface water samples and the underground samples.

Using the same reasoning, the surface and underground waters of field VI and IX can be related. The surface waters include Cowles dam and the more polluted reaches of the Blesbok Spruit below Cowles dam. Underground water includes seepage collected from Grootvlei 3, 4 and 6 shafts and the water in the East Rand Basin.

The ratios of the main elements of some of the surface water, ground water and mine water are very similar. This implies a relationship between these waters. The absolute values of these apparently related samples have been plotted graphically and are given in Appendix 10. From these plots an increase in concentration is evident between the surface and the mine waters, the most significant increase being that of SO_4^{2-}. Sulphate increases do not only take place in the gold mines since the groundwater samples show that contamination is already present in the near surface groundwater.

Boron is commonly used in industry, in boric acid used for galvanic processes, fluxes such as *borax* or sodium borate, leather- and textile impregnation, in disinfectants and in *hard* detergents. It is found in wastewater or in aquifers containing borosilicate minerals, such as: Tourmaline $(Na,Ca)(Li,Mg,Al)(Al,Fe,Mn)_6(BO_3)_3(Si_6O_{18})(OH)_4$, which is commonly found in granites. Because of this strong association with wastewater, and relative rarity in aquifer materials, boron is sometimes used as a tracer showing relationships between wastewater and other waters.

According to Feather *et. al.* (1975) both authigenic and allogenic tourmaline occurs in the gold bearing reefs, but are listed as rare. Thus the geological formations are not expected to contribute high levels of boron to the waters in this study. Most of the boron found can be expected to be derived from wastewater. Thus boron may be useful as a tracer.

Plots of boron vs sample position for surface, ground and mine water shown in Appendix 11, suggest, because both surface and mine water have elevated boron concentrations, that relationships between these waters exist[3]. Groundwater samples usually have undetectable levels of boron.. This together with the evidence presented from the Na:Cl ratio studies adds some weight to a fairly close relationship between surface and mine water.

[3] This evidence should be considered to be incipient as this investigation was not structured to monitor water quality in this area, thus the sampling was not comprehensive. The methods however show that tracing techniques have merit and should be investigated further.

This is not contradictory to the discussion on the source of the water since surface water must enter the mines via the dolomites which lie between the surface water courses and the mine workings.

3.5.5 Predicted Water Quality

3.5.5.1 Factors Affecting Water Quality

Surface water sulphate levels are usually below 400 mg/l, although the highest value measured in the Blesbok Spruit was 1300 mg/l and in the Rietspruit 2300 mg/l, these high levels are not pervasive.

Diffuse surface pollution sources affect the groundwater quality and hence the quality of water entering the mines. Increased SO_4^{2-} levels are indicative of water which has been contaminated in this system and are found in groundwater. There are numerous sources, including sand dumps, slimes dams, defunct coal mines and gypsum management of lands irrigated by effluent. Sulphate levels of up to 1500 mg/l were recorded in groundwater. Leachate from one of the slimes dams in the area had a sulphate content of over 4000 mg/l. This sample also had the lowest pH recorded. The underground seepage had variable chemistry, ranging from similar salt concentrations to the fresh dolomitic groundwater, to a sample with the highest (2869 mg/l) sulphate content of all below surface samples.

Sulphate deterioration also occurs in the underground workings. Stagnant water in gullies had high EC. One such sample had a pH of 2.71 and a SO_4^{2-} level of over 1400 mg/l. This sample, which was taken in a badly kept area where the water had slowly moved through rubble heaps, shows the level of deterioration that is possible. In this case, the gully water could be compared to it's seepage source, showing that TDS had doubled and sulphate trebled while flowing through the loose material.

Most of the water flowing into the mine comes via the dolomitic aquifer and has a high pH. This water buffers the trend to lower pH by sulphide oxidation, so that most of the larger underground water bodies have a relatively high pH. The records show that water pumped from Sallies No. 1 shaft had an average pH of 7.8 (max 8.6, min 6.7). According to Brown (1992) lime was **not** added to this water before pumping (and could never have been added) since there was no infrastructure for lime addition. De Bruin (1992), however, said that while Grootvlei managed the pumping, lime was added at a rate of 71 tons/month. In a special report to celebrate 50 years of gold production at Sallies, Anon (1988) states that the water is treated underground before being pumped to surface.

Until the mined out volume is filled, oxidizing conditions will exist at the air, rock, water interface and deterioration will occur, giving either high sulphate levels, low pH or both. When the mine has filled, oxygen will be eliminated from most places and pH and sulphate levels will only change slightly from the levels of the water entering the system. The water flowing through the mine will follow preferred pathways dominated by holings through the mine boundary pillar at Vlakfontein.

When the mines have filled and water flows out at surface, it will initially have very poor quality since stagnant water will be flushed. The maximum time period for flushing is shown in Table 3.5.3. Due to the presence of preferred pathways, there will be little or no water movement through certain portions of the workings, thus the exchanging volume will be less than the filled volume and the actual time to flush will be less than predicted.

Table 3.5.3 Volume of the East Rand Basin with Flushing based on a Flow Rate Of 61 Ml/day

Total Volume (m^3)	1.78×10^8	
Time to Flush	Days	Years
	2919	8

3.5.5.2 Modelled Water Quality

The water quality of Sallies No. 1 shaft has been modelled using PHREEQE a geochemical modelling program (Parkhurst, *et al.* 1980). The program was used to simulate the removal of lime from the pumped water since all reported analyses reflect the condition as pumped. A recent sample which was bailed from Sallies No 1 shaft when a depth measurement was taken, has also been modelled by PHREEQE, the results are included in Table 3.5.3.

The results show that without lime addition low pH, in the region of 3, can be expected. The geochemical modelling method assumes that equilibrium was attained, as it is unlikely that during the short reaction time allowed by the liming process that equilibrium was attained, therefore higher pH values could be expected. The higher pH values of the bailed sample are therefore realistic. The low pH's found in other parts of the Witwatersrand, such as those reported by Kempe (1983) and Bosman (1983) are not found here due to the higher buffer capacity of the dolomitic water. In the East Rand basin low pH's in the order of 5 can be expected. More recent samples taken at Grootvlei 3 shaft since the East Rand basin level has been reached confirm the idea of relatively high pH. A typical analysis is given in the last column for comparison.

The water quality envisaged here is a worst case type. It is expected, however, that the water quality will improve to a steady state, where what goes in will almost equal what comes out. Thus, the quality of the water will be influenced by the diffuse surface pollution sources. Management of these sources is therefore advisable.

Table 3.5.3 Sampled and Modelled* Water From Sallies No. 1 Shaft.

	Water Pumped from Sallies		Water Sampled at Sallies			Water in East Rand Basin
Elements mg/l	As Pumped	Lime Removed*	As Bailed	CO_2 / Stabilized*	Excess Fe ppt*	Average
Ca	222	199.54	310.03	310.03	310.03	136.32
Mg	118.22	118.22	159.58	159.58	159.58	76.38
Na	206.32	206.32	264.88	264.88	264.88	114.48
K			35.12	35.12	35.12	8.28
Fe	0.02	0.02	63.21	63.21	62.01	19.74
Mn	1.52	1.52	7.83	7.83	7.83	1.08
Al			1.28	1.28	1.28	0.23
Cl	151.23	151.23	148.49	148.49	148.49	162.62
Tot Alk		0.54	269.10	71.31	153.72	190.85
S	851.33	851.33	2347.85	2347.85	2347.85	503.49
N			0.60	0.60	0.60	2.04
P			0.10	0.10	0.10	0.10
F			0.30	0.30	0.30	0.49
B			0.30	0.30	0.30	0.43
pH	6.84	3.12	5.19	5.18	4.65	6.36
pE	1.20	9.66	1.2	3.08	3.08	

Thus the recovered water will have a pH of about 5, high sulphate (>800 mg/l) relatively high chloride and sodium (>200 mg/l). Cloride and sodium levels would be similar to the levels presently found in the stream, lower concentrations observed in some of the mine samples is due to dilution from fresh groundwater. Fe and Mn will also be unacceptably high but their precipitation could be enhanced by air saturation and the resulting ferrichydroxide precipitation could be collected in holding ponds before release to the river. Other heavy metals such s Ni would coprecipitate with the ferrichydroxide.

3.6 Impact Assessment

The most important impact of water recovery in the Far East Rand basin will be the flooding of currently operating mines. These mines will close down permanently as the cost to dewater them at some future date would be astronomical. These aspects and the economic implications for the region have been dealt with in GME (1991) and are not the concern of this investigation.

Two aspects are important concerning the recovered water: Chemical influences on the catchment system and geotechnical implications for the region. These will be dealt with in the following paragraphs.

3.6.1 Catchment Modelling

A complete study of the Vaal River Barrage catchment is being undertaken by the Department of Water Affairs. The area covered by this investigation will be included in the catchment study.

SAPPI, a significant contributor of effluent, is presently installing an effluent purification system. This system should remove some of the chloride and sodium and improve the quality of the water in the Blesbok Spruit from Cowles Dam onward.

With such changes and new information becoming available, the computer model for the assessment of inflows into the Vaal Barrage system, Herold (1980), is presently being updated. Thus the currently available version was not considered to be useful for evaluating the impact of the discharging mine water.

3.6.2 *Geotechnical Implications*

The following unfounded geotechnical hazards have been predicted and have been used as an argument against allowing the water level to recover completely:

- Increased seismic activity.
- Springs will reappear in the Springs area and certain low lying areas will be flooded. Slimes dams and dumps situated in these low areas will become unstable.
- The dolomites will become unstable and sinkholes will develop.
- Water inrushes will occur into ERPM where mining is still active and where the water level, in the ERPM basin, is maintained below 2618 mbd.

3.6.2.1 Seismic Activity

Seismic activity on the Witwatersrand, is due to the relief of accumulated stresses in the rocks surrounding mined excavations, there would be no such activity without mining, the magnitude of the events are proportional to the scale and depth of mining (Fernandez, 1994). The stresses are released by shear failure in the form of instantaneous brittle failure of the rocks, or by movement along existing linear features such as dikes, shear zones or pre-existing failure planes. The end result of failure and movement is closure of the mined openings, after which the system becomes stable, on cessation of mining the seismic potential decreases rapidly and seismic events stop within one to two months. Some of these aspects have been described elsewhere in this report, where it was shown that such closure was experienced to a greater extent in the deeper workings and were the dips are shallow.

Water recovery will influence the seismic activity in two ways:

- By filling the mined excavations with water, additional support will be given to the system and some of the stress around the mine openings will decrease, thus decreasing the potential for seismic events.

- The addition of water to existing linear failure zones will decreases their resistance to failure. Thus an initial increase in seismic activity is possible. The release of stress is often marked by incremental releases, most of these are barely perceptible and cause no damage. With the addition of water the increment size could increase and thus the magnitude of individual events may be larger. Note: This activity would be latent and would have happened at some time in the future anyway.

Unfortunately there are no seismic recording stations in the vicinity of the East Rand mines, as this has traditionally been a relatively stable area. Thus even if a station were established to monitor events during the water recovery stages, no comparisons with previous times could be made.

The workings below 1606 mbd had been flooded before 1988 without seismic incident. Between 1988 and 1991 the water level was maintained at 1606 mbd. Since 1991 a further 385 metre water rise has occurred so that, at the time of writing, the water had reached 1178 mbd. During the recovery period no unnatural seismic activity was reported. The absence of recent mining activity and support given by the water, will mean that the flooded areas are stable. As the remaining dewatered workings become shallower the potential for seismic activity in the dry excavations decreases as stated by Fernandez (1994).

3.6.2.2. Reappearance of Springs

If water is allowed to decant in the Nigel area then no changes are expected to occur in the vicinity of Springs. The lowest points along the Blesbok Spruit where springs reportedly existed in the past will be 20 meters above the decant level in Nigel. Thus a downward flow into shallow mine workings will still be experienced and any losses from the dolomites to the river will be small, seasonal and will not cause large scale inundation.

The river is fed by more water from effluent than it was from springs in the past. This is shown by the fact that the seasonal drying characteristic of the swamp area has changed since Mellor's (1921) observations. Thus the level of water is more dependant on other factors than the occurrence or reoccurrence of springs an even if they did reoccur their effect would be masked by the other sources in the system.

3.6.2.3. Dolomite Stability

Dolomite instability has been experienced on the West Rand associated with gold mining (Wolmerans *et. al.* , 1978). This experience has given rise to the fear that similar experiences could occur on the East Rand. Karst, the term for cavernous dolomite, is found on the West Rand, where it has contributed to enormous mine inflows and dewatering problems. Dikes have divided the karstic dolomites into compartments, springs related to these dikes have very large flow volumes. Dewatering, for mining purposes, on the West Rand has caused some catastrophic collapse in the karstic dolomite.

The potential of dolomite instability is related to the karstic nature of the dolomite. If the dolomite is karstic and there are caverns which have been dewatered by mine pumping, on recharge, as water moves through the caverns, wad, which has accumulated due to weathering of the dolomites and which contributes to support, may be eroded. This will create potentially unstable situations. Once the caverns are completely filled with water, stability will increase.

The potential instability presumes that cavernous dolomite exists, in a report describing the geology of this area, commissioned for this project, Buttrick *et. al.* (1992), do not give any evidence, in this part of the East Rand, of karst or sinkhole development. Experience from the Wast Rand shows that instability became evident during active mine development not during the waning stages of mining, no such instability was reported on the East Rand. It is possible that caverns are present and that because they are stable that they have not been detected. Enslin (1969) discusses geophysical methods which have been used to the delineate such structures. Such studies were not within the scope of this investigation but should be carried out as a priority.

The inflows to the mines although closely associated with the dolomites have been associated with rapidly weathering sills in the dolomites, the thermal alteration zones around those sills and with fissure zones. No inflows were reported associated with karst like features.

The area is traversed by some very prominent dikes these have been discussed in other parts of this report. The work by Day (1980), shows that some of these dikes have a more prominent geophysical identity than the compartmentalising dikes of the West Rand. In spite of this, there has been no evidence of compartmentalisation of groundwater in the dolomites, and springs in this area were related to interbedded chert bands and not with any of the dikes.

Du Toit (1921) noted that there was a marked lag between the spring outflow and a rainfall event. This together with the evidence from this investigation that there is no sudden response to rainfall in the water appearing underground (from the dolomites), suggests that a recession hydrograph for these springs would not have a marked peak relating to flow from a network of high velocity drains, as would be expected in a karst aquifer. Padilla *et. al.* (1994) in a study to characterise karst springs show that this type of response suggests that the water filters relatively slowly to the outflow points with homogeneous characteristics reminiscent of a porous intergranular network.

This evidence therefore suggests that the East Rand dolomites, while being significantly water bearing are not karstic, the water flows in an intergranular network associated with sills and their alteration haloes. This also explains the lack of compartmentalisation and associated springs. The water flowing in a more diffuse way is able to flow through diffuse alteration and fracture zones in the dikes. The compartmentalising effect is not as prominent as it would have been had large volumes of water been moving rapidly through discrete channels in a karst aquifer. For the same reason the inflows to the mines are more diffuse and smaller in volume than similar occurrences associated with karstic dolomite.

When the water reaches about 550 metres below datum it will start recharging the dolomites, will have potential to dissolve the dolomites because of its acidic nature. The evidence from the type of the inflows suggests that the recharge will not follow open channels but will permeate a porous dolomite, this means that dissolution will be spread over a wide area and will not (initially) follow preferred channels. Dissolution of the dolomite has potential to initiate karst development in this area the extent of the karst development will depend on:

- The flow rate of mine water through the dolomites.
- The water quality
- The degree of preferred pathway that may develop through the dolomite.

The first point is difficult to determine before the mines are completely filled. It will depend on the hydraulic gradients that are established under recharged conditions which in turn are related to; recharge, topography, groundwater consumption from the dolomite aquifer and potential (future) water consumption from the dolomites. Each of these aspects would require careful monitoring and investigation.

The present flow system into the mines must have induced a fairly regional hydraulic gradient toward the mines, it is possible that if the outflow points at Nigel are allowed to flow that the gradients in the dolomites will be unaffected and there will always be a flow from the dolomites into the mines. This means that once the lower parts of the dolomitic basin have been recharged with mine water, no further flow will take place through the dolomites. Water flowing through the upper portions of the dolomitic aquifer will be moving from the dolomites into the shallow mine workings, therefore the water involved in exchange in the dolomites will be of good quality.

The water rising in the mines has been frequently sampled, thus a fairly good idea of it's quality can be predicted.

The degree of preferred pathway that may develop is closely related to the amount of water that may flow through the dolomites.

To attempt to quantify the potential dissolution and neutralising effect of the dolomite on the mine water, the recovery was modelled using the geochemical equilibrium model PHREEQE, Parkhurst *et. al.* (1980). Using this model the water was allowed to equilibrate with dolomite and the resulting dissolution was recorded. Three samples were used in an attempt to evaluate the effects of the predicted and worst possible water quality.

The three samples were:

- Rising water in the East Rand Basin,
- Kimberley Reef basin at 4 shaft dam
- Stagnant underground water. This sample had the lowest pH of all samples taken underground on the East Rand.

The following circumstances were assumed to vary as the water recharged:

- The rising water was equilibrated under assumed new environmental conditions in a cavernous dolomite. For example, it was saturated with oxygen and oversaturated minerals were precipitated. This is termed equilibrated water.
- The water was allowed to dissolve dolomite to equilibrium, unnatural over saturation that may have developed during the simulations was constantly removed by precipitation.

The results of this modelling are given in Tables 3.6.1 to 3.6.3

Table 3.6.1 Modelled Four Shaft Dam Water (Concentration mg/l)

	Initial solution	Equilibrated	Recharged
Ca	163.93	163.93	335.47
Mg	115.97	115.97	220.02
Na	232.20	232.20	232.20
K	13.22	13.22	13.22
Fe	0.10	0.00	0.00
Mn	0.50	0.50	0.50
Al	1.10	0.39	0.39
Cl	262.35	262.35	262.35
HCO_3	183.05	175.12	1220.35
SO_4	868.40	868.40	868.40
N	8.80	8.80	8.80
B	1.41	1.41	1.41
P	2.31	2.31	2.31
F	0.40	0.40	0.40
pH	7.4	5.19	6.13
pE	0.53	15.65	14.71

Table 3.6.2 Modelled East Rand Basin Water (Concentration mg/l)

	Initial solution	Equilibrated	Recharged
Ca	82.16	78.98	267.73
Mg	52.51	50.33	165.08
Na	294.27	294.27	294.27
K	13.33	13.33	13.33
Fe	0.10	0.00	0.00
Al	0.30	0.02	0.02
Cl	225.84	225.84	225.84
HCO_3	164.75	142.78	1287.47
SO_4	584.05	584.05	584.05
N	3.21	3.21	3.21
B	0.70	0.70	0.70
F	1.99	1.99	1.99
pH	8.3	5.11	6.18
pE	0.53	13.42	14.67

Table 3.6.3 Modelled Worst Water in East Rand Mines (Concentration mg/l)

	Initial solution	Equilibrated	Recharged
Ca	179.56	179.51	2814.37
Mg	42.06	42.13	1640.40
Na	363.24	364.03	364.03
K	4.03	4.01	4.01
Fe	34.07	0.00	0.00
Mn	2.29	2.29	2.29
Al	29.68	29.64	29.64
Cl	563.70	564.60	564.60
HCO_3	148.27	57.15	1570.53
S	1479.35	1360.96	1360.96
N	0.10	0.10	0.10
B	0.73	0.73	0.73
F	0.80	0.80	0.80
pH	2.71	2.30	4.55
pE	0.6	2.10	-0.78

Since dolomite has the chemical formula $CaMg(CO_3)_2$, the predominant changes in the water relate to the dissolution of this mineral and the associated pH changes. Other element concentration changes are due to precipitation.

For example Iron:

During the simulations pH and Eh conditions change so that the solubility of the iron species changes and iron precipitates as $Fe(OH)_3$. This is a common phenomenon observed in water flowing into underground mine openings. The theoretical chemistry of these observations is explained and documented by many investigators among them; Garrels *et. al.*, (1965), Hem, (1970), Stumm *et. al.* (1981) and Mathess, (1982). The inflow may be a small cascade or diffuse dripping, where mixing with oxygen occurs, the Eh condition of the water changes and iron precipitates. In some of the very old mine openings, this precipitated iron may form stalactite and stalagmite like features while in others it contributes to the clayey sediments which accumulate in the disused workings. These are shown as Plate 1 and 2 in Appendix 1.

The precipitation of iron in this way has the effect of lowering the pH, as can be seen from the release of hydrogen ions in following chemical equation:

$$Fe^{3+}{}_{(aq)} + 3H_2O \rightarrow Fe(OH)_{3\,(s)} + 3H^+$$

The lowered pH of the equilibrated water is explained by this equation.

The pertinent changes in the water chemistry are summarised in the Figure 3.6.1, for 4-Shaft Dam water only. The other samples show similar trends but differ in concentration depending on the beginning water chemistry.

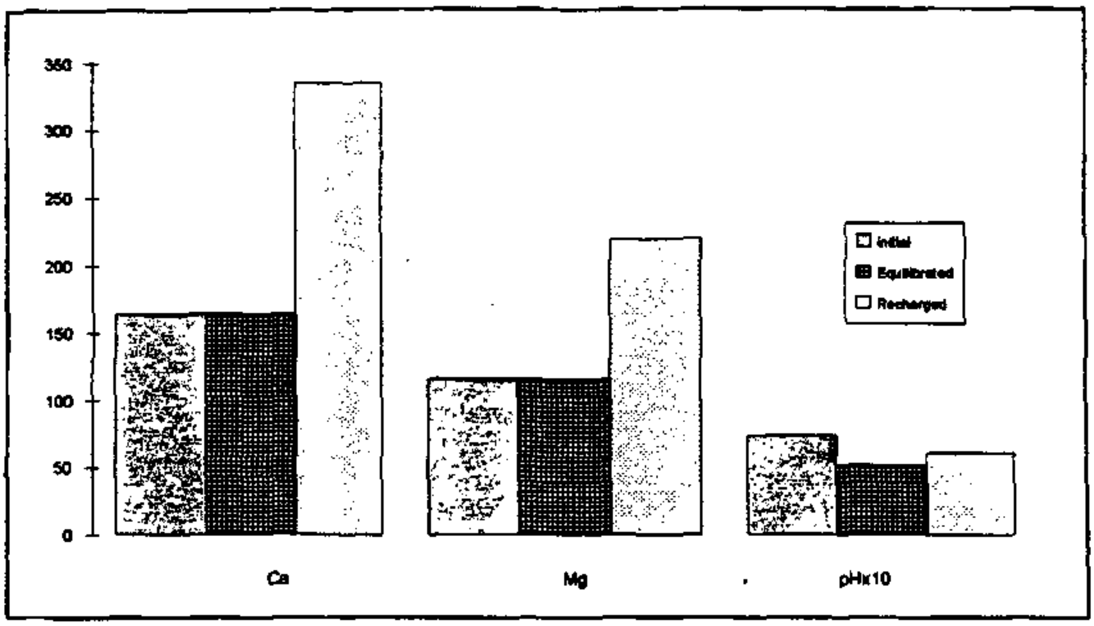


Figure 3.6.1 Chemistry Changes in Mine Water During Recharge of Dolomites

The predicted effect on the dolomite is dependant on the flow rate through the dolomite, this value is unknown and cannot be determined within the constraints of this project. Thus three possible flow rates, viz. 20, 4 and 1 Ml/day have been used to place an order of magnitude value on the amount of dissolution that may be possible using the modelled chemical changes. The tonnages that can be expected to dissolve have been converted into volumes of potential karst development. These results are shown in Table 3.6.4.

Table 3.6.4 Potential Dissolution of East Rand Dolomite

	Flow Rate Ml/day	Tons/day dolomite consumed	Tons/year dolomite consumed	Volume (m^3) per year dissolved
4 Shaft Dam	20	15.98	5828.70	2045.16
Water	4	3.19	1165.74	409.03
	1	0.8	291.44	102.26
East Rand Basin	20	17.58	6414.30	2250.63
Water	4	3.51	1282.86	450.13
	1	0.88	320.71	112.53
Worst Water in	20	245.11	89527.89	31413.29
East Rand Mines	4	49.02	17905.58	6282.66
	1	12.26	4476.39	1570.67

These calculations show that given the predicted water quality at a very low flow rate through the dolomites, which is more probable than a higher flow rate as has been shown in previous discussion, the volume that will be dissolved per year would be around 100 m^3. This is the equivalent to the volume of a large room of just over 6 by 6 by 3 metres. However if the quality of the water is significantly worse than predicted or the flow rates are greater then the volume generated may be significantly different.

The cumulative effect of this type of dissolution with time could increase the karstification of these dolomites significantly.

3.6.3 Inrushes at ERPM

Investigation of the potential for inrushes at ERPM has not been carried out. The potential problem is listed but cannot be commented on at this stage.

3.7 Management

Two aspects must be considered in formulating a management plan, these are the volume of water that will emanate and the quality of the water.

3.7.1 Water Volume

On full recovery certain points have potential to discharge mine water, these have been identified and described in Chapter 4 of this report.

The volume of water discharged to the Blesbok Spruit can be evaluated in context with flow measurements made by Rand Water Board at Heidelberg. These are shown in Table 3.7.1.

Table 3.7.1 Volumes of Water in Blesbok Spruit at Heidelberg

		Mine Outflow Ml/day			
		Maximum		Minimum	
		65		30	
	River Flow Ml/day				
	Measured	River flow plus mine outflow			
		Maximum	Percentage Increase	Minimum	Percentage Increase
Annual Average	109	174	60%	139	28%
Wet Season Average	191	256	34%	221	16%
Dry Season Average	42	107	156%	72	72%
Maximum	459	524	14%	489	7%
Wet season average as a percentage of maximum flow			56%		48%

The table shows that the wet season flow rate at Heidelberg would increase by between 1.2 and 1.3 times, this would still be approximately half of the flow rate after heavy rain. The dry season flow would increase between 1.7 and 2.6 times.

Farmers along the Blesbok Spruit would welcome additional water, some are even prepared to ignore the quality, believing that any additional flow would be good.

These estimates suggest that the channel at Heidelberg will cope with the additional water flow. However the lands or streams close to the identified water discharge points may not be suited to such flow.

Nigel No. 3 shaft is located adjacent to a tributary of the Blesbok Spruit, in a flat sided valley, about 75 metres to the east of the valley bottom. The valley is in a disturbed state, in this area, due to excavation and reclamation of mine waste heaps. Some 100 meters below this point the stream enters the town lands of Nigel where it is channelled for 2.3 kilometres to the confluence with the main channel of the Blesbok Spruit. This stream and channel would be seriously affected by the volume of water flowing from the mine and redesign of the channel would be necessary.

The other possible outflow points:

- Marivale No. 7 Shaft is located 130 metres away from the swampy region of the Blesbok Spruit at Marivale.
- Marivale No. 4 shaft is on the eastern side of the river 600 metres from a small tributary which is 1.8 kilometres from the main Blesbok Spruit river channel.

Channelisation and proper design would have to be planned for both of these situations if outflow occurred at these sites. Discharge of the mine water to the natural wetland may be acceptable since wetlands have been identified as areas in which mine water may be improved.

Piping from near surface may also be possible so that water will not emanate at the identified position but at some other engineered and perhaps more acceptable point. Near surface piping would prevent recharge of the geological formations around the outflow point and the related swampy conditions that may develop, this is an added advantage of this approach.

A solution that has been proposed is that, water should be pumped from below the dolomites at 200 or 300 meters below surface. This is an expensive option but prevents recharge of the dolomites, thus maintaining the present moisture, water levels and hydraulic gradients. The position ofthe pumped outflow could be chosen to best suit the system. Similar volumes would have to be pumped and disposed of into the river system as were pumped during active mining. Treatment would have to cope with a fairly fixed volume. Most of the considerations for this option are the same as if mining on Kimberley Reef continues and the mines are dewatered from 1040 mbd. Pumping costs would be lower due to a head difference of about 500 metres, but the depth component of pumping is only a portion of the cost. For example a pump station would have to be constructed, pumps would have to be indefinitely maintained and the water pH would have to be indefinitely monitored or controlled.

3.7.2 Water Quality

The above discussion about water volumes assumes that the water is of an acceptable standard, or treated so that it can be discharged into the river. This investigation, in Chapter 3.5 has shown that the water will be of poor quality and on outflow, untreated water, will have a detrimental effect on the river system.

The management approach should therefore be to limit the impact on the system. This could be achieved by:

- Water treatment

  Treating the outflowing water to an acceptable standard to be released to the river. This means that a treatment plant would have to be designed and constructed and implies long term operation and management.

  This option would be the least complicated to implement and predictable control could be achieved. Long term escalation of costs and management of the technology may be a problem in a developing country. Sludge and wastes that are generated by any treatment technology would have to be disposed of, this often only changes the location of the original problem.

- Limiting the outflow volume

  Limiting the outflow volume implies that direct inflow positions in river courses must be blocked and groundwater inflow from the dolomitic aquifer should be stopped or slowed down. This could be achieved by establishing a water utilization project from the aquifer. Thus the water would be used before it enters the mines. For this approach to be successful the dolomitic aquifer would have to be investigated in detail, its hydrogeologic variability understood and extraction scenarios modeled.

  Ongoing long term monitoring and management of the extraction system would have to be conducted in order to prevent lowering of the water table and reversal of hydraulic gradients away from the mine aquifers. This would result in flows of mine water into the dolomites and would cause dissolution and pollution problems.

  This system improves the water quality by preventing water from entering the mines where it becomes degraded. Extraction of usable groundwater, makes effective use of a resource, for example, to supply good quality water to near-by developing communities such as Daveyton. It also effectively confines the mine water to the mine aquifers, thus keeping salts in an already spoiled system and not generating new disposal problems.

  Controlling the inflow volume should be investigated, for use in tandem with other options, as it could be used to lower the volume that will have to be pumped (if mining continues) or may lower the volume that will emanate from the identified outflow points. It may be possible to lower the outflow volume to a level where discharge to the stream may be possible without treatment. Alternatively the stream may be used as a natural wetland to attenuate the mine water pollution problem. Such a natural system would eliminate the disadvantages of a treatment plant but could not be used at high flow volumes.

No positive guidelines as to which option would be preferable can be given at this stage since the water quality in the mines cannot be predicted with certainty.

Shafts where depth measurement and water sampling could take place have been identified. Monitoring of these points should be planned. When data is available from such monitoring, various solutions can be more fully evaluated.

More detailed evaluation and monitoring of conditions in the catchment, to obtain reliable long term parameters, will be necessary, before decisions can be made. Suggestions for these requirements are discussed in the next section.

3.7.3 Monitoring

Monitoring of recharging water levels in the mines. *Mine water hydrograph.*

Present bi-monthly monitoring is being undertaken by Grootvlei, their depth measurements are made at suitable points underground, and at the same time, water samples are taken for chemical analysis. Since Grootvlei is located in the northern part of the basin, where most of the inflows occur, it would be important to measure water levels and take samples in the southern part as well. To evaluate the effect of water passing through the system. There are a number of shafts on Sub-Nigel which may be suitable for this purpose.

The monitoring should be conducted at suitable intervals to generate the equivalent of a springflow hydrograph. Initial monitoring may have to be detailed in order to define, for example, response times to rainfall events, subsequent monitoring could then be programmed specifically for monitoring wet and dry periods. This information could be used to define hydraulic parameters for the system, as proposed by Ford *et al.* (1989) and Padilla *et. al.* (1994).

Such monitoring will also be useful for evaluating the effectiveness of other remedial measures, such as preventing inflow

Monitoring recharging water quality. *Mine water Chemograph.*

According to Ford *et al.* (1989) this monitoring is equally important to water level monitoring for the evaluation of the system and can be used, for example, to define the type of recharge whether diffuse or via a surface sink. Thus it could add some evidence to determine whether the water is derived from the dolomites (diffuse inflows) or from surface water courses (line inflows).

The method will also be essential for determining the final water quality.

By monitoring at different positions in the system, the degree of improvement/deterioration of the water due to preferred pathway, density stratification and natural buffer capacity of dolomitic water could be investigated.

Groundwater monitoring.

Borehole survey and continued water level monitoring of boreholes in the East Rand dolomites. The aims of this exercise will be to:

- Define the aquifers potential and long term yield

- Define hydraulic gradients
- Delineate groundwater quality regions
- Comparison with mine water responses to rainfall.
- Calculate recharge
- Help construct a water balance

Some of these parameters will be essential if the *extraction to control inflow* remediation option is chosen.

Surface water monitoring.

Flow gauging and monitoring of the Blesbok Spruit river system. To define volumes and positions of losses to the dolomites or mine openings with the aim of preventing or limiting such losses.

Surface water chemistry is monitored by Rand Water Board, some of the local industries, such as SAPPI and Grootvlei. These results should be used and augmented where necessary for comparison with the mine water chemograph.

Pollution source monitoring

All pollution sources should be identified, their discharges monitored, in an attempt to investigate their influence on the groundwater quality. This will be essential if large scale use of the groundwater in the dolomitic aquifer is to be established.

This information will also be important in evaluating groundwater quality regions.

Rainfall monitoring

This information will be essential for evaluating recharge and for water balance calculation.

Land use and vegetation cover should be evaluated for use with, runoff, recharge and evapotranspiration calculations, changes with time should be monitored.

3.8 Conclusions and Recommendations

3.8.1 Conclusions

The aims of this study were to determine what the long term effects of rising water in the East Rand mines will be. The following points have been addressed:

- **Recovery**

Water flows into the mines are derived from the East Rand dolomites with a minor component from direct recharge after heavy rainfall. The dolomites cover a large area in this region, their storage capacity attenuates seasonal influences so that a fairly constant inflow to the mines is experienced.

The recharge to the dolomites is derived from rainfall in exposed dolomite areas and from effluent disposal into the Blesbok Spruit river system which flows over dolomitic terrain for much of its course through the investigation area. The predominant inflow regions are in the northern and north-eastern part of the investigation area, coinciding with dolomitic cover of the Witwatersrand Supergroup rocks and the course of the Blesbok Spruit.

Due to the constant inflow rate to the mines recovery has followed a linear trend with minor changes in rate determined by mine volume changes. This linear recovery will continue until the dolomites begin to be recharged in the last couple of hundred meters of recovery. Thus predictions of dates, at which water will reach certain levels, can be extrapolated from the linear recovery trend. At present the recovery rate is 0.236 m per day, this can be used to show that recovery to the proposed new pump station at Grootvlei will be achieved in mid 1996 and that recovery to surface from that depth would take a further nine years. Thus if mining were to be discontinued so that dewatering never recommences, complete recovery could be expected in 2005.

- **Discharge**

The mines are interconnected, dewatering of all the mines in the East Rand basin was achieved from the mid 1960's until 1991 from one pumping position. Thus on recovery the water is free to fill all the mined out areas without compartmentalisation. Water flowing into the mining areas in the northern parts of the mine basin has a head of some twenty metres over the lowest shafts connected to the basin, thus water will have potential to decant from those lowest shafts. The lowest shaft which has the greatest potential to decant is the Nigel (Southgo) No. 3 shaft, which is located in the valley of a tributary of the Blesbok Spruit, North of the central business district of Nigel. This outflow point is dependant on a connection between Marivale and Vogelstruisbult mine workings still being open. If this connection is restricted then Marivale 4 or 7 shafts could form outflow points.

The inflow rate has been relatively constant thus the pumping rate gives an indication of the maximum potential outflow rate. The average pumping rate over a period when the water level was static is 64.5 Ml/day. Most service water used during this period was derived from inflowing water, thus inactivity on the mines will not reduce this volume significantly. It has been shown that as water reaches the dolomites, particularly the main inflow depths which are related to sills at approximately 100 metres below surface, some of the inflows will be cut off. Water will recharge the dolomites and hydraulic gradients will change, this will reduce the inflow rate during those stages of recovery.

Since no studies of the hydraulic properties of these dolomites have been undertaken, the potential decrease in flow rate cannot be determined accurately. However the observed flow in the Blesbok Spruit, before changes brought about by development, reported by Mellor (1921), could be used to give an indication of the potential minimum flow rate. The Blesbok Spruit which was fed by springs from the dolomites dried up during the dry seasons of the year, during the wet season, by Mellor's description, the stream and swampy area appears to have carried as much water as it does at present. If the underground workings are receiving all the spring water that would have issued to the stream, then without effluent disposal the stream would be dry all year. Effluent disposal therefore provides what the stream had been gaining from the dolomites, but this volume is continuous. Thus if the dry season can be considered to last for half of the year then the flow volume from the dolomites can be estimated to be half of the effluent disposal to the system. This gives an estimate of the minimum volume that can be expected to issue from the mines on full recovery.

These estimates could be refined by proper stream gauging and a detailed study of the hydraulic properties of the East Rand dolomites.

- **Water Quality**

Factors affecting the quality of the rising water.

The quality of the rising water is strongly influenced by the quality of the recharging water. There are certain areas, related to mine waste disposal, industrial activity, defunct coal mines and poor quality surface water that introduce water of low quality to the underground workings.

Further degradation in the mined openings is possible during the recharge period or during any period when the mines are kept dewatered for continued mining operations. This is due to the oxidation of pyrite in the reefs and in any loose reef material that may be left in stopes or other mine openings. This oxidation lowers the pH of the water.

The water flowing from the dolomites has a high buffer capacity which acts against pH lowering caused by pyrite oxidation, thus pH rarely goes below 5. Sulphates and other salts in solution give the water an unacceptably high TDS, much of this is derived from surface pollution sources.

Study of the water chemistry indicates that boron may be used as a tracer. Surface waters are contaminated with boron, groundwater does not contain boron and there are no significant sources in the mined rocks, these facts suggest that there is a relationship between surface and mine water. This relationship shows that unuasally high Na^+ and Cl^- concentrations in the mine water could also be related to surface sources.

Predicted quality in filled mines.

The water quality in the filled mines is predicted from samples taken of dammed underground water and rising water in the mined basins. This is the best basis for prediction since conditions in these basins are similar to what they will be on full recovery. Water collected in stagnant pools in underground workings is often isolated from the recharge water and may be degraded to a much greater extent thus having very low pH and high TDS. Water in actively filling areas is more dynamic and has not degraded to the same extent. Water in the Kimberley Reef basin should show the level of degradation that will be reached, since typical Kimberley Reef ore has a higher pyrite content than Main Reef ore. Thus representative samples from the Kimberley Reef basin could be used as indicators of the typical water quality that may be expected.

- **Impact Reduction**

Reduction or control of inflow/outflow water.

As long as mining continues the inflow rate will be relatively consistent at an average of 64.5 Ml/day.

If water is allowed to recharge the mined out volume completely until it discharges at surface a minimum of 30 to 33 Ml/day could be expected to discharge. The indications are that this would be a relatively poor quality water and some permanent treatment plant would be required to control pH and remove dissolved solids from the water before discharge to the river system. This is a costly long term option. A better option would be to utilise the groundwater before it enters the mines and becomes degraded. This would, at the same time, minimise the inflow volume, thus reducing the volume of outflowing poor quality water.

A method of control that has been proposed by the mines is to continue pumping, but from shallower depths, their suggestion is from the base of the dolomites. The hydraulic conditions in the dolomite would not change and the pumped volume would be the same as when mine dewatering remained active. This approach would reduce pumping costs due to the lower lift required, but the volume would remain high and pre-pumping and post-pumping water treatment would be required.

Inflow control is a better option since the water flowing into the mines in some places is of good quality, this could be used before degradation occurs.

Better effluent clean up which is being investigated by some of the industries will also ensure that some of the river water has a better quality and hence losses from the river system to the mines will be of improved quality. This improved recharge would also improve the quality, particularly with regard to the Na^+ and Cl^- concentration of the mine water.

Reworking of mining wastes will remove some of the other diffuse sources which contribute to poor quality recharge water. Thus with time and perhaps added control measures the quality of water recharging the dolomites could improve.

Prevention of ingress into the mines where degradation starts or continues would be a good control measure. This could be achieved by consuming water from the dolomites in such a way that a balance is achieved between recharge and consumption which minimises the inflow to the mines.

This investigation has shown that there are areas of excellent water quality in the dolomitic aquifer as well as areas of poor quality. The control measures may have to extract water from all parts in the dolomite, thus a detailed study of quality variations in this aquifer would have to be undertaken, to properly plan water use.

Monitoring and modelling of the situation would be required to note any improvement in water quality with time and to prevent contamination of presently clean groundwater due to hydraulic gradient changes. Such improvement is expected due to:

- The proposed improvements in industrial effluent
- The recovery and rehabilitation of mine waste heaps.

Losses of surface water must also be minimised. These losses would have to be pinpointed by stream gauging in the area and then minimised by channelling the stream and/or blocking surface sinks at appropriate places.

3.8.2 Recommended Further Work

From this investigation certain points where future detailed investigation will be necessary have become apparent:

1. Detailed investigation of the dolomitic aquifers in this region;
   - Determination of stability in the dolomites, identification and delineation of cavernous zones.
   - Detailed water quality assessment, hydrogeological mapping and evaluation of the diffuse sources of pollution into the dolomitic aquifer.
   - Evaluation of the dolomitic aquifer's potential for present and future groundwater supply. The recovered water table levels and quality must be included in this assessment.
   - Environmental isotopic or tracer studies to relate sources of recharged water to surface water and pollution sources. From this the contribution that the mines make to water deterioration can be estimated.

2. Hydrological assessment of the stream(s) at and below the discharge point(s), to ensure that these streams are capable of accepting the qualities and flows indicated by this investigation, without, for example, erosion damage, flooding or de-stabilising dumps in the vicinity.

3. Drilling of deep observation holes or the identification of shafts which can be used to monitor the water level rise. Regular monitoring of the rise in water level and quality at these sites. Suitable equipment will have to be obtained and developed for this exercise. Detailed monitoring during the rainy period can be analysed to identify the parameters of the system.

4. Refinement of the predictions made by this investigation as new data becomes available.

5. Evaluation of the geotechnical implications for ERPM.

Chapter 4 Central Rand

4.1 Introduction

4.1.1 Background

The Central Rand mines were dewatered to the deepest mining depths untill.1974 at which time most of the mines in the central part had stopped working. During the period 1975 to 1977 water was allowed to flood the deepest workings of the Central group of mines up to a level of 1083 mbd. Up to this level the water is confined to the central group of mines by intact or plugged boundary pillars. At the beginning of this investigation the two mines at the extreme, West and east borders of mining activity were still actively mining and dewatering the mines. During the final stages of the investigation one of these mines announced that it would be closing down. This shows the tentative nature of the mining and therefore dewatering in this old mining area. With the complete cessation of mining activity evident in the near future continued dewatering will stop. Unless the government bears the cost of dewatering and treatment of the pumped water, the water will be allowed to fill the mines.

4.1.2 Method of Investigation

No previous geohydrological investigations have dealt with this area, although the companies involved in mining have assessed the water inflow rates for the purpose of designing their pumping facilities. Limited monthly reports were submitted by some companies to the Department of Water Affairs (DWA). This historical data concerning water quality and pumping rates has been used in this investigation together with field investigation to augment the data and for control. The data was obtained from records kept by the relevant mines, the Government Mining Engineer, Rand Water Board and the Department of Water Affairs.

Most of the underground workings are inaccessible, thus information about the water flowing into the mines had to be obtained from monthly records submitted to the DWA. Records were only available for Durban Roodepoort Deep (DRD) and East Rand Proprietary Mines (ERPM). DRD from March 1990 to July 1993 and ERPM from October 1977 to September 1992. These records included the pumped volumes which were calculated from the pump power consumption and water chemistry, which was unfortunately limited to a few select parameters. Thus, neither the reliability of the analyses nor missing parameters could be calculated. Samples were taken at 50 boreholes across the Central Rand to establish the groundwater quality distribution and water elevations, where possible. Regions close to the mining affected areas were concentrated on. Unfortunately boreholes in these areas are fairly rare as they are predominantly industrial areas or residential areas of high density. These are zones where private boreholes are not common.

Rand Water Board publish annual reports, giving monthly averages of the quality of surface water running into the Vaal Dam and Barrage. Four of the most recent reports, 1988 to 1991, and one earlier report, 1976, have been used to study 30 sampling points; Thirteen on the Klip River and Elsburg Spruit and four on the Natal Spruit. An additional 64 samples points were monitored during this investigation at surface water bodies in the area.

Water entering the mines was sampled at 36 different points many of them monitored over three sample periods.

Municipal effluent disposal takes place downstream and onto unrelated geological formations from the mining affected areas. Thus this form of effluent disposal does not affect recharge to the mines.

4.2 Description of the Investigation Area

The study area is referred to as the **Central Rand**, covering 675 km² and including all or portions of the municipal districts of Roodepoort, Johannesburg, Germiston and Boksburg. It is geographically and geohydrologically distinct from other mined areas on the Witwatersrand. The investigation area is defined by the 2895 and 2910 km south and 75 and 120 km east, grid lines of the South African co-ordinate system. The position in context to the rest of South Africa is shown in Figure 4.2.1.

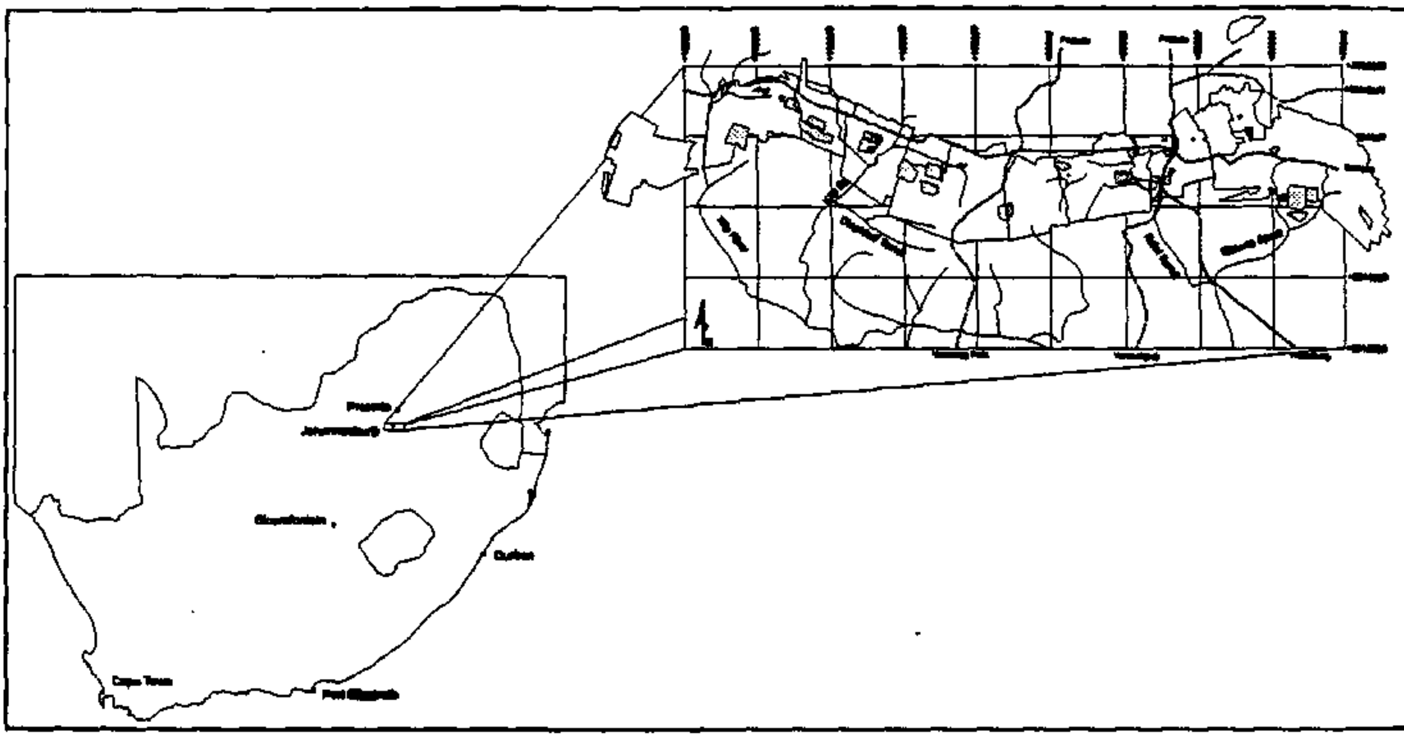


Figure 4.2.1 Location Map of the Central Rand

4.2.1 Topography and Surface Hydrology

The northern boundary of the investigation area forms a watershed between streams flowing north into the Crocodile and then Limpopo Rivers and so to the Indian Ocean, and streams flowing south into the Vaal and then Orange Rivers which flow into the Atlantic Ocean.

The topography consists of a number of parallel hills elongated in an west to east direction. These hills are geologically controlled, in physical geography this type of terrain would be defined as a scarp and vale terrain. The hills and their associated streams are prominent features which have given the area it's name; Witwatersrand, directly translated it means: White Water Ridge. The hills form some of the highest country in the Transvaal with elevations of up to 1800 m above sea level. The valleys between the ridges have elevations around 1640 m above sea level.

The valley forming the centre of the investigation area contains many man-made topographic features, the mine waste heaps. Some of these have the same relief as the natural topography, the highest dump (now removed) having reached 1815.6 metres above sea level. This valley is also the main region of interest, due to the mining activity being concentrated here.

Small headwater streams drain the parallel ridges flowing north or south, depending on the direction of slope, to collect in the valleys between the ridges. Once in the valley they flow eastwards or westwards to join the main streams which have used geologically weak zones to erode through the ridges and flow southward. This drainage pattern is termed a trellised drainage and is geologically controlled. This pattern has significance for this project as the streams cross the outcrop at numerous points. The pattern is shown in Figure 4.2.2.

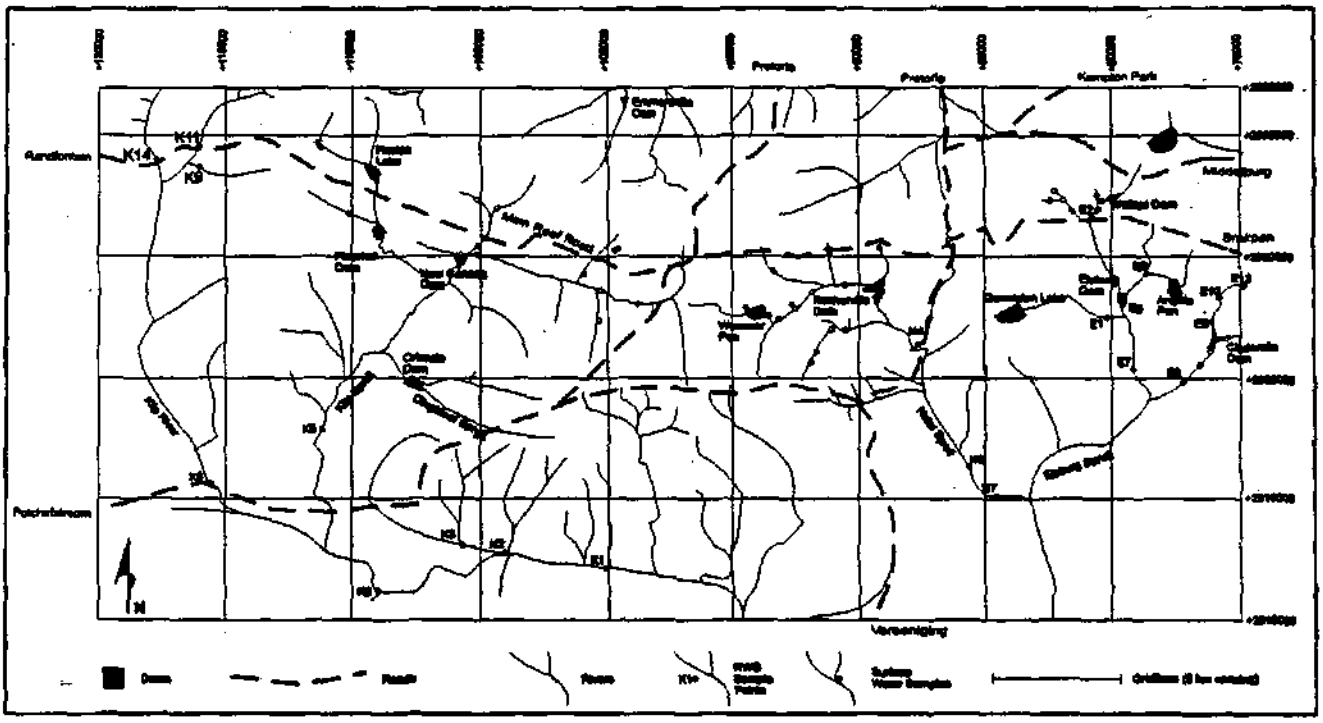


Figure 4.2.2. Drainage Pattern on the Central Rand

The streams in the central and western parts of the area collect into the headwaters of the Klip River which flows southwards via a fault line valley to the main west to east flowing portion of the Klip River. In the central portion the streams converge into the headwater stream of the Natal Spruit and in the east a number of small streams form the headwaters of the Elsburg Spruit. These three rivers flow southward meeting confluences where the subordinate stream name falls away. Thus the Elsburg and Natal Spruits merge to continue as the Natal Spruit, the Natal and Riet (flowing in from the East Rand) Spruits merge to flow to the confluence with the Klip River, as the Riet Spruit, from where the Klip River continues to its confluence with the Vaal River.

In the headwater areas of these streams they flow through some of the most industrialised, developed and densely populated land in South Africa. They also drain an area that is world renowned for mining activity and related mine waste heaps. Drainage from these waste heaps collects in toe dams and seepage control dams in the stream valleys. None of the streams are in pristine condition, many carrying high dissolved solid loads as well as effluent from industries, informal settlement and inadequate sewer systems. If the area were now to be named after the features that originally gave it it's name it would be called the Vuilwatersrand (Dirty Water Ridge). This is unfortunately the price for industrial development in a relatively dry area.

The streams draining this area flow into the Vaal River Barrage, which has, in the past, been the main supply reservoir from which the area derived it's potable water. In recent times it has become too costly to purify the water in the Barrage to the required standards. At the same time sludge disposal from the purification system has become a problem. Thus at present, much of the water supplied to communities on the Witwatersrand is derived directly from the Vaal Dam. This is not considered to be an acceptable long term solution and ways of cleaning or lowering the salination of the Barrage are being sought so that, in future, Barrage water could again be supplied as potable water. This project forms a part of that greater investigation, since possible deterioration due to mine water, needs to be evaluated along with all the other influences on the Barrage water quality.

Water quality monitoring is conducted in this area by Rand Water Board. Many of their sample results have been used, for this project, to give background data on the surface water quality. These sample sites were augmented by 51 other surface water samples, taken during this project, some of which were sampled more than once as a check. Unfortunately the time constraints of this project did not allow for long term monitoring. The relevant sample sites are shown in Figure 4.2.2.

4.2.2 Climate

The climate in this area is temperate, highveld (Schulze, 1966), with a short cold winter and a hot summer. Rainfall occurs in summer predominantly during thunderstorms which are experienced from October to April.

Records published by the Department of Water Affairs (1985), show that an average precipitation of 732 mm/year is recorded at Jan Smuts Airport, with average Symons pan evaporation of 1765 mm/year. For the short period on record, Union Observatory in Johannesburg, recorded an average precipitation of 767 mm/year, with average Symons pan evaporation of 1491 mm/year.

4.2.3 Land Use and Economic Potential

Most of the investigation area is highly developed, including suburban, industrial and central business district type zones. It is one of the most highly developed areas in South Africa. In spite of this there is an undeveloped strip running parallel with and over the mined reef zone on which there has been little development due to the early mining and mine ownership, and later due to waste disposal and geotechnical problems of the ground.

South of the Reef outcrop, the land is covered with mine sand dumps, slimes dams and in some places shafts and mine village settlement. Many of these dumps are being removed, and the newly cleared land, which is often situated close to the Central Business district of Johannesburg, is redeveloped. Industrial parks, office parks and suburban development have been developed, or are planned, on such sites.

Primary mining activity is waning, with one mine still in production at the time of writing. Secondary mining activity is practised at two sites where underground scavenging activities are in progress. Remining of the mine waste heaps has developed since the early 1980's when the first sand reclamation plant, RM3, was developed in the area. Thus there are still a number of metallurgical plants in operation in the area, some of the slimes dams are still active, and gold production has not stopped.

The industries and the financial centre that developed to serve the mining area are still very active, forming the business hub of South Africa. The area is a major work provider and because of this, attracts large numbers of jobless, hopeful people. It is presently one of the fastest growing urban areas in Africa. This inland centre of business activity is unique in the world and is due to the gold mines.

Recent political changes in South Africa have brought about a change in the living style in some of the City Centre areas and Ghettos with much higher density living than the areas were originally designed for, have developed. Apart from the cultural and socio-economic changes found in these parts of the city this change has also placed a strain on the water supply and sewer systems.

4.2.4 Geology

4.2.4.1 Geological Setting and Conditions

Rocks of the Witwatersrand Group outcrop prominently from Roodepoort to Germiston, an area referred to as the Central Rand. The formations continue to the west and east of this type area but in these parts, the outcrop is mostly obscured by a covering of younger sediments. Outcrop can be traced for a strike distance of 38 km and forms the northern boundary to the area of mining activity. For much of this distance outcrop workings were started when mining began and can still be seen today. Outcrop workings can be found on Main, Main Reef Leader, South, Bird and Kimberley Reefs. There are also many incline shafts associated with the outcrop workings, these were used initially to follow the reef which dips at up to 80 degrees.

The Central Rand mining region is terminated in the west by the Roodepoort and Saxon faults which introduce an unmined area of some 2 km between mines of the Central Rand and those of the West Rand. The eastern extension is truncated by a region of gold poor sediments, known as the Boksburg Gap, which separates the mines of this section from those of the East Rand Basin. The southern extremity is undefined, exploration drilling conducted in the mid to late 1980's, some nine kilometres south of the outcrop, revealed that gold bearing reefs continue at depth.

Many of the structures in this area trend roughly N-S, these include faults, joints and many of the trends of near vertical intrusive rocks.

The Witwatersrand sediments and the geology of the area have been extensively described by Mellor (1921), Brock *et. al.* (1964) and Pretorius (1986). Therefore only a brief description of the mined reefs will be given.

On the Central Rand, in the investigation area, the Central Rand Group rocks outcrop, the relevant stratigraphy is given in Figure 4.2.3. A more complete column relating these rocks to the overlying and underlying formations, is given in SACS (1980).

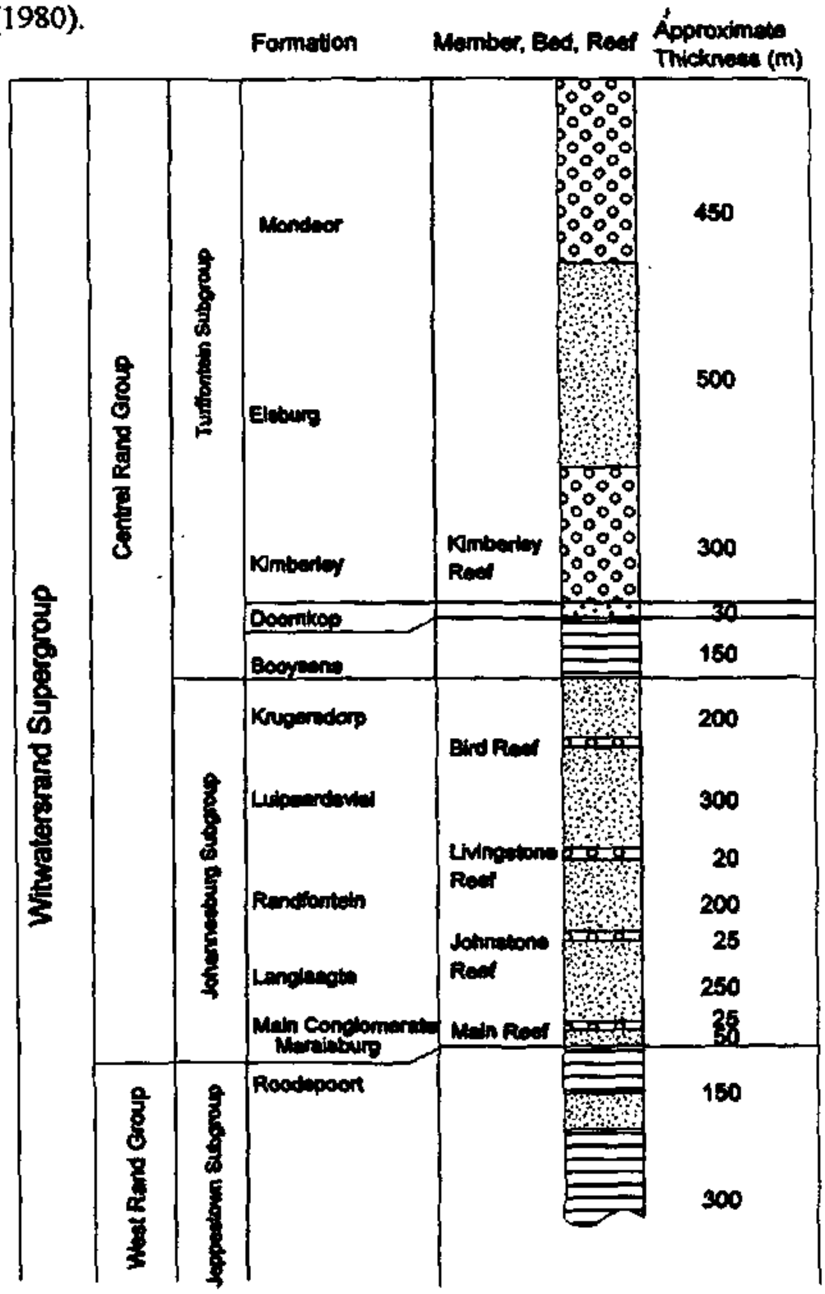


Figure 4.2.3 Stratigraphy of the Central Rand (After SACS, 1980)

The stratigraphy can also be shown as a north to south section across the study area, Figure 4.2.4, where the topographic relationships with the geology are shown.

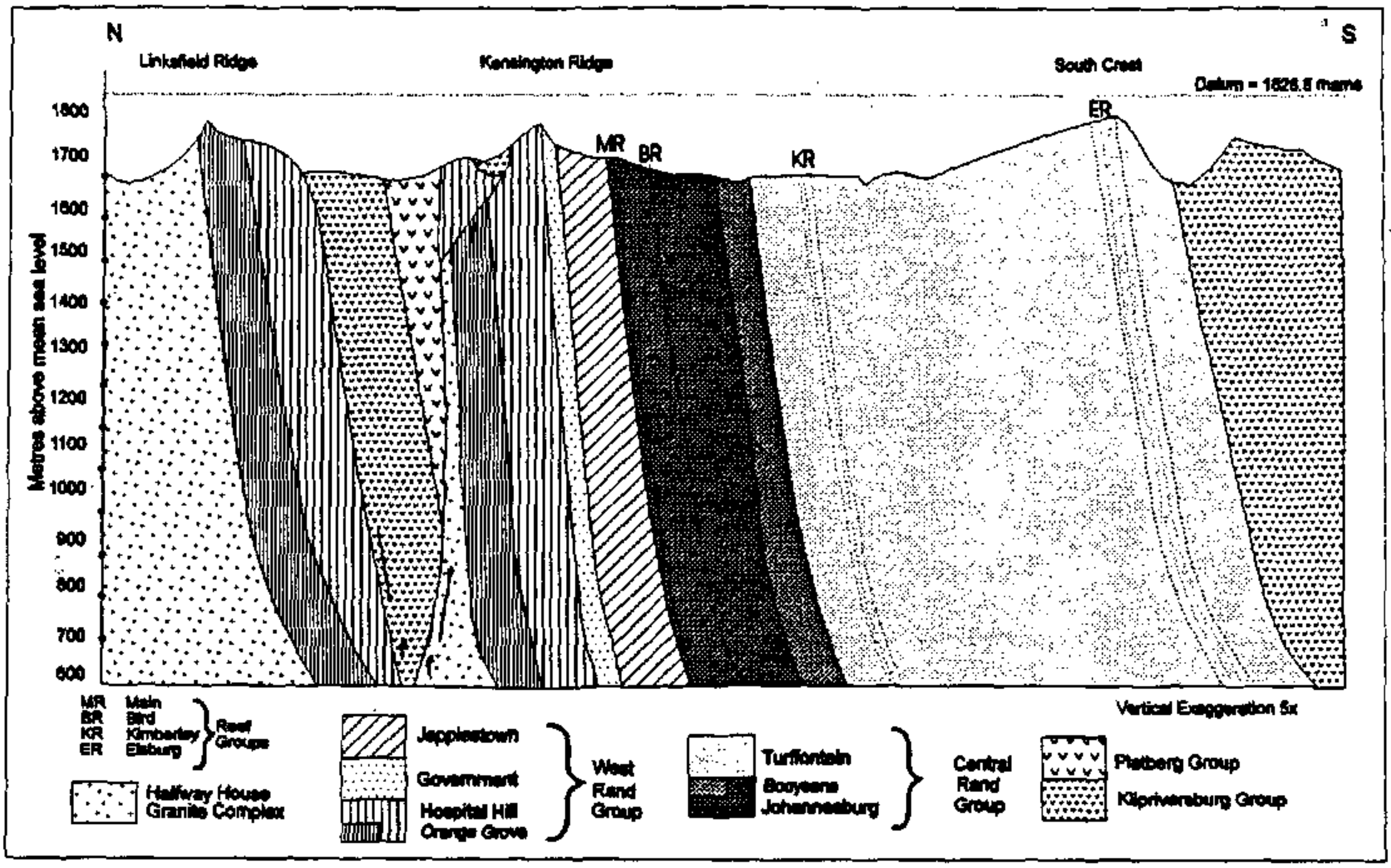


Figure 4.2.4 North South Section from Linksfield Golf course to Klipriversberg

Ten gold bearing reefs have been mined with Main Reef, Main Reef Leader and South Reef having had the most consistent gold values and have therefore been the most extensively exploited. The reefs strike east-west and thin from west to east, so that on the eastern portion of ERPM the three reefs merge, to become what is called the Composite Reef.

Grohmann (1988) shows that this apparent thinning is actually due to South Reef having a low angle unconformity with the lower reefs and truncating them on ERPM. By comparison on the East Rand the Composite Reef is referred to as the Nigel Reef or simply the Main Reef. Some of these features are shown in Figure 4.2.5.

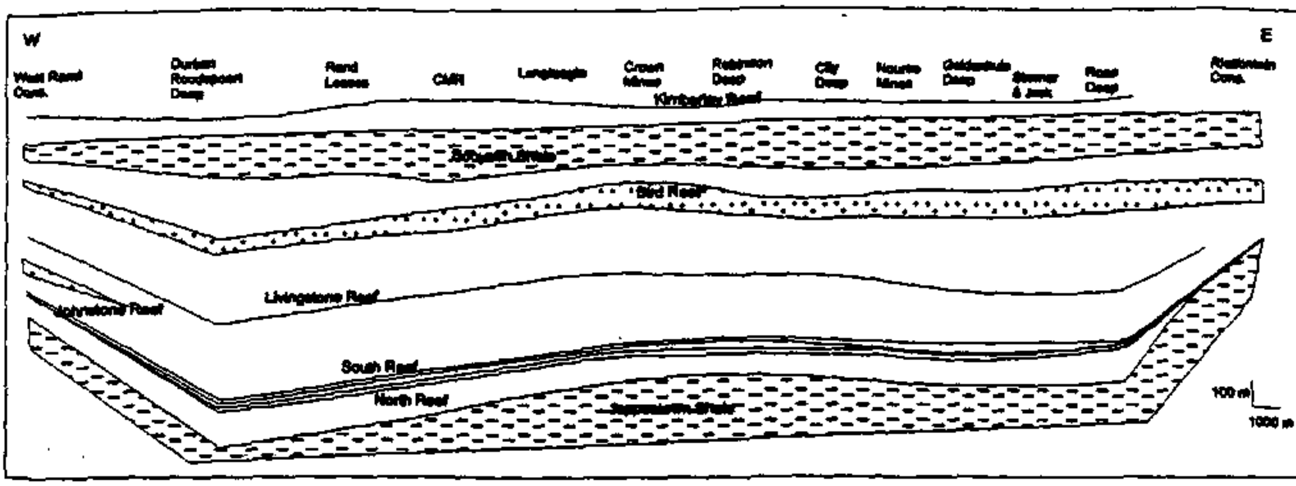


Figure 4.2.5 Strike Section From Roodepoort (W) to Germiston (E), Showing the Truncation of the Main Reefs in the East to Become the Composite Reef. (After Myers *et. al.* 1989)

4.2.4.2. Description of the Mined Reefs

4.2.4.2.1. Main-Bird Reefs

These reefs are steeply dipping at the surface, up to 80°, but the dip decreases with depth and at 120 to 150 m below surface dips of 25 to 30° are found, Brink (1979). At the deepest workings on Crown Mines 3000 m below surface dips of 16° were encountered.

Descriptions of the reef packages are summarised in Table 4.2.1.

Table 4.2.1 Main-Bird Reef Characteristics

Reef	Reef Characteristics	Mining
North Reef	Small pebble Narrow 0.15 to 0.45 m.	Haulage and development often took place on this reef. It has been mined in a few places.
Main Reef	1 to 6 m thick. In some places pyritic quartzites have formed in erosion channels up to 25 m thick.	Main Reef has been worked on DRD and in the east on ERPM until it is cut off by South Reef.
Bastard Reef	Parting between Main Reef and Main reef Leader. It is a shaley quartzite with a few scattered pebbles.	Occurs from Simmer and Jack to ERPM.

Table 4.2.1 Continued

Main Reef Leader	Most important reef mined. 0.5 to 2 m thick located immediately above or very close to the Main Reef. Better sorted larger pebbles than Main Reef. Consistent high gold values.	Mined continuously from Rand Leases to Simmer and Jack This is a narrow conglomerate, so to create reasonable stope heights the underlying, but essentially barren Main Reef was also mined.
Middle Reef	Several conglomerate bands with a total thickness of 0.76 m.	Extends from Crown Mines to Witwatersrand Mine. Was worked in a few places on Village Main.
South Reef	Second most important reef. 0.5 to 3 m thick. Consists of up to 7 small pebble conglomerates. From Simmer and Jack/Rose deep it cuts off the other reefs and contains eroded remnants of these reefs.	This reef occurs from 15 to 60 m above the main reef and has been extensively mined throughout the area. It does not persist as far down dip as Main Reef Leader. In the eastern sections it has been mistaken for Main Reef.
South South Reef	Consists of a number of narrow reefs.	Found between City Deep and Wits Mining Co., but mined only on Simmer and Jack.
Livingstone reef	Consists of up to 25 small pebble conglomerate bands.	Was mined on the Wolhuter mine
The Bird Reefs	3 to 5 reef bands. Individual bands are up to 0.5 m thick.	Limited mining from Rand Leases to Crown Mines on White Reef and Monarch Reef.

4.2.4.2.2. The Kimberley-Elsburg Reefs

The Kimberley reefs have been mined on DRD and to a lesser extent from there to Crown Mines, they are only economically important again east of ERPM. Although 17 reef bands have been identified, only four have gold values that warrant mining and two are prominent and continuous enough to be traced (UK7 and UK9). The Kimberley Reefs contain coarser pebbles than the conglomerates of the Main Reef package and generally also have a higher pyrite content.

The Elsburg reefs are the most prominent reefs in this area, they are coarse pebble conglomerates, with pebbles up to 15 cm in diameter. The reefs are up to 100 m thick but are lenticular and not laterally extensive. They form prominent ridges from Mondeor to Elsburg, see Figure 4.2.5. Because of their Topographic prominence and ease of identification early mining took place on these reefs but the gold values were sporadic. In mines on the West Rand the Elsburg Reefs are mined for their Uranium content.

4.2.5 Ground Water

Ground water has been used in this area since the beginning of mining activity. Most residents in the early Johannesburg obtained household water from dug wells, this implies that there was a shallow water table in the area. According to Brink (1979), there is a trough like depression along the total strike of the Jeppestown subgroup, which was occupied by pans and marshes before development in this area. Florida lake is apparently a dammed remnant of the swamps. Brink (1979) goes on to say that the water table is now confined, in compartments between dikes and sills and varies in depth from 3 to 30 m. He also suggests that the predominance of yellow residual soils in the area is evidence of recent lowering of the water table. For example, the Jeppestown sediments would have decomposed under saturated conditions and yellow hydrated iron oxides would have formed, their continued existence shows that the soils have not yet desiccated.

Brink (1979) also says that the paucity of groundwater found in deep basements of high rise buildings is unusual, compared with similar basements in other cities. Excavation for the Standard Bank Centre, 300 m North of the outcrop, found groundwater at 23 m. At the Carlton Centre, 500 m north of the outcrop, groundwater was encountered at 30 m, and 180 000 l/day were pumped from wells around the perimeter of the excavation to dewater the site during the first 6 months of construction.

The evidence given by Brink (1979) does not give the impression of undue lowering of the water table as he implies. In addition there are large buildings where permanent basement dewatering is necessary, including, Sanlam Centre (Life Towers) and 11 Diagonal street, both located 400 m north of Main Reef outcrop. In contrast to Brink (1979) this evidence suggests that, surprisingly, the groundwater in close proximity to the mined reefs remains undisturbed!

Rather than due to water table lowering, the drying of the swampy area could have been a consequence of:

- Surface water use by the mines. This was in demand from the beginning of mining activity (Werdmüller 1986, Gray 1940 and Jeppe 1946) and was in such short supply before 1895 that the continued operation of the mines was threatened.
- Changes in the biota of the swamps, due to development, can lead to preferred flow paths and channels forming through the swamps. This drainage would dry out parts of the swamps (Rogers 1992).
- Land reclamation for development and canalisation of flow channels would also have drained the swamps.

During the drought of 1985/1986, to overcome their own water restrictions, the Johannesburg Municipality drilled boreholes on Municipal land. This was done at parks, sports fields, cemeteries, swimming pools, fire stations and bus depot's, so that water could be used in gardens, swimming pools and for vehicle washing.

The borehole drilling was supervised by geotechnical personnel and more information is available about these boreholes, than is usually found for privately owned, production wells. Information from the drilling records is summarised in Table 4.2.2.

Table 4.2.2 Johannesburg Municipality Boreholes and Water Level Data.

Borehole Number	Location	Water Strike * Level (m)	Standing Water Level (m)
PR 13	Brixton Cemetery	27, 33 & 41	13.7
PR 15	Civic centre	40 & 56	31
PR 16	Pioneer Park	9 & 37	5.9
PR 17*	Hector Norris Park		6.7
PR 18*	Rotunda Park	56	9.8
PR 19*	Christopherson Park		19.6
PR 23	Roberts Park	25, 43 & 64	4
PR 24	Jubileum Park	27	7.6
PR 25	Arthur Block Park	19 & 36	20
PR 26	Braamfontein Cemetery	16, 32, 43 & 68	18.5
PR 31	Joubert Park Nursery		17
PR 54	Southern Suburbs Sports Club	35.6 & 79	13
PR 55	Bowden Park	62	40
PR 66	Southern Suburbs Sports Club	35 & 60	2.3
PR 67*	Pioneer Park		dry
PR 69*	Southern Suburbs Sports Club	50	16.1
PR 70	Crown Gardens Swimming Pool	30 & 50	3.5
PR 73	Mayfair Swimming Pool	34	18
PR 74	Pullingar Kop	76, 86 &108	25.6
PR 74	Ellis Park Swimming Pool	26 & 30	0.5
CB 1	Robinson Tip Site	18, 25 & 35	10
CD 1	Civil Defence Dog School	21 & 50	2.1
ED 1	Reuven Electrical Workshops		
ED 2	Reuven Electrical Workshops		
FD 1	Brixton Fire Dept.	30 & 75	11.2
FD 4	Fairview Fire Station	15	25
HD 2/HD 2a	Newclair Cemetery	26	11.5
HD 7*	Riverlea		Dry
HD 8	Riverlea Park	49 & 55	38
HD 10	Longdale Stadium	22 & 42	15
HD 11	City deep Compound	26	25
HD 14	Antea Hostel	12, 40 68 & 85	4
HD 15	City Deep Compound	30, 40 & 54	30
MD 1*	National Fresh Produce Market		Dry
MD 2*	National Fresh Produce Market		Into mine

Table 4.2.2 Continued.

MD 3	National Fresh Produce Market	10 & 40	10
TD 1	Trojan Bus Depot	39	10.2
?*	Roadworthy Testing Grounds		Dry
	Average	40	15
	Average First Water Strike	28,5	

* These were unsuccessful boreholes and were not equipped, most have been covered.

* Many of these boreholes are low yielding and although equipped, are not used. This could have been a consequence of using a driller/deviner who must prove the successfulness of his methods by bolstering the success of the hole. For this reason the water strike records may also be questionable.

These boreholes show that, within the vicinity of the reef horizon and often above mined out areas, these groundwater strike depths and rest elevations are normal for this climatic region Hodgson (1993). The rest water levels that are recorded, in all cases but one, show a rise after the initial strike depth. This phenomenon is found in confined/semiconfined and fractured aquifers. The variation in water level between boreholes is a function of topography, it is also caused by fractures and perhaps compartmentalisation by intrusives as suggested by Brink (1979). However most of the intrusives encountered in the old workings at shallow depths (<300 m), are highly weathered, to the extent that they must be supported. Such supports take the form of built arches in the older workings and steel cages in the newer workings. These intrusives are usually also zones of underground seepage providing preferential flows from the intrusive. When mine development cut through such rocks this preferential flow was called an inrush. In this condition these intrusives are hardly likely to form barriers to the near surface groundwater. At depth some of them do confine the water to specific parts of the underground workings since they act as walls when left unmined.

The land use in the vicinity of the reef outcrop is predominantly light-industrial or suburban. Suburbs are characterised by very small properties, with little or no garden. Very few land owners drill boreholes in an area like this, thus there were very few sites where groundwater information could be obtained apart from the municipal boreholes.

The evidence presented suggests that no wide cone of dewatering has developed around the mines. The aquifer is probably of a fractured type and water level fluctuations are predominantly due to the type of aquifer and not to mine dewatering.

4.3 Gold Mining

4.3.1 Introduction

After the discovery of the rich Main Reef horizons in 1886, mining companies soon leased or purchased a continuous band of property along the Main Reef outcrop on the Central Rand. Initially the companies were small, some consisting of only one claim and mining was chaotic. As deeper mining developed the small companies were amalgamated and the originally fragmented properties were joined, the resultant lease boundaries of 1955 are shown in Figure 4.3.1.

At the time of writing there were four mines still working underground. Gold was also being recovered from sand dumps by East Rand Gold Operation (ERGO), Rand Mines Mining and Milling Operation (RM3) and Village Main Reef Mines. Boreholes have been drilled by Rand Mines to evaluate the potential of developing deep mines south of the present lease areas.

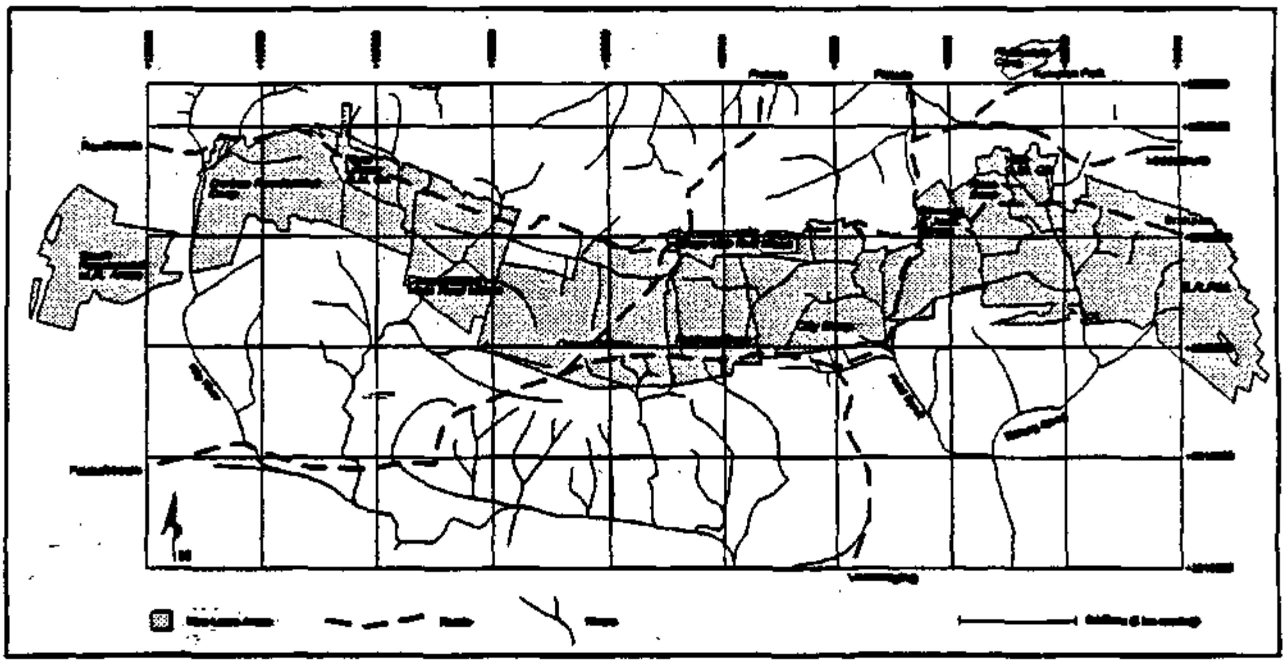


Figure 4.3.1 Mine Lease Boundaries as they were in 1955.

Living conditions in the mining settlement were similar to those of a present day shanty town. Gray *et. al.* (1940) reported that each inhabitant dug a well to obtain water for their private use, this practice was apparently so pervasive that it was dangerous to walk around in the dark. Hand dug wells imply that there was a shallow water table in the sediments and near surface deposits at that time.

Surface water was also at a premium for use on the early workings and each stream was claimed by some operator. Many small dams were constructed in an attempt to provide a continuous supply of water to the mines and recovery plants. These appear to have been poorly constructed as repeated failures and flooding were reported. Flooding affected outcrop mining to a greater extent than deeper workings, due to direct inflow from streams and groundwater recharge and the deeper mines not being connected to surface workings this is shown by reports in SAMI (1904) and SAMJ (1909). The control of water rights was a high priority task of the Mining Commissioner.

Records of water pollution can be traced to the beginning of mining in the area when it was reported that Soda Water was necessary for both washing and drinking in the village, since any other water was contaminated. There was a high incidence of death from typhoid at that time predominantly, according to Jeppe (1946) and Werdmüller (1986), from the polluted groundwater extracted from shallow wells. Water pumped from the mines was reported in SAMI (1904) to be "Heavily charged with acids, preventing its use in boilers successfully without first being treated chemically, it is usually employed in reduction works".

Early mine dewatering controlled water seepage into the mine workings by bailing. When the so called deep mines were established, this was achieved in a shaft sunk down dip of the other shafts and dipping or filling a specially built cage with water to hoist it out, as pumps with the required lift, were not available at that time.

With the closure of most of the mines since 1974, the lower workings have been flooded to 1083 m below datum in the central compartment, 1170 m below datum in the Rose Deep compartment and 1200 m below datum in the Rand Leases compartment. The water is compartmentalised by either intact mine boundary pillars or faulted boundaries. Water levels are maintained by pumping at Durban Roodepoort Deep (DRD) and East Rand Propriety Mines (ERPM). The water quality is poor and the pH is low.

The early mining practices have had an influence on the recovery of water in the mines and it is therefore pertinent to review the history of mining activity in this area in more detail.

4.3.2. History of Mining on the Central Rand.

4.3.2.1. Mineral Exploration in the South African Republic (ZAR)

Antrobus (1986) shows that when the South African Republic was established in 1856, it consisted of burgers who were fanatical in their desire to have their own homeland, they were scared of outside influences, especially British, and did not welcome foreigners. So until 1868 prospecting for minerals was strongly restricted since they felt that this would introduce an influx of aliens. Announcing a discovery of minerals was a punishable offence and a fine of £500 could be imposed. By 1868, after internal dissension and conflict with the indigenous people had depleted the state coffers, the government became more open to exploiting the mineral wealth of the country. In December 1870 the government showed a complete reversal offering rewards for the discovery of precious stones and mineral deposits.. Most of the significant mineral discoveries were made after this date:

- Diamonds at Kimberley in 1870 and 1871
- Gold in the Lydenburg district in 1870
- Gold at Eersteling in 1871
- Gold in the Sabie (MacMac) area in 1873
- Gold at Pilgrims Rest in 1874
- Gold in the Barberton area in 1882.

4.3.2.2. Gold Exploration on the Witwatersrand

From 1874 active prospecting took place in the Witwatersrand area from Krugersdorp to Heidelberg. Many potential sites were discovered, each one creating a rush and concentration of activity in that area on that type of deposit. For example, the initial interest and concentration on quartz veins at Blaaubank and Sterkfontein north of Krugersdorp. Mining on such prospects began in some places, but the deposits proved to be sporadic.

Gold was Initially searched for in quartz veins and alluvial deposits, because it had been found in these associations in Canada and Australia. The relationship with conglomerates was not realised until the Struben brothers proved the connection in 1884 and showed the existence of reefs from Roodepoort to Boksburg (Jeppe, 1946). Werdmüller (1986) questions this claim, stating that the Struben brother's maps include certain details that were not in existence in 1884, and therefore appear to have been compiled in retrospect.

There are many conglomerates among the Witwatersrand sediments, for example, the Kimberley reefs contain 85 conglomerate bands, but only four have payable gold values. Initial prospecting concentrated on some of the better exposed conglomerate outcrops, such as reefs of the West Rand Group and the Elsburg Reefs. The Struben brothers' work was carried out on reefs of the West Rand Group. The first stamp mill was established on Ras' Reef, an early name for the Elsburg reefs. At this time the Main reef group had not been discovered and these other conglomerate reefs were of very low or sporadic grade.

Jeppe (1946) states that the Main reef group was one of the least prominent reefs it was covered by a few feet of soil for most of it's strike. N-S sections across the area reveal that the Main and Kimberley Reefs occur within low lying ground between the Southcrest and Kensington ridges. This can be seen in Figure 4 2.3.

The non-prominence of the main gold bearing conglomerates in this area is of significance to this study. The Gold poor conglomerates of the West Rand Group are associated with quartzites in a predominantly argillaceous sequence, they therefore form prominent hills from Florida to Germiston, including the ridges of Brixton, Braamfontein, Hilbrow, and Kensington. The

Elsburg Reefs are coarse pebble reefs and form prominent ridges which are traceable from the type area south of Boksburg, to Ridgeway, at "Uncle Charlies", a local landmark. The main reef conglomerates are fairly poorly sorted and contain relatively small pebbles, they are not very different from the surrounding quartzites and have weathered in a similar way. Thus they do not form prominent features and occupy the valley area between the ridges formed by the Elsburg conglomerates and the gold poor conglomerates and orthoquartzites of the West Rand Group.

Note: The commonly used, but non-specific term quartzite is used in this discussion, following the practice of most of the referenced authors. A detailed classification and nomenclature has been proposed by Law *et. al.* (1989).

4.3.2.3. Early Mining

The discovery of the Main reef conglomerates is ascribed to George Harrison at Langlaagte in April 1886, these were the main gold bearing horizons in this area and this discovery changed the history of gold mining. Once the reefs had been identified their strike extensions were easily traced to the West and East and by September 1886 most of the area between Krugersdorp and Germiston were declared as public diggings by State President Paul Kruger. Beyond this area the reefs are covered by sediments of the Transvaal and Karoo Supergroups. Outcrop workings were thus confined to the Central Rand area. By September 1886, 4 shafts were operating and the outcrop had been opened up for 48 km. Ore was initially stockpiled since production equipment had to be obtained from overseas. The first ore was crushed on 22 April 1897.

By 1889 there were 52 companies registered, Table 4.3.1 gives a listing of the Mining companies. Most of these names have disappeared, while others have been incorporated into larger holding companies.

Table 4.3.1 Mining Companies Which Have Been Active on The Central Rand. (After Werdmüller, 1986)

Mining Company	Starting Date	Closing Date	Tons Milled
Jubilee	Sep-1887	Jan-1912	904000
Salisbury	Sep-1887	Feb-1912	966000
Jumpers	Oct-1887	Dec-1910	1670000
City and Suburban	Nov-1887	Apr-1920	5832000
Wolhuter	Dec-1887	May-1929	8363000
Langlaagte	Jan-1888	Dec-1946	42221000
Robinon	Jan-1888	Jun-1926	10818000
Meyer and Charlton	Feb-1888	Jul-1932	5082000
Roodepoort United Main Reef	Feb-1888	Jul-1922	5111000
Durban Roodepoort	Apr-1888	Dec-1918	2903000

Table 4.3.1 Continued

Mining Company	Starting Date	Closing Date	Tons Milled
Simmer and Jack	Sep-1888	Apr-1964	58857000
May Consolidated	Jan-1889	Aug-1917	2995000
New Primrose	Jan-1889	Jun-1928	7142000
Witwatersrand	Jan-1889	Nov-1953	30184000
Princess Estates	Feb-1890	Jun-1920	3635000
Glencairn	Nov-1890	Dec-1918	4012000
Treasuery	Dec-1891	Jan-1911	1143000
Village Main Reef	Jan-1892	Oct-1920	1750000
New Rietfontein	Jun-1892	Dec-1915	1835000
New Heriot	Nov-1892	Jun-1920	2663000
Ginsberg	Mar-1894	Jun-1919	2384000
East Rand Prop. Mines	Sep-1894	Still Operating	167462000
Geldenhuis Deep	Nov-1895	May-1947	32542000
Nourse Mines	Jan-1896	Dec-1948	28917000
Bonanza	Aug-1896	Mar-1908	701000
Vogelstruis Estates	Dec-1896	Sep-1918	1397000
Crown Mines	Aug-1897	Mar-1977	162905000
Rose Deep	Oct-1897	Jan-1965	40402000
Consolidated Main Reef	Jan-1898	Aug-1975	68582000
Robinson Deep	Apr-1898	Mar-1966	52090000
Durban Roodepoort Deep	Jul-1898	Dec-1994	109640000
New Unified	Nov-1898	Jun-1923	2525000
New Goch	Jan-1899	Nov-1923	5400000
Aurora West United	Feb-1899	Nov-1927	2765000
Ferreira Deep	Mar-1902	May-1929	12890000
Knights Deep	Aug-1902	Sep-1920	14632000
Witwatersrand Deep	Nov-1902	Sep-1944	18128000
Village Deep	Feb-1905	Jan-1930	12381000
Jupiter	Oct-1908	Aug-1920	2757000
Simmer Deep	Oct-1908	Aug-1920	6437000
Knight Central	Feb-1909	Jun-1923	3895000
Bantjies Consolidated	Sep-1910	Jan-1920	1995000
City Deep	Dec-1910	Nov-1976	67463000
Jumpers-Cum-Treasury	Jan-1911	Jun-1913	242000
Rietfontein Consolidated	Apr-1935	Jan-1967	7553000
Rand Leases	Apr-1936	Jun-1971	56243000
Total			1080414000

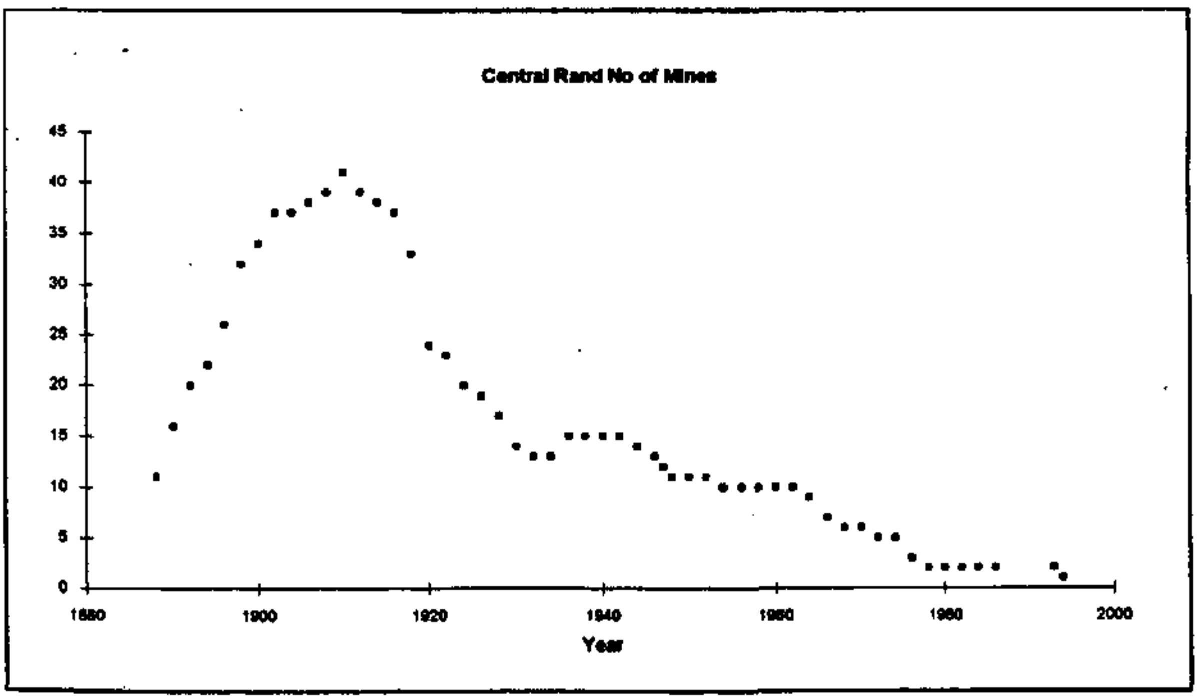
From the total tons milled the volume that this rock occupied can be determined:

Volume Mined (m^3)* = Tons÷Density = 392 877 818

Initial Mining was undertaken by trenching on Main Reef Leader and South Reef from surface. The first thirty metres in the oxidised zone were very rich with free gold. At greater depth the rock became less oxidised and harder to mine. The first mines were open trenches and were not well organised, miners were inexperienced and unsound mining practices were used. The more progressive operators introduced inclined shafts which followed the dip of the reef.

Mining costs were high due to the isolation of the area and the early inefficient mining methods. Initially individuals were able to survive under these conditions because the grades in the oxidised zone were high (about 32 g/t). Below the oxidised zone mining and metallurgical difficulties were encountered and only the technologically advanced operators were able to continue. This led to the merger of individuals and gave rise to the company control of mining that we know today. For example Consolidated Gold Fields came into being in 1887 and The Johannesburg Consolidated Investment company (JCI) was formed in 1889. In 1893 Rand Mines Ltd. was formed the company had a progressive approach having taken over H. Eckstein's interests the latter having been the most advanced of the early operators, for example he was the first to use vertical shafts.

Figure 4.3.2 shows a graphical representation of the increase and decrease in the number of mines that have been active since mining began.



*This volume does not take off reef development, underground waste disposal nor the portion already filled with water into account.

Figure 4.3.2 Number of Mines Operating on the Central Rand

This figure shows a log-normal distribution giving the impression that the greatest mining activity was during 1910, after which mines started closing down. This impression is incorrect since many of the small individual mines were incorporated into larger groups during this period. The number established after the shift from the gold standard in 1930 really reflects the period of greatest activity on the Central Rand. Thus the period 1952 to 1959 was a period of high productivity from this Goldfield.

At Simmer and Jack, the high grades associated with the oxidised zone and the wide ore horizon prompted Anglo American to develop an opencast mine for a kilometre along strike. Figure 4.3.3 shows a sketch section through this development. In this sketch NR, MR, MRL, MiR, SR, LR and SSR refer to the predominant Reefs in the Main Reef package, two reefs would have been stoped from surface during the initial surface mining, these are shown shaded in the figure.

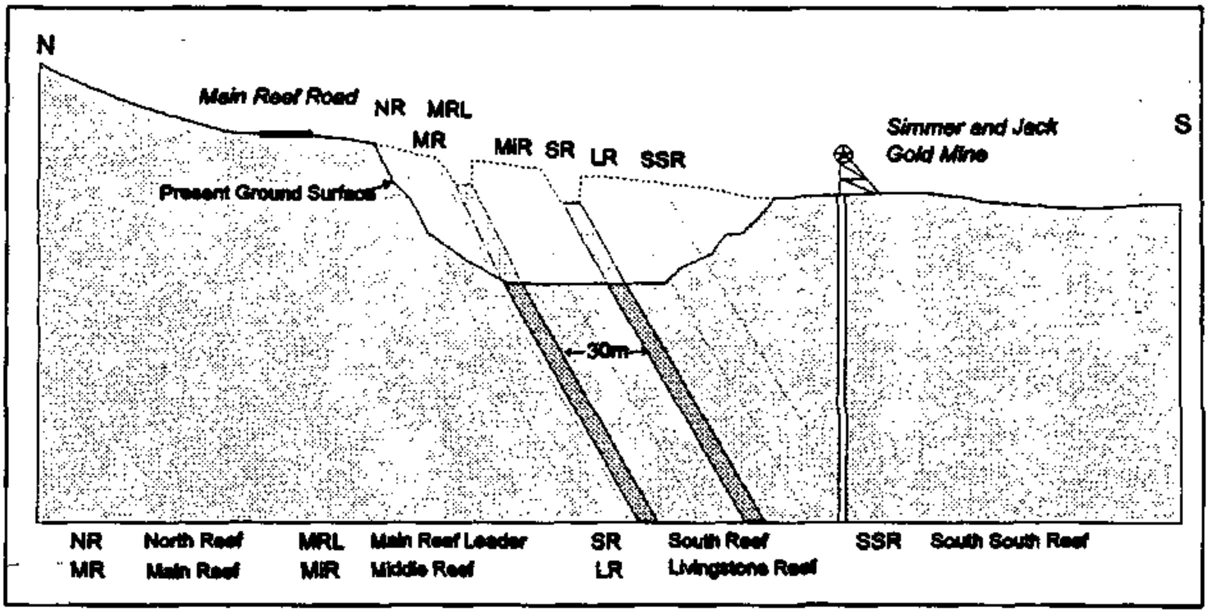


Figure 4.3.3 Sketch Section of the Opencast Gold Mining that Took Place on Simmer and Jack Mines

The opencast has been dormant for many years and the western portion has been filled by municipal dumping. Interested parties are presently negotiating with the owners of the site, Simmergo, to develop the eastern pit as a dump site as well. According to the developers the area has no potential for leachate development, this has been determined by using a formula proposed by Ball (1993). Water collection in a basin of this size must take place and draining into the old workings is inevitable.

Trenching and inclined shafts were inefficient methods of opening up the reef, because faulting and inconsistent dip made it difficult to follow the reef. Thus vertical shafts were sunk, giving rise to the so called *deep* mines, these were initially located some 300 to 520 m south of the reef outcrop. Later a second phase of deep shafts were developed some 1130 m south of the reef outcrop. Both of these vertical shaft arrangements gave limited access to the reef and to reach the deepest workings, some 3100 mbd, subsurface incline and vertical shafts had to be developed. These arrangements are shown in Figure 4.3.4, a section through 15 Shaft Crown Mines. The mining layout thus developed, gave rise to excessive ore, equipment and personnel handling and rehandeling, this inefficiency caused the early demise of the mines in this area (Werdmüller 1986).

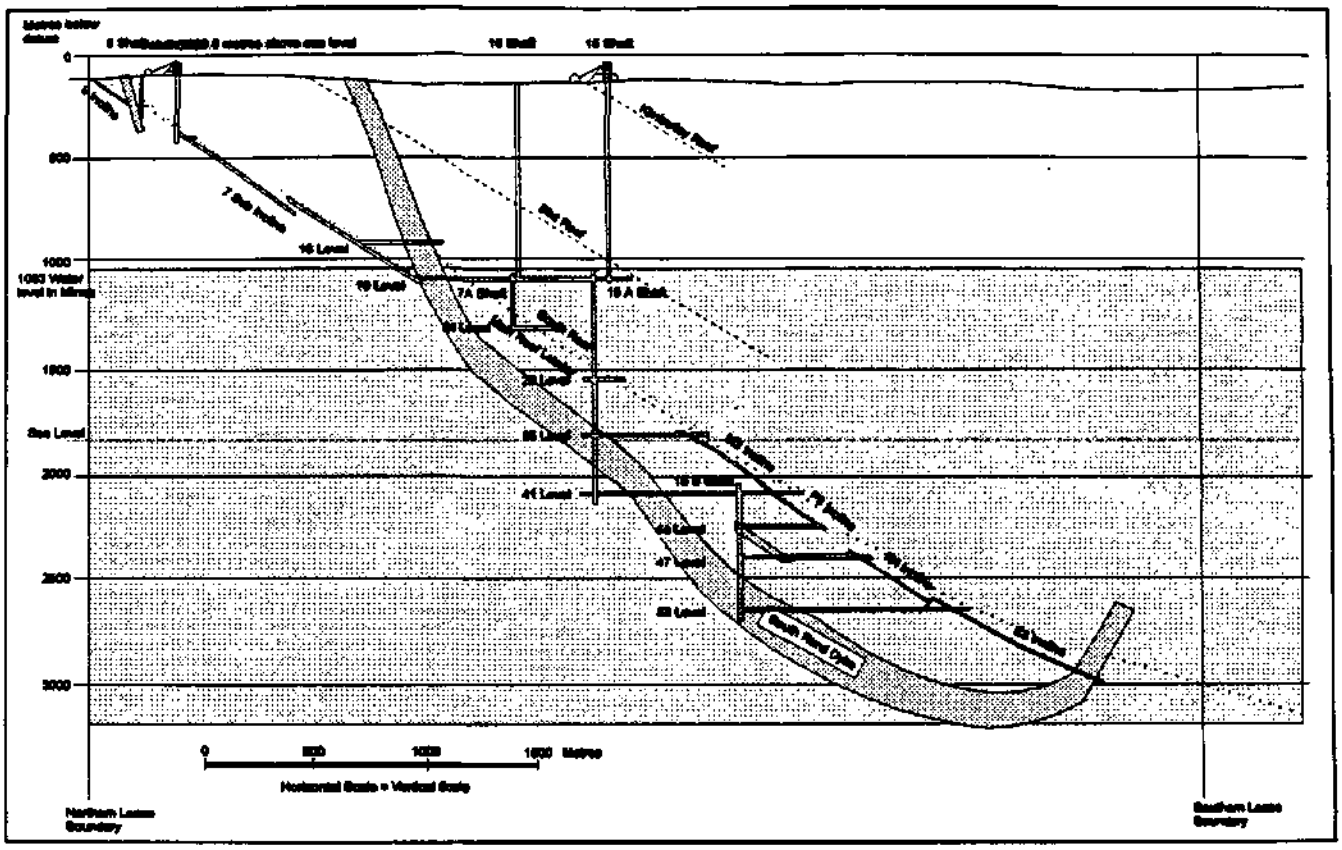


Figure 4.3.4 Section Through 15 Shaft Crown Mines, Showing The Shaft Relationships that Developed with Time to Gain Access to Ever Deeper Workings. (Modified After Crown Mines Shareholder Plan 1964)

4.3.2.4. Present Mining

Of the mining companies shown in Figure 4.3.1, only one is still in full production, East Rand Propriety Mines Ltd. (ERPM) the eastern most mine. Durban Roodepoort Deep (DRD) at the Western extremity was still in production at the beginning of this project, but announced that it would stop mining during the second half of 1994. These mines are owned by Randgold Ltd. (Formerly Rand Mines Ltd.). DRD were mining on Kimberley Reef to a depth of 2200 mbd and on Main Reef above 44 level about 2280 mbd. ERPM are mining the Composite Reef at 69 to 81 level on the East side of their property some 3600 mbd. Kimberley Reef workings on ERPM were started during the high gold price of the early 80's, there was incipient development but they are no longer active.

Two other mining companies are also working underground, Rand Leases a neighbour of DRD and Primrose Gold Mines, which is mining east of Simmer and Jack on Witwatersrand Gold Mining Company and Wits. Deep mines. These two mining companies are not developing new ground, but are scavenging old pillars and faulted blocks that were not previously mined due to the lack of structural information available before 1930. Primrose Gold Mines are also removing unmined hanging wall where values average 5 g/t, such values were too low grade in the 1930's but are attractive under present economic conditions.

Gold production continues on some of the defunct mines. The introduction of carbon in pulp and carbon in leach (CIP and CIL) technology in the early 1980's, ensured that efficient recoveries can be achieved from the sand dumps and slimes dams in the area with grades as low as 1,5 g/t. Thus many of the sand dumps that characterise this area are being removed. ERGO and RM3 are the main producers, with Village Main Reef Mines operating on a smaller scale and using older technology.

Slime, the waste product from these processes, is deposited on rejuvenated slime dams, or in the case of Village Main Reef mines, underground in the old workings. Village Main Reef have a permit to deposit 60 000 tons of sand per month underground at a 1:1 sand to liquid ratio. Smaller reclamation operations have also existed, such as the Badenhorst Mine, where it is evident that slimes were deposited underground. Thus unrecorded and perhaps unmonitored slimes may have been deposited underground from this and other operators. Rolfe (1993) suggests that this would explain the unexpectedly high influx of water found underground.

The land cleared by dump recovery, is close to the central business district. After rehabilitation it is more valuable as Real Estate than for the gold which was recovered from the dumps. Mid income housing and business parks are planned by Rand Mines for large areas to the southwest of the Johannesburg City Centre. This change in land use will introduce large areas of roofing and paving which will change the runoff and recharge characteristics of these areas.

Because the mines have closed due to inefficiency and not lack of reserves the potential exists for deeper mines to be developed south of the existing mines. Rand Mines have investigated this possibility and eleven exploration boreholes, located some 3 km south of present mining activity have been drilled. In the mid 1980's there were reports that mines would be developed on the south side of Moffat Park and in the Klipriversburg Nature Reserve. This has never taken place and Rand Mines do not comment on the feasibility.

4.3.3. Pumping of Mine Water

4.3.3.1. Bailing

During the early mining days dewatering was achieved by bailing. Initial bailing, from open surface workings, was by winch and bucket. With the advent of the deep mines, electric pumps were available but did not have the lift required to pump large quantities of water to surface, Jeppe (1946) reports that, in 1946, pumps that could lift 101 l/s (9 Ml/day) 304.8 m, were available. At that time the mines were already much deeper than 304.8 m. Thus dewatering was achieved by pumping in several stages or by bailing. Bailing was conducted by constructing two shafts, one slightly down dip of the other as a dedicated water shaft, and bailing with a specially designed, bucket-like, cage. Water was either pumped into a subsurface tank or dam from where it could be bled into the bailer or was allowed to collect or pumped into a dam at the bottom of the shaft, the bailer was then dipped directly into this sump.

Modern Pumps used on the mines either have enough lift to pump the water in one stage or water may be pumped in several stages. Pumping presently takes place from; Durban Roodepoort Deep and East Rand Proprietary Mines. the volumes of water that are pumped and the depths from which it is pumped are described in the following section.

Dolan (1961), gives volumes that were pumped by individual mines during a very active period of mining on the Central Rand. This information is given in Table 4.3.2.

Table 4.3.2 Average Daily Pumping Rate (Ml/day) from Central Rand Mines

	1952	1953	1954	1955	1956	1957	1958	1959
Rose Deep	4.5	5.1	4.4	5.6	5.4	5.9	5.6	3.3
Simmer and Jack	4.4	3.8	4.0	5.2	4.1	4.3	4.4	4.1
City Deep	7.4	8.6	8.2	10.1	9.6	9.3	7.1	6.8
Robinson Deep	4.4	4.0	3.6	4.4	4.5	4.8	4.4	4.3
Crown Mines	7.4	7.6	7.1	10.0	9.2	9.4	8.7	8.2
CMR	7.1	6.4	7.6	6.6	6.0	8.1	5.8	6.8
Rand Leases	3.7	4.3	3.1	6.1	4.3	4.4	5.2	3.2
DRD	4.9	6.0	6.1	7.9	7.4	7.0	5.7	7.3
ERPM	10.4	10.2	11.6	12.7	11.6	11.9	12.3	11.9
Witwatersrand G.M.	3.2	2.4	0.0	0.0	0.0	0.0	0.0	0.0
Total	57.5	58.4	55.8	68.8	62.0	64.9	59.2	55.9

Average 1952 to 1959	60.3 Ml/day
Average ERPM 1978 to 1992 Average DRD 1990 to 1993	50.7 Ml/day

This shows that during the 1950's the volume of water that was pumped from these mines was almost 10 Ml/day higher than it is at present. There are three possible explanations:

1. At that time the mines were developing new areas and newly opened fractures may have contributed to inflows, Jeppe (1946) noted that after a new fracture was encountered, once the fissure was dewatered, the flow decreased or stopped. Thus the pumping rate decreased since 1975 when most mines had closed and little development was taking place.
2. The water rising from the deepest workings to its present maintained static level of 1083 mbd, stopped certain inflows thus decreasing the inflow rate.
3. ERPM pump an average of 16.02 Ml/day, of this 12.02 Ml is service water used underground for cooling, dust control, drilling etc. When all the mines were active, as in the 1950's, a large proportion of the pumped water must have been service water. Its absence after the mines stopped would account for the lowered pumping rate.

The third explanation is the most feasible.

4.3.3.2 Volumes and Pumping Positions.

Pumping at DRD takes place from 5 Shaft.

Water collecting in DRD workings is pumped from 44 level, about 2380 mbd, below this level the mine is flooded. About 10.09 Ml/day is made on DRD, the remaining 4.74 Ml/day is drained via boreholes in a boundary pillar plug from Rand Leases at 1413 mbd (equivalent to 32 level), this keeps the water level in Rand Leases at 1200 mbd.

Average figures based on four years of records are shown in Table 4.3.3.

Table 4.3.3 Average Volumes of Mine Water Pumped from DRD (Ml/day)

	Pumped to recovery Plant	Pumped to Klip River	Total
Average	8.67	7.39	15.96
Maximum	11.40	10.93	20.50
Minimum	6.74	0.00	5.65

Pumping at ERPM takes place from SW Vertical and Hercules Shafts.

At SW Vertical Shaft water is brought from Rose Deep via a water cross-cut on 24 level 1253 mbd. The water pumped from SW Vertical shaft is derived from as far west as CMR, however a large proportion appears to be made in the vicinity of Rose Deep and Witwatersrand Mining company. This pumping maintains the water level at 1083 mbd in the central mines (CMR to Simmer and Jack), and 1170 mbd in Rose deep.

Water which collects on ERPM is pumped into an eastern mined out compartment which is intact up to 61 level, about 2100 mbd. and is pumped out at Hercules Shaft. Approximately half of this water is service water, originating from RWB water and ice, which is used to cool the workings. The workings to the west are kept dry to 81 level, some 3600 mbd, by using this approach.

Average figures based on twelve years of records are shown in Table 4.3.4.

Table 4.3.4 Average Volumes of Mine Water Pumped from ERPM (Ml/day)

	SW Vert. Shaft to Angelo Pan	Hercules Shaft to Elsburg Spruit	Total
Average	16.58	16.02	32.60
Maximum	39.83	22.10	61.93
Minimum	2.78	2.06	4.85

In Table 4.3.3 it was shown that the average total pumping from the mines is 50.66 Ml/day, this figure was calculated from records kept by the mines which differ slightly from those submitted to the department of water affairs, the value includes service water used on the mines. The amount of water made on the mines can be derived from the difference between pumped values and records of the volume of service water used, as shown in Table 4.3.5.

Table 4.3.5 Average Water Volumes on Central Rand Mines

Water Pumped		Added Water		Water Made
Position	*Volume Ml/day*	*Source*	*Volume Ml/day*	*Volume Ml/day*
SW Shaft	16.58	Village Main	2.74	13.84
Hercules Shaft	16.02	Service Water	8.93	7.09
DRD (Mine records)	18.06	Service water	3.09	14.97
DRD (DWA records)	15.96			12.87
Total (max.)	50.66		14.76	35.90
Total (min)	48.56			33.80

To summarise, pumping maintains a water level in the Central Rand mines of 1083 mbd, in Rand Leases of 1200 mbd and Rose Deep 1170 mbd, DRD is flooded to about 2380 mbd. ERPM is dry to their deepest workings at 3600 mbd.

These levels and pumping position relationships are shown schematically in Figure 4.3.5.

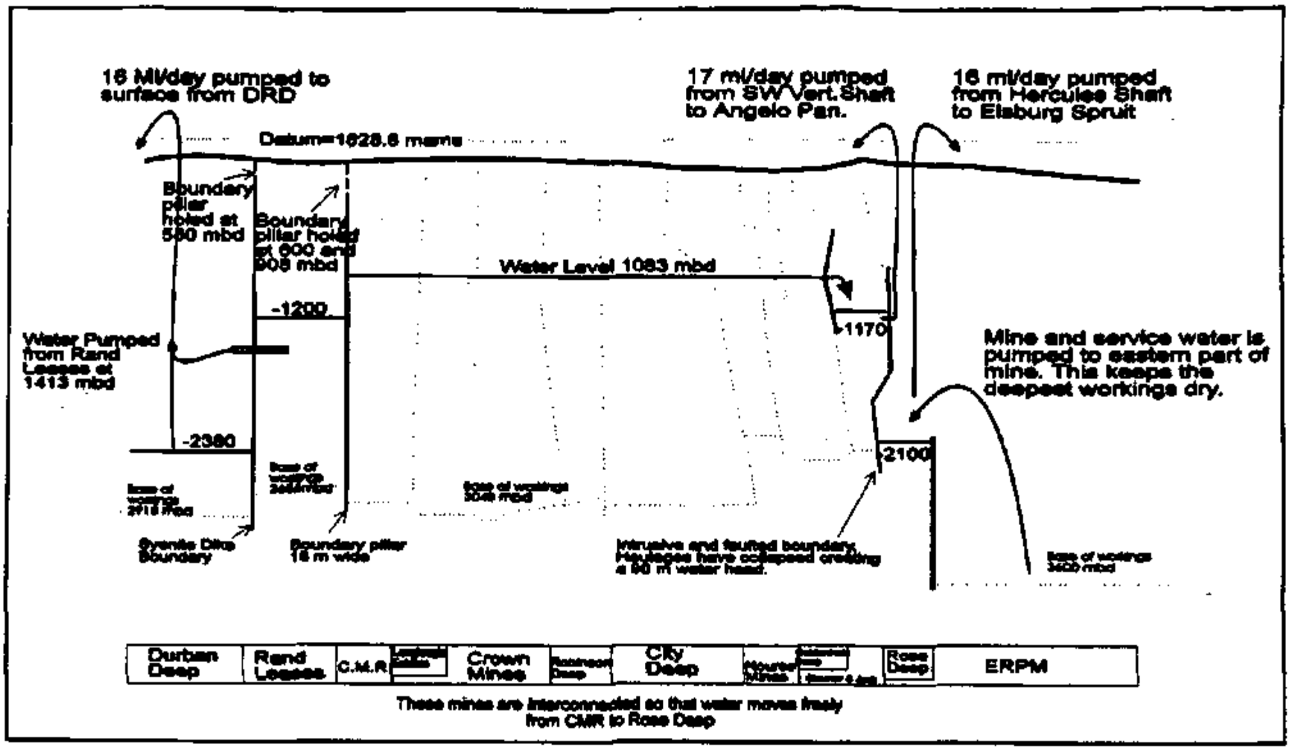


Figure 4.3.5 Schematic E-W Section Showing Water Levels, Compartments and Pumping Positions.

Additional inputs into the system are derived from slimes deposited underground by Village Main Reef Mines. A permit was granted by DWA in 1982, although dumping had started before this date. The permit requirement was the submission of records and a maximum deposition of 120 000 t/month which had to be 50% solid and 50% liquid by weight. Final approval allowed the company to deposit 1 000 000 m^3/year. Records were submitted for October 1991 and 1992, as follows:

	October 1991	October 1992
Tons liquid	78123	84203
Tons solid	62800	52300

The mine is required to compensate ERPM for the additional water that arrives at SW Vertical Shaft because of this dumping practice.

4.3.3.2. Fate of The Pumped Water

According to Wells (1989) the water pumped from underground at ERPM can be divided as shown in Figures 4.3.6 and 4.3.8. His volumes do not correspond to those calculated from reported averages shown in Table 4.3.4. They possibly reflect expected maximum values.

Figure 4.3.6 and the following discussion refer to water pumped from SW Vertical shaft, it has been shown that this water is derived from CMR to Rose Deep.

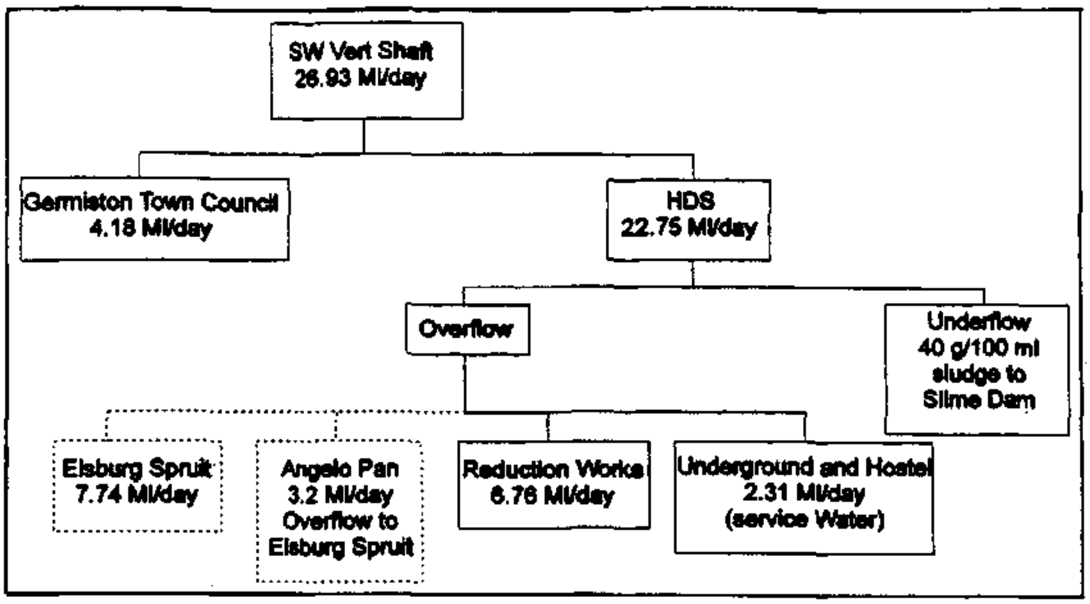


Figure 4.3.6 Fate of the Water Pumped from SW Vertical Shaft

Germiston town council purchase some of the water. The low pH water is used in a Nitrate digestion process at their sewage works. The rest is neutralised with lime and passed through a High Density Sludge process before being released to the Elsburg Stream or to Angelo Pan. In the past pumping at ERPM took place at 49 level, liming was by a conventional process that involved aerating the water and mixing it with lime (CaO), after which, precipitate was removed in a settling tank. When pumping commenced from 24 level, in 1977 a High Density Sludge (HDS) treatment plant was introduced, this has the effect of removing more water from the slimes so that the resultant slimes have a higher pulp density. A schematic of the high density sludge process is shown in Figure 4.3.7.

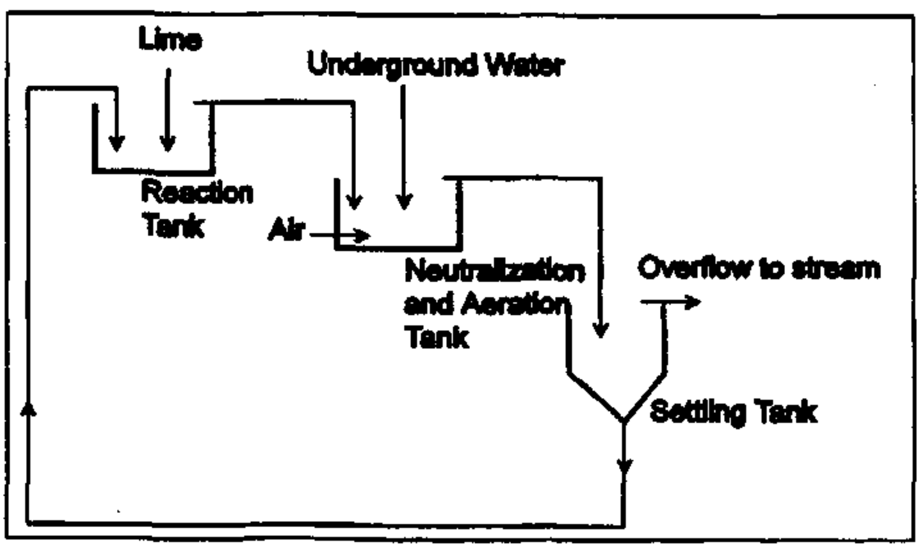


Figure 4.3.7 HDS Treatment Process.

From November 1984 overflow from the HDS plant was used by the mine to replace some of the RWB water that was used on the mine. Thus the HDS overflow was no longer disposed into the Elsburg Spruit and this branch is shown in dotted outline in Figure 4.3.6.

On 11 December 1991 Rand Mines applied for permission to sell 20.3 Ml/day of their water to ERGO. ERGO's extraction plant would be located at Angelo Pan, and they would be supplied with water from the pan. The permit was approved by DWA on 2 March 1992. The initial understanding was that water would be pumped from the mine into Angelo Pan and would be extracted from the pan by ERGO. The Department of Water affairs later, on 29 September 1992, requested that ERGO receive water directly from the mine, thus eliminating disposal into Angelo Pan. Rand Mines indicated that a direct supply had been taking place for some time before the request. Thus the Angelo Pan branch of Figure 4.3.6 should also no longer exist. However it was noticed during the investigation that water is being pumped into Angelo Pan and the conditions in the pan suggest that this is a regular practice. The pan however has no or little outflow because of ERGO's consumption.

Figure 4.3.8 and the following discussion refer to water that is pumped from Hercules shaft. This water has been shown, in previous descriptions, to be water collecting in the workings of ERPM. In a previous report it was stated that water from ERPM is discharged to Cinderella Dam, this is not correct as according to Rolfe (1994) all water is pumped to a liming and sludge removal plant, after which it is discharged to the Elsburg stream in the vicinity of the Germiston Boksburg border. Thus the information supplied by Wells (1989) in an environmental impact study to the DWA&F is incorrect.

All excess water is disposed of into the Elsburg Spruit above Elsburg Dam. This accounts for the poor quality water that is monitored in this stream by Rand Water Board.

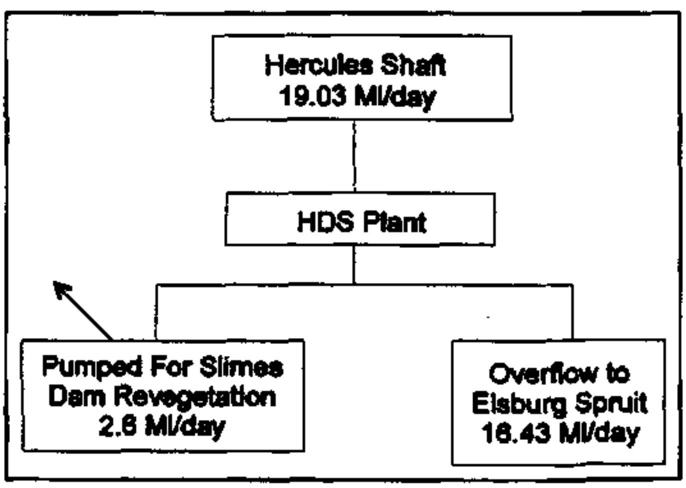


Figure 4.3.8 Fate of the Water Pumped from Hercules Shaft

At **DRD** pumping has taken place in the past but pre 1986 records are sporadic and in 1986 pumping was stopped. Consistent pumping recommenced in May 1990 and records are available. Water is limed underground to a condition suitable for pumping. Some of the water is pumped to a tank where after further treatment it is used in the gold recovery process. It is eventually disposed with the slimes to evaporate from the DRD slimes dam which is located south of the mine on a dolomitic outlier. The remainder of the water is discharged into the headwaters of the Klip River. Mine water is used by most residents of the DRD mine village to irrigate their gardens. Figure 4.3.9 gives a flow diagram for the fate of water pumped from DRD.

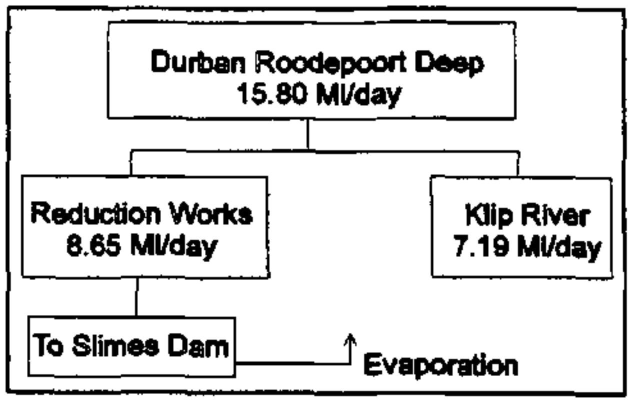


Figure 4.3.9 Fate of the Water Pumped from DRD

4.4 Recovery

4.4.1 Mine Inflows Derived from Surface Water

4.4.1.1 Surface Water Losses Via Geological Structures

Tomic' *et. al.* (1985) describe methods of analysing structural features, such as joints and faults, to determine directions and sources of water inflow into underground workings. Some of the techniques that these investigators describe are commonly used in geological structure analysis, thus results from the structural analysis of the Central Witwatersrand given in Hutchison (1975), Jeffery (1975), Grohmann (1988) and McCarthy *et. al.* (1989) can be used.

McCarthy *et. al.* (1989) in studying the orientation of dikes on ERPM show that the principal orientation is north-easterly. Jeffery (1975) undertook a detailed analysis of joint orientations on ERPM, he found three prominent joint directions:

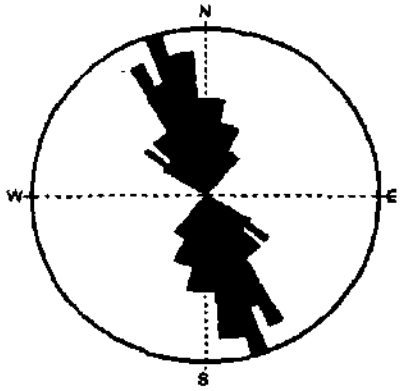
- North-northeast to northeast with steep dips
- East to southeast with steep dips
- Southeast with dips parallel to the bedding, 20 to 50°S.

Hutchison (1975) shows that in the Central Rand two dike directions dominate, north-easterly the most abundant and north-westerly less abundant. He also showed that faults trend east west and north south.

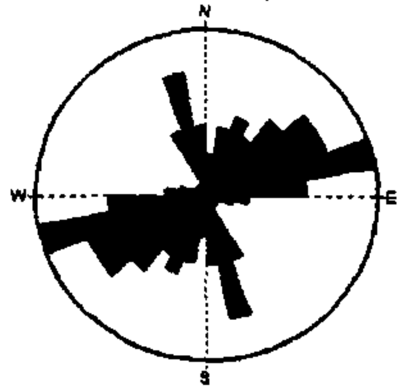
In his analysis Grohmann (1988) differentiated between fault types, i.e. wrench faults, thrust faults and normal faults. The modal directions plotted as rose diagrams in Figure 4.4.1 are a result of normal faulting and show that these fault trends are predominantly oriented northwest-southeast to northeast-southwest. Wrench and thrust faults tend to be oriented in an east to west direction and have dips similar to that of the sediments.

The work of these authors therefore shows that there are major structures; normal faults, dikes and joints which have similar orientations. Thrust faults, wrench faults and shallow dipping joints oriented parallel to the bedding also exist.

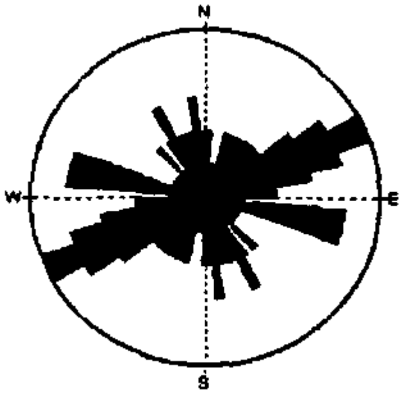
To compare the orientations of structural features and erosion features, measurements of erosion feature orientations were made on 1:10 000 orthophoto maps. The results of these measurements as well as measurements made on visible outcrop orientation are given in Figure 4.4.2. This figure, read in conjunction with the information given by the quoted authors, shows that erosion features, including major rivers follow the major north-northwest to north-northeast trend of normal faults, intrusions and joints. Thus the streams are structurally controlled.



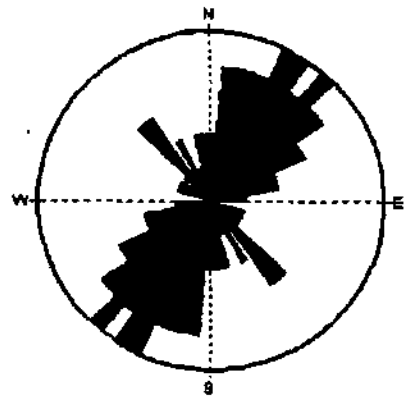
1. Orientation of Faults on DRD to Rand Leases. n=80



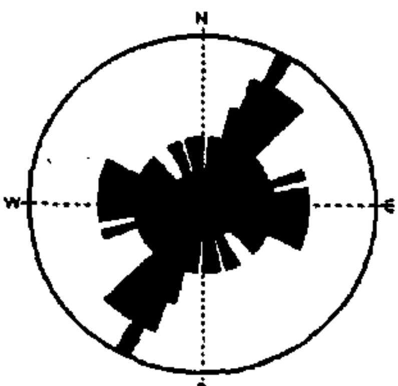
2. Orientation of Faults on Rand Leases to CMR. n=154



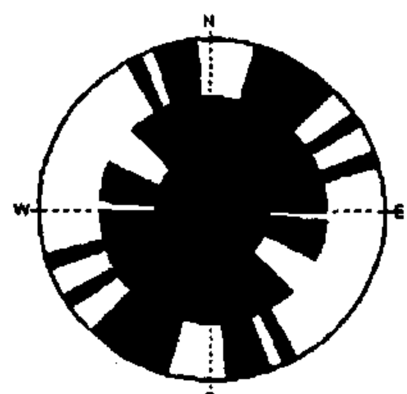
3. Orientation of Faults on Crown Mines. n=175



4. Orientation of Faults on City Deep. n=117

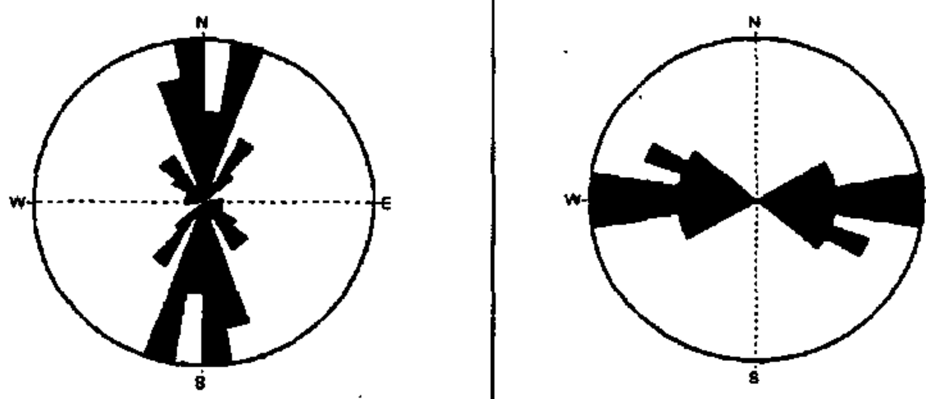


5. Orientation of Faults on ERPM. n=384



6. Orientation of all Central Rand Faults. n=952

Figure 4.4.1 Trends of Faults Measured on Mines in the Central Rand (Modified after Grohmann, 1988)



7. Orientation of Erosion Features. n=50

8. Orientation of Outcrop. n=19

Figure 4.4.2 Equal Area Projection Showing Trends of Erosion Features

Figure 4.4.2 shows that a small proportion of the erosion features are oriented east to west*.

In a similar analysis of dip orientations, data was obtained from published results and from information given on the geological map of this area, the poles to dips were plotted on an equal area stereo-net and are shown in Figure 4.4.3.

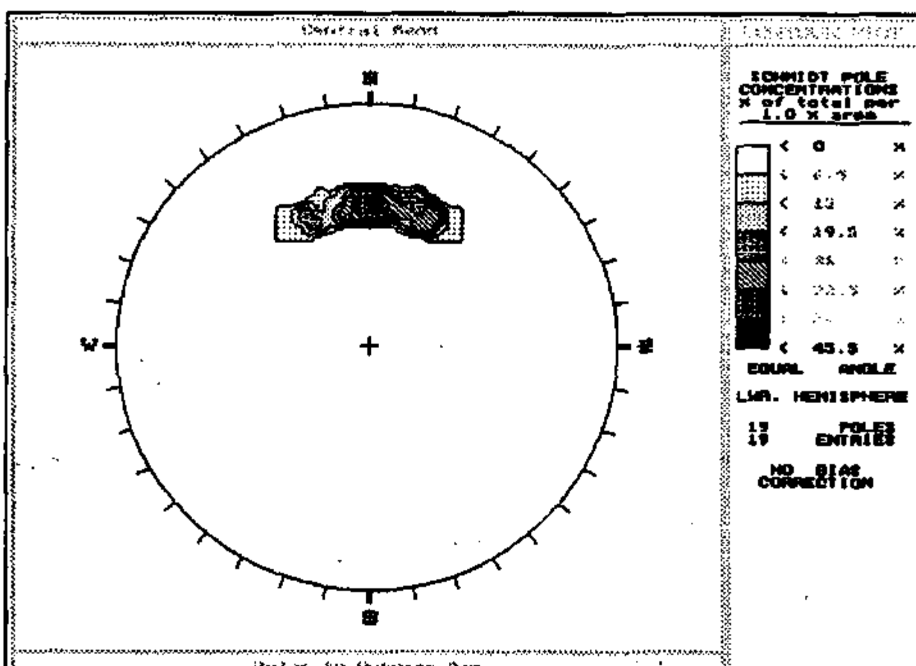


Figure 4.4.3 Equal Area Projection Showing Poles to Main Reef Outcrop Dips

From these plots and the information given by Jeffery (1975) and Grohmann (1988), it can be seen that the reef outcrops, outcrop workings as well as thrust

*Note: this analysis did not take erosion feature size into account, small and large features were treated equally. Some of these east west features are much more significant than many of the small features making up some of the other measurements.

and wrench faults and bedding plane joints are usually oriented at right angles to the erosion features. Where this is not the case erosion features follow the strike of the outcrop, in other words they follow the other prominent structural orientation in this area.

Thus streams follow major structural features and water losses to these features are possible. The flow orientation also ensures that streams cross outcrop areas where further water losses are possible.

4.4.1.2 Surface Stream Flows

Workers on the mines have stated that water enters the workings via streams and swampy areas that cross reef outcrop and outcrop workings. Such observations have been made by: Jooste (Rand Mines), Wells (Rand Mines), Botha (Rand Leases), Mortlock (Primrose Gold Mine) Rolfe (Rand Mines) Burger (Dept. Min. and Energy Affairs) and others. The orientation studies, discussed in the previous section, show that recharge to the underground workings via losses from streams crossing the outcrop is encouraged by the structural relationships.

There are numerous small, streams in the area which flow all year. This is surprising in this area which experiences a seasonal climate. Most of the smaller streams rise on high ground in the north or south and flow toward the valleys developed on the Booysens shales. These relationships are evident in Figures 4.2.2 and 4.2.4 shown on pages 96 and 100 of this report, respectively.

Streams flowing in a north to south direction, rise in suburban areas and flow through light industrialised areas and mining areas in their course southward. These streams cross the Main Reef and Bird Reef outcrop zones before entering the main east-west valley. Streams flowing in a south to north direction rise on high ground associated with Elsburg Reefs. They flow through suburban, light industrial or mine dump land-use areas and cross the Elsburg and Kimberley Reef outcrop before joining the main east-west valleys.

Some streams appear to derive much of their water from industrial effluent, the stream flowing past Rand Mines Mining and Milling plant (RM3) is an example. Some streams appear to carry raw sewerage derived from an inadequate sewage system. Many flow over eroded sand dumps and at the same time derive seepage from the sand dumps. Thus the northern and southern headwater regions of the streams are generally fresh, while the quality deteriorates rapidly downstream. By the time many of the streams have reached areas where losses to the mines occur, they are already contaminated to some extent.

4.4.1.3 Observed Stream Losses

There are documented occurrences of these streams loosing to the reefs and surface workings:

- The stream from Bloudam at Amalgam has been channelised since early mining days due to losses to the reef outcrop at Langlaagte.
- In 1972 DRD constructed a cement canal to lead the outflow from Florida lake over the Main reef outcrop zone. Approximately 20 m^3/day from the stream was lost as it passed over these outcrops, this constituted one third of

the estimated stream flow. Burger (1992) estimated that 11 Ml/month enters the underground workings where this stream crosses Bird Reef outcrop.

- The Stream from Witfield dam has been reported to lose to the underground workings (Laszig, 1991), there are two inflows into the area and at times, no outflow, storage and evapotranspiration could not account for all the loss.
- Northrup (1993), says that at DRD water enters via incline shafts and outcrop workings in the vicinity of the Klip River.
- Botha (1993) says that Rand Leases 6-Shaft has water inflows derived from Florida Lake. At Rand Leases, there are 13 shafts located between the mine plant and Fleurhof Dam, a distance of 1.3 km. Much of the area between these two points is occupied by a Vlei formed from the Florida Lake outflow. Thus there is significant water, lying above an intensely mined area, available to enter the workings.

If similar losses occur at other streams crossing or running parallel to the reef outcrop, a large proportion of the volume of water entering the underground workings could be derived in this way. At the time of writing the canalising of the stream from Florida Lake over the Bird reef outcrop was being planned.

4.4.1.4 Water Flowing in the Mines

Water flowing in the mines was sampled at numerous points below surface. In many places strong flows were observed. Flows occur from old stopes and from diffuse dripping and seepage in fracture zones or related to intrusive contacts.

While water is seeping in a diffuse manner into the mines it flows slowly and is even stagnant in some places. It is often dammed against heaps of rubble or mined rock that has not been removed. Water that has collected in stopes often flows out of boxholes, at these points there is often an accumulation of mined rock, thus the water drains through this ore. In the haulages there are usually accumulations of fine material that has collected over the years during ore transport, many haulages are also partly backfilled with waste rock. Water moving through these areas must pass over or through this material.

The diffuse drips, seeps and trickles combine to form ever stronger flows as they collect in drainage channels from where they cascade down boxholes or into shaft openings. Once in the shafts rapid inclined or vertical flow occurs. Some of these rapid flows in the shafts start from surface, where direct losses occur.

At Village Main Reef Mines strong flows were observed down incline shafts at fairly shallow depths. There were no points where the source of the inflow could be identified.

Inflows down Main-Shaft Waverley Gold Mining Co. which is located in the vicinity of the Witfield Stream, were visited at 5 level some 299 metres below datum (122 metres below surface). At this point there are two inflows into the incline shaft flowing from inaccessible areas to the north-west and south-west. The chemistry of each inflow was distinct, that from the NW having an EC of 1100 and pH of 2.5, while the stronger flow from the SW had an EC of 590 and a pH of 3. The combined flow rate was an estimated 35 l/s. Mortlock (1993) states that in many other parts of the mine dripping and running water can be heard, but these areas are inaccessible due to stope collapse.

Indirect evidence of direct inflow was seen at Primrose Gold Mining Company, there were several places in the haulage where grey slime had been deposited, the soft sediment had ripple marked surfaces showing that it had been deposited by flowing water. When the miners were questioned about this phenomenon, they said that shortly after significant rain water flows through the mine, often carrying with it slimes eroded from surface dumps.

In February 1994 proof of the above observations was obtained after a particularly continuous wet period. Slimes and sand dumps collapsed down an incline shaft which had been covered by the mine wastes, there was no loss of life but some of the workers reported sick after inhaling cyanide gas which was generated when the cyanide carrying slimes mixed with the low pH water in the mines. This was reported by Louw (1994) although the identity of the gas was misrepresented.

These observations indicate a very close relationship between rainfall and water flowing into the workings. Rolfe (1991) has made similar observations and states that there is a relationship between pumping rates and rainfall.

4.4.1.5 Correlation with Rainfall

The relationship between inflow and rainfall can be investigated by comparing pumping rates with rainfall or plug pressure. The pressure head of water above certain water barriers or plugs was monitored by the mines, to prevent the barrier from being over pressurised. The pressure is thus directly related to the water level and could thus also be compared to rainfall.

Detailed daily data on rainfall, plug pressure and pumping rate was obtained from 1-1-86 to 19-5-93, a total of 2696 measurements. Comparison between rainfall and plug pressure or pumping rate yielded results which are shown graphically in Figures 4.4.4 to 4.4.10.

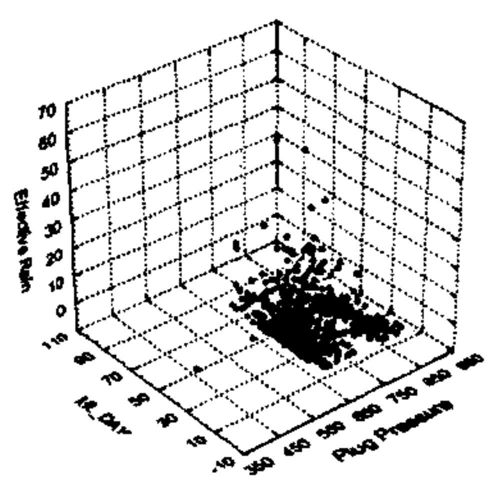


Figure 4.4.4 Scatter plot of rainfall and the two dependant variables: Pumping rate and Plug pressure. n = 2690.

Multiple regression analysis of this data shows that there is no correlation between the variables as shown in Table 4.4.1 these results are to be expected from the scatter plot.

Table 4.4.1 Correlation coefficients between Rainfall-Pumping Rate-Plug Pressure

	Pumping Rate	Plug Pressure	Rainfall
Pumping Rate	1.00	0.21	0.02
Plug Pressure	0.21	1.00	-0.01
Rainfall	0.02	-0.01	1.00

Because of the jagged nature of the data smoothing techniques, such as moving average, were applied to help with the comparison. A technique to couple pumping and plug pressure trends was also used, this is valid since these two parameters are interdependent. A time series plot of smoothed rainfall and pumping/plug pressure data is given in Figure 4.4.5. The time axis is numbered sequentially.

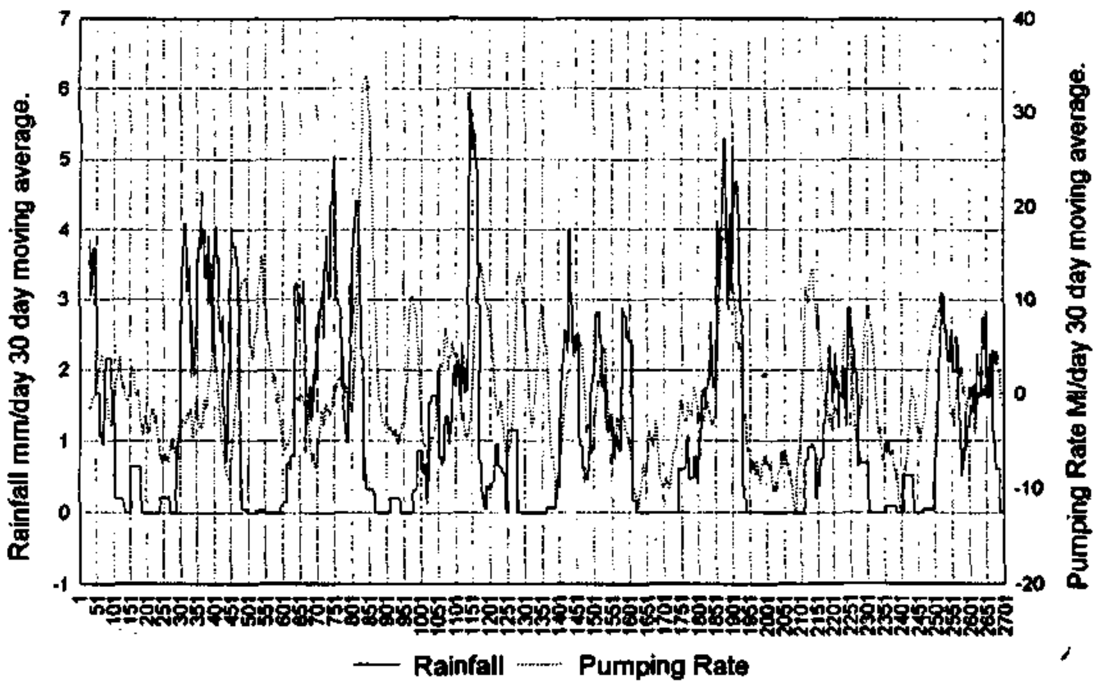


Figure 4.4.5 Time series plot of rainfall and pumping/plug pressure data.

The corresponding cross-correlation results for these two series is shown in Figure 4.4.6. The best correlation of about 0.34, with a lag of 20 days is not significant. Thus there is no apparent relationship between pumping rate and rainfall. Unfortunately pumping rates are influenced by human choice and may vary between over and under adjustment, this helps to obscures any relationship between rainfall and pumping rate, it also has an effect on the plug pressure-rainfall relationship. Thus no conclusive relationships could be defined.

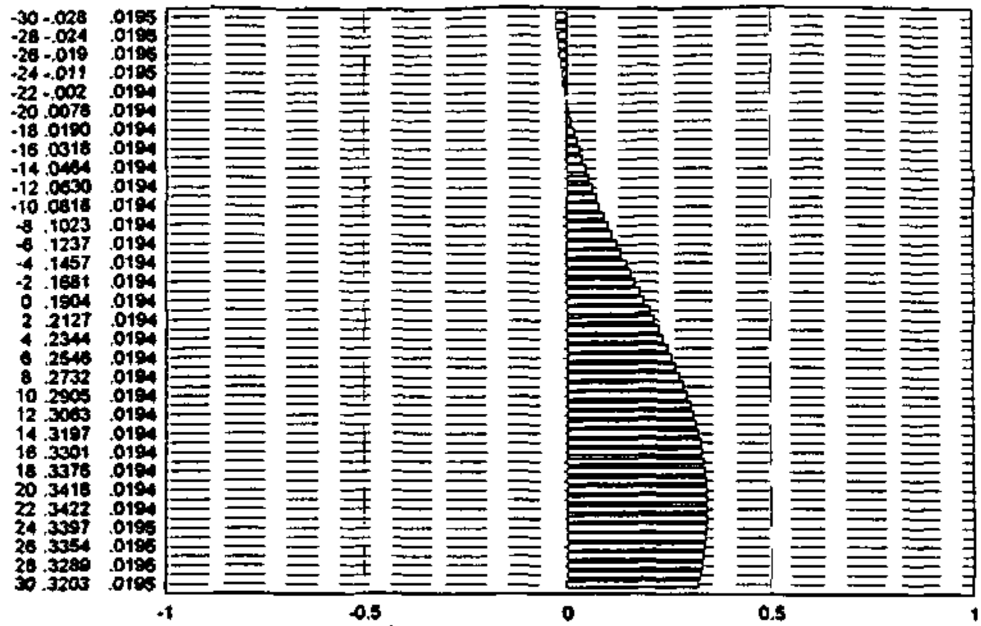


Figure 4.4.6 Cross-correlation Function with Correlation Coefficient, Lag and Standard Error for the Pumping/Plug Pressure Relationship with a 30 Day Moving Average Rainfall

It was assumed that these daily influences that affect the results may be less influential when averaged over a month and monthly average rainfall, pumping rates, and plug pressures for ERPM are compared graphically in Figure 4.4.7.

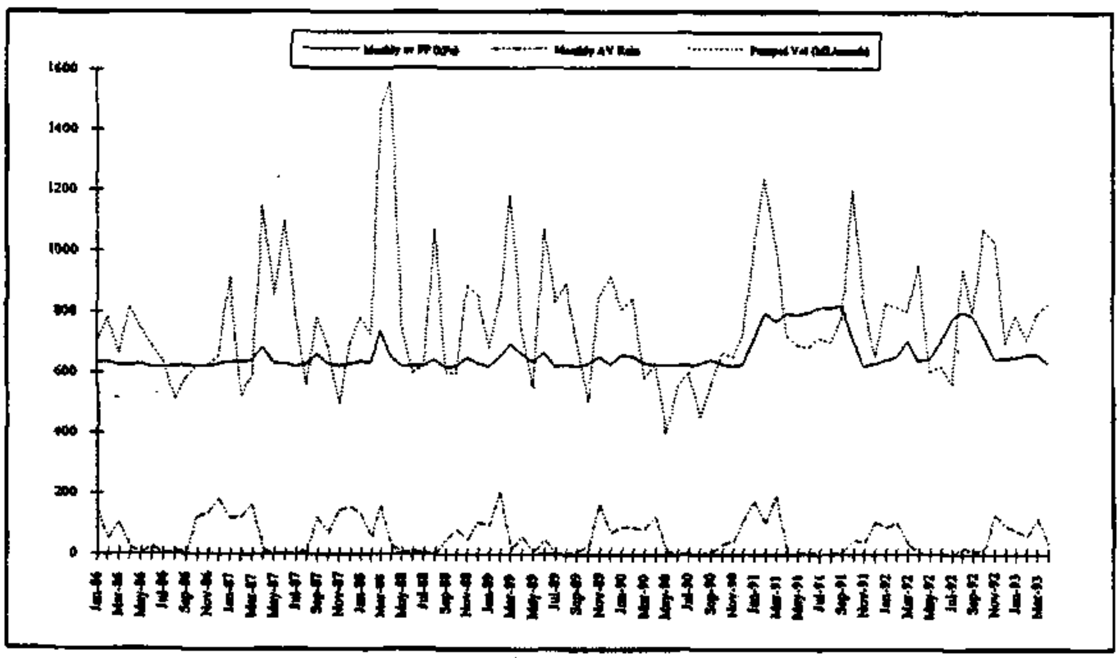


Figure 4.4.7 Monthly Average Rainfall, Plug Pressure and Daily Pumping Rate at ERPM

After the application of smoothing techniques, including quarterly moving averages and plotting the data on separate scales it appears as in Figure 4.4.8.

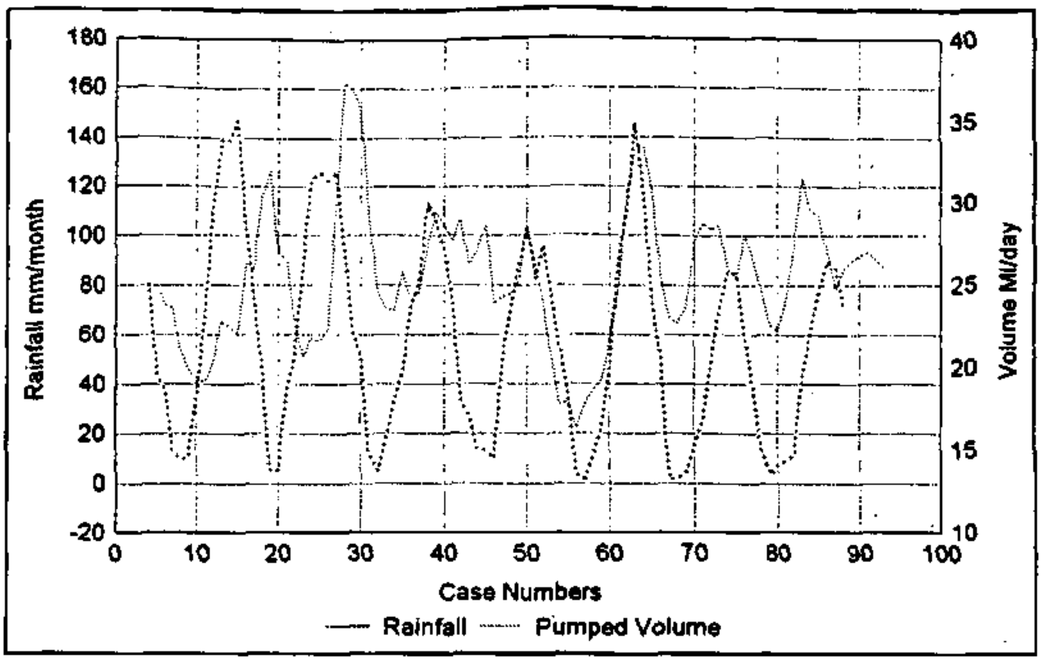


Figure 4.4.8 Smoothed Rainfall and Pumping Data

The corresponding cross-correlation results for these two series is shown in Figure 4.4.9. The maximum correlation of 0.34 within the first month is again inconclusive, other maxima occur at 12 month lags.

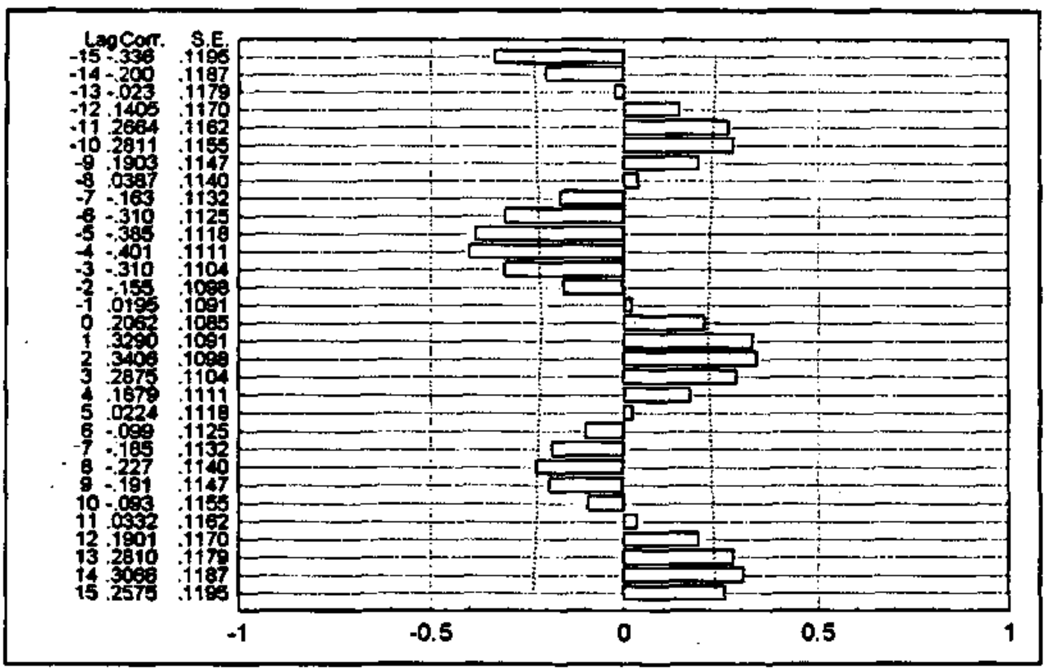


Figure 4.4.9 Cross-correlation Function with Correlation Coefficient, Lag and Standard Error for the Four Month Moving Average Monthly Rainfall and Pumping Data.

The cumulative difference technique of Temperley has been successfully applied to rainfall and ground water levels by Bredenkamp (1994). The equivalent cumulative difference plot to the data plotted in Figure 4.4.6 is given in Figure 4.4.10.

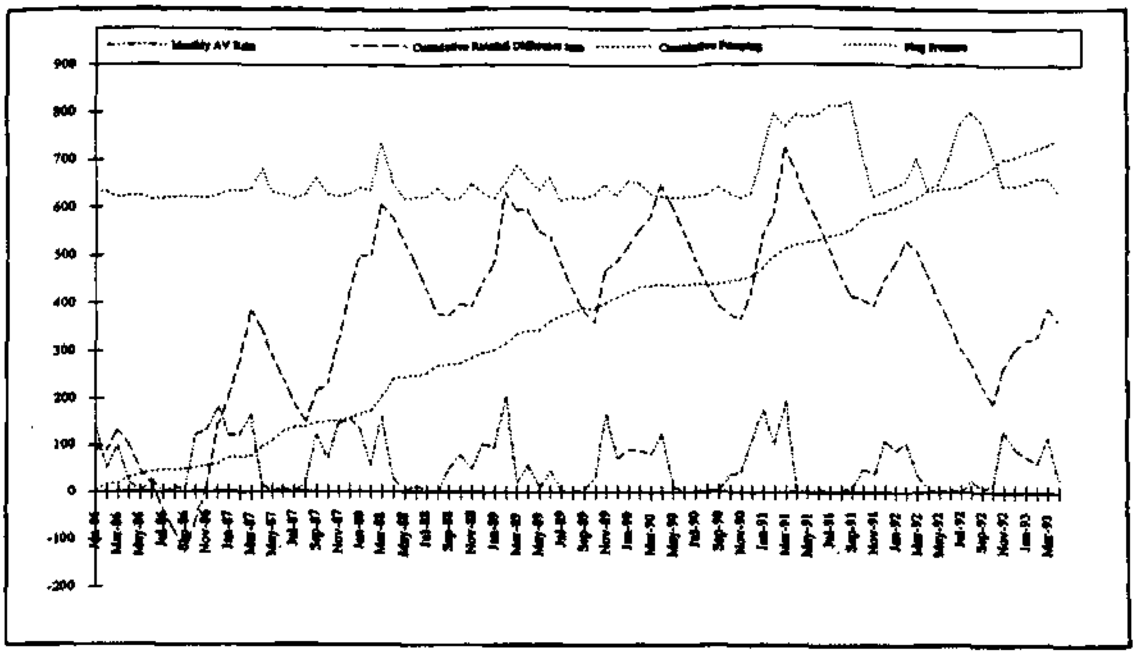


Figure 4.4.10 Cumulative Difference Monthly Average Rainfall and Daily Pumping Rate Compared with Monthly Average Rainfall and Plug Pressure at ERPM

Although not conclusive the pumping rate/plug pressure rainfall relationship suggests a fairly short (some 4 to 7 days) response time to a rainfall event. This suggestion is strengthened by the observations about inflow from surface sources described in the previous sections.

To fully quantify flows and losses of water to the subsurface, proper stream-flow gauging would have to be introduced at numerous points within the system. Measurements over a number of seasons would be required to generate meaningful, reliable data.

4.4.2 Mine Inflows Derived from Groundwater

The occurrence of groundwater has been described in section 4.2.5, it was shown that it is difficult to monitor groundwater in the vicinity of the reef outcrops because the land is commonly occupied by mines, mine waste heaps, and commercial and industrial areas, groundwater is rarely used in these areas. Suburban areas in this vicinity are either owned by the mines or have very small stands, in such areas privately owned boreholes are rare. Exploration drill-holes, which are common on mine property, make no mention of water intersection, or levels in their logs. These drill-holes are either plugged with a concrete block or have been destroyed by later surface activity, such as development.

Since there is no direct evidence of groundwater inflows and suitable monitoring boreholes do not exist or have never been used for monitoring groundwater, some conceptual ideas are presented here.

Groundwater seepage to the dewatered mine openings must occur, since there is hydraulic continuity between the near surface water bearing formations and the dewatered mine openings. This continuity does not occur everywhere but is confined to:

- Positions where deep penetrating structures, such as faults or intrusions, connect the mine openings to the near surface.
- The vicinity of surface workings where weathered porous, or closely fractured rocks and the mine openings are in hydraulic communication.
- Positions where vertical shafts connect the near surface porous saturated formations with the deep dewatered openings.

There is a hydraulic gradient caused by dewatering, thus water flows from the near surface aquifers into the mines. It is not possible to quantify this flow, but it forms part of the flow into the mines which may be described by relationship 4.1:

$$GW = PR-(SW + SL + DR + O) \qquad 4.1$$

Where:

GW = the ground water component of inflow

PR = the long term pumping rate

SW = service water brought in for use on the mine

SL = surface water losses from streams flowing over outcrop or in structurally controlled valleys

DR = direct recharge to the outcrop area

O = other additions such as purpose water dumping underground.

Values are available for all of these parameters except surface water inflows, thus a separate groundwater component cannot be directly calculated. Using average values the groundwater plus surface water inflow to the mines can be shown to be 31.30 to 32.55 Ml/day (these determinations will be discussed in more detail in the following section).

To put the groundwater component into perspective, the potential groundwater recharge of the catchment defined by streams flowing in the vicinity of reef outcrop was calculated. The relevant data is given in Table 4.4.2.

Table 4.4.2 Estimate of Potential Groundwater Recharge

Catchment Area (m^2)	Volume of rain (m^3/day)	Recharge %	Recharge Volume (m^3/day)	Recharge Volume (Ml/day)
309 286 991.59	601 214.96	4	24 048.60	24.05
		3	18 036.45	18.04

From the observation made by Burger (1993) that the stream from Florida Lake looses 11 Ml/month to Bird Reef outcrop, an estimation of the order of magnitude of the groundwater component can be made. The following assumptions have been made:

- The streams all have approximately equal flows
- Losses to Main Reef outcrop areas are twice the losses to Bird Reef

- Losses to Kimberley Reef outcrop areas are one quarter of the losses to Bird Reef
- Losses to Elsburg and other reef outcrop areas are negligible

From these assumptions and the number of stream crossings it can be shown that 8.22 Ml/day could be derived from streams loosing to outcrop regions. This is probably a conservative figure since it does not take losses via structures in stream valleys into account, this investigation has shown that most streams are in structure controlled valleys thus such losses are expected to be significant. Thus a **maximum** of 23.05 to 24.30 Ml/day is expected to be derived from groundwater.

Groundwater losses to this situation would occur from lateral movement of groundwater towards the highly transmissive mine aquifer with its steep hydraulic gradient, this would generate a cone of depletion in the fractured aquifer around the mine workings. Due to the steep gradients and steep dip of the openings this cone of depletion would not be detectable on the northern side, while on the southern side it might be detectable depending on the, position of the monitoring borehole and the hydraulic properties of the rocks. No suitable boreholes were found in this area to test this assumption. Groundwater inflow would form a continuous baseflow to the mine water recovery.

4.4.3 Recharge

From the description of the effects of mining on the subsurface hydraulic conditions, it is possible to describe the mine openings on the Central Rand as: A dipping mine aquifer, whose confining rocks are impervious meta-sediments of the Witwatersrand Supergroup. The recharge region of this aquifer consists of an excavated and disturbed zone some 75+ metres wide in the vicinity of the outcrop. Recharge occurs as:

- Direct recharge from rainfall to the disturbed outcrop zone, which because of the excavations and disturbance will have very high infiltration.
- Direct losses from streams crossing the outcrop.
- Losses via fractures and other structures connecting surface water to dewatered mine excavations
- A baseflow from groundwater contained in superficial, near-surface, secondary aquifers.

The first form of recharge will have strong seasonal variation. The second and third forms may have seasonal components, but they would be masked by effluent disposal to the streams.

In this region the rocks overlying the mine aquifers are sediments of the Witwatersrand Supergroup, these sediments have undergone regional metamorphism at 350°C (Phillips 1990). In unweathered form they are crystalline rocks with very low primary porosity. In the near surface region, some 40 metres below surface, the rocks may be weathered and fractured significantly enough to form secondary aquifers. Below 40 metres to a depth of about 100 metres the fracture density decreases until the rocks become dense with very low hydraulic conductivity and do not transmit water. These relationships influence the area around the surface workings and thus influence recharge of the underground workings.

The outcrop of the reef zone is a topographically flat area over much of the Witwatersrand thus direct recharge to open workings in this zone is possible. Even in places where the workings have been filled or rehabilitated, recharge will be high. The recharging water finds its way into the mines. The shallow secondary aquifer will be recharged in areas unaffected by surface mining but will lose water to the mine openings. These relationships are shown in Figure 4.4.11.

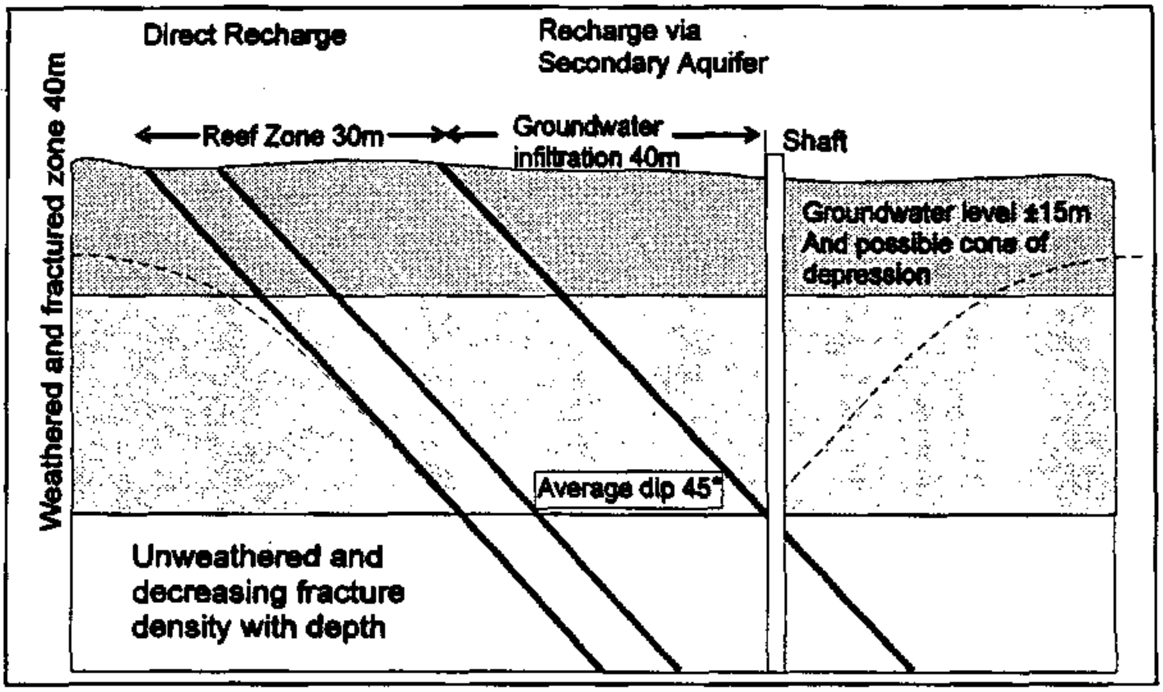


Figure 4.4.11 Depths and Surface Expression Relating to Recharge Areas on Main Reef, Central Rand Area.

Thus if the surface area affected by the reef zone can be determined, a value for the volume of direct recharge from rainfall can be calculated. By using:

- Recharge percentages from 10 to 95% depending on: surface cover, land use, presence of visible outcrop workings, and gradient.
- Measurable outcrop zone of 14.79 km.
- A width of 75 to 95 m affected by surface mining
- Average Rainfall of 730 mm/year.

It can be shown that 1.25 Ml/day can recharge directly to the outcrop zone of the Main Reef.

This recharge volume calculation has not taken the following other sources into account:

- Recharge to the remaining 25 km of reef outcrop which cannot be measured because of rehabilitation or development
- Infiltration to Kimberley Reef or Bird Reef (these reefs also have surface workings and outcrop areas)
- The contribution from streams crossing the reef and losing to it
- Groundwater losses to the excavated reef zone.

The calculation is therefore very conservative but was performed to get an order of magnitude for the volume of direct rainfall recharge. The distance measured constitutes about one third of the outcrop, if the other areas, of possible direct recharge, were also taken into account the calculated figure could be doubled. Even so, it is still a fraction of the 34 to 36 Ml/day that is flowing into the mines.

Occasional deep fractures and weathered intrusions may also be water bearing, These would penetrate the mine workings at greater depths than 40 metres, their positions could be vary sporadic and the volumes of the related inflows variable. Vertical shafts could also contribute some water, particularly the old vertical shafts which were close (up to 520 metres) to the outcrop. Cementation and grouting procedures were introduced from about 1915 to control inflows during shaft sinking. On the Central Rand many of the most troublesome inflows during shaft sinking occurred as fissure flows at depths of 300 to 900 metres, these were usually successfully cemented. Thus inflows can be expected from old shafts where cementation was never used or where it has collapsed with age and neglect.

Direct recharge from rainfall can be between 1.25 and 2.5 Ml/day. This is an average value over the whole year so the actual inflows would be much larger during the wet season.

Average pumping from this aquifer is 48.56 Ml/day. At least 12.02 Ml/day is derived from service water, some 2.62 Ml/day is added by underground mine waste disposal and direct recharge contributes 1.25 to 2.5 Ml/day. Thus groundwater and stream losses must contribute some 31.30 to 32.55 Ml/day.

It has been shown that stream losses could, conservatively, account for 8.22 Ml/day, thus 23.05 to 24.30 ML/day is derived from groundwater. This is of the same order of magnitude as the estimated groundwater recharge to this area, thus large groundwater drawdowns around the mine openings cannot be expected.

4.4.4 Rate of Recovery

The time to flood is given by Johnson (1985), as a simple relationship involving inflow rate and the mined out volume.

$$\text{Time} = \frac{\text{Mined out Volume}}{\text{Inflow Rate}} \frac{D^3}{D^3 / T} \qquad \text{4.2}$$

This implies that a constant rate of recovery will be experienced.

4.4.4.1. Inflow Rate

If the natural inflow rate is equal to the groundwater contribution, plus surface water losses and direct recharge, then it can be determined from the average pumping rates, which were monitored by the mines.

$$\text{Inflow Rate} = GW + SL + DR \qquad \text{4.3}$$

The pumping rate can be obtained by rearranging relationship 4.1 and is equal to the inflow rate plus additional water used for cooling, drilling, humidifying, and drinking, this is collectively termed service water, plus additional disposed water.

$$PR = GW + SW + SL + DR + O \quad \text{.......... 4.4}$$

Thus

$$\text{Inflow Rate} = PR - (SW + O) \quad \text{.......... 4.5}$$

Where for relationships 4.3 to 4.5:

GW	=	the ground water component of inflow
PR	=	the long term pumping rate
SW	=	service water brought in for use on the mine
SL	=	surface water losses from streams flowing over outcrop or in structurally controlled valleys
DR	=	direct recharge to the outcrop area
O	=	other additions such as purpose water dumping underground.

The pumping rates were recorded by the mines and reported to the DW&F.

Relationship 4.5 holds as long as static underground water levels were maintained, in other words while no storage or losses were experienced due to dewatering or recovery. Plug pressure can be related to the static head of water, the pumping rate is then set to maintain constant plug pressures and hence constant water levels, Rolfe (1991). Thus the pumping record, during constant plug pressures, is a good indication of the inflow rate. Average pumping figures have been given in Table 4.3.5, on page 94 of this report.

4.4.4.2. Mined out Volume

Most of the workings are already flooded, so that only the upper extensively mined areas are presently dry.

The mined out volume can be calculated in two ways shown by relationships 4.6 and 4.7.

$$\text{Volume} = \text{stope area} \times \text{stope height} \quad \text{.......... 4.6}$$

The area affected by stoping is continually kept up to date by mine survey departments. Concise maps showing development, completed stoping and areas still containing ore, called shareholder plans, are published by the mines for investor evaluation. From the shareholder plans the stoped out areas can be determined, calculating the volume then requires that the stope height be known. Since most of the mines closed down many years ago, some of the shareholder plans were not available. Estimations therefore had to be made for the following mines, Robinson Deep, Rose Deep, Witwatersrand GMCo. and Rand Leases. As well as mines such as Mayfair, Geldenhuis Deep and others for which there are no plans. These estimates were kept conservative and introduce underestimation.

$$\text{Volume} = \frac{\text{Tonnage}}{\text{Density}} \quad \ldots\ldots 4.7$$

The total tonnage of rock that was milled at each of the mines has been recorded by the Chamber of Mines since it's inception in 1887, this data is now available from the Minerals Bureau. The tonnage conversion to volume was calculated using a density of 2.75, which is the value used on the mines for density related calculations.

The tonnage milled was predominantly ore mined in the stopes, it does not take off-reef development into account. Typical off reef tonnage is estimated to be 15% of reef tonnage by Nel (1993). Rock from off-reef development may be sent to the plant at times, such as during,

- the start up period of mining
- times of labour unrest
- periods of mine disaster
- the waning stages of the mines life.

Thus some of the figures recorded as ore milled, by the chamber of mines, may include off reef or waste rock.

4.4.4.3. Historical Evidence

When Crown Mines stopped their deep workings at the end of 1974, deep de-watering of the central mines was no longer necessary. Thus in 1975 the pumping level at SW Vertical Shaft was raised from 49 level, 2058 meters below surface, to 24 level, 1253 meters below surface. A record kept in the Department of Water Affairs files for ERPM states that, when pumping stopped the water level rose at **0.8** metres per day.

The dates given are imprecise, but it is stated that before February 1975 pumping took place from 49 level S.W. Vertical shaft and started at 24 level in October 1976. Thus the rate of water rise can be calculated: Water had risen 805 metres in some 660 days, a rise of **1.22** metres per day.

These figures may have been estimates, which would explain the discrepancy, but they give an indication of the type of water rise that can be expected and are therefore useful for comparison with the rates predicted from other calculations.

4.4.4.4. Indeterminable Factors

This report has highlighted some of the factors that have influenced the current situation on these mines. The history, especially ownership changes and developing mining techniques has influenced the interconnectedness of the mines and the mined out volume. The scale of mining is also different from that reported by Johnson (1985), in his investigation the mine influenced a region of less than 1 km². Measurement of the mined out volume in this situation is not trivial and many aspects remain indeterminable.

The following description of some of the factors that influence the remaining volume explains why they are indeterminable:

- Underground slimes disposal.

  Disposal by Village Main Reef mines is permitted thus their contributions could be taken into account. There has been and may still be, unrecorded disposal such as at Badenhorst Gold Mine, such contributions are indeterminable.

- Packing of waste underground.

  In many of the old mines waste rock has been neatly packed in any available space such as haulages and in stoped areas. This practice added support and allowed for increases extraction of ore.

- Stope sagging and roof collapse.

  According to Camden-Smith (1993) closure factors are difficult to estimate but at ERPM there is little closure from surface to 1500 metres below surface. Where mining has occurred to 3200 metres, total closure occurs after 5 months. In the very old workings, the wooden supports are completely friable and yet, above 700 metres there is no closure, this has been observed at DRD and ERPM. There are occasional rock pillars and backfilling in the shallow areas which give support, but even without these the areas would probably be stable.

  Brink (1979) shows that where dips are steep less support is necessary. Steeper dips are found near the surface thus the near surface areas are more stable.

  Mortlock (1993) states that where reefs have been mined individually, total collapse has taken place up to 1800 metres below surface, this is due to the thin partings between reefs which cannot support themselves. Where wide stoping included a number of reef bands, the stopes are open and stable. In some places very wide stoping of 2.5 to 3 metres was developed before 1912, these areas are now unstable to surface. A main road, Johan Rissik street, in Germiston was closed due to this form of mining induced instability.

- Filling of surface workings.

  Before 1930 the surface workings were filled to a depth of a couple of 100 metres. The fill material included sand, and rubble, but was predominantly ash. Ash waste was plentiful being derived from the steam engines that were used to drive most machines such as stamp mills, hoists and locomotives.

- Existing underground water bodies.

  Standing water and small scale compartmentalisation that is already full of water could occur in places, but because many of the old workings are inaccessible its influence is indeterminable. The volume determination based on tonnage milled cannot take into account the volume that has already been filled with water up to 1083 mbd.

- Processed waste rock.

  During the last years of the life of many of the mines, waste rock was sent to the plant to increase the tonnage milled. This happened because the mine layout introduced a large amount of ore handling, thus ore delivery to the plant was slow and the plant could not be kept fully supplied. Many ore processing plants were designed to run at full production, in addition plant operators were paid a bonus for tonnage milled. Thus waste rock was milled to run the plant at optimum efficiency.

4.4.4.5. Results

The results of volume calculations and predicted times of recovery are given in Table 4.4.3.

Table 4.4.3 Results of Volume Measurement and Calculations

Data source	Total Mined Area (m^2)	
Determined from mine plans	1)	106 591 757
Determined from maps prepared for this report	2)	163 290 710
	Mined Volume (m^3)	Time to Fill (Years)
Area (1) × Stope height (0.5 m)	52 575 387	4.30
Area (1)× Stope height (0.8m)	84 120 620	6.88
Area (2) × Stope height (0.5m)	224 524 726	18.13
Volume Calculated from Tonnage	283 712 009	22.90
Time calculated from water rise in 1975-1976		3.71

These results seem to indicate such a wide range as to be totally useless. Area measurement from mine plans is very difficult because of the detailed display of scattered working. Small, isolated stoped areas and off-reef development may not be included because of measurement difficulties. Many of the older mines were not measured at all because there are no maps available. Thus area 1 is underestimated and the resultant volumes and times are smaller than expected.

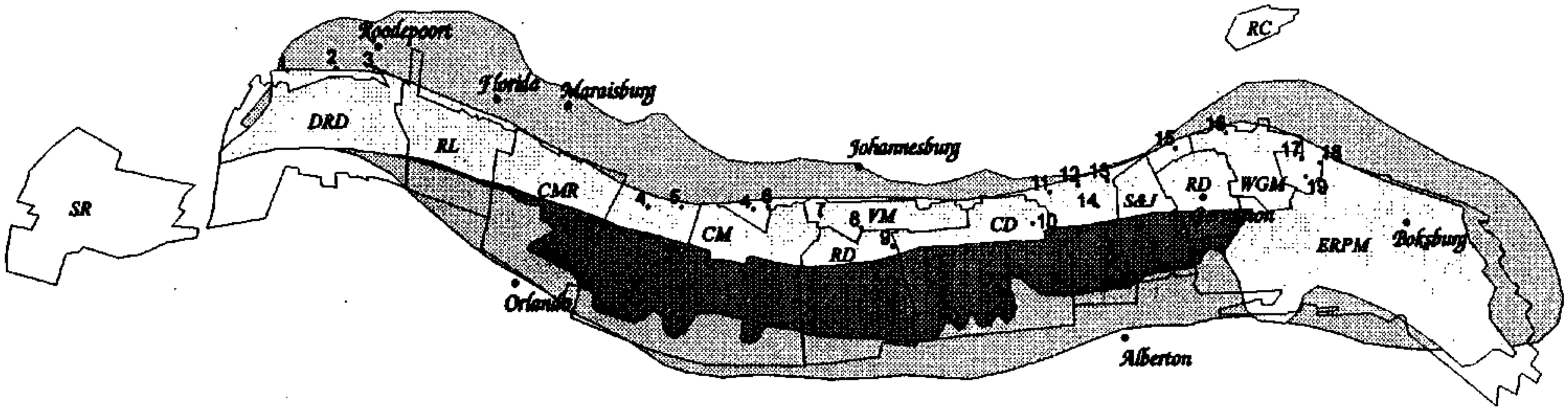
The rate of rise indicated by historical observations (discussed in section 4.4.4.3), involved a volume in the deeper parts of the central group of mines. At this depth mining was not as continuous as it is at shallow depths, thus the volume was smaller. This is particularly applicable to South Reef which was not mined to the same depths as Main Reef Leader. Stope closure at this depth would also be significant due to depth and the shallow dip (±16°), but this may not have significantly affected the volume as has been discussed previously in this report. Thus with significantly smaller volume the rapid rise is not surprising.

The indicated rise taking 18 to 23 years is corroborated by volumes calculated from Pretorius (1964, 1986), whose data referred to conditions in 1964. From this data the calculated time was 12 years. Pretorius also based his calculations on mines for which reliable data was available thus data for many mines was not included even as an estimate.

A linear recovery rate is assumed since the inflow rate per year will be constant, seasonal variations will be smoothed when looking at the recovery over many years. The rate will decrease logarithmically over the last 50 metres of recovery.

A plan showing the total extent of the Central Rand catchment, the related mining lease areas, and the extent of the filled and dewatered mine aquifer is given in Figure 4.4.12.

The mine workings are interconnected at 894 mbd (934.8 m above sea level), a head of 60 m could develop between the highest elevation, found on DRD, and the lowest elevation, found on ERPM. The recovered water level elevation will be within the groundwater zone and some recharge of the groundwater by mine water could be expected. Recharge will be enhanced by the fracture zones around mine workings which are caused by collapse Brink (1979) and geological structures. Groundwater will still follow a path of least resistance and emanation at the low shafts is expected. These matters require further investigation for quantification.



Area Definition

- CM — Gold mining Co. Lease Area
- Surface Water Catchment
- Mined Out Area
- Volume already filled with water
- Volume still to be filled

Gold Mining Company Boundaries

SR *South Roodepoort Main Reef Areas*
DRD *Durban Roodepoort Deep*
RL *Rand Leases G.M. Co.*
CMR *Consolidated Main Reef Mines and Estates*
CM *Crown Mines*
RBD *Robibson Deep*
VM *Village Main Reef G.M. Co.*
CD *City Deep*
S&J *Simmer and Jack Mines*
RD *Rose Deep*
WGM *Witwatersrand G.M. Co.*
ERPM *East Rand Proprietary Mines*
RC *Rietfontein Consolidated Mines*

Defunct Mines

1 Princess Mine
2 Wilford Mine
3 Roodepoort Mine
4 Langlaagte Estate Mine
5 Croesus mine
6 Mayfair Mine
7 Robinson Mine
8 Ferreira Deep Mine
9 Village Deep Mine
10 Nourse Mines
11 Heriot Mine
12 Jumpers Mine
13 Stanhope Mine
14 Geldenhuis Deep Mine
15 Primrose Mine
16 Waverley Mine
17 Driefontein Mine
18 Balmoral Mine
19 Witwatersrand Deep Mine

Figure 4.4.12 Position of Gold Mines and Related Water Catchment Details.

4.4.5 Discharge Points

4.4.5.1 Mine Shaft Positions

To investigate the positions of potential outflow points the elevations of as many shafts as could be identified were determined. The position of some shafts, particularly incline shafts, have been lost and obscured and no concise records are available. The available data is listed in Table 4.4.4.

This table shows that the lowest shaft has an elevation of 1601 m above sea level, this being ERPM South East Shaft. The highest shaft has an elevation of 1761 m above sea level and is DRD 1 shaft. These relationships are shown in a three dimensional topographic plot in Figure 4.4.13.

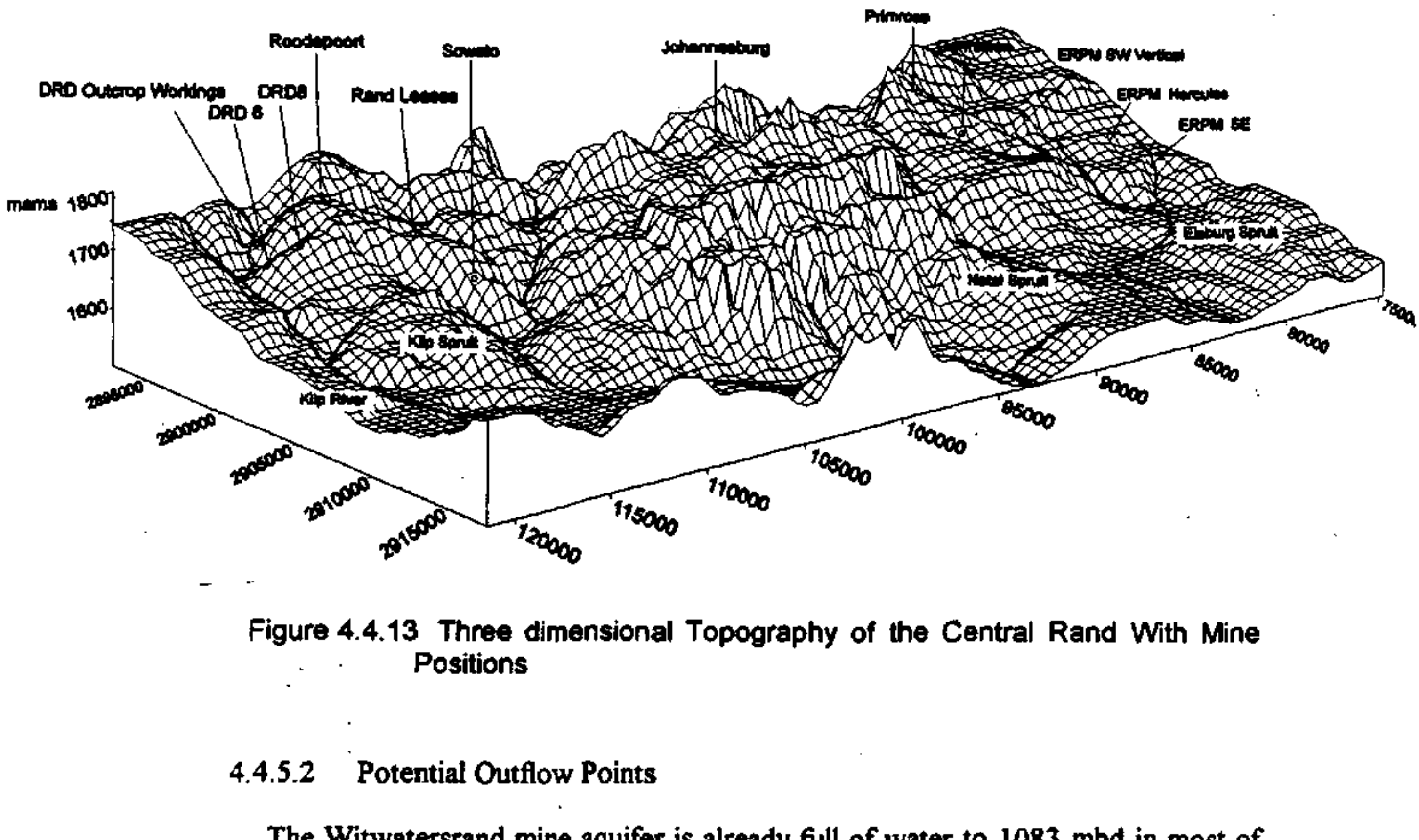


Figure 4.4.13 Three dimensional Topography of the Central Rand With Mine Positions

4.4.5.2 Potential Outflow Points

The Witwatersrand mine aquifer is already full of water to 1083 mbd in most of the mines. When it is completely filled, it will have the characteristics of a confined aquifer as was explained in section 2.4. Since a piezometric level will be established in the aquifer, vertical shafts which intersect the aquifer, can be considered to be piezometers where the piezometric level could be measured. Shafts with collar elevations lower than the piezometric level will become discharge points from the mine aquifer equivalent to artesian boreholes. These relationships are depicted in Figure 4.4.14.

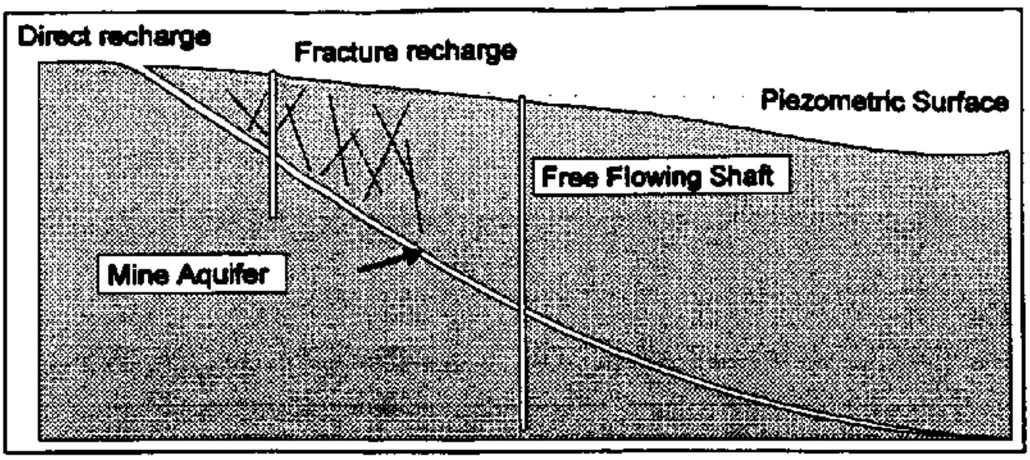


Figure 4.4.14 Mine Aquifer, Piezometer Shafts and Piezometric Surface.

Historical evidence has shown that the main inflows are occurring at the outflow from Florida Lake, in the vicinity of Village Main Reef Mines, and at the Knights and Waverley mines. The surface elevation of these points ranges between 1670 and 1720 m above sea level. The measured groundwater level in the vicinity of these areas has an average of 15 m below surface, the piezometric level would be similar or slightly lower than this level. Thus if it were at 1660 mams then the expected head for each known shaft can be calculated relative to this level. The results of such a calculation for some of the main shafts in the Central Rand are given in Table 4.4.4. The expected head is shown in the third column of this table, where:

- A negative value indicates that the piezometric level is below the shaft collar elevation
- A positive value shows that the piezometric level will be above the shaft collar elevation. Shafts with positive values could be free flowing.

Table 4.4.4 Shaft Names, Elevation and Relative Piezometric level at each Shaft

*Shaft Name	×Y	×X	×Collar Elevation (mams)	Piezometric level m below (-) or above (+) collar elevation.
Crown Mines				
1	97500	2900870	1700	-40
14	98425	2903225	1698	-38
2	98080	2900650	1738	-78
3	98520	2900920	1734	-74
6	99430	2901070	1725	-65
7	99850	2900940	1723	-63
16	101870	2903270	1706	-46
15	100230	2902920	1694	-34

* Shafts identified from shareholder plans

× Co-ordinates measured from Orthophoto Maps

Table 4.4.4 Continued

Shaft Name	Y	X	Collar Elevation (mams)	Piezometric level m below (-) or above (+) collar elevation.
Robinson Deep	96750	2901300	1705	-45
Village Deep	95100	2901280	1730	-70
City Deep				
1	91630	2901620	1666	-6
2	92950	2901500	1687	-27
4	92850	2902790	1682	-22
Simmer & Jack	85410	2899530	1687	-27
Waverley Gold Mine	82263	2897998	1675	-15
Witwatersrand GMCo	80950	2897820	1651	+9
East Rand Proprietary Mines				
South West	81670	2900900	1646	+14
Ventilation	81170	2900590	1645	+15
SW Subvertical	81850	2901140	1640	+20
Angelo Main	77140	2899410	1641	+19
Angelo West	78010	2900560	1617	+43
Central Shaft	77950	2901840	1626	+34
Hercules	76480	2901260	1616	+44
Comet	76570	2899870	1640	+20
Hercules South	76370	2903220	1602	+58
South East	75710	2903620	1601	+59
Far East Vertical	73277	2905470	1606	+54
Cason	75380	2899950	1635	+25
Cinderella E	73830	2902190	1617	+43
Leeupoort	72990	2902470	1620	+40
Durban Roodepoort Deep				
Outcrop Inclines	116270	2895370	1685	-25
	116130	2895320	1695	-35
	116030	2895330	1695	-35
	117680	2895380	1715	-55
	117570	2895320	1710	-50
Princesses	117060	2895900	1732	-72
4	117770	2896020	1716	-56
6	116330	2897030	1698	-38
9	116230	2897230	1710	-50
3	114300	2895720	1751	-91
2	113830	2895720	1755	-95
1	113020	2895780	1761	-101
Circular	113710	2896360	1728	-68
5	113760	2896840	1729	-69
8	114330	2897055	1731	-71
7	112740	2897500	1737	-77

Table 4.4.4 Continued

Shaft Name	Y	X	Collar Elevation (mams)	Piezometric level m below (-) or above (+) collar elevation.
Rand Leases	110230	2897950	1695	-35
Consolidated Main Reef				
Aurora	107480	2897890	1715	-55
New Unified	106610	2898230	1698	-38
8	107750	2898750	1705	-45
3	105950	2898650	1691	-31
5	107730	2898980	1694	-34
Central	105230	2898770	1730	-70
9	106980	2899120	1694	-34
3 (KReef)	105750	2899790	1660	0
6	106450	2900550	1647	+13
Mooifontein	103430	2899960	1700	-40

From the table it can be seen that all the shafts on ERPM are below the proposed piezometric level, the Witwatersrand Gold Mining Co. shaft would also be 9 m below the piezometric level and CMR 6 shaft would be 13 m below the level. These shafts would therefore all have potential to become free flowing. One Shaft on CMR is borderline and, depending on the accuracy of the proposed piezometric level, has potential to be a discharge point.

From this list the most convenient shaft for this outflow could be chosen by plugging the others and thus forcing the emanation to occur at one point. Unless the lowest shaft is chosen, allowing a higher shaft to discharge will recharge the secondary aquifer with polluted mine water. This will particularly be a concern if the shaft is unlined or the shaft lining breaks down with time.

Given the large heads that would exist at the ERPM shafts it is unlikely, if these are allowed to flow, that any of the other shafts would become out-flowing since a steady state would be set up and most of the water would flow from the lowest shafts.

The steady state that will develop will be given by relationship 4.8:

Volume recharging = volume discharging...4.8

Since the recharge is associated with rainfall and stream flow, it will vary seasonally. A baseflow contribution from groundwater will ensure that there is always a minimum flow estimated to be between 23 and 24 Ml/day.

This investigation assumes that the lowest shaft, ERPM South East Shaft which has a predicted head of 59 m is allowed to flow. The shaft is located adjacent to the Elsburg Spruit at Cinderella Dam. The impact of the outflow on the stream has been modelled and will be described in section 4.5.6 of this report.

4.5 Water Quality

4.5.1 Introduction

The aims of this part of the investigation were to answer the question "Where does acid generation occur?" The answer to this question will determine how the outflow water derives its quality and whether there is anything that can be done about it.

The following list gives possible areas of acid generation:

- On surface, in association with the many poorly controlled slime and sand dumps
- In old backfilled workings
- In mine openings such as stopes or travelling ways
- Underground in the deep flooded portions

Samples were taken, not to evaluate pollution on the Witwatersrand, but to try to get evidence that would answer this question. Inflows to the mines and in the mines show variable quality, while the deep flooded water has a consistent quality.

Repeat samples were taken at some of the underground sites during the 1993/1994 rain season, in an attempt to determine relationships between rainfall and inflow water.

4.5.1.1 Source of Information

The water quality investigation on the Central Rand involved gathering data* from the following sources:

- Rand Water Board monitored results. Four consecutive years of the most recently published data and one year representing a period covering the final stages of mining activity in the area were evaluated. In this study the variation in water quality with position has been concentrated on, rather than the variation in water quality with time. Water flowing in the vicinity of potential recharge areas, sand and slimes dumps, and related to pumped water discharge points, was of particular interest. For this reason average values over the five monitored years have been used to give an indication of the water quality at the points of interest.

- Sample analyses of as many other points in the area as possible. These were one-off samples, as the time constraints of the project did not allow for a monitoring program to be established. The aim of this exercise was to

* All the data gathered in this investigation will be available on disk.

- Fill in surface water samples, where RWB samples were too widely spread, especially in the vicinity of potential inflow areas.
- Sample as many boreholes which were as close to the area influenced by mining, as possible.
- Sample subsurface mine inflows to get an idea of the water quality flowing into the underground environment.

Samples were split into two, one filtered and preserved with nitric acid to a pH of 2, the other taken as raw water. Electrical Conductivity and pH were measured in the field. In the Laboratory the filtered and acidified sample was analysed for Ca, Mg, Na, K, Fe, Al, Mn, Zn, Ni, Cu, Cd, Co, Ba, B, and Sr. while the unfiltered sample was analysed for the following anions; SO_4, Cl, NO_3, NO_2, PO_4, F and Br as well as having its laboratory pH, Alkalinity and EC measured. From this relatively complete inorganic analysis numerous other parameters could be calculated for each sample, such as HCO_3, CO_3, Mg Hardness, Ca Hardness, TOT Hardness, Ion-balance, Langelier Index and TDS (sum).

- Data submitted to the Department of Water Affairs pollution control directorate.
- *Other monitored data obtained from the mines and municipalities in the area.*

4.5.1.2 Pollution Index

In investigating the water quality a reliable indicator of pollution was sought so that each of the analysed parameters would not have to be plotted for each sample position.

By selecting a water sample that represents the least polluted water and assuming that this represents background conditions, a pollution index can be defined.

$$PI = \frac{X_i}{X_b} \qquad \text{.......... 5.1}$$

Where: X_i = the concentration of a selected element for the i th sample
X_b = the concentration of that element from the least polluted or background sample.

Once the pollution index has been calculated for all the elements of each sample; those elements that consistently show high indices are considered to be the best indicators of pollution for the site. This may be determined by averaging the pollution indices for each element, those with the highest average and a low standard deviation are identified as good indicators of pollution.

Nazari *et. al.* (1993) claim that this method is useful for:

- Identifying the primary pollution indicators for a study area.
- Assessing the relative loading of major ions and trace elements above baseline concentrations

- Evaluating the mobility potential of major ions and trace elements

It is important that a pollution index for each identified water group should be determined, for example, surface water and groundwater pollution indices should be determined separately.

In the Central Rand, samples using these techniques showed that Mn is a reliable indicator of the influence of mining on the water chemistry. The technique showed that Fe, Al and Sulphate were also fairly reliable indicators.

4.5.2 Measured Surface Water Quality

The sampling points used in this investigation are shown in Figure 4.5.1.

From the results of the pollution index investigation Mn and SO_4 have been plotted against other elements commonly used to indicate pollution. In these plots averaged values based on RWB monitoring and one off sample data have been plotted together, to simplify the presentation the ranges obtained from the averaged results have not been included. This conforms to the approach of evaluating spatially variable concentrations rather than changes with time. Cyclic time variations are evident but their evaluation does not fall within the scope of this investigation.

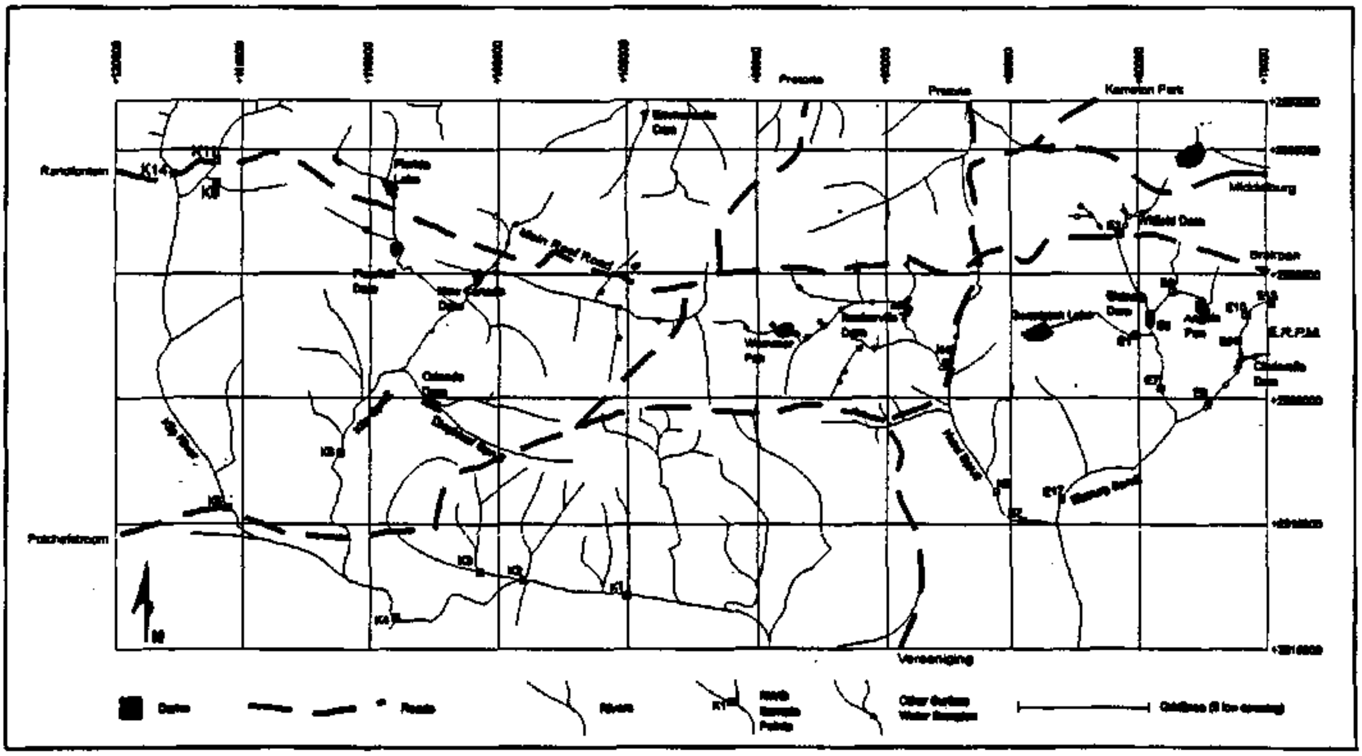


Figure 4.5.1 Sample Sites on The Klip River, Elsburg and Natal Streams

4.5.2.1 Klip River

Description of RWB Klip river sampling points:

- K9 is below DRD and therefore reflects the mine water that is pumped into the river above that point.
- K14 the main headwater tributary drains the mining area of East Champ D'Or and Chamdor industrial area, therefore it is also influenced by mining activity.
- K11 is a headwater tributary that drains Roodepoort town. This part of the stream is a fault line valley following the trend of the Saxon fault zone. Market gardening takes place along the banks of the stream in Roodepoort.

These three headwater tributaries flow over the Main Reef outcrop and are therefore important to this study.

- K6 this sampling site is on the Potchefstroom road, squatting and township development is taking place along the river upstream of this point. Below the entry point of the headwater streams, the stream flows over Bird Reef and Kimberley Reef outcrop. The upper part of the stream also follows the trend of the Saxon fault.
- K5 is a sampling site on the Klip Stream, this stream's headwaters rise in Roodepoort and Johannesburg and drain Rand Leases, CMR and Crown Mines mining areas. The stream then flows through Soweto.
- K3 is on a Klip River tributary, the Harrington Stream, below the Bushkoppie Sewage works.

The other sampling points are at progressively downstream locations and are influenced by numerous tributaries, they show considerable dilution. The order of progression downstream is as follows: K4⇨K2⇨K1⇨K21⇨K10⇨K19⇨K18. The one off sample points covered streams that are not sampled in the Rand Water Board monitoring program, these are predominantly headwater streams of the Klip Spruit.

The chemistry changes in the Klip River between sampling points are shown in Figures 4.5.2 to 4.5.5. The influence of mining activity is identified by raised SO_4 and Mn values. Iron is also a useful indicator but under oxidising conditions above a pH of about 5 it precipitates, whereas manganese under these conditions remains in solution up to pH 7. Thus Mn is a more reliable indicator of Acid Rock Drainage under oxidising (surface) conditions.

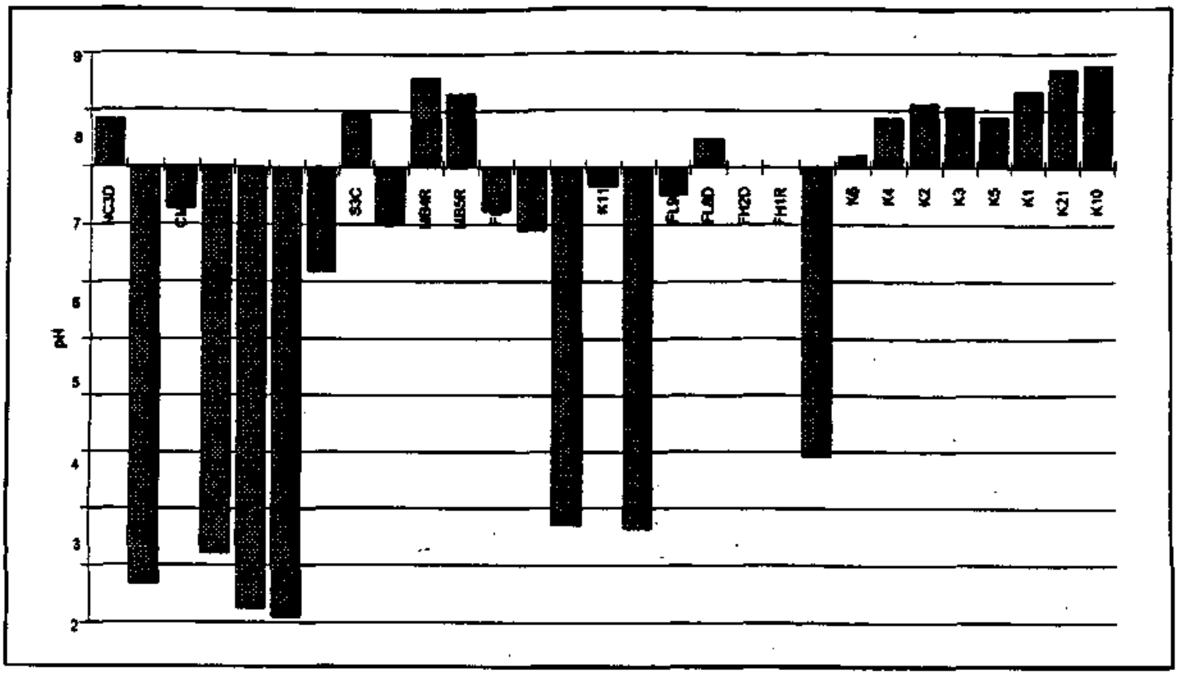


Figure 4.5.2 pH in the Klip River and Associated Tributaries

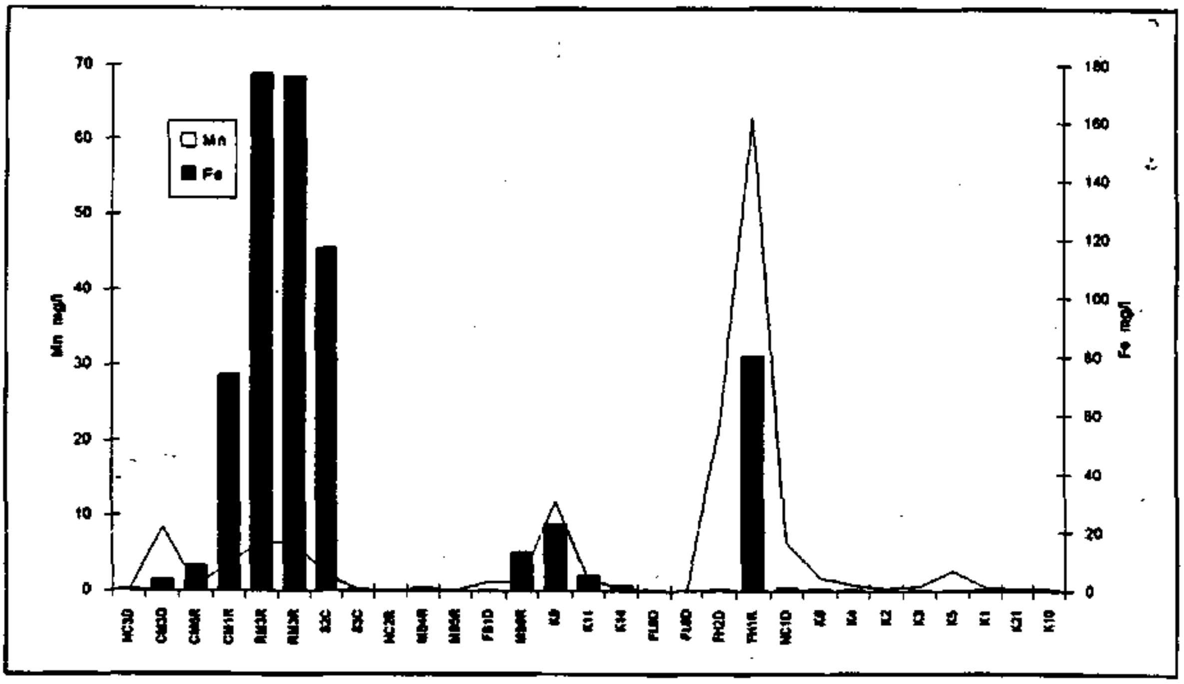


Figure 4.5.3 Fe and Mn in the Klip River and Associated Tributaries

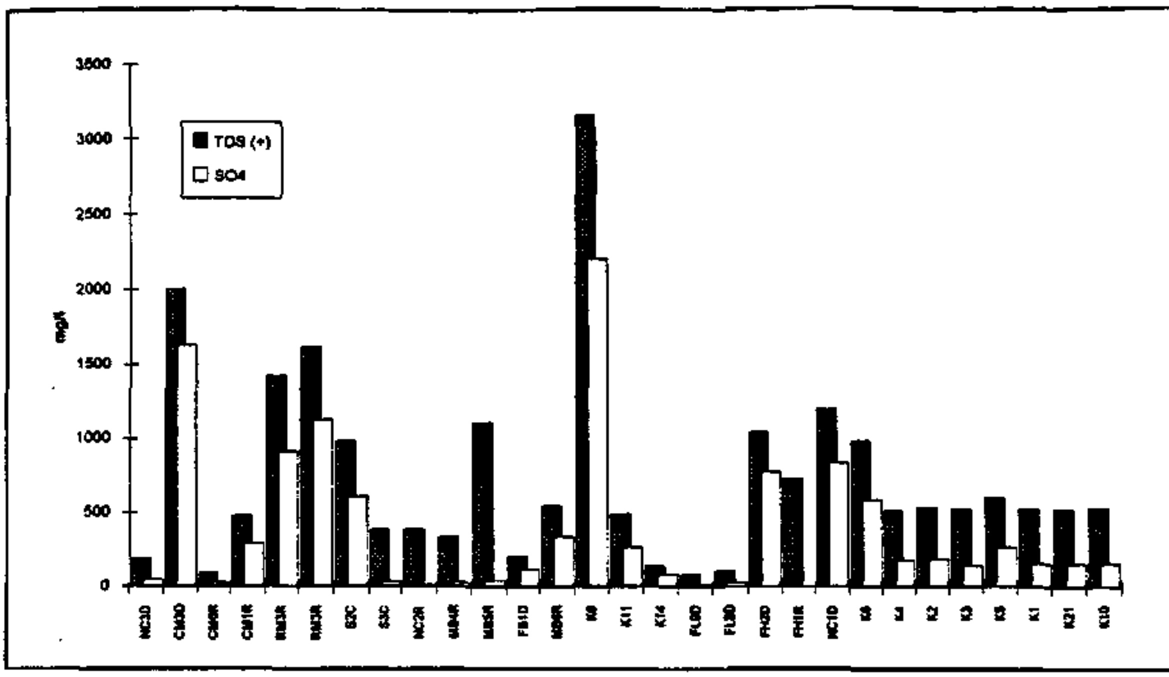


Figure 4.5.4 TDS and Sulphate in the Klip River and Associated Tributaries

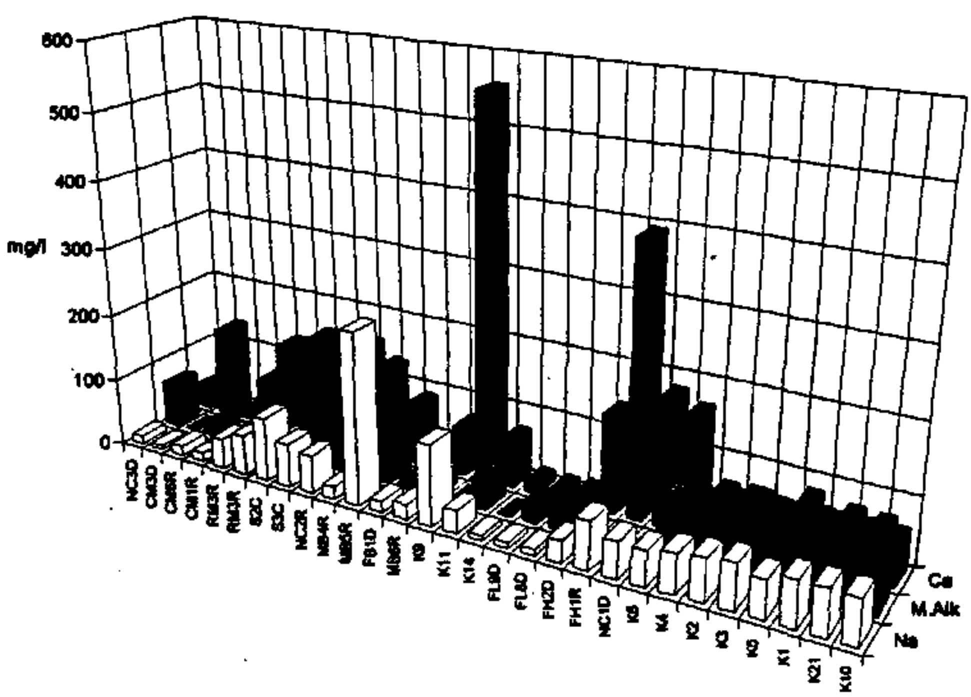


Figure 4.5.5 Ca, Na and Alkalinity in the Klip River and Associated Tributaries

The element concentrations increase in the vicinity of mining areas such as at the sample points labelled K9 near DRD, FH at Rand Leases and RM on Crown Mines, at downstream sites such as K6, to K21 dilution has occurred and the concentrations reach a fairly constant level. In spite of this, the river flow increases downstream, and the salt load increases. as shown in Figure 4.5.6.

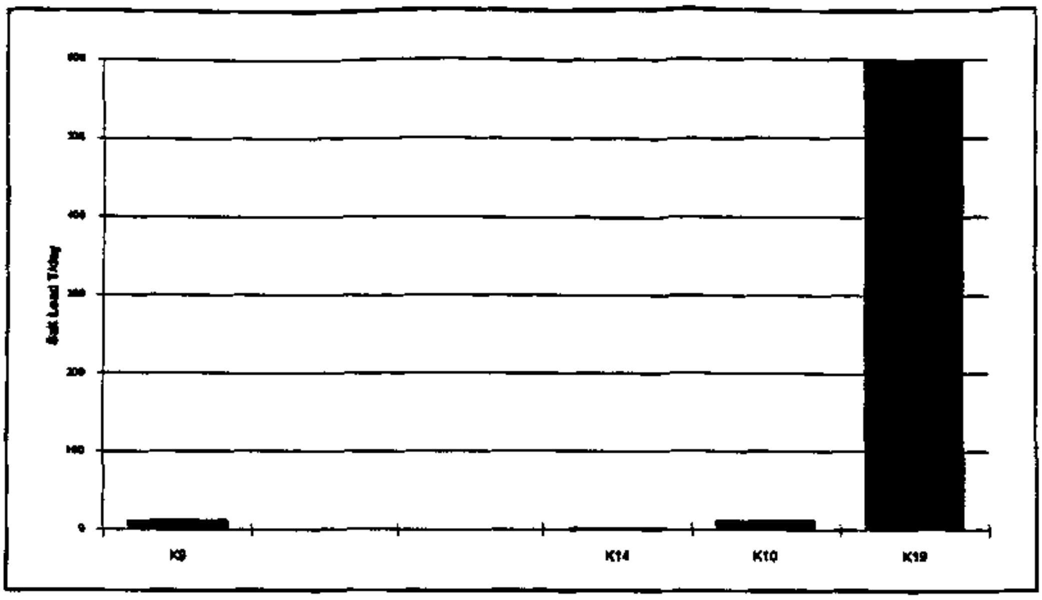


Figure 4.5.6 Salt Load in the Klip River

4.5.2.2 Elsburg Spruit

The chemistry changes in the Elsburg Spruit between sampling points are shown in Figures 4.5.7 to 4.5.11. The identifiers (raised Mn and SO_4) of the influence of mining activity are evident in these samples.

The RWB Sampling points can be described as follows:

E13 is on the inflow to Boksburg Lake, E10 is the outflow from the lake (inflow to Cinderella Dam) and E9 is on a tributary above Cinderella Dam.

E8 is located below Cinderella Dam.

E2 is on the outflow from Witfield Dam in the vicinity of Main Reef outcrop.

E6, 5 and 7 are sites progressively downstream of Angelo Pan and other headwater streams of the Elsburg Spruit, the discharge of mine water into this part of the river system is evident in these samples. Sample site E6 is located in the vicinity of Kimberley Reef outcrop, Angelo Pan is on a similar stratigraphic level although at that location the Witwatersrand sediments are covered by Karoo.

E1 is on the outflow from Germiston Lake.

E11, 12 and 17 are progressively downstream of the other sample sites and reflect dilution from incoming tributaries. E17 is the only site which may show some influence of sewage disposal, since Rondebult sewage works is upstream of this point.

Figure 4.5.7 pH in the Elsburg Spruit and Associated Tributaries

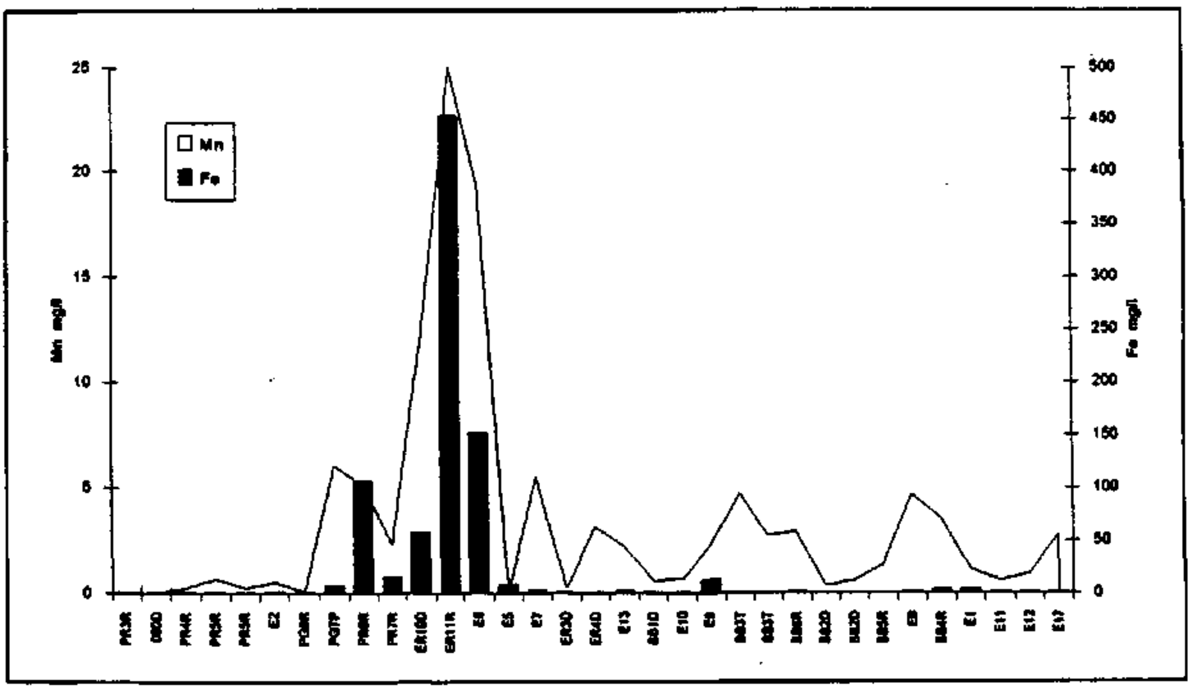


Figure 4.5.8 Fe and Mn in the Elsburg Spruit and Associated Tributaries

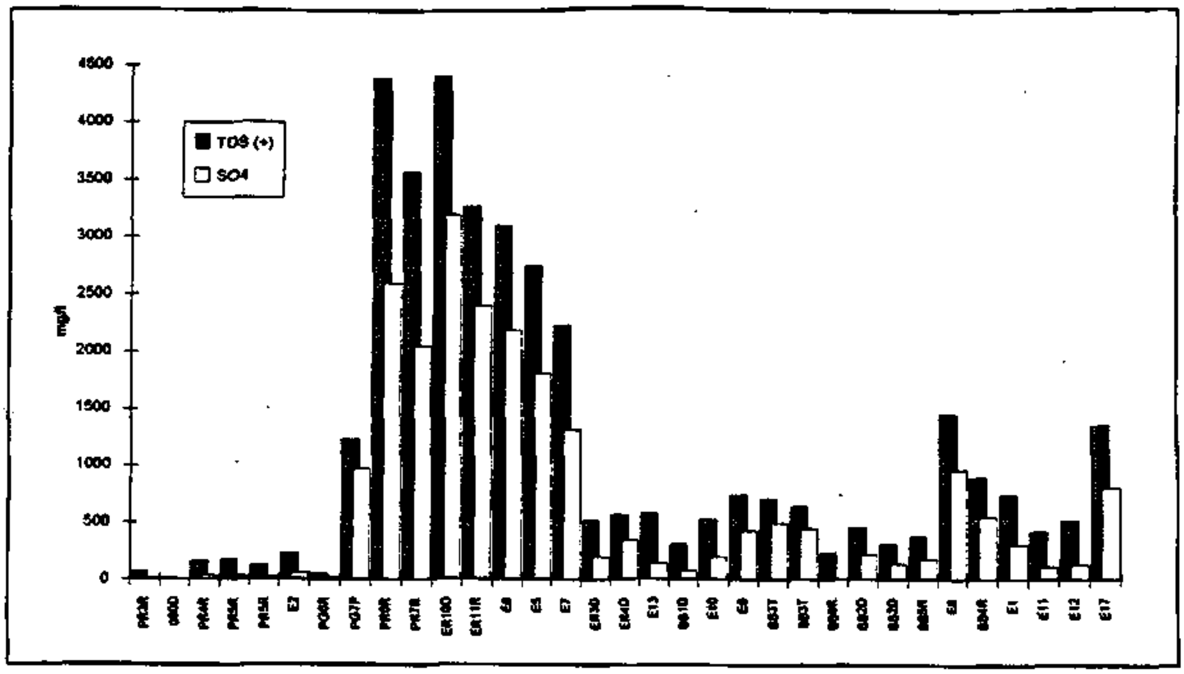


Figure 4.5.9 TDS and Sulphate in the Elsburg Spruit and Associated Tributaries

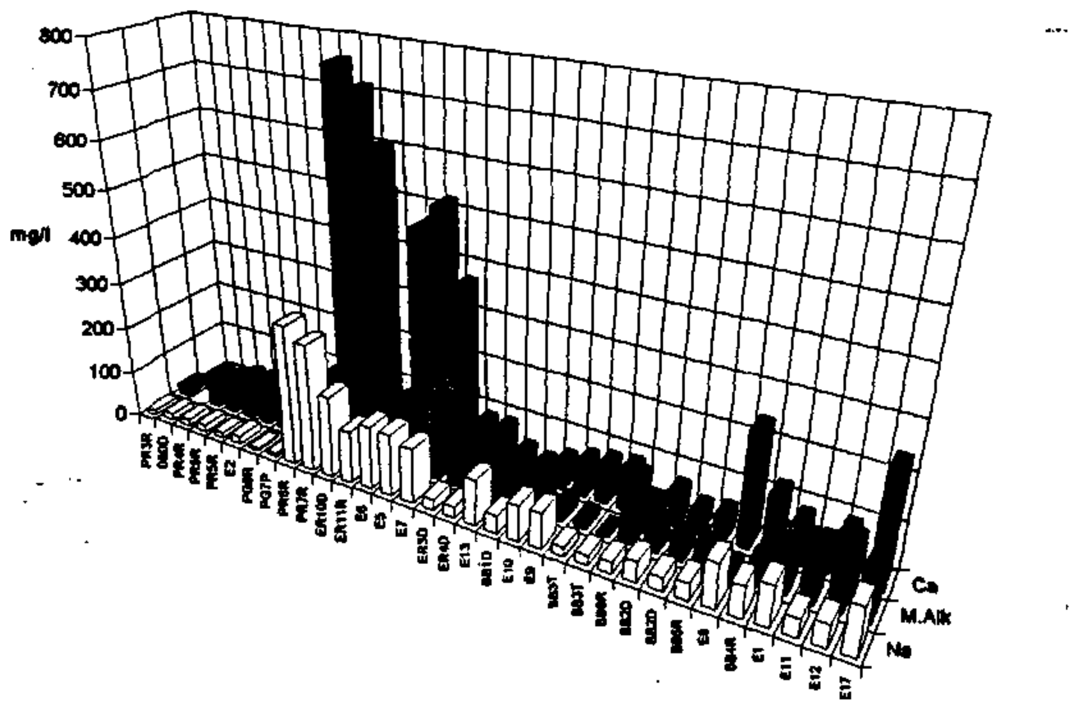


Figure 4.5.10 Ca, Na and Alkalinity in the Elsburg Spruit and Associated Tributaries

The stream loads are summarised in Figure 4.5.11. In the upper reaches of the stream tonnages are higher, here mine water disposal forms a predominant part of the water in the stream. Dilution further down in the stream lowers the tonnages, this is a reversal of what is observed in the Klip River.

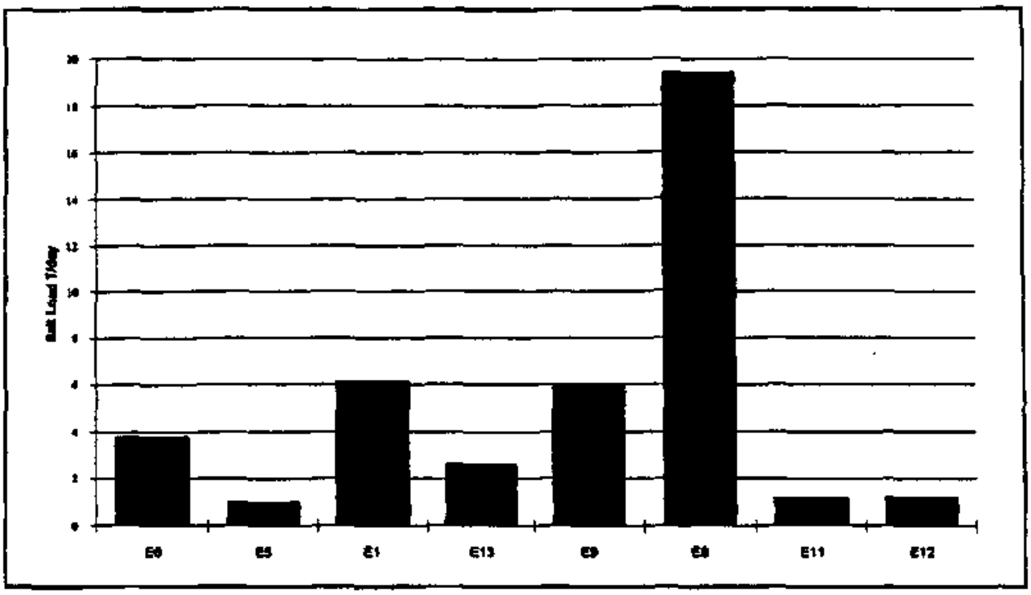


Figure 4.5.11 Salt Load in the Elsburg Spruit

4.5.2.3 Natal Spruit

Three RWB sampling sites on the Natal Spruit have relevance to this investigation:

N4 the stream at Rand Airport Road, at this point the stream which rises in Wychwood Germiston has crossed Main Reef outcrop workings and has passed the Geldenhuis, Badenhorst and Simmer and Jack Mines over property covered with extensive sand and slime dumps.

N6 and N7 are downstream locations in the vicinity of Alrode, an industrial area.

The chemistry changes in the Natal Spruit between RWB sample points and the sampling conducted for this investigation are shown in Figures 4.5.12 to 4.5.15.

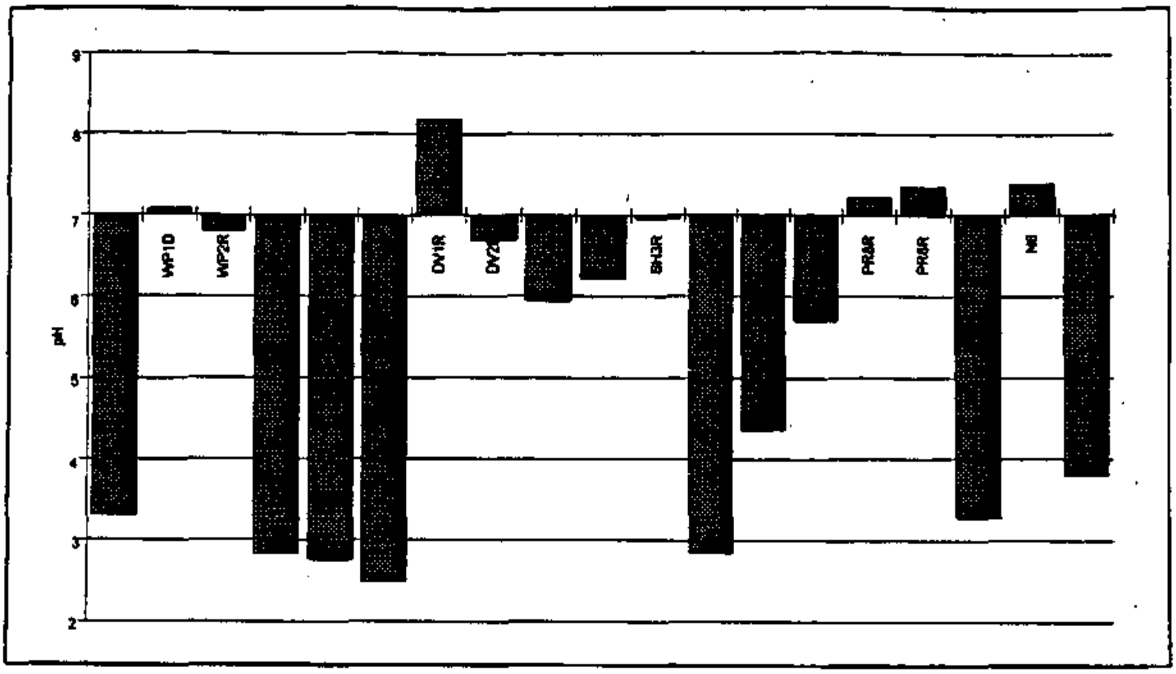


Figure 4.5.12 pH in the Natal Spruit and Associated Tributaries

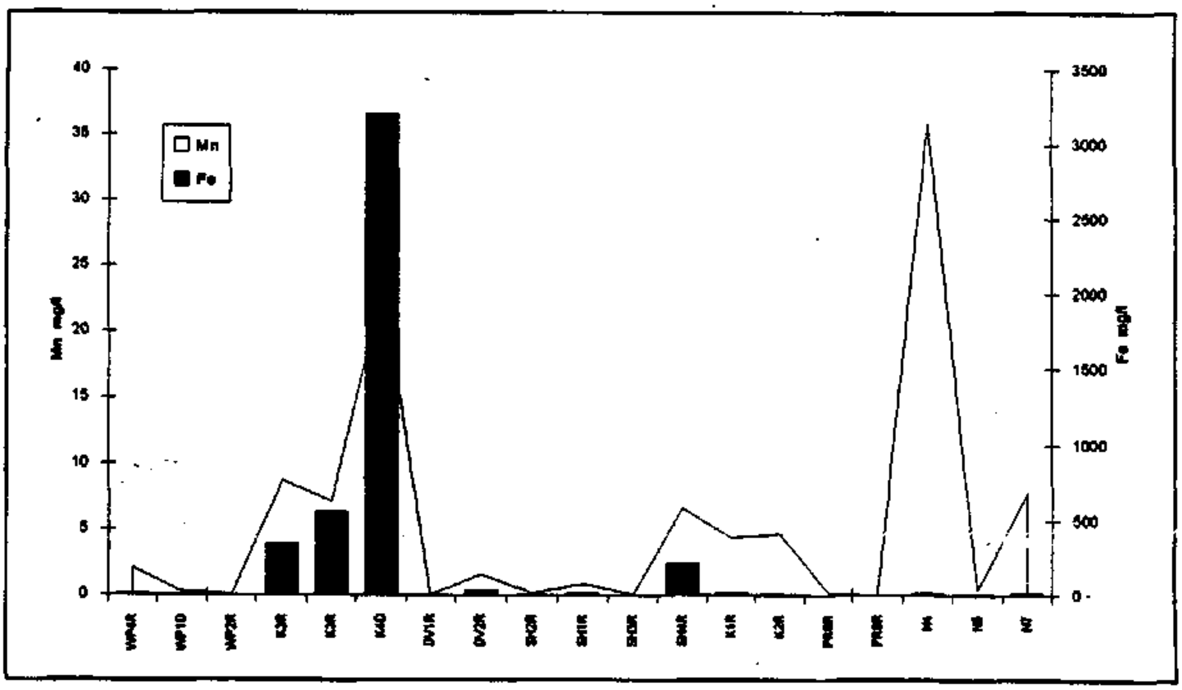


Figure 4.5.13 Fe and Mn in the Natal Spruit and Associated Tributaries

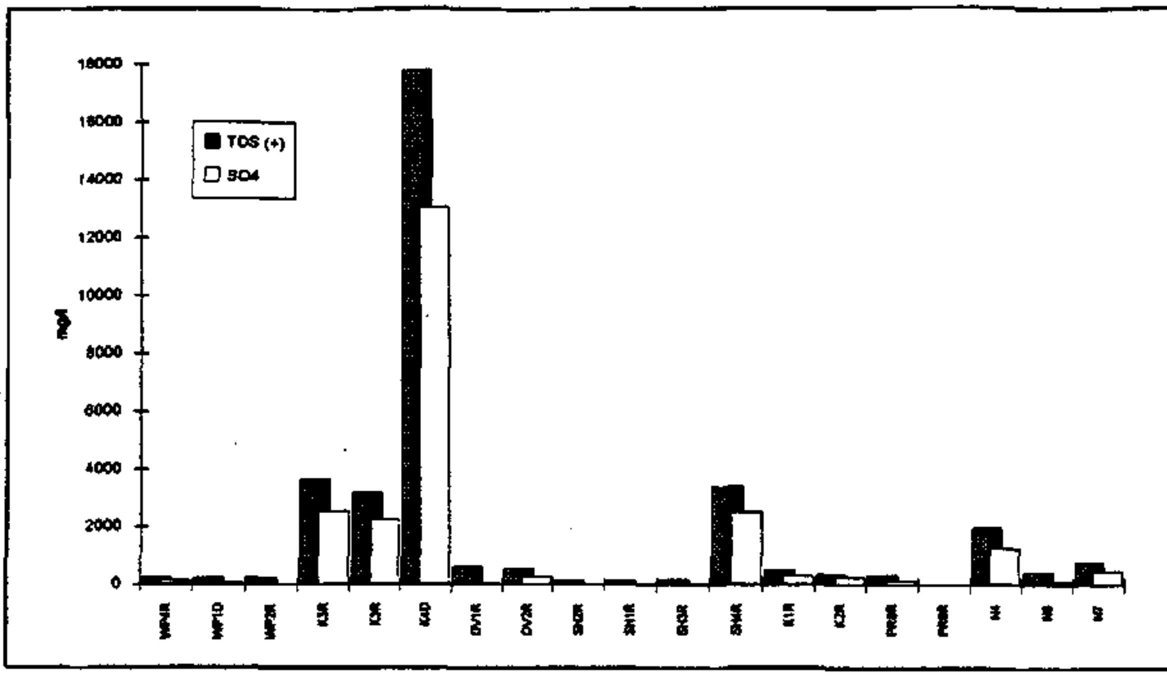


Figure 4.5.14 TDS and Sulphate in the Natal Spruit and Associated Tributaries

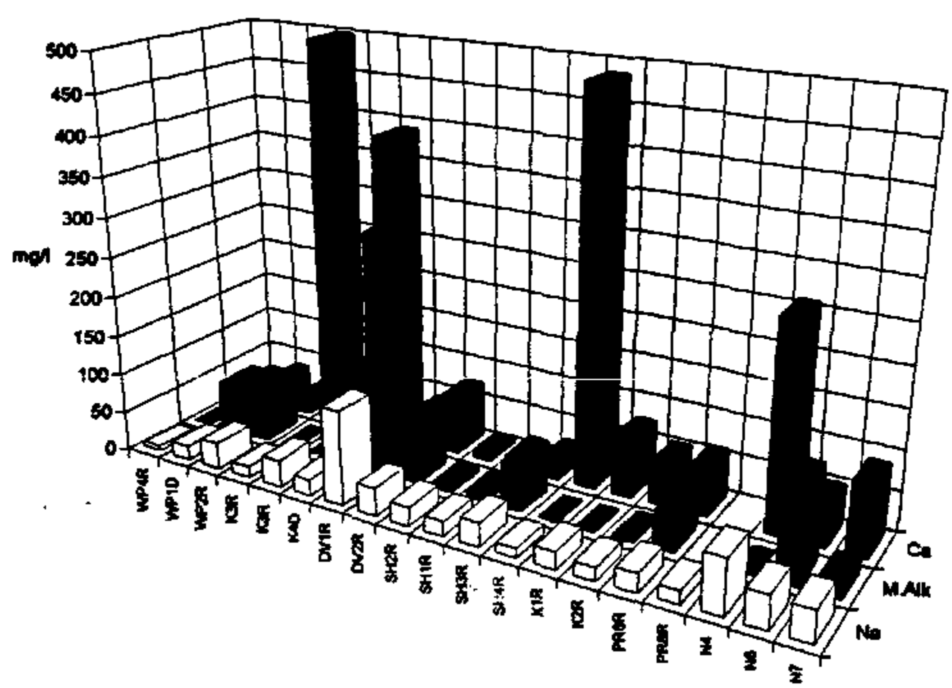


Figure 4.5.15 Ca, Na and Alkalinity in the Natal Spruit and Associated Tributaries

Tonnages are given in Figure 4.5.16. Sample point N4 is at Rand Airport Rd. below an area covered by mine wastes and point N8 is at the confluence with the Riet Spruit, a long way downstream. Point N8 is also below the confluence with the Elsburg Spruit, so could be equally have been added to Figure 4.5.11.

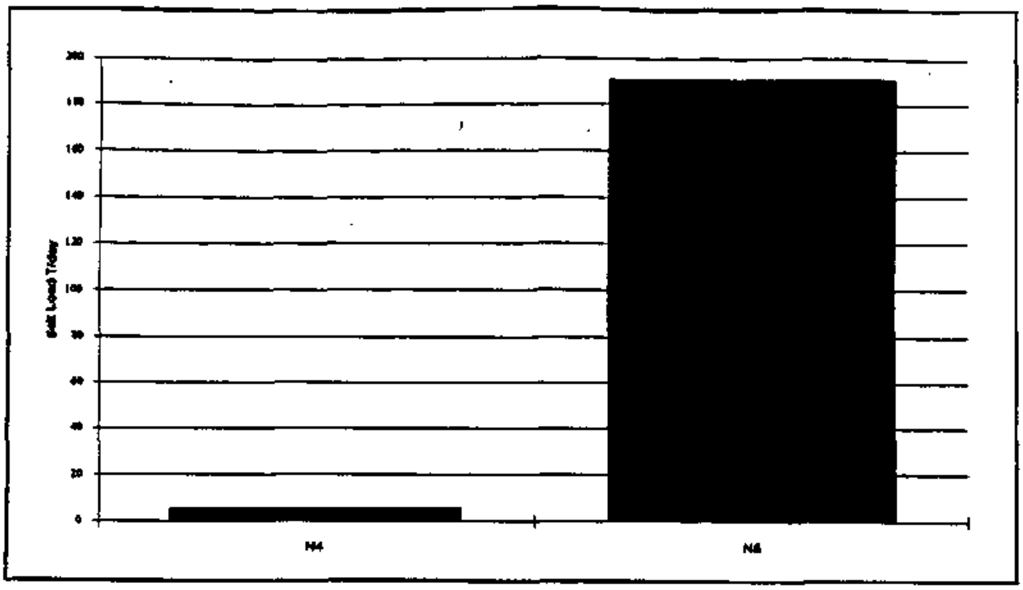


Figure 4.5.16 Salt Load in the Natal Spruit

The sample point N8 is used only to show tonnages in the Natal Spruit, it therefore does not appear in the other plots.

Note: The stream loads in this report must be regarded as estimates, they have been calculated from river flows that were reported by RWB in the mid 1970's. As there is no evidence of stream gauging construction at these sites, measuring techniques may have been of questionable reliability. The more recent RWB reports do not give flow values at most of these sites.

4.5.3 Measured Groundwater Quality

Figure 4.5.17 Groundwater pH

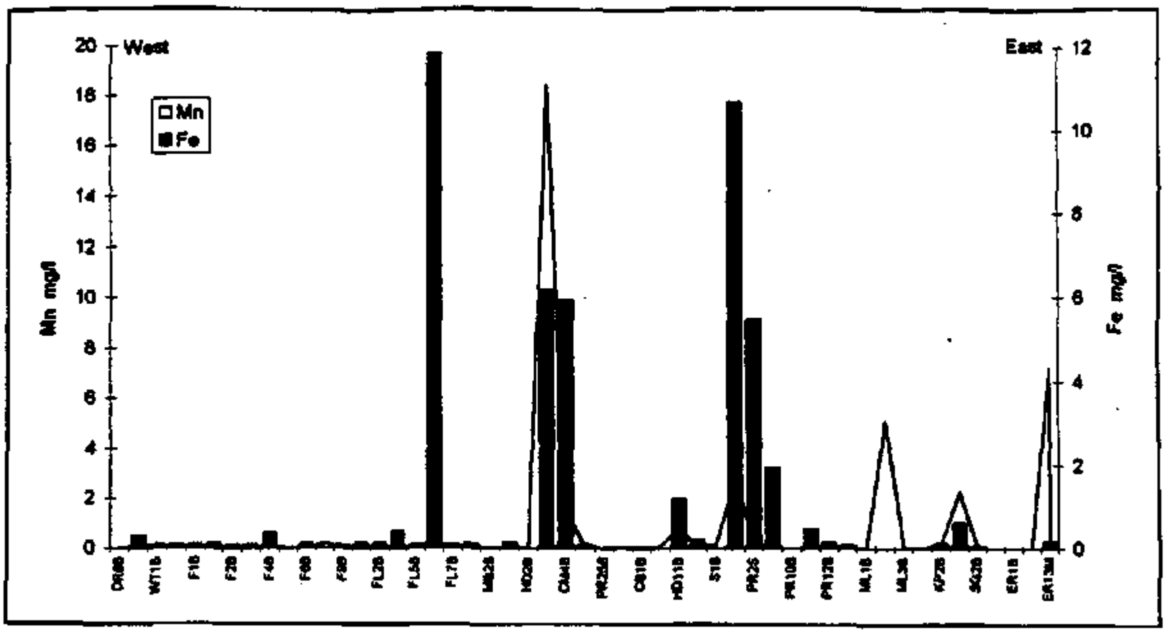


Figure 4.5.18 Groundwater Fe and Mn

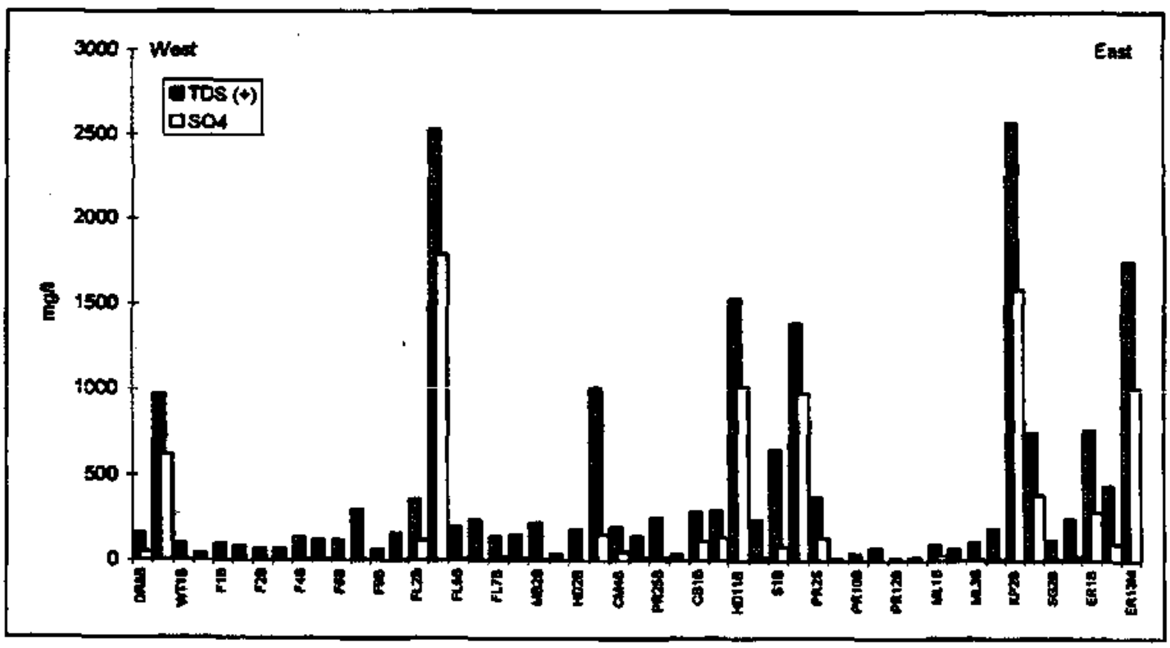


Figure 4.5.19 Groundwater TDS and Sulphate

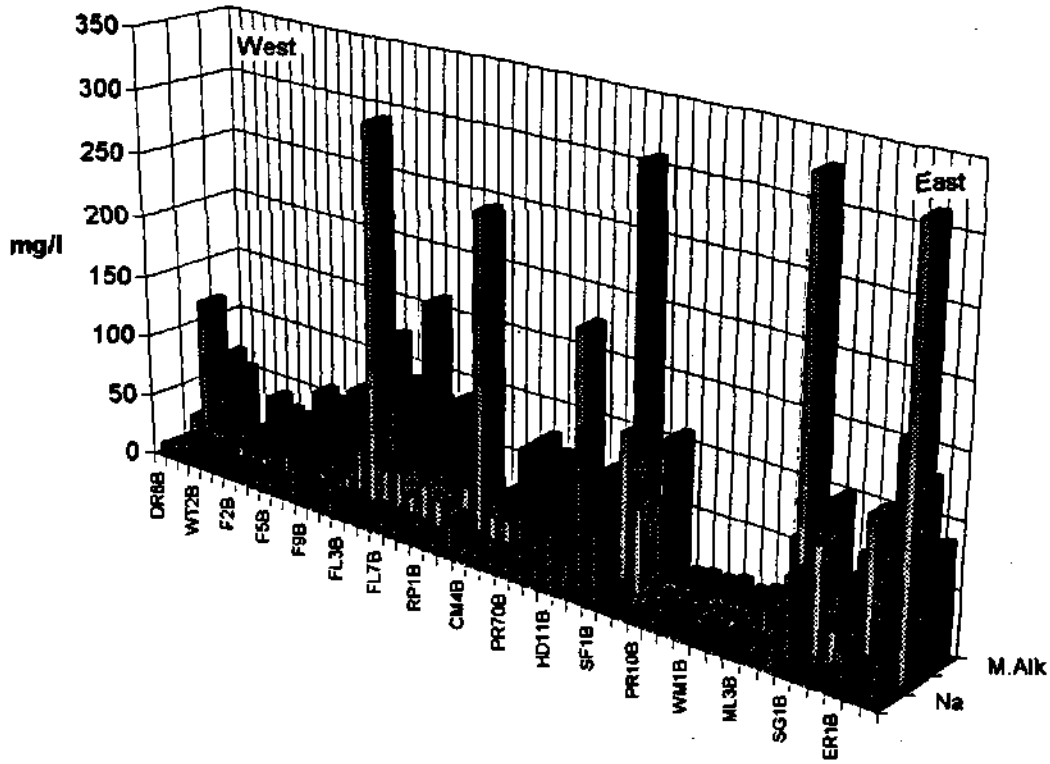


Figure 4.5.20 Groundwater Ca, Na and Alkalinity

The aim of this project has not been to comprehensively study water quality in this area. Since there are many factors that influence the quality of groundwater, an in-depth analysis of the results, after this brief sampling exercise, would be presumptuous. The samples can however be used for classification. It is also evident from the plots that there are some samples that have been influenced by mining activity. When those samples that show high Mn or SO_4 are traced to their origin it is not surprising to find that they are located within areas surrounded by mines and mine waste heaps. For example, sample SM1B is at Stormill south of Main Reef Rd on CMR property, SF1B is in a suburb now on Simmer and Jack Mines property, while HD11B is on City Deep property.

Many of the groundwater samples are of good quality, showing that there is potential for groundwater utilisation in this area.

4.5.4 Measured Mine Water Quality

Samples were taken underground at mines that were willing to participate. Co-operation in this regard was obtained from Village Main Reef Mines Ltd, ERPM, Primrose Gold Mining Company and Rand Leases where underground visits were arranged whenever requested. Durban Roodepoort Deep ltd. were unwilling to arrange an underground visit but took samples for the investigation, thus these sample sites cannot be evaluated against the other samples as the conditions cannot be conceptually compared.

Rudimentary analysis of the water pumped from Durban Roodepoort Deep is submitted monthly to the Department of Water Affairs, regular records are available for six months, from September 1992 to February 1993. Water is limed underground. On surface approximately half of the water is pumped to a tank from where it is used in the metallurgical recovery plant, the other half is discharged to the mine's western boundary (into the Klip River). Samples are analysed from these two points. Average values of the recorded analyses have been included with the underground sample list for comparison.

At ERPM rudimentary monthly analyses are available for nine and a half years for water pumped from SW Vertical shaft and Hercules shaft. Averages from these two points are included with the other samples for comparison. The results are presented in Figures 4.5.21 to 4.5.24.

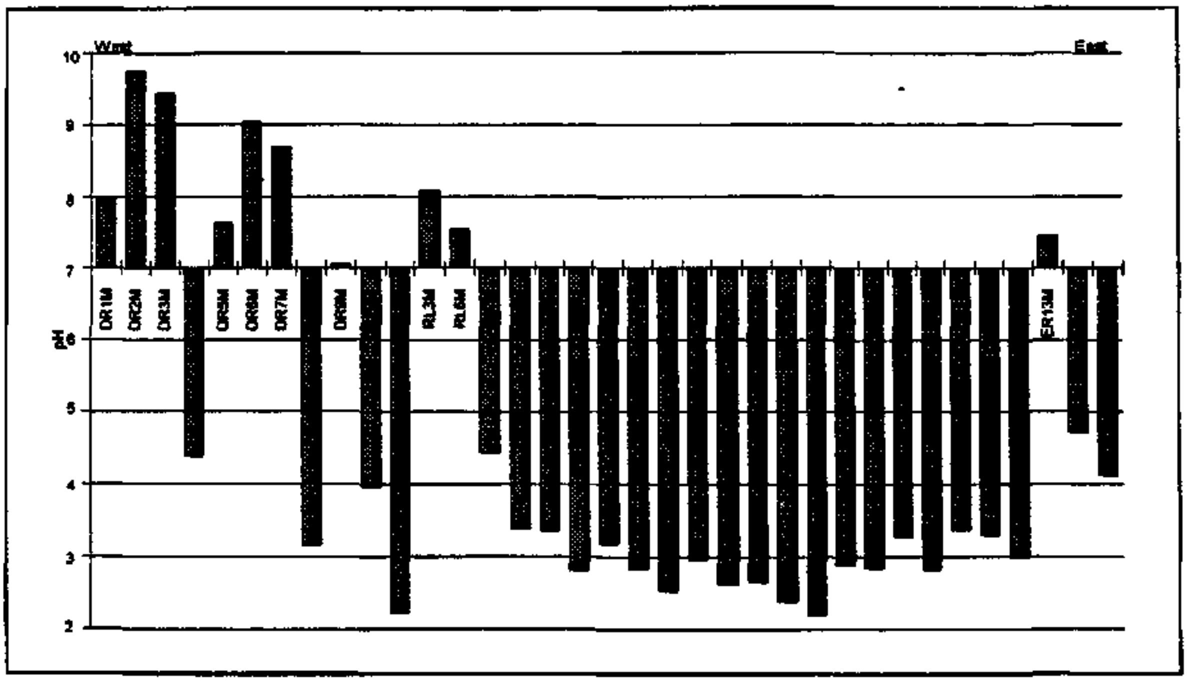


Figure 4.5.21 Mine Water pH

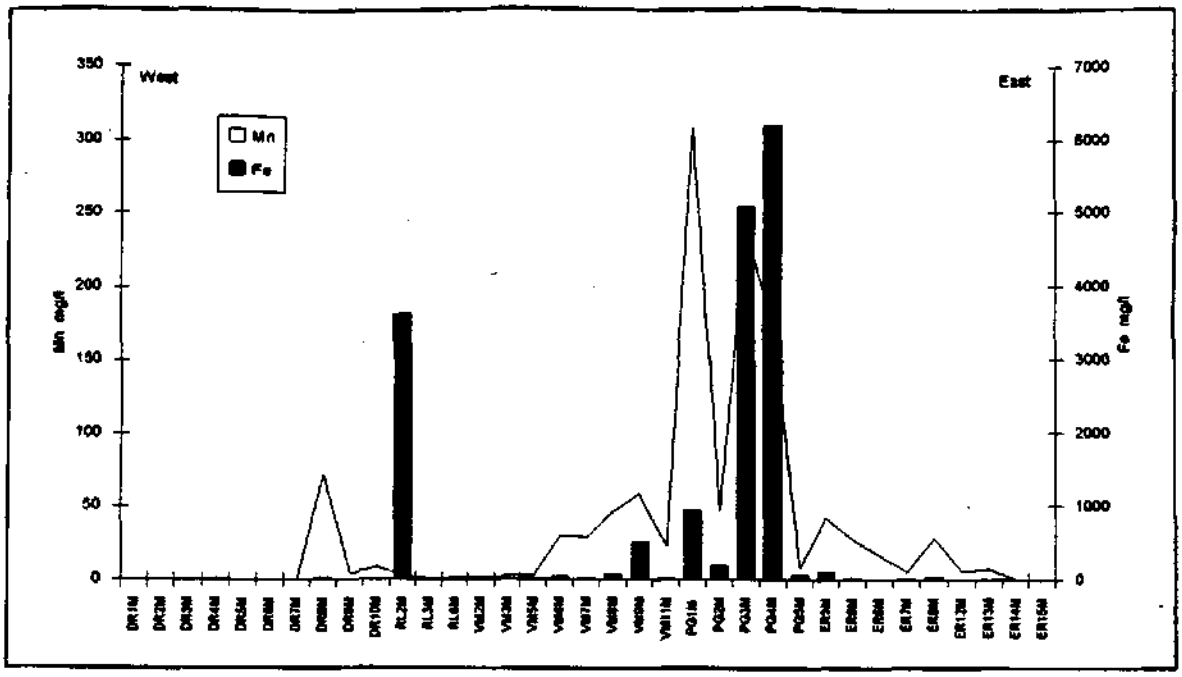


Figure 4.5.22 Mine Water Fe and Mn

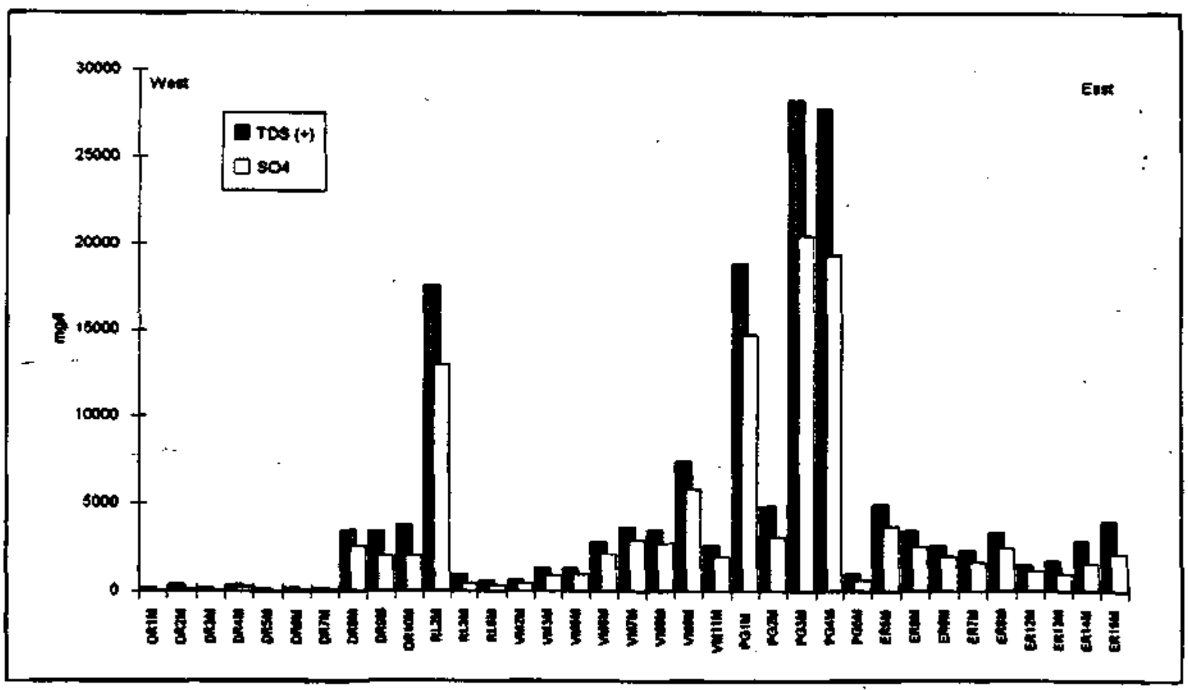


Figure 4.5.23 Mine Water TDS and Sulphate

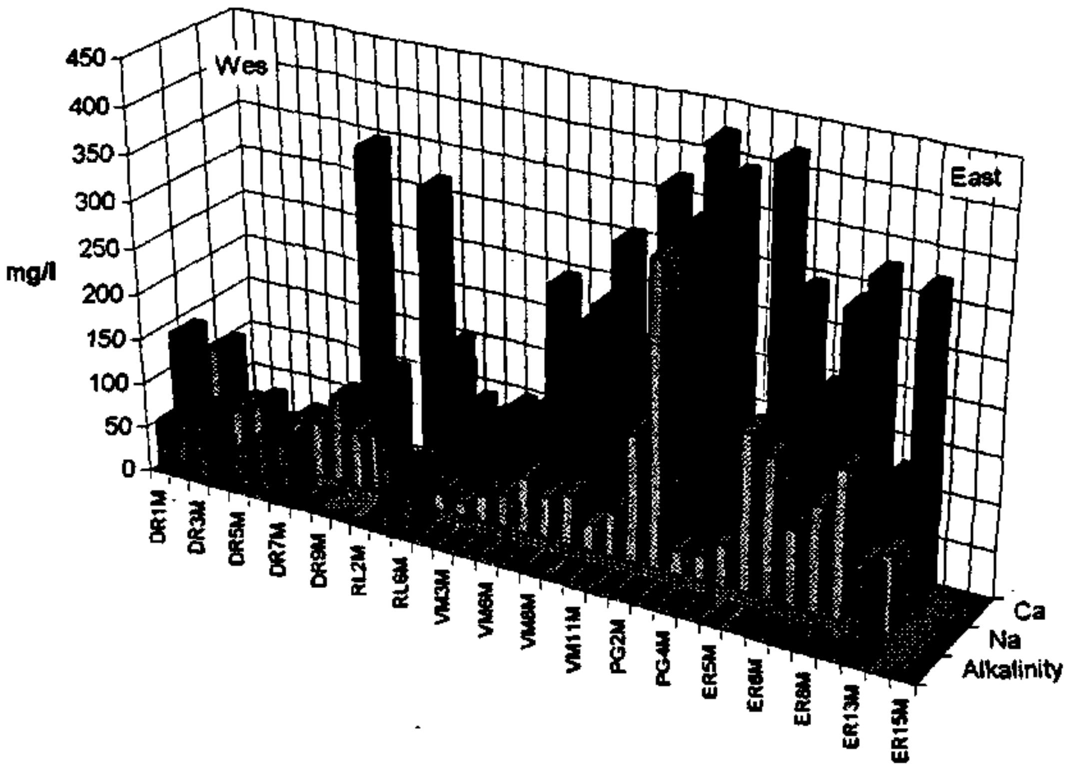


Figure 4.5.24 Mine Water Ca, Na and Alkalinity

The pumped water carries with it a certain salt load, some of which ends up in slimes dams. Salt loads are given in Figure 4.5.25.

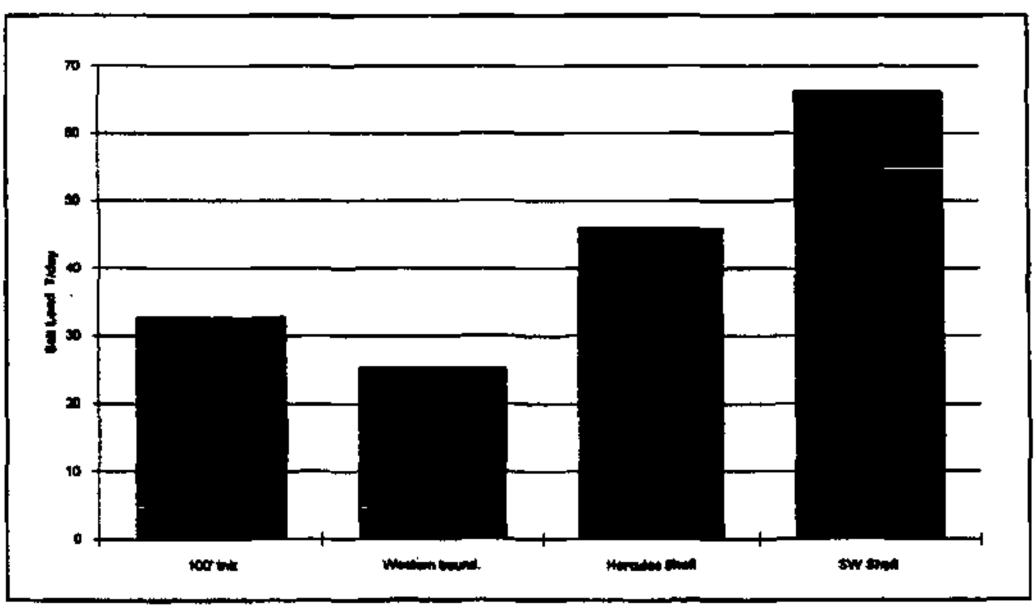


Figure 4.5.25 Mine Water Salt Load

The mine water samples collected from the central and eastern mines all have low pH and associated high dissolved solids. One sample from Hercules south is an exception, no mining has been developed from this shaft, it is now full of water. It thus resembles a very large borehole and the water may have been better grouped with the groundwater samples. Samples taken on Durban Roodepoort Deep and Rand Leases showed that some mine inflow water could be of reasonable quality. Samples RL2M and PG3M were taken in stagnant underground pools where water may have had a long time to deteriorate.

Water pumped from Hercules Shaft contains Rand Water Board water and it's quality is better than that pumped from SW Vertical shaft. The water from Hercules shaft is used underground and tends to circulate due to reuse, thus its quality deteriorates. All pumped water is limed for pH control.

4.5.5 Analysis of Results

4.5.5.1 Water Classification

All the samples taken in the Central Rand have been plotted on an expanded Durov diagram for classification. One diagram, Figure 4.5.26, was used so that broad relationships could be seen. A discussion of individual relationships is inappropriate as more detail must be known about the samples than will be generated by this investigation. This detail would need to include, for example, grouping waters from related surface water bodies, from different aquifers or from different mine inflow sources. Detailed water classification will only be reliable when this information can be included.

The type of information suggested above would be generated by a thorough hydrochemical study of the area. This has not been the requirement of this project, although these tentative results show that an investigation of this nature should be undertaken and would yield interesting results.

The following symbols have been used to identify the three broad water groups in Figure 4.5.26:

× - surface water   + - groundwater   o - mine water

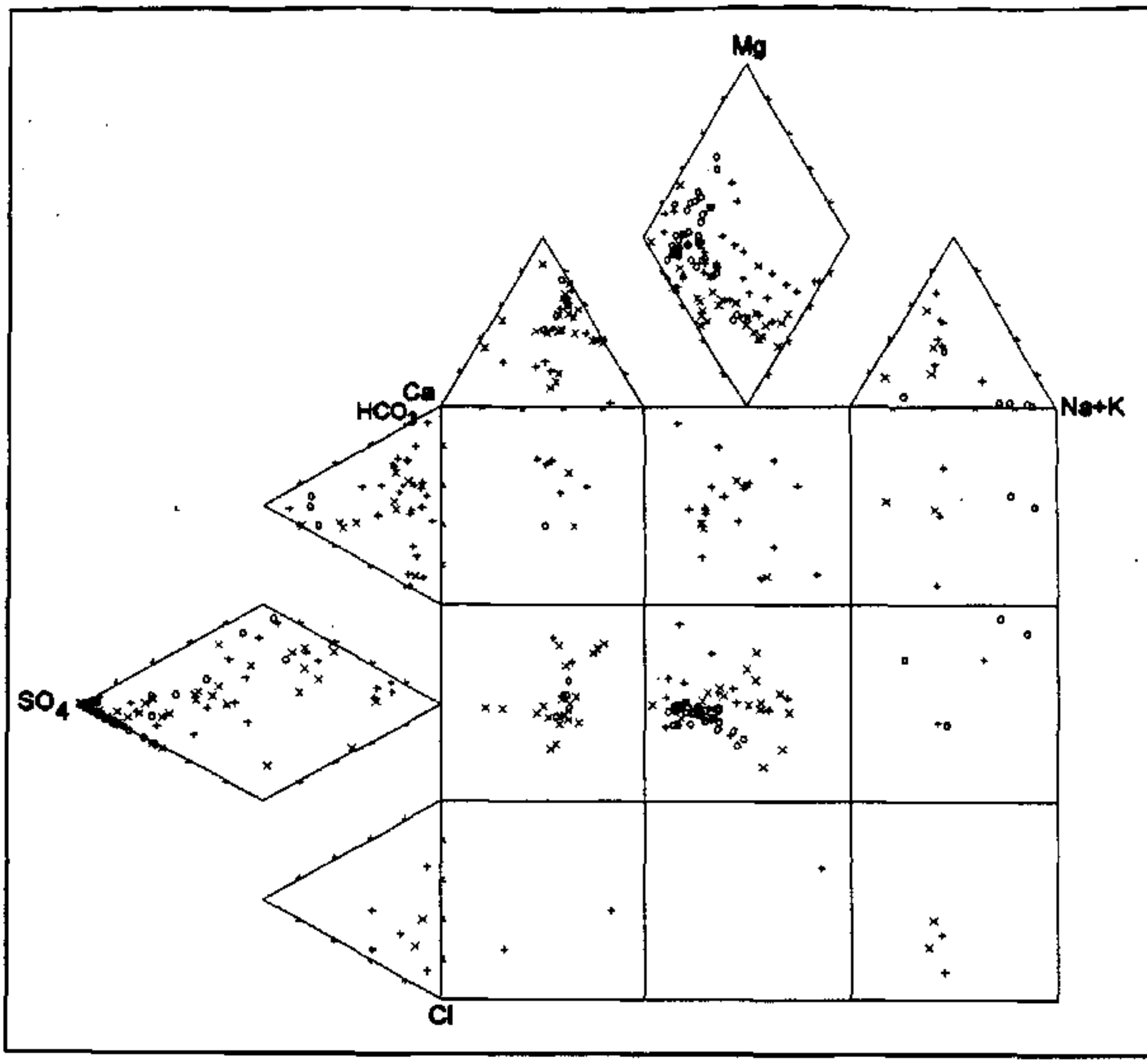


Figure 4.5.26 Expanded Durov Diagram of Surface, Ground- and Mine Water

The classification shows two distinct groups of surface water (×).

1. SO_4 dominant water. This water has been affected by sulphide oxidation.
2. No dominant anions or cations. This water is possibly a result of mixing of SO_4 dominant water with the fresh water types.

The classification shows three distinct groups of groundwater (+).

1. Ca HCO_3 water. This is freshly recharged unpolluted water
2. Mg + (Ca Na) HCO_3 water. This is a common water type for groundwater
3. No dominant anions or cations. This water is possibly a result of mixing of SO_4 dominant water with the fresh water types.

The classification shows one mine water group, with a few scattered samples (o).

1. No dominant anions or cations. This water is possibly a result of mixing of SO_4 dominant water with the fresh water types.

2. The sodium rich mine water plots on the right hand side of the classification are the unpolluted samples from DRD.

Other samples are scattered across the diagram, their classification cannot be assessed with the present lack of information.

4.5.5.2 Surface and Recharge Relationships to Water Quality

The classification study suggests that:

- Surface water is closely related to certain groundwater areas and to the water flowing into the mines. Thus surface water, with an identifiable chemical identity, is a source for some groundwater and mine inflows.

or

- There are similar degradation processes affecting the surface water and the mine water chemistries and to a lesser extent some of the groundwater. This means that if fresh water in the three different regimes were acted on by the same chemical and physical processes the three waters would end up with similar chemistry. Most mine samples were taken at points where the water was flowing, very few stagnant pools were sampled.

Recharging water may have passed through:

- mine waste dumps which have been placed over outcrop
- backfilled surface workings
- shallow open workings.

Recharge mechanisms can be envisaged as:

- Rapid point losses from surface water sources. These have entered large mine openings such as incline shafts either directly or via surface outcrop workings. They cascade rapidly down gradient in preferred channels to meet the rising mine water body. There is little further degradation of this type of water, it retains its recharge identity.

- Slow diffuse losses. These are smaller, slower surface water losses via geological structures and groundwater losses which are also related to structures such as dikes or fissure zones. They occur as diffuse dripping or trickles anywhere mine openings intersect such water bearing structures. This water often moves through stopes, may dam up against ore heaps left in the stopes or haulages, it collects in some places forming stagnant pools. Because it mixes with standing water in the mine, or reacts with sulphide bearing broken rock, this water degrades in the mine. The diffuse drips and trickles combine forming flows, collect in drains and become larger flows eventually joining the other water flowing rapidly to the deep flooded regions.

The following evidence shows that water quality degradation is a surface or near surface process:

- Water samples taken at gushing inflows less than 100 m below surface show significant quality deterioration with extremely high TDS and low pH.
- Some of these inflows are closely related to rainfall events their flow increases soon after such events.
- Groundwater in the vicinity of mining activity and mine wastes has been degraded and has similar characteristics to the mine water.
- The chemistry classification shows that mine water is closely related to surface water types.

This suggests that the much of the recharge water is of poor (mine water like) quality before it reaches the underground mine openings.

No precipitation of the dissolved constituents will take place in the water body since low pH and high temperature will prevent this.

Density stratification will occur since the poor quality water will have a density equal to or greater than 1.02.

During the investigation period underground samples were taken during winter (1993), after the first significant rainfall of the beginning of the 1993 to 1994 rain season and at the end of the 1994 rainy season. The aim of this exercise was to evaluate the effect of rainfall on the mine inflows. The data is based on one season only due to the time constraints of the project. The results of typical samples are presented in Figures 4.5.27 to 4.5.29. These are equivalent to the chemograph which Ford *et. al.* (1989) and Padilla *et. al.* (1994) consider to be an important aspect of monitoring in Karst. They show the potential that this technique holds for monitoring mine inflows.

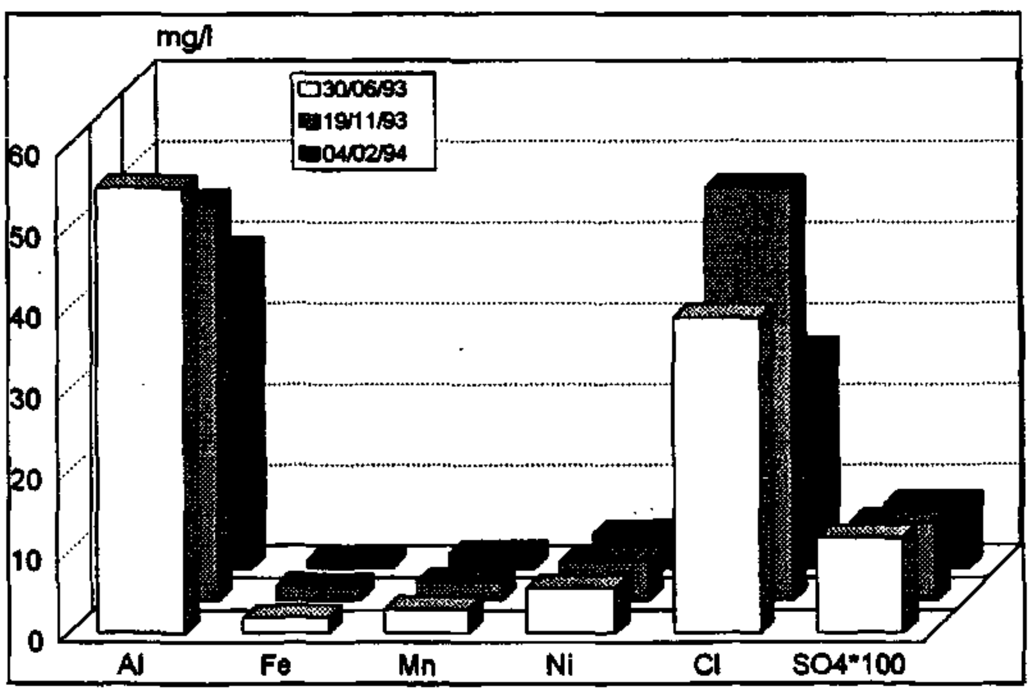


Figure 4.5.27 Sample VM5M shows continued improvement after rainfall

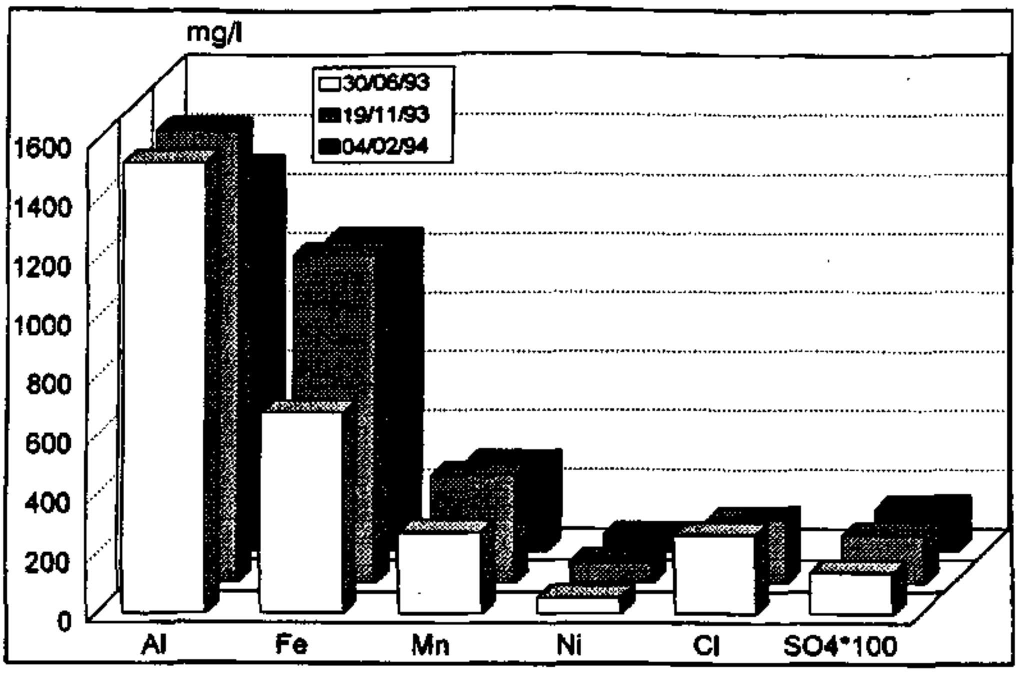


Figure 4.5.28 Sample PG1M shows deterioration then improvement after rainfall

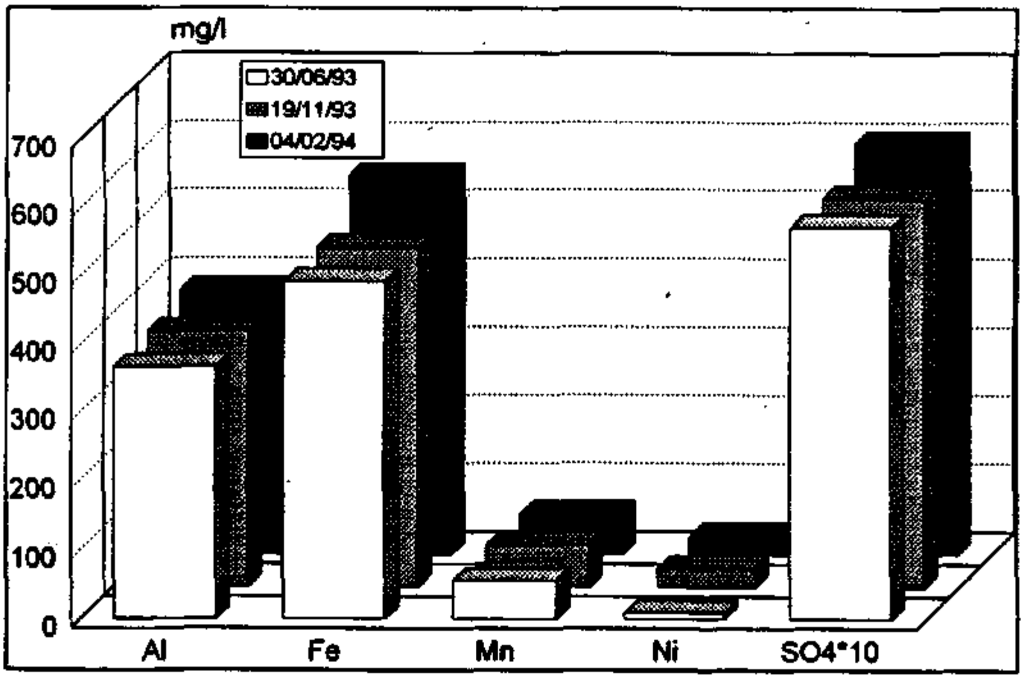


Figure 4.5.29 Sample VM9M shows continued deterioration after rainfall

The study of water quality variation with rainfall presents three possible models:

1. Dilution

   Direct connection to surface workings or outcrops: Here the quality improves with rainfall and the water flows down well used, flushed, sometimes eroded channels. The quality varies with the season improving as the wet season commences.

2. Dilution plus mixing.

   This happens when the sample point does not have as direct a connection to the surface, the inflowing water is recharged via outcrops and surface workings. The flow paths are not well defined, sometimes the gradients are low, for example in nearly horizontal haulages, or the passage of water is blocked by heaps of loose rock. The water mixes with stagnant pools of very poor quality water lying in the open workings. Thus the quality first deteriorates and then improves as the pathways and pools are flushed.

3. Continued Deterioration

   The inflowing water quality steadily gets worse as the wet season commences. This is due to fresh, oxygenated rainwater infiltrating dumps, reacting with pyrite to produce acid mine drainage (AMD). The more rainfall, the deeper the infiltration of the dumps and new pyrite particles are oxidised. The water quality continues to deteriorate.

This analysis is incipient due to the paucity of data, but these initial results show that this chemograph method of evaluation may be useful for monitoring mine inflows and suggests that correlation with other monitored data such as rainfall can be used to identify water sources.. Chloride was noted to respond differently to the other elements in many of the samples. Regular monitoring of inflows would provide useful information and further research to establish the most efficient procedures should be undertaken.

4.5.5.3 Factors Affecting Water Quality

It has been suggested by Herold (1994) and Pulles (1994) that the water quality in the filled mines will improve with time. This possibility would depend on fresh water recharging the mines and eventually forming a pool of clean water which takes part in all water exchange to and from the mine.

This investigation has shown that the water recharging the mines is degraded within the region of recharge so that fresh water does not recharge the mine. If a pool of inflow quality water were to form underground there are natural chemical processes which could cause the water quality to change. These include:

Physical factors

- Flow related dispersion
- Dilution
- Density stratification

Chemical factors

- Reaction: neutralisation, further sulphide oxidation
- Precipitation
- Reduction oxidation processes
- Retardation: ion exchange, adsorption

Because of the nature of the mine aquifer medium some of these processes can be disregarded. Water is flowing in channels with little contact between matrix and water this eliminates the possibility of change due to dispersion and retardation.

Dilution is a factor that cannot be evaluated, to take it into account inflow monitoring would have to have been conducted during the active mining stage. The significant inflows that were encountered during this investigation were of poor quality, during the course of this investigation nobody volunteered information about the possibility of good quality inflows, by implication they do not exist.

There were no carbonate strata within the Witwatersrand sequence. Although minor vein and fracture filling may contain calcite and some of the metamorphosed intrusives, stratabound mafic rocks and phyllites may now be calk-silicate assemblages Phillips *et. al.* (1994), these are of relatively limited extent or are not exposed within the mined horizons. Therefore neutralisation reactions will not have any effect. Most of the minerals in the rocks to which the rising water is exposed are unreactive or, in the case of pyrite, react to further degrade the water.

Density stratification will trap some of the worst water in the deepest parts of the mine, but the inflowing water is of poor quality with a relatively high density (1.02) so that the better water stratified at the top will still be of unacceptable quality. In the inflowing areas where rapid movement and mixing occur there will not be enough time to develop stratification.

Thus of the listed natural processes that may tend to better the water quality within the mines there remain two processes that may have an influence: precipitation and redox reactions. The influence that these processes may have on the mine water was evaluated using PHREEQE and the results will be discussed in the next section.

4.5.5.4 Predicted Water Quality

This report has extensively discussed the numerous factors that contribute to water quality degradation. However the aim of the investigation was to predict what the water quality would be, as most of the data that would be necessary to make such predictions has never been gathered, a precise prediction cannot be made.

The major influences on the water quality are near surface: Oxidation of sulphides in mining wastes, oxidation of sulphides in rocks and wastes in shallow workings, and polluted river losses.

When the mines are completely flooded some subsurface deterioration will continue since the upper sections in the inflow region will never be flooded. But most of the workings now contributing to deterioration will be flooded and will therefore no longer contribute. The zone which remains dry will mainly comprise the oxidised zone, which was initially mined, and which contained very few unoxidised sulphides. Thus the contribution to deterioration from this zone will be limited.

Some of the mine waste heaps are presently being removed thus the surface sources are dynamic and the situation should improve with time. It presently takes some ten years for a large dump to be removed. Thus the expected improvement will only become evident long after the predicted complete recovery and outflow time.

Density stratification will confine the worst water to the deep mined out parts. However dynamic processes in the inflow regions will ensure that shallow inflowing quality will be the same as the discharge quality.

Thus the outflow water will be similar to the shallow inflowing water that has been monitored during this investigation. Long term improvements will take place but may only happen many decades after the mines are full.

Thus the present pumped water qualities and monitored inflow qualities are the type of water that could be expected to emanate from the mines with slight modifications due to precipitation, redox changes and minor reaction with wall rock minerals. the extent of these changes have been evaluated with the geochemical equilibrium program PHREEQE (Parkhurst, *et. al.*, 1980). and are shown in Table 4.5.1.

Table 4.5.1 Modelled Water Quality Improvement in Flooded Central Rand Mines. (25°C, concentrations in mg/l)

	Model Run No.									
Element	1	2	3	4	5	6	7	8	9	10
Ca	418.9	418.9	418.9	418.9	418.9	418.9	418.9	418.9	418.9	418.9
Mg	264.7	264.7	264.7	891.5	891.5	891.5	891.5	306.5	306.4	307.9
Na	171.1	171.1	171.1	171.1	171.1	69.4	69.4	171.1	171.1	171.1
K	9.9	9.9	9.9	9.9	0.0	0.0	0.0	9.9	9.9	9.9
Fe	112.0	0.0	0.0	0.0	0.0	0.0	0.0	72.7	171.0	0.0
Mn	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	41.7	29.4
Al	89.3	89.3	89.3	387.5	360.7	241.2	206.4	105.6	54.5	106.2
Si	0.5	0.5	0.0	990.8	942.4	91.6	6.5	1.4	0.0	2.3
Cl	128.4	128.4	128.4	128.4	128.4	128.4	128.4	128.4	128.4	128.4
SO_4	3700.4	3315.0	3315.0	3315.0	3315.0	3315.0	3315.0	101.9	22.0	101.9
N	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
pH	2.8	2.3	2.3	5.4	5.3	3.7	3.6	3.9	3.9	2.6
pE	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	-5.1	17.3
Total Alkalinity	0.7	0.0	0.0	6.6	4.7	0.2	0.2	0.0	0.0	0.0

Description of model runs:

1 Inflow water chemistry
2 After pyrite precipitation
3 After reaction with quartz
4 After reaction with chloride
5 After reaction with K feldspar
6 After reaction with Na feldspar
7 Precipitate all oversaturated species
8 Precipitate all oversaturated species and reaction with Fe phases
9 Reduce water
10 Oxidise water

These results show the direction in which the water chemistry will tend given equilibrium conditions. Under these conditions chemical changes go to completion, it is questionable whether some reactions in this environment will ever go to completion. Such as, the reaction of silicate minerals with the mine water or the precipitation of sulphates. The water quality shown in model run 8 is the result of reaction and precipitation and would be the water quality that mine water would tend toward. The effects of redox changes are evaluated in model runs 9 and 10. In these simulations sulphate precipitation was responsible for the removal of most of the sulphate in the final water.

The evidence gathered by this investigation suggests that inflow quality on DRD is better than elsewhere on the mines. It is possible therefore that if the recovery in this mine were plugged at the present holings it could be allowed to fill separately. Thus a proportion of the outflow would be marginally better quality and would be reserved to emanate in the vicinity of the Klip River. This will not change conditions in that area much since a similar volume of mine water is already discharging into the river. It would reduce the volume of very poor quality water that enters the Elsburg Spruit.

4.5.6 Water Chemistry Modelling at the Outflow Points in Boksburg

4.5.6.1 Introduction

In section 4.4.3 it was shown that the South East Vertical shaft has the greatest potential to form an outflow point and that the water could easily be transferred from the shaft to the Elsburg Spruit. Mine Water discharged to the Elsburg Spruit will affect the quality of the stream. In an attempt to quantify this influence, the water quality was modelled using the geochemical equilibrium program PHREEQE (Parkhurst, *et. al.*, 1980).

Since the absolute values of the chemical constituents, discussed in the sections 4.5.2 to 4.5.4, do not convey the whole message. In those sections, where possible, the amount of salt moved, or the salt load of the streams were estimated. Fairly full analyses were used in the modelling so that the end results could be used to calculate salt loads to be comparable with the other results.

4.5.6.2 Description of the Modelled Area

In this area the Elsburg Spruit is made up of two tributaries.

The Western tributary drains good quality water from Witfield, but at Knights and Delmore the stream flows through an area covered by mine waste heaps where active dump reclamation is in progress, and its quality deteriorates. In this vicinity the stream also loses to outcrop. At Delmore, Hercules shaft water is added to the stream from a High Density Sludge plant (HDS). The process used in this plant neutralises the water and removes the resultant calcium sulphate. An average of 16.02 Ml/day is released into the Elsburg Spruit adjacent to the HDS plant. The stream flows into the Elsburg Dam and joins the Eastern stream near Elsburg. Overflow from Angelo pan flows into this stream above the Elsburg Dam.

The following RWB sample points relate to this stream:

E6	Stream south of Commissioner Street at old road bridge
E5	Outflow from Elsburg Dam
E1	Outflow from Germiston Lake
E7	Stream before the confluence at Elsburg.

The Eastern tributary drains from Boksburg lake into Cinderella dam and on to the confluence at Elsburg. Above Cinderella dam the mine waste heaps are vegetated and well kept, below Cinderella dam they are not well maintained and they affect the water quality. The South East shaft is located adjacent to Cinderella Dam and a tributary of the Elsburg Spruit. Outflow water could easily be piped to the stream or dam. The following sample points relate to this stream:

E10	Outflow from Boksburg Lake
E9	Stream from Reigher Park
Cinderella Dam	Sample taken at the outflow weir
Bokkie Park	Stream from Boksburg City green belt*
E8	Stream before the confluence at Elsburg.

The relevant features and sample points are shown in Figure 4.5.30.

4.5.6.3 Model Methodology

The modelling of water quality in the Elsburg Spruit, used mixing of the various water sources in three steps, to achieve the end result water.

The modelling requires river flow rates as the waters are mixed in ratios depending on the flow volume. No accurate flow measurements have been made in this system, however Rand Water Board give flow estimates at some of the sample points in their older records. These estimates were used for this

* Water in this stream is monitored by Boksburg Municipality

modelling. But because of the uncertainties regarding stream flow-rates in the area, the first sequence of modelling used the existing water chemistries with unknown flow parameters to generate the water quality at a known point downstream (E17).

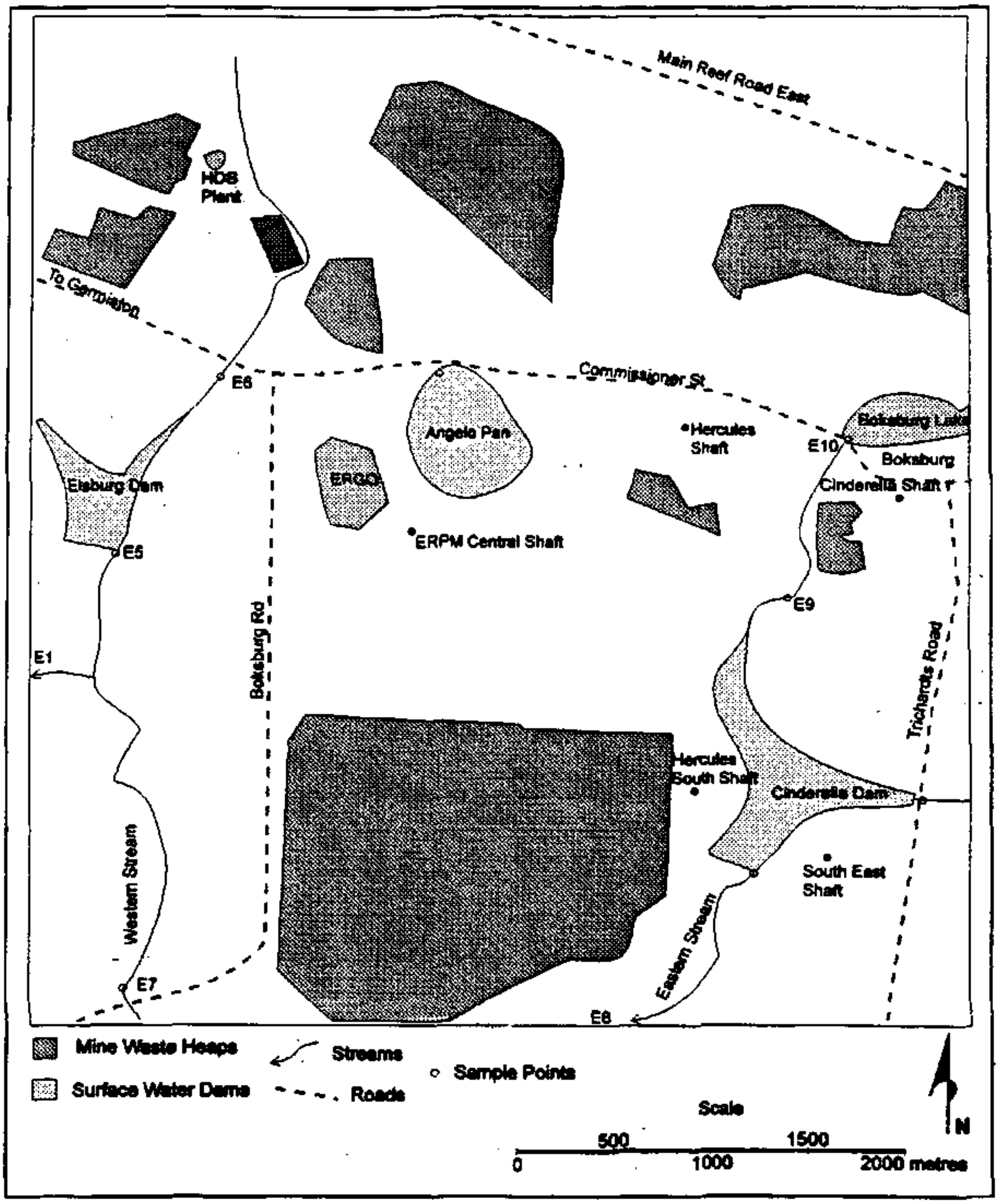


Figure 4.5.30 Surface Features in the Vicinity of ERPM and the Elsburg Spruit

When this water was successfully simulated the flow parameters were assumed to be of the correct order and the model could be used to evaluate the result of the changed chemistry in the stream. There are many permutations that could result in the correct water quality at E17 but considering the lack of flow measurements and other parameters which are not monitored the results are a best available approach.

The comparative chemistry is shown in Table 4.5.2.

Table 4.5.2 Monitored and Simulated Chemistry at RWB monitoring Site E17

	Measured (mg/l)	Simulated (mg/l)
pH	5.3	5.0
Alkalinity	94.0	14.3
Ca	237.0	284.6
Mg	67.0	82.3
Na	101.5	102.8
K	16.0	13.8
Fe	1.3	2.5
Mn	2.8	5.0
Al	0.9	3.8
Nitrate	1.6	1.3
Tot Phosphate	0.7	0.1
SO_4	805.4	366.1
Cl	84.2	89.4
TDS Sum	1355.4	951.6

Step 1. The eastern Elsburg Spruit tributary flowing from Boksburg Lake and Cinderella Dam was mixed with mine water emanating from the South East Vertical Shaft. This is the most probable shaft from which mine water will flow. Two possible discharge routes were modeled:

i) Discharge to Cinderella Dam
ii) Discharge to the Elsburg River below Cinderella Dam

Step 2. The stream was then mixed with water from the western Elsburg Spruit tributary, which flows from Witfield to Elsburg Dam and from Germiston Lake. The water in this tributary is presently influenced by mine water disposal, but when pumping stops, this will no longer be the case. Thus the water quality in this stream under no-pumping conditions will be better than it is at present.

Step 3. Beyond the point modeled in step 2, sewage water from the main sewage works in this area, Rondebult, is added to the stream. At this point the Rand Water board monitoring point E17 can be used as a control.

The envisaged steps are summarized graphically in Figure 4.5.31.

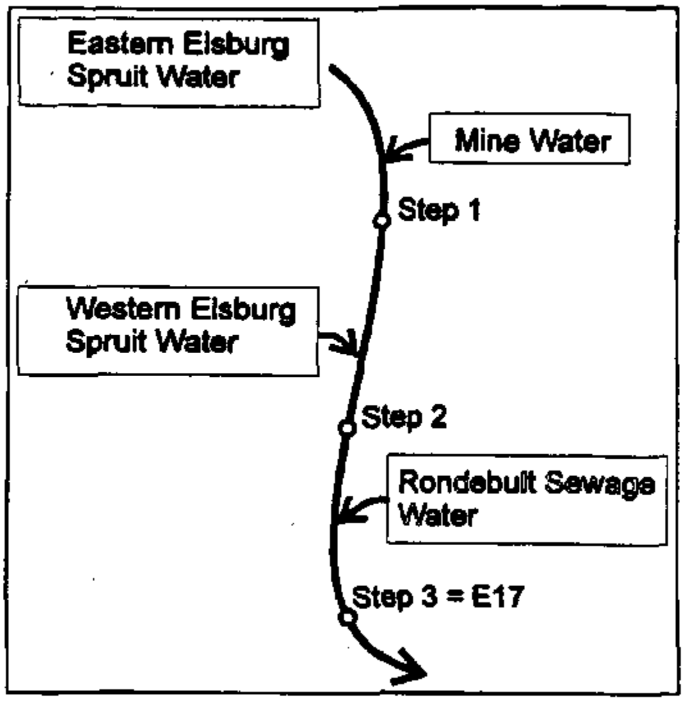


Figure 4.5.31 Schematic of the Chemical Modelling Stages.

The water analysis for Rondebult outflow was not complete and certain parameters had to be estimated (Ca, Mg, K, Fe, Mn and C), some of the parameters (e.g. SO_4 and Cl) were based on one or two analyses and may therefore not be representative. The analysis is given in Table 4.5.3.

Table 4.5.3 Rondebult Sewage Works Outflow Water

	Rondebult Sewage Water (mg/l)
pH	6.9
Alkalinity	98.5
Ca	130.1
Mg	70.1
Na	160.7
K	10.0
Fe	0.001
Mn	0.001
Al	0.1
Nitrate	2.4
Tot Phosphate	0.6
SO_4	525.4
Cl	170.2
TDS Sum	843.1

Other contributions to the stream which influence its quality but could not be quantified and were thus not included in this model, include:

1. Seepage from dumps below Cinderella Dam and before the confluence with the western Elsburg Spruit.

2. Groundwater contribution. Groundwater in the vicinity of the Newmarket dump site in Alberton is acidic, according to Whitfield (1994), who assumes that the source of this poor water is mine waste dumps. This site is six kilometres south and 60 to 80 meters lower than the nearest dumps on Simmer and Jack Mines, and the underlying stratum is stratigraphically higher, on dolomite. The quality of the Natal Spruit in this reach is poor with a pH of 3.79, closer to the mine dumps the pH is 3.27. It is possible that groundwater has been influenced by the Natal Spruit, rather than by mine water movement from the Simmer and Jack Mine area. A groundwater sample taken on the Klipoortjie agricultural holdings (sample KP2B), southeast of Wadeville also shows the influence of mining activity, it is adjacent to the Elsburg Spruit and mine waste heaps.

This highlights the complexity in this system showing that a thorough study of all aspects is necessary to properly understand what is happening. The study should include stream flow gauging, a groundwater census and water balance calculations. Such a water balance will be the only way of evaluating the effect of the proposed mine water discharge on this part of the stream. Surface and groundwater quality monitoring could be introduced at the same time.

4.5.6.4 Water Chemistry

Data regarding the existing water chemistry has been obtained from the RWB monitoring records, Boksburg Municipality monitoring records, and samples taken during this investigation. The water chemistry at the points of interest is given in Tables 4.5.4 and 4.5.5.

In the western stream: Flow from Elsburg Dam (E5) is of relatively poor quality, this has been influenced by upstream disposal of mine water, this can be seen in the quality monitored at sample point E6. The quality at the outflow from Elsburg Dam is monitored by RWB as is the flow from Germiston Lake (E1) and the quality of the stream downstream of the confluence between the Germiston Lake and Elsburg Dam outflows (E7).

Table 4.5.4 Water Quality in the Western Limb of Elsburg Spruit

	E6	E5	E1	E7
Flow (l/s)	12.2	6.2	82.3	
EC (mS/m)	306.0	266.2	101.6	210.9
pH	3.4	4.0	6.9	5.1
Alkalinity	2.7	11.1	105.1	19.1
Hardness	1718.2	1750.1	351.5	1268.2
Ca	467.3	519.7	81.1	366.1
Mg	133.9	110.0	35.4	86.0
Na	133.5	132.0	84.9	117.3
K	13.8	18.5	16.1	19.0
Fe	152.3	8.4	4.0	2.7
Mn	19.3	0.1	1.2	5.5
Zn	4.2	1.5	0.3	0.8
Ni	4.8	1.8	0.2	1.0
Al	40.6	10.8	2.4	4.8
Ammonia	3.9	2.0	1.6	1.7
Nitrate	4.5	3.4	4.5	3.1
SO_4	2180.4	1813.5	310.9	1313.5
Cl	98.7	103.3	77.8	104.3
TDS	2754.0	2396.1	914.1	1898.4

In the eastern stream: Flow from Boksburg Lake is of good quality, this has been monitored by Rand Water Board (sample point E10), Boksburg Municipality and the IGS. The quality deteriorates somewhat between Boksburg Lake and Cinderella Dam, due to the presence of mine waste heaps (sample point E9). A smaller ephemeral inflow draining a Boksburg city green belt, enters the dam from the east. The water quality of this inflow is good.

A Rand Water Board monitoring point (E8), some 2.5 km below Cinderella dam, shows that the water at this point has deteriorated from what is found in Cinderella Dam, probably due to seepage and erosion from the mine waste heaps located in that area. The monitored qualities are given in Table 4.5.5.

Table 4.5.5 Water Quality in the Eastern Limb of Elsburg Spruit

	E10	E9	Bokkie Park	Cind. Dam	E8
Flow (l/s)		100.9			150.0
EC (mS/m)	70.8	99.7	42.5	61.0	170.4
pH	7.0	4.2	7.1	7.9	5.08
Alkalinity	91.7	27.5	213.1	64.0	11.5
Hardness	216.5	307.1		257.7	919.0
Ca	53.4	69.4		67.0	235.9
Mg	19.9	32.9		22.0	79.8
Na	75.4	75.4		43.0	94.0
K	10.3	10.0		5.5	10.7
Fe	1.1	13.1	3.3	0.1	2.4
Mn	0.7	2.3		0.4	4.7
Zn	0.1	0.7		0.1	0.7
Ni		0.5			2.0
Al	0.7	7.0		<0.3	3.2
Ammonia	0.6	1.1			1.2
Nitrate	0.5	0.7		0.3	3.5
SO_4	203.8	431.7		224.0	966.4
Cl	73.9	71.9	34.8	32.0	80.4
TDS	637.5	897.0	297.5	459.0	1533.2
Daily Salt Load Tons		5.9			19.4
Monthly Salt Load Tons		181.0			589.0

From these tables, using indicator parameters such as pH and TDS, the difference in quality between the two streams is readily seen. The reasons for the differences are summarised as:

Western Stream	Eastern Stream
Receives pumped mine water	No Mine Water
The area consists of poorly kept vacant land strewn with mine wastes, most of which are not in use.	Land is suburban, paved and has with well kept parks and gardens. Mine waste is mostly in good condition. Many of the mine waste heaps are still in use.
Mine wastes in some places are being reworked.	No reworking has started in this area.

4.5.6.5 Results

The results of these simulations are given in Tables 4.5.6 and 4.5.7

Table 4.5.6 Simulated Chemistry with Mine Water Added to Cinderella Dam

Route 1	Step 1	Step 2	Step 3
	Mine Water + Cinderella Dam	After Inflow From Western Stream	After Sewerage Inflow
pH	3.9	3.9	4.0
Alkalinity	17.3	12.7	3.7
Ca	301.7	261.6	203.0
Mg	183.9	156.9	118.2
Na	128.5	120.6	138.4
K	8.4	9.8	7.7
Fe	74.8	61.9	34.3
Mn	28.0	23.1	12.8
Al	59.5	49.6	27.5
Tot Carbon	26.4	45.3	92.6
Nitrate	0.5	1.2	1.7
Tot Phosphate		0.1	0.3
SO_4	2 542.8	2 136.6	1317.6
Cl	96.3	92.9	127.4
TDS Calculated	3 441.7	2 927.0	1 992.6

Table 4.5.7 Simulated Chemistry with Mine Water Added Below Cinderella Dam

Route 2	Step 1	Step 2	Step 3
	Mine Water + Stream Below Dam	After Inflow From Western Stream	After Sewerage Inflow
pH	4.0	4.0	4.0
Alkalinity	21.6	13.0	3.2
Ca	350.4	301.4	225.0
Mg	195.5	166.3	123.4
Na	142.3	131.8	144.7
K	10.2	11.2	10.7
Fe	70.9	58.7	32.5
Mn	27.8	23.0	12.7
Al	57.0	47.5	26.4
Tot Carbon	116.2	118.4	132.0
Nitrate	0.2	0.3	0.4
Tot Phosphate	0.0	0.1	0.1
SO_4	893.1	749.5	493.5
Cl	110.4	104.5	133.8
TDS Calculated	1 879.4	1 607.4	1 206.5

These simulations show that the pH at E17 will drop by 1.3 pH units and the TDS will increase 1.5 times if the water is discharged to Cinderella Dam and will stay almost the same if the water is discharged below the dam.

Since the waters were mixed in ratios, accounting of the flows is possible and the final tonnages can be calculated. The results are shown in Table 4.5.8. Here it can be seen that the final check with the water at E17 is reasonable. The amount that it is out could be due to the unquantifiable parameters and uncertainties in measurement that have been described.

Table 4.5.8 Measured and modelled Stream Loads in the Elsburg Spruit

		Ml/day	TDS mg/l	Tons/day	Tons/day without mine water
1	Stream at E8	9.95	846.894	8.425	
2	Mine water	16.58	2 471.973	40.985	
Step 1 = 1+2	Combined	26.53	1 879.441	49.858	
3	W Stream	5.90	510.802	3.015	
Step 2 = 1+2+3	Combined	32.43	1 607.422	52.129	
4	Rondebult	26.06	735.521	19.170	
Step 3	Calculated Flow at E17 and modelled TDS	58.49	1206.539	70.575	45.094
Step 3	Sum of given chemistries			71.595	30.610
Step 3	RWB Measured value at E17		1355.424	79.284	

4.6 Impact Assessment

4.6.1 Catchment Modelling

The effects of the mine water discharge into the total catchment have not been monitored as this was not the requirement of this project. A project involving the modelling of the total catchment is presently underway at the Department of Water Affairs, the information generated by this project will be used in that model.

However the implications from this study for such modelling can be emphasised.

If all the water is allowed to decant to the Elsburg Spruit, The character of the eastern, Cinderella Dam stream will change. Lower down in the river after the Rondebult inflow the effect will be less noticeable and the main change will be a lower pH. As this water flows into the Klip River basin natural neutralising processes, related to the dolomitic substratum, will raise the pH, as well as the TDS. These changes must be taken into account in the catchment modelling exercise.

An alternative scenario is possible, this has not been evaluated in detail in this study since more detailed investigations are necessary. However the main implications will be described here.

The Durban Roodepoort Deep Mine could be isolated from the other mines on the Central Rand, by plugging a holing in the boundary pillar which occurs at 580 m below datum. If this was done, as the water rises it will not flow from DRD eastwards through the other mines, but will collect and discharge on DRD. This approach has merit since it appears from this investigation that the water entering DRD is of better quality than water inflows to the other mines. It may therefore be possible to isolate a body of better quality water on DRD. These assumptions assume that there are no other connections shallower than 580 mbd.

If the water were allowed to rise in DRD from the present the following filling times are expected.

Inflow up to Rand Leases Borehole	4.97 years
Inflow from Rand Leases Boreholes to surface	8.70 years

Thus the expected time to fill the DRD workings is 13.67 years. Possible outflow points would be some of the old incline shafts in the Klip River Valley or DRD No 6 Shaft. About 8.13 Ml/day is expected to flow from the mine to the Klip River. This volume is similar to what was discharged during the operational period of the mine (7.39 Ml/day).

This approach would reduce the outflow at ERPM South East Shaft from some 33.8 Ml/day to 25.7 Ml/day and would reduce the salt load of the discharge by approximately 24%.

4.6.2 Geotechnical Implications

The eastern part of this area where mining is still active has the highest incidence of mining related seismic events. According to Fernandez (1994) seismic potential decreases rapidly after mining stops, thus after 1 to 2 months there are no recordable events. Recovering water levels will add to the post mining stability of the area.

In the central section the present water level is at 1083 mbd, which means that over the Central Rand it is presently between 1000 to 900 metres below surface. In most places the surface is stable due to the steep dips that were mined, the recharging water will further increase the stability in these areas. In places where surface instability has been experienced such as in Primrose, a suburb of Germiston, stability should increase as the water recharges.

The envisaged head between the outflow points and the apparent main recharge points will ensure that large scale groundwater recharge by poor quality mine water will not occur. This may occur on a small scale around the discharge point or if deep abstraction schemes are employed, these may be able to draw mine water toward abstraction points.

4.7 Management

Mine water recovery will go through three stages each will exist for longer or shorter periods. For each stage different management options must be employed. The stages are:

1. Mining continues and the present dewatered subsurface conditions prevail. This is the current stage and there is no way of predicting how long it will continue
2. Mining stops and the mines begin to flood. times of recovery have been predicted by this investigation.
3. Flooding is complete and outflow results. This will continue indefinitely.

4.7.1 Mining Continues

Management of this option will involve all the established procedures relating to permit compliance from the Department of Water Affairs and the Government Mining Engineer. Certain other monitoring procedures should be introduced. These could form part of the EMPR of the mine and should ensure that the unknown parameters, that this project has identified to be necessary, are known when stage two and three begin.

These include:

- Continuous monitoring at some of the inflow points to generate subsurface hydrographs from which baseflow (ground water) and quickflow (rain events) components could be determined.
- Continuous monitoring of the quality at the inflow points will provide quality vs. time plots or chemographs which will show the relationships of how and where the water quality is being degraded.
- Stream gauging and calculation of an accurate water balance for this area are important. Stream gauging will identify areas where losses to the mine cavities are occurring.
- Inflow reduction must be investigated and planned while the mines are still operating and while they are filling, so that, the techniques can be implemented once the mines are filled.
- A groundwater census and monitoring program must be started. The aims of such a program should be to monitor quality changes in time and space, evaluate water utilisation potential, and establish flow rates and directions.
- Continued mine pumping rate and plug pressure monitoring data should be kept.
- Mine waste removal and recovery should be encouraged. Mine wastes on surface are a major source of pollution, both of surface and subsurface water. This practice has often transferred the mine waste, and related water

problems, to some other region. Therefore disposal of slimes into the underground cavities is a good idea and should be encouraged as it does not shift the problem to some other area. This will also speed up the recovery rate so this option should be incorporated into the next stage.

- Management and rehabilitation plans for the land cleared by mine waste removal, should take cognisance of the reef outcrop areas and areas of possible recharge to the mine cavities.

4.7.2 Mining Stops and Flooding Commences

Once the decision to curtail all mining has been made, the mines should be allowed to flood as quickly as possible. This will limit the degradation of water.

The deep confined nature of the mine cavities means that they are good repositories for mine wastes, an example of this type of waste disposal is being undertaken by Village Main Reef Mines. This form of disposal will speed up the filling process and reduce the storage capacity for low quality water. The technique is therefore desirable.

Relevant monitoring from stage 1 should continue.

4.7.3 Flooding is Complete and Mine Water Decants

On full recovery density stratification will ensure that the worst water remains deep within the mine cavities.

The outflowing water will be of poor quality and will negatively impact on any stream system. Thus once recovery has been achieved, limiting the outflow rate must be addressed. In many instances, reasonable quality groundwater or surface water is lost to the mine cavity system where it becomes contaminated by further degradation (the predominant process at present) and mixing (the future main degradation process). Two methods of preventing water from becoming wasted in this way are envisaged; inflow control and groundwater utilisation.

4.7.3.1 Inflow Control

Surface water losing sites must be positively identified

Better stream management, controlling pollution inputs and stream flow in the vicinity of mine dumps.

Canalising water where it flows over reef outcrop as the loss and subsequent deterioration is a waste of generally good water. This method is used on the West Rand to prevent pumped water from re-entering the mines.

4.7.3.2 Ground Water Utilisation

Once the baseflow component from groundwater has been established from monitoring in the previous stages, the area should be investigated hydrogeologically and a groundwater development program should be planned to minimise groundwater losses to the mines as these are a waste. By siting the boreholes correctly good quality water could be supplied for a conjunctive use program. Preliminary evaluation suggests that some 18 Ml/day could be supplied in this way.

4.7.4 Legislation.

This project has delved extensively into old records and the history of mining in this area. If one considers the number of earth scientists who have spent their working lives in the area, it is surprising to find that the most basic natural resource was treated as a nuisance. It is strange that non of these professionals ever questioned where the water comes from. Now it is too late to accurately investigate that question. Mining was conducted with no concern for groundwater, which was a nuisance that had to be disposed of as cheaply and quickly as possible. Legislation should be aimed at reversing this attitude.

No studies were undertaken of local aquifers and there was no monitoring of water levels. Hundreds (Werdmüller *et. al.*, 1990) of exploration boreholes have been drilled in this area, none mention groundwater. These holes should be made available for groundwater monitoring, instead they are plugged or covered and lost. Had the mining companies used some of these for monitoring, the water table gradients could have been established in the local aquifers. Thus flow directions and inflow areas could easily have been defined.

Legislation must be introduced to facilitate this form of investigation in future. This should include:

- Enforcement of monitoring programs at existing mines.
- Exploration boreholes should record groundwater occurrences in as much detail as they would any other mineralization related to potential mineral resources.
- Information at the mines should be made accessible to investigators.

4.8. Conclusions and Recommendations

4.8.1. Conclusions

In the initial agreement with the department of Water Affairs it was agreed that the following questions should be addressed by this investigation:

- Investigate the mechanisms and rate of water level recovery in the mines
- Identify discharge points and the volume of water that will discharge
- Identify factors affecting the quality of the rising water
- Predict the quality of water in the filled mines
- Investigate methods of management or control
- Identify possible geotechnical problems

Conclusions covering these points are listed in the following paragraphs:

4.8.1.1. Water Volume

Water flowing into the Central Rand Mines is pumped to dewater the presently active mining areas. From the mines' water consumption and pumping records it can be shown that 33.8 Ml/day enters the mines naturally and makes up the bulk of the water that is pumped. An additional 14.64 Ml/day is added from service water and permitted waste disposal. When all mining in the area is inactive, this contribution will not affect the recovery. The water flowing in naturally is derived as follows:

Durban Roodepoort Deep	8.13 Ml/day
Rand Leases	4.74 Ml/day
Central Mines (CMR to Rose Deep)	13.84 Ml/day
ERPM	7.09 Ml/day
Total	33.80 Ml/day

Mine pillars have mostly been removed, where they have not, holings exist at certain levels so that, as far as the recharging water is concerned, the mines are continuous.

4.8.1.2. Water Sources and Mechanisms of Inflow

A large proportion of the water flowing into Central Rand mines recharges directly from rainfall and river losses to outcrop areas. A minimum of 9.47 Ml/day (28%) is derived in this way. Many of the rivers on the Witwatersrand have low pH and carry poor quality water due to interaction with mine wastes and seepage from mine wastes. Thus a certain proportion of the water entering the workings already has a low pH and low buffer capacity.

The river pattern in this area is an almost textbook example of a trellised drainage pattern. This is a river pattern controlled by geological structures. Thus rivers flow in fault, joint, bedding strike or intrusive rock controlled valleys. Losses to the underground excavations via these structures are probable. These cannot be quantified and hence the reported minimum of 9.47 Ml/day is conservative. These water sources are closely related to rainfall and will show seasonal variation. From this investigation a rapid relationship to rainfall, of the order of a few days, is indicated.

The remaining proportion of the inflow approximately 24.3 Ml/day (maximum of 72%) is derived from groundwater losses and is also affected by recharge via surface mine wastes and outcrop areas. In the vicinity of the mines groundwater has been contaminated, showing increased Mn, Fe and SO_4 levels. These being the indicator elements, identified by this investigation, which show the influence of mining activities on water quality. The mining areas and mine wastes often occupy low lying ground so that a short distance away, upgradient groundwater is of good quality.

Estimated recharge from rainfall to groundwater in the area influenced by mining is 18 to 24 Ml/day. This is the same order of magnitude as the estimated groundwater inflows, thus large groundwater draw-downs around the mines cannot be expected. The groundwater derived inflows provide a relatively constant base-flow which masks the seasonal variation of the other inflows.

4.8.1.3. Recovery Rate

The time of recovery has been calculated from an elementary relationship between volume and inflow rate. This relationship assumes that a linear recovery takes place. This holds for the predominant recovery period, while the mine cavities act as a hollow vessel and are filled from a relatively constant (over a multi-season time period) source. The investigation has shown that recovery could take between 14 to 22 years to be completed. More accurate prediction is not possible due to the uncertainty in determining the volume of the underground cavities.

It may be possible to plug holings in the boundary pillar between Durban Roodepoort Deep and Rand Leases and so isolate DRD from the other Mines. This would slow the recovery rates in the central mines from 14 to 22 years to 17 to 27 years. While the constructed DRD compartment would take from 10 to 14 years to fill.

4.8.1.4. Discharge Points

On complete recovery water will flow from the lowest shaft connected to the mined out volume. As all the mines are interconnected, there will be no compartmentalisation forcing multiple discharges to occur so that all the water will emanate at one shaft. This investigation shows the South East Shaft on ERPM to be the lowest. This shaft is located within the valley of the Elsburg Spruit, adjacent to the Cinderella Dam.

If a compartment is constructed on Durban Roodepoort Deep, the outflow from this mine would occur at some of the old incline shafts in the Klip River Valley or at DRD No. 6 Shaft.

4.8.1.5. Water Volume

If all the water is permitted to discharge at one point it is expected that up to 34 Ml/day will discharge.

If DRD is compartmentalised, then some 8 Ml/day will discharge on DRD while the discharge volume at ERPM South East Shaft will be reduced to 26 Ml/day.

4.8.1.6. Factors Affecting Water Quality

The factors affecting water quality include:

1. Poor quality recharging water

- Surface water through intimate interaction with mine wastes takes on a very similar identity to the water found in the mines.
- Groundwater which is affected by seepage from mine waste heaps has the same chemical identity as the water in the mines.

  Both of these water sources contribute to water flowing into the mine cavities. The mine waste heaps are located above shallow surface workings and outcrop and are thus in communication with the deep mine cavities. Seepage may be lost directly and contaminated surface water flowing between the mine wastes can lose to surface workings and outcrop.

- The area is highly industrialised and densely populated thus the surface streams carry a wide variety of effluent in addition to mine waste derived seepage. None of the streams are in pristine condition. These streams, losing to the subsurface, contribute a diffuse pollution load.

2. Subsurface degradation

A proportion of the water recharging the mines arrives as a number of widely-distributed, small drips, trickles and seeps, most enter via geological structures.

- This water has passed through different geological horizons where mineral water interaction will have caused further degradation from what may have happened on surface.
- In the mines these diverse flows pass through a variety of conditions, such as; backfilled waste rock, loose ore in stopes and haulages that has never been removed and fine material that has collected in travelling ways. These materials are pyrite bearing, thus the flows are exposed to pyrite in many of their courses. The mines are open and even in abandoned sections, natural air circulation, due to up-draught shafts, ensures that there is enough oxygen

for oxidation of the pyrite. In addition bacterial growth in the warm humid underground conditions is evident as filamentous web-like growths which are found in most disused areas. Bacteria catalyse the oxidation of the pyrite so that the rate is rapid. These factors contribute to the lowering of the inflowing water's pH. Thus mine water is characterised by very low pH in the region of 2 to 3 and high TDS.

When an equilibrium is reached between inflowing and outflowing water the water level in the mines will be within the region of the deepest surface workings which penetrated the oxidised zone, in this zone pyrite had already been oxidised in antiquity. Thus with much of the subsurface flooded, anoxic conditions will prevent, or slow down, continued degradation. The non-flooded region will contain little unoxidised pyrite thus subsurface degradation will be at a minimum. The degradation process will be predominantly driven by surface sources.

Surface sources are dynamic and some are being removed by recovery of the mine waste heaps, others can be controlled by legislation and policing.

4.8.1.7. Water Quality

The immediate recovered water will be similar to the water presently pumped from underground.

Natural chemical processes that could cause improvement are precipitation, reaction with minerals and redox processes. The possible effects of these processes were evaluated using geochemical modelling and are shown in Table 4.8.1, where the modelled water represents an end product, assuming equilibrium, that the water will tend toward.

Table 4.8.1 Modelled Water Quality

Element	Inflowing Water	Modelled Water	Stream at Market
Ca	418.9	418.9	498.0
Mg	264.7	306.5	107.0
Na	171.1	171.1	14.0
K	9.9	9.9	5.9
Fe	112.0	72.7	342.0
Mn	41.7	41.7	8.7
Al	89.3	105.6	55.0
Si	0.5	1.4	
Cl	128.4	128.4	37.0
SO_4	3700.4	101.9	2548.0
N	0.6	0.6	2.2
pH	2.8	3.9	2.8
pE	0.5	0.5	
Alkalinity	0.7	0.0	0.0

The long term water quality will be most strongly affected by surface sources, thus the worst surface water also gives an indication of what is possible.

4.8.1.8. Management

Once the decision to curtail all mining has been made, the mines should be allowed to flood as quickly as possible. The deep confined nature of the mine cavities means that it is a good repository for mine wastes of the type being undertaken by Village Main Reef Mines, this form of disposal will speed up the filling process.

On full recovery density stratification will ensure that the worst water remains deep within the mine cavities.

The outflowing water will be of poor quality and will negatively impact on any stream system. Thus once recovery has been achieved, limiting the outflow rate must be addressed, since in many instances, reasonable quality groundwater or surface water is lost to the system where it becomes contaminated by mixing or further degradation in the mines. To prevent this water from becoming wasted in this way inflow control must be established.

Surface water losing sites must be positively identified and canalised where possible to prevent losses. Groundwater utilisation should be increased, 18 to 24 Ml/day should be available in this catchment. Use of the groundwater before it enters the system and is degraded should be investigated.

4.8.1.9. Geotechnical Implications

The mining area is predominantly stable due to the paucity of mining activity. The rising water column will add support and increase the stability of the mines.

Mine water recharge of near surface aquifers and contamination of usable groundwater will be confined to areas around the discharge points, particularly if the shaft linings have broken down.

4.8.2 Recommended Further Work

The investigation has uncovered many interesting and yet elusive questions regarding the mines and water on the Witwatersrand.

Answers are hard to obtain because,

- Most of the mines have closed down and underground workings are inaccessible
- The large scale of the disturbances caused by mining activity and the many variables that play a part in mine water deterioration mean that a multi-disciplinary approach must be taken to gather data.

- Lack of appropriate information and little monitoring, in the past, have meant that obtaining useful information has been difficult. The size of the investigation area and time limits of this project have meant that it was not possible or it was too late to install a monitoring system. Sampling that was introduced by this project was rudimentary.

The project identifies certain techniques that must be introduced:

- Stream gauging and calculation of an accurate water balance for this area are important. Stream gauging will identify areas where losses to the mine cavities are occurring.

- Continuous monitoring at some of the inflow points to generate subsurface hydrographs from which baseflow (ground water) and quickflow (rain events) components could be determined.

- Continuous monitoring of the quality at the inflow points will provide quality versus time plots or chemographs which will show the relationships of where the water quality is being lowered.

4.8.2.1. Management Options

These should include:

- Better stream management, controlling pollution inputs and stream flow in the vicinity of mine dumps.

- Canalising water where it flows over reef outcrop as the loss and subsequent deterioration is a waste of generally good water. This method is used on the West Rand to prevent pumped water from re-entering the mines.

- Once the baseflow component has been established, the area should be investigated hydrogeologically and a groundwater development program should be planned to minimise groundwater losses to the mines as these are a waste. By siting the boreholes correctly good quality water could be supplied for a conjunctive use program. Some 18 Ml/day could be supplied in this way thus reducing demand on the Vaal Dam.

Such prevention and reduction of inflow would slow the recovery rate down this would increase the acid production underground. Thus inflow reduction should be investigated and planned while the mines are filling and only implemented once they are filled.

- Mine wastes on surface are a major source of pollution, both of surface and subsurface water. Removing the wastes is a good idea and should be encouraged. Unfortunately this practice has transferred the mine waste, and related water problems, to some other region. Thus disposal of slimes into the underground cavities is a good idea and should be encouraged as it does not shift the problem to some other area. This will also speed up the recovery rate.

4.8.2.2. Legislation.

Mining has been conducted with no concern for groundwater, it was a nuisance which had to be disposed of as cheaply and quickly as possible. Legislation should be aimed at reversing this attitude.

Legislation must be introduced to facilitate this form of investigation in future. This should include:

Enforcement of monitoring programs at existing mines. Groundwater quality and water levels should be monitored.

Exploration boreholes should record groundwater occurrences in as much detail as they would any other mineralization related to potential mineral resources.

Exploration boreholes should be used for groundwater monitoring.

Information at the mines should be made accessible to investigators who may need legal back-up to enforce co-operation.

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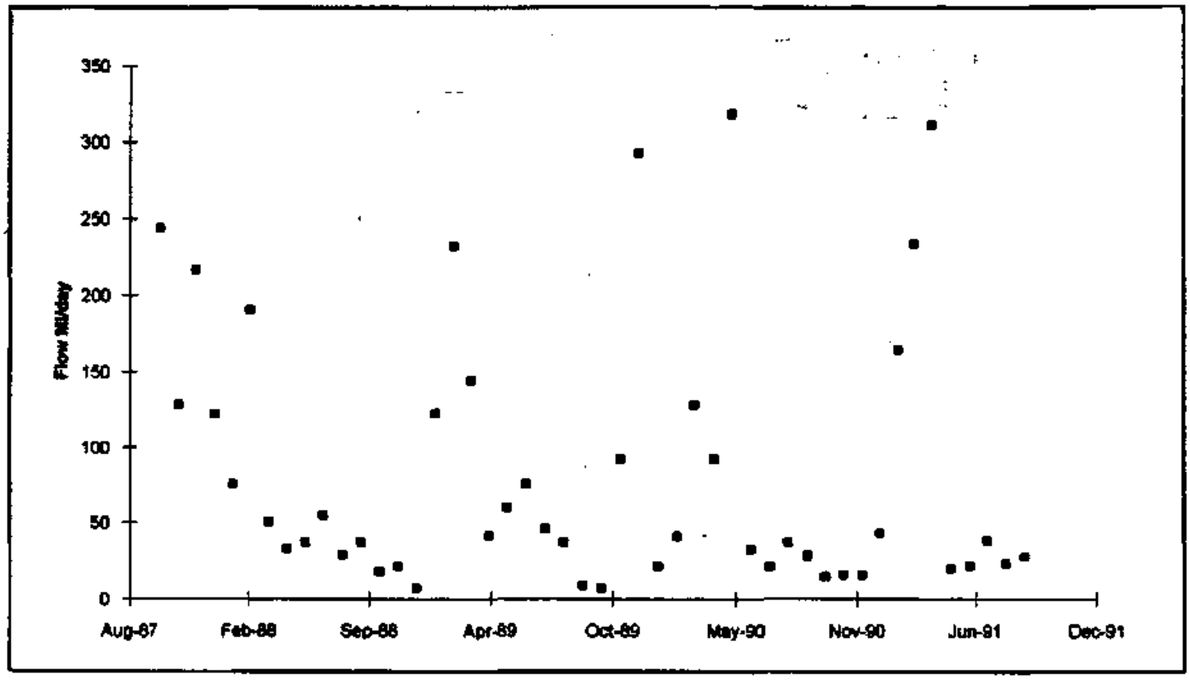
Plate 1 Stalagmite and stalactite like deposition of $Fe(OH)_3$ at dripping inflow. (Waverley Gold Mine). Scale = 30 cm

Plate 2 Deposition of $Fe(OH)_3$ at flow down a grizzly. (Waverley Gold Mine)

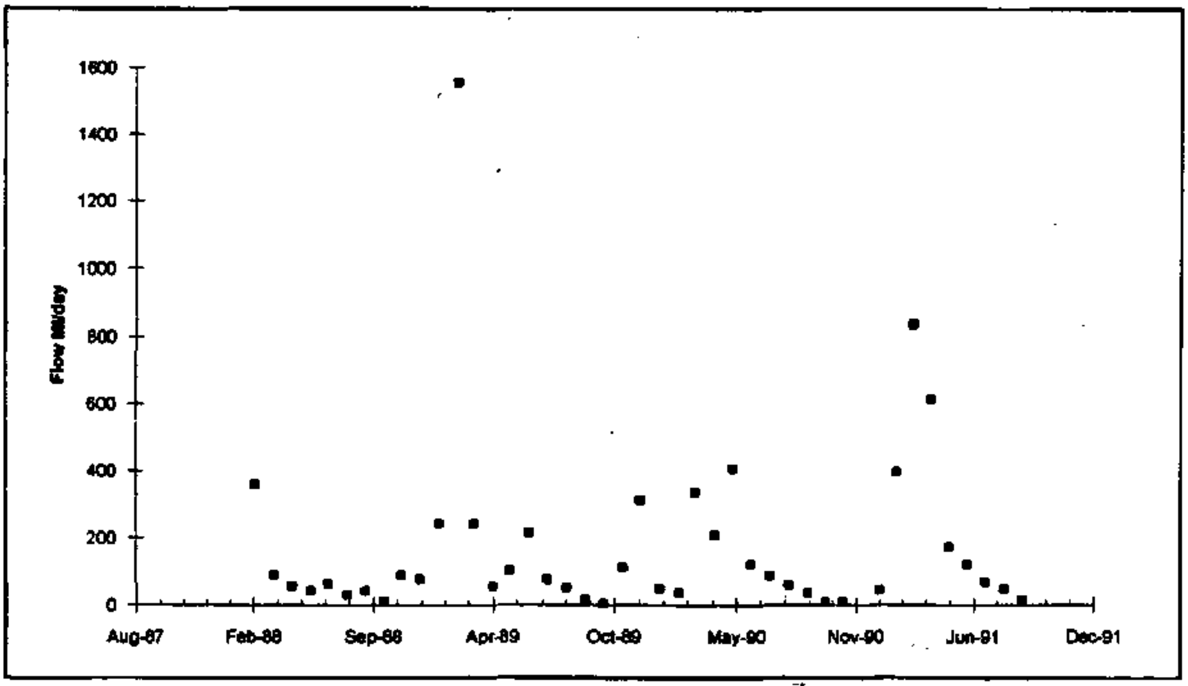
Scale = 30 cm

Appendix 1

Scatter plots of river flow gauging on rivers related to the East Rand



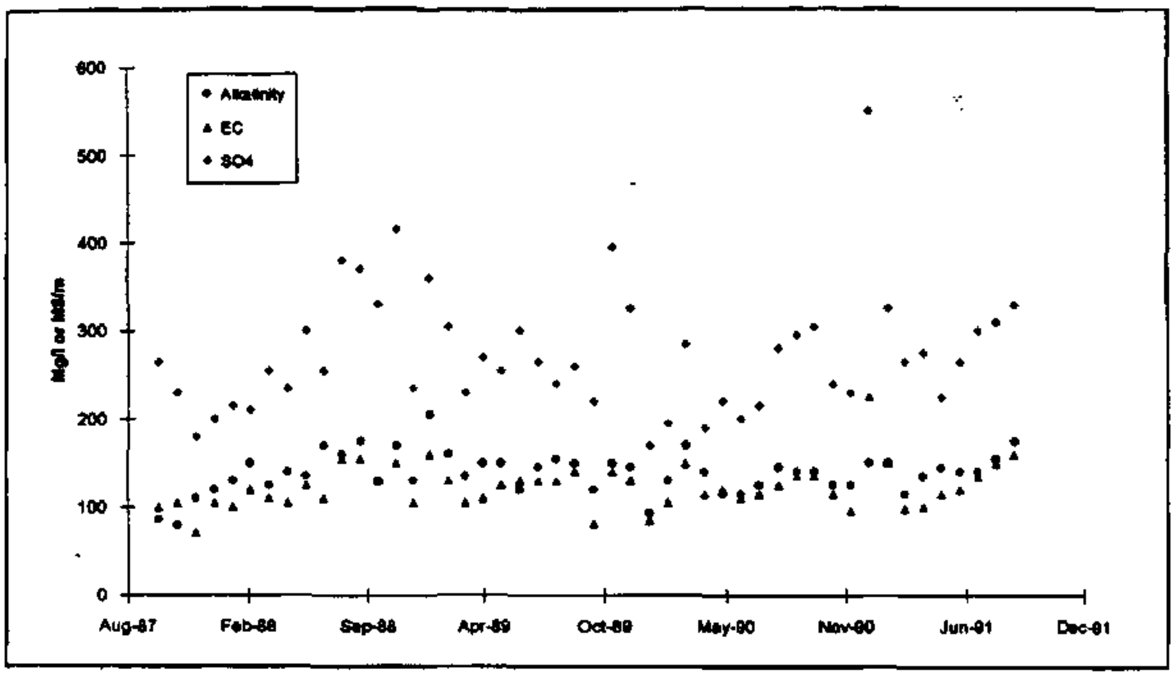
B10 Blesbok Spruit near Heidelberg



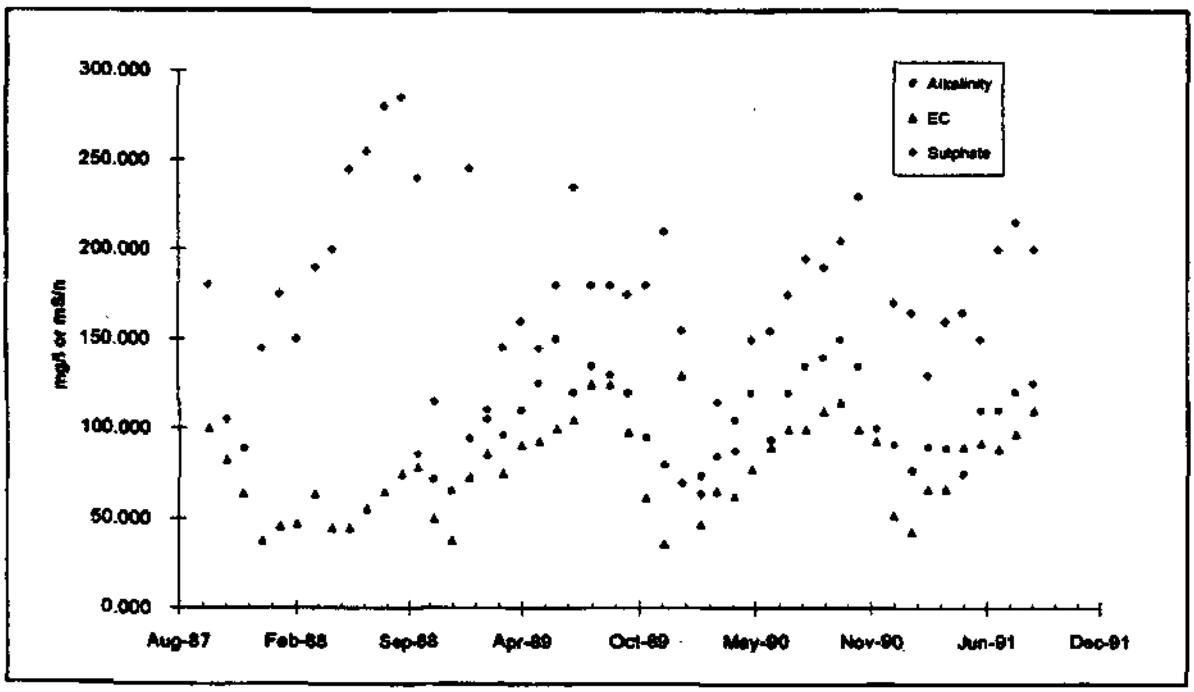
S2 Suikerbosrand river near Vereeniging

Appendix 2

Scatter plots of the major elements for selected sample sites



Blesbokspruit at B10 - below Heidelberg.



Suikerbosrand river at S2 (RWB monitoring point).

Appendix 3

Surface Water Chemistry

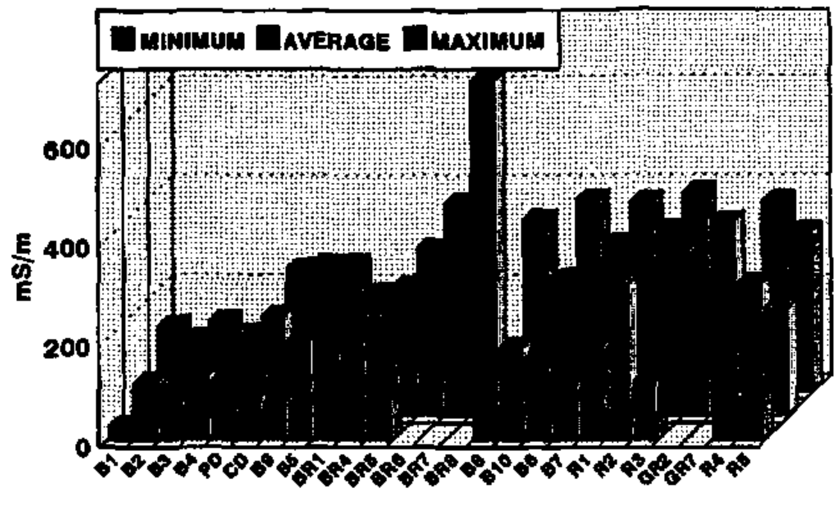
Bar Charts showing Minimum Average and Maximum values for selected parameters. Proposed maximum permissible limits in drinking water are shown, for the parameters, as a reference.

The specified limit refers to limits specified in the drinking water standards proposed by Kempster *et. al.* (1985) for South Africa.

These can be divided into three levels

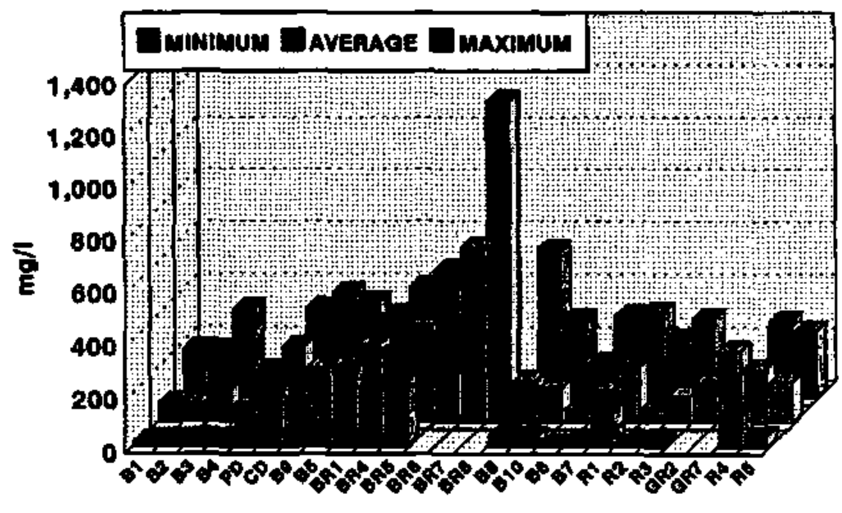
- The recommended or working limit, this is the limit which should ideally not be exceeded.
- The maximum permissible limit, is safe for consumption but if this limit is exceeded remedial/preventative action should be planned
- The crisis limit is a level at which extreme action is needed especially if the element is toxic.

ELECTRICAL CONDUCTIVITY
BLESBOKSPRUIT, RIETSPRUIT AND TRIBUTARIES



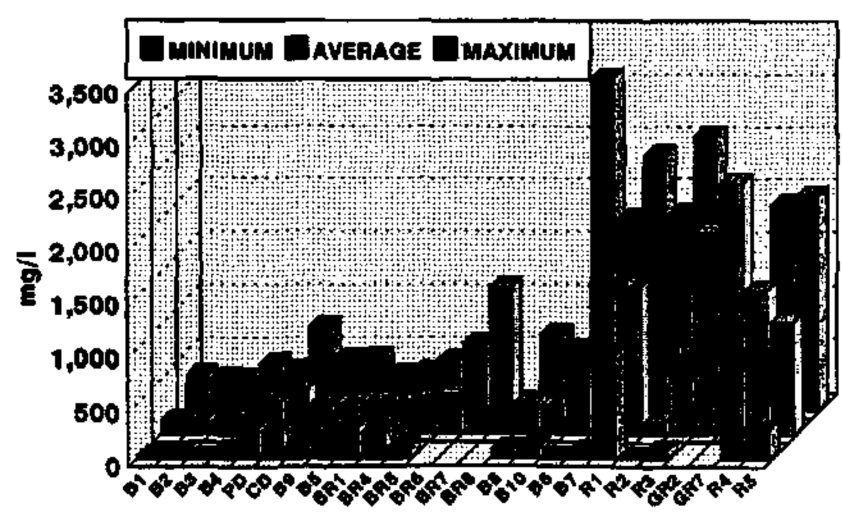
Max. Permissible Limit = 300 mS/m

SODIUM
BLESBOKSPRUIT, RIETSPRUIT AND TRIBUTARIES



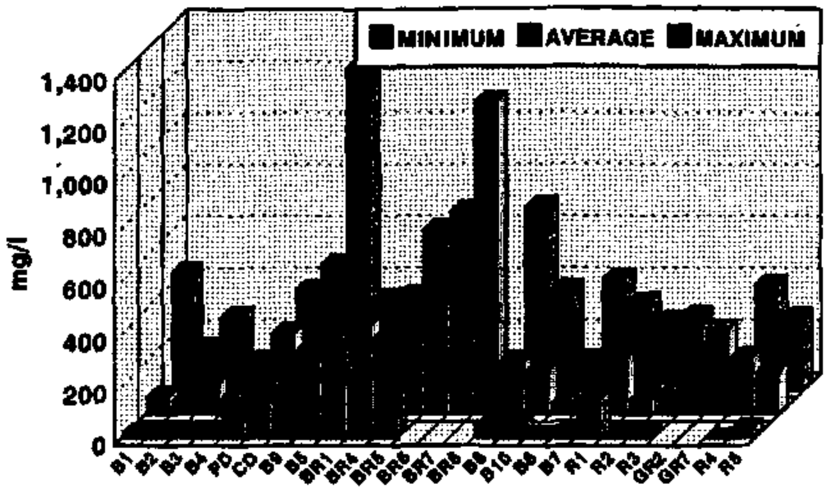
Max. Permissible Limit = 400 mg/l

SULPHATE
BLESBOKSPRUIT, RIETSPRUIT AND TRIBUTARIES



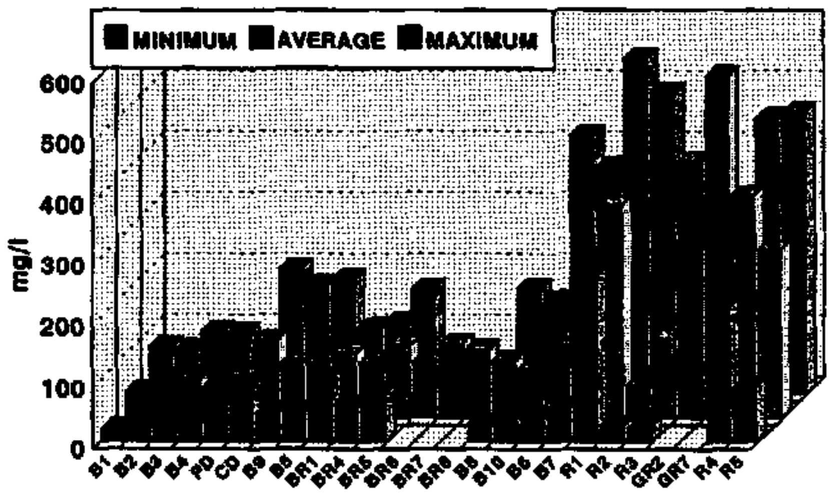
Max. Permissible Limit = 600 mg/l

CHLORIDE
BLESBOKSPRUIT, RIETSPRUIT AND TRIBUTARIES



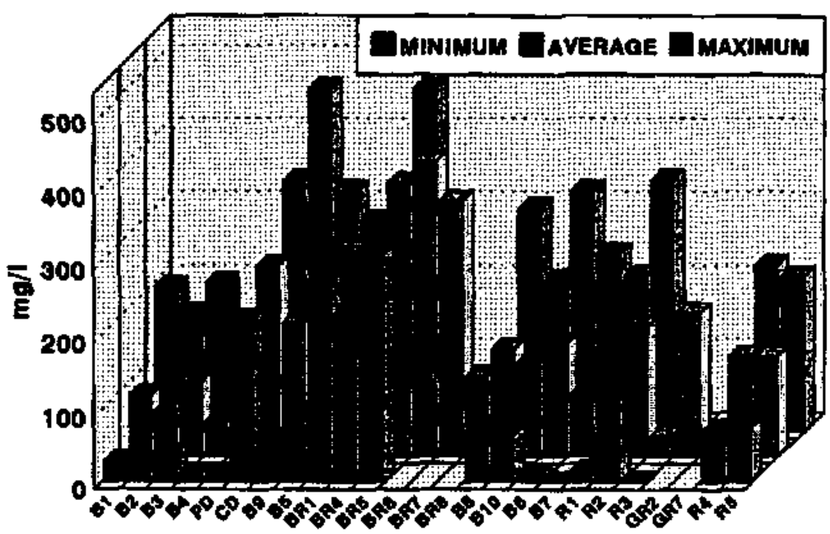
Max. Permissible Limit = 600 mg/l

CALCIUM
BLESBOKSPRUIT, RIETSPRUIT AND TRIBUTARIES



Max. Permissible Limit = 200 mg/l

ALKALINITY
BLESBOKSPRUIT, RIETSPRUIT AND TRIBUTARIES



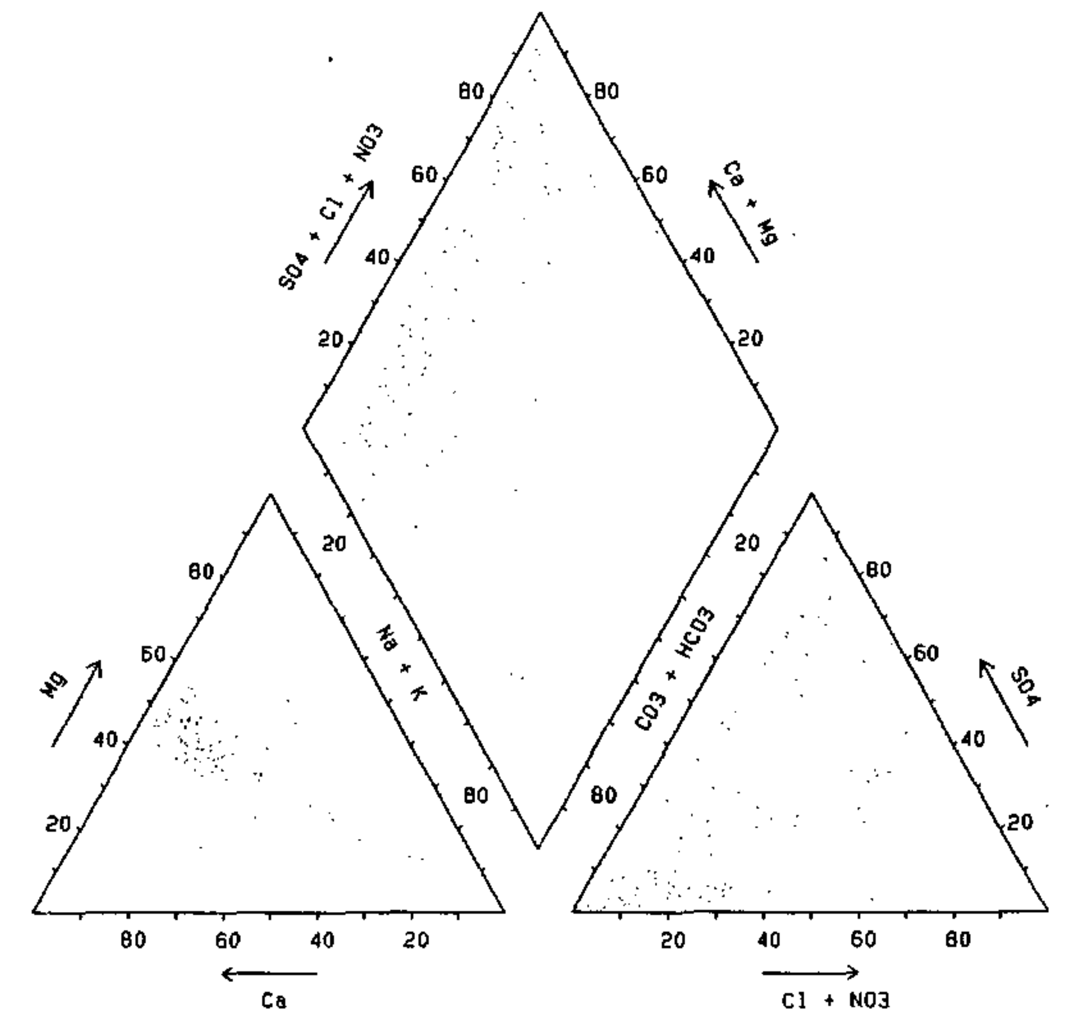
Appendix 4

Groundwater Classification diagrams

- Piper Diagram
- Durov Diagram
- Expanded Durov Diagram

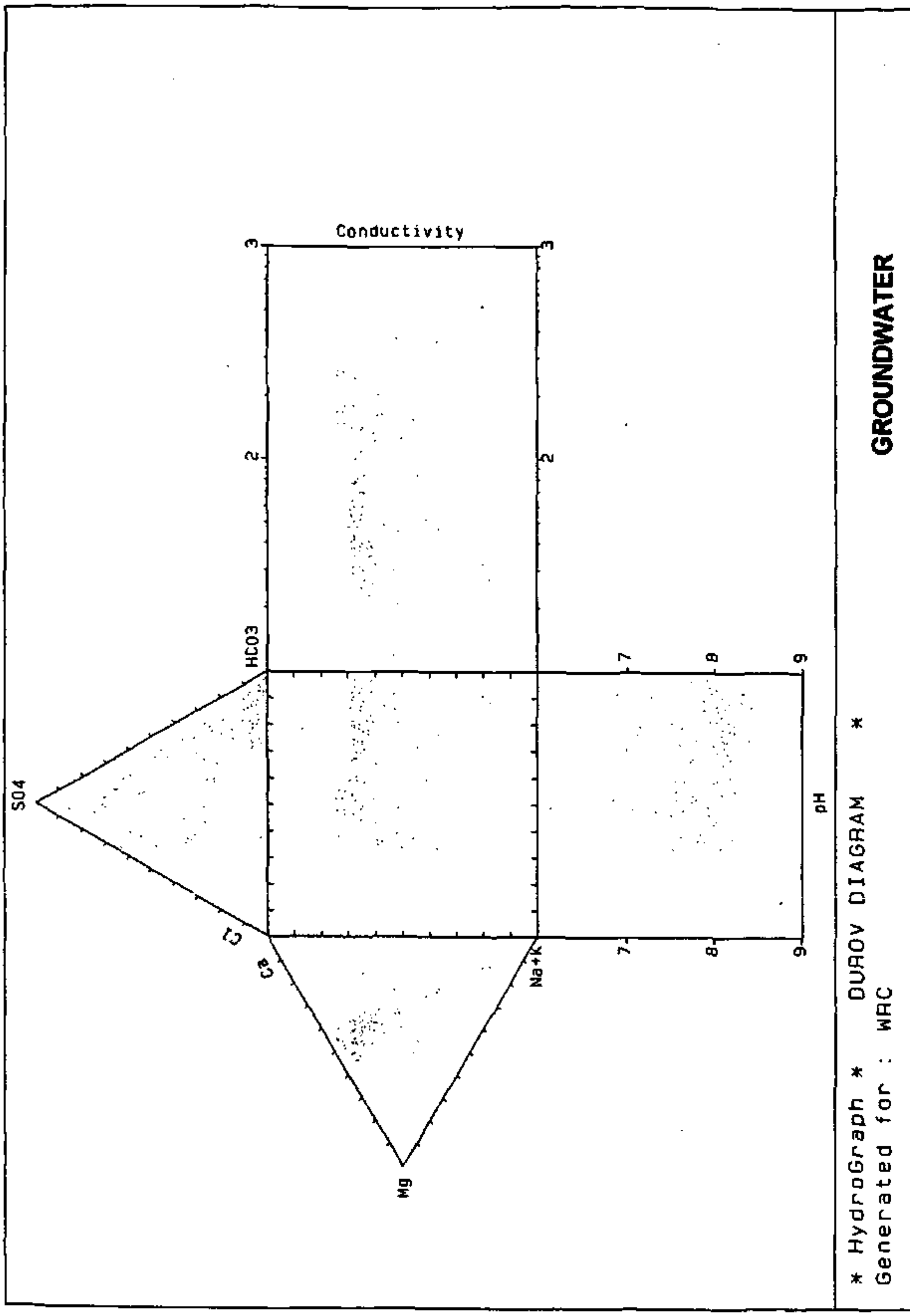
I	II	III
IV	V	VI
VII	VIII	IX

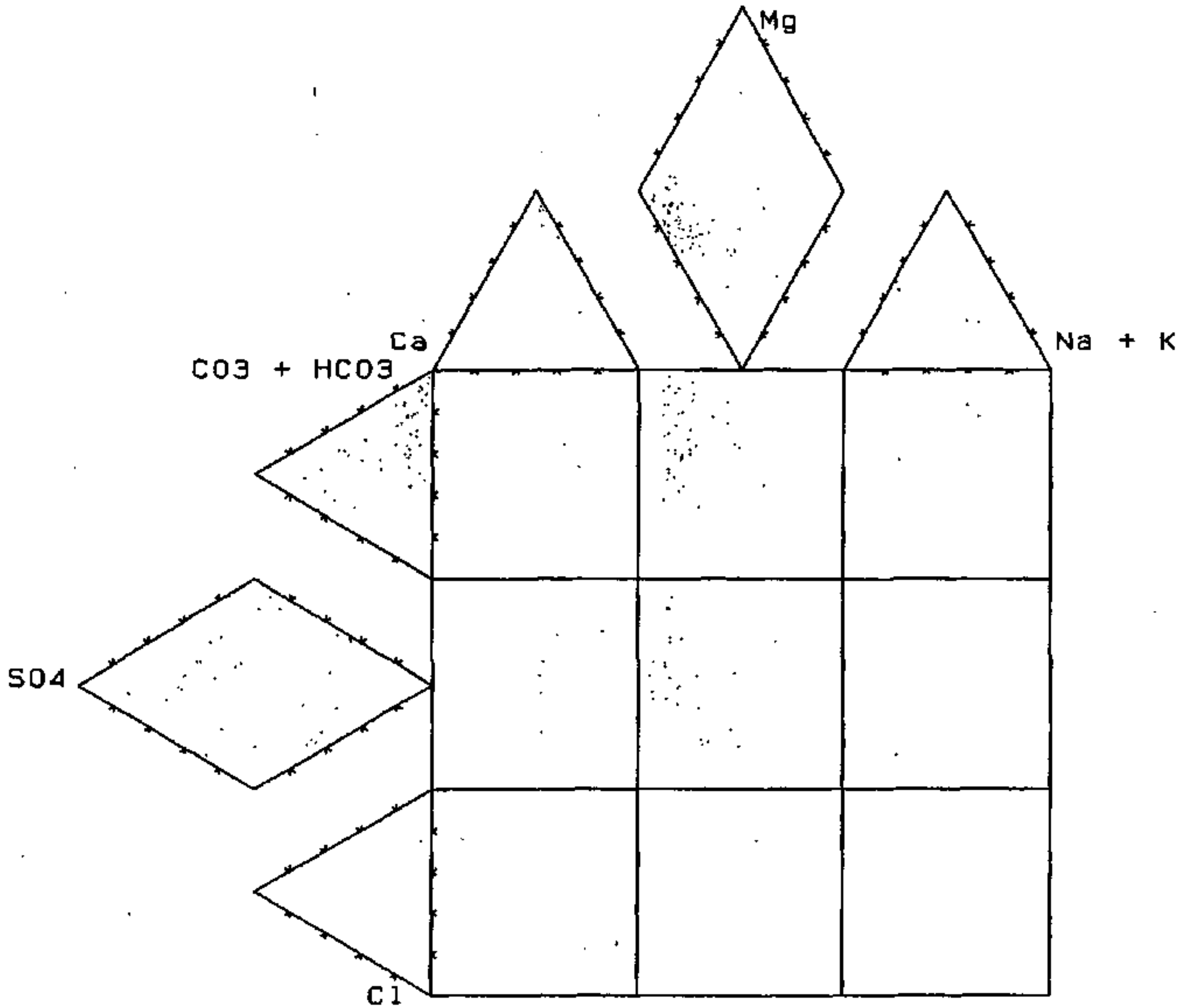
Key to the Expanded Durov diagram field numbers referred to in the text in section 3.5.2 Groundwater, page 65.



* HydroGraph *   PIPER DIAGRAM   *
Generated for : WRC

GROUNDWATER


Conductivity
HCO3
SO4
Cl
Ca
Mg
Na+K
pH
* HydroGraph * DUROV DIAGRAM *
Generated for : WRC
GROUNDWATER



* HydroBase * EXPANDED DUROV DIAGRAM *
Generated for : WRC

GROUNDWATER

Appendix 5

Groundwater Chemistry

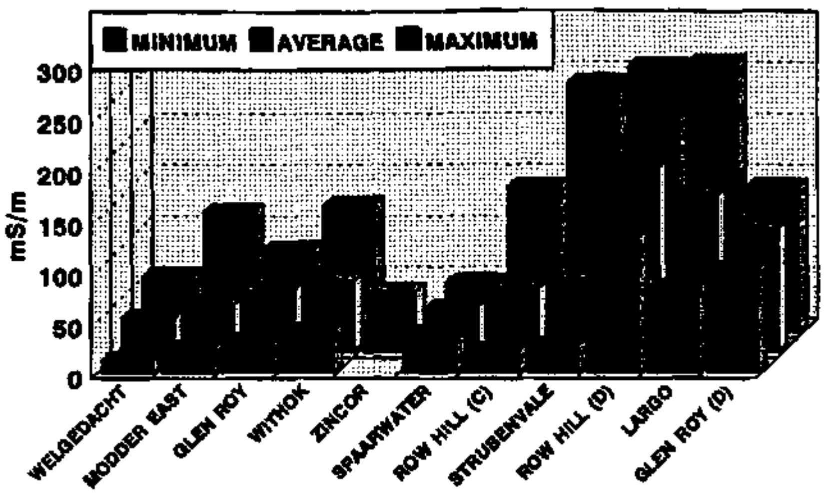
Bar Charts showing Minimum Average and Maximum values for selected parameters. Proposed maximum permissible limits in drinking water are shown, for the parameters, as a reference.

The specified limit refers to limits specified in the drinking water standards proposed by Kempster *et. al.* (1985) for South Africa.

These can be divided into three levels

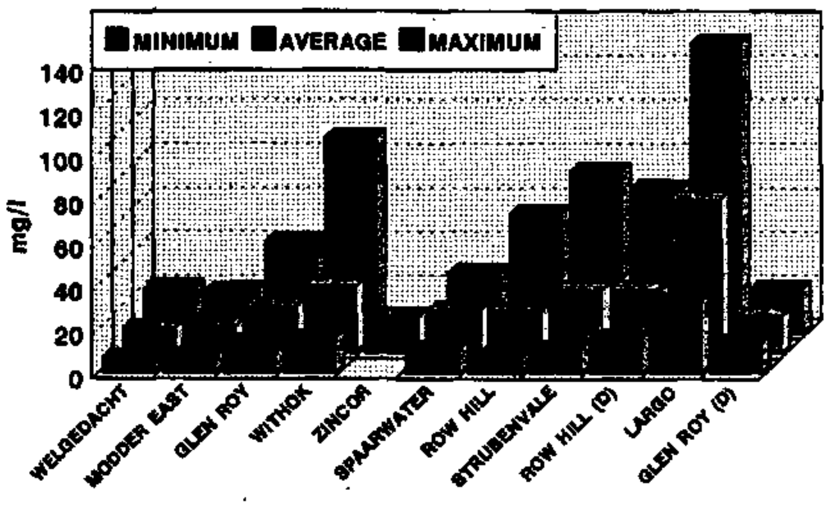
- The recommended or working limit, this is the limit which should ideally not be exceeded.
- The maximum permissible limit, is safe for consumption but if this limit is exceeded remedial/preventative action should be planned
- The crisis limit is a level at which extreme action is needed especially if the element is toxic.

ELECTRICAL CONDUCTIVITY
EAST RAND GROUND WATER



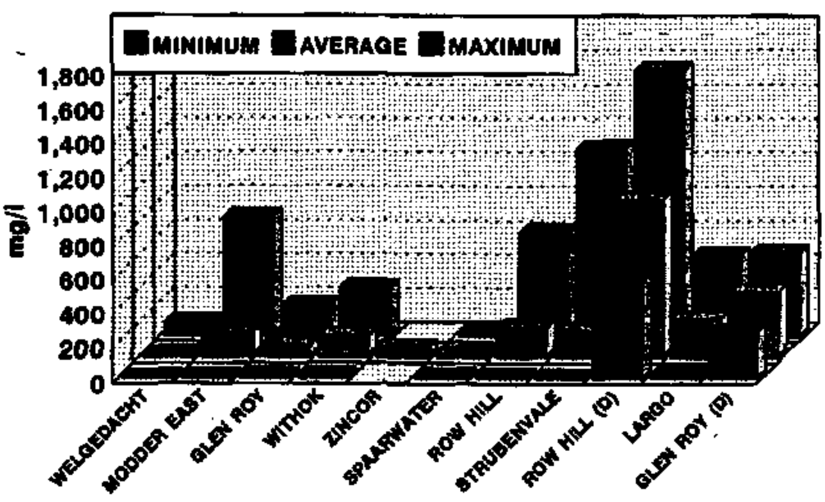
Max. Permissible Limit = 300 mS/m

SODIUM
EAST RAND GROUND WATER



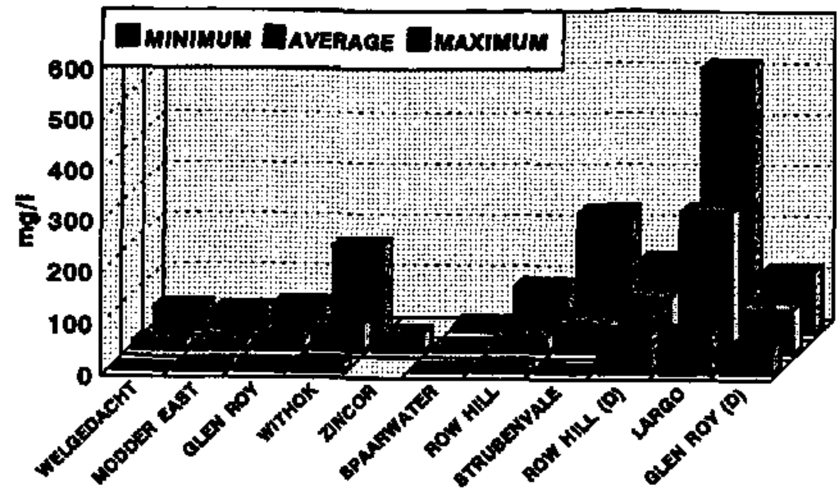
Max. Permissible Limit = 400 mg/l

SULPHATE
EAST RAND GROUND WATER



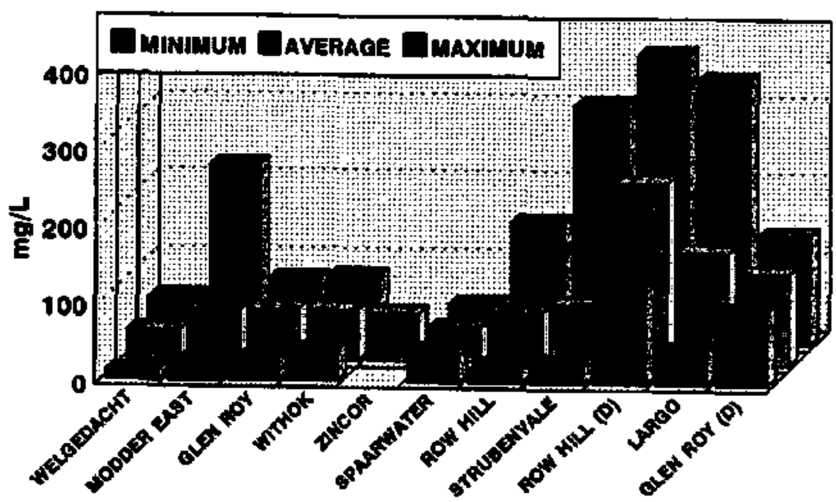
Max. Permissible Limit = 600 mg/l

CHLORIDE
EAST RAND GROUND WATER



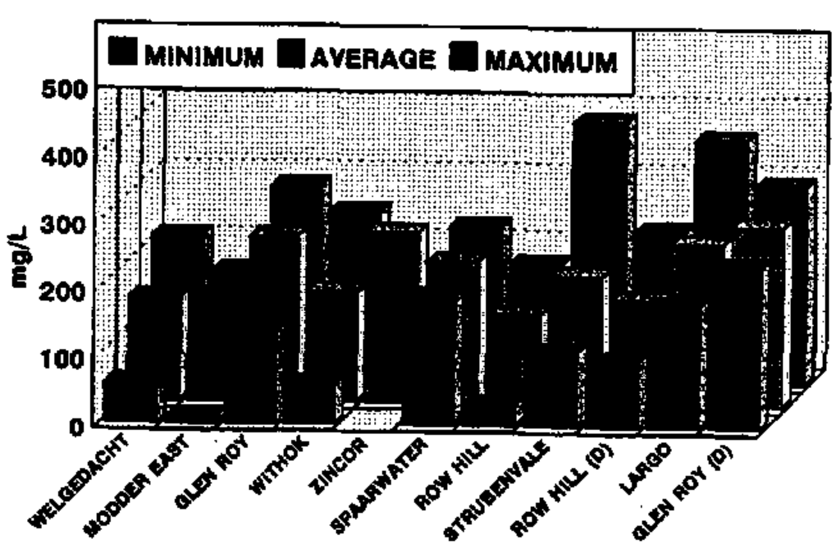
Max. Permissible Limit = 600 mg/l

CALCIUM
EAST RAND GROUND WATER



Max. Permissible Limit = 200 mg/l

ALKALINITY
EAST RAND GROUND WATER



Appendix 6

Mine Water Chemistry

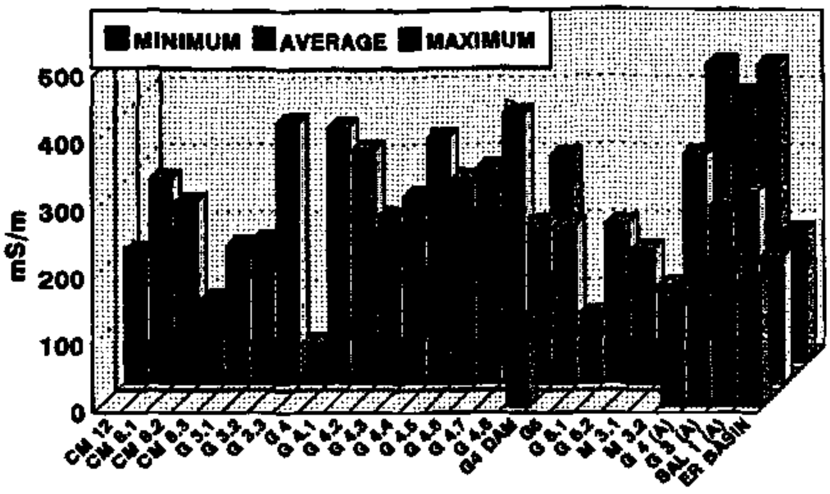
Bar Charts showing Minimum, Average and Maximum values for selected parameters. Proposed maximum permissible limits in drinking water are shown, for the parameters, as a reference.

The specified limit refers to limits specified in the drinking water standards proposed by Kempster *et. al.* (1985) for South Africa.

These can be divided into three levels

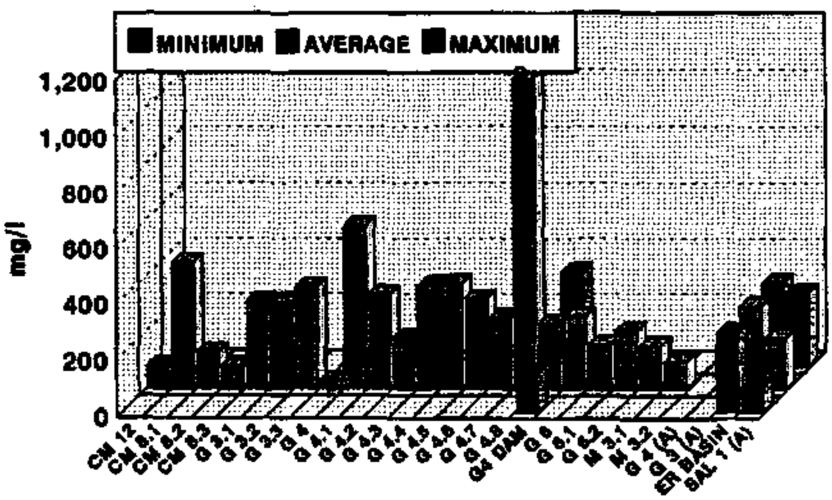
- The recommended or working limit, this is the limit which should ideally not be exceeded.
- The maximum permissible limit, is safe for consumption but if this limit is exceeded remedial/preventative action should be planned
- The crisis limit is a level at which extreme action is needed especially if the element is toxic.

ELECTRICAL CONDUCTIVITY
EAST RAND MINE WATER



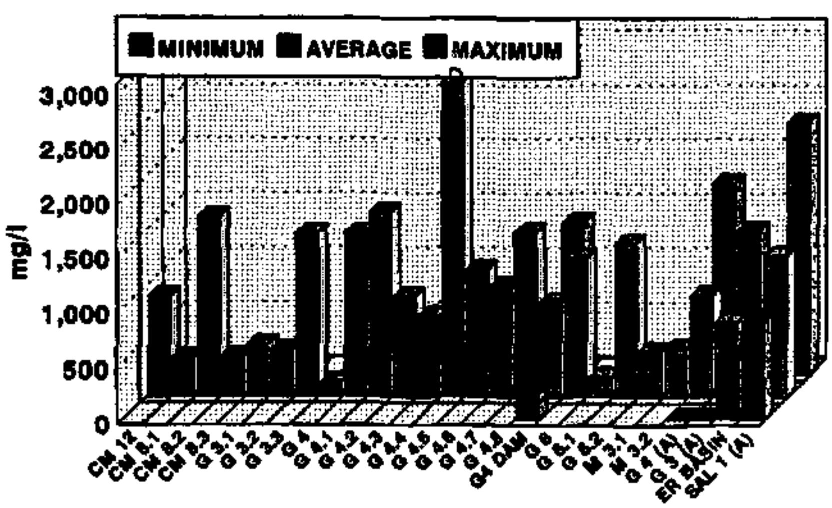
Max. Permissible Limit = 300 mS/m

SODIUM
EAST RAND MINE WATER



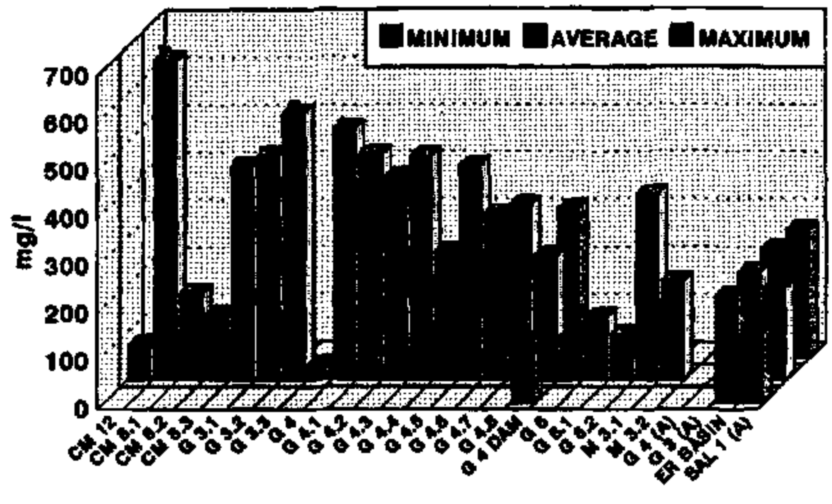
Max. Permissible Limit = 400 mg/l

SULPHATE
EAST RAND MINE WATER



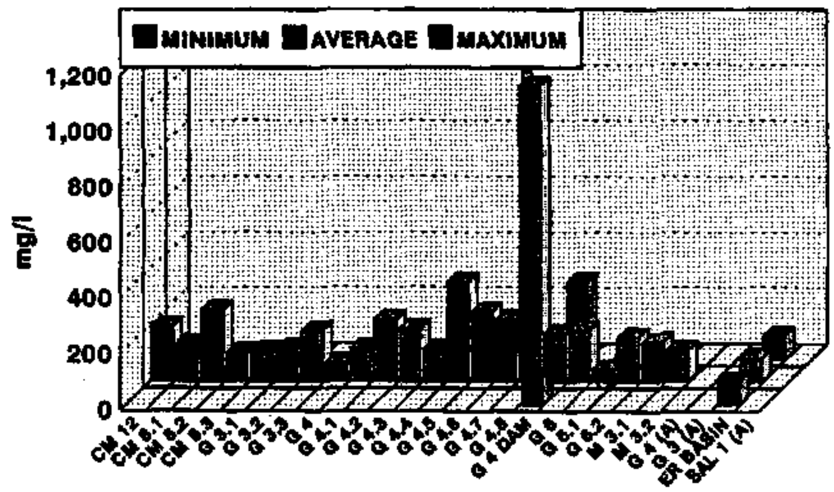
Max. Permissible Limit = 600 mg/l

CHLORIDE
EAST RAND MINE WATER



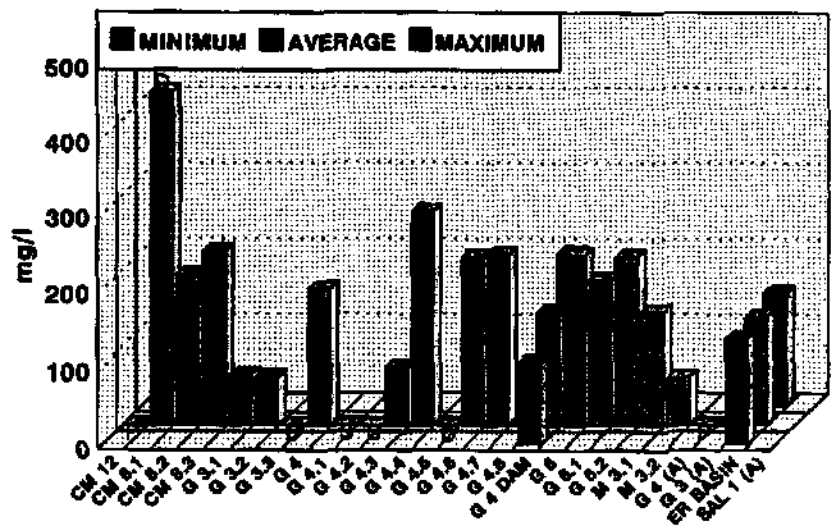
Max. Permissible Limit = 600 mg/l

CALCIUM
EAST RAND MINE WATER



Max. Permissible Limit = 200 mg/l

ALKALINITY
EAST RAND MINE WATER

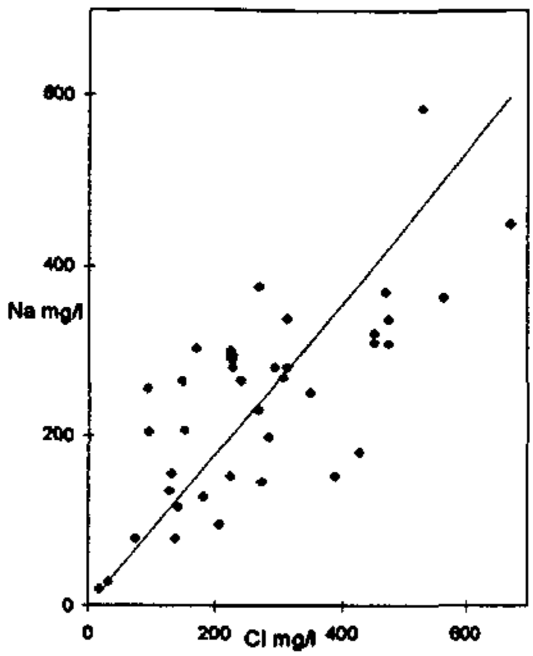


Appendix 7

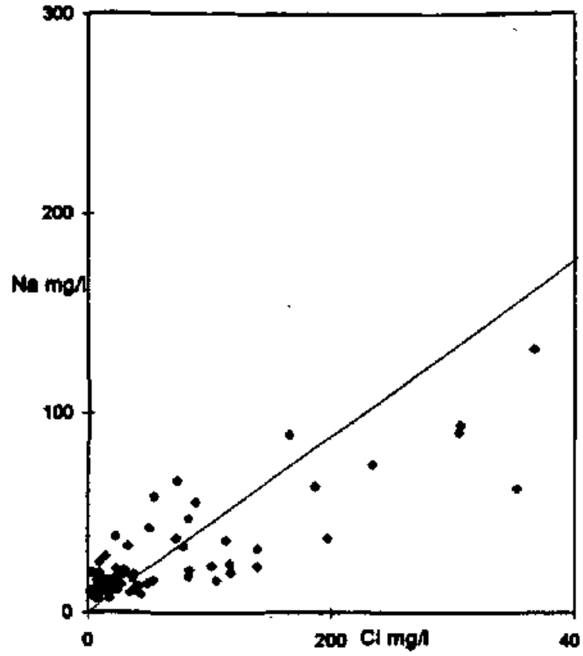
Sodium vs chloride plots of water chemistry data gathered during this project as well as published data.

Other data sources include:

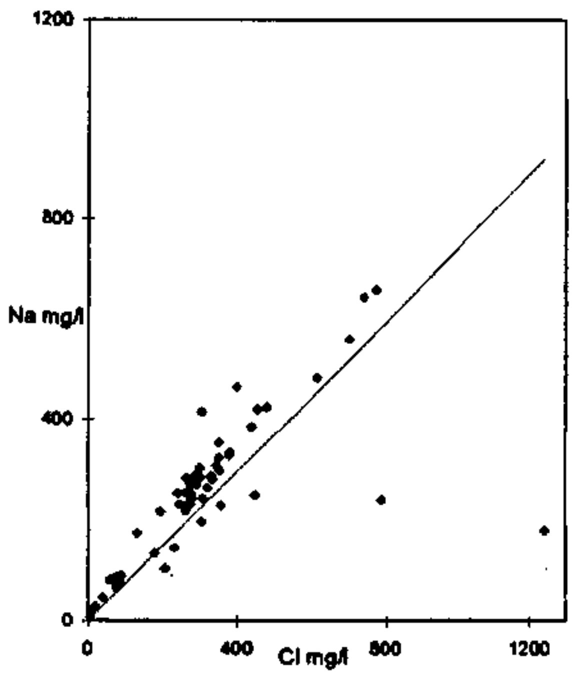
Cogho *et. al.* (1992), Coetzee (1960), Wittmann *et. al.* (1976) and DWA&F records of surface water in the Free State.



East Rand Mine Water



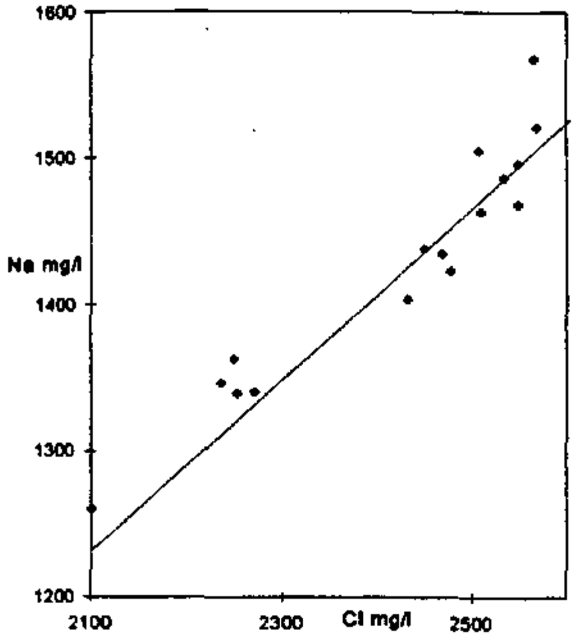
East Rand Groundwater



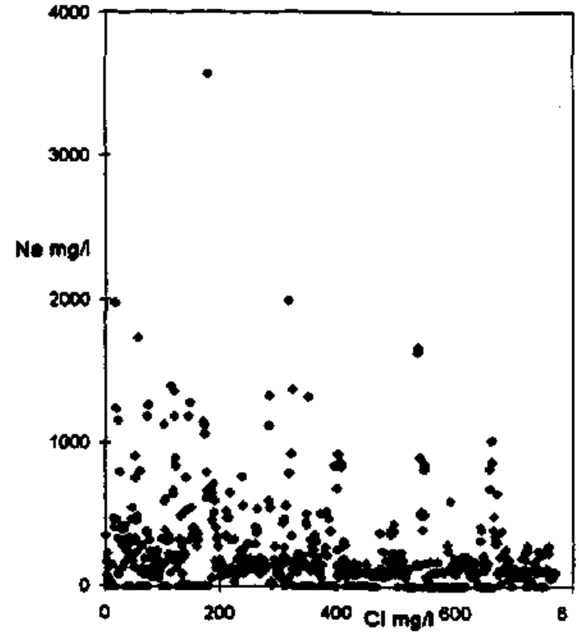
East Rand Surface Water

Line equations

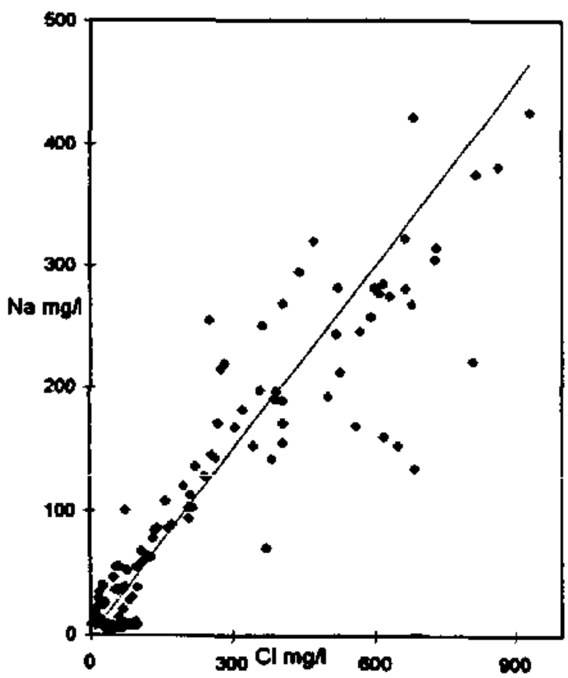
East Rand Mine Water	$y=0.9x$
East Rand Groundwater	$y=0.4x$
East Rand Surface Water	$y=0.7x$



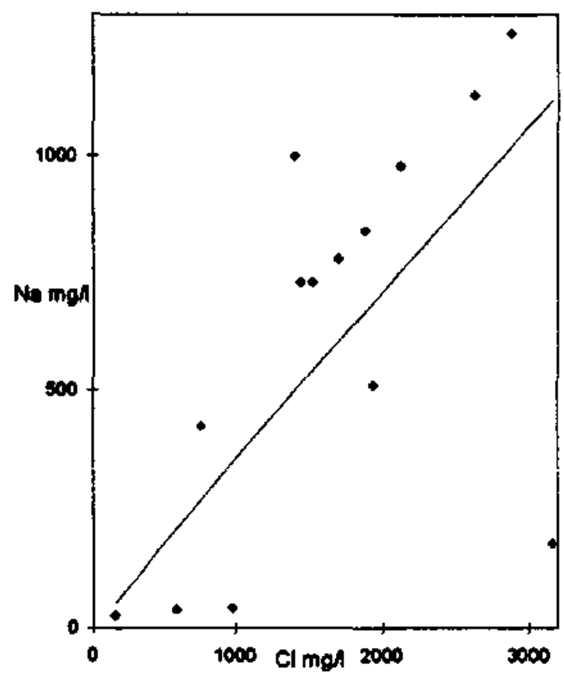
Free State Mine Water



Free State Groundwater



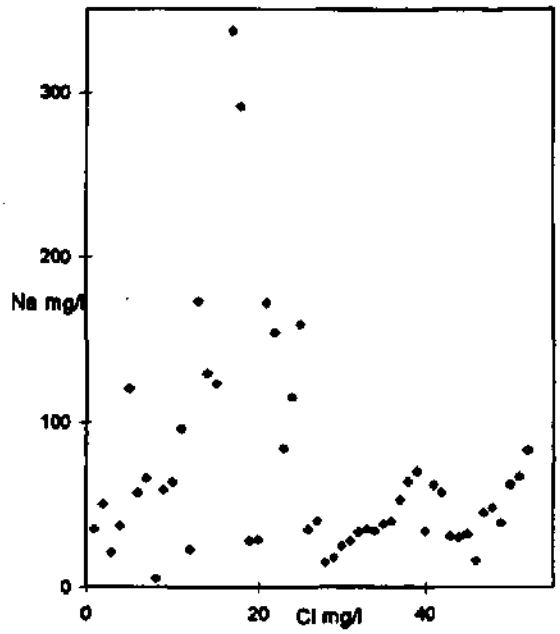
Free State Surface Water



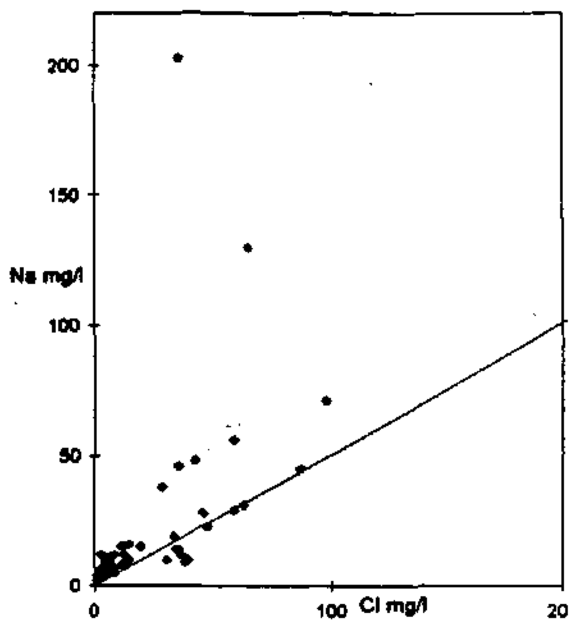
Free State Dump Leachate

Line equations

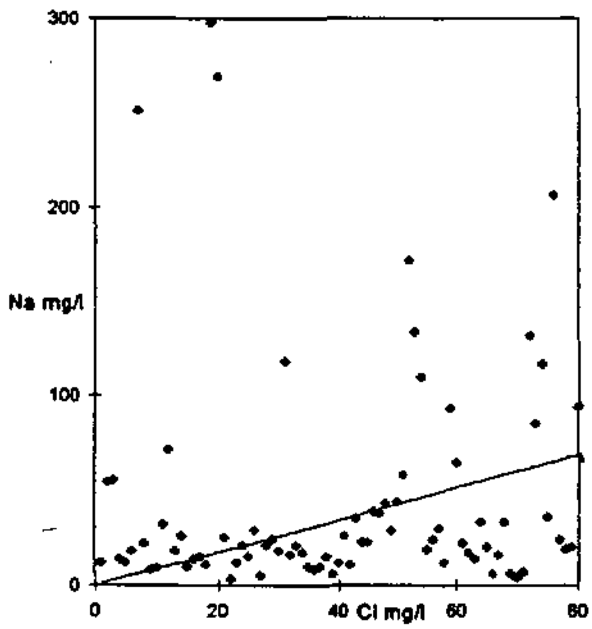
Free State Mine Water	y=0.6x
Free State Surface Water	y=0.5x
Free State Dump Leachate	y=0.4x



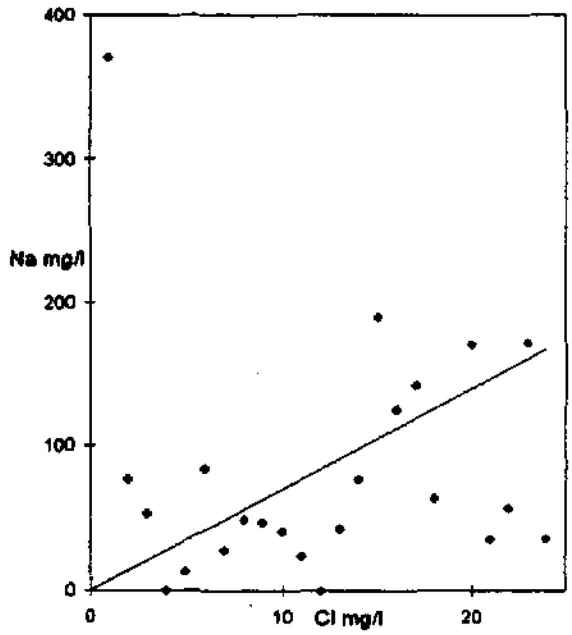
Central Rand Mine Water



Central Rand Groundwater



Central Rand Surface Water



Witwatersrand Dump Leachate[1]

Line equations

Central Rand Mine Water	y=1.8605x
Central Rand Groundwater	y=0.5034x
Central Rand Surface Water	y=0.8537x
Witwatersrand Dump Leachate	y=6.9918

[1]The published data used for this plot covered the East and Central Rand.

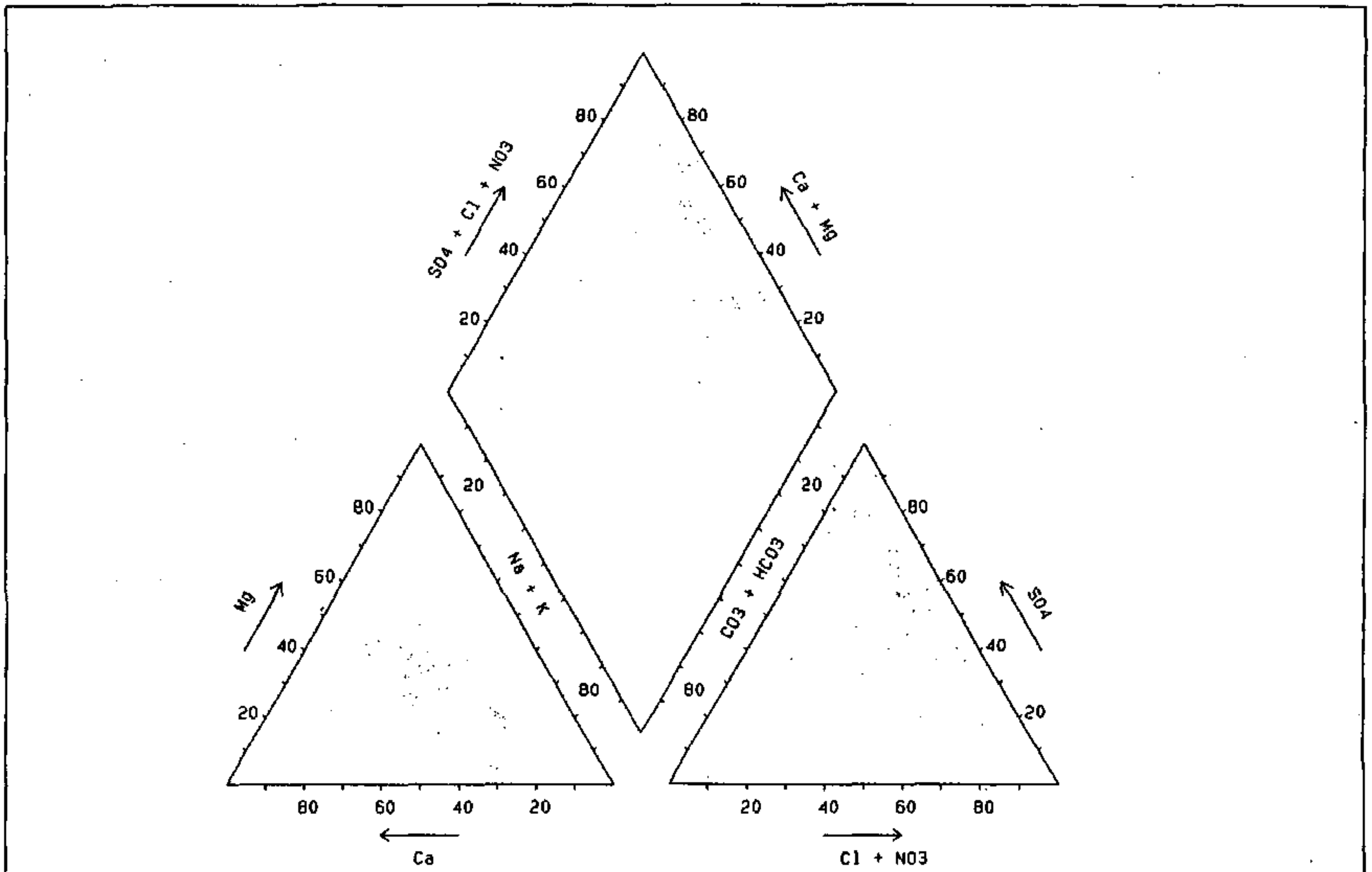
Appendix 8

Mine Water Classification

- Piper Diagram
- Durov Diagram
- Expanded Durov Diagram

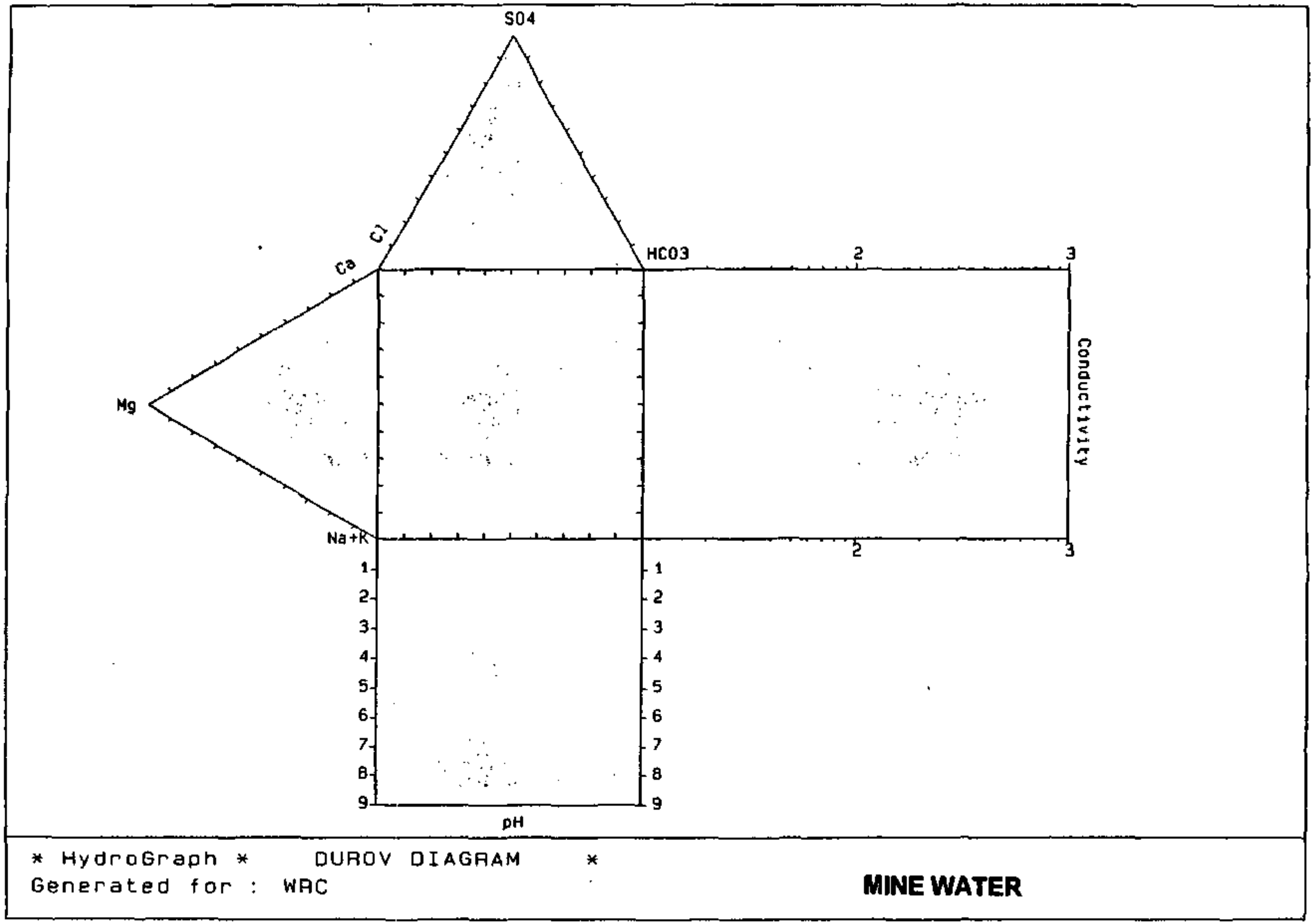
I	II	III
IV	V	VI
VII	VIII	IX

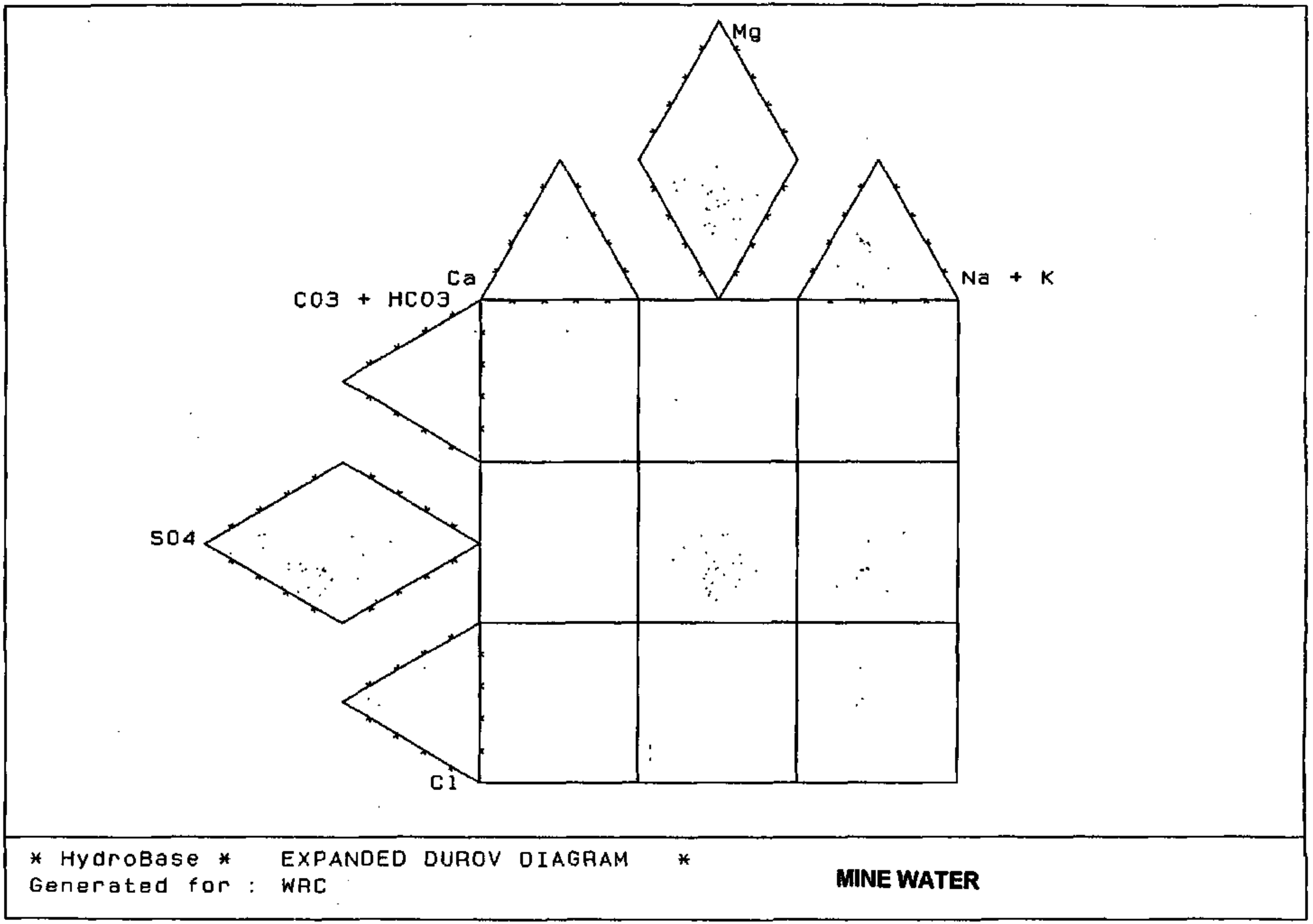
Key to the Expanded Durov diagram field numbers referred to in the text in Section 3.5.3, Mine Water on page 71 and 72.



* HydroGraph * PIPER DIAGRAM *
Generated for : WRC

MINE WATER


SO4
Cl
Ca
HCO3
Mg
Na+K
2
3
Conductivity
1
2
3
4
5
6
7
8
9
pH
* HydroGraph * DUROV DIAGRAM *
Generated for : WRC
MINE WATER


Mg
Ca
Na + K
CO3 + HCO3
SO4
Cl
* HydroBase * EXPANDED DUROV DIAGRAM *
Generated for : WRC
MINE WATER

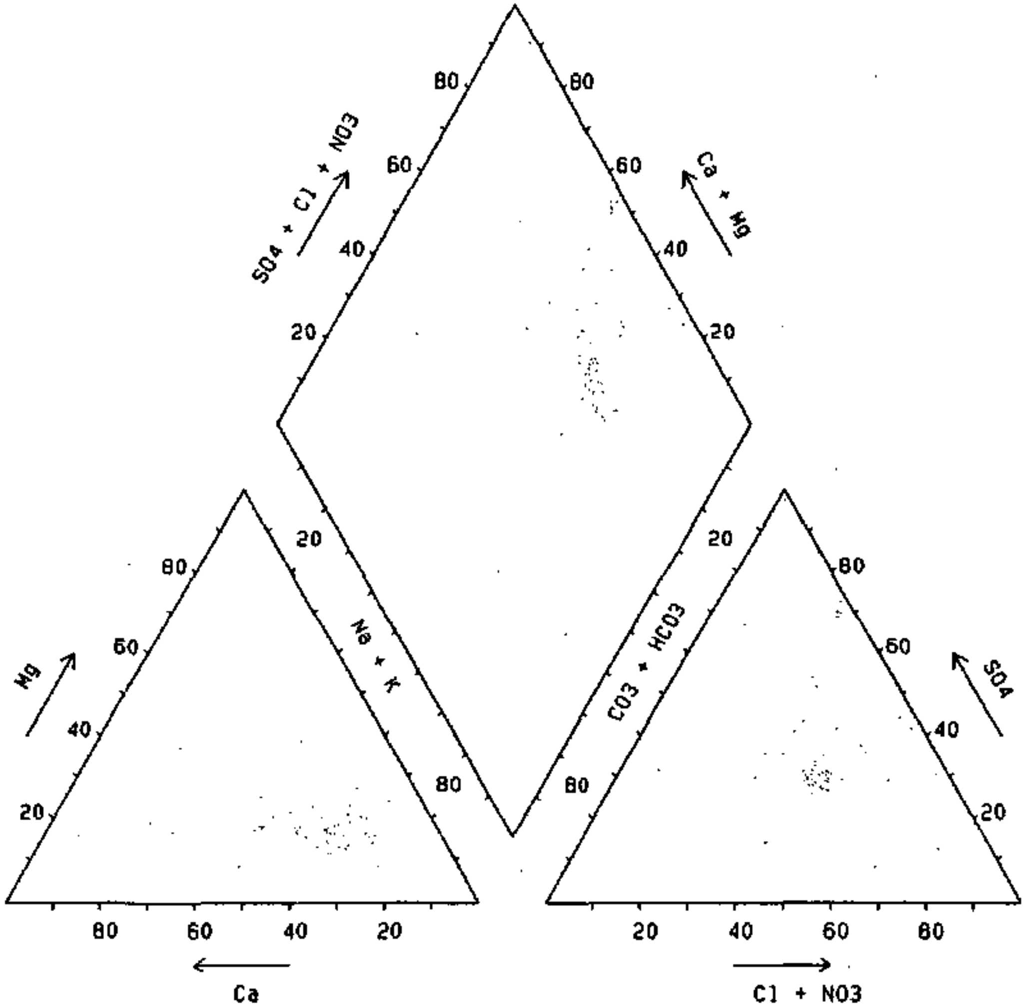
Appendix 9

Surface Water Classification

- Piper Diagram
- Durov Diagram
- Expanded Durov Diagram

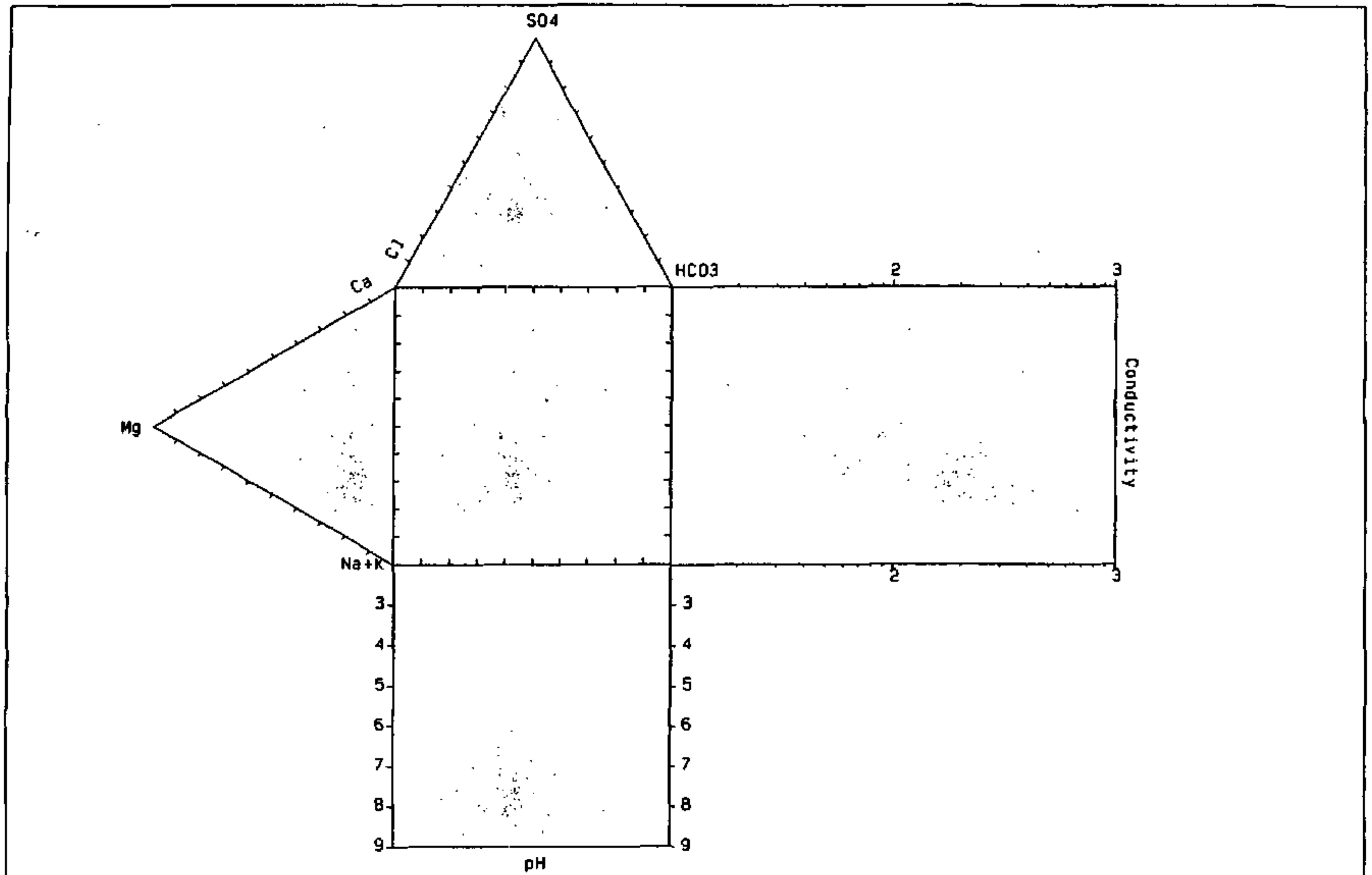
I	II	III
IV	V	VI
VII	VIII	IX

Key to the Expanded Durov diagram field numbers referred to in the text in Section .3.5.4 Relationships Between Waters, on page 72 and 73.



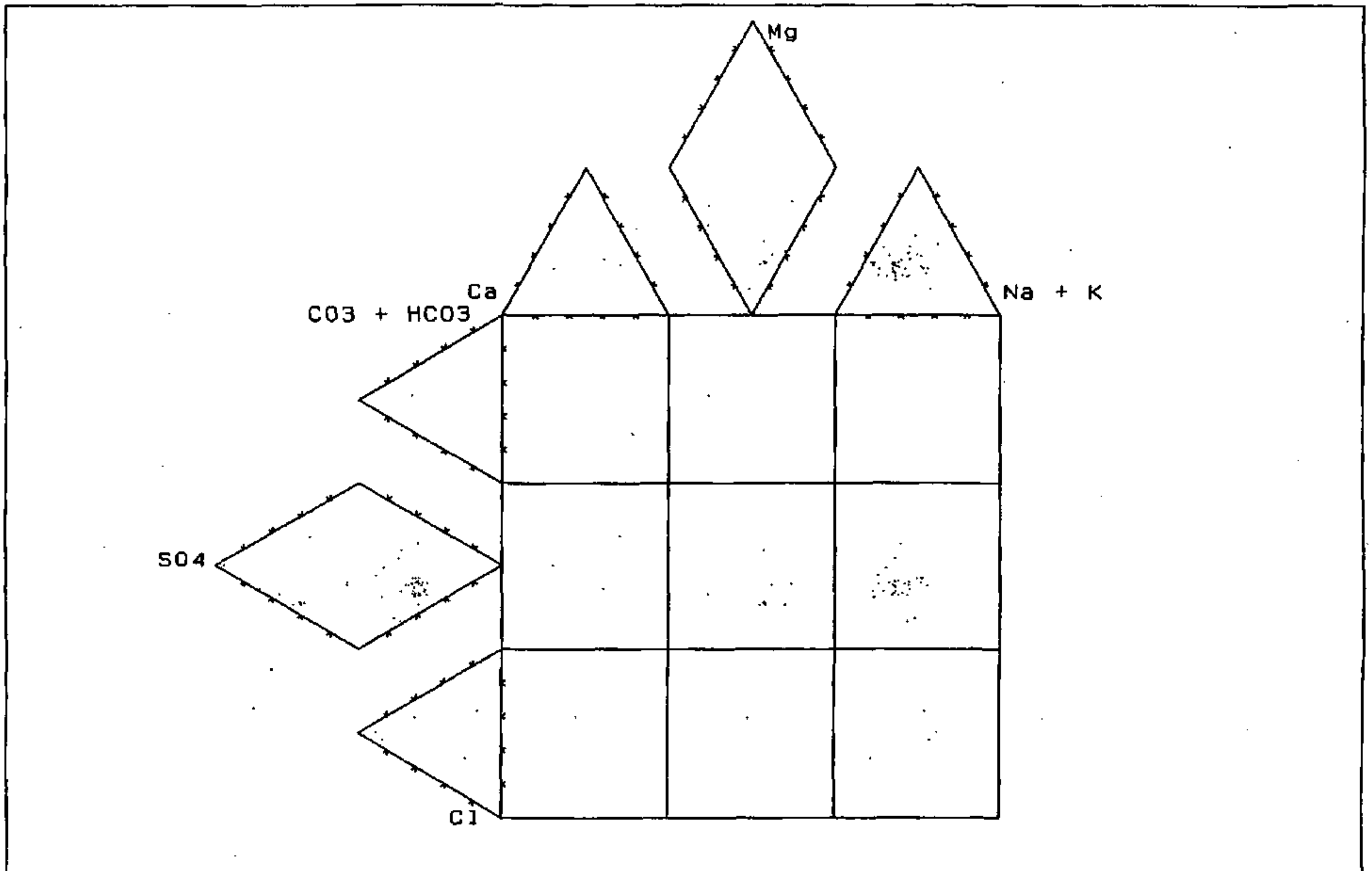
* HydroGraph *   PIPER DIAGRAM   *
Generated for : WRC

SURFACE WATER



* HydroGraph *   DUROV DIAGRAM   *
Generated for : WRC

SURFACE WATER



* HydroBase *   EXPANDED DUROV DIAGRAM   *
Generated for : WRC

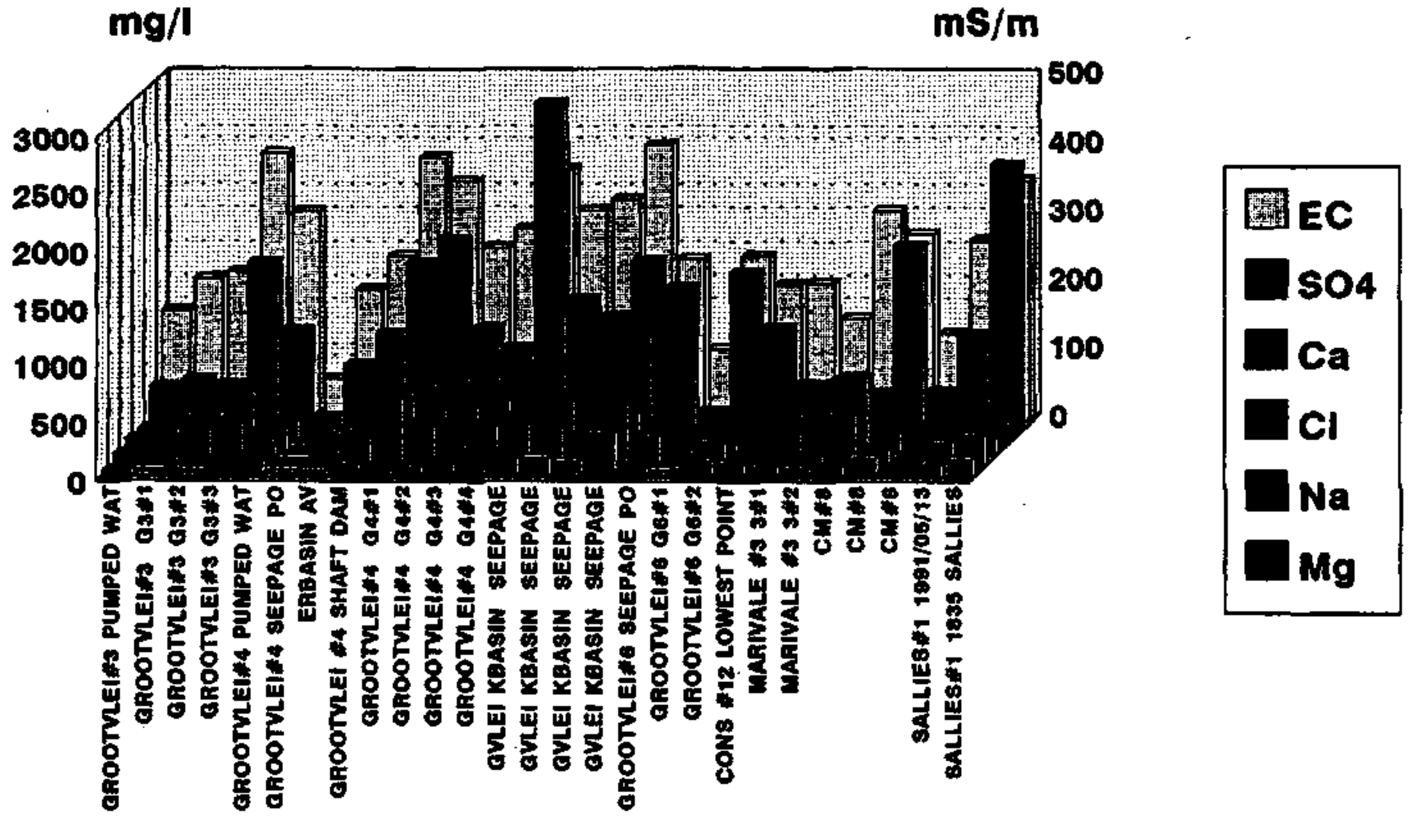
SURFACE WATER

Appendix 10

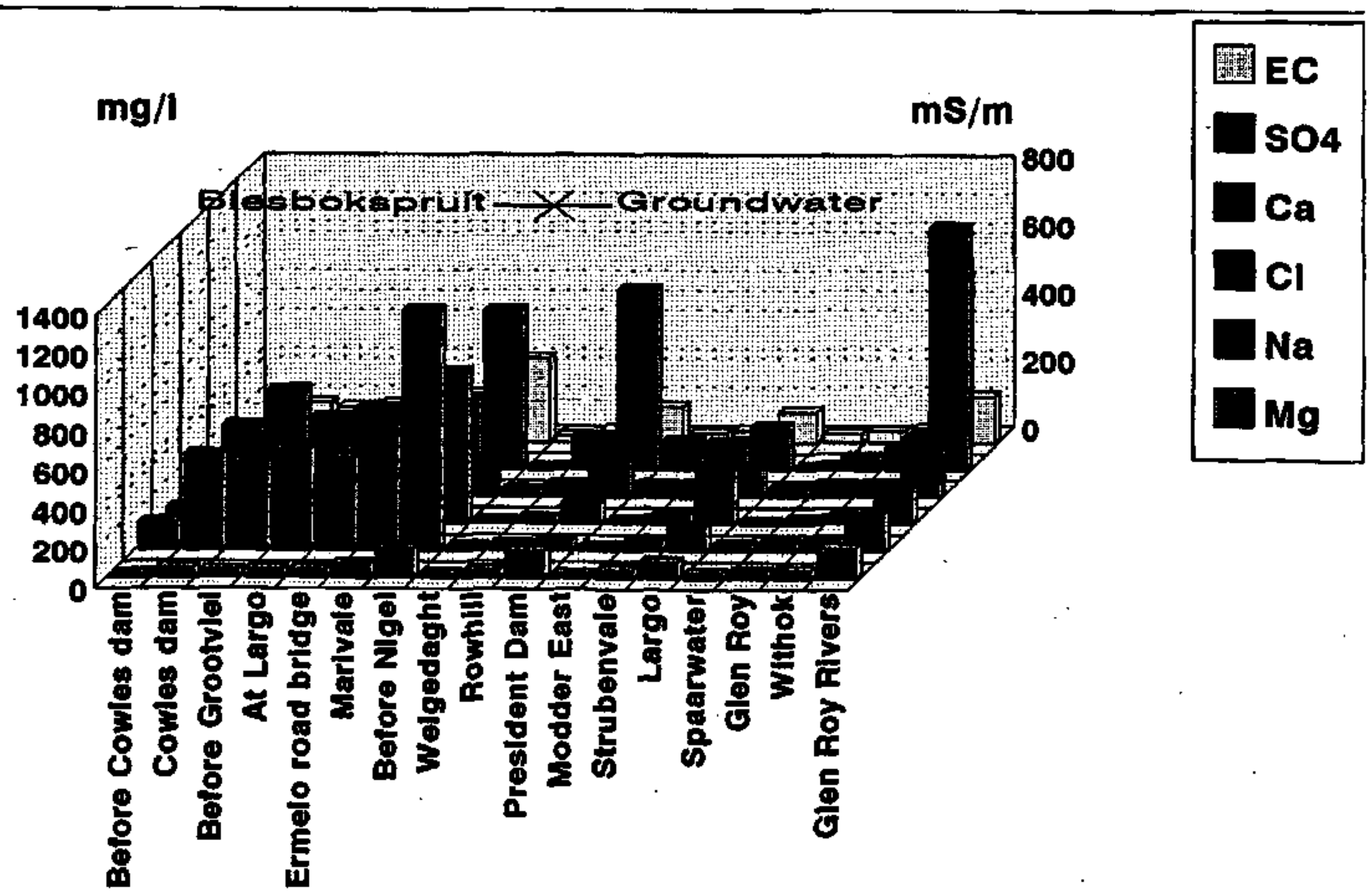
Comparison Bar Charts between surface, ground and mine water for selected elements

Surface and groundwater values are averages of related samples. The relationship being shown by the classification studies.

MINEWATER

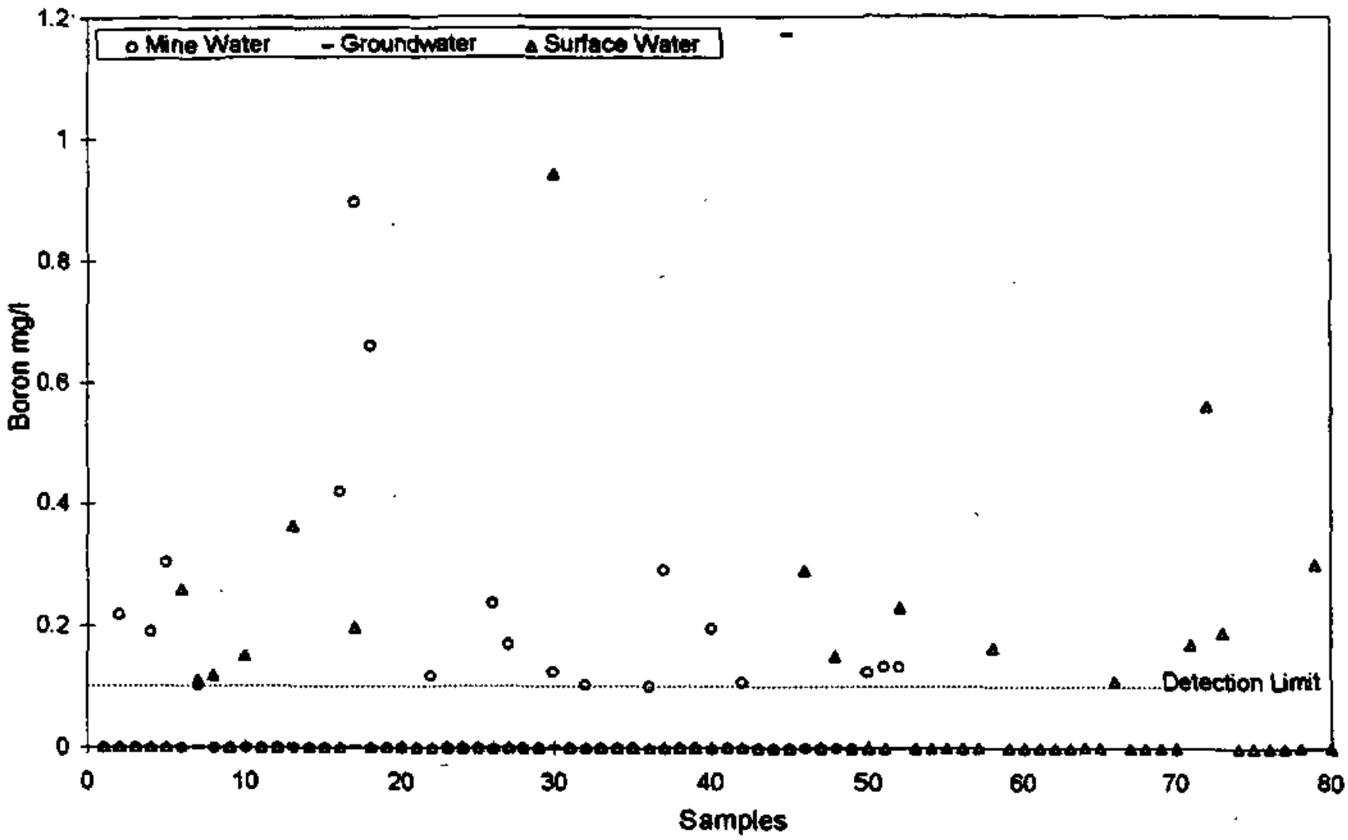


SURFACE AND GROUNDWATER CHEMISTRY COMPARISON

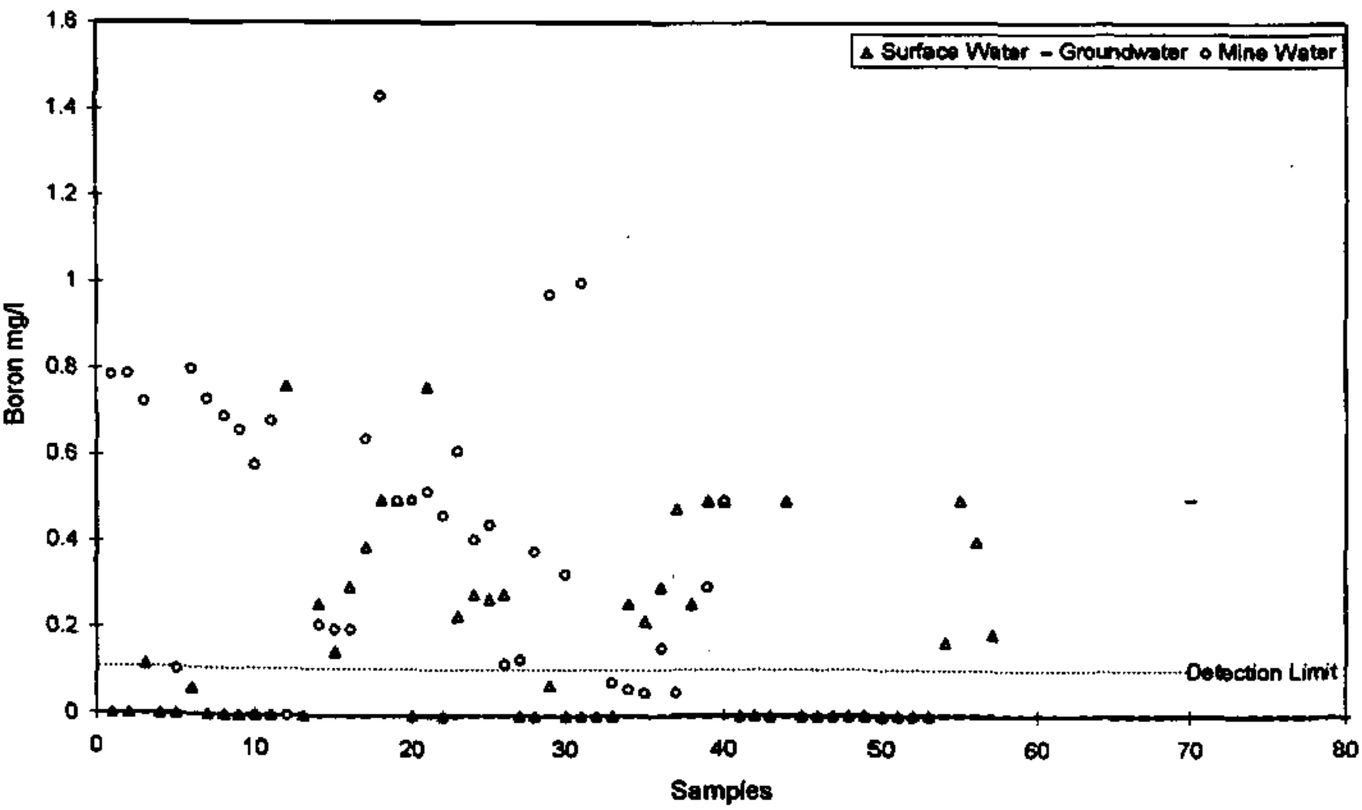


Appendix 11

Plots of boron versus sample position for water chemistry evaluated during this investigation.



Boron in Central Rand Waters



Boron in East Rand Waters