The Development of Techniques for the Evaluation and Effective Management of Surface and Groundwater Contamination in the Orange Free State Goldfields

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WRC Report No.224/1/92

THE DEVELOPMENT OF TECHNIQUES FOR THE EVALUATION AND EFFECTIVE MANAGEMENT OF SURFACE AND GROUND-WATER CONTAMINATION IN THE ORANGE FREE STATE GOLDFIELDS

BY

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January 1992

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University of the Orange Free State

WRC Report No. K5/224

Obtainable from:

Water Research Commission
P O Box 824
PRETORIA
0001

ISBN 1 874858 42 X

ACKNOWLEDGEMENTS

The research described in this report resulted from a project funded by the Water Research Commission entitled:

"The development of techniques for the evaluation and effective management of surface and ground-water contamination in the Orange Free State Goldfields"

The Steering Committee responsible for this project, consisted of the following persons:

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The financing of the project by the Water Research Commission and the contributions of the members of the Steering Committee are acknowledged gratefully.

This project was only possible with the cooperation of many individuals and organizations. The authors therefore wish to thank the following:

Loraine Gold Mine, Freegold North and South, St Helena Gold Mine, Unisel Gold Mine, Harmony Gold Mine, Oryx Gold Mine, Beatrix Gold Mine and H J Joël Gold Mine, in particular:

Mr J Caulkin (Freegold North),

Mr A Howard (Freegold South),

Mr H C Morkel (Freegold South),
Mr E H Bekker (Harmony Gold Mine),
Mr C N O'Connor (Oryx Gold Mine),
Mr B J Pretorius (Loraine Gold Mine) and
Mr A F Janse van Rensburg (St Helena Gold Mine)

for collecting and providing crucial data.

The members of the Mining Subcommittee:

Mr D R Fleming (Freegold South),
Mr D R Young (H J Joël Gold Mine),
Mr J C Steenkamp (Loraine Gold Mine),
Mr K Eick (Harmony Gold Mine),
Dr H N S Wiechers (Chamber of Mines),
Mr W Pulles (Chamber of Mines),
Mr J D Wells (Rand Mines),
Mr D A Parfitt (Unisel Gold Mine) and
Mr A F Janse van Rensburg (St Helena Gold Mine)

for their time spent and their valuable contributions to the outcome of the study.

The municipalities of Welkom, Odendaalsrus and Virginia and in particular Mr P Bezuidenhout (Welkom) for the storage and other facilities at the Theronia Sewage Works.

All the farmers in the study area, who willingly provided important information to the outcome of the study.

Mmes M Botha and C le Roux of the Institute for Ground-water Studies, who worked on the project with patience and thoroughness.

EXECUTIVE SUMMARY

INTRODUCTION

Water can be regarded as a scarce commodity in South Africa and one cannot rely solely on the discovery of new water resources to meet the ever-increasing demands. As the industrial and mining activities on the Witwatersrand increased from the turn of the century, so did the contamination of the Vaal River. Repetition of this situation in other drainage basins must, as far as possible, be prevented. As the Orange Free State Goldfields occur in an area isolated from many of the pollution sources found within, for example the Vaal River Catchment, its impact on the environment can therefore be investigated more easily and the results obtained can be used to elucidate ground-water quality problems in areas of diverse mining and industrial activities.

The area under investigation stretches from Allanridge in the north to just north of Theunissen in the south, covering approximately 2 100 km^2. Many of the possible pollution sources have been present in the area since mining commenced in the early fifties, while other sources have only been ongoing for a few years. The Sand River crosses the study area from east to west, eventually draining into the Bloemhof Dam. This is regarded as a major seasonal stream in the region and its water quality presently deteriorates from 140 mg/l (TDS) to 700 mg/l, as it passes through the Orange Free State Goldfields.

Many chemical elements detrimental to humans, animals and vegetation occur in surface effluent water and leachates from solid waste disposal sites. As those elements may eventually find their way into ground water and subsequently surface water resources, quantification in terms of time of travel and distance from potential pollution source is vital to managing waste disposal activities.

This research project into the water quality of the Orange Free State Goldfields constitutes a three-year contract between the Water Research Commission and the Institute for Ground-water Studies at the University of the Orange Free State.

The research commenced on January 1st, 1988.

OBJECTIVES

According to the agreement, concluded between the Water Research Commission and the Institute for Ground-water Studies, the following aims were proposed for the investigation:

- To determine the source of possible pollutants to the surface and ground-water regime.
- Quantify the contribution from different sources.
- Study the migration rate of pollutants through the aquifers.
- Determine chemical alterations to pollutants while on surface and in the aquifer.
- Model local and regional movement of pollutants through the aquifer and predict future water qualities.
- Enter information into a computerized data base.
- Suggest management strategies whereby the influence of disposal can be minimized.

POTENTIAL SOURCES OF CONTAMINATION

The Orange Free State Goldfields produce many different types of waste (solid or liquid), contributing in varying quantities to the total water quality of the area. A large portion of all the waste generated in the area is associated with mining activities. Wastes found in the study area are:

(i) Mine:
  (a) Solid waste (rock waste, scrap metal and domestic waste).
  (b) Slimes and return water dams.
  (c) Evaporation areas.
(ii) Municipal:
  (a) Urban solid waste.
  (b) Urban liquid waste.
  (c) Industrial effluent.

1 HYDROLOGY

The area forms part of the highveld region and has an average elevation of about 1 360 m above mean sea level. Most of the area has a gentle undulating surface and rarely are any prominent landmarks visible. The Orange Free State Goldfield area is situated in a semi-arid region with a mean annual precipitation of 518 mm. The identification of rainfall cycles as well as a probability analysis for flood occurrence can be important, as excessive unpotable water is one of the major issues in the area.

The annual precipitation for the area was 897 mm in 1988. It was observed that the 331 mm recorded in February 1988, has a return period of 100 years.

Although high values of annual precipitation do not usually give rise to floods, they should be taken into account when designing effluent disposal facilities. It is, however, the high rainfall of shorter durations that has to be watched closely with respect to floods, as government regulations stipulate water storage capacity requirements on the basis of a balance, which incorporates average monthly rainfall and rainfall with a recurrence interval of 1:100 years of one-day duration.

2 GEOLOGY AND GEOHYDROLOGY

The area under investigation is extensively covered by soil and sands of aeolian origin. Outcrops are therefore limited to surface limestone, river terrace gravel, dolerite, kimberlite and sediments of the lower Beaufort Group, the upper Ecca Group and lava sediment of the Ventersdorp Supergroup. In the western and north-western parts of the area, extensive pan development has taken place and may have an effect on the water quality of that specific part of the region.

From the reconnaissance and extended sampling, it was found that two basic aquifers exist in the area:

(a) A shallow aquifer which lies within the weathered and fractured zone of the Karoo sediments.

(b) A deeper aquifer which is developed in the fractured and faulted Ventersdorp and Witwatersrand rocks.

Furthermore, it was evident that the occurrence of ground water in the shallow aquifer is geologically controlled. Boreholes with moderate to high yields are associated with the intrusion of dolerite. The average yield of the boreholes in the Beaufort sediments is 3,2 l/s, whereas the average yield in the Ecca sediments is 1,03 l/s.

Ground-water levels closely follow the surface topography, implying that ground-water levels are topographically controlled and that vertical leakage to the deeper aquifer is negligible. South and north-east of the Sand River, the slope of the water levels is generally towards the Sand River. In the western and north-western parts of the study area where the surface drainage is poorly developed, ground-water movement is mostly restricted to local vlei and pan systems. The regional ground-water gradient is, however, towards the west of the study area.

A model was developed to estimate the salt load that the environment is exposed to, due to the large quantities of water (with a dominant NaCl-character) pumped from the Witwatersrand rocks daily (155 Ml/d) and discharged into evaporation areas and pans. In simulating the water levels for 37 years, about 1 240 x 10^6 m^3 of water was pumped to the surface. If the pumped water has an average electrical conductivity of 450 mS/m, the total dissolved solids in the water are in the order of 3 000 mg/l. This amounts to a total of 3,717 x 10^6 tonnes of salt having been pumped to the surface.

3 HYDROCHEMISTRY

More than 5 000 hectares of land in the Orange Free State Goldfields are used as evaporation areas for effluent water (155 Ml/d). This water either evaporates or infiltrates into the ground.

As the Sand River flows through the area, its water quality deteriorates dramatically as a result of various pollution sources, of which the Sand River canal is the major source. The canal flows continuously throughout the year, receiving its water mainly from seepage and overflow from evaporation areas. The water in the canal is of poor quality, with electrical conductivities ranging from 550 to 1 200 mS/m.

On various occasions, effluent water spilled into streams and natural vlei systems. Although these discharges did not occur continuously, evidence suggests they contributed quite considerably to the spread of the pollution throughout the area.

As in the case of the borehole yields, the natural ground-water quality in the Goldfields also exhibits a strong geological control. The ground-water quality in the Ecca sediments seems to be generally of poorer quality than the ground water found in the Beaufort sediments. This can be ascribed to the mixing of connate water of marine origin with meteoric water, thereby explaining the high salinity in the ground water from the Ecca Group.

A relatively large portion of the possible pollution sources are generated by the mining industry. These wastes may impact on the environment, due to high concentrations of Na^+, Cl^-, SO_4^{2-}, Ca^{2+} and, to a lesser extent, heavy metals, CN^- and other organic constituents used in the gold extraction process.

One of the major problems encountered during this investigation was to distinguish between ground water with a naturally poor quality and ground water that is polluted, due to mining and other activities. By evaluating all the ground water with high conductivities on hydrochemical diagrams, as well as calculating specific ionic ratios (Ca/Cl, Na/Cl and Ca/Na), two groups of ground water appeared, i.e. water with a natural poor quality and ground water polluted due to mining, industrial and municipal activities.

In the central, north and north-western parts of the area, mining (Loraine, Freegold, St. Helena, Unisel and Harmony Gold Mines) has been going on for more than 40 years, in some instances. Due to the fact that the disposal sites in these areas are mainly located on Ecca sediments which have low permeabilities, as well as the fact that the area is very flat, pollution has probably reached a quasi steady state situation (within four to six kilometres (downstream) from the pollution sources). In the southern parts of the study area, most of the disposal sites are situated on Beaufort sediments which are more permeable than the Ecca sediments. Mining (Beatrix, Oryx and H.J. Joël Gold Mines) has been ongoing for more or less 10 years. The disposal facilities in this area are consequently much younger than those of the mines in the central and norther parts of the region. Combining this with the fact that drainage in this part of the study area is reasonably well-developed towards the Sand River and its tributaries, one may suggest that the respective contaminants are still actively dispersing. The contamination levels in this area are not as high as in the northern parts, while the contaminants are generally located closer to the respective disposal sites (within 1 km), except in the case where shallow-lying dolerite structures control the spread of the pollution. The main reasons for the limited spread of contaminants in this region is the relative young age of the disposal facilities and a large dilution factor which limits the impact of the contaminants on the region, due to the fact that the sites are situated on Beaufort sediments.

If specific target areas are looked at in more detail, it is observed that Cl^- has spread to a greater extent than any of the other relevant ions, due to its inherent characteristic as a conservative tracer. The spread of Cl^--contamination can therefore be used to conservatively estimate the maximum spread of the pollution. Heavy metals seem only to have elevated concentrations in close proximity of pollution sources, especially slimes dams which tend to generate acid mine drainage. If the spread of the pollution at specific disposal sites is correlated with the local ground-water gradients, it is noted that the spread of the pollution closely follows the direction of the ground-water gradients.

Due to the presence of surface effluent water with a predominant NaCl-character, reverse ionic exchange seems to take place in the vicinity of mine disposal sites. The effect of reverse ionic exchange is that the ground water appears to become enriched with calcium.

The spread of pollution in most cases was helped on by sporadic discharges of effluent water into natural surface water systems, e.g. the Mahem Spruit which is polluted up to Gans Pan, near Wesselsbron.

4 MANAGEMENT OPTIONS

In the past, many of the disposal facilities were sited without proper investigations of factors such as:

(i) Geological environment.

(ii) Hydrology.

(iii) Geohydrology.

(iv) Monitoring.

It is suggested that quite a number of the current problem areas could have been confined to a much smaller scale, had the site selection process been more thorough. Future site selection should include all the above-mentioned aspects, as well as a risk assessment of environmental effects and risks associated with various waste management alternatives.

Currently, the evaporation areas pose the largest pollution threat, due to the large quantities of unpotable water which are stored in them. It was found that sufficient evaporation areas existed in the study area for present disposal needs. However, if additional evaporation surfaces are needed, natural salt-pans can be utilized more extensively due to their effluent characteristics.

All the slimes dams in the area are assumed to be constructed and managed in accordance with best engineering principles, thus minimizing their acid generation capabilities and consequently the pollution potential. However, unless these structures are regularly maintained and monitored in future, they will pose a long-term pollution threat.

CONCLUSIONS

The following is a list of the primary aims of the research project and the extent to which these were achieved during the study period:

(i) Determine the source of possible pollutants to the ground-water regime.

All the possible pollution sources throughout the study area were located, sampled and evaluated. Due to the fact that a large number of the pollution sources are duplicated throughout the area, specific target areas were selected and studied in detail. Very little research was done on possible agricultural pollution sources.

(ii) Quantify the contribution of the different sources.

Quantification of contaminant loads to which the environment is exposed, was done only to a very limited extent, in that the total salt load of the deep aquifer water, discharged by all the mines in the region, was estimated by means of a finite element model. However, to quantify the contribution of different organo-chemical species is virtually impossible, primarily due to the lack of relevant historical data for a representative water balance or mass transport model.

(iii) Study the migration rate of pollutants through the aquifers.

The spread of any contaminant is closely correlated with the migration rate of the relevant contaminant. The study of the migration rate of different pollutants in the Orange Free State Goldfields was limited to the target areas, as well as to the more important anions and cations (Ca^{2+}, Na^{+}, Cl^{-}, $SO_4{}^{2-}$) and some of the heavy metals. As in the case of the quantification of contaminants, the study of the migration rates could have been done in more detail by a multi-solute transport model with sorption, ion exchange and equilibrium chemistry. This was not done due to the lack of historical data.

(iv) Model local and regional movement of pollutants through the aquifer and predict future water qualities.

Bearing the above-mentioned in mind, no mass transport models were constructed, to predict future water qualities throughout the region, on either a local or regional scale.

(v) Determine chemical alterations to the pollutants while on surface and in the aquifer.

Infiltration of polluted effluent water into the ground-water regime will involve chemical alterations. Chemical alteration mechanisms were identified and discussed in some detail, especially in the case of the different target areas. No attention was devoted to the alteration of organic compounds, used by either the agricultural or mining sectors.

(vi) Enter information into the ground-water data base.

During the course of the research project, a ground- and surface water data base for the Orange Free State Goldfields data was created on HydroCom and was constantly updated as new information was generated and collected.

(vi) Suggest management strategies whereby the influence of disposal can be minimized.

Suggesting management options/strategies whereby the influence of waste disposal sites can be minimized was an important aim of the research project. This aspect is covered in detail by the report and should help mining companies, municipalities and industries in the location and development of future waste disposal sites, as well as in the maintenance of existing disposal facilities. The management options should also be incorporated in the waste management strategy of the Department of Water Affairs, especially relating to ground-water resources.

Although not all the initial aims of the research project were fully achieved during the course of the project, sufficient information was gathered and evaluated to suggest meaningful management options. Furthermore, suggested aims and objectives of the research project were met to such an extent that future monitoring and waste management can effectively be applied throughout the entire area, due mainly to a well-established data base, which has to be constantly maintained and updated. Future monitoring and management of all waste disposal sites in the study area should be co-ordinated by the Department of Water Affairs and Forestry.

A number of the more important conclusions are summarized and listed below:

- Contamination of surface and subsurface water resources by municipal, industrial and mining activities, throughout the area, has taken place in the past and is currently taking place. **This is, however, at a significantly reduced scale, due to the preventive actions taken by the responsible organizations.**

- Contamination of ground-water resources is generally contained within close proximity of the disposal site, depending on the age of the site as well as the local ground-water gradients in the vicinity of the site. Thus, although the pollution risk in the Orange Free State Goldfields is relatively large, due to the abundance of pollution sources, the vulnerability of ground-water resources in this region is relatively small, due to favourable geological conditions.

- Spillages of effluent water into natural river and vlei systems have spread the contaminants over relatively large distances.

- Of all the waste disposal structures, evaporation pans and dams currently pose a large pollution potential. Currently, the spread of pollution around the slimes dams appears to be limited. However, unless these structures are vegetated and managed according to sound engineering principles, they will pose a long-term pollution threat.

- Detailed geohydrological investigations, as well as a risk assessment of environmental effects and risks associated with the waste management of each future waste disposal site, will have to be done.

It is important to mention that the cooperation of all the concerned organizations throughout the duration of the research project was very good, especially in the case of the mining companies. As problem situations were identified to them, they, in almost all cases, initiated remedial actions curbing the deterioration of the particular situation.

RECOMMENDATIONS

Management

In future, managing water resources will increasingly involve the prevention of pollution of the limited water resources of Southern Africa. Preventive measures should include identification and control of polluted run-off from urban, industrial and mining areas. Such measures can include the following:

- Better planning for example, before establishment of a mine. This is required to prevent possible pollution from, for example evaporation areas, situated on a shallow dolerite sill, as well as where large quantities of water are disposed of on unconsolidated deposits.
- Better water budgeting at mines, for example in dry periods, the mines use all their excess water, but during wet periods, the additional run-off can cause problems as is presently experienced. This can be avoided if better planning is done by the mines. They can, for example, budget for more storage capacity (e.g. utilize natural salt-pans) or cut down on other water sources during periods of high rainfall, while old and new mines can share evaporation facilities, by means of an interconnecting pipeline.
- Implementation of present legislation concerning ground-water pollution has proven to be difficult. An additional complicating factor is the fact that water resources in South Africa are divided legally into public (generally surface water) and private water (ground water). Ground water and surface water are hydrologically connected, thus making it difficult to separate them legally, hence complicating the management of water resources in South Africa. Thus, legislation which considers ground- and surface water in a holistic manner should be promulgated. Such legislation has to include compulsory monitoring of waste disposal sites and a detailed geohydrological investigation to prevent the establishment of any disposal site on unsuitable geohydrological structures.

- The current legislation concerning mine, municipal and industrial effluent appears to be adequate. If the current application of legislation is performed in conjunction with the "Receiving Water Quality Management Objective" approach of the DWA and the current monitoring program is continuously revised and maintained, future potential pollution can be minimized.

Currently, the evaporation areas pose the largest pollution potential in the study area, due to the large quantities of unpotable water which are stored daily in them. In the event of closing any of the older mines in the region, this surplus water can be stored in such a mine once the impacts of such disposal have been carefully investigated. Precautions, however, have to be taken to seal off the old mine workings, such that the danger of flooding neighbouring active mines is minimized.

Research

A number of pollution sources, especially agricultural sources, such as:

(i) fertilizers and
(ii) pesticides (herbicides and insecticides).

have not been studied in any detail during the course of the project. It is suggested that such research is conducted in the near future, hence estimating the impact on the environment by the agricultural sector.

Insufficient historical data have prevented the research team from quantifying the contribution of the different pollutant sources. The investigations which have been done to date, can be regarded as a firm basis for the development of a solute transport model, which can be used to quantify the contribution as well as predict future water qualities in the region.

A matter of concern is the existence of palaeodrainage channels in the central-western parts of the region. This particular area forms part of the Sand River Irrigation Scheme. The regional ground-water gradient in this region is from east to west. Large evaporation areas are situated in close proximity to such a palaeodrainage system. For future waste management to be effective, these structures have to be identified and investigated in detail, in order to determine their influence on the spread of pollution. Such an investigation would necessarily involve a detailed geophysical and drilling program.

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CHAPTER 1

INTRODUCTION

1.1 SCOPE OF INVESTIGATION

As the mining and industrial activities on the Witwatersrand increased from the turn of the century, so did the contamination of the Vaal River. Water can be regarded as a scarce commodity in South Africa and one cannot rely solely on the discovery of new water resources to meet the ever-increasing demands. Thus, repetition of the above-mentioned situation must be prevented. As the Orange Free State Goldfields is an isolated area, its impact on the environment can therefore be investigated more easily and the results obtained can be used to solve problems in areas of divers industrial and mining activities.

The area under investigation stretches from Allanridge in the north to just north of Theunissen in the south, covering approximately 2 100 km^2. Many of the possible pollution sources have been present in the area since mining commenced in the early fifties, while other sources have only been ongoing for a few years. The Sand River crosses the study area from east to west, eventually draining into the Bloemhof Dam. This is a major seasonal stream in the region and its water quality presently deteriorates from 140 mg/l (TDS) to 700 mg/l, as it passes through the Orange Free State Goldfields.

Many elements toxic to humans, animals and vegetation occur in surface effluent water and leachates from waste disposal sites. It is important that these be quantified in terms of time and distance from the possible pollution source, as they tend to move into the ground water.

This research project into the water quality of the Orange Free State Goldfields constitutes a three-year contract between the Water Research Commission and the Institute for Ground-water Studies at the University of the Orange Free State. During the first year of the research project, a regional investigation was conducted, whereas in the remaining two years, the investigation was focussed on more detailed investigations.

The primary aims of the investigation are the following:

- Determine the source of possible pollutants to the ground-water regime.

- Quantify the contribution of the different sources.
- Study the migration rate of pollutants through the aquifers.
- Determine chemical alterations to the pollutants while on surface and in the aquifer.
- Model local and regional movement of pollutants through the aquifer and predict future water qualities.
- Enter information into the ground-water data base.
- Suggest management strategies whereby the influence of disposal can be minimized.

1.2 PREVIOUS WORK

Much work has been done on the effect of mining activities on both ground- and surface water, however, very little work has been done in the Orange Free State Goldfields.

Hodgson (1987) touched the subject of water quality in the Orange Free State Goldfields very briefly. A short summary of his conclusions is as follows:

The mine water which is disposed of on the surface seems to recharge the ground water and this recharged ground water reflects some of the characteristics of the mine water. The chemical constituents in the ground water which originate from mine water seem to be aluminium, calcium, chloride, sodium, sulphate and zinc. Chemical constituents originating from mine waters which are not reflected in ground water, are cyanide and lead.

Dilution of ground water seems to contribute to the fact that at a distance of 3 km from any source of pollution, the ground water can be used for many purposes. This indicated that the pollution of ground water is restricted to the immediate vicinity of the pollution sources. Water originating from Virginia and Welkom seems to pollute the Sand River, because the quality of the water deteriorates by a factor of five, as it flows through the Goldfields.

Verhoef (1982) investigated the pollution of ground water, due to the activities of the Buffelsfontein Mine in the Western Transvaal. He concluded that high levels of sulphate, ammonia and heavy metals (especially manganese) are found in the polluted ground water.

In 1965, James and Mrost stated that pyrite oxidation in slimes dams is confined to a surface layer of about 2 m in depth and that oxidation is limited to the depth to which oxygen can gain access. These results were verified by Mrost and Lloyd (1970). According to Van der Westhuizen *et al.* (1982), a ^{35}S tracer study indicated that the H_2SO_4 velocity is greater in the vertical than in the horizontal direction. They furthermore stated that it took more or less one year of leaching before the ^{35}S tracer reached a depth of below 1 m. However, more work should be done to gain further insight into water and solute transport of mine dumps. According to Marsden (1986), the resultant release of sulphate, due to the oxidation of pyrite, is negligible in old slimes deposits, mainly due to the fact that oxidation does not proceed below a depth of 2 to 3 m in slime and 10 m in sand deposits.

Several authors have documented the effect of acid mine drainage on the water in rivers and streams (Dyer, 1977, and Hoehn and Sizemore, 1977). They deduced that the low pH, high total dissolved solids and high concentrations of heavy metals cause considerable damage to ecosystems.

Thomas (1970) states that the mineral pollution of the streams in the Witwatersrand catchment area arising from run-off from slimes dams, is probably South Africa's major pollution problem.

Jones *et al.* (1988) investigated the present contribution of mine deposits to the pollution load in the Vaal Barrage. They concluded that the contribution of slimes dams to the salt load can be neglected and that only sand dumps are considered to contribute to the total salt load. They also stated that direct surface run-off is not a significant source of the salts that can be found in the stream water, but that the recharge of the streams by ground water is of more significance. They also concluded that the hydrogeological aspects proved to be more important than had first been expected.

Morin *et al.* (1981) conducted an investigation to determine the movement of contaminated ground water from inactive uranium tailings through a sand aquifer in Ontario, Canada. Their conclusions are that pyrite oxidation produces ground water with a high iron and sulphate content, as well as a low pH. They calculated ground-water velocities in the upper sand layer as a few hundred metres a year near the tailings dam and metres a year far away from the dam. However, the velocity of the pollution plume is only a few per cent of the ground-water velocity. This retardation of movement is caused by a rise in pH, which causes the contaminants to be removed from solution by adsorption or co-precipitation.

Development of techniques for the evaluation and management of surface and ground-water contamination for any specific area requires a thorough knowledge of the area comprising aspects such as:

- Hydrology.
- Geology.

- Geohydrology.
- Hydrochemistry.
- Existing management strategies.

In Chapter 2 of this report, the hydrology of the study area, including the physiography, precipitation, evapotranspiration and drainage and run-off are discussed in some detail.

The migration of dissolved solids in the subsurface is entirely controlled by the hydraulic characteristics of the substratum, depending on the different geological formations in the study area. Chapter 3 discusses the geology of the area, with special reference to the pan development in the western and north-western parts of the study area.

During any research project, large quantities of data are collected, which are dictated by the study objectives. The types of data collected, as well as the various sampling procedures, including the drilling phases, are discussed in Chapter 4.

Chapter 5 discusses geohydrological aspects such as:

- ground-water occurrence,
- ground-water abstraction and
- ground-water movement

of the different aquifers in the study area in detail.

The evaluation of hydrochemical data forms an integral part of such a research project. In Chapter 6, all the hydrochemical data of surface and subsurface water resources, which have been collected during the time span of the research project, are evaluated and discussed in detail.

A primary aim of the research is to develop and suggest management options for the Orange Free State Goldfields. A detailed discussion covering a wide range of management options, with special reference to the contamination of surface and subsurface water resources, is discussed in Chapter 7.

Possible pollution sources identified in the Orange Free State Goldfields are discussed in Appendix I, whereas more detail on the chemical processes involved in the hydrochemistry of the study area, is listed in Appendices II and III.

CHAPTER 2

HYDROLOGY

2.1 INTRODUCTION

In the current evaluation of the water qualities in the Orange Free State Goldfields, surface and subsurface water resources are investigated. Both sources form an important part of the hydrological cycle. In this chapter, only the major hydrological components contributing to the surface water resources, will be considered. The following relation depicts the respective components of the hydrological cycle:

$$\Delta S = P - R - E - I$$

where

ΔS = change in storage within the system
P = precipitation
R = run-off
E = evapotranspiration
I = infiltration

Components, such as precipitation, run-off, evapotranspiration, as well as the physiography of the area, will be discussed briefly.

2.2 PHYSIOGRAPHY

The area forms part of the Highveld region and has an average elevation of about 1 360 m above mean sea level. Most of the area has a gentle undulating surface and rarely any prominent landmarks are visible. The only prominent landmark in the surrounding area is Koppie Alleen at Riebeeckstad, which has a height of 1 443 m. The highest trigonometrical station is found on the farm, Zwartpan 572, in the east of the study area, with an elevation of 1 471 m. The Sand River forms meanders and flows in an alluvial flat almost throughout its entire length. The valley of the Sand River has an elevation of 1 300 m in the east and 1 257 m in the west (Coetzee, 1960).

According to the Köppen classification (Viterito, 1987) (Figure 2.1), the area under investigation is classified as the Northern Steppe, which is defined as a climate with chronic water shortage, i.e. the annual potential to evaporate water exceeds the precipitation, as depicted in Figure 2.2. Most of the unploughed land is covered by grass and *xeraphytic* (dry loving) vegetation. This coincides well with the classification by Acocks (1975), who describes the entire region as covered by sour grassveld (*Cymbopogon-Themeda* veld). There are 15 species of plants that generally occur and the total number of species are 150. The Karoo invasion is well under way, as patches of Karoo type vegetation are developing in certain areas. Along the flood plain of the Sand River, thorn trees are quite abundant. The soils are very suitable for the cultivation of maize, wheat, ground-nuts and sunflowers.

The Orange Free State Goldfields area is situated in a semi-arid region with an annual rainfall of between 400 and 600 mm. Local thunderstorms and showers are responsible for most of the precipitation during the summer, from October to March and peaking in January (Figure 2.2). Hail is sometimes associated with the thunderstorms and mainly occurs in the early summer from October to January with its highest frequency in December.

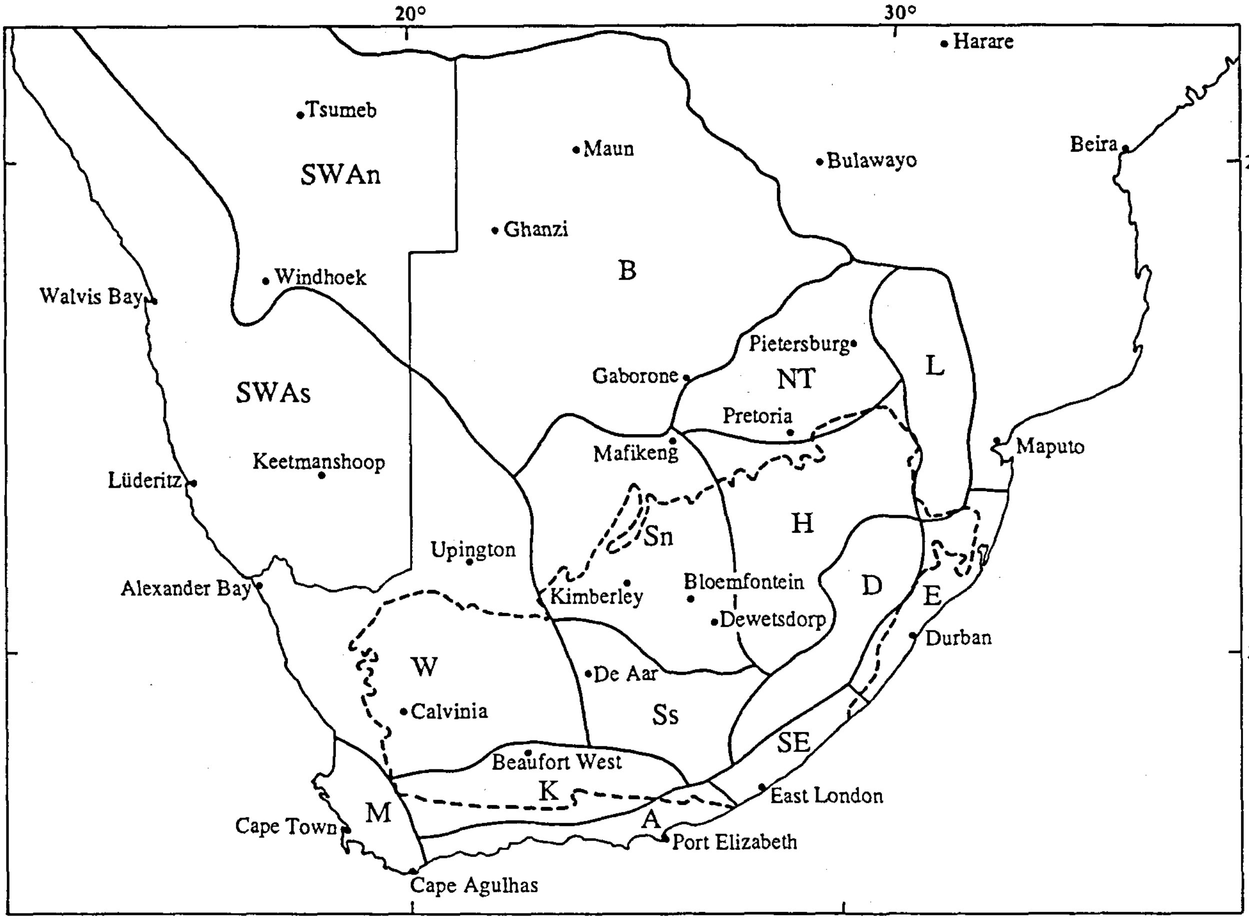
Temperatures show large daily and seasonal variations. Temperature statistics for the Welkom area, as tabulated in the Climate of South Africa (WB 40), are listed in Table 2.1.

TABLE 2.1. TEMPERATURE STATISTICS OF THE WELKOM AREA

	January (°C)	**June (°C)**
Maximum	34,0	21,9
Mean daily maximum	29,4	17,2
Mean daily temperature	23,0	9,7
Mean daily minimum	16,6	2,3
Minimum	12,1	-2,9

Mean temperatures reach a maximum in December/January and a minimum in June/July (Figure 2.2). The period during which frost can be expected lasts about 100 days (June to August).

The winds in the region are usually north-westerly and reach their maximum speed in the afternoon.



REGION, AREA and CLIMATE

A	Southern Cape Coastal Belt : Rain during all seasons
B	Botswana : Warm, Steppe, summer rain
D	Drakensberg region : Temperate to warm with summer rain
E	East Coast : Warm to hot and humid subtropical climate
H	Highveld : Temperate to warm with summer rain
K	Little and Great Karoo : Mainly semi-arid climate
L	Lowveld : Warm, Steppe
M	South-western Cape : Mediterranean climate
NT	Northern Transvaal : Warm, Steppe, summer rain
SE	South-eastern coastal region : Temperate to warm, mainly summer rain
Sn	Northern Steppe : Semi-arid climate
Ss	Southern Steppe : Semi-arid climate
SWAn	Northern South West Africa : Warm, Steppe, summer rain
SWAs	Southern South West Africa : Desert and poor Steppe
W	Namaqualand and North-western Cape : Desert climate

Figure 2.1. Climatic regions of South Africa (after Schulze, 1986).

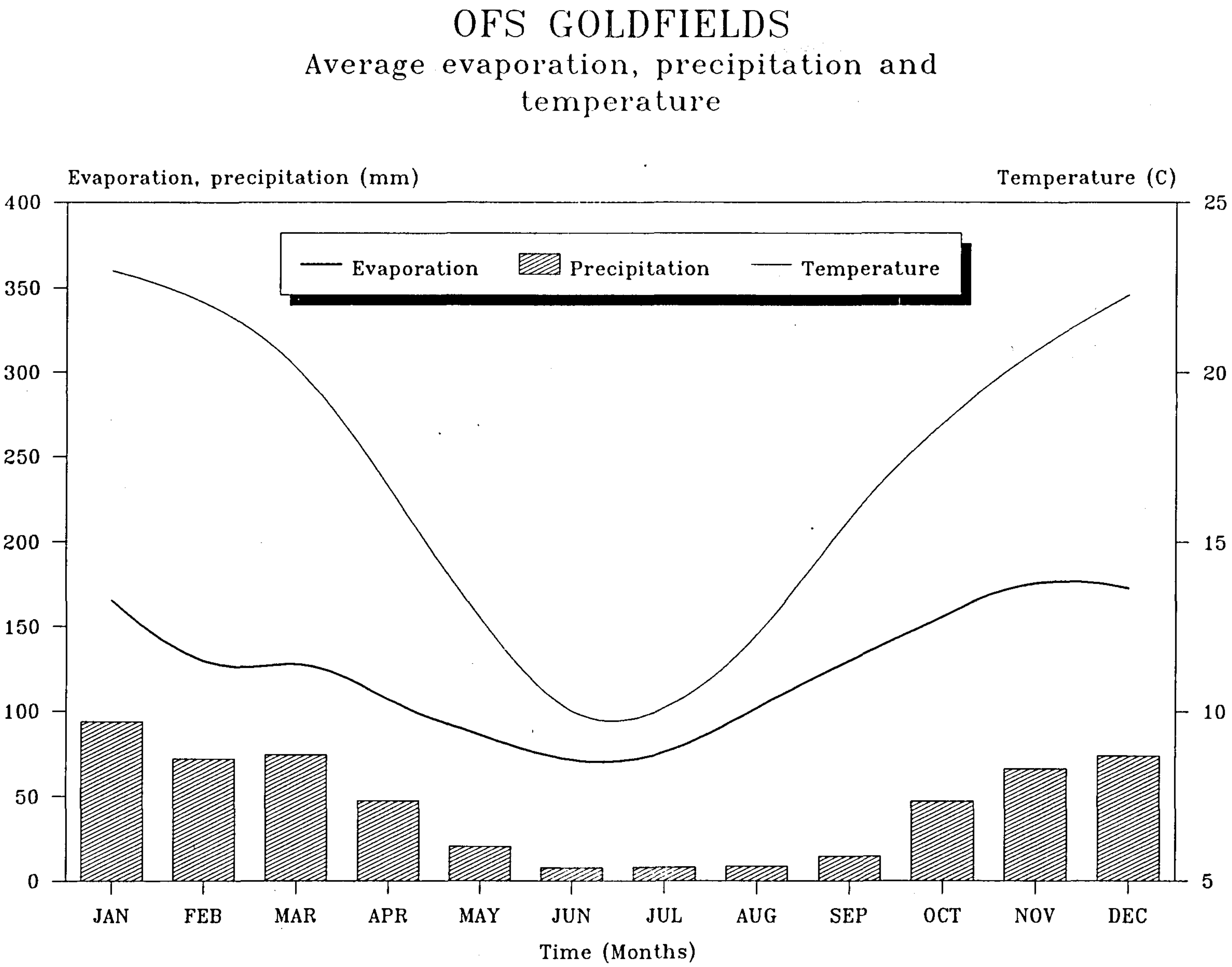


Figure 2.2. Average precipitation, evaporation and temperatures of the Orange Free State Goldfields.

During thunderstorms, strong and gusty south-westerly winds are common. The duration of these winds, however, is very short. During a prolonged drought, dust-storms may frequently occur.

2.3 PRECIPITATION

Rainfall records, varying from 70 years to only a few years in length, are available at 21 stations scattered over the region. The mean annual precipitation for the region, calculated from these stations, is 518 mm.

To determine whether the annual precipitation of the respective rainfall stations correlates with one another, three rainfall stations situated at the top, middle and bottom-left of the area, were selected. A continuous record of data from 1925 - 1986 exists for all three stations. The three stations are situated at Odendaalrus, Adamsonvley (Welkom) and Grootkuil (Theunissen) and their mean annual precipitation is 502, 518 and 491 mm respectively. Missing data values at the respective stations were calculated by using the following formula:

$$P_X = N_X/3\ (P_A/N_A + P_B/N_B + P_C/N_C)$$

where

$P_{A,B,C}$ = precipitation at the different stations
$N_{A,B,C}$ = mean annual precipitation at the different stations
P_X = precipitation to be calculated

Although these values are calculated, they are more accurate than estimated values. By comparing real values with calculated values, it is observed from Table 2.2 that the calculated values correspond to the real values.

TABLE 2.2. COMPARISON BETWEEN REAL AND CALCULATED RAINFALL DATA

Real value	Calculated value	% Deviation from the real value
95	103	8,4
86	96	11,6
115	107	7,0
9	6	33
162	147	9,3

When comparing the cumulative rainfall of the three stations, a good indication of the correlation between the stations can be obtained (see Figure 2.3).

From the figure, it can be seen that the correlation between the three stations is good. The reason for the Adamsonvley curve having a larger cumulative rainfall lies in the fact that this station has a higher annual rainfall.

The above data were also analysed statistically, by means of the cross-correlation technique. The cross-correlation coefficient between the different stations is as follows:

Adamsonvley and Odendaalsrus - 0,69
Adamsonvley and Theunissen - 0,78
Odendaalsrus and Theunissen - 0,65

From the above-listed coefficients, it is noticed that the data sequences of the three rainfall stations correlate fairly well with one another. Combining the above results with the mean annual precipitation of the available rainfall stations, it can be concluded that the rainfall distribution over the area is fairly uniform.

The identification of rainfall cycles and a probability analysis for flood occurrence in the Orange Free State Goldfields can be important, as excess water of poor quality is one of the major issues in the area. Continuous, above average, rainfall could lead to large-scale pollution, as storage facilities of mines can exceed their capacity during such events. However, if rainfall cycles can be identified and floods can be predicted, mines could use such data to help them design optimal storage facilities for mine effluent, as well as any surplus run-off water.

Rainfall cycles were identified by Tyson and Dyer over periods of 70 to 100 years, varying from 18 - 23 years (Tyson and Dyer, 1975). By using a 5-term binomial filter (also known as the Dyer filter):

$$Y_i = 0{,}38\ (Y_i) + 0{,}25\ (Y_{i-1} + Y_{i+1}) + 0{,}06\ (Y_{i-2} + Y_{I+2})$$

where Y_i = rainfall at year i,

to smooth the data, certain rainfall cycles can be identified. A new weighed value is attained for every year, consisting of a certain fraction of the value for that specific year, as well as fractions of the values for two years before and two years after that specific year.

Since the Adamsonvley station is situated in the centre of the area, the Dyer filter was performed on data from this station. Figure 2.4 shows a plot of the raw and filtered data.

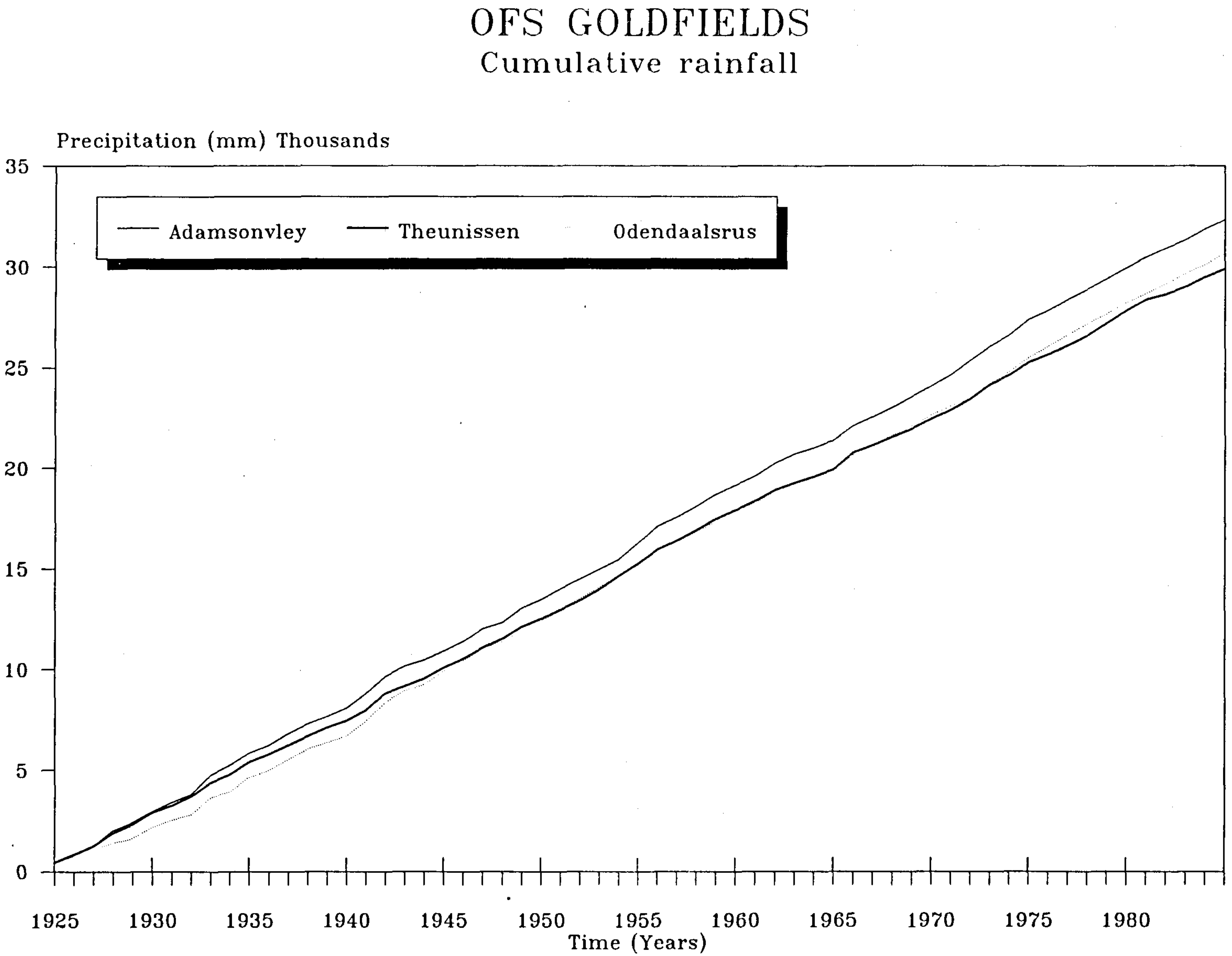


Figure 2.3. Cumulative rainfall at three stations in the Orange Free State Goldfields.

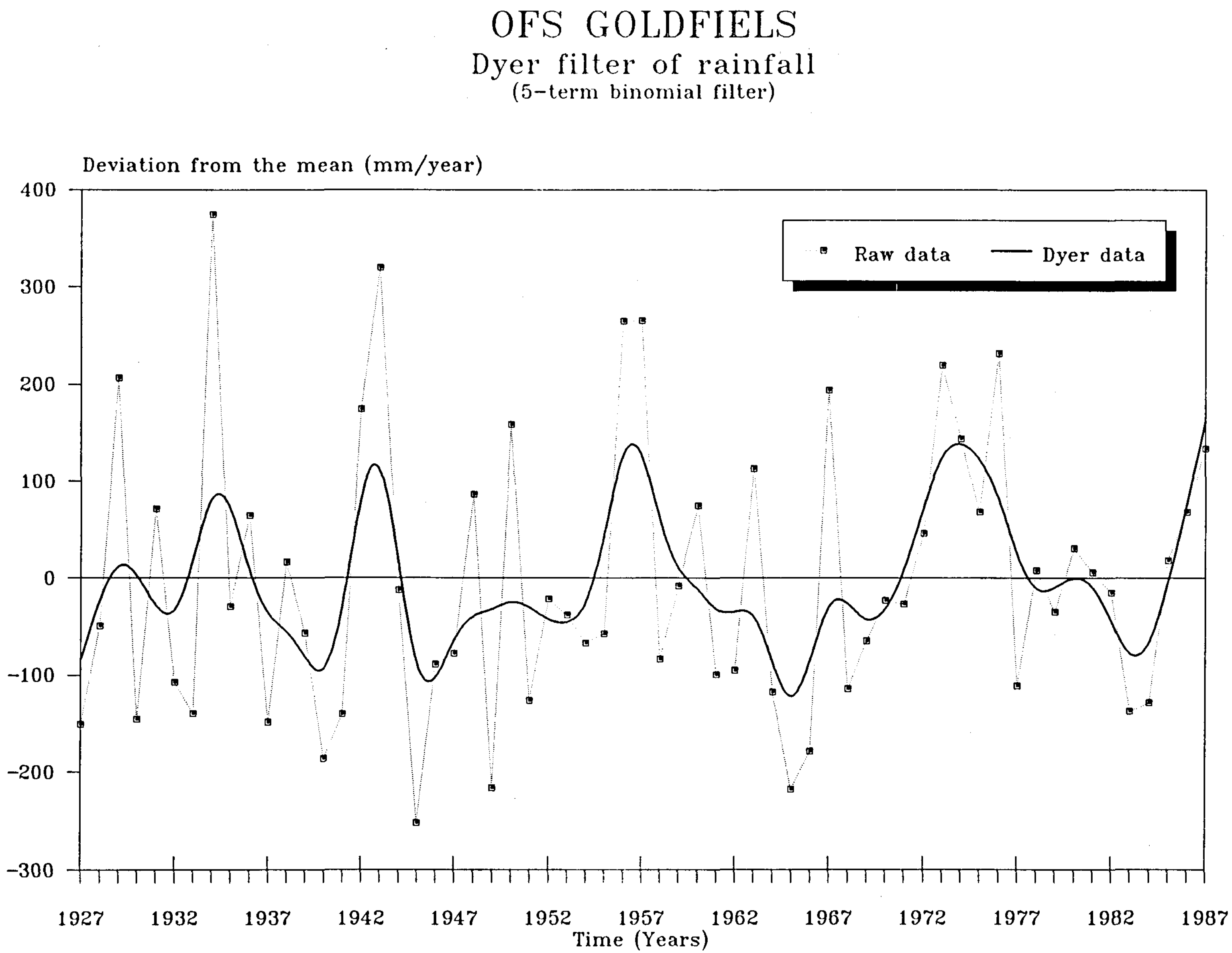


Figure 2.4. Rainfall cycles identified by performing the Dyer filter on Adamsonvley rainfall data.

From 1945, a definite pattern can be seen, namely two ascending and two descending cycles (quasi 18-year cycles; 1946 - 1965 and 1965 - 1983).

The length of these cycles varies between 8 and 11 years. Interesting to note is that within each cycle, a smaller cycle can also be observed. This is due to the fact that during a dry spell, above average rainfall can occur and vice versa.

If 1985 can be taken as the inflection point of a descending to an ascending cycle, the next 8 - 11 years will be an ascending cycle, and above average rainfall can be expected. However, it must be stressed that although the general tendency will be that of an ascending one, any rainfall predictions for a specific year would be impossible. Since long-term climate predictions are based on statistics, great care should be taken with the interpretation of such data.

A probability analysis was performed on the rainfall data from the Adamsonvley station. Figure 2.5 shows the cumulative frequency distribution of the data, using

$$F_i = (m/n+1) \times 100$$

where F_i is the cumulative percentage frequency of the variable, or percentage of years with a rainfall equal or less than the particular annual rainfall, having ranked m and n, are the annual precipitation values according to their size. Giving the smallest rainfall, the rank m=1, and the largest rainfall, a rank m=64, a 64-year rainfall period is observed. From Figure 2.5, it can be seen that the probability of a rainfall event of higher than 900 mm/a, occurring in any year, is 5%.

The annual precipitation for the Orange Free State Goldfields in 1988 was 897 mm. A probability analysis was performed on the maximum 30-day rainfall amount per year. From Figure 2.6, it can be seen that the 331 mm of the February 1988 flood, has a return period of 100 years. Figure 2.7 shows that an annual rainfall of 900 mm has a return period of 50 years, while an annual rainfall event of more than 725 mm, as well as less than 320 mm, can occur once every 10 years.

Although high values of annual precipitation do not usually give rise to floods, they should be taken into account when designing effluent disposal facilities, as they can cause relatively large volumes of excessive run-off. It is, however, the high rainfall of shorter durations that has to be watched closely with respect to floods. Furthermore, government regulations stipulate water storage capacity requirements on the basis of a balance, which incorporate average monthly rainfall and rainfall of recurrence interval 1 : 100 years of one-day duration.

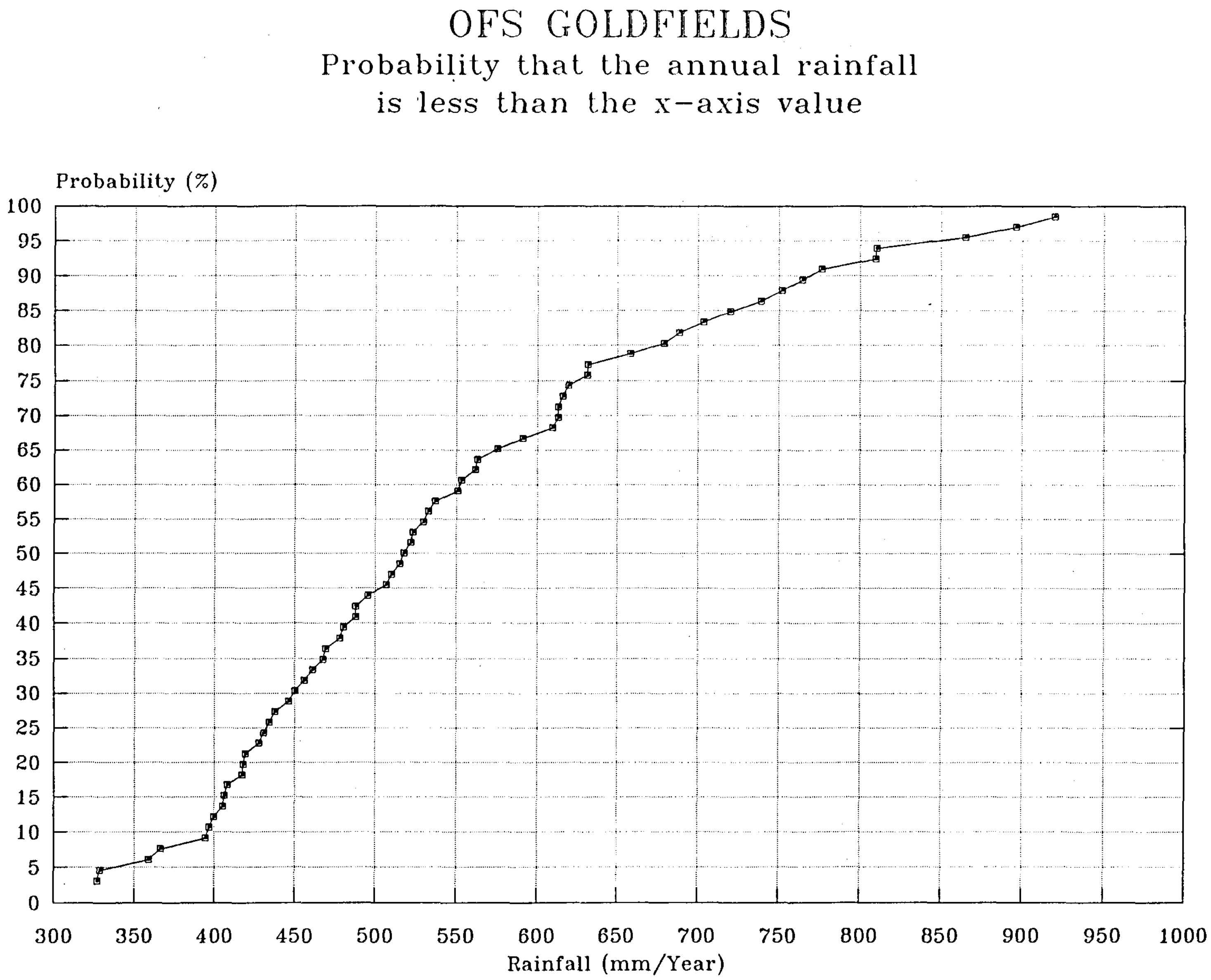


Figure 2.5. Cumulative distribution of annual precipitation in the Orange Free State Goldfields.

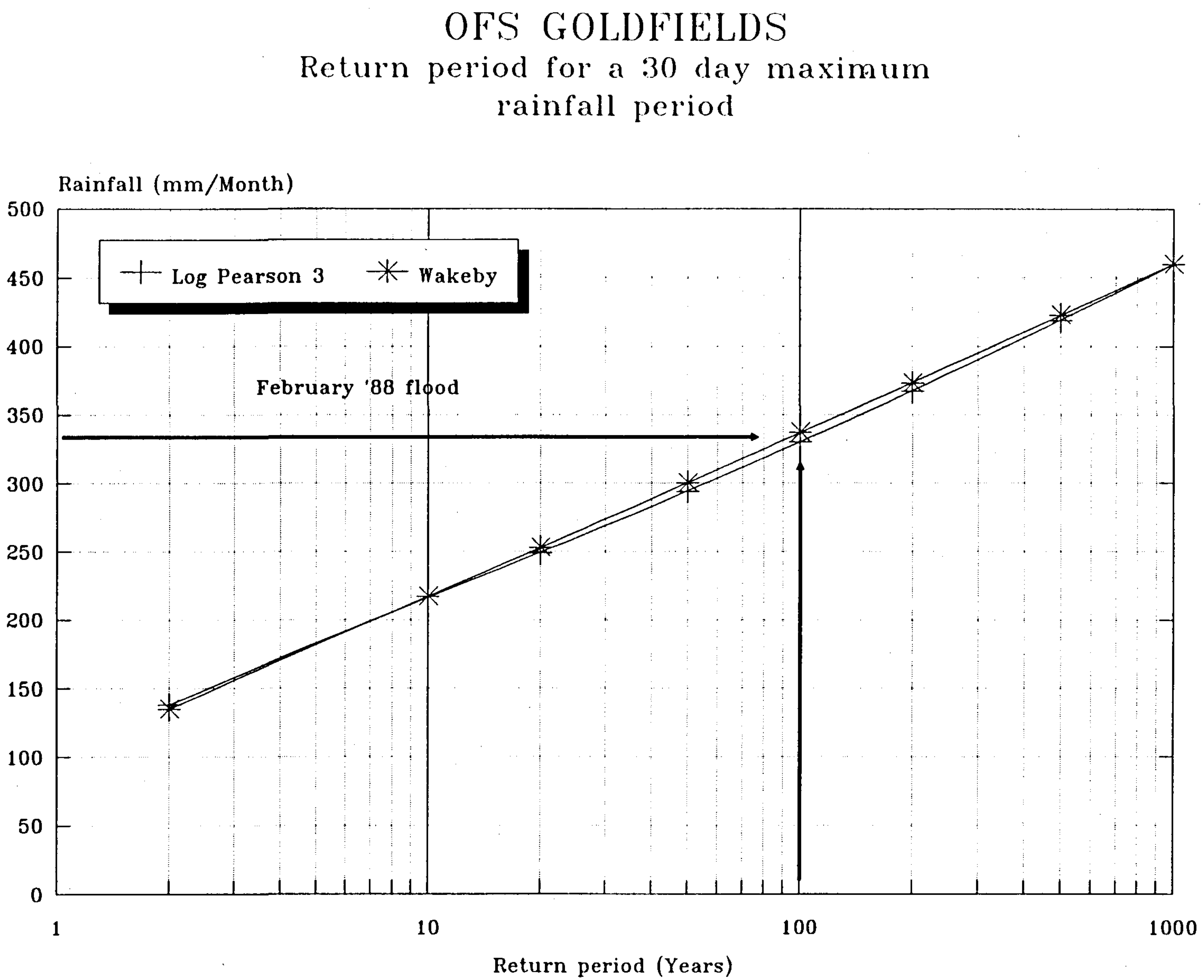


Figure 2.6. Probability analysis of a maximum 30-day rainfall period.

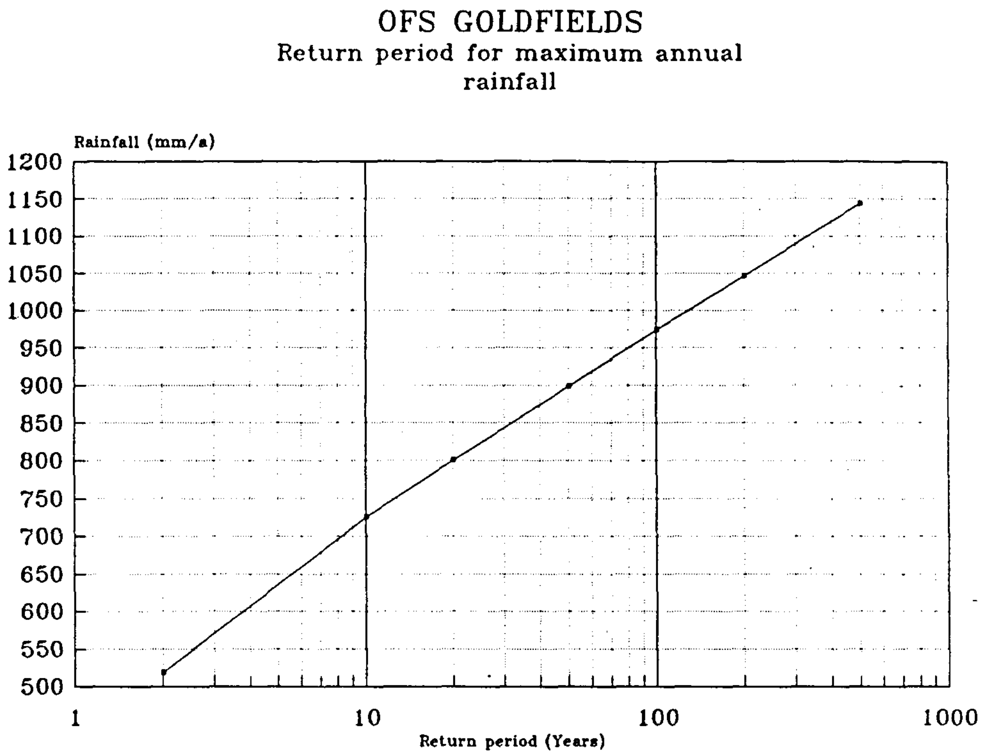


Figure 2.7(a). Probability analysis of a maximum annual rainfall.

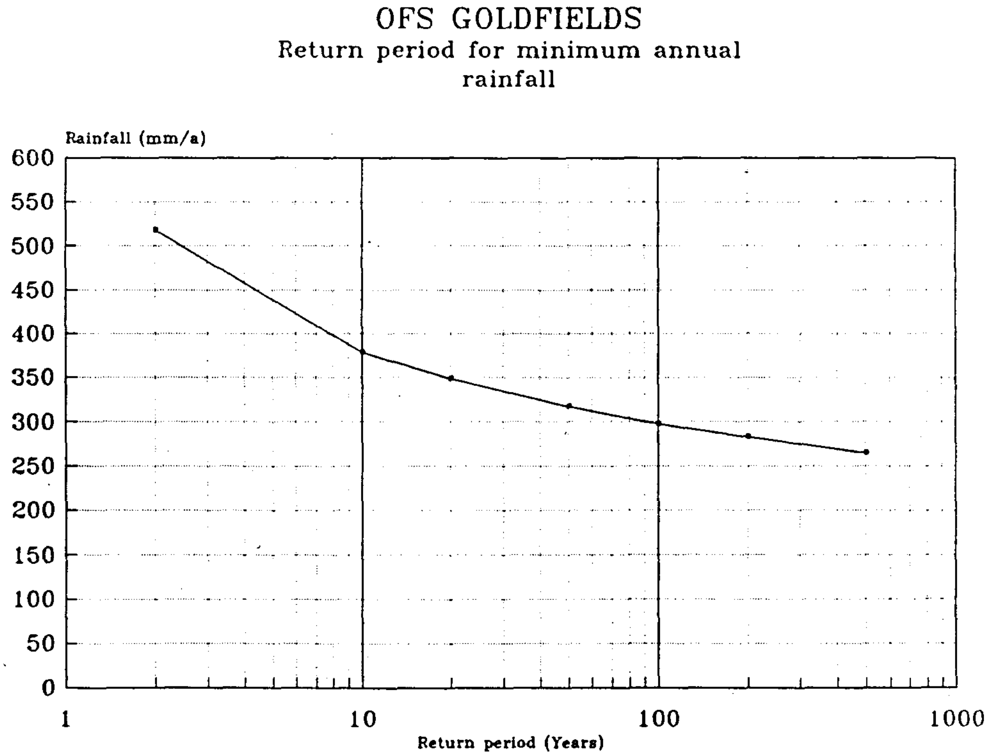


Figure 2.7(b). Probability analysis of a minimum annual rainfall.

The mean annual rainfall distribution from 1925 - 1989 and the monthly rainfall for the first two years during the period of investigation, for the Adamsonvley station, are shown in Figure 2.8.

2.4 EVAPOTRANSPIRATION

The combined effects of evaporation and transpiration in returning water to the atmosphere are frequently grouped together as evapotranspiration.

2.4.1 TRANSPIRATION

Transpiration is the process that plants use to release water to the atmosphere. Only a small fraction of the water that plants absorb is retained in the plant. Transpiration depends on the following:

(i) Soil type.
(ii) Type of vegetation.
(iii) Availability of moisture.
(iv) Density of the vegetation.
(v) Density of the roots.

Transpiration can be measured directly with a phytometer or can be calculated with the Blaney-Criddle formula:

$$\mu = 2{,}54\ Ktp/100 \text{ in cm}$$

where

μ = moisture consumption
K = coefficient of a certain crop
t = mean annual temperature °F
p = monthly daylight hours as % of the year

2.4.2 EVAPORATION

Evaporation is the process through which water is transferred from the land and the water masses back to the atmosphere. Evaporation is a function of the following:

(i) Solar radiation.
(ii) Temperature.

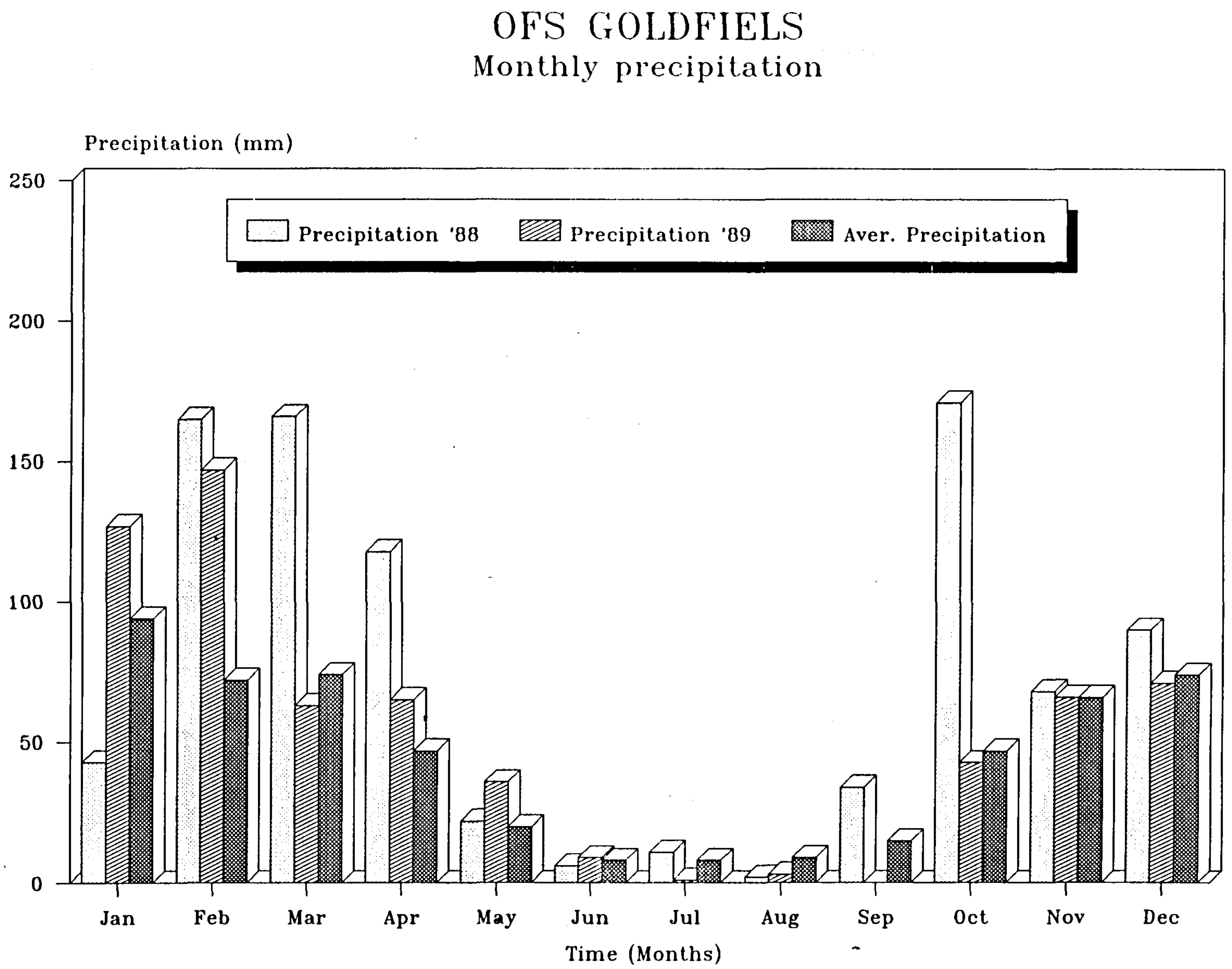


Figure 2.8. Mean annual rainfall distribution of the Adamsonvley weather station.

(iii) Velocity of the wind.
(iv) Atmospheric pressure.
(v) Difference in vapour pressure between the water surface and the layer of air.
(vi) Salinity of water reduces the vapour pressure of waterbody.

Evaporation can be measured directly with a Symon's tank or a Class A pan or can be calculated by various formulae. The rate of evaporation from small areas is greater than that from large areas. In order to adjust this, a coefficient that varies seasonally as well as geographically through the year must be applied to the observed values. Table 2.3 lists pan coefficients as determined by the Department of Water Affairs.

TABLE 2.3. SYMON'S PAN COEFFICIENTS FOR SOUTH AFRICA

Month	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Weighted averages of all the data	0,90	0,85	0,85	0,86	0,88	0,88	0,86	0,82	0,81	0,82	0,92	0,88
Summer rainfall	0,68	0,60	0,80	0,80	0,86	0,86	0,81	0,81	0,75	0,74	0,83	0,72
Winter rainfall	0,94	0,94	0,90	0,91	0,89	0,90	0,89	0,86	0,89	0,91	0,92	0,92

Evaporation data from three meteorological stations were selected:

(i) Welkom Airport, with records from January 1985 - December 1989, and is situated in the centre of the study area.

(ii) Erfenis Dam, with records from March 1957 - April 1987, and is situated just to the south of the study area.

(iii) Balkfontein, with records from May 1969 - April 1987, and is situated just to the north of the study area, in the vicinity of Bothaville.

According to Dunne *et al.*, 1978, monthly totals of evaporation are usually normally distributed, while the average monthly evaporation at a place is expressed in terms of the arithmetic mean. Monthly statistics of the above-mentioned unconverted evaporation data are listed in Table 2.4.

TABLE 2.4. MONTHLY EVAPORATION DATA OF THE WELKOM AIRPORT, ERFENIS DAM AND BALKFONTEIN WEATHER STATIONS

	Welkom Airport		**Erfenis Dam**		**Balkfontein**	
	Mean (mm)	Standard deviation (mm)	Mean (mm)	Standard deviation (mm)	Mean (mm)	Standard deviation (mm)
Jan	253,82	38,86	255,80	46,96	220,61	41,74
Feb	190,25	31,44	203,93	35,52	175,00	36,26
March	181,00	33,61	182,26	31,48	163,17	29,67
April	133,75	20,22	127,97	26,67	126,00	21,19
May	102,64	15,56	97,10	13,93	100,94	14,58
June	83,36	5,20	73,23	9,19	79,06	9,28
July	93,00	10,57	84,10	9,60	86,94	7,37
August	139,33	16,64	120,73	15,34	120,83	14,11
Sept	175,50	26,20	175,73	23,64	161,50	26,72
Oct	218,58	40,10	218,60	28,54	192,67	24,59
Nov	218,75	26,50	240,50	36,78	206,94	27,93
Dec	224,50	27,95	268,90	36,73	227,33	39,52

The above-listed evaporation data were converted by the pan coefficients corresponding to the summer rainfall areas. A mean annual evaporation of 1529, 1544 and 1409 for the respective stations was calculated.

The correlation between the three stations can be listed as:

Welkom Airport and Balkfontein - 0,982

Welkom Airport and Erfenis Dam - 0,977

Balkfontein and Erfenis Dam - 0,996

Although quite a difference in mean annual evaporation is observed between the Balkfontein data and the Welkom and Erfenis data, the evaporation pattern over the area seems to be fairly constant.

From the correlation coefficients and the cumulative evaporation (see Figure 2.9), it can be seen that the correlation between the stations is fairly good, implying that evaporation is fairly uniform over the area, as depicted in Figure 2.10. Furthermore from Figure 2.10, it is apparent that evaporation reaches a minimum during the winter, as would be expected. It is also clear that the evaporation exceeds the precipitation every month of the year. However, since these are monthly average values, daily precipitation may exceed daily evaporation. The potential water loss reaches a maximum during September, October and November, whereas the potential evaporation, as seen from the evaporation/precipitation ratio, reaches a maximum in August. This is due to the fact that although the evaporation reaches its maximum during the summer months, more water to evaporate becomes available due to rainfall, which also reaches a maximum during the summer season. Thus the evaporation potential is reduced.

2.5 DRAINAGE AND RUN-OFF

(a) Drainage

The area can be divided into two major drainage regions, i.e. C 340 and C 325. Each of these regions can be further subdivided into secondary drainage regions, shown in Figure 2.11.

The watershed between the two major drainage regions in the area is very flat, wide and difficult to pin-point exactly. The areas south, east and north-east of the Sand River are fairly well-drained, whereas the areas north and north-west of the Sand River are relatively poorly drained, due to the absence of small streams and vleis. In this area, the drainage occurs mostly along the streams and vleis into pans. The few defined watercourses in the area, north of the Sand River, drain towards the north-west, i.e. away from the river.

A further feature of this area is the abundant development of pans. In section 3.7.2, the development of pans will be discussed in more detail.

(b) Run-off

The Allemanskraal Dam is situated to the east of the study area in the Sand River. The dam reduces, as well as to a certain extent, controls the run-off of the Sand River through the Goldfields. The Vet River joins the Sand River west of the area and increases the run-off, which flows into the Bloemhof Dam. The Erfenis Dam is found south-west of the area in the Vet River.

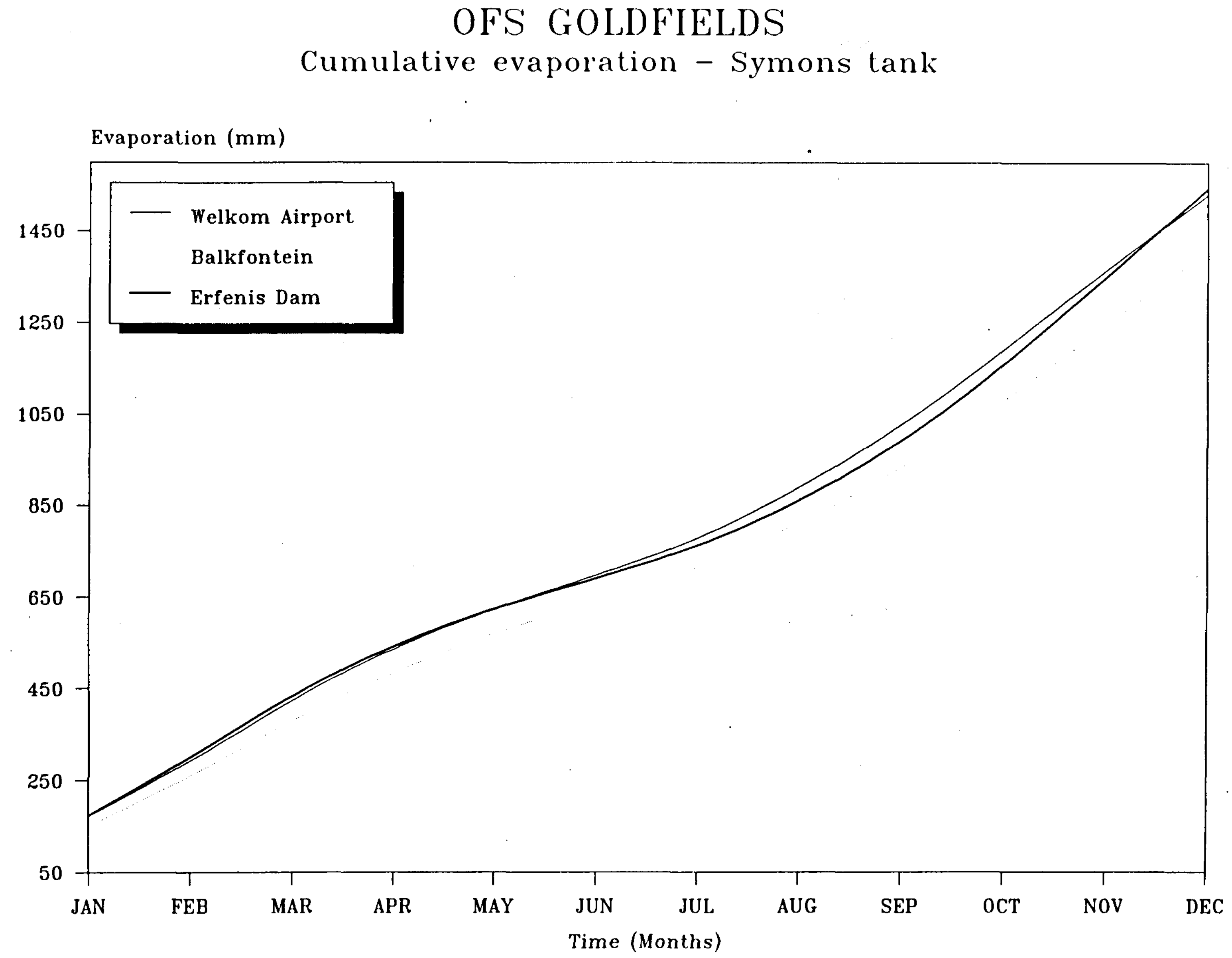


Figure 2.9. Cumulative evaporation for the Orange Free State Goldfields.

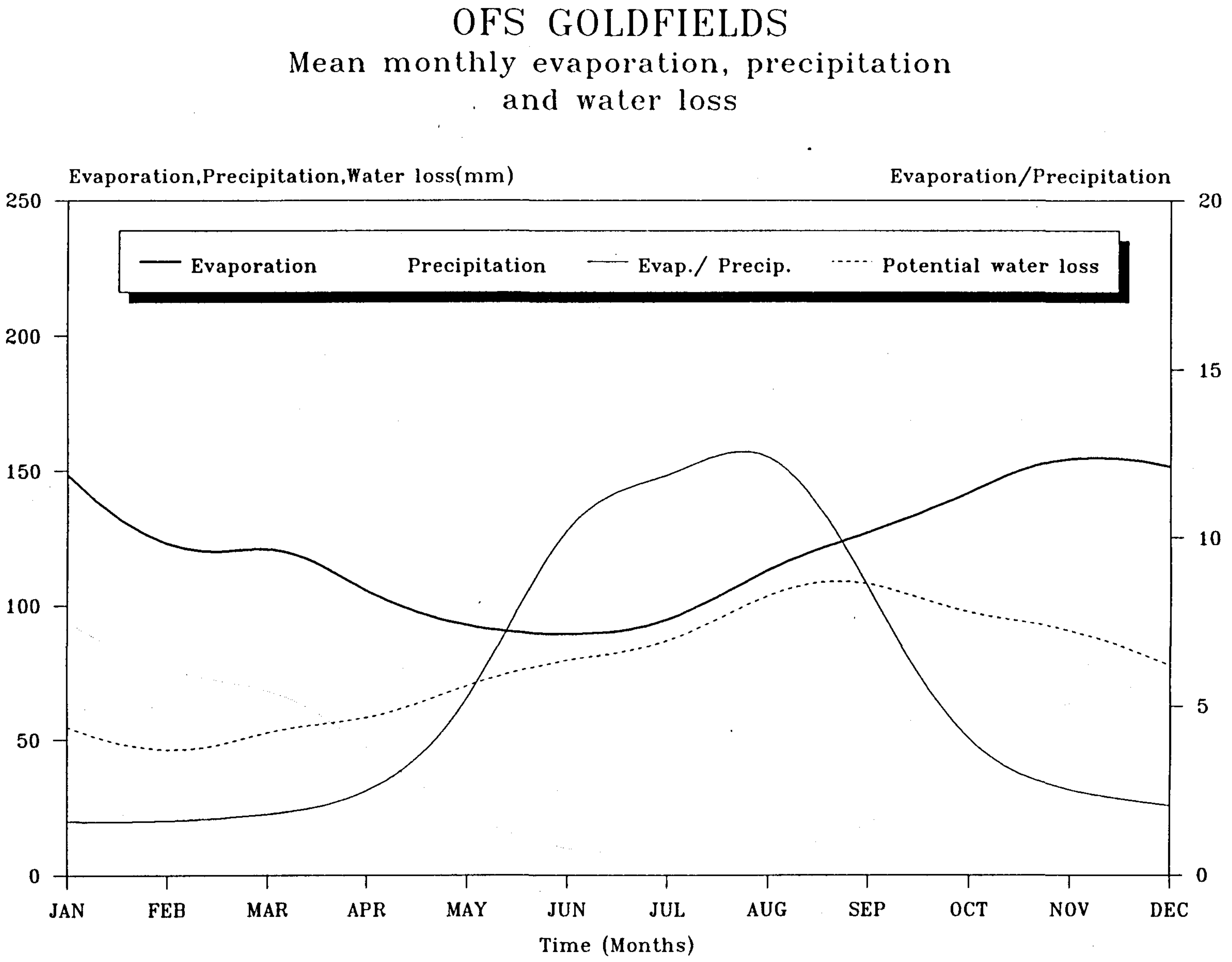


Figure 2.10. Potential evaporation of the Orange Free State Goldfields.

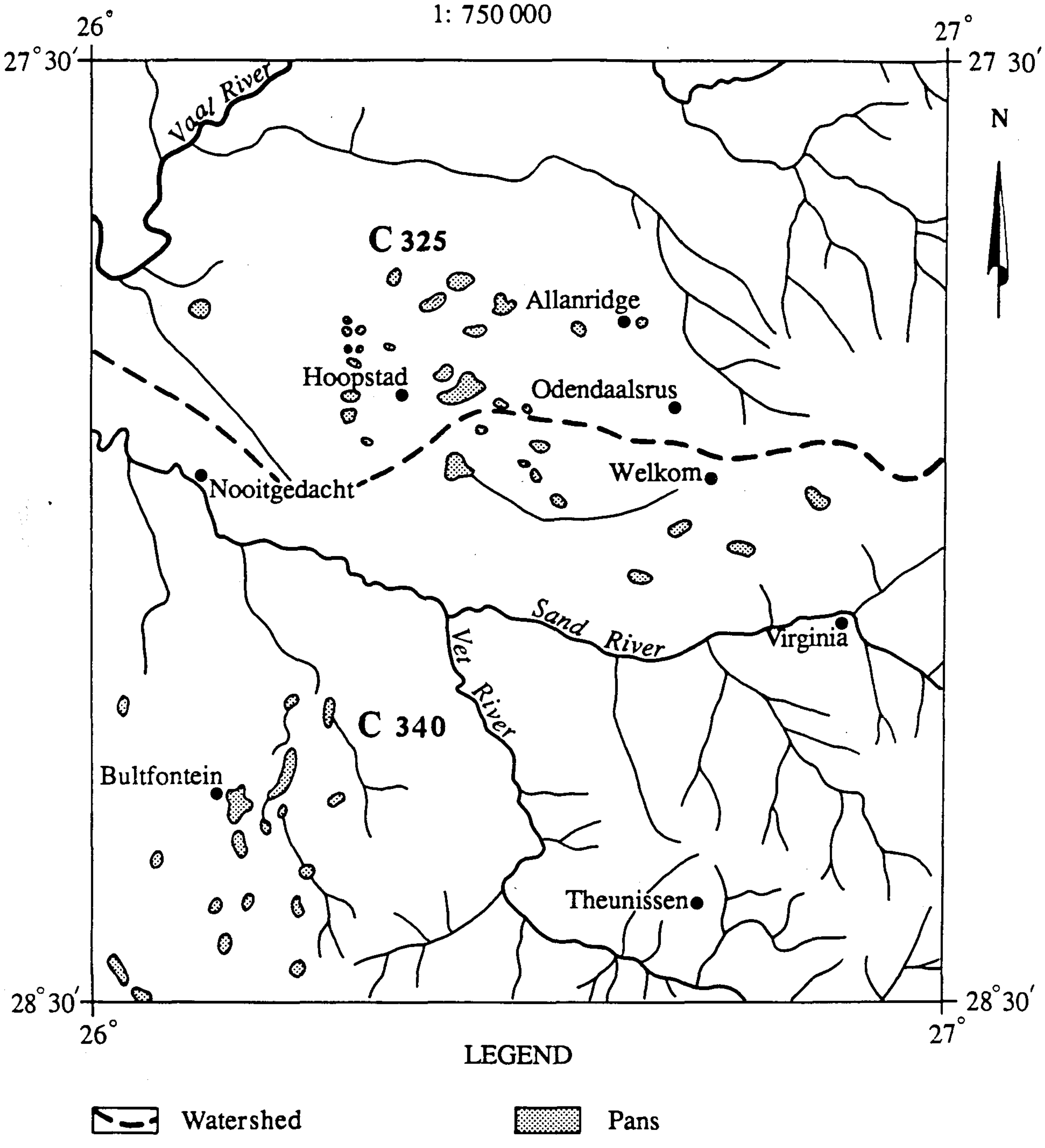


Figure 2.11. Main drainage regions in the Orange Free State Goldfields.

The Sand and the Vet Rivers are seasonal rivers and in summer they may convey large quantities of water. In winter, these rivers are almost dry, except for frequent water-holes. The flow of the Sand River through the Goldfields mainly depends on two factors, namely (a) rain falling in the catchment area and (b) water released from the Allemanskraal Dam. Flow gauging stations are found at the Erfenis- and Allemanskraal Dam. Figure 2.12 depicts the flow at the Allemanskraal Dam for the period January 1988 to July 1989. Generally, high peak flows occur during the summer months, while low flows occur during the winter months, correlating well with the mean monthly rainfall of the area. However, as the Allemanskraal Dam is quite a large surface water reservoir, water is released into the Sand River, influencing the flow patterns of the river.

The hydrochemistry of the water released from the Erfenis- and Allemanskraal Dam, as well as that of the Sand River, will be discussed in Chapter 6.

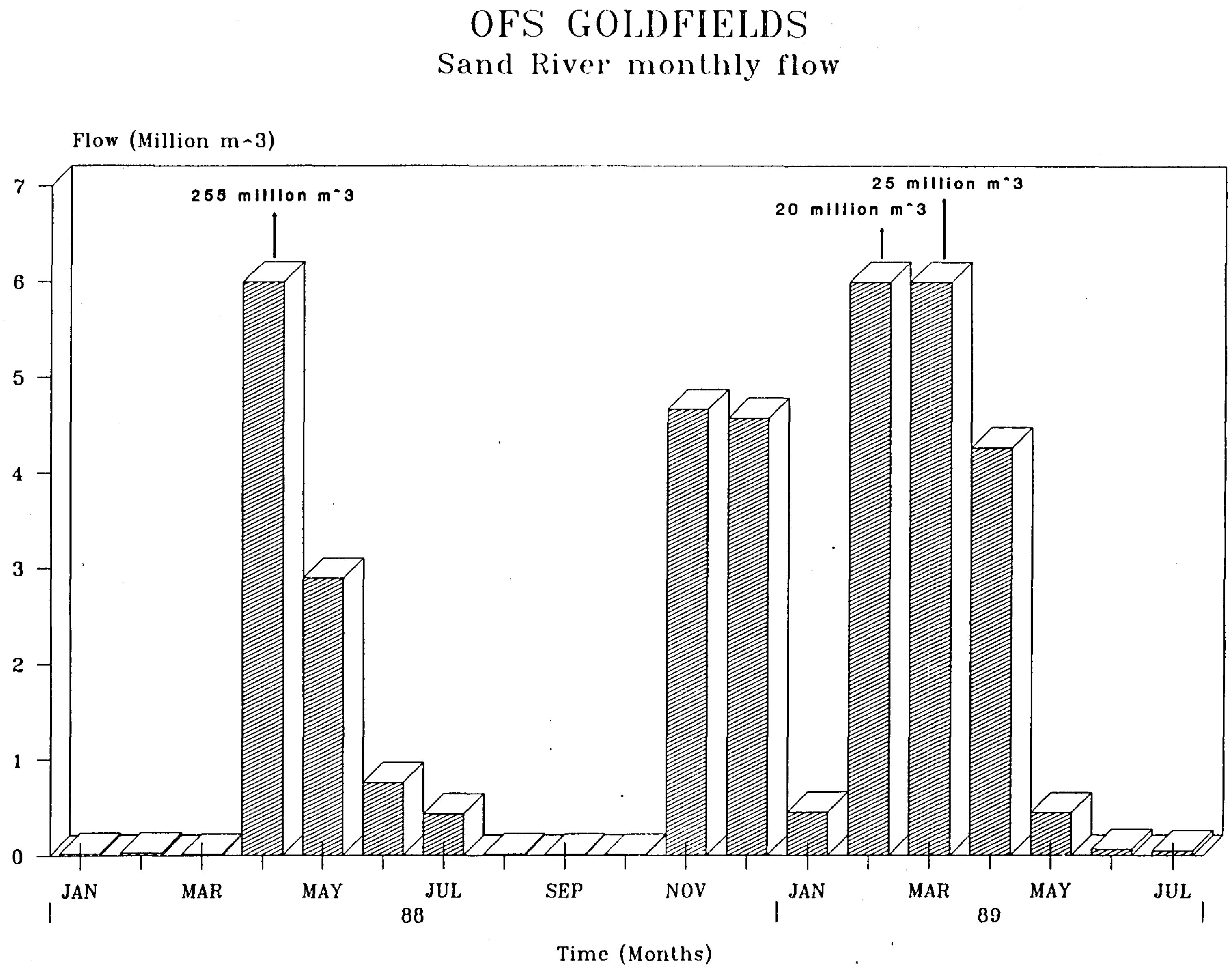


Figure 2.12. Mean monthly flow volumes at the Allemanskraal Dam.

CHAPTER 3

GEOLOGY

3.1 INTRODUCTION

As a detailed account of geological formations present in the Orange Free State Goldfields does not lie within the scope of the investigation, only a short discussion of the prevailing geological formations will be given. However, due to the influence the extensive pan development in the north-western parts of the region may have on the ground-water quality, this matter will be discussed in more detail in the latter part of this chapter.

Due to the low relief of the region, as well as the extensive soil and aeolian cover, outcrops in the area are limited to surface limestone, river terrace gravel, Karoo dolerite, kimberlite, sediment of the lower Beaufort Group and the upper Ecca Group and lava sediment of the Ventersdorp Supergroup. Pre-Ventersdorp rocks are not exposed. A geological map of the area is shown in Figure 3.1.

The geological succession (see Figure 3.2) is discussed from the Ventersdorp Supergroup upwards.

3.2 VENTERSDORP SUPERGROUP

The Ventersdorp Supergroup can be subdivided into the Allanridge Formation, the Klipriviersberg Group and the Platberg Group. The Klipriviersberg Group and the Platberg Group consist mainly of andesitic lava, whereas the Allanridge Formation mainly consists of tuffaceous shale, quartzite and conglomerate (Coetzee, 1960). Only a few outcrops of the Ventersdorp Supergroup occur as indicated on the geological map.

3.3 THE KAROO SEQUENCE

Rocks of the Ecca Group and the Beaufort Group cover the entire area, with the exception of a few inliers from the Ventersdorp Supergroup. The Karoo sediments dip gently to the east and are intruded by dykes and sheets of Karoo dolerite. The formations are covered

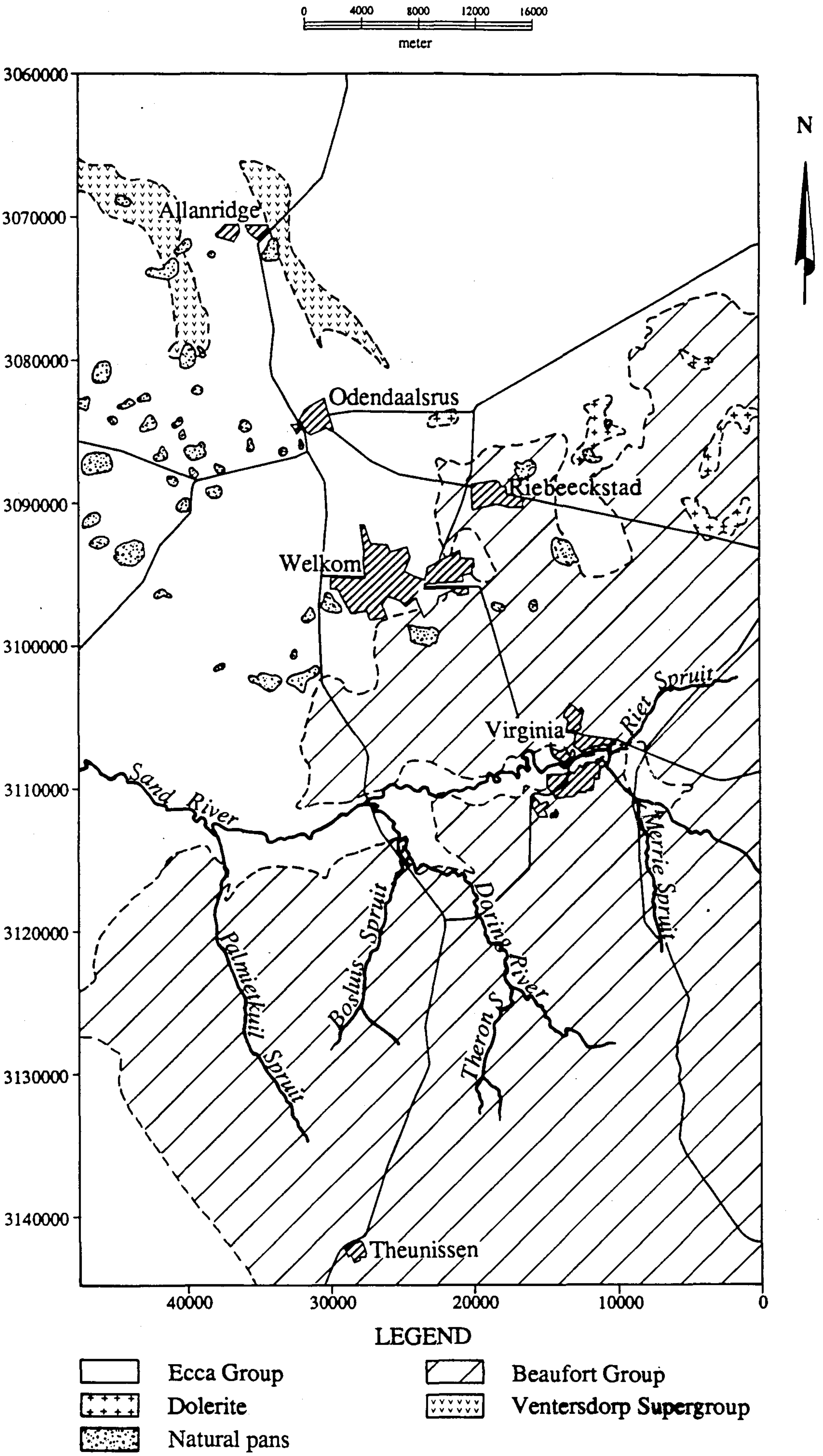


Figure 3.1. Geological map of the Orange Free State Goldfields.

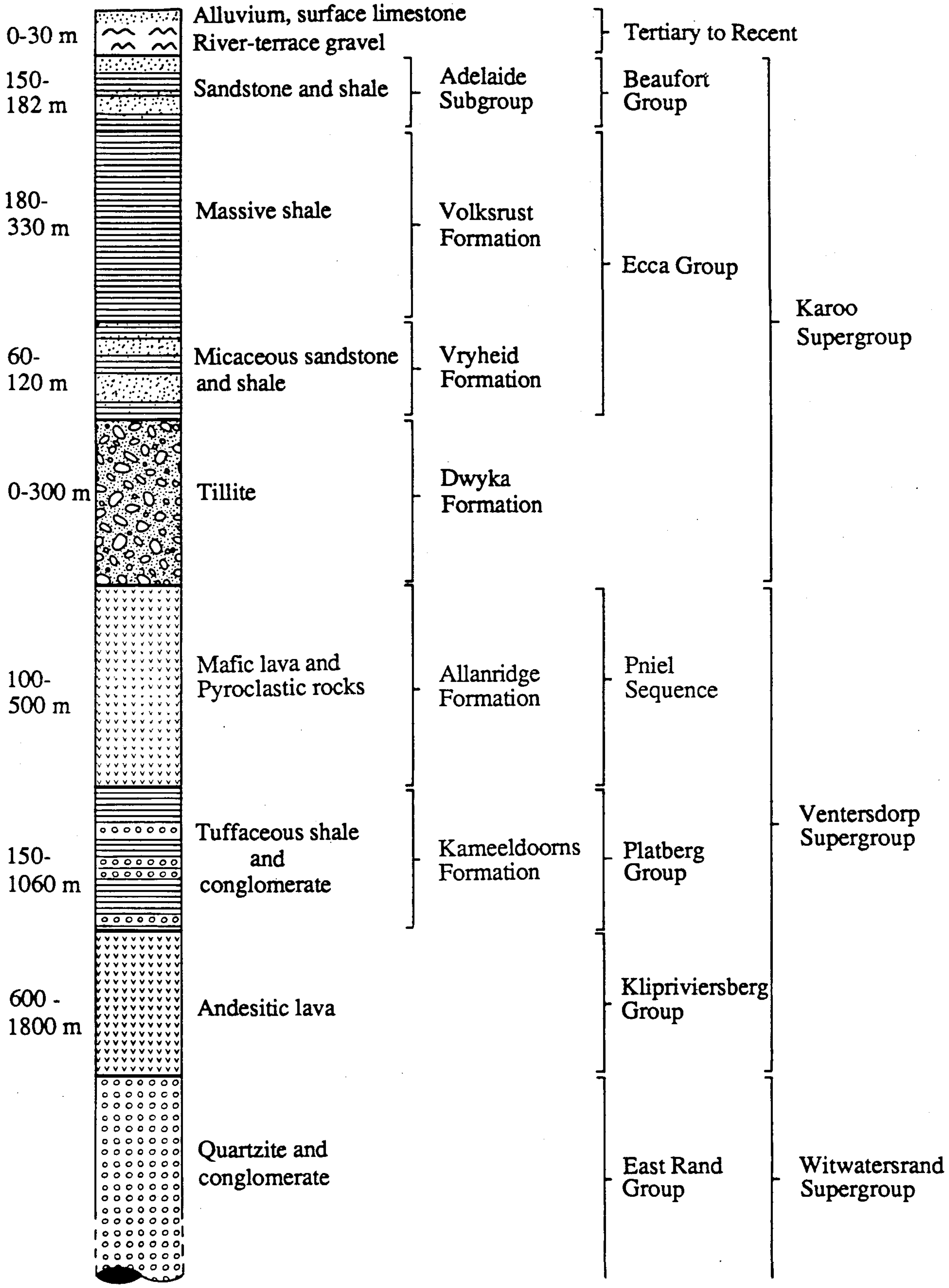


Figure 3.2. Geological succession of the Orange Free State Goldfields.

extensively by soil, sand and secondary limestone and this contributes to the fact that the outcrops of the Karoo rocks are more numerous along the Sand River and its tributaries than elsewhere. The boundary between the Ecca and the Beaufort Groups was determined from the logs of exploration boreholes as well as regional geological mapping. This contact can be seen on the geological map as it trends diagonally across the area, more or less from the south-west to the north-east.

The outcrops of the Ecca Group consist of yellowish-weathered shale, whereas outcrops of the Beaufort Group consist of coarse-grained white and buff-coloured sandstone.

The following subdivisions of the Karoo Supergroup are present within the area:

The Adelaide Subgroup - Beaufort Group.
The Volksrust Shale Formation - Ecca Group.
The Vryheid Formation - Ecca Group.
The Dwyka Formation.

3.3.1 THE DWYKA FORMATION

The Dwyka Formation lies unconformably on the pre-Karoo rocks and occurs occasionally throughout the area. Coetzee (1960) stated that in 250 boreholes drilled within the Odendaalsrus-Virginia area and the adjoining country, the Dwyka Formation is absent in 38% of the boreholes, and that it is less than 15 m thick in 56% of the holes in which it occurs. Where the Dwyka Formation is thin, it generally consists of tillite or conglomerate. However, where it becomes thicker, bands of sandstone or shale may occur.

3.3.2 THE ECCA GROUP

3.3.2.1 The Vryheid Formation

The beds of the Vryheid Formation consist of whitish and grey, fine- to coarse-grained, micaceous sandstone, argillaceous sandstone, sandy, grey, micaceous shale, carbonaceous shale and, in places, coal seams. In the Odendaalsrus area, the Vryheid Formation consists predominantly of sandstone and carbonaceous shale, whereas around Virginia and south of the Sand River, it consists of micaceous and carbonaceous shale.

3.3.2.2 The Volksrust Shale Formation

The formation consists mainly of blue-grey and black shale which is massive or thinly bedded, and, in places, sericitic. Intercalations of sandy material generally occur, particularly in the upper and lower parts. The shale ranges in thickness between 180 and 230 m. When exposed to air and water, the shale disintegrates in places, and the clayey mass which is formed, swells while it is wet and contracts as it dries. Where bands of sandstone comprise the upper portion of the Vryheid Formation, or the basal portion of the Beaufort beds, the upper Volksrust shale can be delimitated properly.

3.3.3 THE BEAUFORT GROUP

The area under investigation lies to the west of the regional boundary of the Tarkastad Subgroup and, therefore, the Beaufort Group is represented by the Adelaide Subgroup only. The Adelaide Subgroup consists of blue-grey and black shale, with thin sandy partings, sandy shale and white and greenish sandstone. The thicker sandstone bands frequently show marked cross-bedding. The thickness of the beds usually varies between 136 and 180 m.

3.4 SURFACE DEPOSITS

3.4.1 RIVER TERRACE GRAVEL

Scattered pebbles, probably derived from river terrace gravels, have been observed on certain farms in the area (Coetzee, 1960). These gravel deposits are generally found near the Sand River on a surface which is very much higher than the top of the alluvium in the valley along the river. These deposits can reach a thickness of 18 m and are normally covered by a red, sandy soil, approximately 1 m thick. Furthermore, the deposits are cross-bedded and different types of aggregate tend to wedge out over short distances. The deposits are unconsolidated and consist of brownish clay, yellowish silt, coarse greenish sand and lenses of pebbles.

3.4.2 SURFACE LIMESTONE

In that part of the area which is underlain by the Beaufort sediments, fragments and small outcrops of surface limestone appear frequently. Where the area is underlain by the Ecca sediments, outcrops of surface limestone also occur, but they are not nearly as abundant as the above-mentioned.

3.4.3 ALLUVIUM AND SOIL

A long strip of alluvium, varying from 400 m to 1,6 km in width, occurs along the Sand- and Vet River and a shorter strip is found along a tributary of the Sand River, the Doring River. To the north of the Vet River's flood plain (below its junction with the Sand River), large sheets of aeolian sands are present (Behounek, 1980). The alluvium may attain thicknesses of up to 20 m.

In most places, the Beaufort sediments are covered by reddish, sandy soil, while the Ecca sediments are covered by a vlei-like soil, which is dark grey in colour.

3.5 INTRUSIVE ROCKS

The following intrusive rocks have been identified in the area: dolerite, kimberlite and dioritic rocks. Dolerite is the only one which is of prime interest for this investigation and will thus be discussed briefly.

The Karoo sediments have been intruded by sills and dykes of dolerite. The sediments in contact with the intrusions have been altered by contact metamorphism. These altered sediments are of some importance to the geohydrologist, due to their favourable water-bearing properties.

According to Coetzee (1960), doleritic intrusions occur more frequently in the arenaceous beds of the Vryheid Formation and in the Adelaide Subgroup than in the argillaceous Volksrust Formation. When present in the Volksrust Shale Formation, they tend to follow the base of the shale.

The dykes in the region are generally thin and seldom have thicknesses of more than 5 m. Some of the dykes are several kilometres in length and their strike may change quite abruptly. Figure 3.3 depicts an interpretation of aeromagnetic data for the study area. According to Stettler (1989), quite a large number of sills occur at different depths in the area; shallow sills, at depths between 0 and 100 m, and deeper sills at depths of over 100 m. It has been observed in the geological logs of mine exploration holes that the sills may reach thicknesses of more than 100 m. Another feature of the sills is their undulatory character.

3.6 GEOLOGICAL STRUCTURE

The topography of the pre-Karoo surface is characterized by a number of well-defined ridges and valleys and it has a slope which is generally towards the south. The Karoo sediments lie relatively undisturbed upon the pre-Karoo surface, although the dolerite intrusions have caused relatively small displacements in the strata invaded by them.

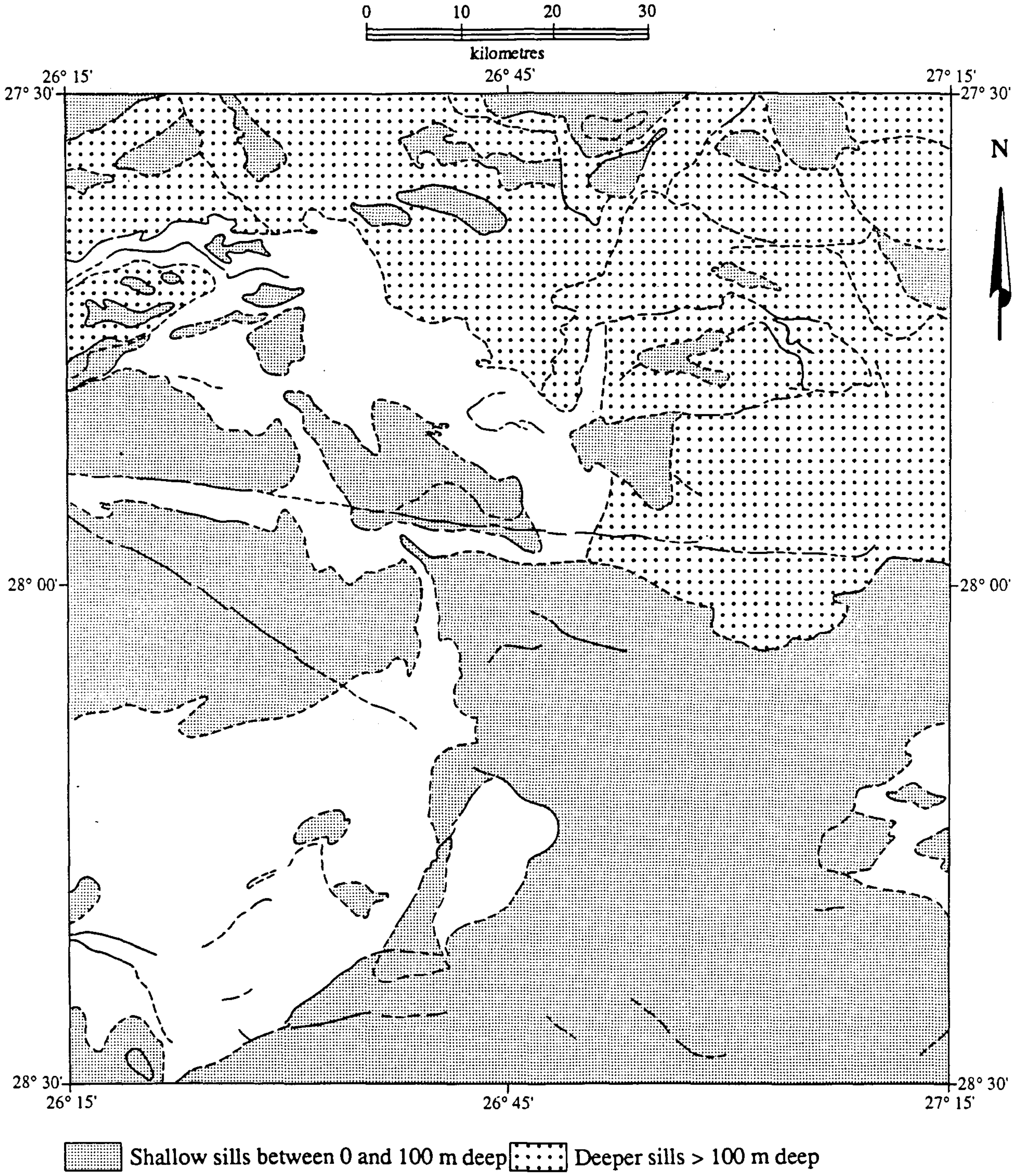


Figure 3.3. Interpreted aeromagnetic data of the Orange Free State Goldfields.

3.7 PAN DEVELOPMENT

3.7.1 THE DISTRIBUTION OF PANS IN THE AREA

The occurrence of pans is limited to the north, north-west and west of Odendaalsrus and the west of Welkom and Virginia. Only a few pans occur east of Odendaalsrus and Welkom (see Figure 3.1). The distribution of pans seems to be geologically controlled, as pans are much more abundant in the Ecca sediments than in the Beaufort sediments. The fact that the Ecca sediments are softer and therefore more easily weathered, seems to be the main reason for this specific distribution.

According to De Bruiyn (1971), the pans in this area can generally be classified into two major groups, namely lime pans and clay pans. A pan is classified into a certain category, e.g. lime, if the pan contains lime in the pan floor itself and not in the surrounding bedrock. When it only contains lime in the surrounding bedrock, it cannot be classified as a lime pan. Also, according to De Bruiyn, the major occurrence of salt pans is restricted to an area to the west and south-west of the Goldfields.

3.7.2 ORIGIN OF THE PANS

The origin of the pans cannot be linked to one factor only, but must be a combination of a series of events. These factors will be discussed briefly.

Due to high temperatures and low rainfall, vegetation will be eliminated and erosion will take place more easily.

The thermal expansion of salts also contributes to the fact that the rocks are eroded more easily. This is due to the fact that the expansion of salt, for a certain temperature increase, is considerable higher than the thermal expansion of any rock. Salt crystals will also tend to keep growing, in spite of a space problem, and this can also speed up the rate of erodation (De Bruiyn, 1971).

Dolerite cone structures frequently occur in the area and, according to De Bruiyn (1971), the association of these structures with the occurrence of pans, is very striking. The cone-shaped nature of dolerite intrusions gives rise to the formation of hollows, because the dolerite is more resistant to weathering than the sediments it intruded. This will lead to an inward drainage pattern and the accumulation of rain water.

The prevailing north-western wind also assists in the formation of pans by removing the fines from the pans, which originate from the above-mentioned processes.

Several researchers have either speculated or postulated an intimate relationship between palaeodrainage and pan formation. Reconstruction of the palaeodrainage of the area shows that the pans represent the disrupted remains of a well-integrated stream system (the Wessels Spruit) (Marshall, 1987). Parallel to the Wessels Spruit, is a second palaeodrainage system, the Allan Spruit (Figure 3.4). Using morphotectonic analysis, Marshall postulated that the maximum extent of the Wesselsbron panveld is developed over a peripheral collapse-graben on the northern flank of a granite dome and that this also corresponds to the most disrupted segment of the Wessels Spruit profile. River capture and reorientation of drainage have occurred as a result of reactivated vertical movements on the bounding faults to both the dome and the graben. According to Marshall, any subsurface graben that may exist beneath a drainage system, may disrupt it into a disjointed pattern of lakes which may subsequently evolve into pans under a desiccating climate.

Grobler *et al.* (1987) also reconstructed a palaeodrainage for an area south of the Sand River and visualized that the panveld around Wesselsbron and the one further south might once have been continuous, but that the sandveld covered the gap between them. They postulated that tectonic causes for the choking of the palaeodrainage would have to explain tilting to the north, south and east and would thus have to be multi-staged. Furthermore, they concluded that calcretization could be used as an indicator to verify the palaeodrainage system.

A poor drainage and a warm, dry climate are necessary for the formation of calcrete. The origin of the calcium in calcrete can be explained by the disintegration of dolerite, although small quantities can originate from sedimentary rocks. Calcrete is formed by the precipitation of $CaCO_3$ from the unstable bicarbonate that is dissolved in water.

De Bruiyn links the origin of the pans to two major factors, i.e. thermal expansion of salts and the occurrence of dolerite cone structures. Grobler and Marshall, on the other hand, postulate an intimate relation between palaeodrainage and pan formation. Whether the dolerite cone structure is a major contributor to pan development is doubtful, as the abundance of doleritic structures in the vicinity of pans is questioned. These structures also do not explain why many of the pans tend to be distributed along a line. For this reason, the palaeodrainage mechanism is favoured. Furthermore, during the drilling phase, a few boreholes were drilled on possible palaeodrainage structures. In all of these boreholes, large quantities of river gravels were encountered, up to a depth of 24 m. The gravel contained pebbles of agate, fossilized wood and quartz and correlate well with river terrace gravels, mentioned by Coetzee. It can, therefore, be deduced that palaeodrainage was one of the major (if not the major) contributors to the genesis of the pans in the area. Chemical and physical weathering of the rocks also contributed to the origin of the pans.

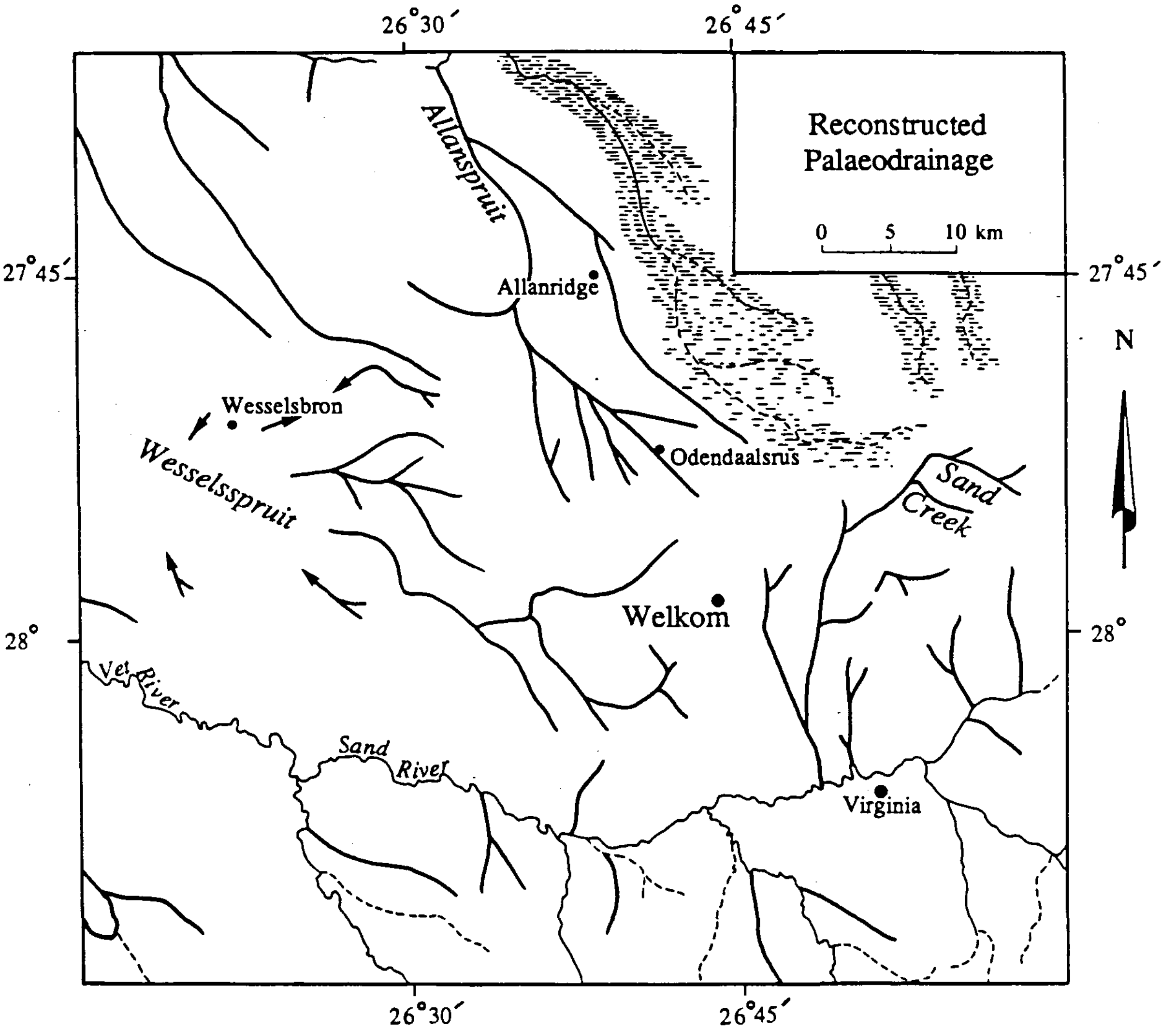


Figure 3.4. The reconstructed palaeodrainage of the Wesselsbron panveld (After Marshall, 1987).

CHAPTER 4

FIELD AND SAMPLING PROCEDURES

4.1 INTRODUCTION

During any research project, the parameters to be determined during the study will be dictated by the study objectives. An intensive literature study, covering the possible pollution that could occur in the Orange Free State Goldfields area, helped in planning the sampling strategy to determine the type of information needed to establish an effective data base. Two basic types of data are required for the study:

(a) General hydrological and geohydrological data.

(b) Hydrochemical data of surface and subsurface water sources.

The measurement of parameters at the source (either surface or subsurface) is carried out for the purposes of assessment, as well as to provide control for laboratory measurements. Especially in the case of physical measurements, the control for laboratory measurements is important, in that the physical conditions of a sample may change between the time of sampling and the laboratory measurements.

The general hydrological and geohydrological data include items such as:

(i) Precipitation.

(ii) Evaporation.

(iii) Run-off.

(iv) Borehole diameter, depth, equipment and use.

(v) Borehole yield.

(vi) Water level.

(vii) Aquifer.

The hydrochemical properties include:

(i) Electrical conductivity.

(ii) Temperature.

(iii) pH.

(iv) Macro elements (major cations and anions).

(v) Micro elements (mainly heavy metals).

Of the hydrochemical properties only:

(i) electrical conductivity,

(ii) temperature and

(iii) pH

are measured in the field (see Appendix III for a short discussion of these parameters).

Figure 4.1 shows some of the data collected during the survey. The different field and sampling procedures, as well as the reasons for the different actions, are discussed in the following section.

4.2 SAMPLING

4.2.1 RECONNAISSANCE SAMPLING

According to Hodgson (1987), all boreholes within 3 km from possible ground-water recharge areas should be sampled, to ensure representative background values on the natural ground-water chemistry. He pointed out that at a distance of 3 km from a pollution recharge point, the effect of dilution is so great that the ground water is usable for many purposes. Thus, during this first phase of sampling, an area of 3 km around any mine boundaries, mine lease areas and municipal areas was covered.

Every farm situated in the specified area was visited and water samples, as well as pH, temperature and electrical conductivity measurements, were taken of all surface- and ground-water sources. Due to the high cost of water analyses, water samples were taken selectively, dependent on the electrical conductivity of the water. All waters with a high electrical conductivity (250 mS/m and higher) were sampled, whereas waters with low electrical conductivities were sampled selectively, ensuring a true representation of natural waters in the area. Borehole water was generally sampled a few minutes after the pump was started. However, due to the presence of many windmills in the area, this procedure was not consequently followed, as many windless days were experienced. In such cases, water samples were taken from adjacent reservoirs, if such existed.

All relevant data of each separate site, on the respective farms, were obtained from the farmers. Where possible, water levels of the boreholes were also measured.

WATER INFORMATION SHEET FOR THE WELKOM PROJECT

TOPO MAP NUMBER __________ NUMBER ON MAP _______ TIME______ DATE ___________

SITE NAME & # ________________________ FARMER NAME _________________________

ADDRESS ____

Y-COORD ____________ X-COORD _____________ COLLAR ELEV _____________________

TOPOGRAPHY _____________________________________ (SLOPE, FLAT, NEXT TO RIVER)

DRAINAGE REGION _____________ WATER USE __________________________________

EQUIPMENT ___________________________ DATE LAST MAINTENANCE _______________

TYPE OF PUMP _______________________ POWER RATING _________________________

PUMP DIAMETER ____________ (mm) DIAMETER OF DISCHARGE PIPE ______________ (mm)

WATER TASTE _________________ SMELL _________ COLOUR __________ TEMP ____ C

pH _______ ELECTRICAL CONDUCTIVITY _________ mS/m TOTAL ALKALINITY __________ mg/l

SITE TYPE _________________ DIAMETER ________________ COLLAR HEIGHT _______ (m)

DEPTH OF HOLE _____ (m) DATE DRILLED ____________ METHOD CONSTRUCTED __________

CASING DEPTH __________ (m) YIELD _________ (l/s) ABSTRACTION FREQ ___________ h/d

DEPTH OF PUMP INTAKE _____ (m) WATER TABLE BELOW TOP OF CASING ______________ (m)

WATER-LEVEL STATUS __________ AQUIFER ____________ AREA IRRIGATED ___________ (m^2)

SIZE OF RESERVOIR __________ (m^3) RESERVOIR TYPE _____________________________

WATER SAMPLES:

SAMPLE NUMBER ____________DEPTH _______ (m) TIME AFTER PUMP STARTED _______ (min)

SAMPLE NUMBER ____________DEPTH _______ (m) TIME AFTER PUMP STARTED _______ (min)

SAMPLE NUMBER ____________DEPTH _______ (m) TIME AFTER PUMP STARTED _______ (min)

COMMENT ____

____

____

Figure 4.1. Water information sheet.

In addition to the surveys carried out on the surrounding farms, a comprehensive survey was made of the water quality in the Sand River and the Doring River. The Sand River was sampled, from about 2 km east of Virginia to about 40 km west of Virginia.

All the water samples collected during the reconnaissance survey were sent to the Glen Agricultural College, where they were analysed for the major cations and anions.

4.2.2 EXTENDED SAMPLING

A preliminary analysis of the collected data, as well as the analysed data, showed that certain areas to the west of Odendaalsrus and Welkom needed further investigation. The reason for this being sporadic occurrences of ground water in the area with a conductivity in excess of 250 mS/m. To investigate this phenomenon in more detail, an area of 15 - 20 km west of Odendaalsrus and Welkom was covered.

All the mines in the Goldfields area were visited and water samples were taken from all water related structures such as: slimes dams, evaporation dams, return water dams, etc. Information regarding the quantity and disposal of the stagnant ground water discharged from the mines was also obtained.

From all the municipalities in the area, the quantities of raw sewage and final effluent were obtained, as well as the positions of their disposal sites for the purified sewage effluent and solid waste. Samples of the final sewage effluent, as well as from any pan situated next to a disposal site, were taken.

All the data collected during this phase of the research project, were imported into the HydroCom data base.

4.2.3 ROUTINE SAMPLING

Based on the reconnaissance and extended sampling as well as the first drilling phase, discussed in section 4.3.1, a water quality monitoring programme was initiated. Once a month, water sampling at specific points in the Sand River, Doring River and Theron Spruit is done. The main pollution source into the Sand River, the Sand River channel, is also being monitored monthly.

Seven water-level recorders have been installed to provide a continuous record of water-level changes throughout the area. Furthermore, water levels in all the newly drilled observation boreholes are measured on a monthly base and entered into HydroCom.

4.3 DRILLING PHASE

A total of 52 boreholes were drilled, in two phases, throughout the study area during the research project. Thirty-nine boreholes were drilled during the first phase, while 13 boreholes were drilled in the second phase.

Evaluating all available data, numerous pollution sources were identified. Due to the fact that many of the pollution sources are duplicated at different mines and municipalities, target areas for a proposed drilling program were selected. The target areas were selected in such a way that all the different pollution sources in the area were covered. Due to the fact that the ground-water occurrence in the Karoo sediments is commonly associated with the occurrence of dolerite structures (dykes and sills), these structures will control the spread of any pollutant present in the ground water. A ground-magnetic survey was conducted at each proposed target area. Where possible, boreholes were sited on magnetic anomalies. However, where no magnetic anomalies were encountered, boreholes were placed in such a way as to effectively intercept and trace any possible pollution.

Figure 4.2 shows the position of 39 boreholes drilled during the first phase in the various target areas. The reasons for drilling certain holes at specific places are as follows:

(1) Boreholes 1, 2, 3 : A dolerite dyke crosses Swart Pan, into which the mines dispose their water. The movement of water along the dyke is investigated.

(2) Boreholes 7, 4, 8, 9, 10 : Mine water spills into natural vlei systems. Possible contamination of ground water along the vlei systems is investigated.

(3) Boreholes 15 - 21 : The possible existence of palaeodrainage systems and its contribution to ground-water pollution are investigated, as well as the influence of huge quantities of mine effluent disposed in the Wolve Pan system.

(4) Boreholes 5, 6, 12, 29, 30 : The influence of slimes dams on ground-water quality is investigated. These boreholes are situated next to old and new slimes dams, as well as slimes dams where uranium and pyrite have either been extracted or not been extracted from the slimes before depositing the slimes.

(5) Borehole 31 : To monitor the influence of yeast effluent on the ground-water quality.

(6) Boreholes 13, 14 : The influence of solid waste and purified sewage effluent on ground water is investigated.

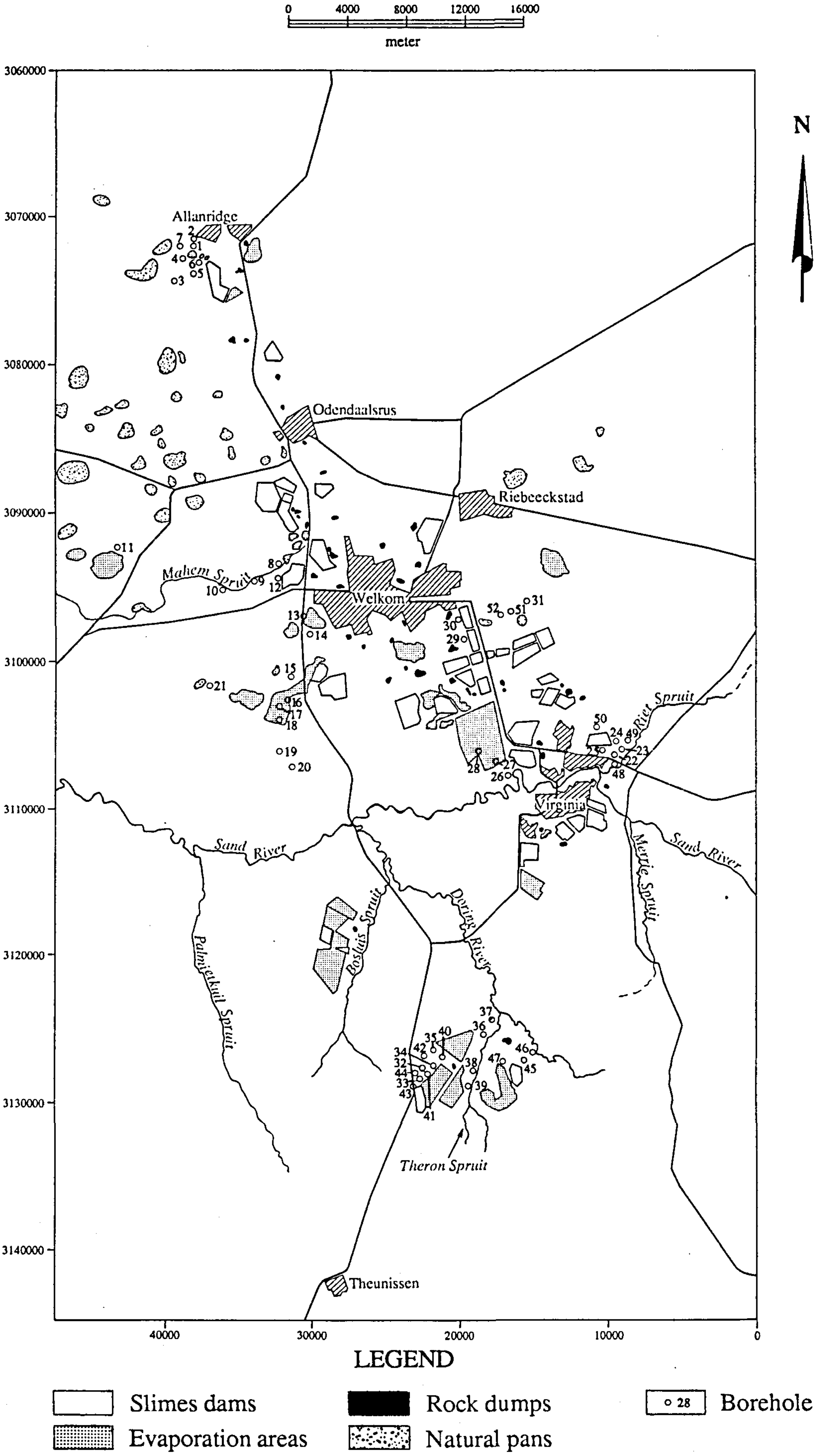


Figure 4.2. Positions of the boreholes drilled in the Orange Free State Goldfields.

(7) Boreholes 26 - 28 : These boreholes are situated in old evaporation areas, sloping towards the river. The movement of ground water towards the river is investigated.

(8) Boreholes 32 - 39 : The area is situated on a shallow dolerite sill and includes large evaporation areas. The influence of this sill on the ground-water quality is investigated.

(9) Boreholes 22 - 25 : These boreholes are located next to a new slimes dam and return water dam. Good background values can be obtained from these boreholes for future monitoring purposes.

(10) Borehole 11 : To investigate the influence of a dolerite dyke, crossing the Dankbaar Pan, on the quality of the ground water. Large amounts of mine water are disposed in the Dankbaar Pan.

A second drilling phase, during February 1990, was initiated to observe the pollution in more detail in some of the newer mining areas, including:

(i) Beatrix Goldmine - disposal sampler

(ii) H.J. Joël Goldmine - disposal sampler

(iii) Harmony Goldmine - new slimes dam complex

Borehole positions at the Beatrix disposal complex were located in conjunction with the CSIR, who is currently researching the detection of pollution using geophysical techniques. Borehole positions in the remaining two areas were located with the purpose to extend the existing monitoring facilities. Figure 4.2 shows the position of the 13 boreholes (boreholes 40 - 52) drilled during this phase.

All the boreholes were geologically logged to identify the geological succession in each of the boreholes, as well as the aquifer in which the water was struck. All these data were entered into HydroCom data base.

4.4 ELECTRICAL CONDUCTIVITY LOGGING AND WATER SAMPLING

All the boreholes were drilled in close proximity of existing pollution sources. To see whether these boreholes were affected by the pollution source, it was decided to log the electrical conductivity of the boreholes, providing a continuous record of each borehole's electrical conductivity. This would also identify any possible stratification in the borehole water, hence used to plan detailed sampling of the respective boreholes.

A major problem encountered during the logging of the boreholes, was that the majority of the boreholes had water of which the electrical conductivity exceeded the range of the instrument, i.e. 200 mS/m. At closer inspection, it was found that the conductivity logger was inaccurate and that the logged values could not be used. Thus, the identification of stratification in the borehole water became very difficult. To overcome this problem to a certain extent, all the boreholes were sampled at two depths:

(i) A shallow water sample - 5 m below the water level.

(ii) A deeper water sample - 25 m below the water level.

Due to the current high costs of scientific apparatus, the Institute for Ground-water Studies developed its own water sampler, as shown in Figure 4.3. The entire sampler is constructed of locally manufactured materials, making it relatively inexpensive.

The function of the water sampler is as follows: When the sampler is submerged, the non-return valve is pushed up by the water, enabling the water to fill the sample chamber. Applying pressure upon the water in the sample chamber through the gas supply pipe, the non-return valve is forced down, closing the opening and causing the water to be pumped through the water supply pipe into a sample container at the surface.

The major advantage of the water sampler is that the borehole water can be sampled at different levels, minimizing the mixing effect of the remaining water column, due to sampling disturbances.

4.5 CHEMICAL ANALYSES

One of the major problems during the first year of the research project, was the difficulty in having the water analyses done at reasonable prices. All collected water samples were, during this period, analysed for the major cations and anions by the Glen Agricultural College. A solution to this problem was to start a chemical laboratory at the Institute for Ground-water Studies. Having the water samples analysed at the University itself is certainly preferred, since this will allow experimentation and in-depth research into the chemistry of water from the Welkom area. In collaboration with the University of the Orange Free State, the Institute for Ground-water Studies started its own laboratory in January 1989.

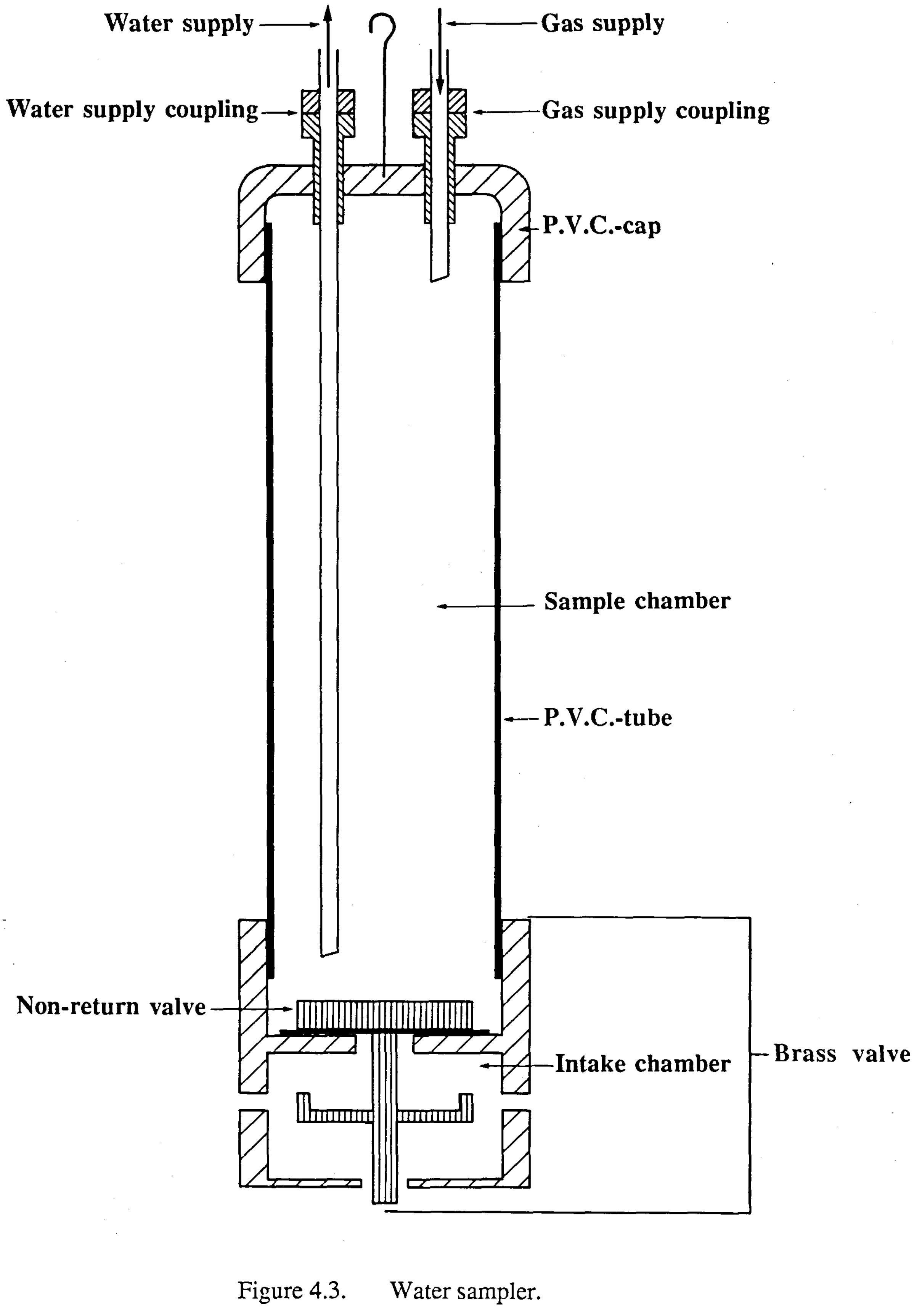


Figure 4.3. Water sampler.

An ARL ICP-spectrophotometer was bought to perform cation analyses, while the anion analyses are performed on a DIONEX 2000 ion-chromatograph. Furthermore, an automatic titrator was bought to perform the pH- and alkalinity measurements. All the instruments are connected to micro computers, automating the entire analytic process.

4.6 SOIL WATER

To determine the soil water content, as well as the soil water movement of the respective sites (slimes dams) in the study area, 13 neutron access tubes were installed on three slimes dams in the area:

(i) Loraine slimes dam - old, used slimes dam.

(ii) Western Holdings slimes dam - relatively young slimes dam.

(iii) A Harmony slimes dam - old, unused slimes dam.

All the above-mentioned sites were monitored on a monthly basis from December 1988 to April 1990.

The soil water content and wet density were determined radiometrically with a neutron moisture gauge and a gamma ray density gauge.

A water retention curve was obtained from the literature.

The total water potentials were determined from the above readings and the retention curve.

The Darcian approach was followed to determine the unsaturated hydraulic conductivity (K_S) for a specific site.

A number of saturated K_S-values were determined with the permeameter. To verify the previous results, Campbell's equation (Campbell, 1985) was used to determine another set of K_S-values for the respective sites. The clay and silt fraction of a soil were used for the calculation of the K_S-values. The equation is expressed mathematically as follows:

$$K_S = 2 * 10^{-3} \bullet e^{-4,26\,(m_s + m_c)}$$

where

m_S = silt content (%)

m_C = clay content (%)

K_S = saturated hydraulic conductivity (m/s)

K_S-values were also obtained from Steffen, Robertson & Kirsten in Welkom, and were used to compare with the above determined values.

The potential gradient ($d\phi/dz$) and the unsaturated hydraulic conductivity [$K(\theta)$] were used to calculate the Darcian flux (q) with the following equation:

$$q = - K(\theta) - d\phi/dz$$

where $d\phi$ is the difference in the total water potential for a difference in depth dz.

Calibration curves of the above-mentioned data are shown in Figure 4.4, while the relevant coefficients were calculated as follows:

α = 0,128377
β = 2271,709328
γ = - 0,149744
a = 0,087294
b = 357,976842

The actual normalized moisture meter readings from all the access tubes showed a similar behaviour during the study period. Because of this similarity, only one set of readings of the respective access tubes was analysed. The total water potentials were determined from a water retention curve, determined experimentally by Klute *et al.* (1978), on uranium mill tailings with a bulk density of 900 to 1100 kg/m^3 and a particle size distribution, ranging from 100% passing 125 µm to 5,9% passing 3 µm. Figure 4.5 represents the wetting and drying legs of the water retention curve.

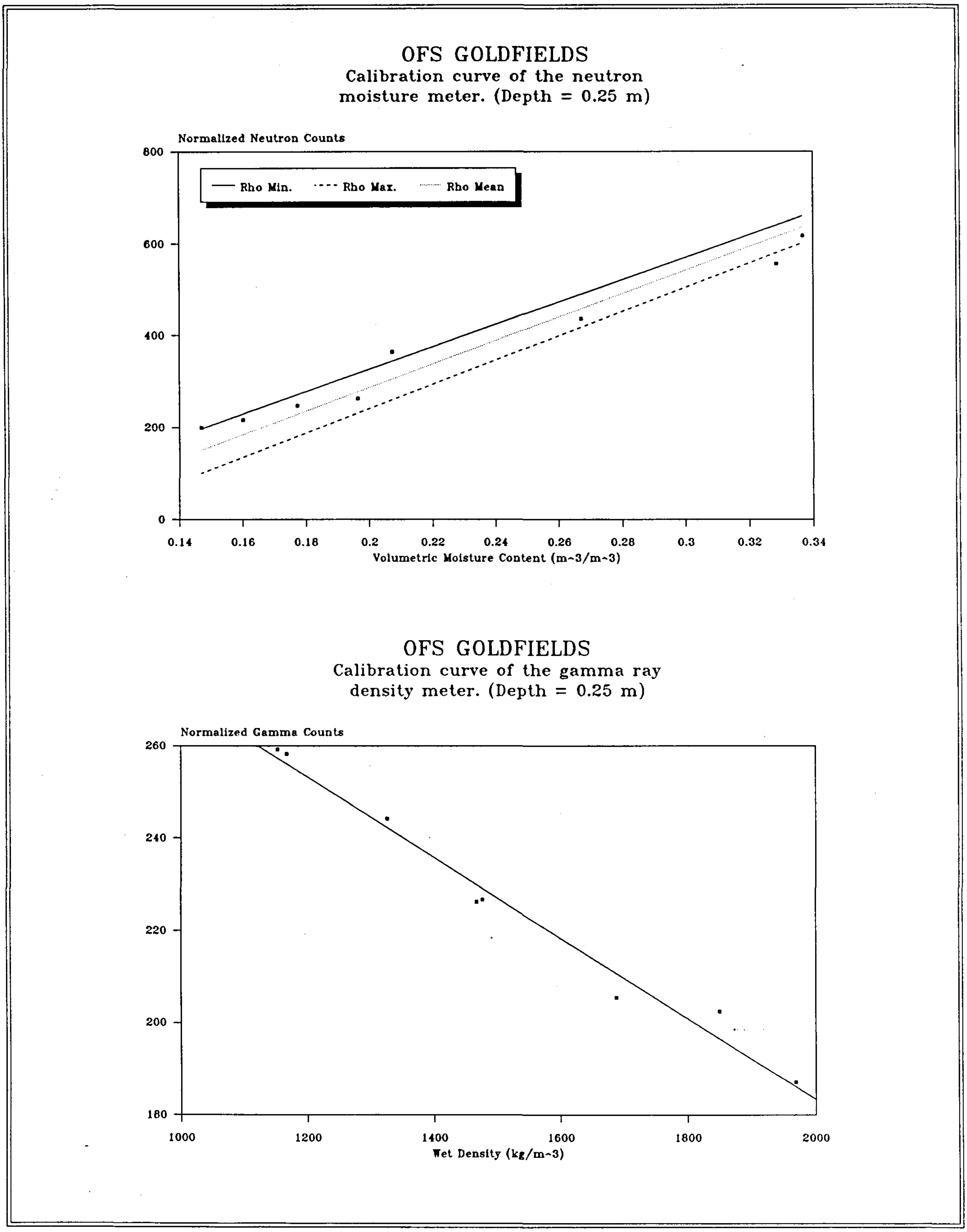
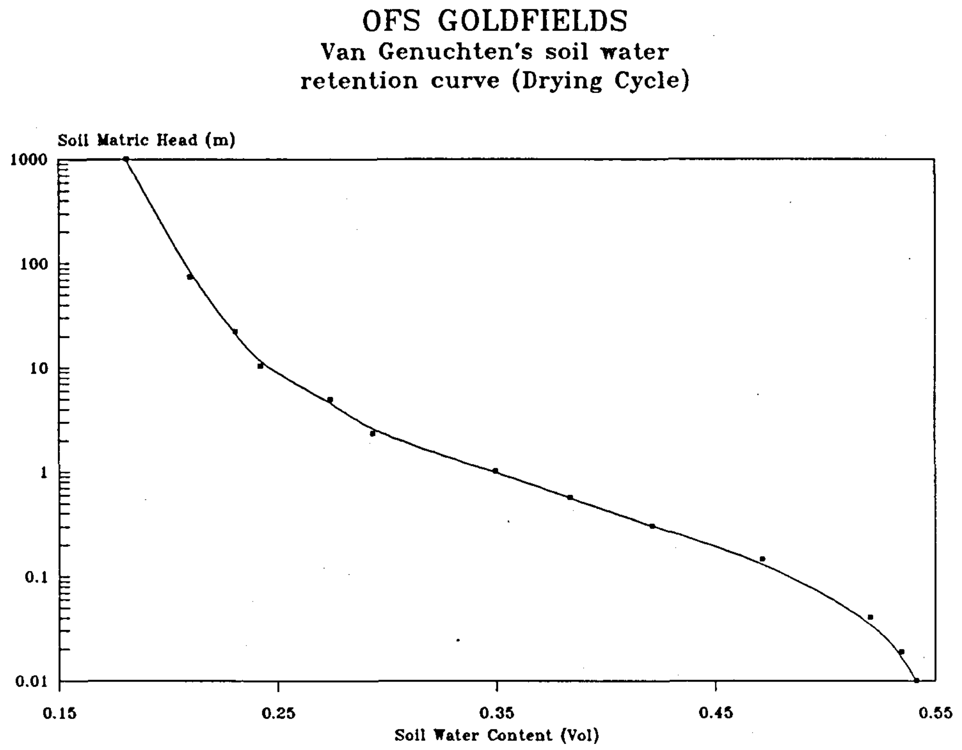


Figure 4.4. The calibration curves of the neutron moisture meter and the gamma ray density meter.



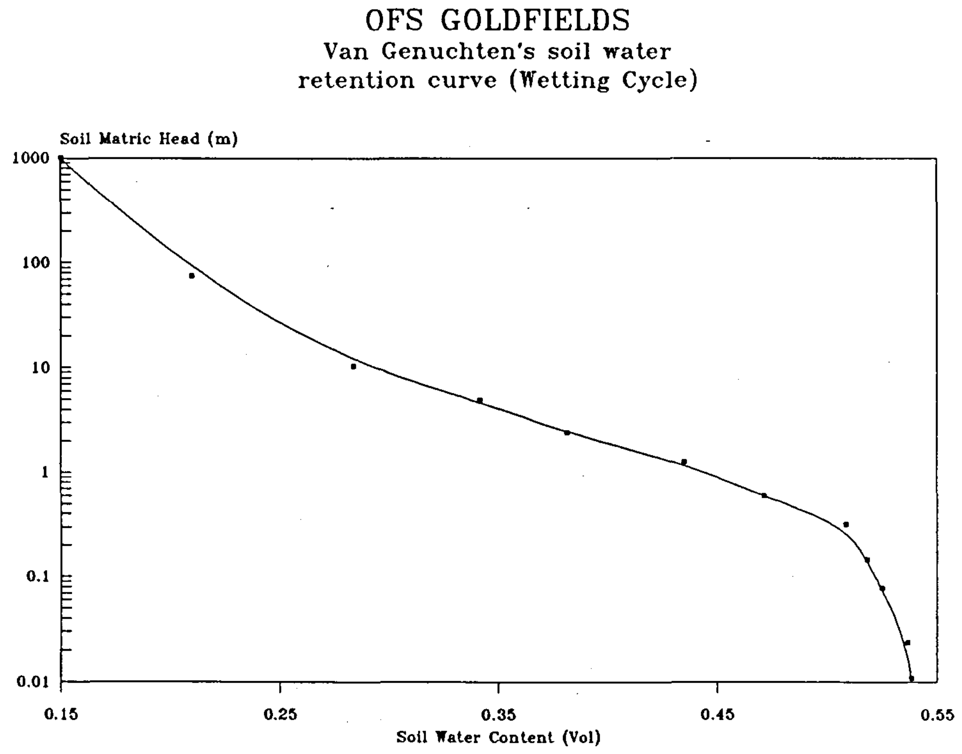


Figure 4.5. The drying and wetting cycles of the soil water retention curve.

CHAPTER 5

GEOHYDROLOGY

5.1 INTRODUCTION

Almost all the ground water in the region occurs in secondary aquifers. Secondary aquifers are weathered and fractured and lie directly beneath the soil surface. The quantity of ground water stored in the saturated portions of these secondary aquifers is limited, while the permeability of such aquifers is generally also low. Thus, the exploitation potential of these secondary aquifers is generally low. Ground water in the region is mainly used for domestic and stock watering. If these limited potable ground-water resources are threatened by possible pollution sources in the surrounding area, the available amount of potable ground water is even further decreased. It is therefore important to identify and delineate possible ground-water occurrences in the area.

Two main aquifers exist in the area:

(a) A shallow aquifer which lies within the weathered and fractured zone of the Karoo sediments.

(b) A deeper aquifer which is developed in the fractured and faulted Ventersdorp and Witwatersrand rocks.

No obvious hydraulic connection exists between the two aquifers, because the large-scale drawdown of the deep aquifer's water level, over the last 37 years, did not have any effect on the water level of the shallow aquifer. One of the major reasons for the phenomenon may be the fact that none of the numerous faults that occur in the Ventersdorp and Witwatersrand rocks can be detected in the Karoo sediments. This also applies to the faults that are tectonically active at present. Therefore, at great depths (300 - 1200 m), due to the absence of faults and the compaction of the sediments, the permeability of the Karoo sediments will be very low and ground-water movement will be negligible. However, in the Allanridge region where the Ventersdorp rocks outcrop, vertical leakage between the two aquifers may be possible.

5.2 THE SHALLOW AQUIFER

The shallow aquifer can be delimited as follows:

The Ecca shales.

Sandstone and shales of the Beaufort.

Dolerite intrusions.

Alluvial sands.

Weathered lava of the Ventersdorp Group.

Of the five groups, the first three are the most abundant, whereas the latter occur in only a few boreholes, with the alluvial aquifer occurring more frequently than the lava aquifer.

5.2.1 GROUND-WATER OCCURRENCE

A borehole survey indicated that the occurrence of ground water in the shallow aquifer is geologically controlled. Boreholes with moderate to high yields are associated with the intrusion of dolerite. The exception may be in the Beaufort sediments, where joints in the sediments sometimes contribute to a relatively high yield. During the drilling phase, it was observed that moderate quantities of water (0,13 - 1,5 l/s) were struck on the contact between the sandstones and shales of the Beaufort sediments. According to Walton (1970), the specific yield of sandstone can be more than three times as high as that of shales. Due to the relative abundance of sandstone in the Beaufort sediments and its absence in the Ecca sediments, it is therefore not surprising that the yields of the boreholes drilled in the Beaufort sediments are considerably higher than those drilled in the Ecca sediments.

As mentioned earlier, boreholes with a relatively high yield tend to be associated with dolerite. The intrusion of dolerite into a host rock may cause fractures and joints in the host rock and these secondary interstices may have large water-holding potentials. Due to the relative impermeability of the Karoo sediments, fracturing of the sediments is essential for a constant water supply. Dolerite intrusions are, therefore, essential to improve the regional ground-water yield of the Karoo sediments. Especially in the Ecca shales, boreholes that are not drilled next to dolerite tend to have a zero or a very low yield. During the drilling phase, only two of the 13 boreholes in which dolerite were encountered, were dry, whereas 10 of the remaining 26 of the boreholes drilled in either sandstone or shale, were dry. This illustrates the necessity for the presence of dolerite for a successful borehole.

Unconsolidated sands that overlay the Ecca sediments, south-west of Welkom, also have a relatively constant yield of between 0,13 - 0,5 l/s. Although the yields are not particularly high, the positioning of the boreholes is not as vital as in the case with dolerite, and a successful borehole can be obtained much easier. However, the boundaries of this alluvial deposit have not been pin-pointed yet.

The tendency for the occurrence of ground water to be geologically controlled, is confirmed in Figure 5.1(a). This figure represents the average yield of the boreholes in the Beaufort and Ecca sediments. According to the figure, the average yield of the boreholes in the Beaufort sediments is 3,2 l/s, whereas the average yield in the Ecca sediments is 1,03 l/s. In both cases, this figure includes the boreholes drilled next to or within dolerite, as it is difficult to separate the boreholes drilled in dolerite and sediments due to a lack of information.

Figure 5.2 represents the borehole yield contours of the study area. It must be stressed that the zero yield contour is not exactly zero, as this figure was rounded off. All the yields in the interval > 0,1 l/s and < 0,5 l/s were rounded off to zero.

As can be seen from Figure 5.2, higher yields tend to occur in the southern and eastern portions of the area, with lower yields in the north-west. When looking at the Beaufort-Ecca contact, a definite pattern is observed. Boreholes with higher yields occur in the Beaufort sediments, while boreholes with lower yields are mainly found in the Ecca sediments.

Figures 5.1(b) and 5.1(c) represent the histograms of the boreholes with a yield in the Ecca and Beaufort sediments respectively. The only resemblance between the two figures is that the majority of the boreholes have yields less than 5 l/s, and as the yield of the boreholes increases, the number of boreholes drastically decreases. In the Ecca sediments, 92% of the boreholes have yields less than 5 l/s, whereas this figure is 73% in the Beaufort sediments. This implies that only 8% of the boreholes in the Ecca sediments has a yield in excess of 5 l/s and that this figure for the Beaufort sediments is 27%. This clearly illustrates that the yields of the boreholes in the Beaufort sediments are much higher than those in the Ecca sediments. These figures also show that boreholes with a yield in excess of 15 l/s do not occur in the Ecca sediments, whereas almost 5% of the boreholes in the Beaufort sediments exceeds that figure. Another interesting feature is the fact that 71% of the boreholes with a yield less than 5 l/s in the Ecca sediments have yields less than 1 l/s. This same figure for the Beaufort sediments is 31%.

By taking all the borehole data, the average depths of the boreholes in the Ecca and the Beaufort sediments were calculated. The average depths are 41,0 m and 36,6 m in the Ecca and Beaufort sediments respectively. Due to the similarity of these depths, it can be concluded that there seems to be no relation between the depth of the boreholes and the

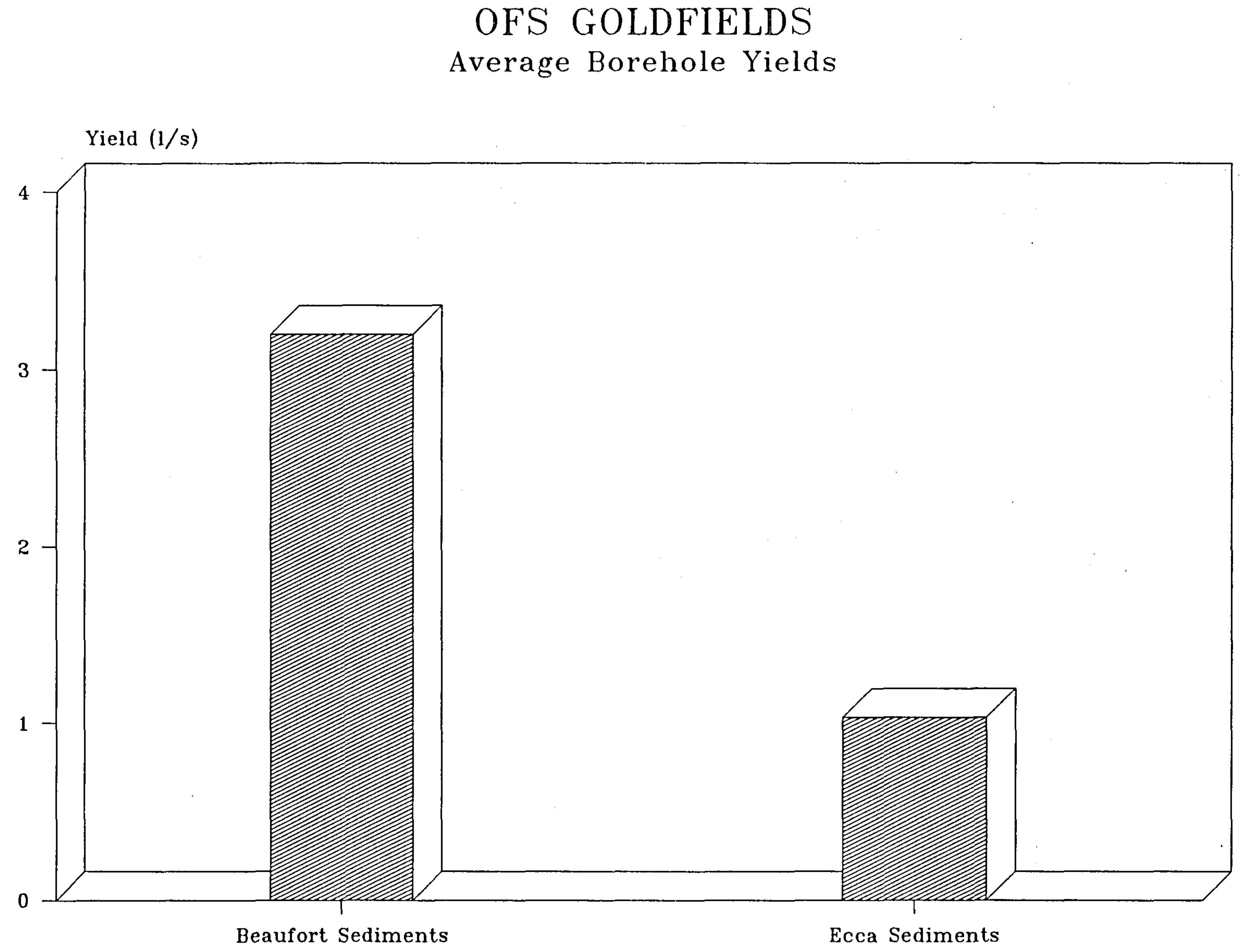


Figure 5.1(a). Average borehole yields in the Beaufort and the Ecca sediments (l/s).

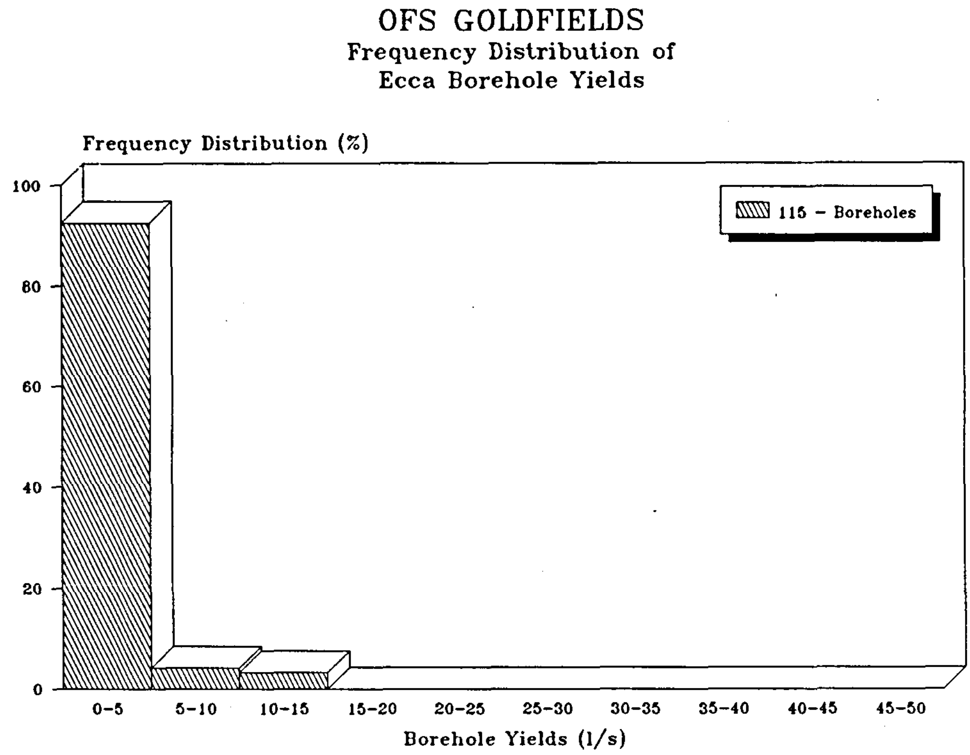


Figure 5.1(b). Frequency distribution of borehole yields in the Ecca sediments (l/s).

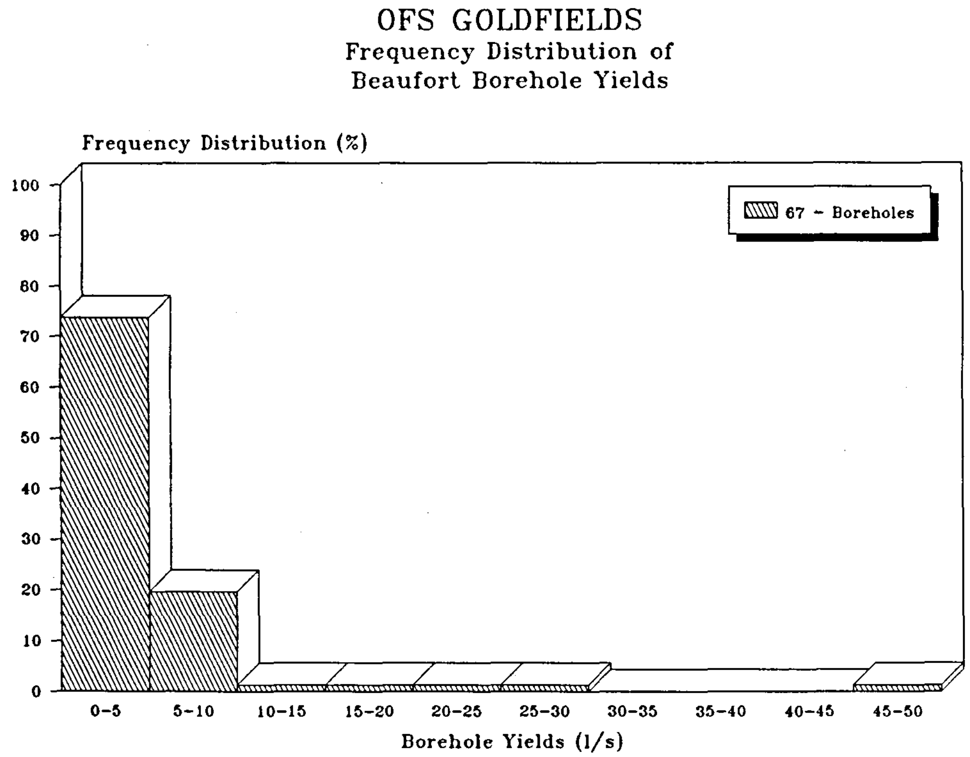


Figure 5.1(c). Frequency distribution of borehole yields in the Beaufort sediments (l/s).

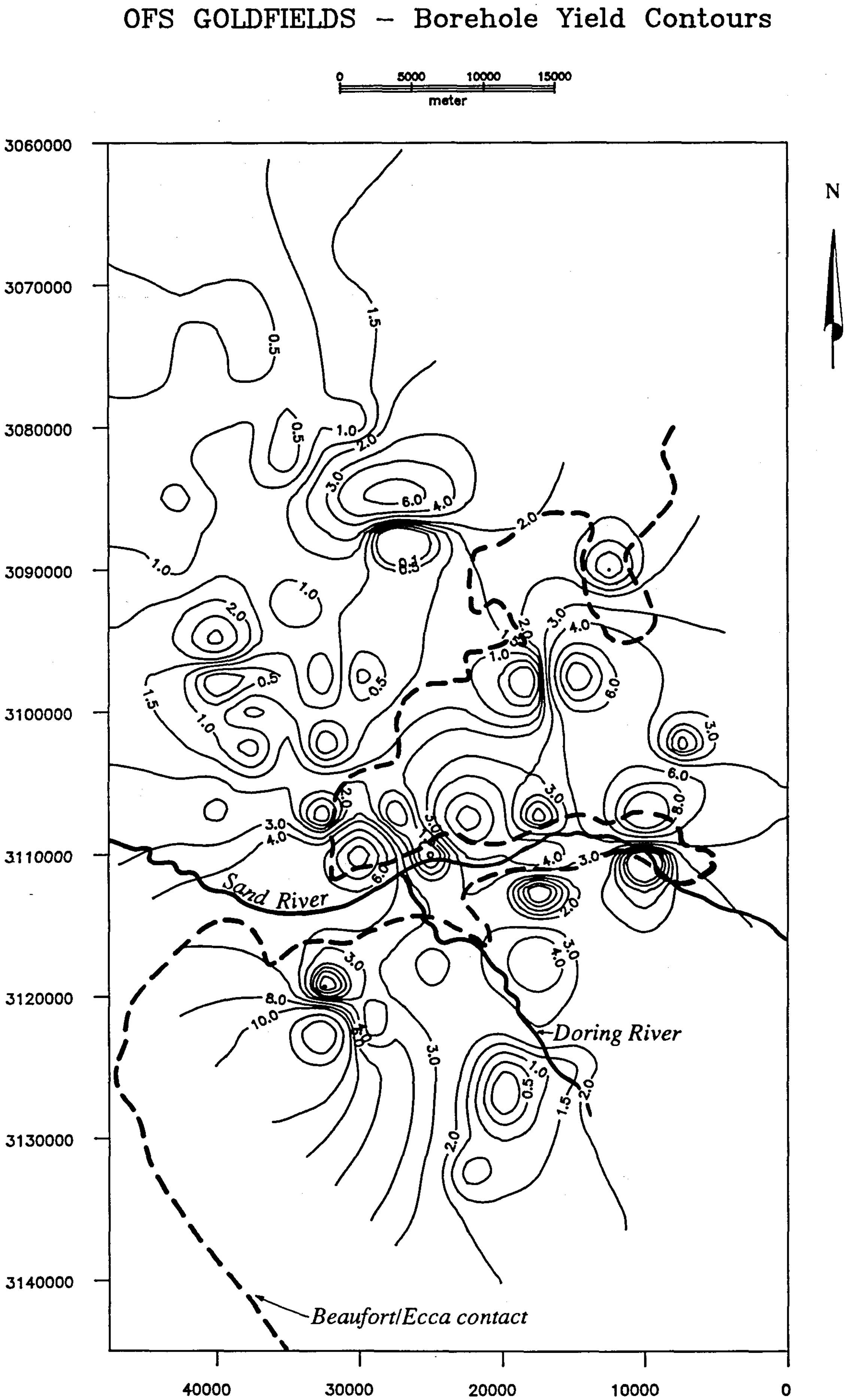


Figure 5.2. Borehole yield contour map of the Orange Free State Goldfields (l/s).

strata into which it was drilled. There also seems to be no relation between the depth and the yield of the boreholes.

Table 5.1 lists the boreholes drilled for this investigation as well as their estimated blow-out yield, stratigraphical unit and aquifer.

TABLE 5.1. BOREHOLE YIELDS AND AQUIFER TYPES

Borehole Number	Yield (l/s)	Geological Formation	Aquifer
DC 315 (1)	0,06	Ecca	Dolerite contact with shale
DC 316 (4)	0	Ecca	-
DC 317 (2)	0,50	Ecca	Dolerite contact with shale
DC 318 (7)	0	Ecca	-
DC 319 (3)	0,06	Ecca	Dolerite contact with shale
DC 320 (5)	0,06	Ecca	Joint in shale
DC 321 (6)	1,0	Ecca	Calcrete
DC 322 (8)	0	Ecca	-
DC 323 (12)	0	Ecca	-
DC 324 (9)	0	Ecca	-
DC 325 (10)	0	Ecca	-
DC 326 (13)	0	Ecca	-
DC 327 (11)	2,5	Ecca	Weathered dolerite
DD 54 (30)	0,38	Beaufort	Sandstone
DD 55 (31)	0	Ecca	-
BA 218 (15)	0,03	Ecca	Dolerite contact with shale
BA 219 (16)	0,06	Ecca	Dolerite contact with shale
BA 220 (17)	0,25	Ecca	Clay
BA 221 (18)	0,25	Surface deposit	Sand
BA 222 (19)	0,06	Ecca	Weathered dolerite
BA 223 (20)	0,13	Surface deposits	Sand
BA 224 (21)	0,13	Surface deposits	Sand
BA 225 (14)	0,25	Ecca	Weathered shale
BB 215 (22)	0	Beaufort	-
BB 216 (23)	2,5	Beaufort	Dolerite contact with shale
BB 217 (24)	0	Beaufort	-
BB 218 (25)	1,0	Beaufort	Dolerite contact with sandstone
BB 219 (27)	0,75	Beaufort	Contact of dolerite and sandstone
BB 220 (28)	0	Beaufort	-
BB 221 (26)	1,5	Beaufort	Clay, contact of sandstone and shale
BB 222 (29)	0,63	Beaufort	Sandstone and shale
BB 223 (36)	0,13	Beaufort	Contact of sandstone and shale
BB 224 (37)	0,13	Beaufort	Contact of sandstone and shale
BD 52 (32)	0,06	Beaufort	Shale
BD 53 (33)	0	Beaufort	-
BD 54 (34)	0,5	Beaufort	Weathered dolerite
BD 55 (35)	3,13	Beaufort	Shale
BD 56 (38)	0,19	Dolerite	Calcite vein in fresh dolerite
BD 57 (39)	1,0	Beaufort	Shale
BD 70 (40)	0,40	Beaufort	Weathered and jointed sandstone and shale
BD 71 (41)	1,20	Dolerite	Weathered dolerite
BD 72 (42)	0,50	Beaufort	Weathered and jointed sandstone and shale
BD 73 (43)	0,50	Beaufort	Weathered and jointed sandstone and shale
BD 74 (44)	2,50	Beaufort	Weathered sandstone

BD 75 (45)	0,06	Beaufort	Weathered and jointed shale and sandstone
BD 76 (46)	0,06	Beaufort	Weathered and jointed shale and sandstone
BD 77 (47)	0,10	Beaufort	Weathered and jointed shale and sandstone
BB 315 (48)	2,5	Dolerite	Weathered dolerite
BB 316 (49)	0,30	Ecca	Jointed shale and sandstone
BB 317 (50)	0,37	Ecca	Jointed shale and sandstone
DD 65 (51)	0,37	Ecca	Jointed shale and sandstone
DD 66 (52)	0,37	Ecca	Jointed shale and sandstone

To distinguish the boreholes from one another on a small-scale map, each borehole was given a number which is much shorter than the original map number. The number appears in brackets after the map number (see Figure 4.2).

Evaluating the data in Table 5.1, reveals the following: Of all the boreholes drilled in the Ecca sediments, 35% were dry, while 13% of the boreholes drilled in the Beaufort sediments were dry. The average borehole yield in the Ecca sediments was 0,42 l/s, while the average yield in the Beaufort sediments was 0,83 l/s, taking only boreholes with a yield into consideration. When all boreholes are taken into account, the average yield values are 0,27 l/s and 0,69 l/s respectively.

The reason why these yields are considerably less than those previously discussed, is mainly due to the fact that the newly drilled boreholes were placed in such a way around the pollution source, to assure an optimal interception of any contamination. Consequently, many of the boreholes drilled on sites where dolerite is absent, have a very low or a zero yield.

It is also interesting to note that in the 12 dry boreholes, which were placed strategically next to pollution sources, dolerite was encountered in two of the boreholes. In borehole BD 53, dolerite was struck about 2 m from the surface, well above the water table, while in borehole BB 217, dolerite was struck well beneath the water table. In this case, however, the contact zone (chilled zone) is virtually absent. Although the chance of a successful borehole is dependent on the occurrence of dolerite, it is also dependent on the structure of the contact zone, as well as the permeability of the surrounding sediments. To illustrate the effect the permeability of the surrounding sediments has on a borehole, the following example is included: Borehole DC 326 was drilled next to Toronto Pan, one of the largest pans in the area. The borehole was drilled about 15 m from the water's edge, to a depth of 40 m. The entire borehole was drilled in Ecca shales and not a drop of water was encountered. After the drilling phase was completed, water levels were measured in all the boreholes. Although some of the boreholes appeared to be dry during drilling, all of the boreholes had water levels, a few metres from the top, a month after the drilling phase was completed.

Borehole BD 56 was drilled entirely in solid dolerite. However, water was struck on 21 m, due to the presence of a calcite vein. The estimated borehole yield is approximately 0,19 l/s. This phenomenon proves that impermeable material can be capable of yielding water, if fractures and joints are present in the rock.

In contrast to the solid dolerite, weathered dolerite has a relatively high yielding capacity. Boreholes DC 327, BB 315 and BD 71 were drilled in weathered dolerite, yielding approximately 2,5, 2,5 and 1,2 l/s respectively, which is reasonably high for their respective regions.

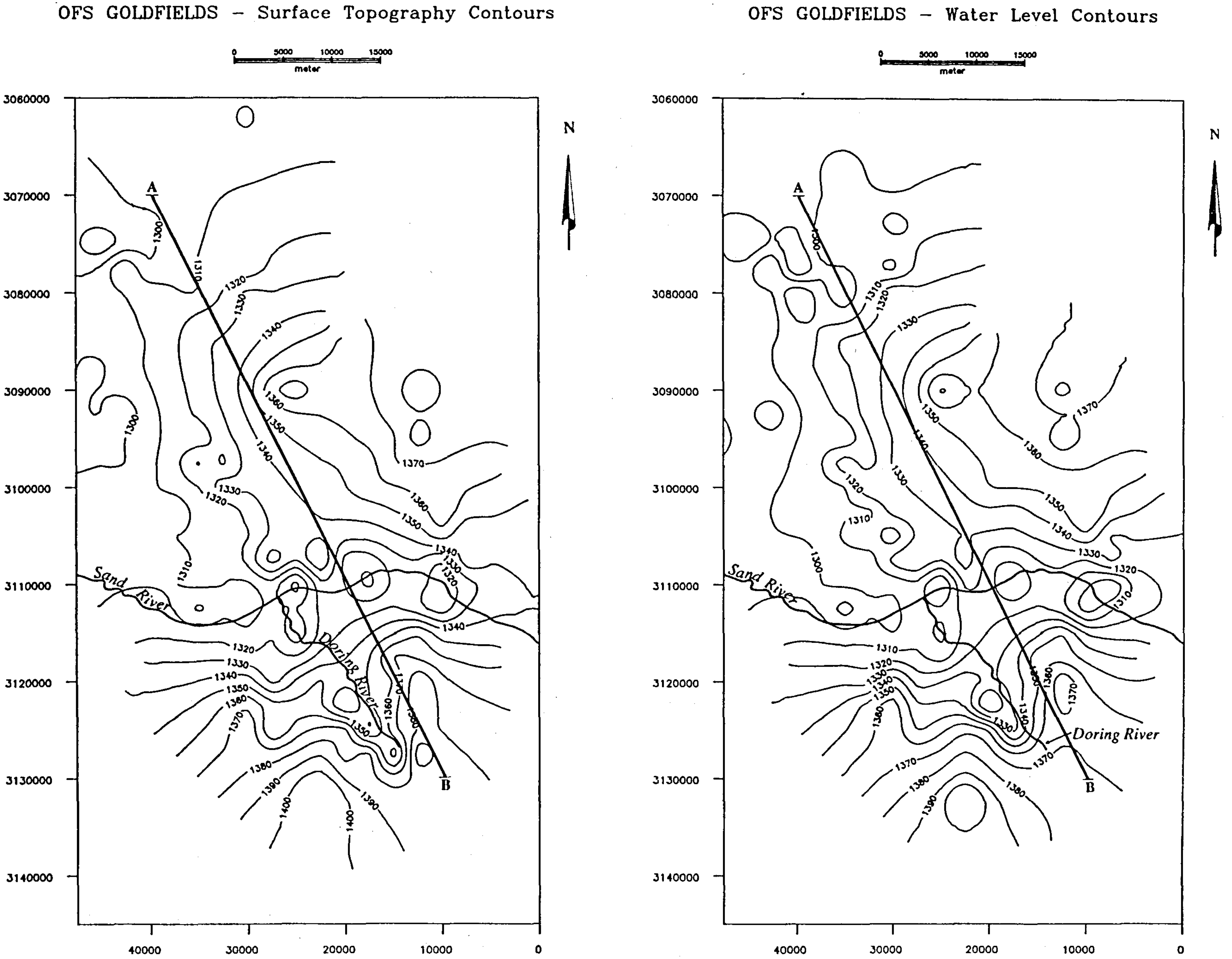
The surficial deposits, consisting of gravel and sand, also seem to have a moderate yield, and boreholes that were only placed in these deposits were more successful than those placed in the Ecca and Beaufort sediments.

5.2.2 GROUND-WATER ABSTRACTION

Most of the ground water in the area is used for agricultural purposes. Stock watering seems to be the major consumer, with gardening and household use requiring less water. The frequency of abstraction is determined by the needs of the farmers and the wind, since most of the boreholes are equipped with windpumps. The low yielding capacity of the Karoo sediments and the presence of the Sand-Vet Water Scheme are the two major reasons why the exploitation of ground water for irrigation purposes is almost nil.

5.2.3 GROUND-WATER MOVEMENT

A water-level contour map, using water levels from available boreholes in the shallow aquifer, as well as the topographic contours of the study area, is depicted in Figure 5.3. Comparing these diagrams with each other, it is noted that the ground-water levels closely follow the surface topography (Figure 5.4, which depicts the interpolated ground-water level/topography relationship in a profile). This implies that the water levels are topographically controlled and that vertical leakage to the deeper aquifer is negligible. South and north-east of the Sand River, the slope of the water levels is locally towards the Sand River. This corresponds very well with the surface water drainage in the vicinity of the Sand River. However, in the western and northern side of the area where the drainage of surface water is very poor, due to the absence of well-defined watercourses (although those which exist, drain towards the north and west), the regional ground-water gradient is towards the west. Therefore, it seems that the ground-water movement seems to correlate well with the drainage of the surface water.



OFS GOLDFIELDS – Surface Topography Contours

OFS GOLDFIELDS – Water Level Contours

Figure 5.3. Surface topography and water-level contour maps of the Orange Free State Goldfields.

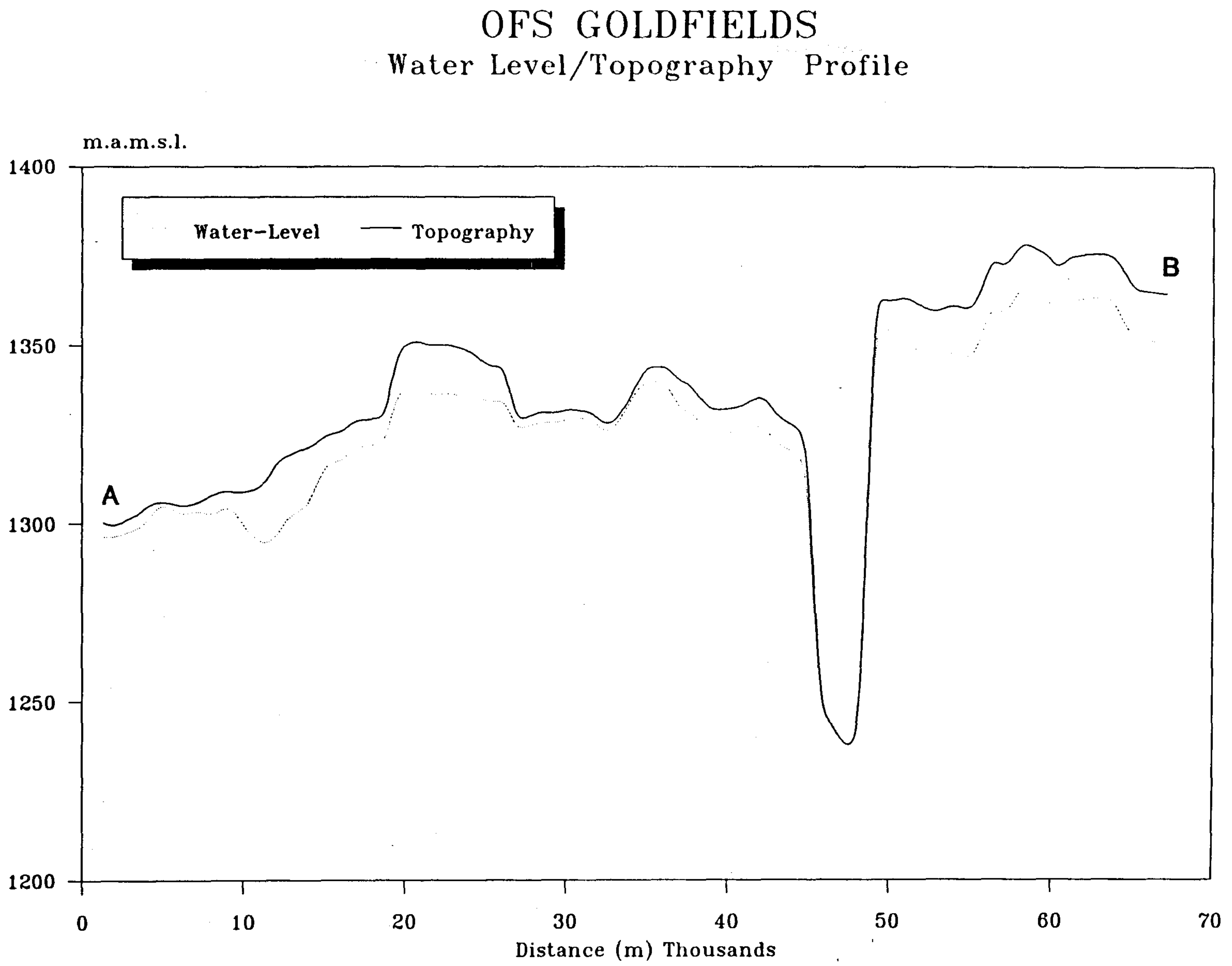


Figure 5.4. Surface topography/ground-water level relationship.

It can, therefore, be concluded that although the local ground-water movement is towards the Sand River, the general direction of ground-water movement is towards the west.

Due to the fact that the ground-water levels closely follow the topography in the region, this can be used as a guess to estimate ground-water levels at unknown points. The Bayes estimation procedure, as discussed by Van Tonder (1990), was used to determine the ground-water levels in three of the target areas:

(i) Loraine Gold Mine disposal area.
(ii) Beatrix Gold Mine disposal area.
(iii) Harmony Gold Mine disposal area (new).

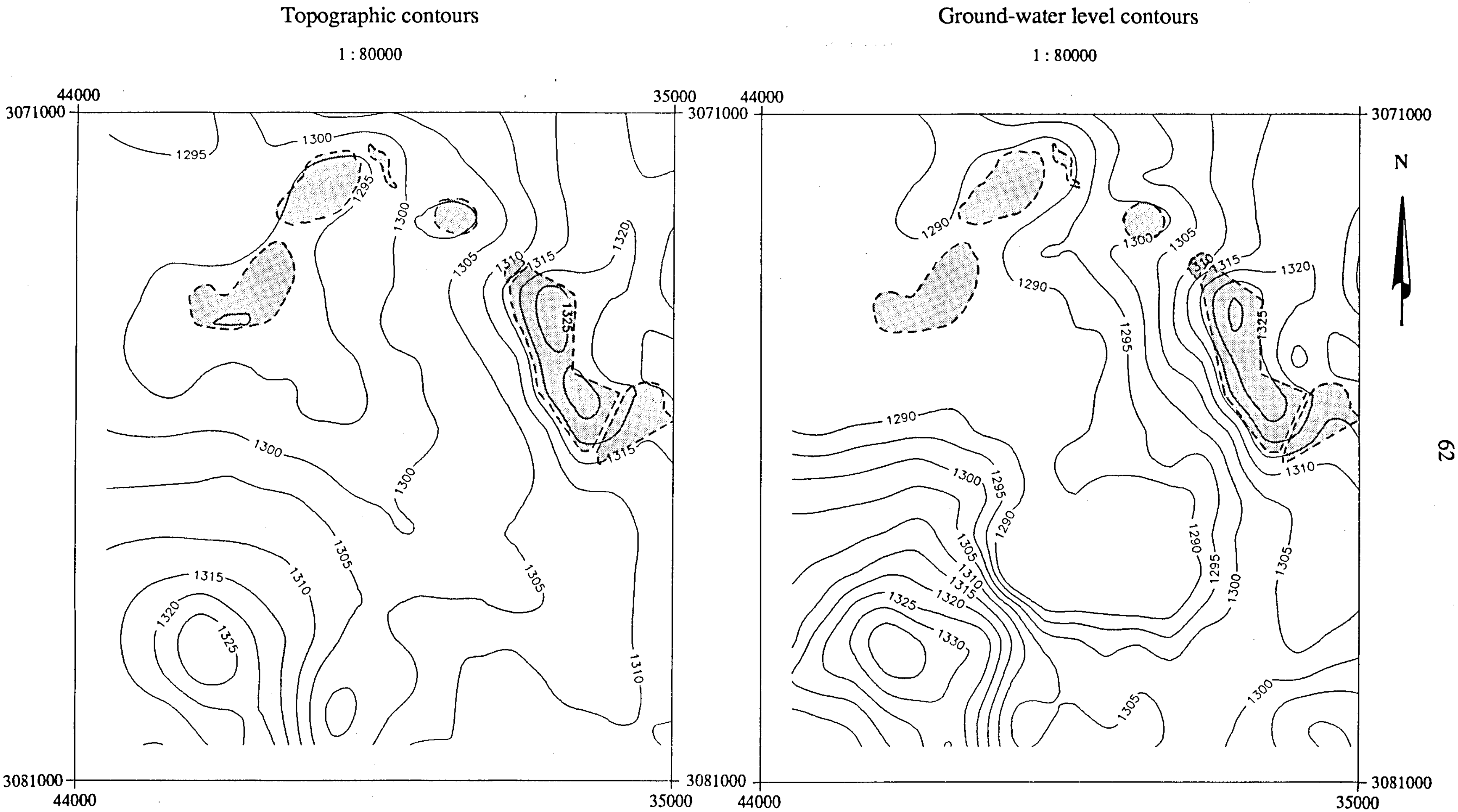
Figures 5.5 to 5.7 show the contours of the water levels at the three target areas, derived from the Bayesian procedure and using topographic values, obtained from ortho-topographical maps of the target areas, as guesses for the ground-water levels.

Pollutant migration almost entirely depends on ground-water flow patterns, which are mainly controlled by the existing ground-water gradients, locally as well as regionally. In order to calculate ground-water gradients over the target areas, the ground-water level distribution, obtained from the Bayesian estimation, was assimilated into a finite element computer program which calculated the ground-water gradients for the different target areas. The direction of ground-water flow, as indicated by these gradients, is represented by arrows and can be seen in Figures 5.8 to 5.10. The main direction of pollutant migration can also be obtained from these figures, as it correlates closely to the ground-water flow direction. The gradients can also be used to site monitoring boreholes more effectively.

Figure 5.11 represents the monthly water-level fluctuations, as measured by four water-level recorders throughout the study area. If the monthly water-level measurements, from July 1988 to April 1990, are evaluated, it is evident that the water levels did not vary significantly, except for seasonal variations and changes due to pumpage.

These small variations in water levels throughout the area can be ascribed to the fact that the study area is mainly utilized for dry land crop cultivation and grazing land. Some irrigation schemes are situated along the Sand River, as well as in the central west of the area. However, the water utilized for irrigation purposes, is obtained from a canal system, supplied by the Allemanskraal Dam.

Of the group of boreholes, borehole M 323 (DC 323) depicts a rather odd behaviour towards the latter part of the hydrograph. If borehole M 323 is looked at more closely, it is noticed that the latter part of the hydrograph changes considerably. The observed peaks

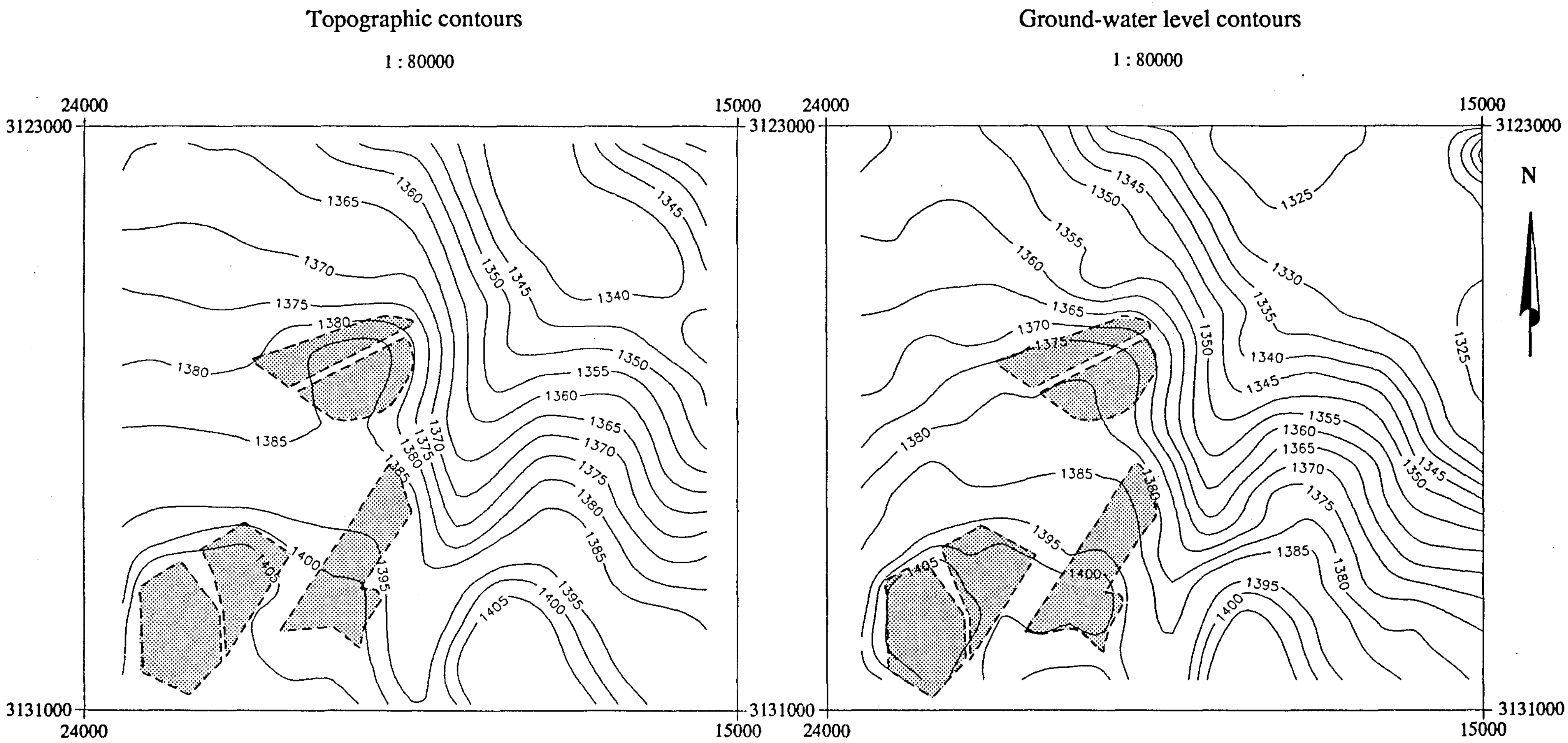

Topographic contours

1 : 80000

Ground-water level contours

1 : 80000

Figure 5.5. Surface topography and Bayesian ground-water level contours of the Loraine Mine disposal facility.



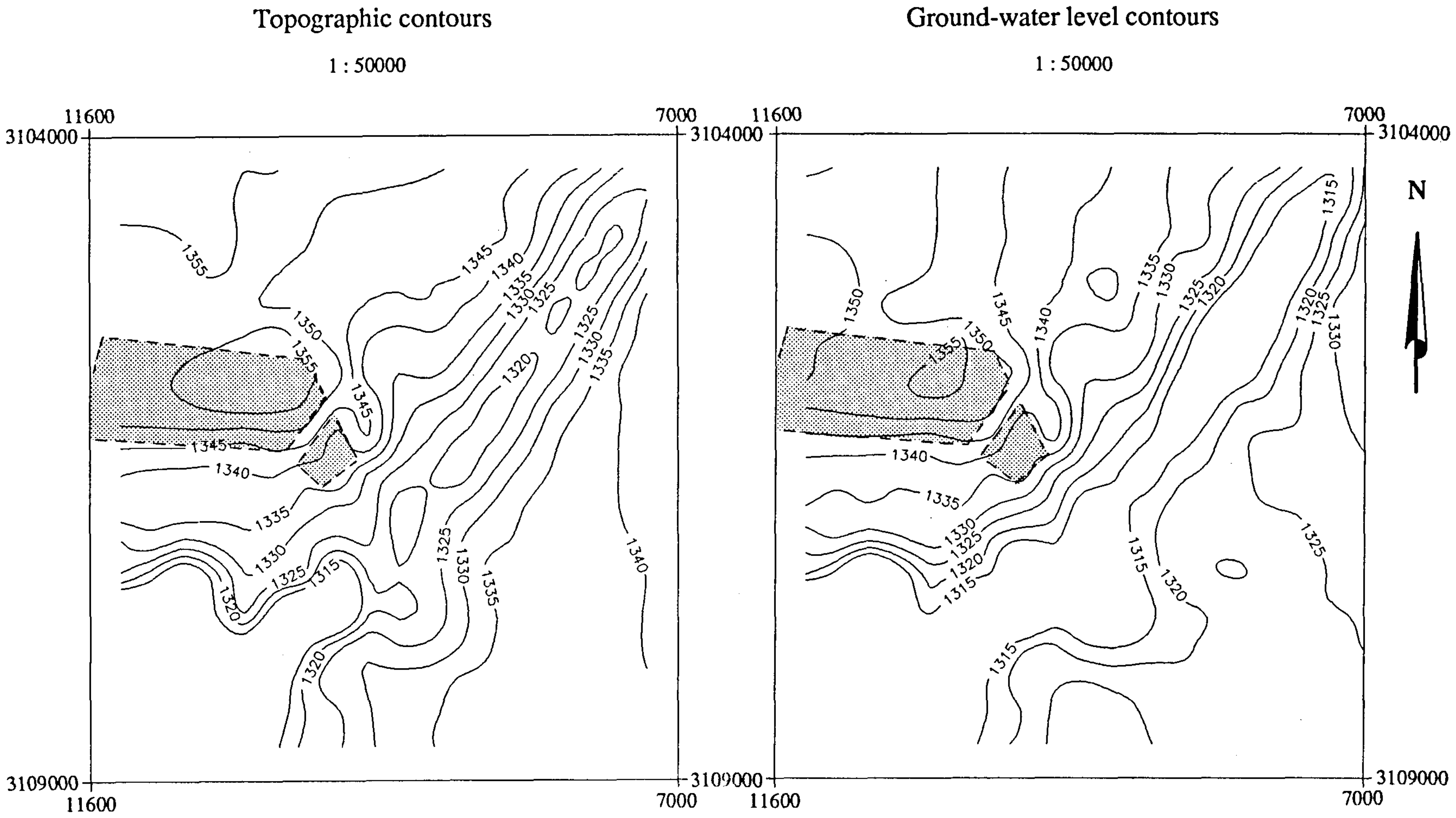
Topographic contours

1 : 80000

Ground-water level contours

1 : 80000

Figure 5.6. Surface topography and Bayesian ground-water level contours of the Beatrix Mine disposal facility.



Topographic contours

1 : 50000

Ground-water level contours

1 : 50000

Figure 5.7. Surface topography and Bayesian ground-water level contours of the Harmony Mine disposal facility.

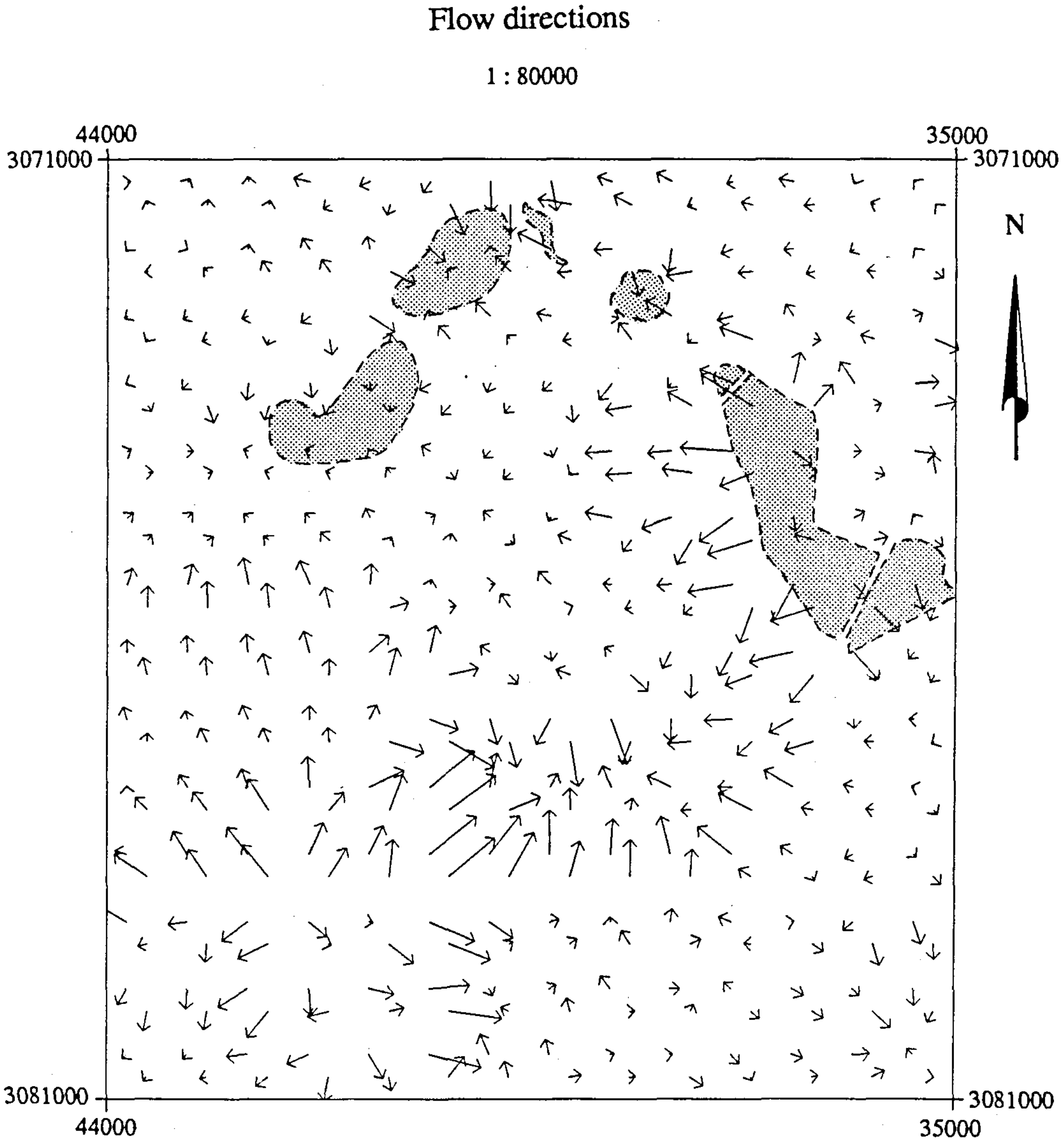


Figure 5.8. Ground-water flow directions at the Loraine Mine disposal facility.

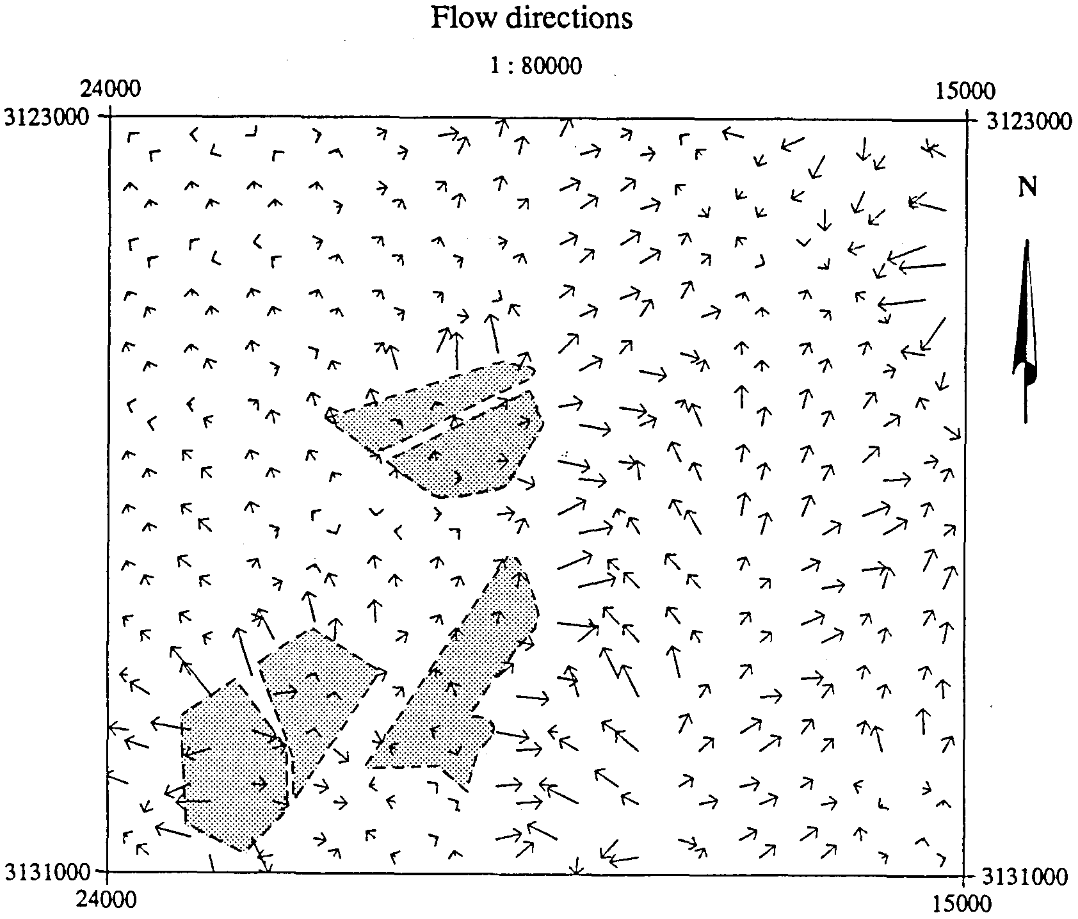


Figure 5.9. Ground-water flow directions at the Beatrix Mine disposal facility.

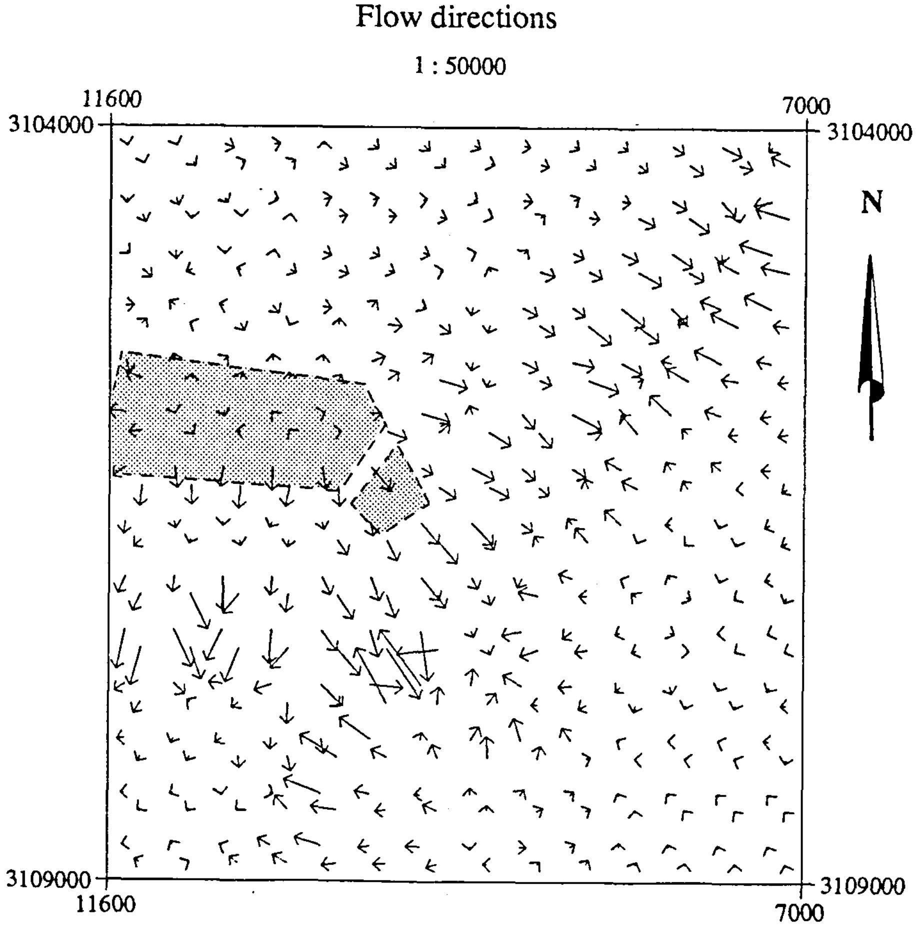
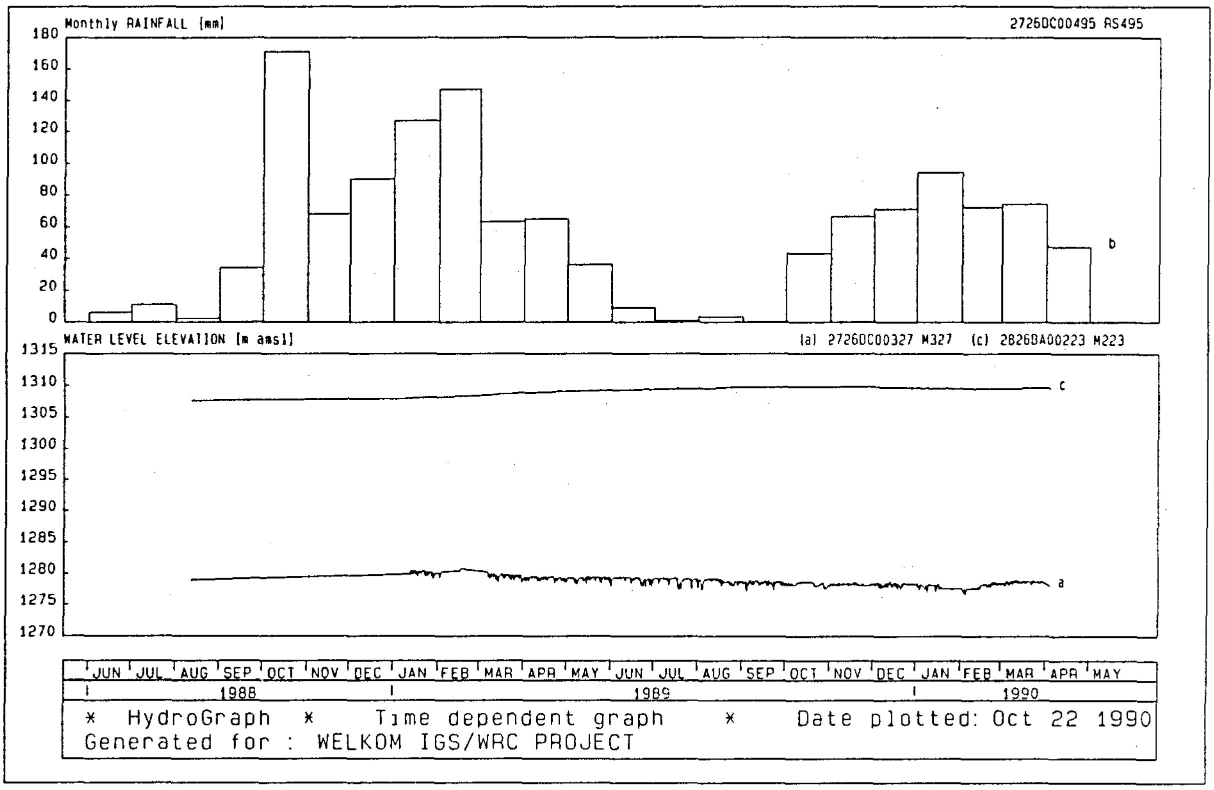


Figure 5.10. Ground-water flow directions at the Harmony Mine disposal facility.



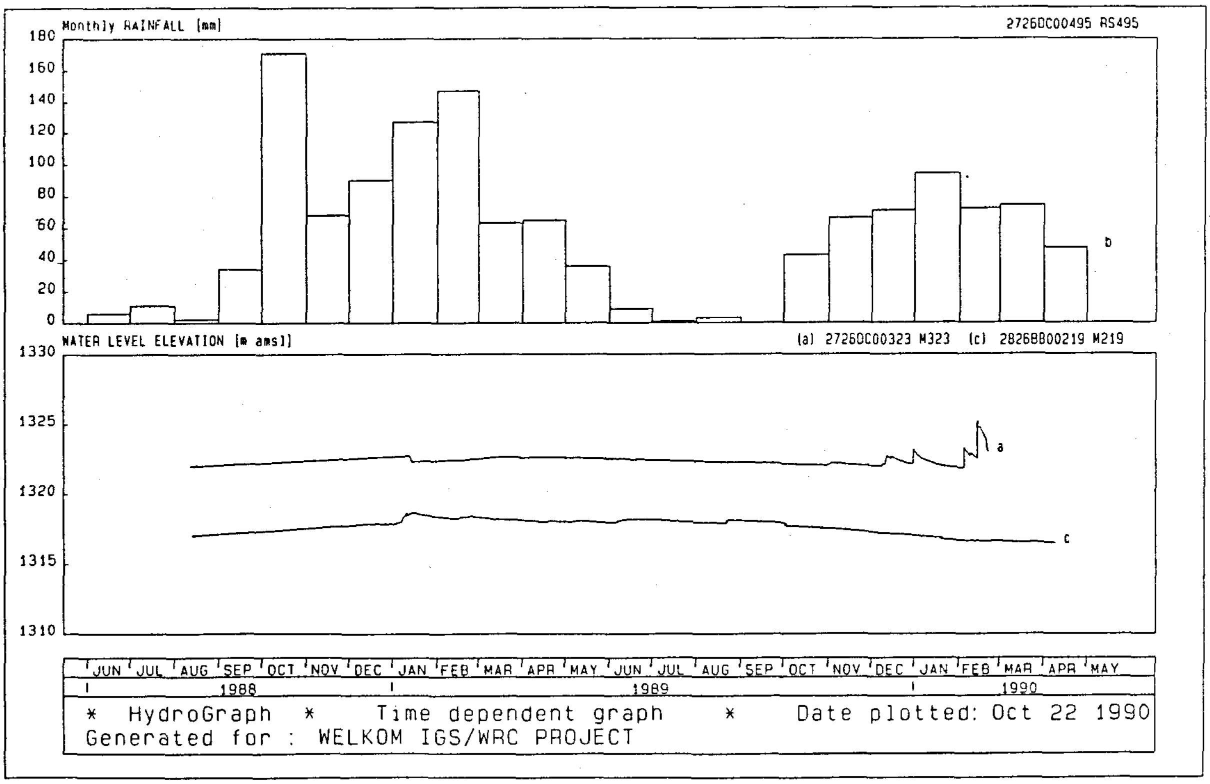


Figure 5.11. Monthly water-level fluctuations in the Orange Free State Goldfields.

correlate quite well with rainfall events during the period. Furthermore, the borehole was dry when drilled, explaining the sharp response to recharge (instantaneous), which might have occurred via cracks, ant or mice tunnels.

5.3 THE DEEP AQUIFER

As mentioned earlier, the faulted and fractured rocks of the Witwatersrand Group and the Ventersdorp Supergroup are the two major aquifers that occur beneath the Karoo sediments.

5.3.1 GROUND-WATER OCCURRENCE

Large quantities of deep ground water, with a dominantly NaCl-composition, are pumped to surface in the Orange Free State Goldfields. This ground water generally occurs hundreds of metres beneath the surface in the form of a confined aquifer. The piezometric water levels of the exploration boreholes in the area prove that this is a confined aquifer. In contrast with the Karoo aquifers, the deep aquifer has a large water-yielding capacity, because a mine such as Beatrix discharges about 10 to 25 Ml/d of deep ground water into surface reservoirs.

Another characteristic of the deep aquifer is the fact that although the water level has dropped hundreds of metres since pumping commenced 37 years ago, enormous quantities of water are still being pumped from underground. The origin of these huge quantities of water is also unknown.

As in the case of the shallow aquifer, the water is also concentrated in fractured zones, caused by faults and the intrusion of igneous rock. This is possibly one of the reasons why certain underground areas are dry, whereas other areas can be flooded by large volumes of water.

5.3.2 GROUND-WATER ABSTRACTION

Due to the large quantities of water present in the Witwatersrand rocks, an enormous quantity of this water is pumped to surface each day to dewater these areas to make it accessible for mining activities. The total discharge from all the mines is presently in the order of 155 million l/d.

This ground water has conductivities in the order of 500 mS/m, with a high Na^+ and Cl^--content and, therefore, it cannot be used for drinking or irrigational purposes. Consequently, the water from the deep aquifer is discharged in several ways. A small portion of this water is diluted by potable water and this mixture of water is then used in the gold reduction process and in underground coolers. However, the largest portion of underground water is discharged into evaporation areas and pans.

5.3.3 MODELLING THE DEEP AQUIFER

Calculation of the salt load, which has been introduced into nature in this way, can be done by simple arithmetic calculations. No projections have to date been made on the effect of additional dewatering, due to the expansion of mining. To examine future dewatering, pumpage and salts to be disposed of, a computer model is required.

As mentioned above, to obtain a reasonable estimate of the possible salt load to which the environment is exposed, the quantity of water extracted from the mines must be known. Such an estimate can easily be obtained for mine waters extracted up-to-date. However, if such an estimate is based on the past, as well as future water extraction from the mines, a major problem is encountered, i.e. future mine water extraction is unknown. At present, the only way to overcome this problem, is by the construction of a suitable numerical model.

According to Bear (1979), the two-dimensional flow of ground water can adequately be described by the diffusion equation:

$$S\,\partial h/\partial t = T\,(\partial^2 h/\partial x^2 + \partial^2 h/\partial y^2) - Q - K/l'\,(h - h_w) - C\,(h - h') \qquad (5.1)$$

where

C = transient leakage coefficient (d)

T = transmissivity (m^2/d)

S = storage coefficient

Q = discharge rate (m^3/d)

K = hydraulic conductivity of a confining layer (m/d)

l' = thickness of the confining layer (m)

h_w = hydraulic head in adjacent aquifer (m)

h' = initial hydraulic head in the aquifer (m)

t = time (d)

Equation (5.1) is a linear parabolic partial differential equation, for which a solution always exists, controlled by prescribed initial and boundary conditions. Unfortunately, boundaries of aquifers are irregular and complex, making it impossible to obtain an analytical solution of the above equation. Thus, one has to resort to numerical methods. Various numerical techniques exist, of which the finite difference and finite element techniques are the most frequently used in ground-water modelling. Due to the flexibility of the finite element method in handling irregular boundaries, this method was chosen for the ground-water model of the deep aquifer.

Two types of boundary conditions are generally encountered in aquifers:

(i) 'Dirichlet' or prescribed head (constant head) boundary conditions.

(ii) 'Neuman' or prescribed flux boundary conditions.

Dirichlet boundary conditions imply that the water levels along the boundaries of the aquifer are kept at a prescribed level. Such boundary conditions are mainly used when the water levels near the boundaries of the aquifer change little. Furthermore, this information must be known.

Neuman boundary conditions comprise prescribed flux across the boundaries. These conditions are commonly used when rivers or dams intersect the aquifer. They may also be used when the physical boundaries of the aquifer are not well-defined, but one has to have some knowledge regarding the water flow across the boundary. In the case of the Orange Free State Goldfields, Neuman boundary conditions apply.

Where water is abstracted at node (x_i,y_i) and pumped at specific rates $Q_w\ (x,g,t)$, the discharge can be expressed mathematically as:

$$Q\ (x,y,t) = \sum_{i=1}^{n} Q_w\ (x_i,y_i,t)\ \delta\ (x - x_i)\ (y - y_i) \tag{5.2}$$

where the dirac delta function (δ) has the property that when integrated over x and y, the function Q will equal Q_w at (x_i,y_i).

5.3.4 FINITE ELEMENT IMPLEMENTATION

This system of first order differential equations can now be solved numerically. Fundamental to the finite element method is the concept of discretization, where a continuous domain is represented as a number of adjacent subareas (finite element mesh). Figure 5.12 represents the constructed finite element mesh. Due to the large size of the area, as well as the sparse data, the elements are large (2,5 km x 2,5 km). The mesh consists of 645 square elements and 700 nodes.

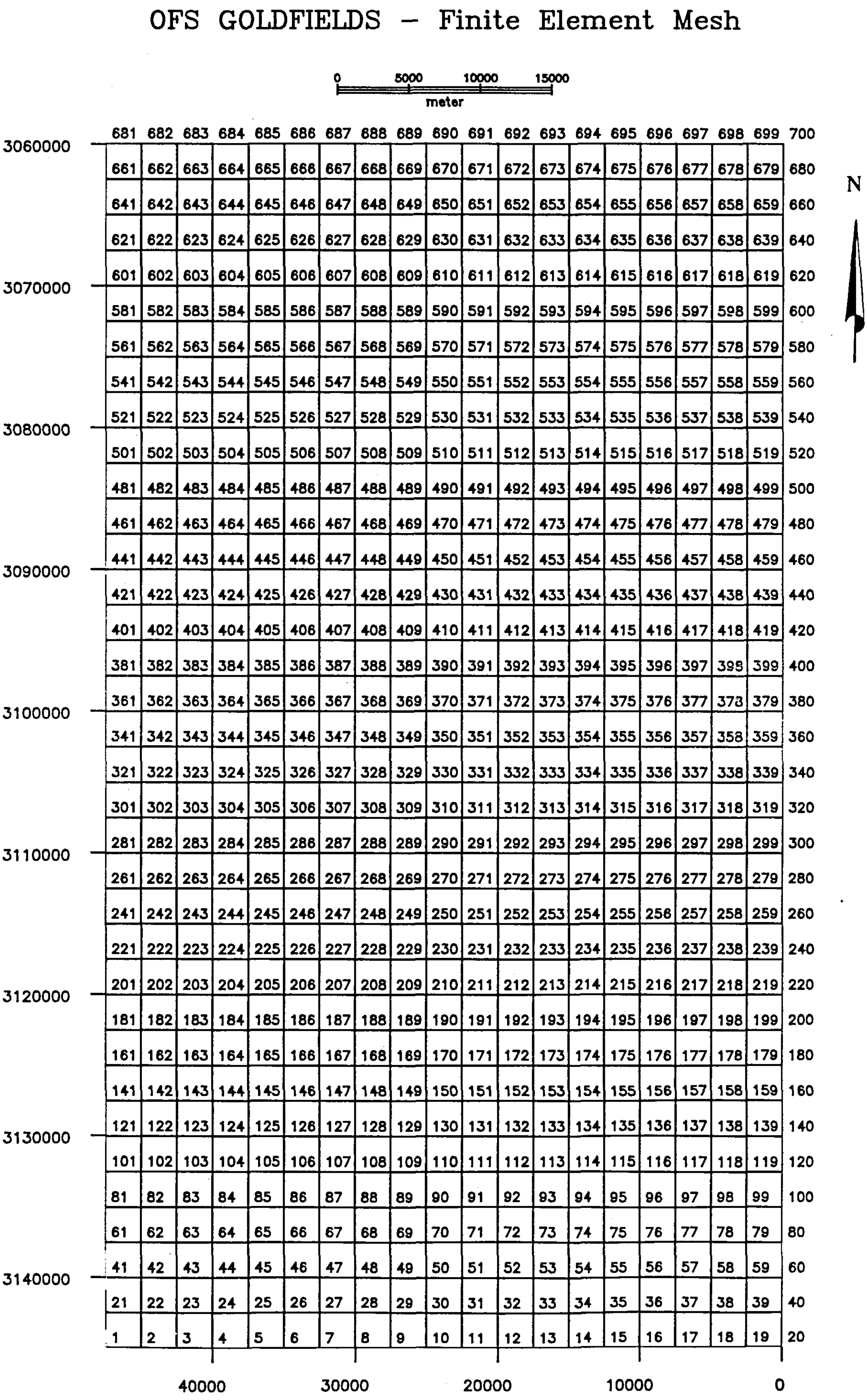


Figure 5.12. Constructed finite element mesh used for the simulation of the deep aquifer's water level.

A ground-water model of this kind requires input of the transmissivity (T), storage coefficient (S) and the rest water level at each node. The reaction of a ground-water system can only be judged from its observed water-level distribution (Müller and Botha, 1986). When modelling any aquifer, special attention should be given to the initial hydraulic heads of the aquifer. In the case of the Orange Free State Goldfields, these values are almost non-existent. Only a few water levels at different times and localities were obtained and used. Hence, it was decided to start the simulations from a horizontal plane. This implied that although the simulated water levels would not be accurate, one could still use hydraulic parameters (transmissivity and storativity) to simulate future water extraction in the area. Naude (1988) suggested a transmissivity of 5 m^2/day and a storage coefficient of 5×10^{-4}. Naude also stated that the initial rest water level of the deep aquifer at Beatrix mine was about 100 m below surface. As no other records of these parameters are available, these values were taken as initial conditions, at each node over the whole area.

Although taking the water level uniformly over the whole area as 100 m may evoke criticism, the question arises whether taking the water level at 50, 100 or 300 m will make any difference. As all the variables are estimated values, calibration of the model would be impossible and only a general tendency would have to be observed. The only way the model can be calibrated, is by knowing the present water levels in the mines, and by manipulating the T- and S-values, the water levels can be simulated to fit the water levels observed in the mines.

According to Botha and Bakkes (1980), a problem that is encountered near or at an abstraction point (sink) is that the solution tends to be inaccurate. This is because the mathematical solution has a logarithmic singularity at the position of such a sink, meaning that the water-level drawdown at a sink is inaccurate.

5.3.5 SIMULATION OF THE DEEP ORANGE FREE STATE GOLDFIELDS AQUIFER

The program simulates the drawdown for any number of specified time steps. By comparing the simulated water levels with observed water levels at specific mines, an idea can be formed whether the initial T- and S-values are correct.

After more than 30 simulations, by using a $T = 10$ m^2/d and a $S = 0{,}001$, the simulated water levels approximated the historic water levels, the latter presently being:

Beatrix Mine about 900 m below surface
President Brand Mine about 1 300 m below surface
Loraine Mine about 300 m below surface

The positions of the mines are given in Figure 5.13.

Figures 5.14, 5.15 and 5.16 represent the simulated drawdown after 10, 24 and 37 years respectively. The start of the simulation was in 1952.

Figure 5.15 represents the drawdown after 24 years, just before Beatrix Mine commenced pumping. As can be seen from the figure, the drawdown at Beatrix Mine, at this stage, was 50 m and the water level thus 150 m below surface. This correlates reasonably with the 100 m used for an initial water level in the simulation.

In simulating the water levels for 37 years, about 1 240 million cubic metres of water was pumped to the surface. If the pumped water has an average conductivity of 450 mS/m, the total dissolved solids in the water are in the order of 3 000 mg/l. The total amount of salt pumped to the surface amounts to 3,717 million tonnes. As most of this water has been evaporated, the salts either precipitated or seeped into the ground.

The ground-water model can now be used for prediction of future pumpage and salt loads. To demonstrate the use of the model, suppose a new mine is started in the north-eastern corner of the area. The resultant dewatering, after a further 20 years (57 years in total), is shown in Figure 5.17. A pumping rate of 20 Ml/d has been assumed for the new mine. In total, about 2 218 million cubic metres of water will have been pumped to the surface. The total amount of salt pumped to the surface is about 6,7 million tonnes, which is approximately twice the amount pumped to the surface during the first 37 years.

Comparing Figure 5.16 with Figure 5.17, it can be seen that the extent of the cone of dewatering does not increase dramatically. However, over the same period, the drawdown increases quite sharply, displaying a steep slope.

To conclude, the development of new mines in the area might result in additional environmental pollution, as the required dewatering activities would lead to an increased volume of water being pumped up to the surface.

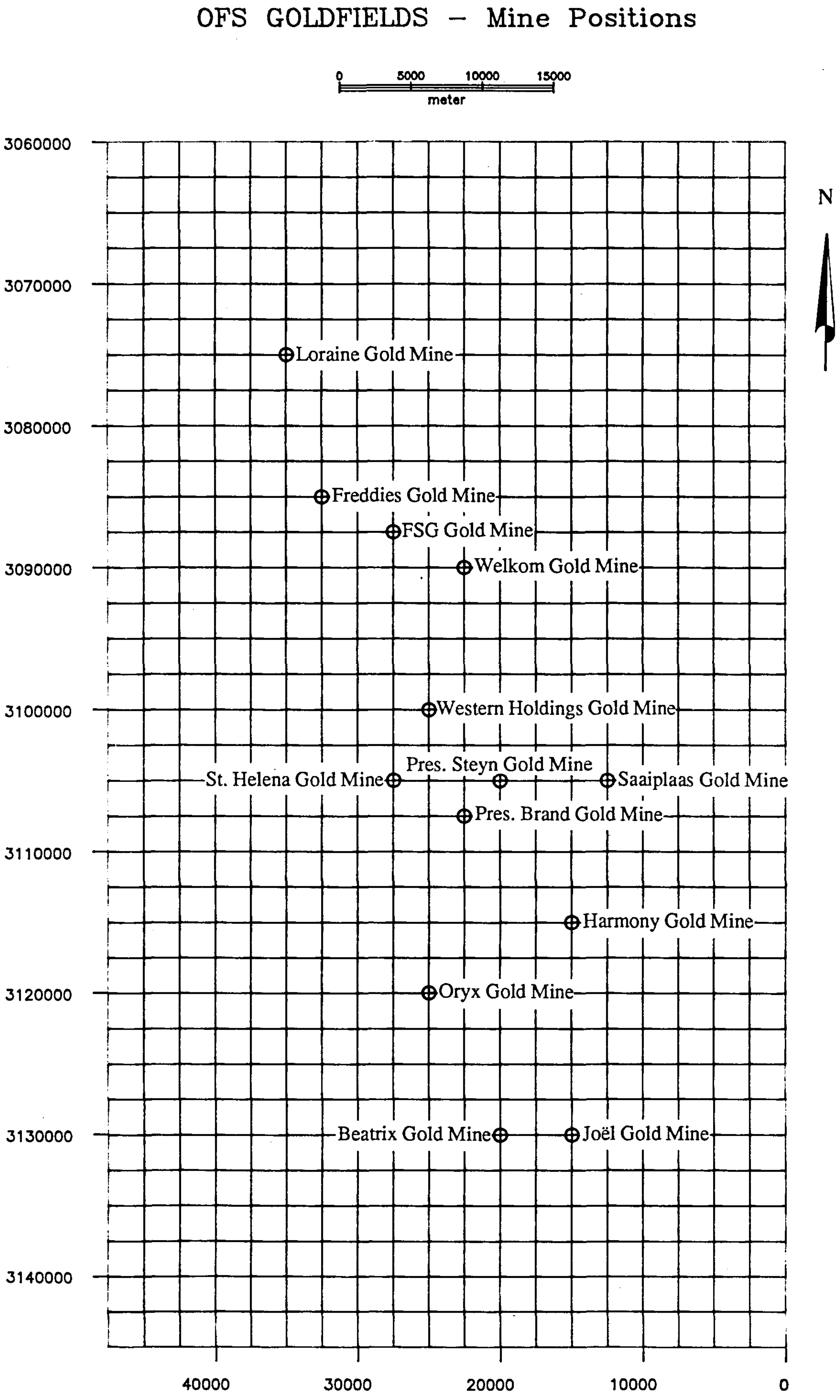


Figure 5.13. Positions of the mines at which water levels of the deep aquifer are known.

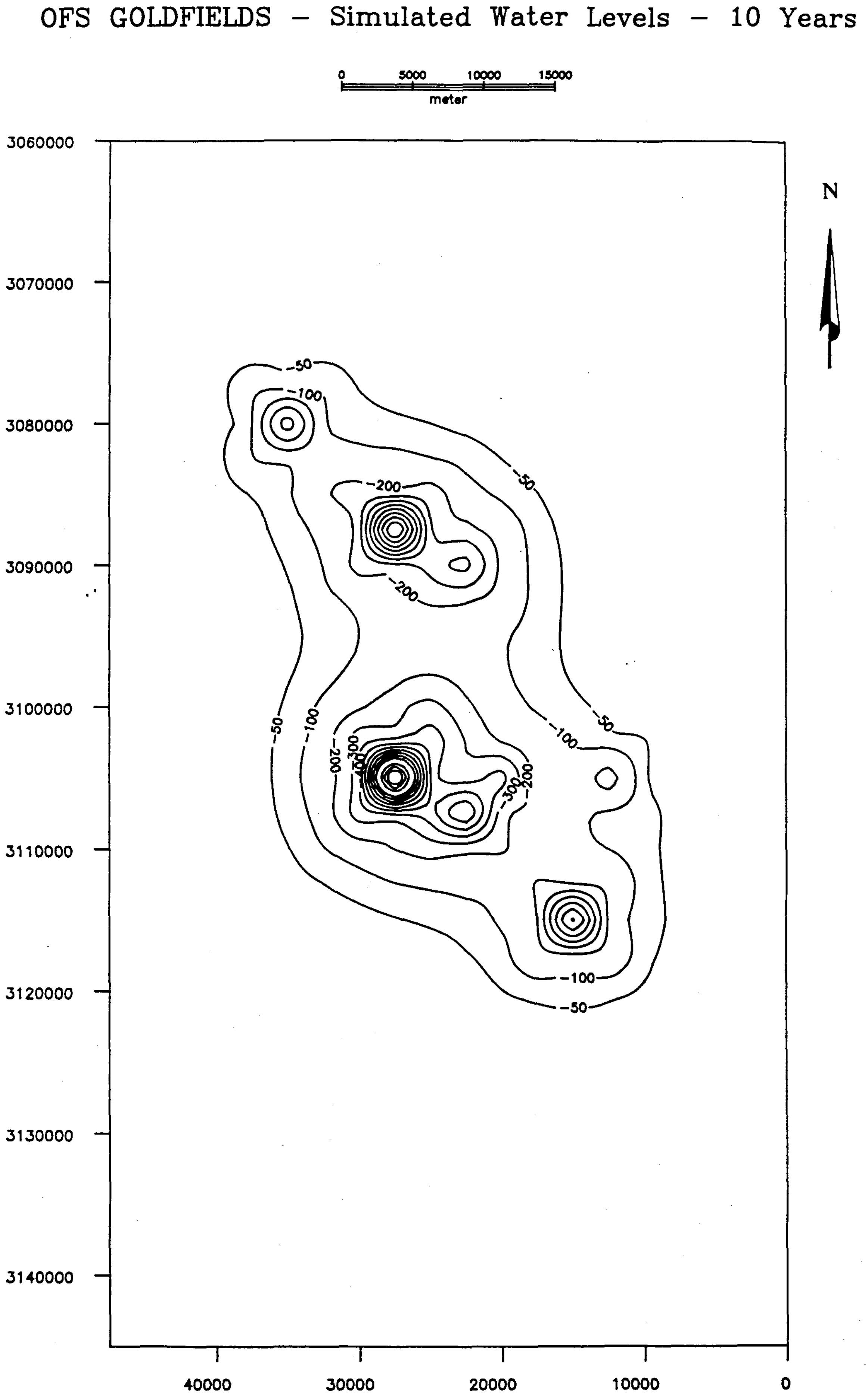


Figure 5.14. Simulated drawdown of the water levels in the deep aquifer after 10 years (1962).

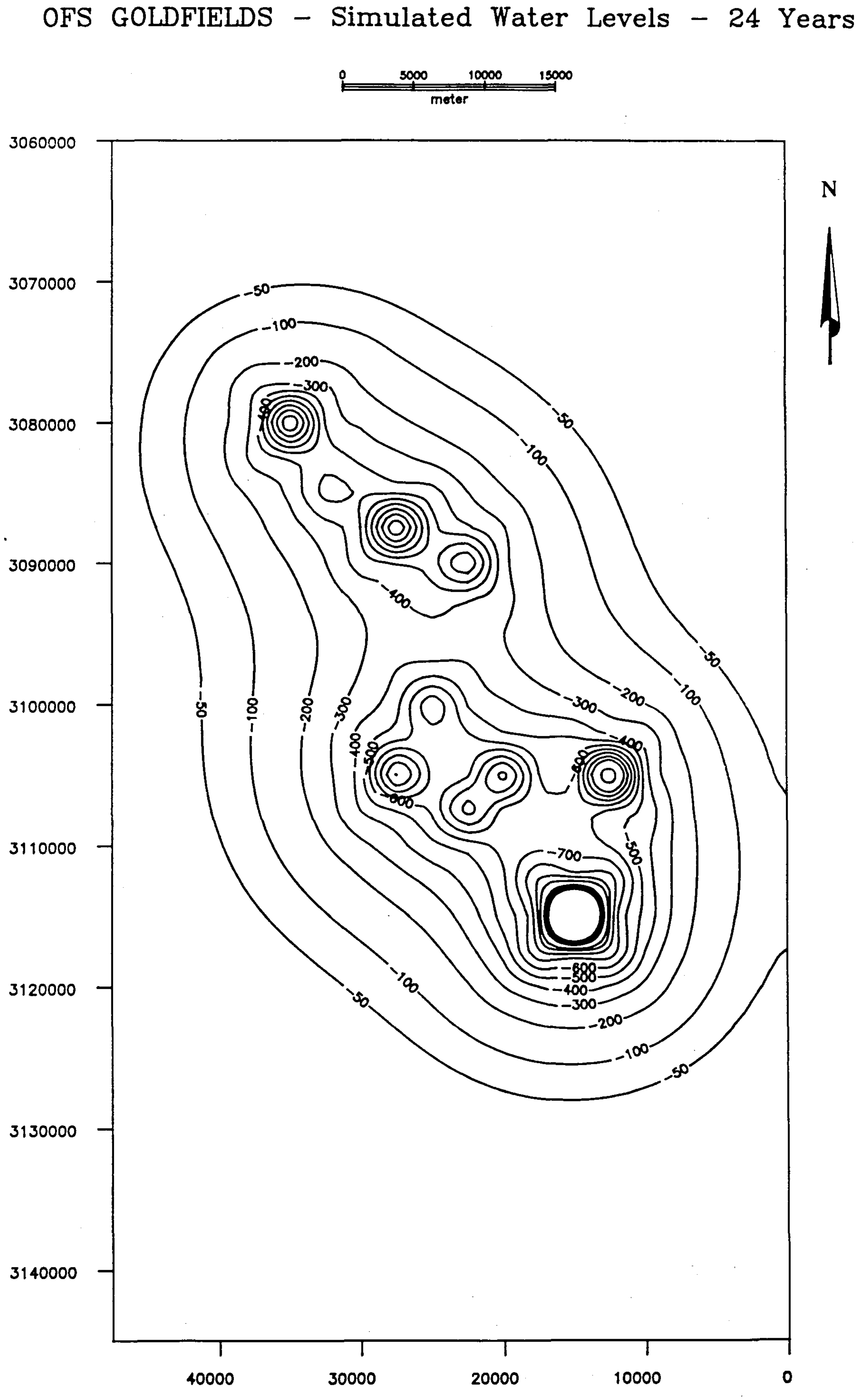


Figure 5.15. Simulated drawdown of the water level in the deep aquifer after 24 years (1976).

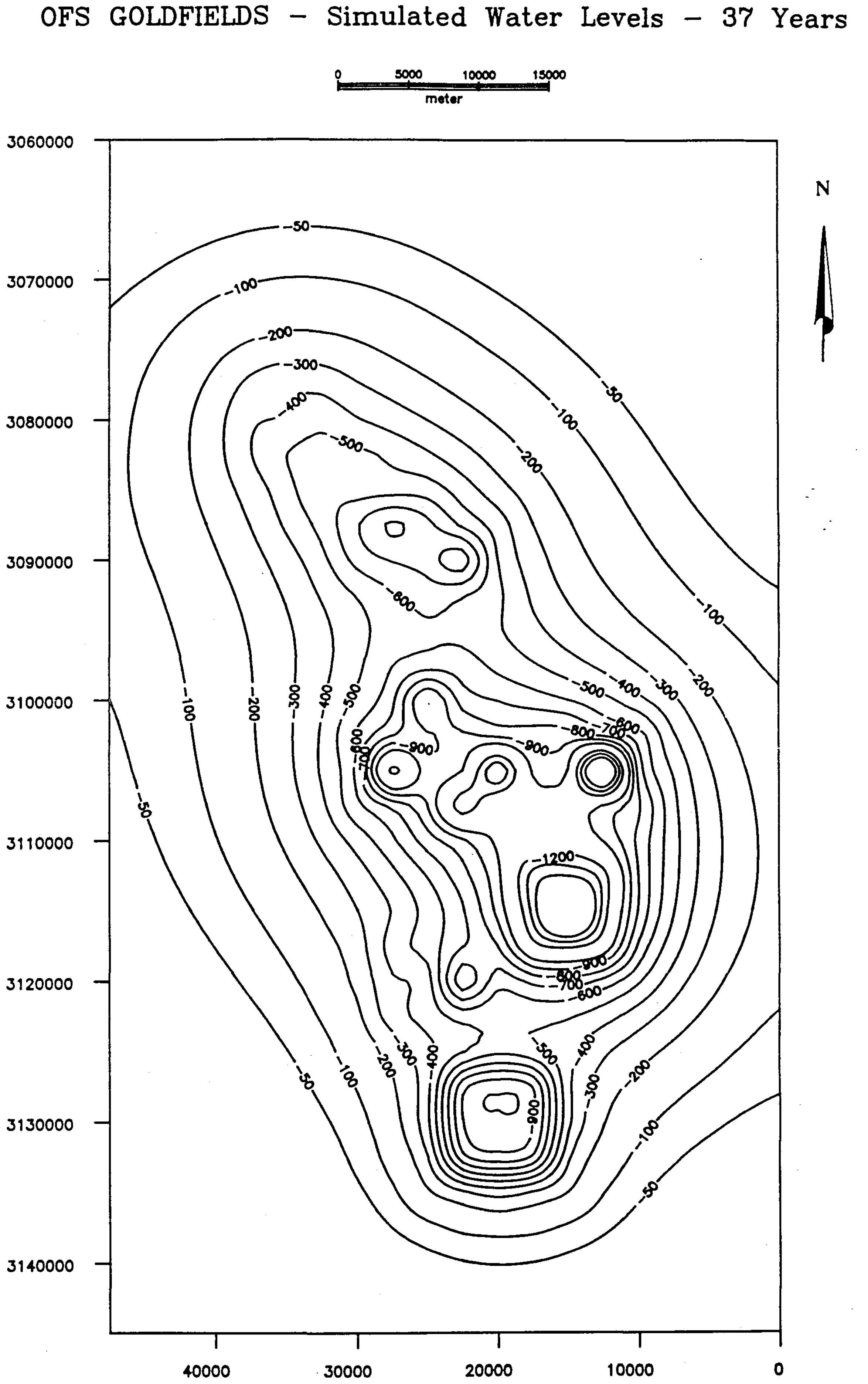


Figure 5.16. Simulated drawdown of the water level in the deep aquifer after 37 years (1989).

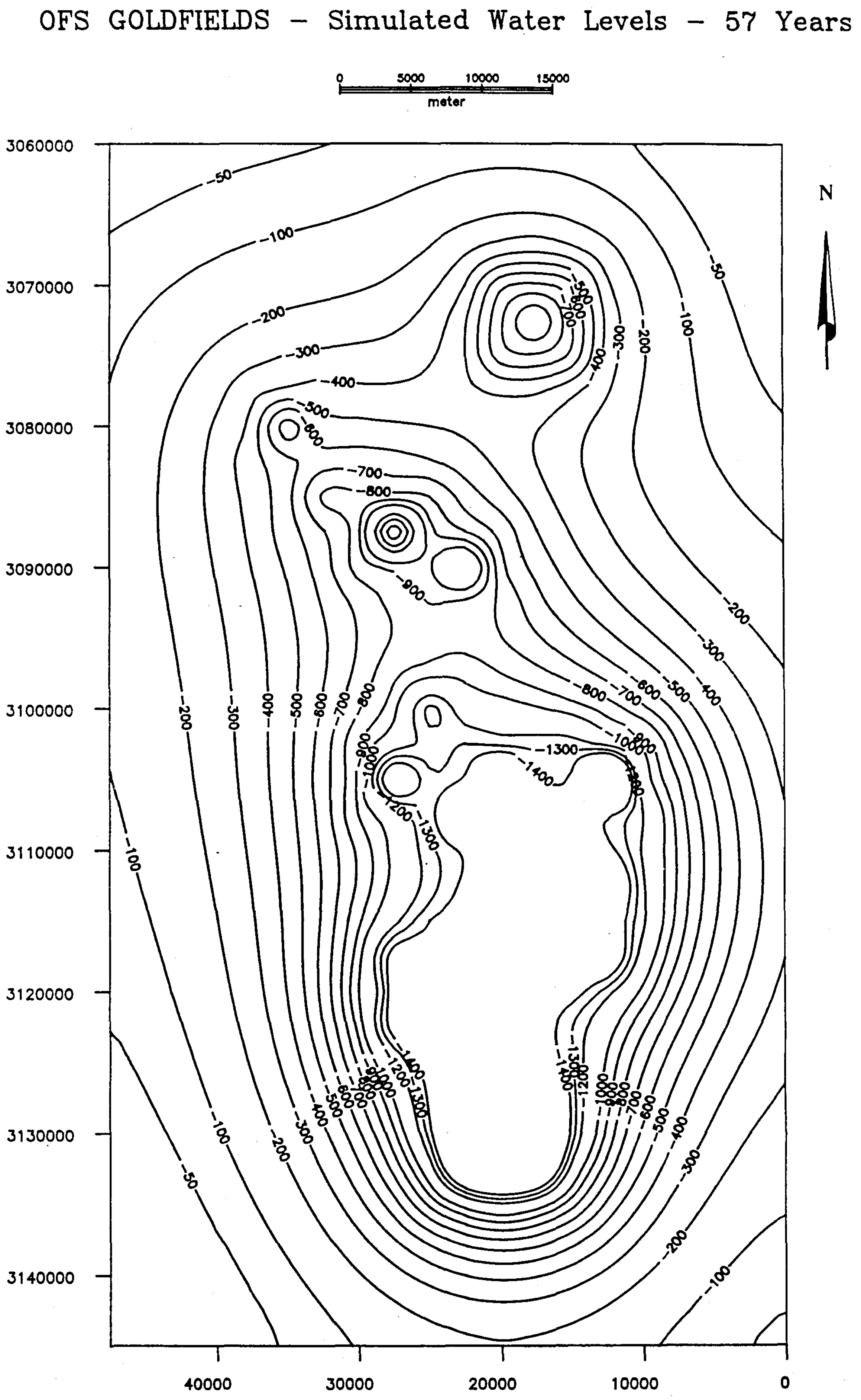


Figure 5.17. Simulated drawdown of the water level in the deep aquifer after 57 years (2009).

CHAPTER 6

HYDROCHEMISTRY

6.1 INTRODUCTION

Both surface and ground water have been sampled extensively for chemical analyses of the macro constituents and for specific micro elements. This chapter is intended to show the distribution of these constituents and to indicate trends and anomalies to date.

6.2 EXISTING WATER QUALITY CRITERIA

Due to the presence of heavy metals, organic compounds, high concentrations of the macro constituents and high cyanide content in the case of mining effluent, water originating from industries, mining activities and municipalities can be toxic. Table 6.1 presents typical chemical constituents in mine water and industrial effluent, as well as limits and possible effects which the elements may have.

TABLE 6.1. PROPOSED DRINKING-WATER CRITERIA AND GENERAL STANDARDS FOR INDUSTRIAL EFFLUENT (After Kempster and Smith, 1985)

Chemical Constituent	Recommended	Maximum	Industrial General Standards	Possible effect
Aluminium (Al)	150 µg/l	500 µg/l	-	-
Boron (B)	500 µg/l	2000 µg/l	1000 µg/l	More toxic to plants
Bromide (Br)	1000 µg/l	3000 µg/l	-	-
Cadmium (Cd)	10 µg/l	20 µg/l	50 µg/l	Accumulative poison Associated with Zn
Calcium (Ca)	150 mg/l	200 mg/l	-	Excessive tartar forming, Essential nutritional element

Chloride (Cl)	250 mg/l	600 mg/l	-	Undesirable in irrigation water. Corrosion of warm water systems
Copper (Cu)	500 µg/l	1000 µg/l	1000 µg/l	Essential nutritional element
Cyanide (CN)	200 µg/l	300 µg/l	500 µg/l	Toxic
Iron (Fe)		100 µg/l	1000 µg/l	- -
Lead (Pb)	50 µg/l	100 µg/l	100 µg/l	Toxic in soft waters
Magnesium (Mg)	70 mg/l	100 mg/l	-	Hardness. Diarrhoea in new users
Manganese (Mn)	50 µg/l	1000 µg/l	400 µg/l	Essential nutritional element
Nitrate (N)	6 mg/l	10 mg/l	-	Infant methaemoglobinaemia
Potassium (K)	200 mg/l	400 mg/l	-	Purgative
Sodium (Na)	100 mg/l	400 mg/l	Not to be increased by more than 50 mg/l above that of the the intake water	Injurious to people with heart-, kidney- and circulation of the blood problems
Sulphate (SO_4)	200 mg/l	600 mg/l	-	Purgative to new users
Zinc (Zn) samples of		1000 µg/l	5000 µg/l	5000 µg/lScreen concentration > 1000 µg/l for Cd or Pb
pH	6,0 - 9,0		5,5 - 9,5	Corrosive potential
Electrical conductivity	70	300 mS/m	250 mS/m	Corrosive potential

Table 6.2 depicts typical concentrations of some of the macro elements found in polluted or unpolluted ground- and surface water. If these values are compared to the general standards for industrial effluent, it is observed that virtually all the polluted samples exceed the recommended maximum limit.

TABLE 6.2. COMPARISON OF TYPICAL POLLUTED AND UNPOLLUTED GROUND- AND SURFACE WATER IN THE STUDY AREA

Site Description	Ca mg/l	Mg mg/l	Na mg/l	K mg/l	Cl mg/l	SO4 mg/l	EC mS/m
ECCA	61	25	225	3,5	240	6	180,0
ECCA	55	22	40	3,5	30	24	52,0
ECCA	74	30	117	5,8	32	31	94,0
ECCA	81	38	194	18,4	247	75	150,0
ECCA	116	66	144	19,8	221	64	150,0
ECCA	47	45	94	10,6	151	231	53,0
ECCA	68	33	189	2,3	63	111	61,0
ECCA POL	1182	548	1238	38,4	4770	1591	1385,0
ECCA POL	41	53	800	19,5	1220	37	480,0
ECCA POL	248	46	550	10,9	1414	287	400,0
ECCA POL	623	200	541	23,1	953	2345	555,0
ECCA POL	48	84	7759	20,0	7484	4297	2760,0
ECCA POL	50	80	1064	26,6	1569	121	567,0
ECCA POL	310	192	670	22,3	886	1765	533,0
BEAUF	44	2	145	0,8	58	1	67,0
BEAUF	131	27	78	7,4	40	2	81,0
BEAUF	184	18	103	4,3	76	2	90,0
BEAUF	190	26	94	8,6	130	6	100,0
BEAUF	67	32	39	13,5	75	3	75,0
BEAUF	47	24	95	2,1	11	54	60,0
BEAUF	23	10	93	5,5	9	13	50,0
BEAUF POL	955	388	1669	59,0	4937	828	1320,0
BEAUF POL	1443	655	872	53,0	5614	1249	1462,0
BEAUF POL	375	123	490	19,3	1350	250	430,0
BEAUF POL	120	50	318	8,7	557	299	232,0
BEAUF POL	599	304	197	25,9	2010	116	660,0
BEAUF POL	637	338	108	24,8	2151	126	639,0
BEAUF POL	728	504	147	46,2	3075	62	843,0
EVAP.M	957	373	351	115,0	4731	4512	1677,0
EVAP.M	694	210	179	10,5	1791	116	527,0
EVAP.M	173	35	550	31,0	897	534	350,0
EVAP.M	281	105	562	28,2	944	855	490,0
EVAP.M	501	365	1629	46,1	2835	1909	920,0
SEWAGE	89	50	181	29,2	183	404	144,0
SEWAGE	78	22	86	17,2	94	93	75,0
S.DAM	631	105	787	31,3	1170	1402	500,0
S.DAM	621	310	634	14,9	1252	3264	610,0
S.DAM	551	95	950	40,7	1329	1232	450,0
S.DAM	561	84	550	23,1	1059	803	400,0
S.DAM	812	104	696	26,2	1262	1069	370,0
S.DAM	1072	334	1976	44,2	4118	1921	770,0

ECCA - Ecca ground water
BEAUF - Beaufort ground water
ECCA POL - Polluted Ecca ground water
BEAUF POL - Polluted Beaufort ground water
S.DAM - Slimes dam
EVAP.M - Evaporation dam (mines)
SEWAGE - Sewage works

A short discussion of the significance of the presence of these constituents, as well as the hydrochemical processes and their significance to the ground-water quality, is found in Appendix III.

6.3 CHEMISTRY OF THE SURFACE WATER

6.3.1 PANS AND DAMS

More than 5000 hectares of land in the Orange Free State Goldfields are used as evaporation areas for effluent and mine water, with a total storage capacity in excess of 145 x 10^6m^3. Table 6.3 lists the evaporation pans and dams in the area, as well as the type of effluent they receive.

TABLE 6.3. STATISTICS OF PANS AND DAMS RECEIVING EFFLUENT WATER

Mine or sewage works	Total effluent Ml/d	Pan, dam or stream	Type of water	Surface area (ha)	Effluent remain in the system Ml/a	Effluent recycled
Welkom Wit Pan (sewage works)	23	Wit Pan	SW+PSE	293	4015	12 Ml/d re-use by municipalities 11 Ml/d flow into Wit Pan
Welkom Theronia (sewage works)	19	Toronto Pan Flamingo Pan	SW+PSE PSE	292 131	1650	Winter: 8 Ml/d re-use by municipalities 11 Ml/d flow into Flamingo and Toronto Pan Summer: Everything re-use by municipalities
Odendaalsrus (sewage works)	4	N.Vlei	RW+UG+ PSE	53	438	2,8 Ml/d re-use by municipalities 1,2 Ml/d flows into N.Vlei
Virginia (sewage works)	18,5	Sand River	SW+PSE			Re-use by mines and municipalities A portion flows into the Sand River
Allanridge and Loraine (sewage works)	2	Stink Pan	SW+PSE	120	730	
FSG (sewage works)	4	D Dam	RW+UG+ PSE	35	1460	
Beatrix (sewage works)	1	Theron Spruit	SW+PSE			
Joël (sewage works)	1	Doring River	SW+PSE			
Oryx (sewage works)	1	Bosluis Spruit	SW+PSE			

NCP (yeast)	0,195	Farm Blesbok Pan		24	71
Freegold	103,7	12A Dam	RW+UG+SW	76	
		12B Dam	RW+UG+SW	18	
		12C Dam	RW+UG+SW	45	
		13 Dam	RW+UG+SW	137	33405
		RWD Dam	RW+UG+SW	36	
		D Dam	RW+UG+SW	35	
		N Vlei	RW+UG+SW	53	
		Dankbaar Pan	RW+UG+SW	300	
		Doring Pan	UG+RW	220	
Loraine	4,4	Swart Pan	RW+UG	125	1608
Joël		Evap. Dams	RW+UG	111	
St. Helena	13	Wolve Pan and Riet Pan System	RW+UG+ PSE	699	4687
Beatrix	1,1	Evap. Dams	RW+UG	431	400
Oryx	16	Evap. Dams	RW+UG	816	5832
Harmony	30	Evap. Dams	RW+UG	11000	10814
TOTAL				5100	65110

PSE = purified sewage effluent
RW = reduction works water
UG = deep ground water
SW = storm water

Although the Piper diagram is generally used to classify ground waters with different chemical composition, it was used to classify the surface waters of the Orange Free State Goldfields. The reason being to correlate some of the chemical characteristics of the surface water with the ground-water chemistry.

Figure 6.1 is a Piper plot of water samples taken from the evaporation areas and the slimes dams environment. In the anion triangle, a clear tendency exists towards the Cl^-- and SO_4^{2-}-portions of the diagram, whereas in the cation portion of the diagram, the trend from the Na^+-corner towards water with a higher percentage of Ca^{2+} is also evident. Considering the evolutionary process through which mine water goes, as it is pumped from the mine, through the reduction works, then onto the slimes dams, back to the reduction works and finally, after numerous cycles, into the evaporation areas, the trends demonstrated in these diagrams, are to be expected. In more detail, the mine water is a dominantly NaCl-water. On the slimes dams, sulphate is introduced through bacterial oxidation of the pyrite. In the reduction works, calcium oxide is added to raise the pH of the water well above 7,0. The degree to which the original mine water has therefore been changed by man-made activities, towards a water high in SO_4^{2-} and Ca^{2+}, is clearly demonstrated in this diagram.

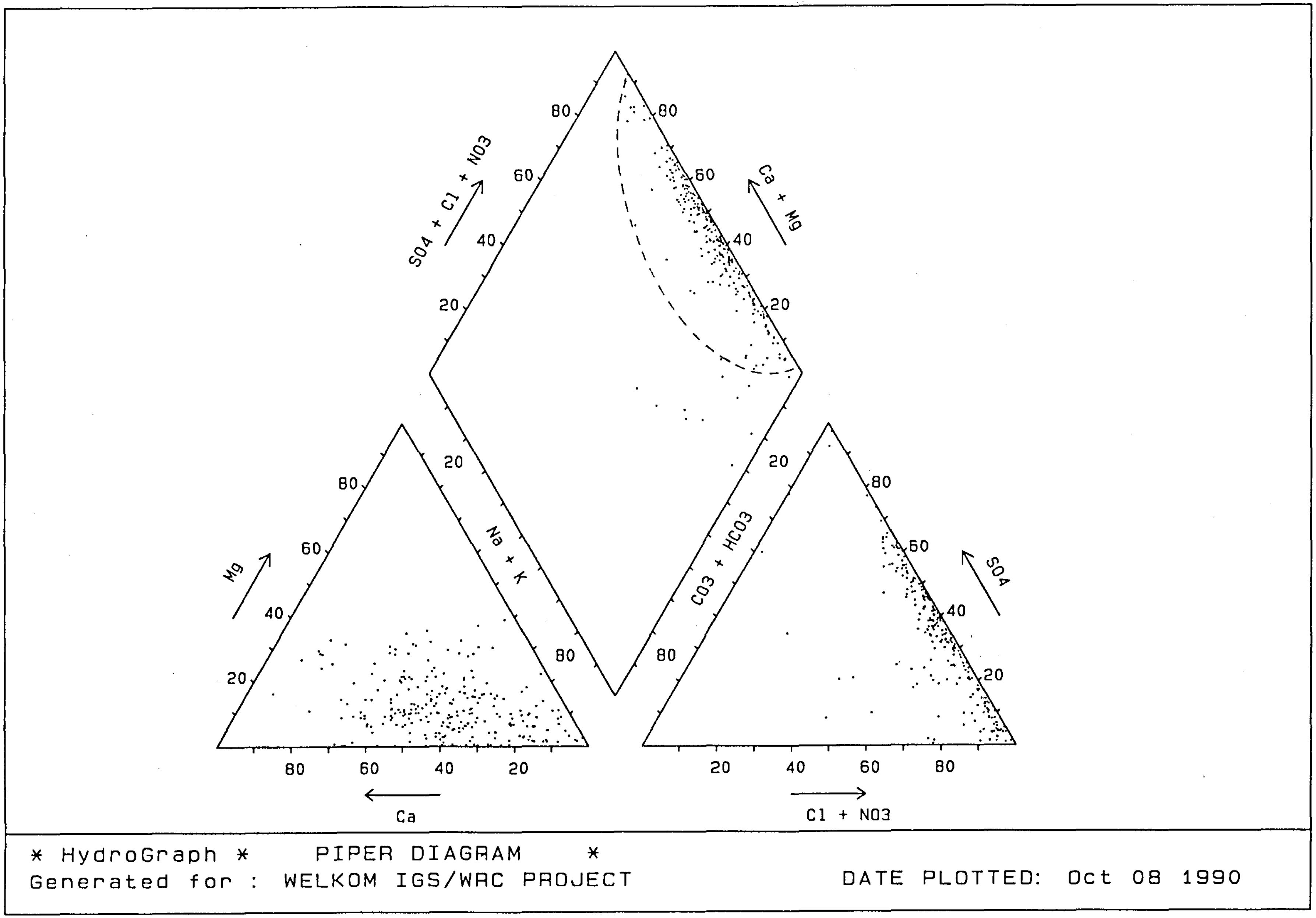


Figure 6.1. Piper plot of excess mine water.

In Figure 6.2, all surface waters sampled during this investigation, have been plotted. This constitutes the same plot as in Figure 6.1, with samples taken from water sources not directly used for evaporation purposes, also included. The latter constitutes only a few additional points on the diagram, some of which plot towards the CO_3^{2-}/HCO_3^--corner of the diagram.

To enhance the chemical differences in the surface waters even more, six of the basic anions and cations were plotted on triangles, similar to the Piper diagram (Figure 6.3). All the surface water samples, as well as samples from the Loraine- (old) and Beatrix Goldmine (new), were plotted on these diagrams. Furthermore, the samples were divided into electrical conductivity ranges, depicted on the legend of the figure. From the figure, it is noted that in all three cases, the fresh water (EC ranging from 0 - 100 mS/m) is almost situated in the centre of the diagram, i.e. the respective ions are almost in equal ratios to one another. However, as the electrical conductivity increases, the Ca, Na, SO_4 and Cl-ratios increase, coinciding with typical mine effluent.

If the Loraine surface waters are compared to the Beatrix surface waters, it is found that in both cases the Cl-ratio increases significantly as the conductivities increases. Furthermore, the Loraine samples also show an increase in SO_4, which is almost totally absent in the Beatrix surface waters. This correlates exceptionally well with the older and newer mines. The older mines have been almost totally dewatered, thus there are not great volumes of stagnant water (NaCl-character) available, whereas the SO_4-production has been going on for almost 40 years. In contrast to the old mines, the younger mines, such as Beatrix, are dewatering extensively, i.e. large quantities of stagnant water (NaCl-character) are pumped to the surface and are stored in large evaporation areas. Sulphate production at these mines is also low if compared to the older mines.

It should be kept in mind that although the Piper diagram is well-suited to identify trends in the evolutionary process of water chemistry, it gives no indication as to the true salt content of the individual water samples. The fact that the water in the evaporation areas seems to plot as a continuous trend with that of the fresh surface water, should not be taken that a clear distinction does not exist between these two waters. The total salt load of the water left in the pans is an order or two higher than that in the natural surface water.

During the course of the investigation, some of the evaporation pans and dams were full and overflowed into nearby watercourses (Figure 6.4). The following are some of the main localities where effluent water, at some stage in the past, overflowed into public watercourses, beyond specified boundaries.

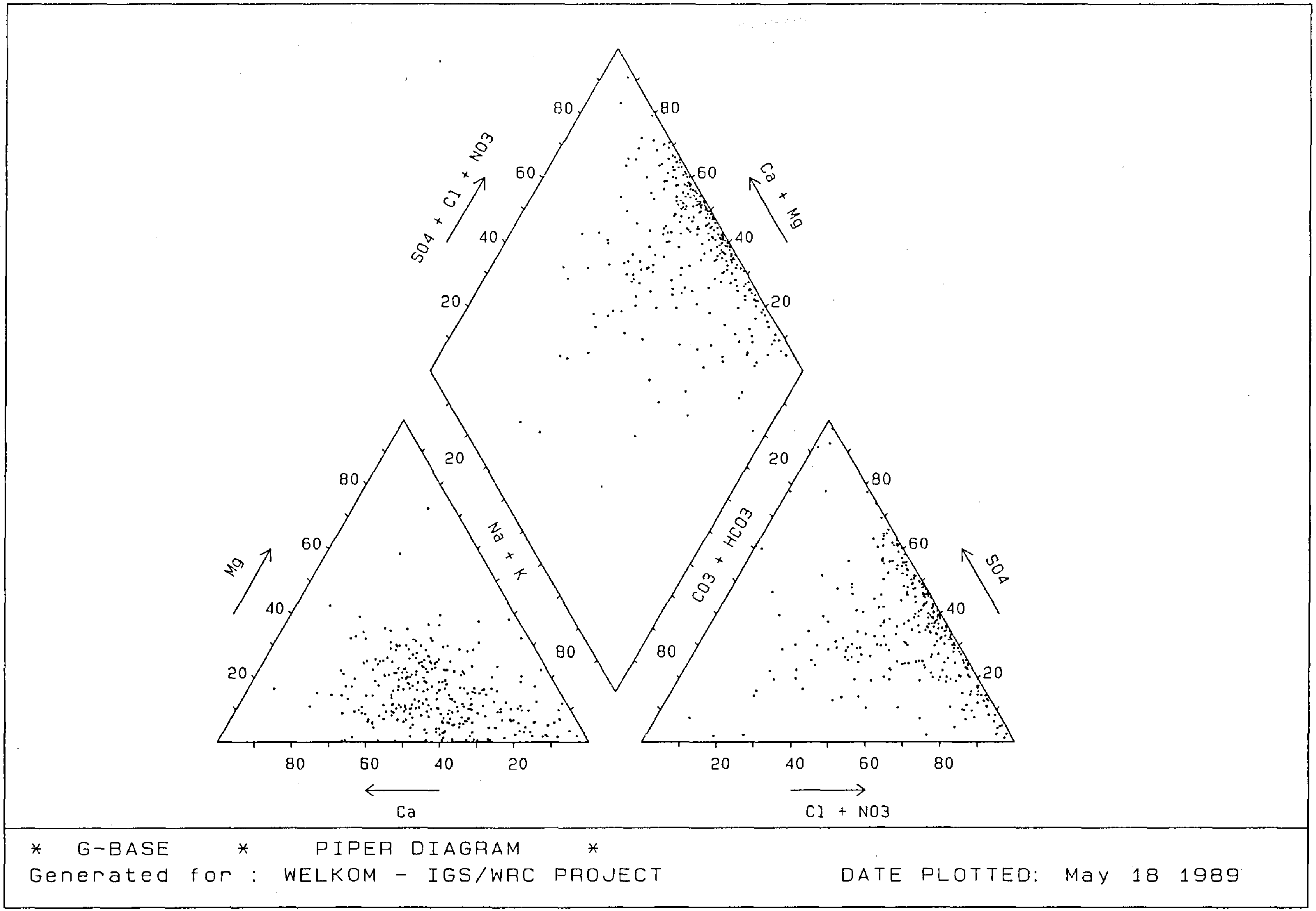


Figure 6.2. Piper plot of surface water.

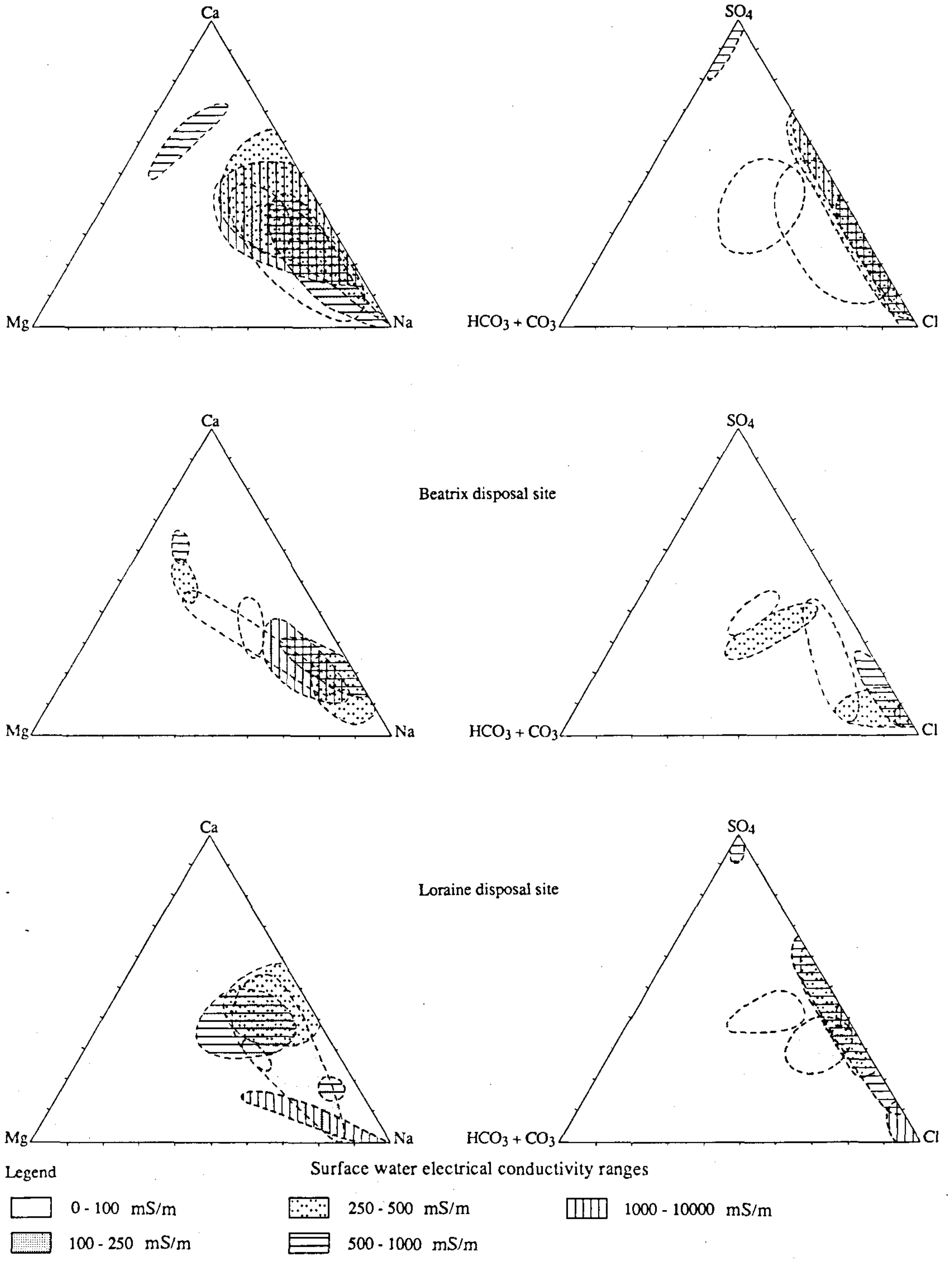


Figure 6.3. Triangular plot of basic anion and cation fields of surface waters in the Orange Free State Goldfields.

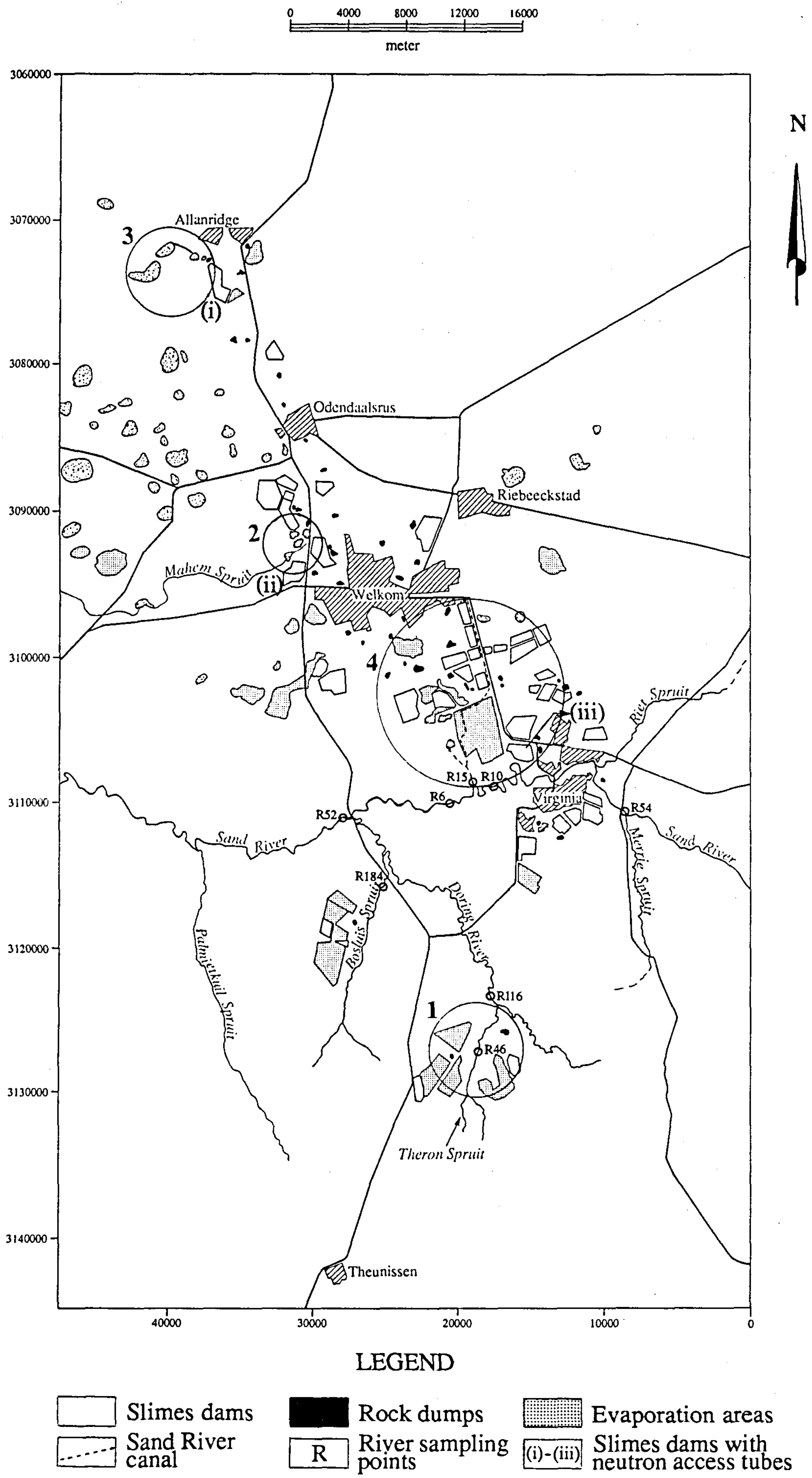


Figure 6.4. Positions (1 - 4) where overflowing of reservoirs into nearby watercourses did occasionally take place.

Position 1: Evaporation dams of the Beatrix Mine discharged excess effluent water via two canals into the Theron Spruit, which reaches the Doring River and finally flows into the Sand River.

Position 2: A man-made canal coming from within the premises of the Western Holdings Gold Mine and in close proximity of the D dam return water facility, discharges effluent directly into a farmer's dam which, in turn, overflows into the Mahem Spruit. Water with an electrical conductivity, > 350 mS/m, has been sampled more than 6 km from this facility, as it flows down the spruit.

Position 3. During the above normal 1988 rain season (897 mm) excess plant effluent water from the Loraine Gold Mine spilled into Swart Pan. As the pan reached full capacity, it overflowed into a vlei system, then into a farmer's dam and finally into a system of low-lying natural pans.

Position 4. The Sand River canal collects and discharges excess effluent into the Sand River.

It should, however, be mentioned that in cases 1, 3 and 4 measures have been applied to prevent future spillage into natural watercourses.

6.3.2 SLIMES DAMS

The slimes pumped onto the slimes dams have pH values above 7,0 and may be as high as 11,5 due to the addition of lime during the reduction process. Figure 6.5 is a plot of pH values for water at various slimes dams. The high pH values indicate the degree to which lime is added, in order to maintain a fairly high level of alkalinity for the precipitation and cementation process, as well as to protect the cyanide ion during the leaching process (Stanley, 1987). This, in itself, is of no environmental concern, since the calcium will precipitate as the water is exposed to carbon dioxide from the air, and the pH will drop to a value around 8,0. In actual fact, the over-liming of the slimes water could reduce bacterial activity in the slimes dams, since it has been suggested that *Thiobacillus ferrooxidans* can only multiply and thrive at pH levels below 5,5. The great number of samples in this plot, with pH levels below 5,5, indicate that the addition of the lime is not sufficient to completely counteract pyrite oxidation. In fact, in some cases the pyrite oxidation is so severe that the calcium carbonate which precipitate from the alkaline slimes, is insufficient to neutralize the acid.

Furthermore, contrasting the old slimes dams against the new slimes dams, the different types of slimes against one another, can prove to be useful when evaluating pyrite

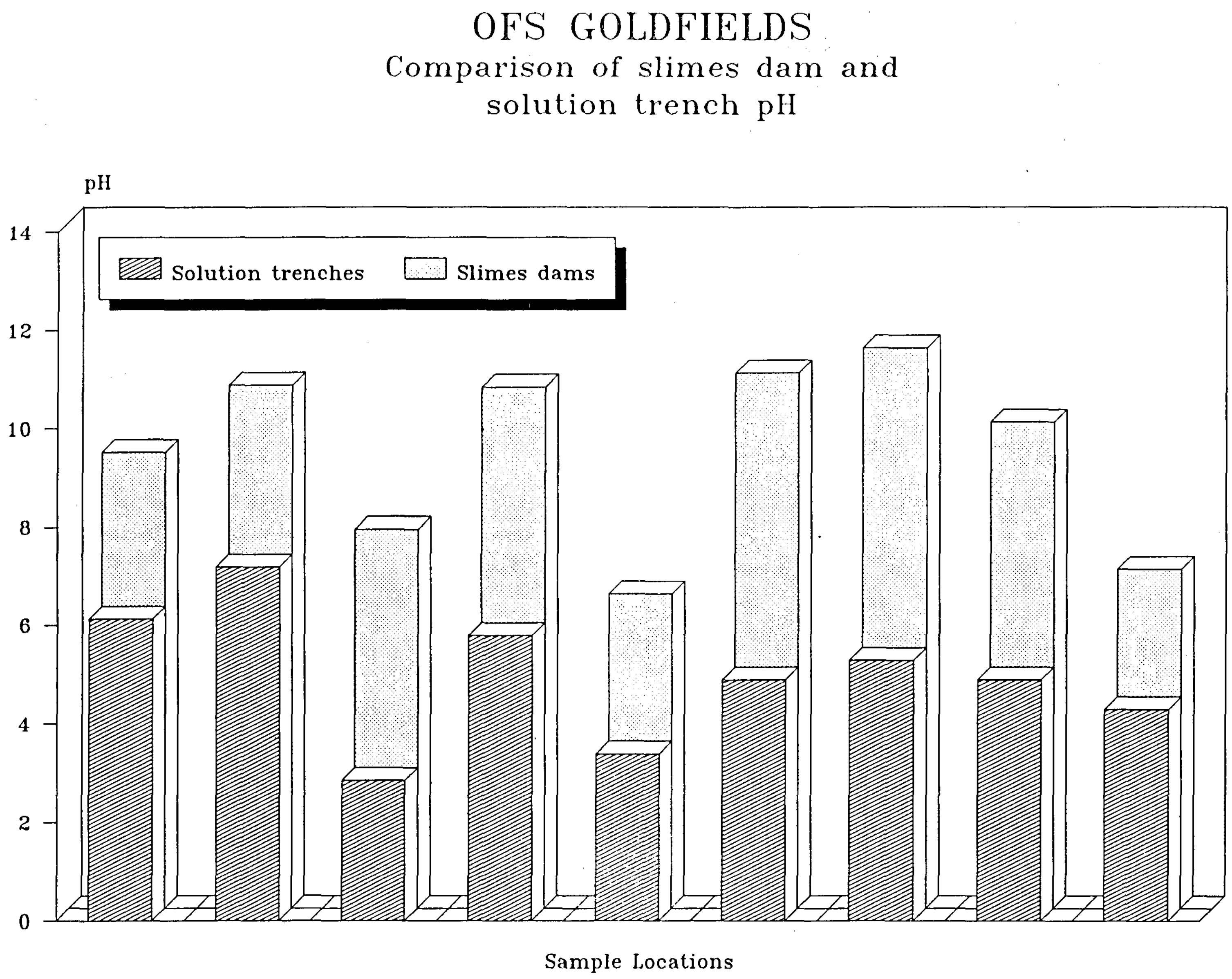


Figure 6.5. Comparison between the pH of slimes dams and solution trenches.

oxidation and pH levels in slimes dams, as well as the pollution hazard of the respective disposal sites.

A comparison of the pH between old and new slimes dams and their respective solution trenches are given in Figure 6.6. Looking at the figure, it seems that the pH of the solution trenches of the old slimes dams are lower than that of the new slimes dams, although this pattern is not very distinctive. However, in both groups a significant drop in the pH of the water is observed, as the water moves through the slimes dams to the solution trenches. Thus, although a slimes dam can be classified as old in years, new slimes are continuously deposited onto the dam, therefore supplying pyrite which can be oxidized.

Pyrite oxidation is primarily responsible for the drop in pH in slimes dams, as well as the potential sulphate production of slimes dams. The comparison of slimes dams where pyrite has been extracted and slimes dams where pyrite has not been extracted, can be used to depict differences in the pollution hazard by the respective slimes dams. Figure 6.7 shows such a plot. According to the figure, the pH of the slimes dams where pyrite has been extracted and their respective solution trenches do not vary a great deal. This can mainly be ascribed to the lower concentration of pyrite in these slimes dams. The slimes dams where pyrite is not extracted, show a considerable drop in pH, as can be expected, due to the oxidation of pyrite, with the resultant release of H_2SO_4. As described in Chapter 2, at low pH, metal salts become very soluble, therefore the extraction of pyrite can reduce the pollution potential from the slimes dams.

According to Stanley (1987), 3 to 4% of the gold-bearing matrix consists of pyrite, which makes pyrite a minor but important constituent of gold residues, as it constitutes a source of both ferrous iron and sulphate. Thus, due to the fact that slimes dams constantly (daily) receive large quantities (in excess of 5 million tons/month) of slimes (silt mixed with water), they do possess a potential pollution hazard. It is therefore necessary to examine the construction and water transport potential of these structures in more detail (Appendix I). According to Stanley (1987), gold tailings may be described as a rock flour, comprising 0 - 15% fine sand and 0 - 10% clay fraction, with some 80% of the material falling within the silt classification. Figure 6.8 represents grading curves for gold mine tailings, which can be coarse or fine. An intermediate grading (solid line) was used for further calculations.

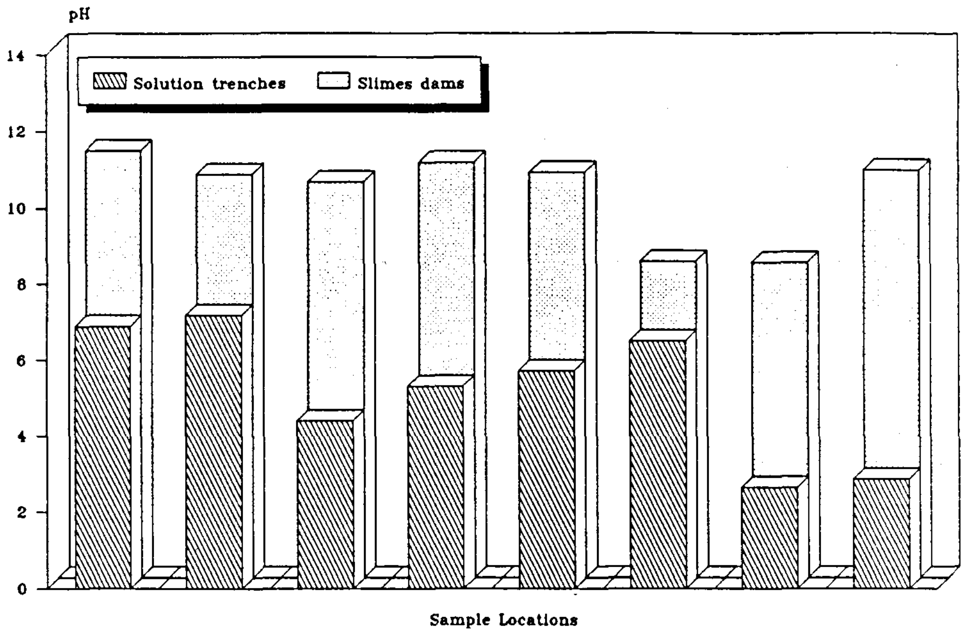
To monitor potential water movement through the slimes dams, a number of neutron access tubes (13 tubes) were installed on three different gold slimes dams in the area:

(i) The Loraine slimes dam, being one of the oldest, but still in use.

(ii) The Western Holdings slimes dam, which is a relatively young slimes dam.

(iii) The Harmony slimes dam, which is old and not in use any more.

OFS GOLDFIELDS
Old slimes dams
(Older than 15 years)



OFS GOLDFIELDS
New slimes dams
(Younger than 15 years)

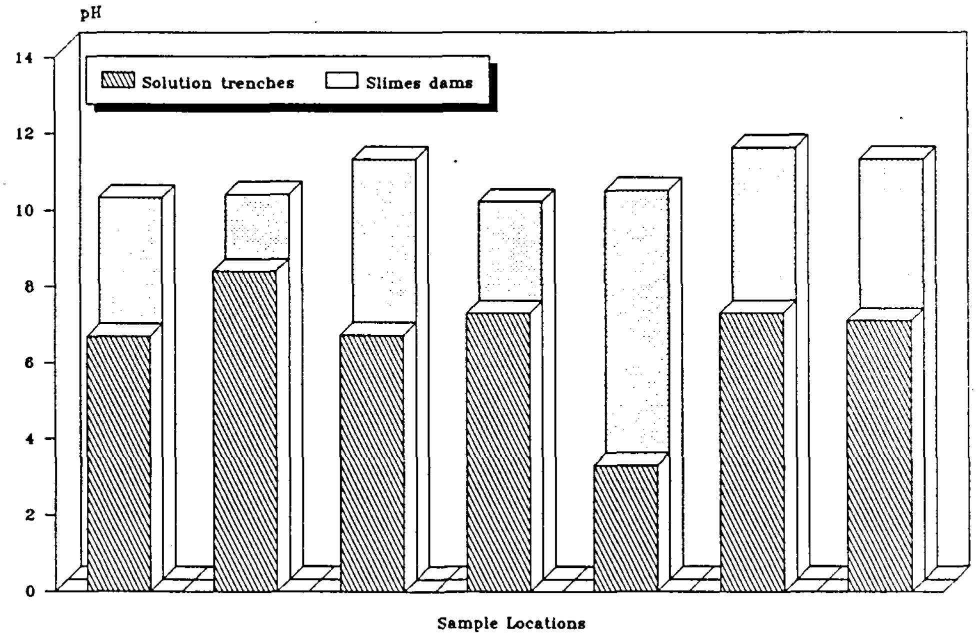


Figure 6.6. pH of old and new slimes dams and their respective solution trenches.

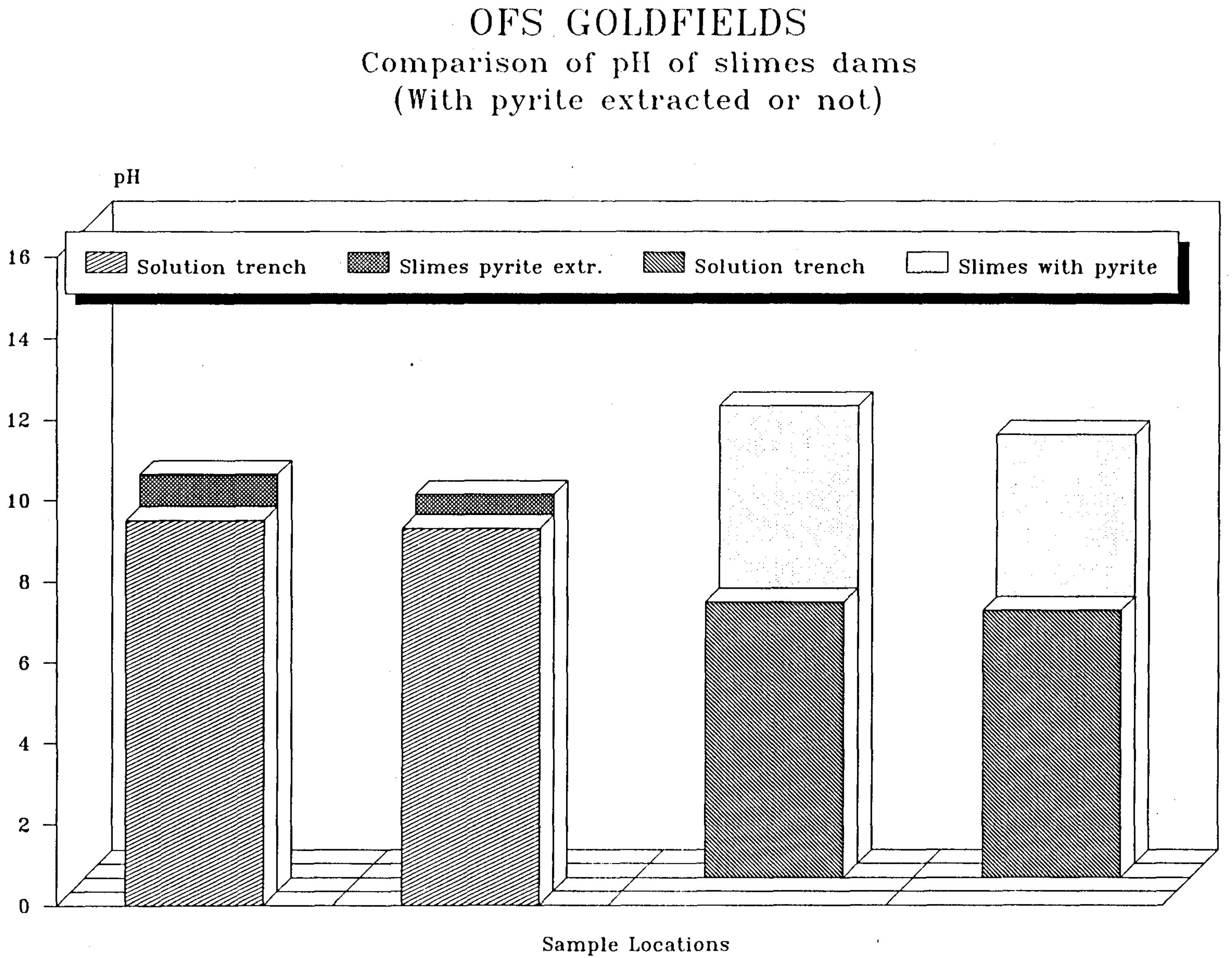


Figure 6.7. Comparison between slimes dams (with pyrite extracted or not).

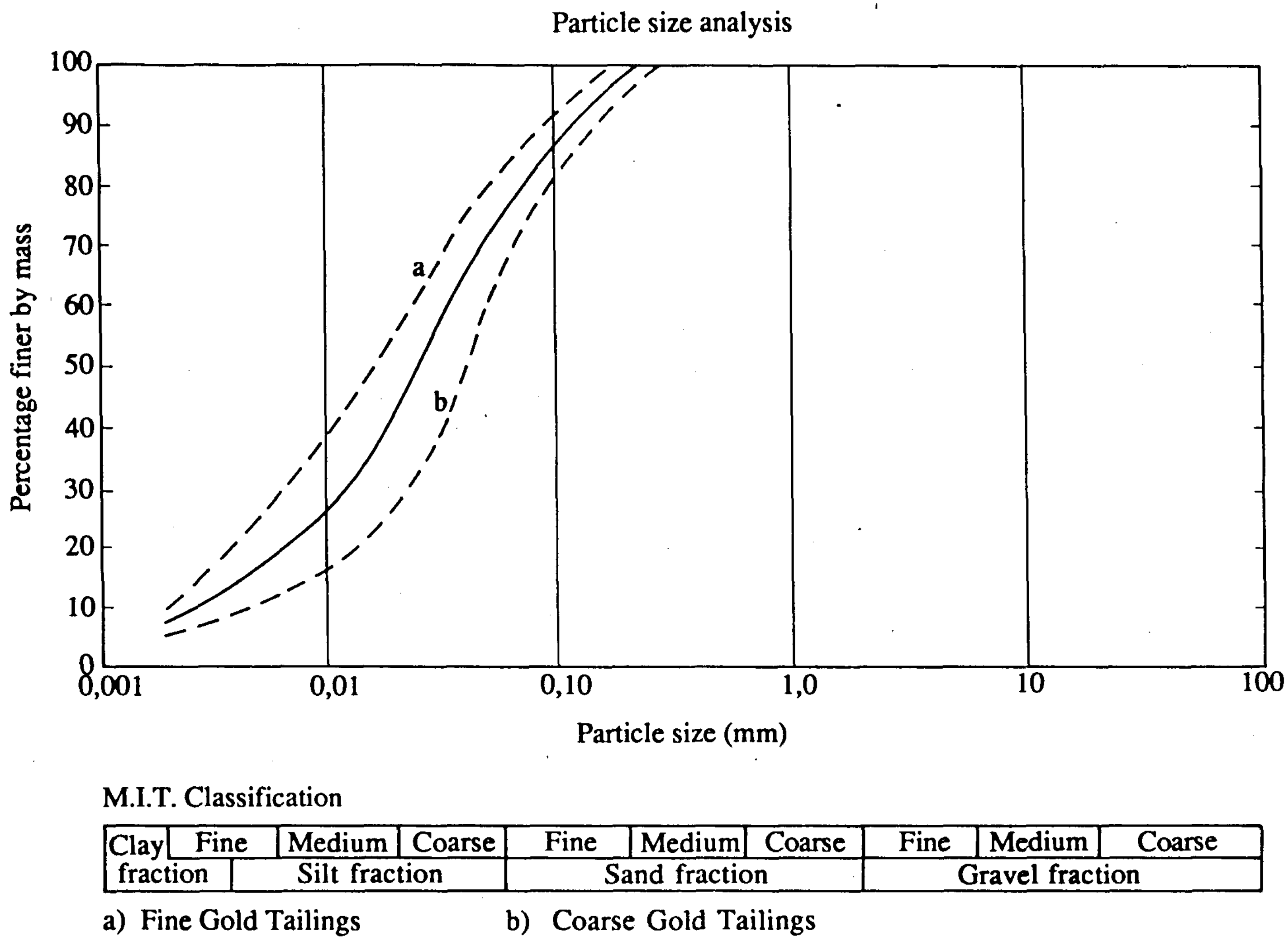


Figure 6.8. Particle size distribution of gold tailings (after Stanley, 1987).

The locations of the above-mentioned slimes dams are shown in Figure 6.4.

The neutron access tubes were monitored on a monthly basis, over a period of 15 months, starting in January 1989 till the present. Figures 6.9 to 6.12 represent some of the results of the monthly neutron density readings. Evaluation of these results can be divided into two categories:

(i) A detailed evaluation of the Western Holdings slimes dam moisture transport, shown in Figures 6.9 and 6.10.

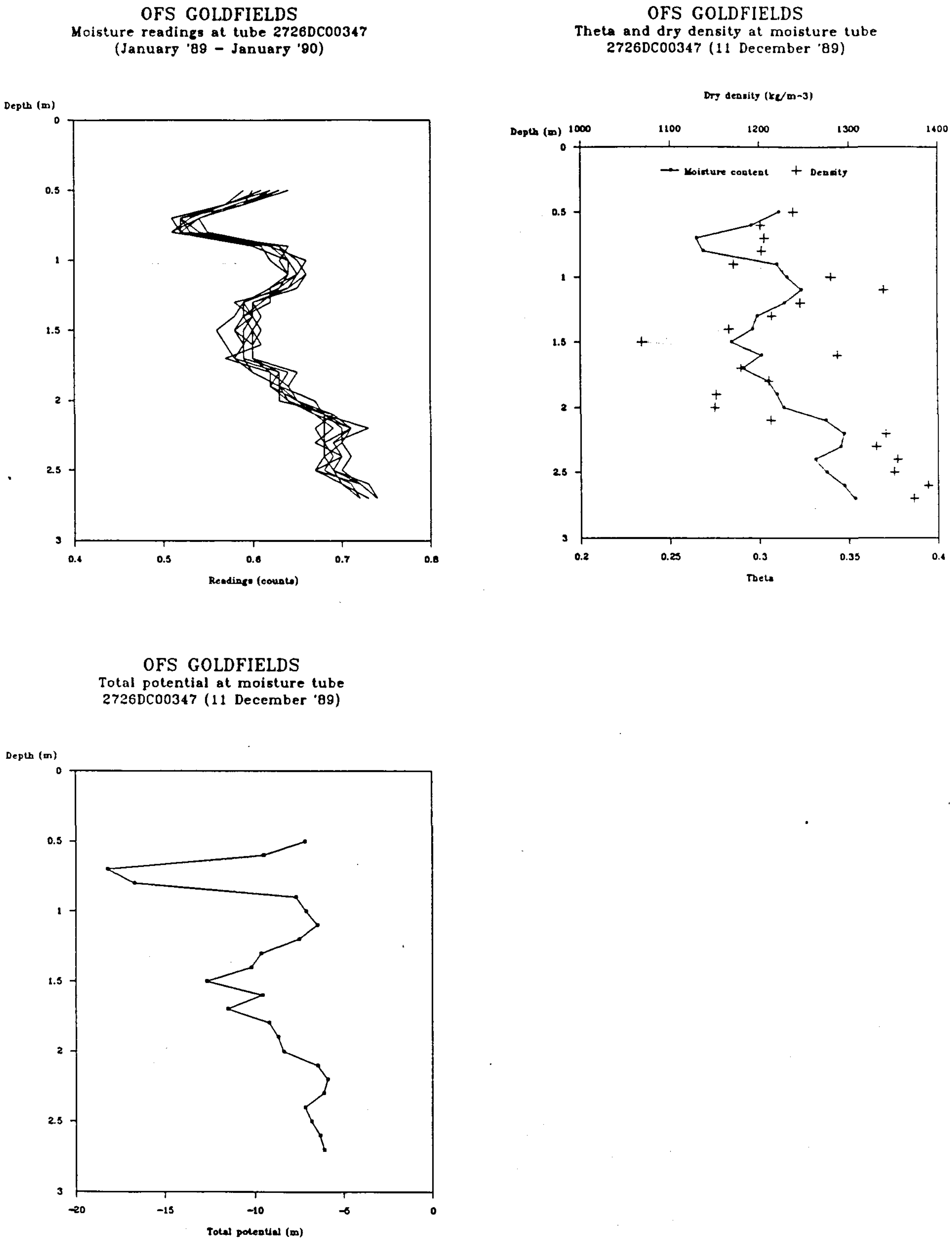
(ii) A more superficial analysis of the Loraine and Harmony slimes dams moisture transport, using an average density across the whole depth profile, shown in Figures 6.11 and 6.12 respectively.

From Figures 6.9 and 6.10, it is noticed that the moisture readings, water content (θ) and the total potential display the same trend with increasing depth, meaning that the densities at the different depths do not have a significant influence on any of the calculations.

Comparing Figures 6.9 and 6.10 with one another, a difference in water content is observed. This can mainly be ascribed to the fact that the neutron access tubes are situated on different levels of the slimes dam with respective altitudes of 1330 and 1337 m.a.m.s.l.

Neutron access tube DC 347 which is situated near the base of the slimes (1330 m.a.m.s.l.) displays a relative high moisture content due to the fact that it is situated closer to the phreatic surface of the slimes dam (see Figure 6.9, as reference). Neutron access tube DC 350 is situated at a higher level (near the top) of the slimes dam, thus further away from the phreatic surface. Furthermore, from the matrix potential it is noticed that up to a depth of about 1,5 m, a downward gradient exists. This means that up to a depth of 1,5 m, there is vertical movement of moisture, after which the moisture has to move horizontally, either to the centre of the slimes dam or to its side, where it can evaporate, explaining the precipitation of sulphates on the slimes dam surface. It furthermore means that there is no vertical flow past the depth of 1,5 m, at the specific tube locations.

Figures 6.11 and 6.12 represent results from the old slimes dams respectively, i.e. an old slimes dam (DC 345) in use and an old slimes dam (BB 286) which is not used any more. From the figures, it can be seen that the soil moisture profile in tube DC 345 reacts similarly to the ones monitored on the Western Holdings slimes dam, i.e. for the first 2 m a vertical downward gradient exists, after which the gradient changes to an upward gradient, meaning that no vertical flow occurs past this depth, limiting the influx of water as well as pyrite oxidation. This also correlates well with the work done on residue dump leaching



OFS GOLDFIELDS
Moisture readings at tube 2726DC00347
(January '89 - January '90)

OFS GOLDFIELDS
Theta and dry density at moisture tube
2726DC00347 (11 December '89)

OFS GOLDFIELDS
Total potential at moisture tube
2726DC00347 (11 December '89)

Figure 6.9. Results of the monthly neutron density readings for DC 347.

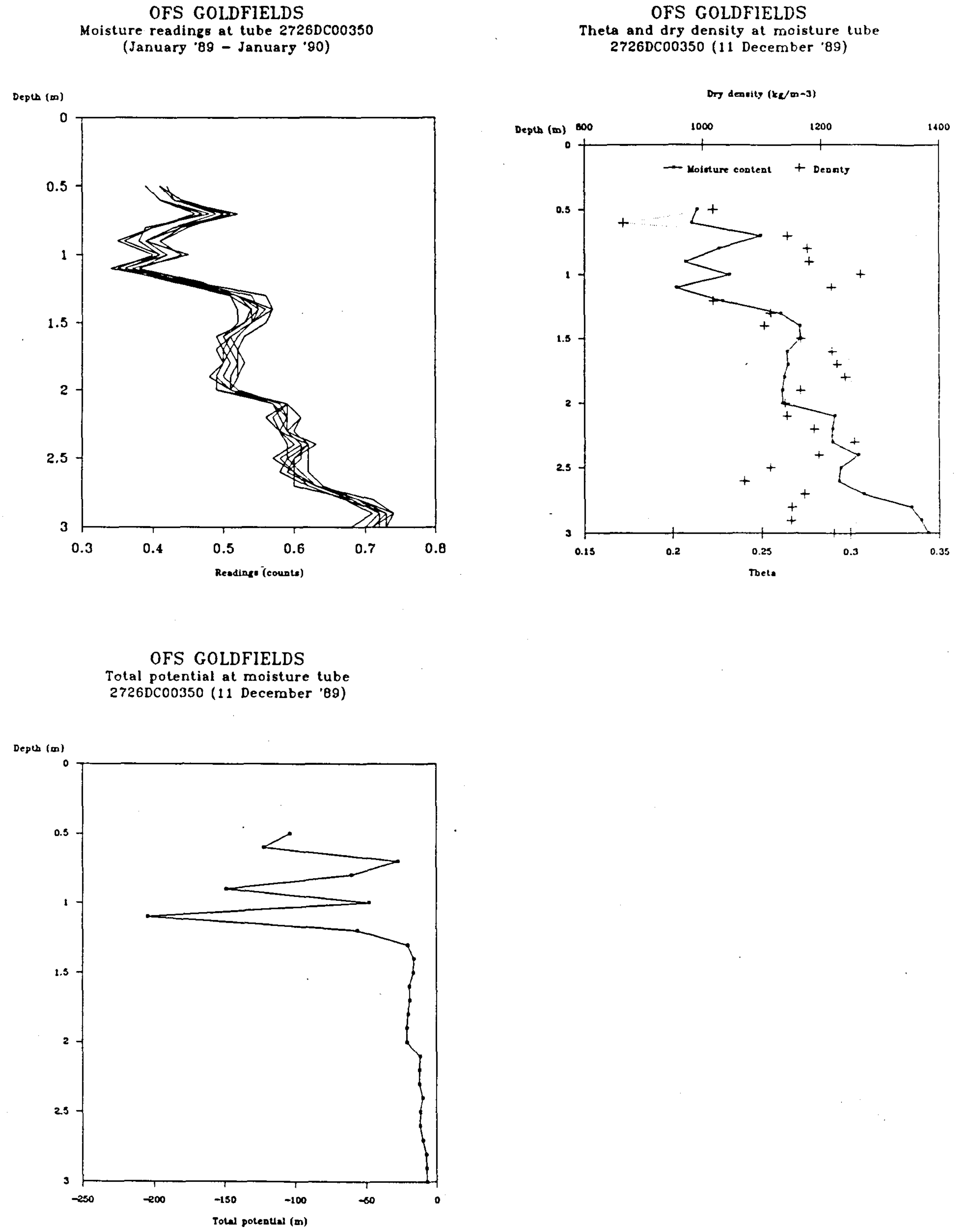
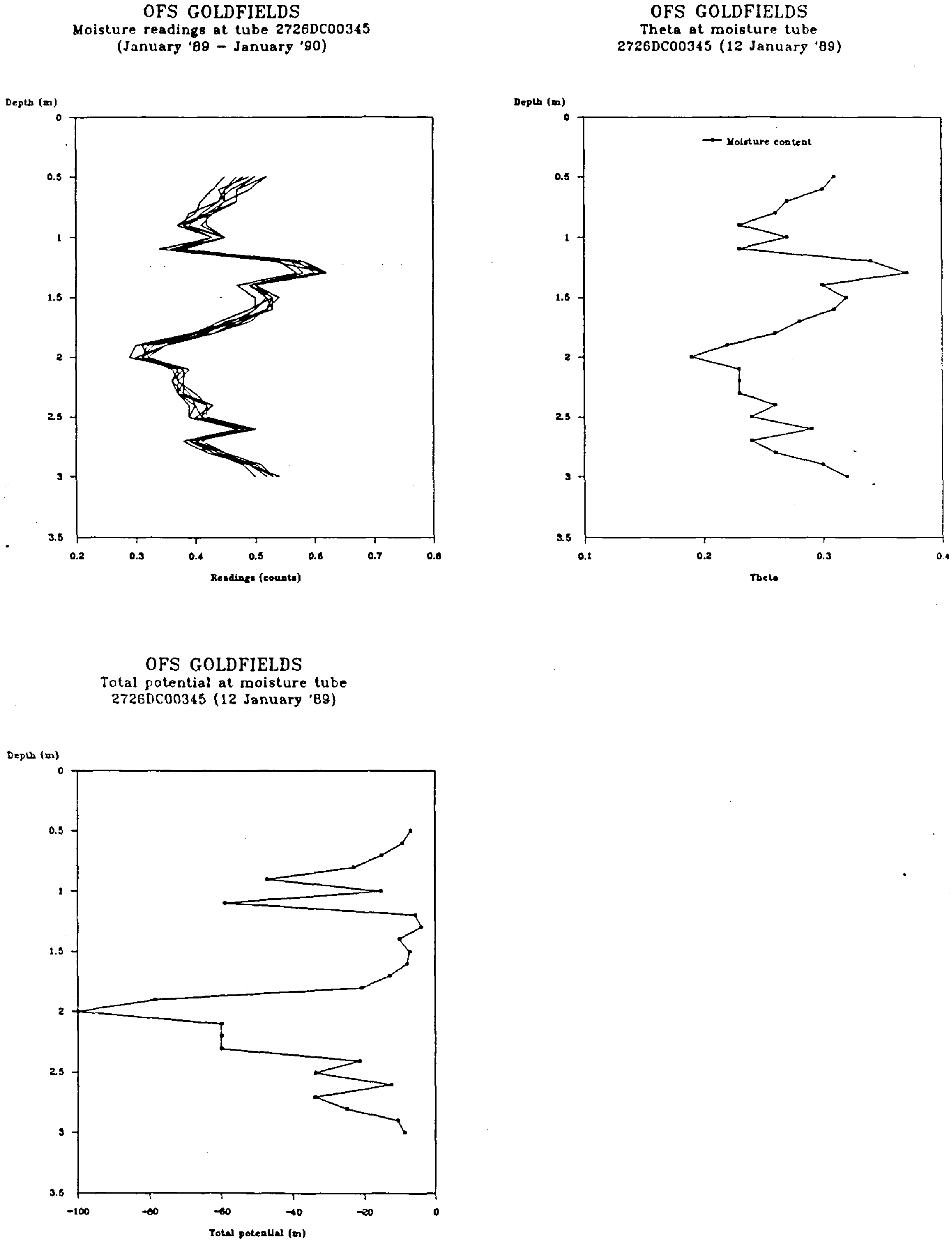


Figure 6.10. Results of the monthly neutron density readings for DC 350.



OFS GOLDFIELDS
Moisture readings at tube 2726DC00345
(January '89 – January '90)

OFS GOLDFIELDS
Theta at moisture tube
2726DC00345 (12 January '89)

OFS GOLDFIELDS
Total potential at moisture tube
2726DC00345 (12 January '89)

Figure 6.11. Results of the monthly neutron density readings for DC 345.

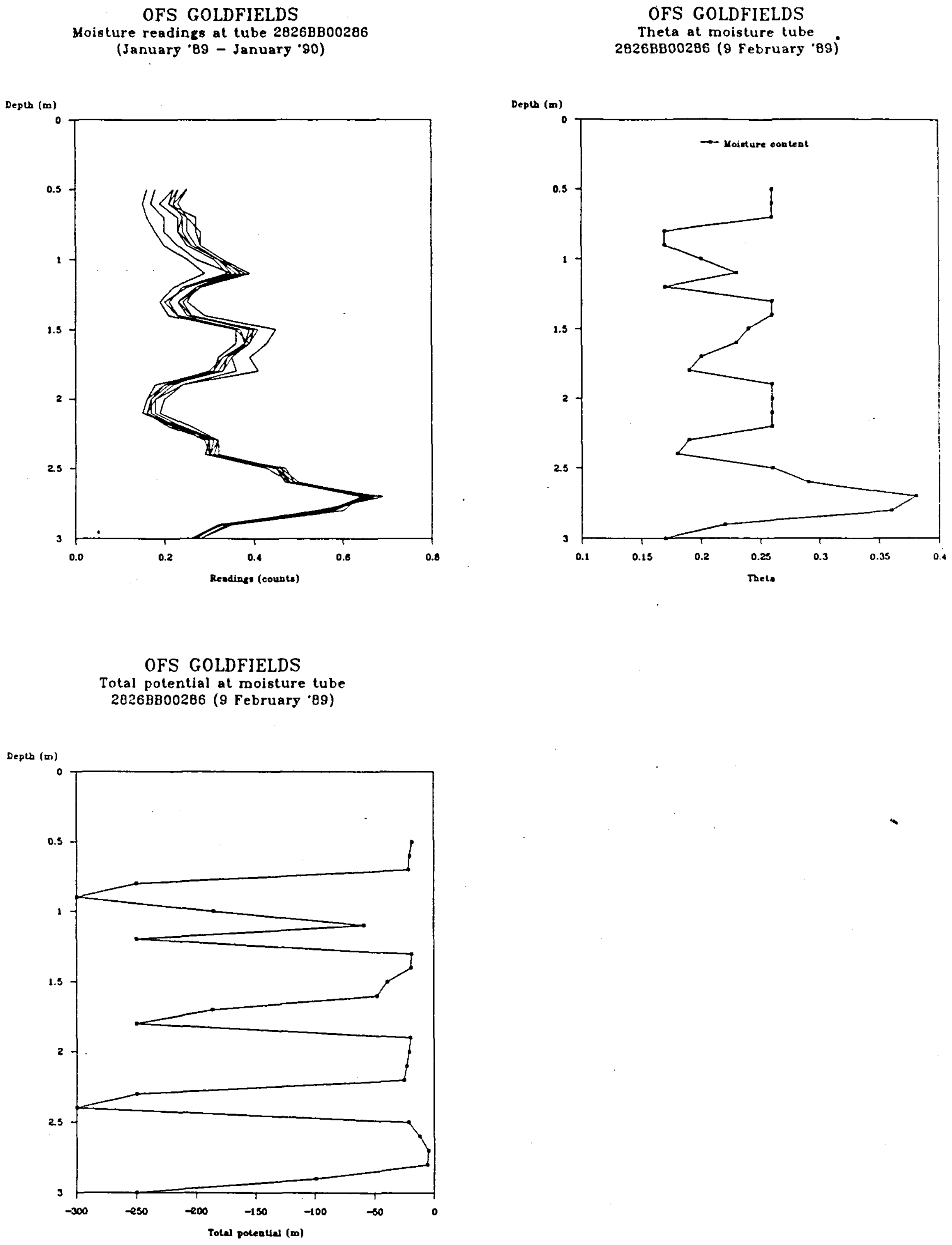


Figure 6.12. Results of the monthly neutron density readings for BB 286.

procedures by Mrost and Lloyd (1971). The above-mentioned has the implication that water movement below a depth of 2 m is essentially in the horizontal direction, towards the sides of the slimes dam, where it evaporates, or towards the saturated central part (pool area), where it is intercepted by the drainage system of the slimes dam.

It should, however, be stressed that the above-mentioned water movement only applies to parts of the slimes dam above the phreatic surface, i.e. the unsaturated part of the slimes dam. If the saturated part of the slimes dam (i.e. the part beneath the phreatic surface) is considered, the situation changes significantly: in this region, there always exists a downward flux (see Figure I-3, Appendix I), due to the hydraulic gradient between the saturated part of the slimes dam and the surrounding ground-water regime. There also exists a chemical gradient between the two regimes, caused by the difference in chemical composition of the water in the two regimes.

If the results of BB 286 (unused old slimes dam) are calculated, it is clearly seen that the structure as a whole is much drier than the used slimes dams. Furthermore, it is noted that the stratification of finer and coarser layers in the slimes dam is distinguished by their water content. Generally fines tend to retain a larger portion of the moisture than coarser materials. This is also evident in the active slimes dams, but to a lesser extent.

The above results were used to calculate a possible flux of water through the slimes dam. This is, however, difficult to achieve, as the soil moisture characteristics of a slimes dam can change significantly towards the centre (pool area) of the slimes dam. Two locations were therefore used:

(i) Along the side of the slimes dam (paddock area), representing the measured data.

(ii) In the centre of the slimes dam (pool area), representing a totally saturated area.

An average saturated hydraulic conductivity (K_S) valve of 1 x 10^{-7} m/s was obtained by means of laboratory experiments, as well as Cambell's formula. This value also compared favourably with values obtained from Steffen, Robertson & Kirsten in Welkom, as well as values published by James and Mrost (1965) and Mrost and Lloyd (1971). Calibration and evaluation of the monthly neutron density readings yielded an estimated flux (q) of 1,7 x 10^{-11} m/s was obtained for the paddock area (unsaturated area), while a value of 1 x 10^{-7} m/s was obtained for the pool area (see section 4.6).

From the above discussions, it is evident that varying quantities of contaminated water, depending on the size of the slimes dam, can seep through the slimes dams.

The amount of water able to cross the boundary between the slimes dam and the ground surface, as well as the rate of infiltration, will furthermore depend on the under-drainage of the slimes dam and the hydraulic properties of the underlying sediments respectively.

6.3.3 RIVERS

Water quality in the Sand River has been studied in detail by the Department of Water Affairs since 1972. Results prior to this date, are also available, though not to the same degree of detail. Three monitoring stations exist. The first being the Allemanskraal Dam, some 40 km upstream of the Goldfields. This serves as a reference station of the river water quality above the Goldfields. The second station is some 60 km downstream of the Goldfields, at Nooitgedacht, which is located in the Sand River, before it reaches the Bloemhof Dam and Vaal River. The third station lies in the Vet River, south of the Goldfields, and is not affected by activities in the Goldfields. The Vet and Sand Rivers join before the monitoring station at Nooitgedacht.

The average concentration of some chemical constituents measured at the Allemanskraal Dam, Erfenis Dam and Nooitgedacht monitoring stations, is shown in Figure 6.13(a). From the figure, it is evident that the Nooitgedacht monitoring station shows a marked increase in Ca^{2+}, Na^{+}, Cl^{-} and SO_4^{2-}. This increase is derived from the Virginia and Welkom areas, as water from the Allemanskraal Dam is of a very good quality.

Figure 6.13(b) shows the maximum chemical values recorded at each site and the trend seen in Figure 6.13(a) is confirmed. In both figures, all the ion-concentrations at Nooitgedacht are much higher, except for the K^{+}-concentration which is the same at all three stations. The constant K^{+}-concentrations can be ascribed to the fact that no K^{+} is being introduced through any mining activity. The Cl^{-}-anomaly in Figure 6.13(b) cannot be linked to any hydrological event and can therefore only be ascribed to water with a high Cl^{-}-content that entered the Sand River via the Sand River (Mosterd) canal.

The distance between Nooitgedacht and the Goldfields, as well as the fresh water from the Vet River, contributes to the fact that the water at Nooitgedacht is diluted. Because of the dilution of the water at Nooitgedacht, the water quality would seem to be better, as for example at Bloudrif. However, the total salt load stays the same.

Figure 6.14 shows chemical analyses of the Sand River at various locations and one of its tributaries, over a period of 18 months, from February 1988 to July 1989. Sample locations are shown on Figure 6.19. From the figure, it is evident that the chemical composition of the Sand River water changes significantly during this period. If, however, the chemical analyses are correlated with the daily flows at the Allemanskraal Dam (Figure

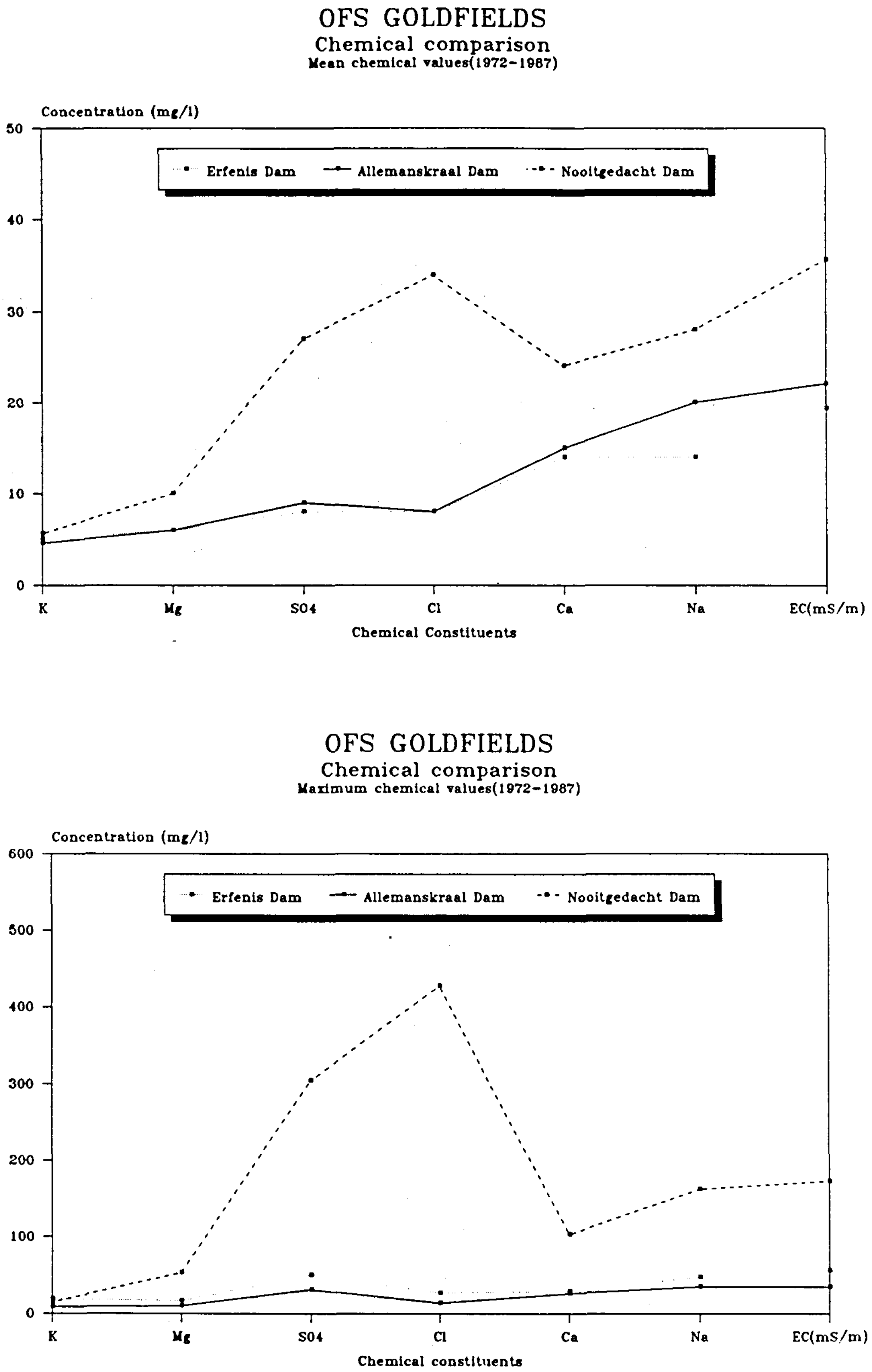
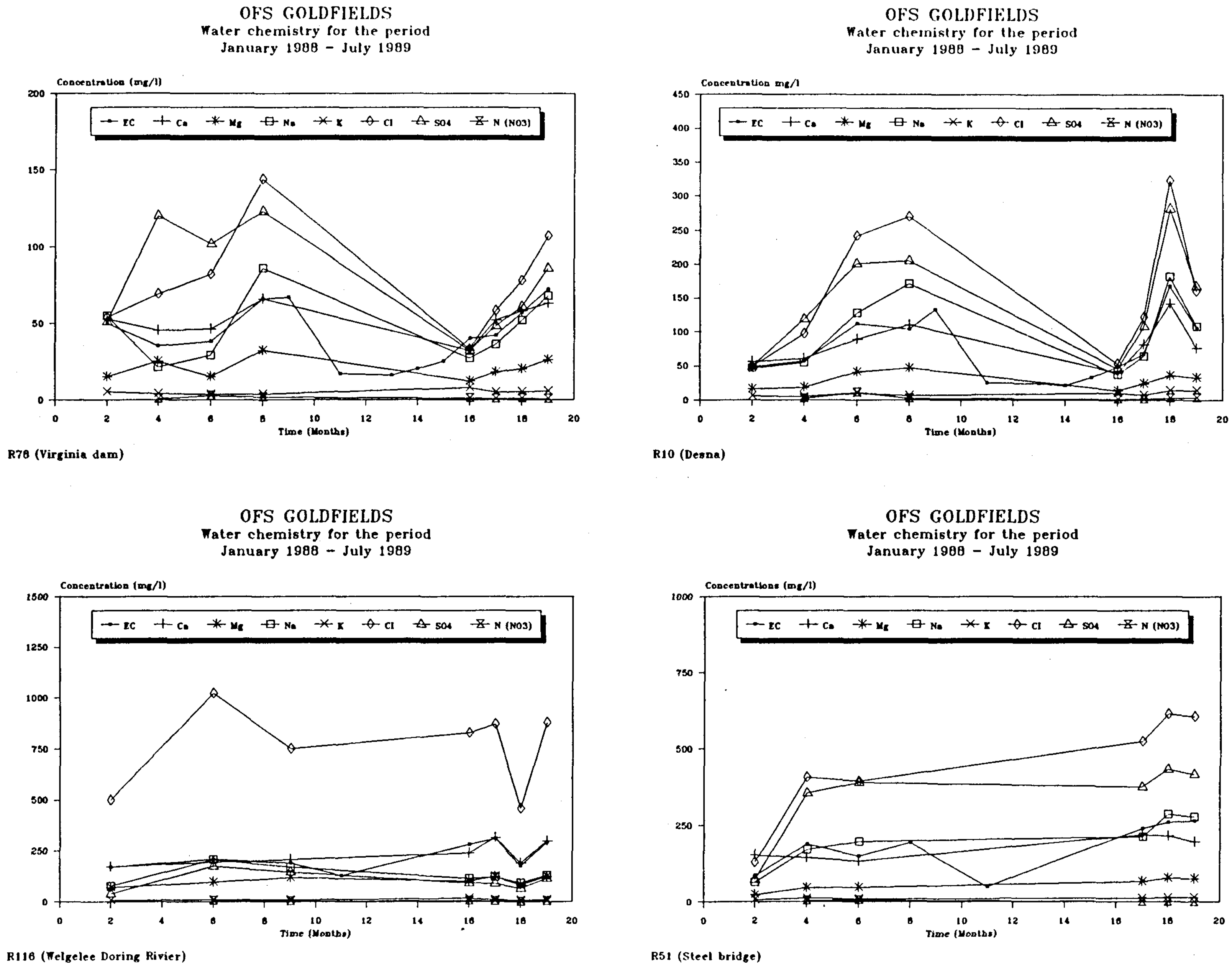


Figure 6.13. Comparison between the mean and maximum chemical analyses of the major ions at Allemanskraal Dam, Erfenis Dam and Nooitgedacht Station.



R78 (Virginia dam)

R10 (Desna)

R116 (Welgelee Doring Rivier)

R51 (Steel bridge)

Figure 6.14. Chemical analyses of the Sand- and Doring River water.

6.15), it is seen that high salt concentrations coincide with low river flows and vice versa, explaining the anomalous pattern. If the chemical analyses of the Doring River are evaluated, anomalous Cl-concentrations are observed. Other than the Welkom/Virginia area (adjoining the Sand River), in which some of the oldest mines are located, the Doring River is contaminated by the younger southern mines, mainly discharging large quantities of stagnant water (NaCl-character), into adjoining evaporation areas, which then leak into the streams via seepage.

Measurements made during this investigation, show that the water immediately above Virginia has an electrical conductivity in the order of 15-32 mS/m, similar to the water quality of the Allemanskraal Dam. As the Sand River flows through Virginia, the influence of effluent water from the mines and other sources becomes evident. Figure 6.16 illustrates the electrical conductivity of the water at different points along the river, measured at different times during the year. The diagrams in Figure 6.16 also show the electrical conductivity of the water in the Sand River canal; a canal which starts in the northern portion of the Goldfields (Figure 6.18) and which discharges water all year round into the Sand River.

Figure 6.17 shows the salinization of the Sand River as it flows through the Welkom area. The salinity hazard is very low at the sampling point on the left of the diagram which represents the water sampled above Virginia. The sampling point at the right of the diagram has the highest salinity hazard. This water was sampled directly below the Sand River canal. Further downstream from the inflow of the canal, the salinity hazard decreases due to dilution, although it is still high. As the Sand River flows through the Virginia area, the salinity hazard increases and this water has a medium salinity hazard. Therefore, it is evident that the salinity hazard of the Sand River's water below the inflow of the Sand River canal is very high.

Electrical conductivities of the water at different points along the canal are listed in Table 6.4. The sampling points are depicted in Figure 6.18.

TABLE 6.4. CONDUCTIVITIES OF THE SAND RIVER CANAL AT DIFFERENT POINTS

Position number	Electrical Conductivity (mS/m)
1	380
2	390
3	460
4	500

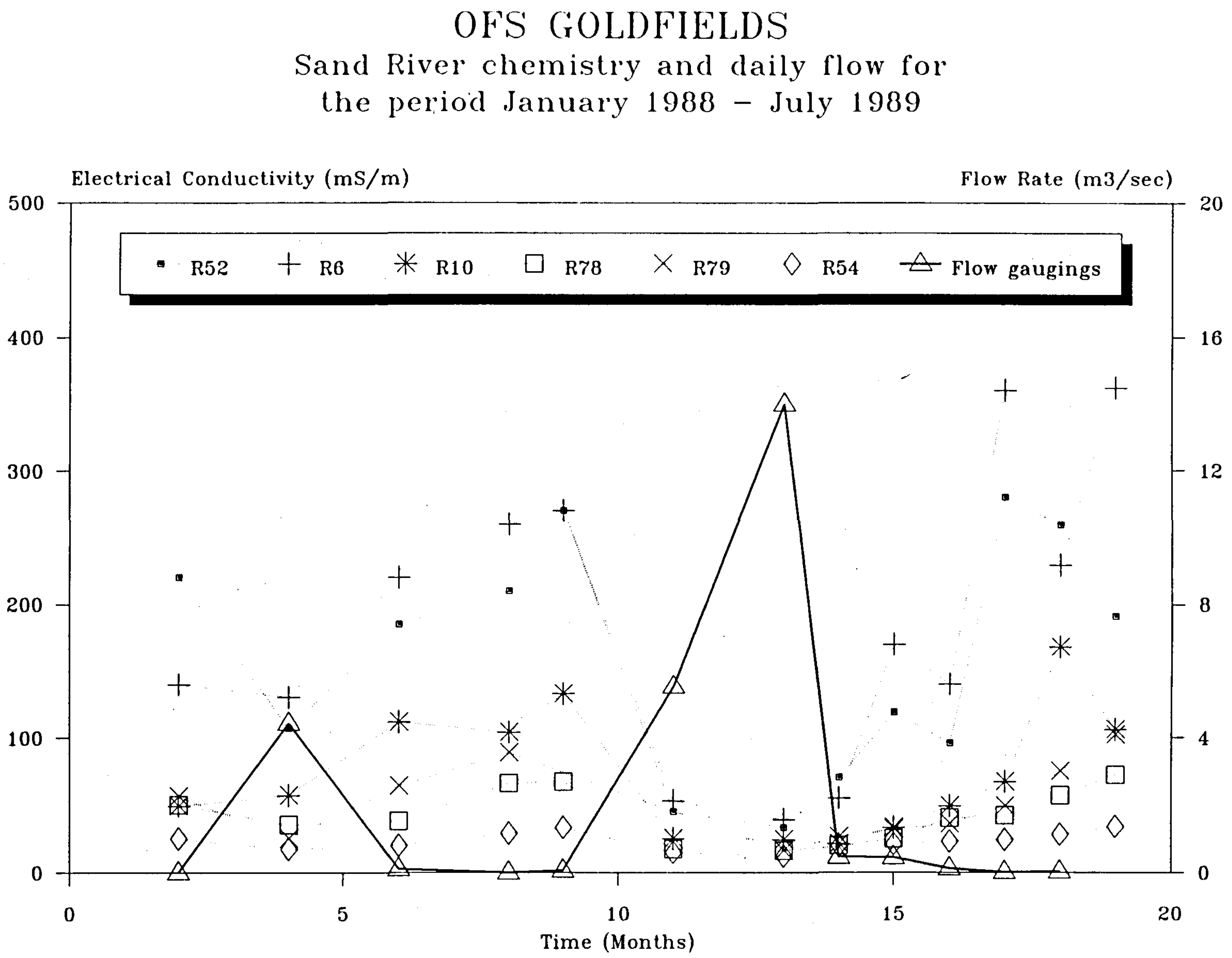


Figure 6.15. Comparison of the Sand River water chemistry and daily flows.

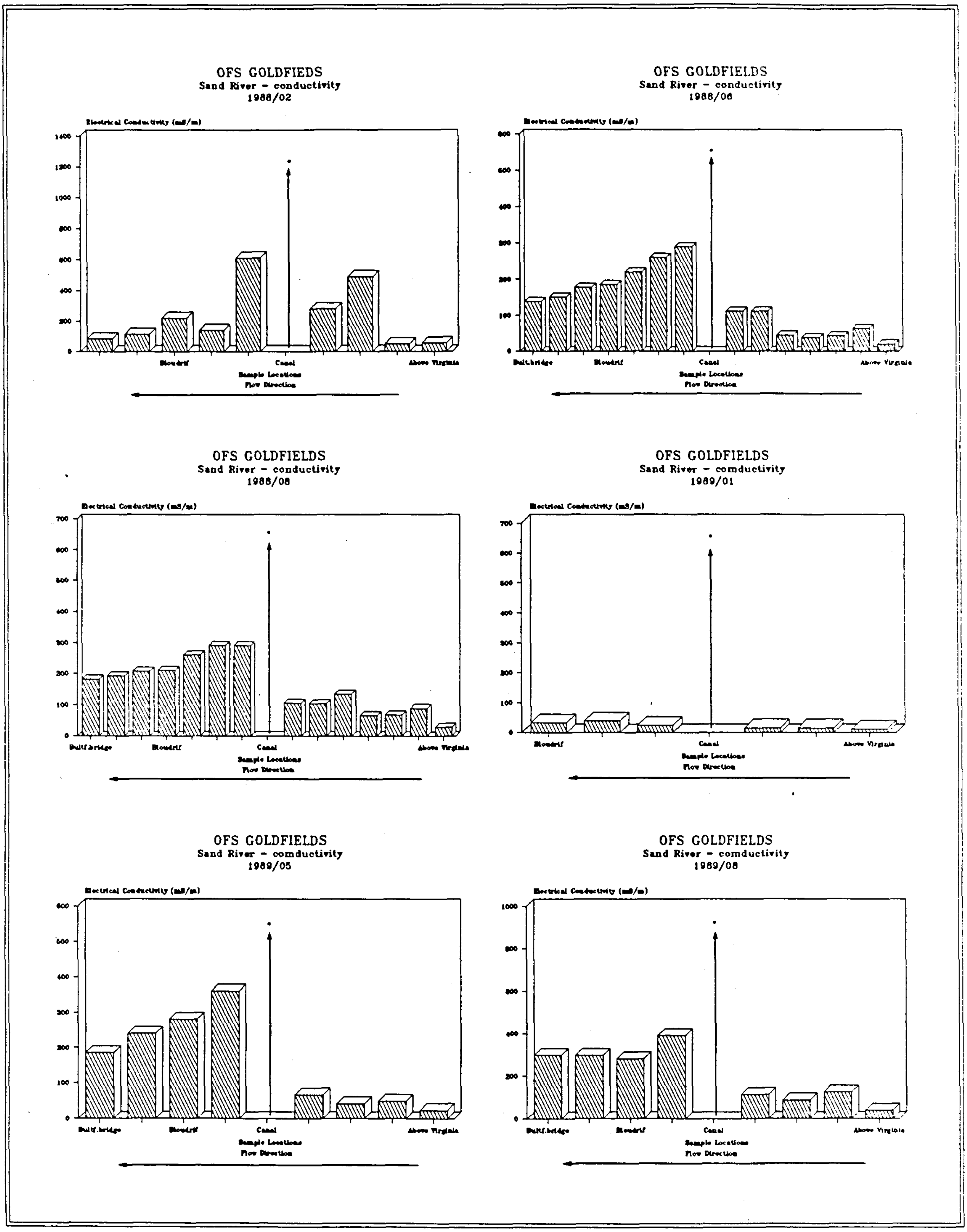


Figure 6.16. Graphical representation of the electrical conductivity measured at different points along the Sand River, at different times during the year.

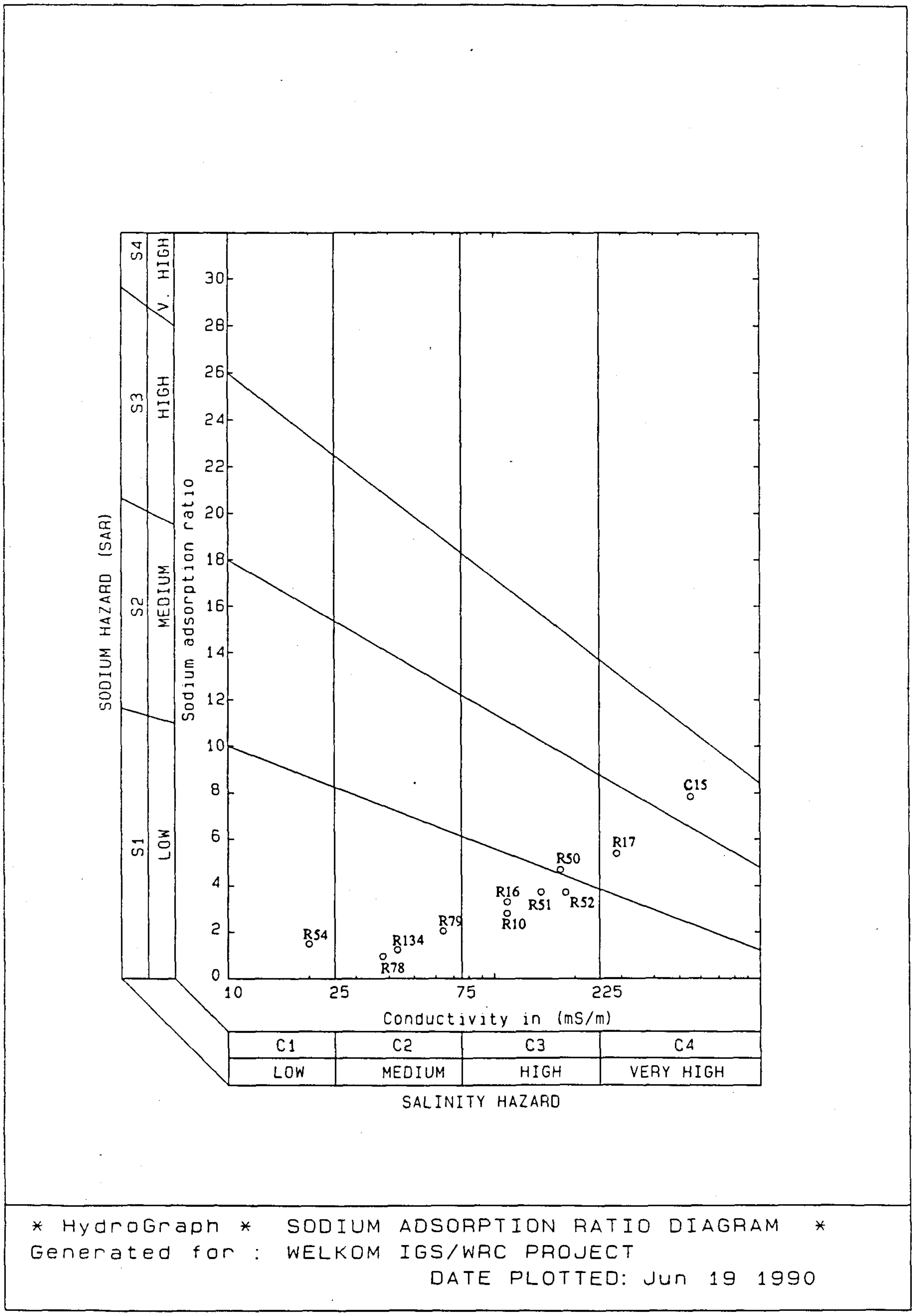


Figure 6.17. Salinization of the Sand River as it flows through the Welkom area.

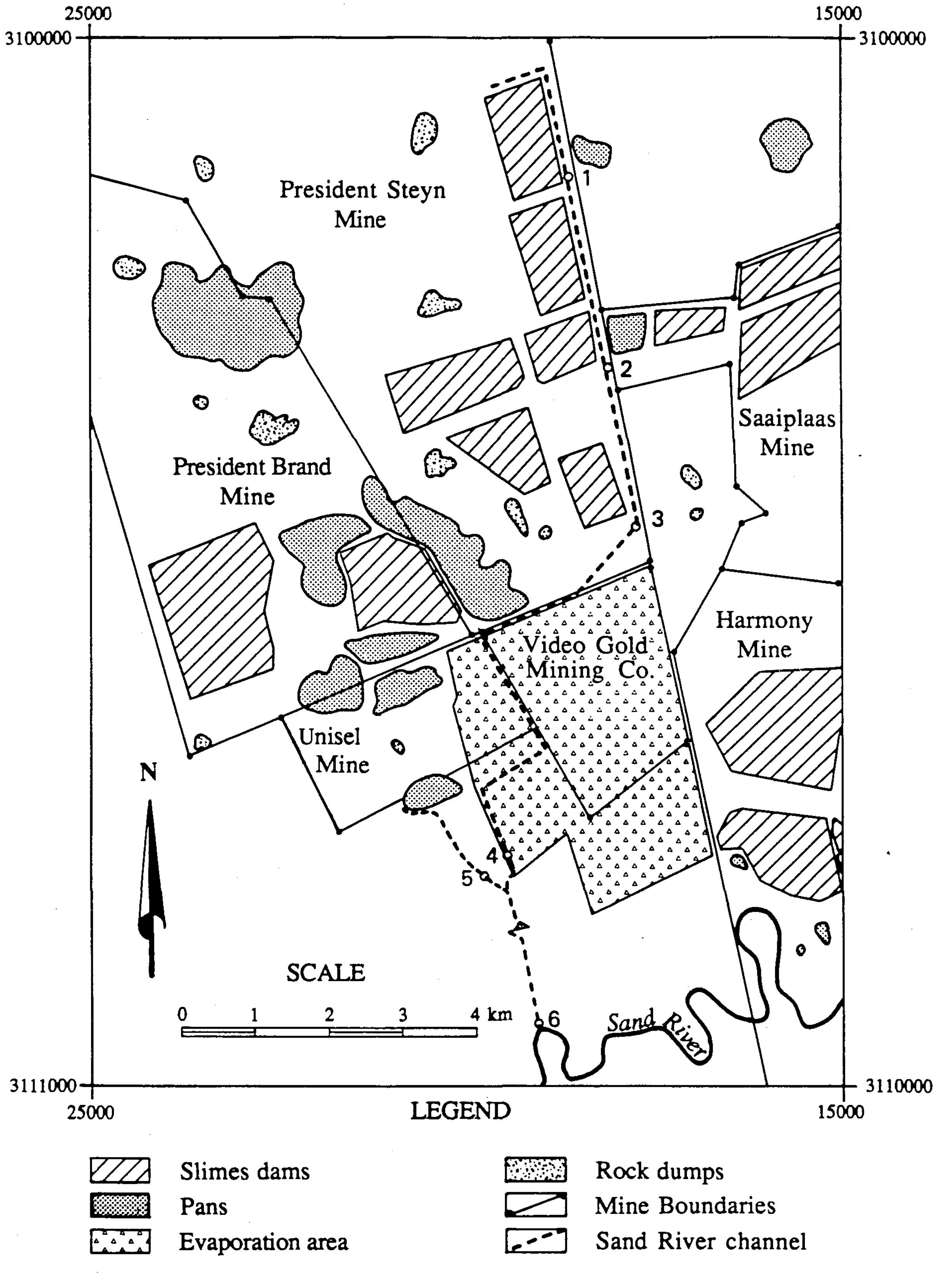


Figure 6.18. Origin and course of the Sand River channel.

5	800
6	740

The water quality of two of the Sand River's tributaries, the Doring River and the Bosluis Spruit, are also adversely affected by mining effluent. Table 6.5 gives an indication of the estimated salt load of the Sand River and the Sand River canal. The flows were estimated with the velocity-area method. The formula is as follows:

$$V = (\alpha \times d \times v)c$$

where

V = volume in m^3
α = width of the river in metres
d = average depth of river in metres
v = velocity in m/s
c = constant = 0,88

TABLE 6.5. SALT LOADS OF THE SAND RIVER AND THE SAND RIVER CANAL

Site	**Conductivity** mS/m	**Flow** m^3/s	**TDS** mg/l	**Salt load** tonnes per day
Above Virginia	19	7,9	124	85
Above canal	112	8,16	728	541
Sand River canal	550	1,8	3575	556
Bloudrif	185	11,5	1202	1194

The salt load increases from about 85 to 1194 tonnes a day, and the Sand River canal contributed 556 tonnes a day. It is difficult to pin-point other sources, as it is mostly seepage water and smaller streams that flow into the river.

When evaluating all the surface water qualities, certain areas in the region seem to correlate exceptionally well with high concentrations of various ions, such as Ca, Mg, Na, Cl and SO_4 (see Table 6.5). In almost all the cases, these areas coincide with mining activities. Figure 6.19 depicts the various areas, coinciding with high concentrations. The only area which does not coincide with mining activities, is area 2. This area coincides with the pan development to the west and north-west of the region.

Due to the mining activities in the area, the high concentrations of calcium, magnesium, chloride, sodium and sulphate in the surface water can be ascribed to the following factors:

- Calcium is added as lime in the reduction process.

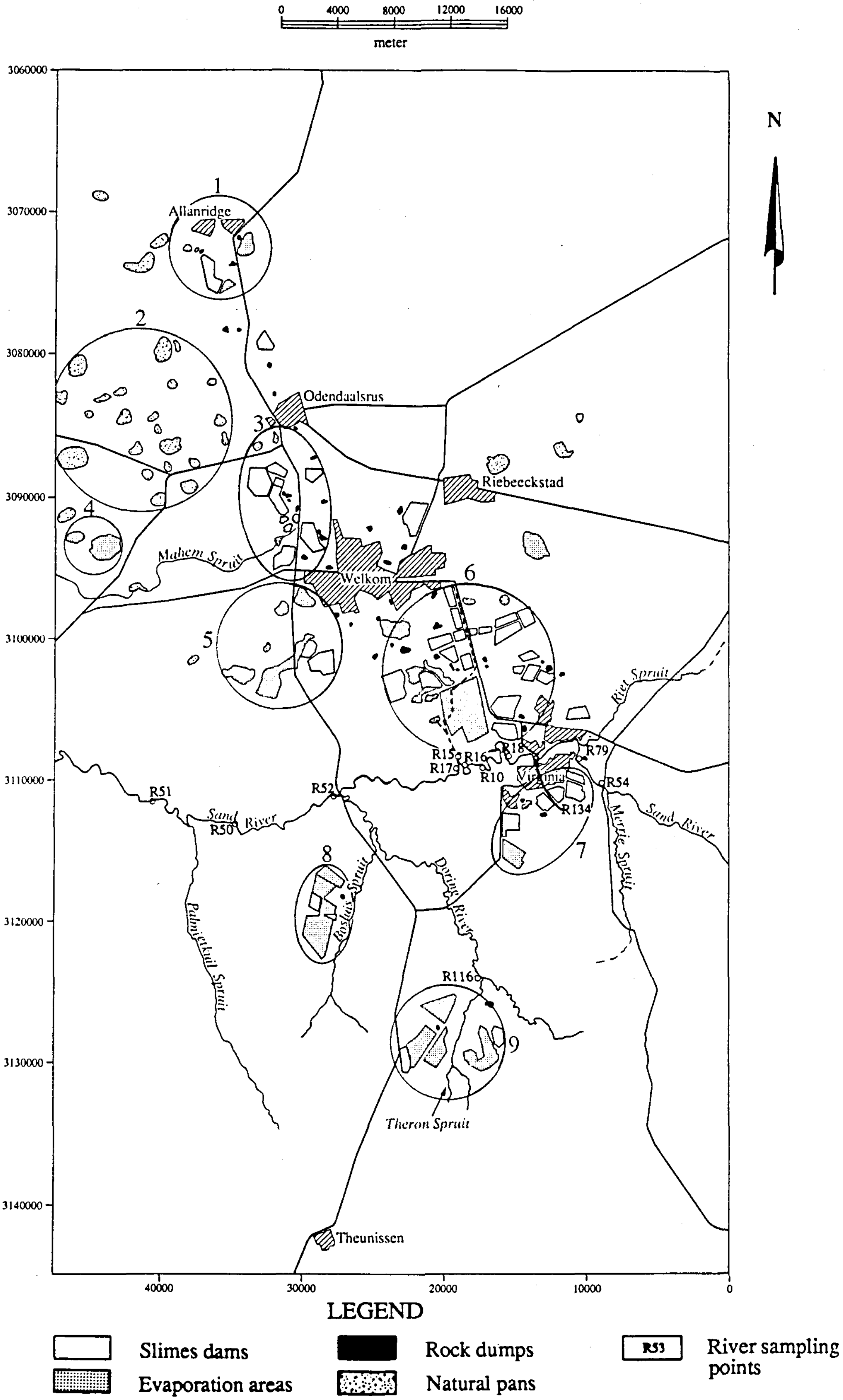


Figure 6.19. Areas that coincide with high concentrations of various ions.

- The deep ground water pumped to the surface has a predominant NaCl-character.
- High sulphate concentrations originate from the oxidation of pyrite in the slimes, as well as from pyrite oxidation in the stopes of older mines.

The relatively high magnesium concentrations in the surface water can only be ascribed to the type of lime that is added during the neutralization process. The lime use by the mines in the area is supplied by ULCO, which is situated on the escarpment of the Ghaap Plato (Northern Cape), and can be classified as a dolomitic limestone.

TABLE 6.6. CHEMICAL COMPOSITION OF SURFACE WATER STRUCTURES RECEIVING EITHER MINE, MUNICIPAL OR INDUSTRIAL EFFLUENT

Site ID	Ca mg/L	HCO_3 mg/L	Cl mg/L	EC mS/m	$N(NO_3)$ mg/L	pH	K mg/L	Na mg/L	SO_4 mg/L
2726DC00011	957	0	4731	1677,0	20,4	4,45	115,0	351	4512
2726DC00013	709	245	1000	606,0	0,7	7,39	370,1	741	2280
2726DC00012	1753	22	25544	6400,0		3,30	487,6	15593	4632
2726DC00120	131	303	4602	1430,0	0,0	8,38	111,0	3579	1214
2726DC00125	50	187	701	340,0		9,60	10,2	574	259
2726DC00132	89	161	164	138,0	11,2	7,66	28,1	158	337
2726DC00163	1051	11	3473	1335,0	2,0	9,22	57,5	2129	3582
2726DC00218	842	167	1039	470,0	31,3	7,74	28,9	671	1345
2726DC00221	731	131	1044	420,0	19,7	7,80	25,8	774	1924
2726DC00236	255	57	670	240,0	15,2	9,23	13,7	459	550
2726DC00238	439	81	2624	740,0	1,4	9,23	28,9	2159	1912
2726DC00241	691	51	2822	720,0	4,2	9,23	28,9	1361	489
2726DC00246	631	31	1595	490,0	38,8	6,29	34,0	908	1960
2726DC00253	721	49	2492	670,0	1,9	9,31	13,7	1797	2450
2726DC00264	405	181	941	270,0	28,9	5,40	23,5	774	646
2726DC00273	548	20	695	425,0	6,6	6,24	45,7	355	1524
2726DC00283	240	67	1229	330,0	79,5	8,00	35,6	826	819
2726DC00290	741	37	1330	610,0	54,0	5,30	37,9	216	1254
2726DD00029	2619	92	43533	7750,0	32,4	8,00	771,0	25471	7117
2726DD00047	812	124	4432	180,0	33,2	6,90	98,9	1708	1873
2726DD00057	198	161	1408	550,0	0,1	7,41	40,1	1022	955
2826BA00004	631	76	2645	780,0	0,4	8,40	76,0	1515	1615
2826BA00055	287	54	1767	460,0	30,7	8,00	22,7	1051	537
2826BA00057	306	32	1198	500,0	4,9	9,00	41,0	718	771
2826BA00059	89	157	183	144,0	3,7	8,70	29,2	181	404
2826BA00073	103	43	2179	260,0	3,0	9,30	15,6	1425	136
2826BA00190	319	124	1931	510,0	18,3	7,70	20,3	1155	1604
2826BA00191	388	65	1993	550,0	62,3	10,20	37,1	1232	1011
2826BA00195	174	57	1471	380,0	42,7	8,20	14,5	936	317
2826BA00197	167	51	1438	370,0	29,3	8,30	16,8	895	358
2826BA00200	281	133	1622	430,0	34,3	8,70	23,9	1007	342
2826BA00211	691	13	1736	400,0	5,6	6,40	13,3	1280	2072
2826BA00213	125	49	1617	360,0	17,4	7,60	9,4	1081	117
2826BA00215	852	82	3804	310,0	23,5	7,30	7,0	2345	1984
2826BB00P85	69	113	108	74,0		7,40	21,1	78	123
2826BB00P86	128	133	534	270,0		9,10	41,4	373	298
2826BB00138	701	56	707	370,0	9,4	8,00	32,5	55	1489

2826BB00140	812	98	1763	410,0	3,6	8,20	35,6	800	1518
2826BB00143	741	45	650	310,0	16,3	7,30	28,9	384	2229
2826BB00183	326	140	1177	350,0	46,0	8,90	49,3	734	1359
2826BB00189	962	98	2165	430,0	7,5	8,00	40,3	936	1667
2826BB00191	312	70	1440	360,0	35,4	6,80	27,4	867	1448
2826BB00201	491	45	1714	450,0	33,8	4,80	32,5	881	1763
2826BB00210	892	409	749	270,0	41,8	10,70	36,8	448	1333
2826BD00017	144	65	1520	600,0		6,70	16,0	1007	238
2826BD00025	67	168	543	250,0	1,4	7,30	9,0	384	624
2826BD00035	216	81	1790	390,0	41,8	7,50	21,1	1343	356
2826BD00036	278	16	2258	480,0	21,3	9,00	52,4	1155	180
2826BD00048	187	35	1683	440,0	34,1	7,30	21,1	1051	411
2826BD00050	135	32	879	430,0	30,5	6,60	14,1	470	159

Anomalous concentrations of potassium, bicarbonate and nitrate in the surface waters (Table 6.6) tend to coincide with areas storing excess mine effluent water. Furthermore, many mines in the region use purified sewage effluent in their gold extraction process, as well as $Zn(NO_3)_2$ and $Pb(NO_3)_2$. Another source contributing the high NO^-_3-contents in mine efflents originates from the explosives used in the mines. It is therefore not surprising that the NO_3^--anomalies also coincide with mining activity.

6.3.4 MUNICIPAL AND INDUSTRIAL EFFLUENT

(a) Municipal sewage effluent

Various municipalities and mines in the study area produce large amounts of sewage effluent daily. Table 6.7 lists the respective institutions and the effluent volumes they produce.

TABLE 6.7. SEWAGE EFFLUENT VOLUMES OF MUNICIPALITIES AND MINES IN THE ORANGE FREE STATE GOLDFIELDS

Municipality/Mine	Effluent volume Ml/d
Welkom (Witpan) (P 85)	25
Welkom (Theronia) (P 131 & P 132)	17
Virginia	18,5
Odendaalsrus (P 295)	4
Allanridge (P 234)	1
Loraine	1
FSG	4
Beatrix (P 47)	2,5
Joël	1
Oryx	1

TOTAL	75

Figure 6.20 depicts the positions of the sewage plants, as well as a yeast effluent discharge facility in the study area.

In Figure 6.21, the chemical analyses of purified sewage effluent, taken at various sewage plants and adjoining reservoirs, receiving effluent from the plants, are shown. Unfortunately, not all the analyses were initially analysed for PO_4^- and NO_3^-. However, values ranged from 0 to 23,3 mg/l for PO_4^- and 0 to 20,0 for NO_3^-. From the latter, it is evident that both the PO_4^- and NO_3^- concentrations exceed the maximum allowable limits. Furthermore, these high concentrations cause excessive growth of algae in the pans and streams into which the effluent is discharged. It should be kept in mind that the sites (Figure 6.21), with high ion concentrations, are natural pans or vlei systems, constantly receiving municipal effluent and storm-water run-off, as well as occasional mine effluent. Fortunately, large volumes of purified sewage are used by the respective municipalities (irrigation of city parks and gardens) and by various mines in the area, thereby reducing the pollution threat.

(b) Industrial effluent

Apart from the municipal effluent, only one industry discharges significant volumes of effluent. In the past (before 1988), these volumes of effluent were discharged into Doring Pan. Currently, the NCP yeast factory discharges an average effluent volume of 195 m^3/d. The yeast effluent is discharged over an area (open grassveld) of approximately 24 ha, in the vicinity of a system of natural pans and vleis. Large numbers of water birds and fish inhabit this pan system. Table 6.8 lists some of the chemical parameters of the yeast effluent, measured on the surface as well as in a nearby borehole.

TABLE 6.8. YEAST EFFLUENT PRODUCED BY THE NCP YEAST FACTORY

Constituent	Effluent sampled from tanker	Effluent sampled from ground surface	Borehole DD 55
COD	25000-30000	3100	967
pH	4,5	7,7	7,1
EC	4571	1505	460
TDS	32000	9933	3583

From the TDS-values in the above table, it is evident that the effluent constitutes high levels of total dissolved solids, which can pollute the surface as well as subsurface waters extensively. However, a more important indicator of the effluent's pollution hazard is the very high COD-values. During the 1988/1989 rain season, large amounts of the yeast

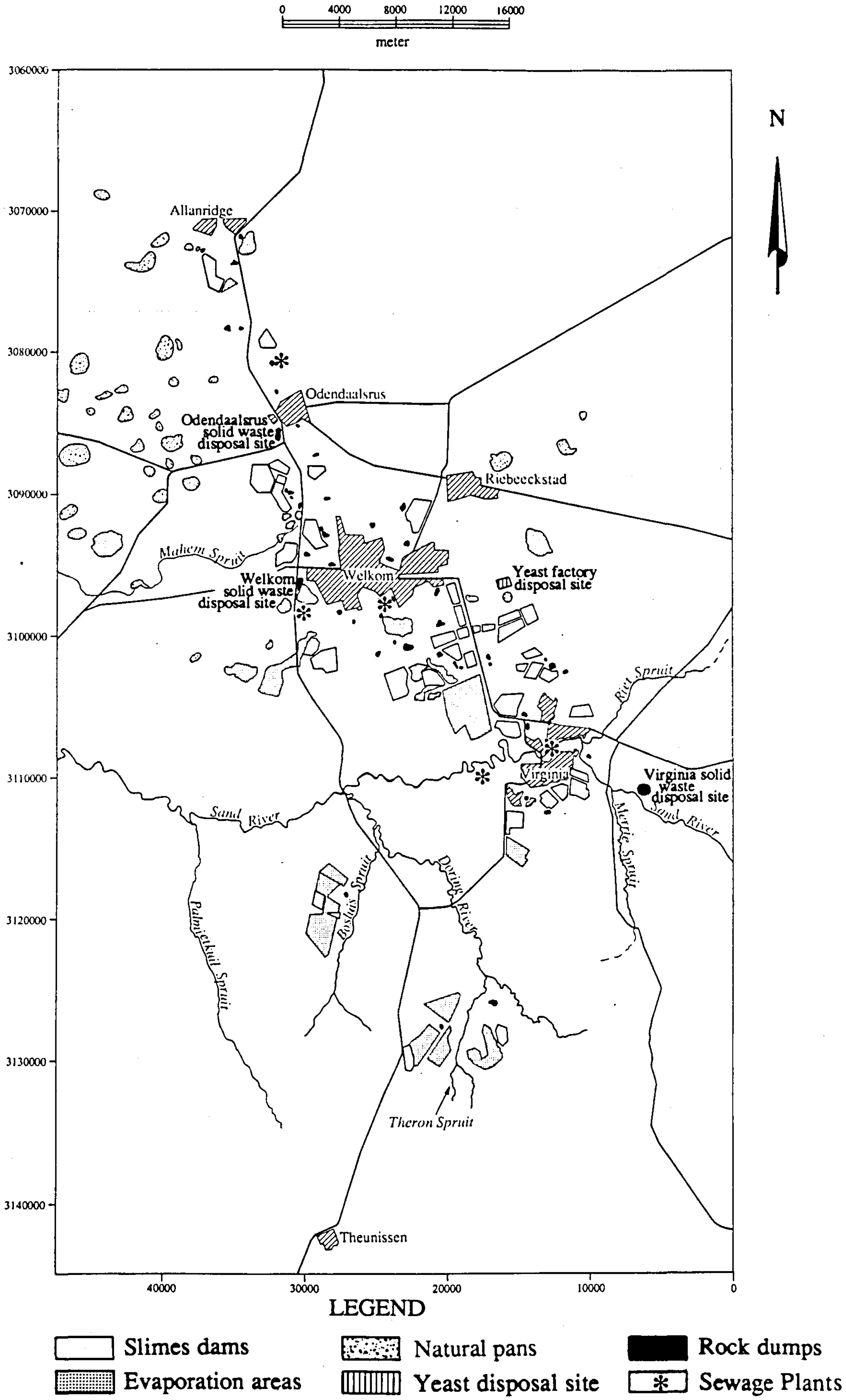


Figure 6.20. Locations of solid waste disposal sites and yeast effluent facility in the Orange Free State Goldfields.

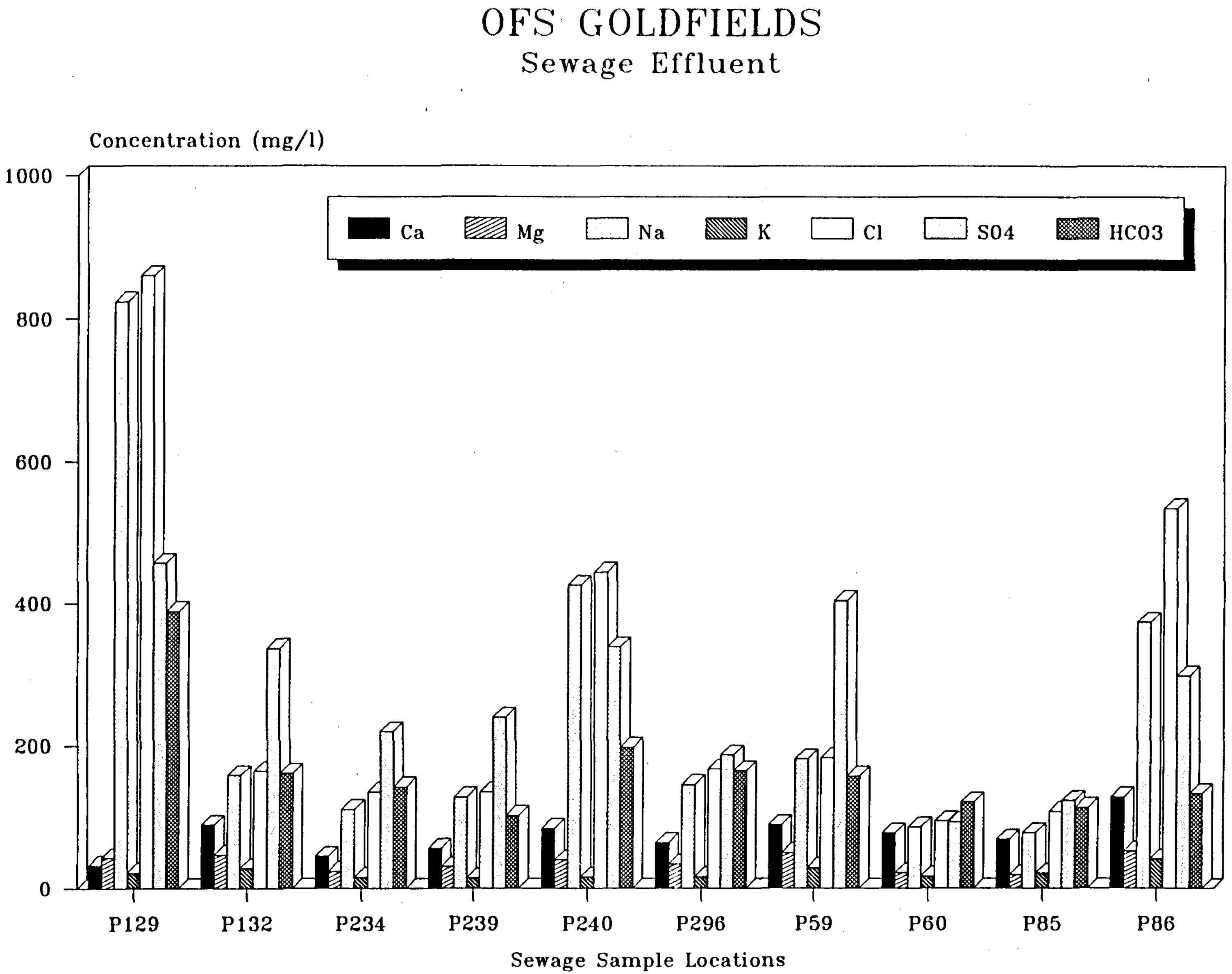


Figure 6.21. Chemical analyses of the purified sewage effluent.

effluent contaminated some of the pans in the system, killing fish and birds associated with the respective pans.

Three boreholes (DD 55, DD 65 and DD 66) were drilled in the vicinity of the disposal site and pan system (see Figure 6.22). Chemical analyses of all the boreholes near the disposal site are shown in Figure 6.23. From this figure, it is clear that samples DD 55 (Borehole) and DD 57 (Pan) are contaminated to the greatest extent. The reason for borehole DD 55 being affected so severely, is that at one stage effluent was discharged in close proximity of the borehole, directly leaking into the borehole along cracks and along the casing. Yields obtained from boreholes during both drilling phases varied from 0 to 0,4 l/s, which indicate that the general permeability of the Ecca sediments in the region is very low. This means that the potential for the contaminant to spread via ground-water flow in the area is small. However, if the effluent is freely discharged in the local vlei and pan system, the contaminant is spread quickly over large distances, thus increasing the potential of the surrounding boreholes to be contaminated.

(c) Municipal solid waste

When complex organic compounds are degraded, inorganic compounds, like sulphate and phosphate, are produced. The acids resulting from the degradation of solid waste may dissolve the minerals, resulting in a highly mineralized leachate. The quality of the leachate from a solid waste disposal site is determined by factors such as the age of the dump, the composition of the solid waste and the geohydrological characteristics of the underlying strata.

Solid waste produced by the residencial areas and commercial establishments in the study area is dumped at three major sites, of which two are located in natural pans (Welkom and Odendaalsrus), while the remaining site (Virginia) is located on the bank of the Sand River (Figure 6.20).

The surface water of the respective pans and river, adjacent to the sites, was analysed for possible pollution from the respective solid waste disposal sites. No significant contamination was observed in all three cases.

Two shallow boreholes (3 m deep) were drilled in the vicinity of the Welkom solid waste disposal site, to monitor the leachate from the solid waste. Borehole DC 351 was drilled between Toronto Pan and the base of the waste disposal site to the south of the disposal site, while borehole DC 352 was drilled at the base of the disposal site to the east of the disposal site.

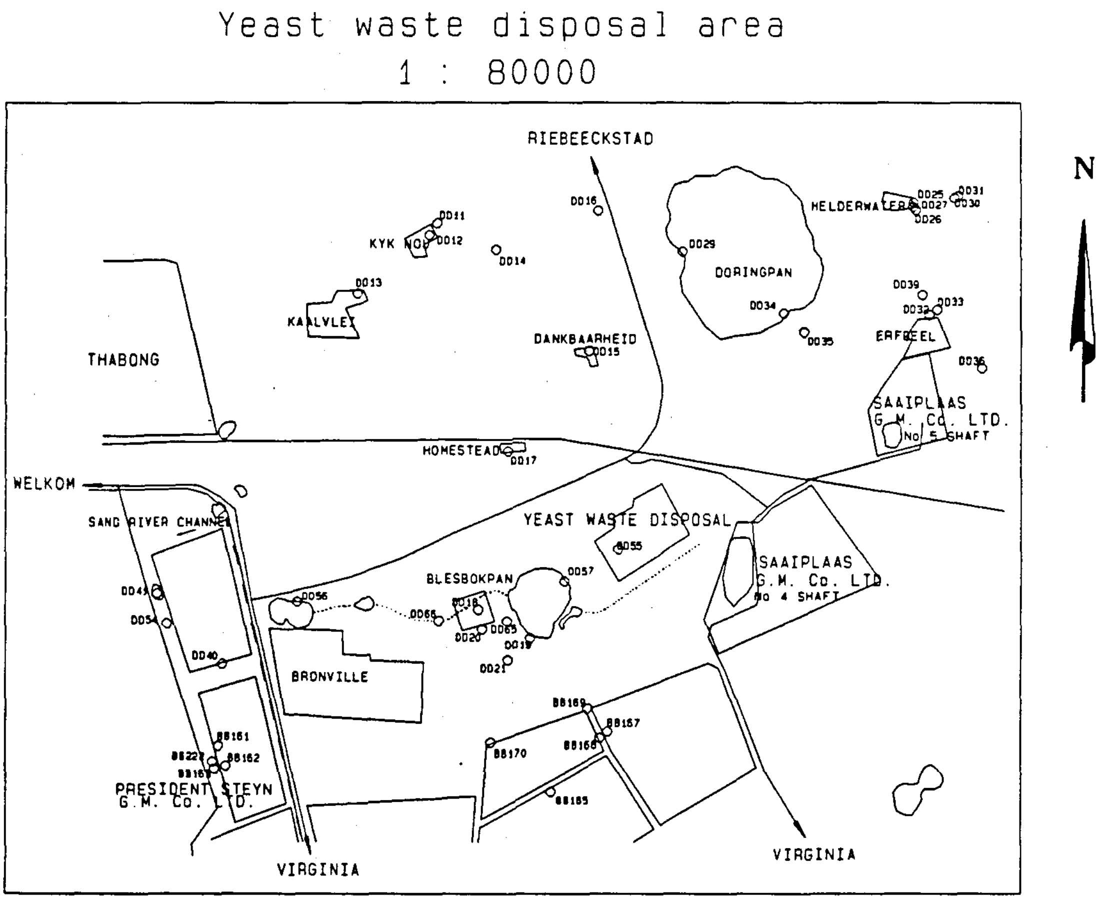


Figure 6.22. Yeast disposal site.

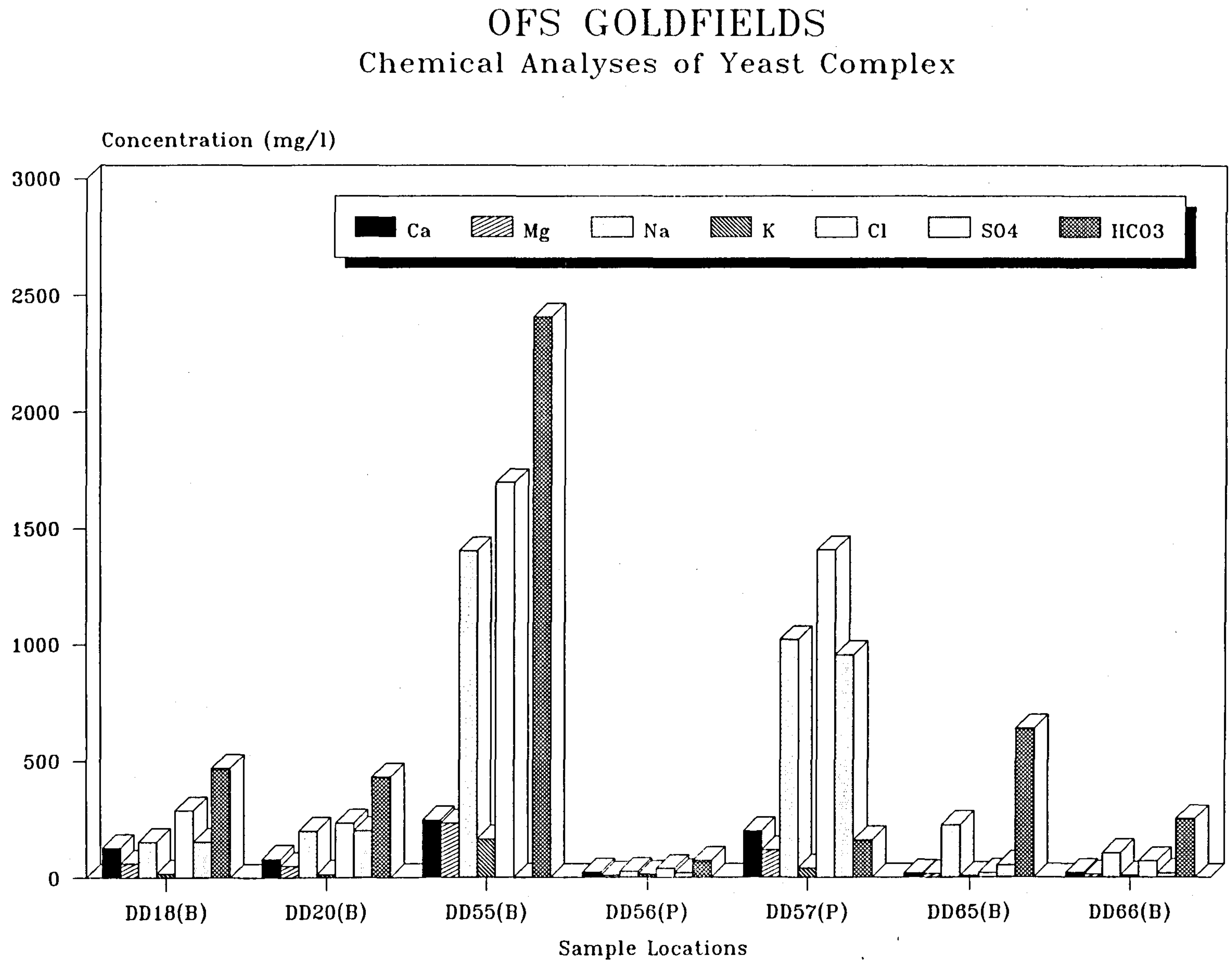


Figure 6.23. Chemical analyses of borehole and pan water at the yeast disposal site.

Figure 6.24 depicts the heavy metal and the major cation and anion concentrations of the two boreholes and Toronto Pan respectively. From the figure, it is evident that the influence of the pan is much higher in the case of borehole DC 351, resulting in the higher Na^+ and Cl^--concentrations. When comparing the heavy metal concentrations with the general standards in Table 6.1, it is noted that the ground water in the two boreholes is polluted by leachate, from the solid waste, to quite a large extent. A variation of the heavy metal concentrations is observed at different sampling dates. This variation could be ascribed to the variation in the monthly rainfall that occurred during this period, as well as the moisture content of the refuse that was dumped.

6.4 CHEMISTRY OF THE GROUND WATER

In view of the large amounts of water in the pans and evaporation areas, one can accept with confidence that at least some of this water will penetrate into the ground, to reach the water table. The chemistry of the ground water is thereby changed to more closely resemble that of the surface water, from which it originates.

Many chemical changes may occur in the surface water, before it finally joins with the ground water. Typical changes are:

- Base exchange and inverse exchange reactions.
- Solution and precipitation.
- Chemical reaction.

The degree to which each of these processes is active in the Orange Free State Goldfields, depends on many variables, such as:

- The availability of clays in the unsaturated zone.
- The salt load in the seepage water.
- The rate of fluid percolation.
- The volume of fluids passing into the ground water.

In Chapter 5, it was concluded that the borehole yields in the Orange Free State Goldfields are geologically controlled. In this section, it will be shown that the ground-water qualities in the area are also geologically controlled. Furthermore, the influence of the surface water quality on the ground-water quality will be discussed in some detail, to see whether contamination of the latter source has taken place.

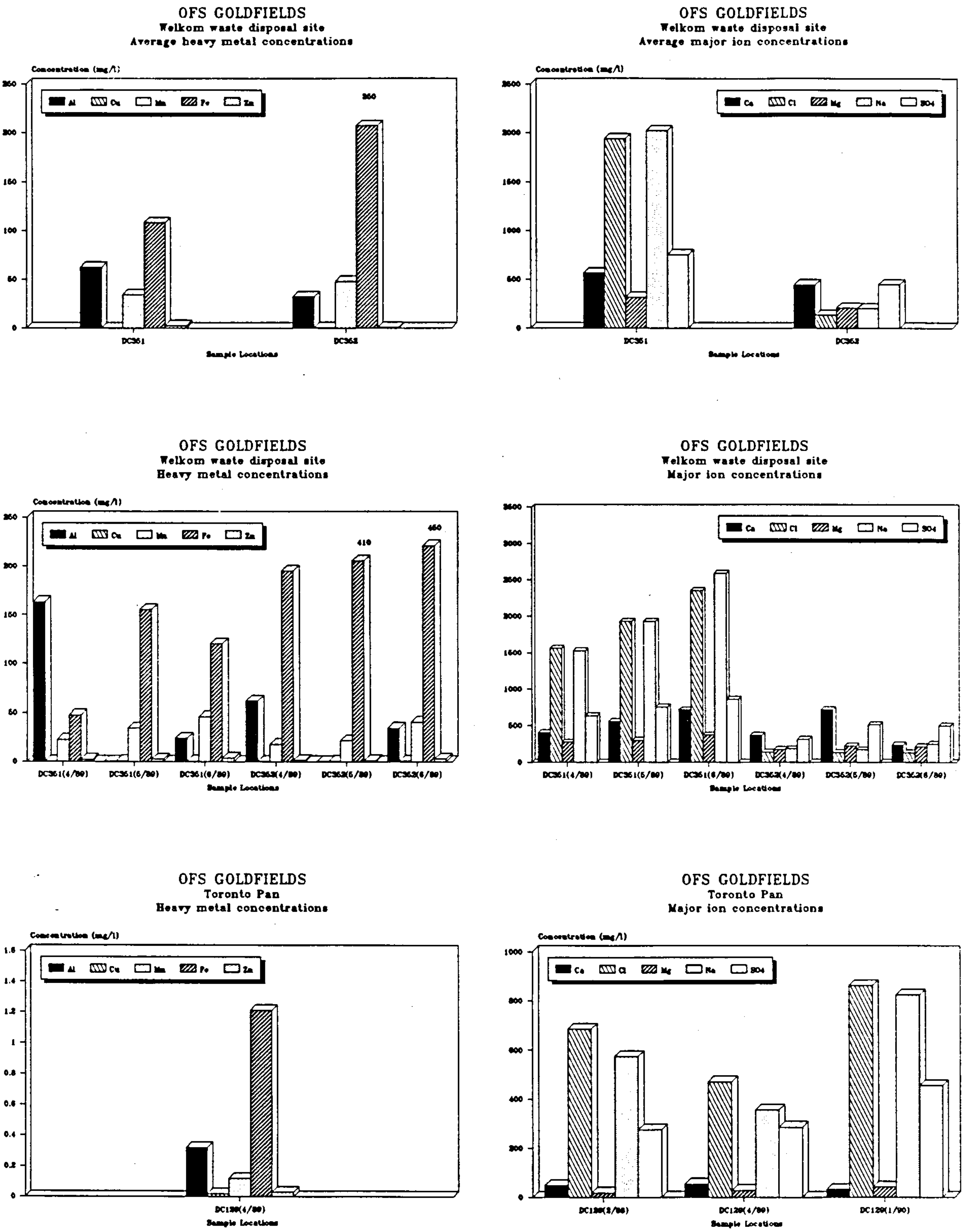


Figure 6.24. Heavy metal and major cation and anion concentrations at the Welkom solid waste disposal site.

6.4.1 GENERAL GROUND-WATER CHEMISTRY OF THE ORANGE FREE STATE GOLDFIELDS

Figure 6.25 represents a Piper plot of ground-water qualities in the study area. As can be seen from the figure, no definite pattern in the composition can be observed. This means by implication that the ground water in the Orange Free State Goldfields is subjected to different hydrochemical processes, such as:

(i) ion exchange,
(ii) mixing and dissolution, and
(iii) precipitation.

When evaluating the cations (Figure 6.25), it is noted that Ca^{2+} is more dominant than Mg^{2+}, whereas Na^+ and K^+ seem to be the most dominant cations in almost all the ground-water samples. At low Na^+-percentages, both Ca^{2+} and Mg^{2+} seem to increase.

When looking at the anions (Figure 6.25), it is striking to observe that the SO_4^{2-} in the ground water seldom exceeds the 30% level. This is in sharp contrast with the actual analyses, where the ground water is enriched in SO_4^{2-}, as can be seen in Figure 6.26. The line in Figure 6.26 represents the recommended drinking-water limit for sulphate as proposed by Kempster and Smith (1985). Thus, although the SO_4^{2-}-concentration may be high, it is only a fraction of the total anion-concentration, due to the relative high Cl^--and HCO_3^--concentrations. This clearly illustrates the major drawback of the Piper diagram, i.e. that it depicts ion percentages and not real concentrations. The lower percentage of SO_4^{2-} present in the ground water relative to that of the surface water, can mainly be ascribed to bacterial reduction, adsorption and oxidation of SO_4^{2-}. In almost half of the ground-water samples, the chloride content seems to exceed 50%. Therefore Cl^- seems to be the major anion.

Contour maps of the major cations and anions (Ca^{2+}, Mg^{2+}, Na^+, K^+, Cl^-, SO_4^{2-}) of the water samples were constructed, representing a general view of the ground-water quality in the Orange Free State Goldfields.

The positions of all the sampled boreholes are shown in Figure 6.27, while Figures 6.28 to 6.34 represent the contour maps of the electrical conductivity, as well as the respective macro elements. (Refer to Figure 6.19 for the identification of the different groups mentioned in the following section).

From the electrical conductivity contours (Figure 6.28), it is observed that all the anomalies identified coincide with surface water structures containing excessive effluent. The Ca^{2+}-,

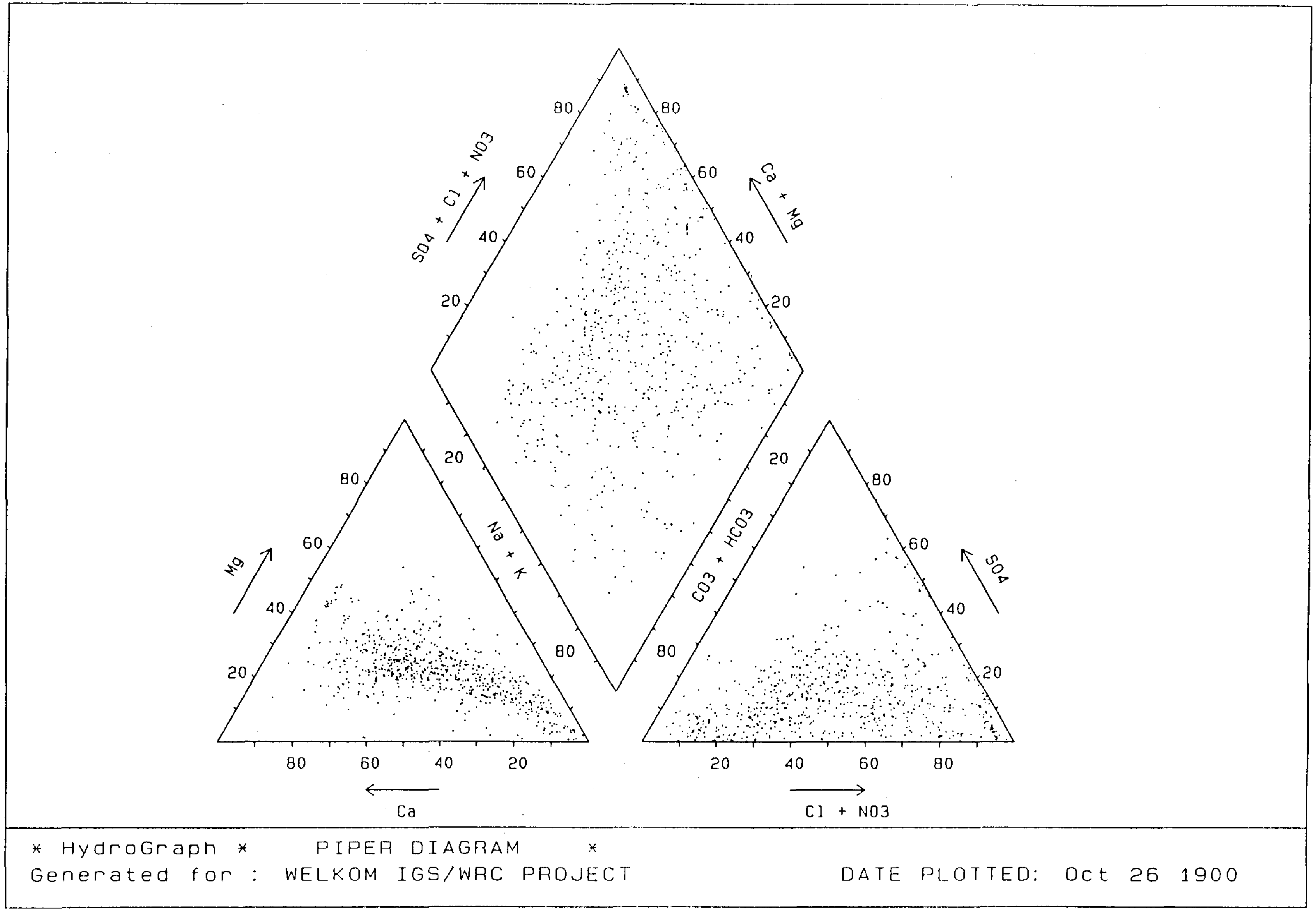


Figure 6.25. Piper diagram of all the ground-water samples.

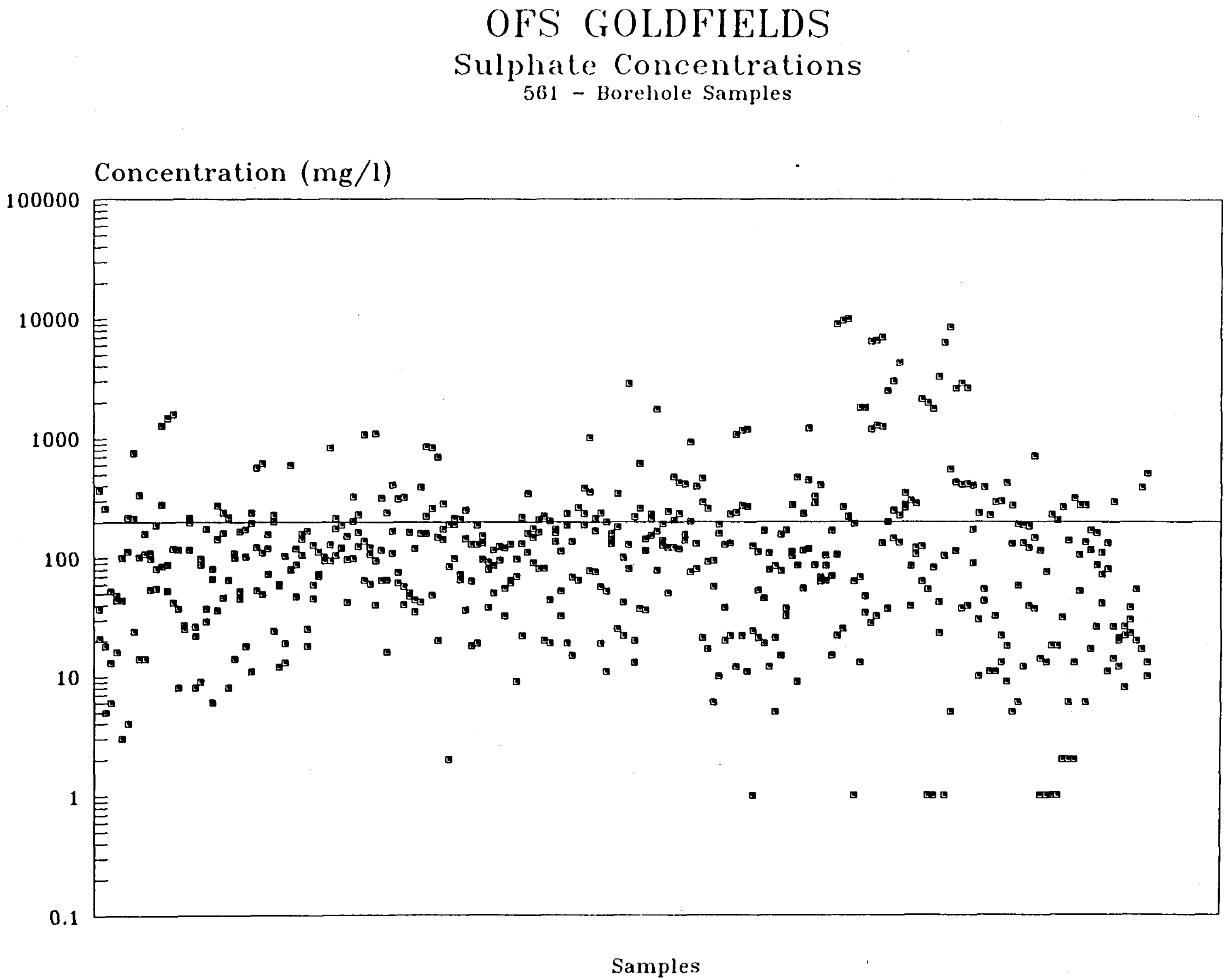


Figure 6.26. Sulphate concentrations of the ground water (mg/l).

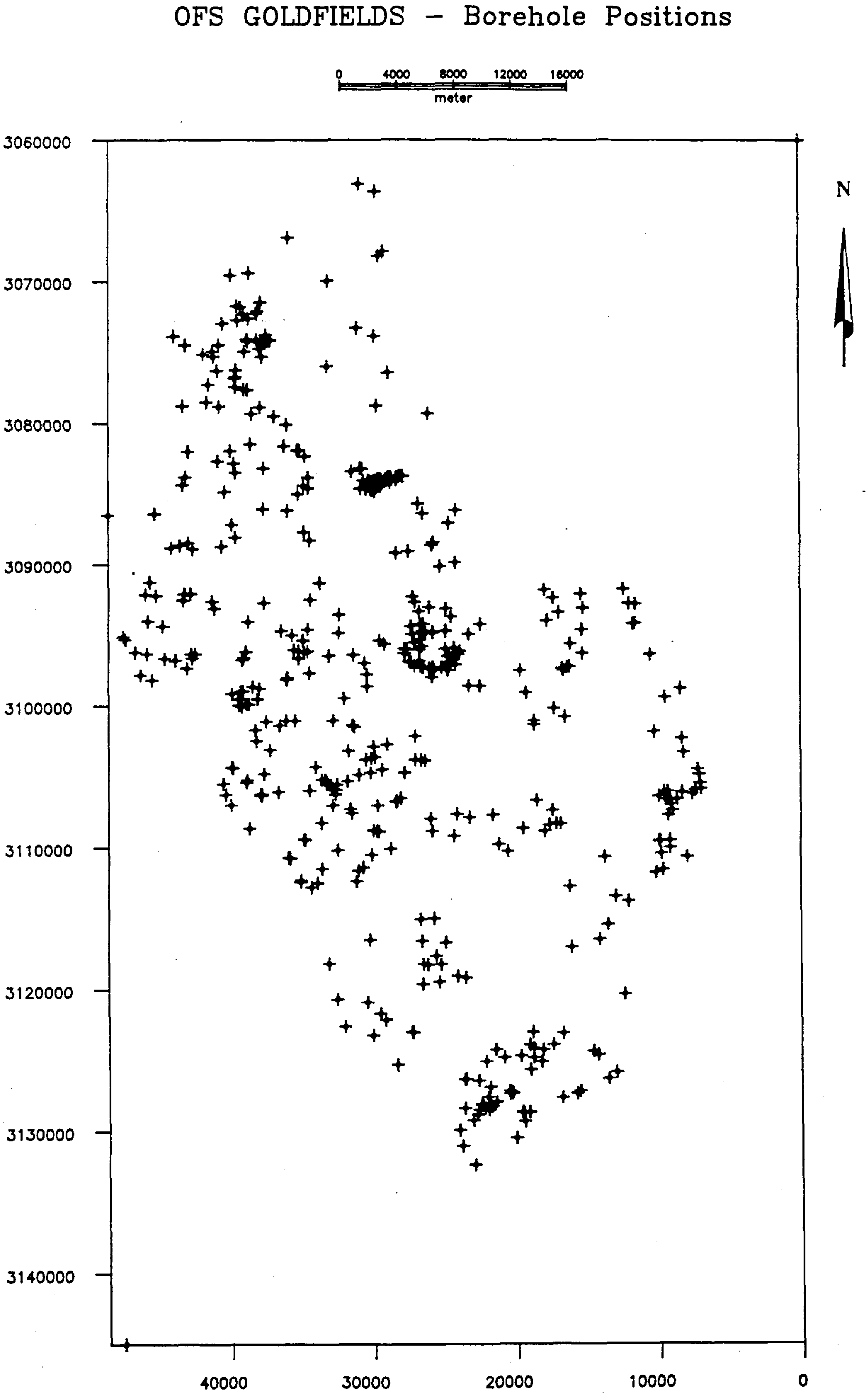


Figure 6.27. Borehole sampling positions in the Orange Free State Goldfields.

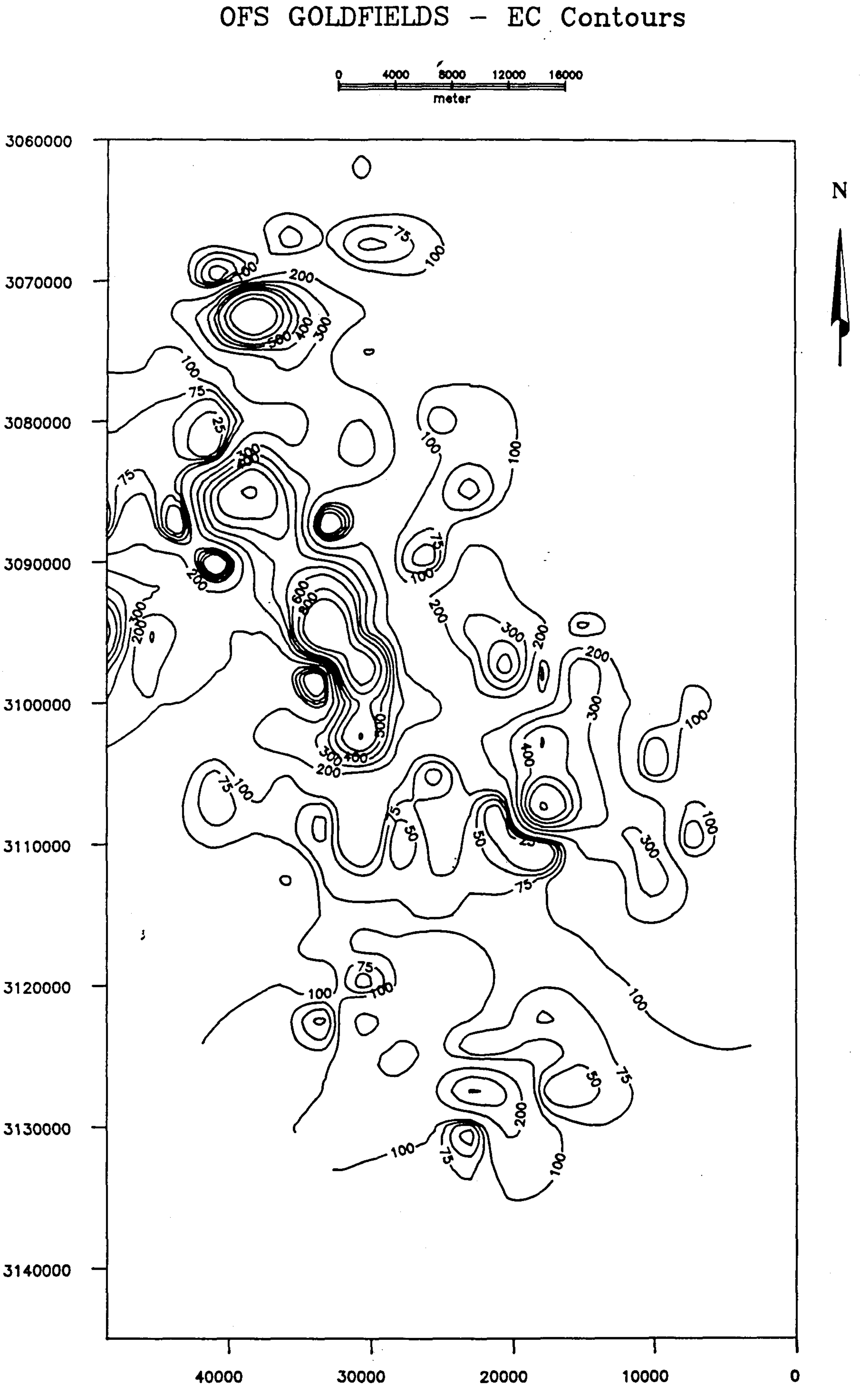


Figure 6.28. Electrical conductivity contour map of the ground water (mS/m).

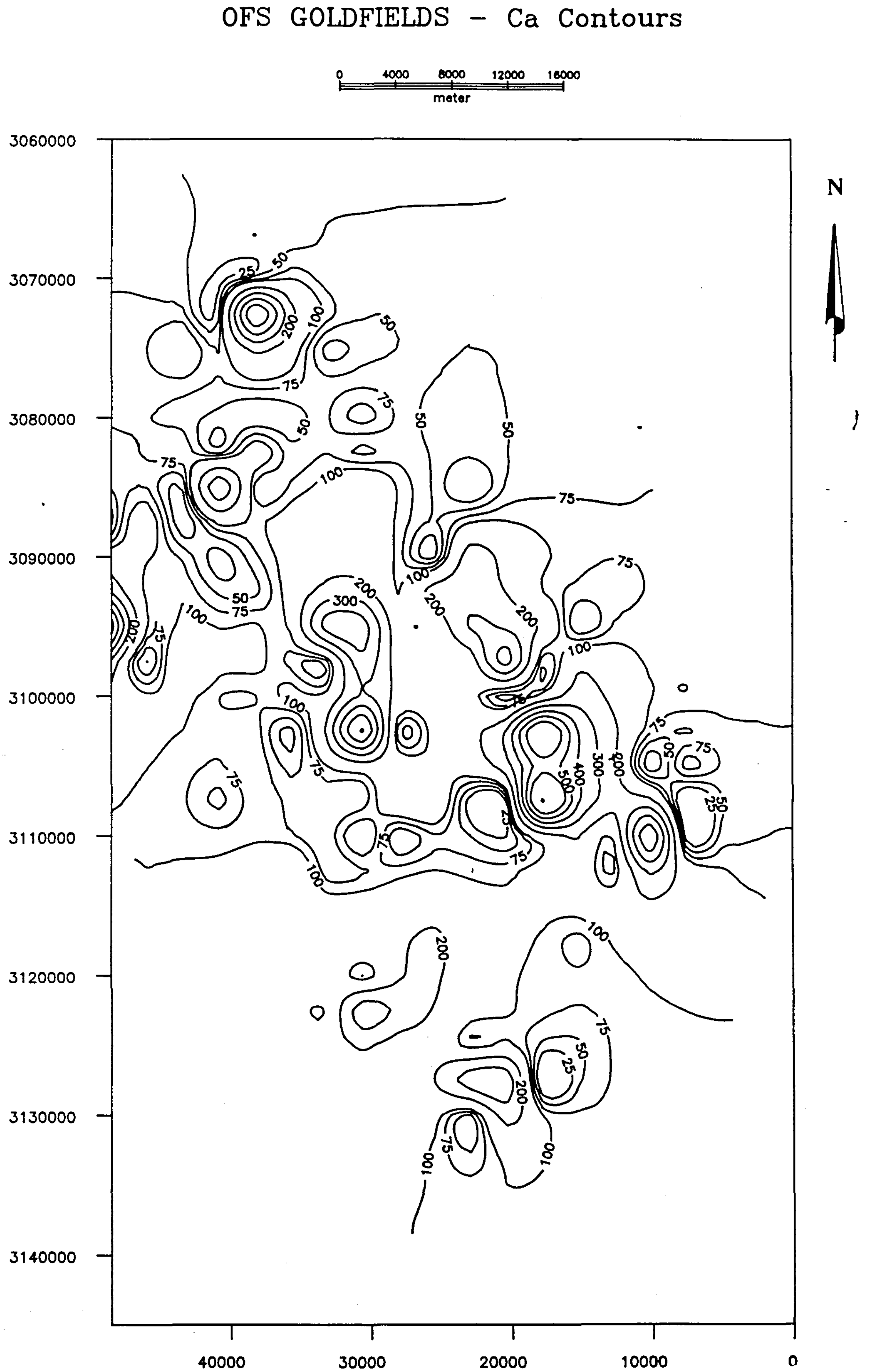


Figure 6.29. Contour map of the calcium concentrations in the ground water (mg/l).

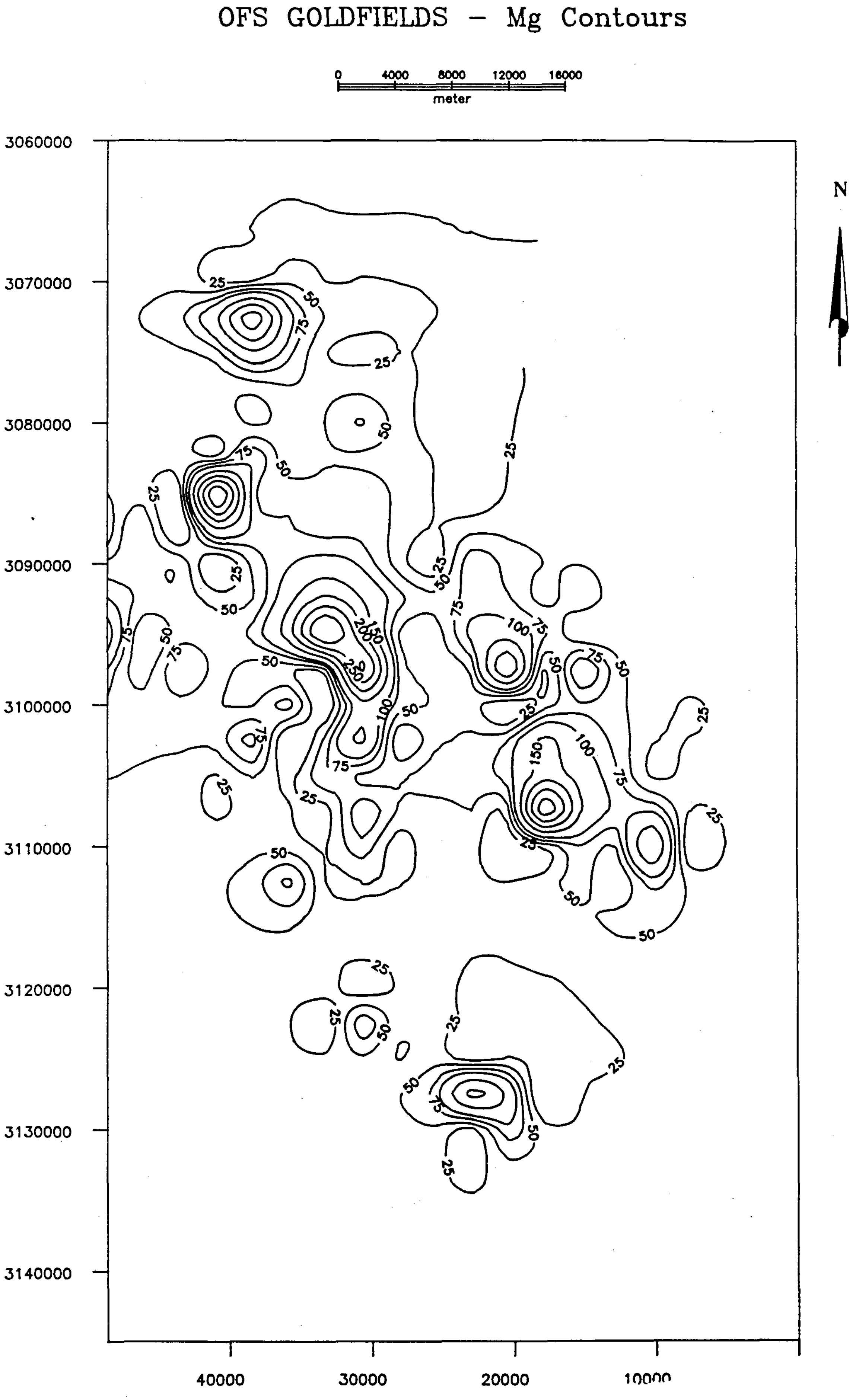


Figure 6.30. Contour map of the magnesium concentrations in the ground water (mg/l).

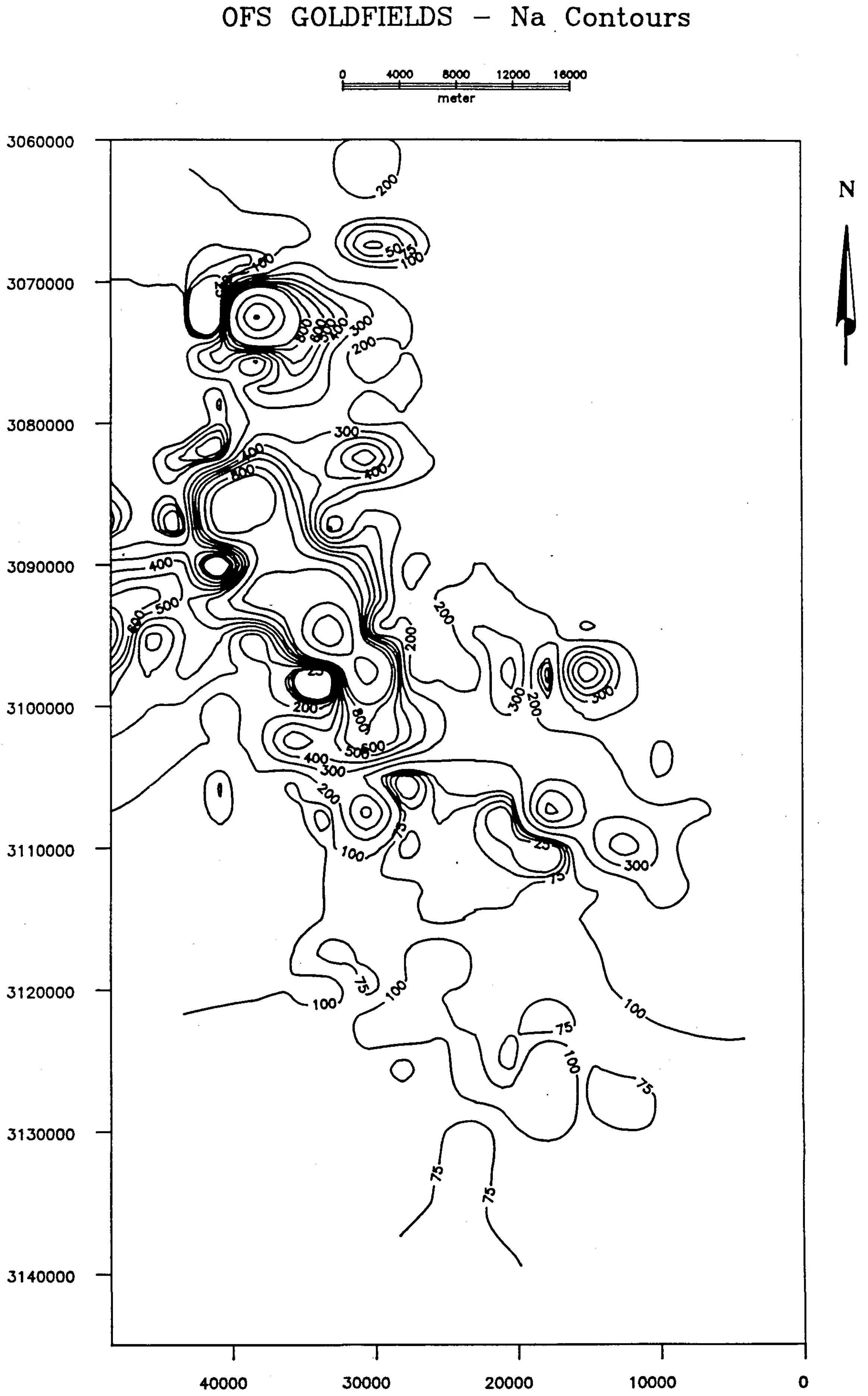


Figure 6.31. Contour map of the sodium concentrations in the ground water (mg/l).

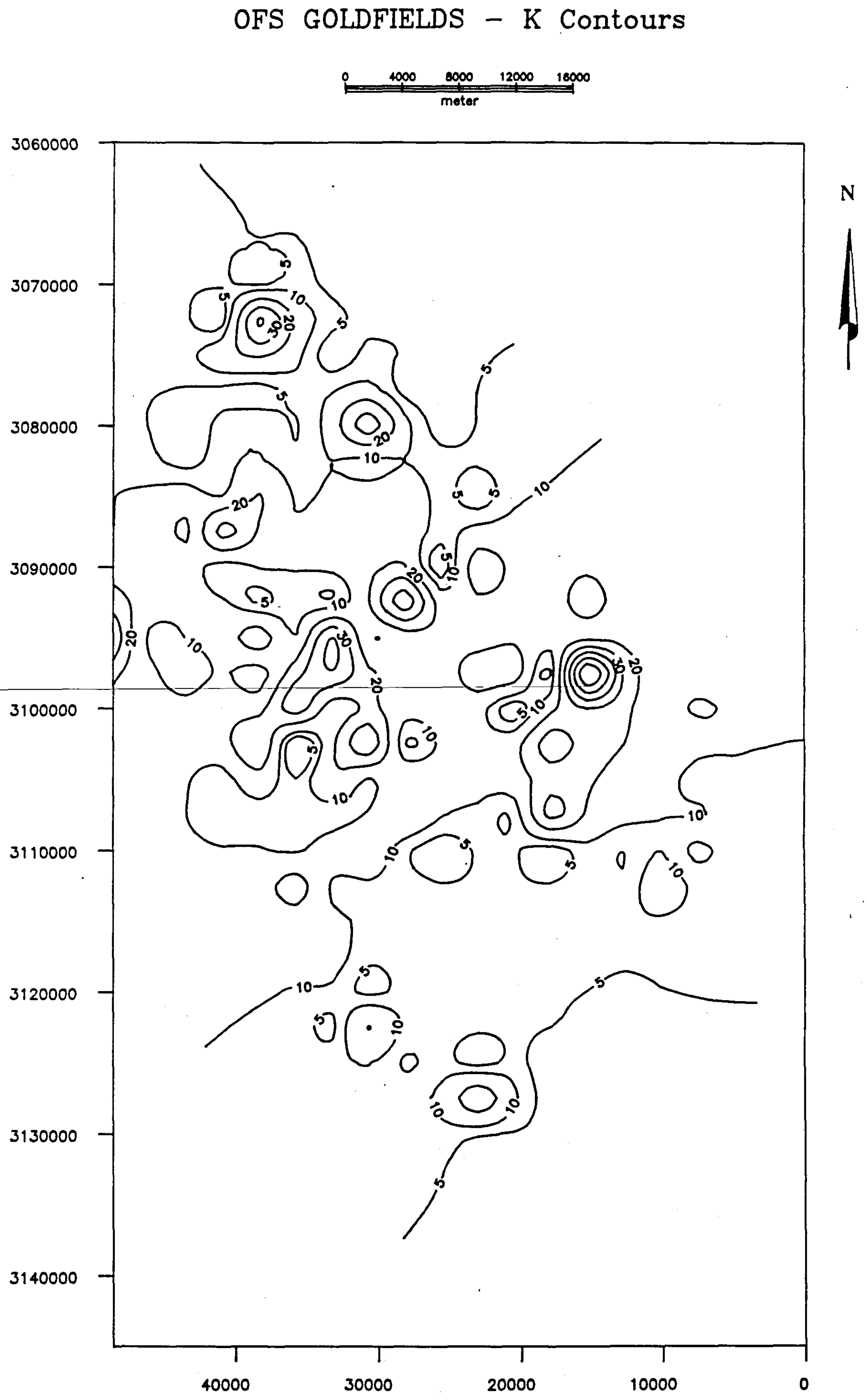


Figure 6.32. Contour map of the potassium concentrations in the ground water (mg/l).

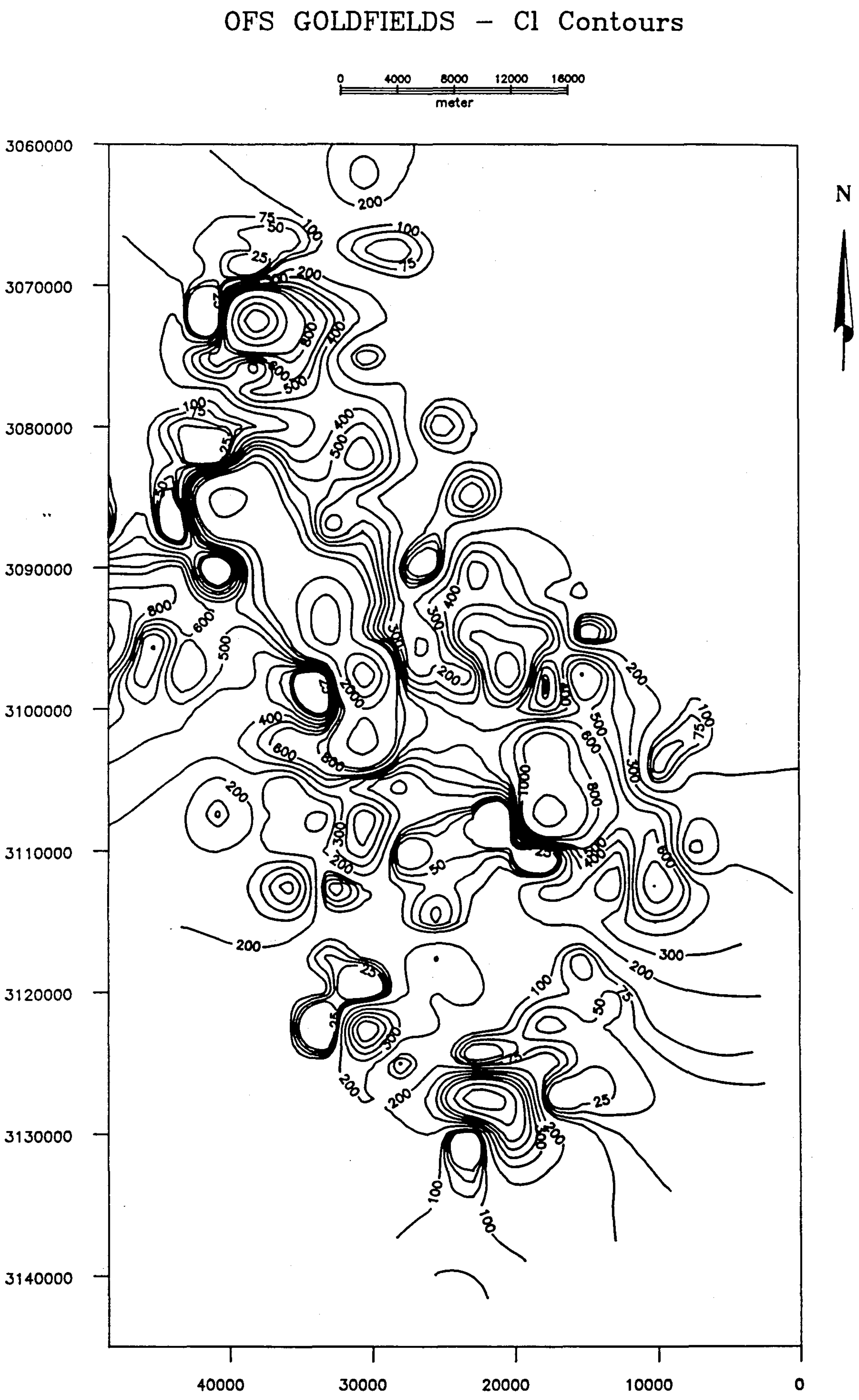


Figure 6.33. Contour map of the chloride concentrations in the ground water (mg/l).

OFS GOLDFIELDS - SO4 Contours

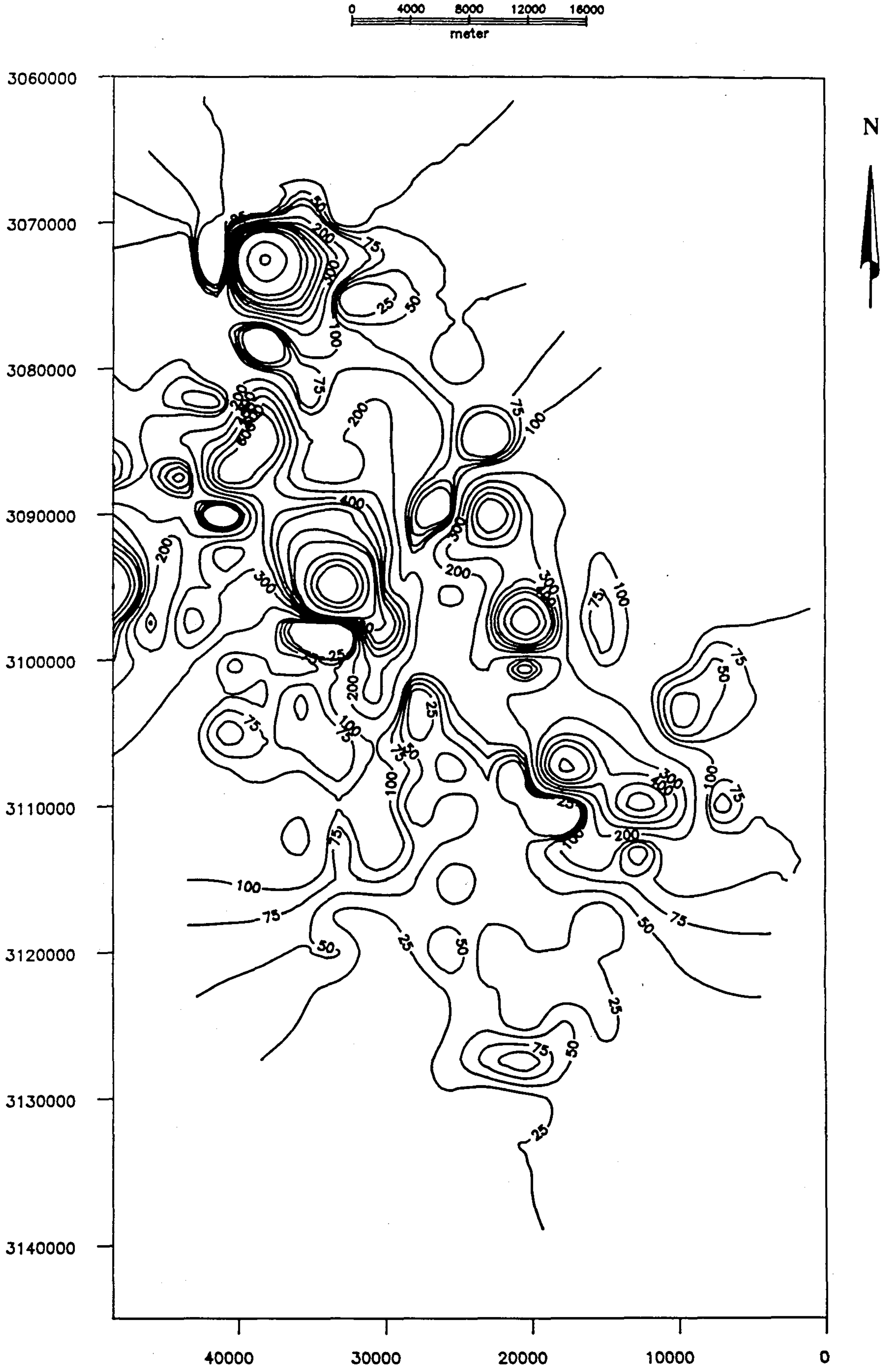


Figure 6.34. Contour map of the sulphate concentrations in the ground water (mg/l).

Mg^{2+}-, Na^+-, Cl^-- and SO_4^{2-}-contour maps correlate reasonably well with the conductivity map, due to the coinciding anomalies. When evaluating the ion-concentrations depicted in the respective contour maps in some more detail, it is evident that concentrations in the south of the study area (groups 8 and 9) are much lower than the ion-concentrations towards the north of the area. Both these groups coincide with new mines in the area. Recharge of the ground water due to the infiltration of the surface water has just started in these areas, whereas in the other areas, it is in a very advanced stage. A further reason for the better water qualities in the south of the region is that these boreholes are situated in the Beaufort sediments. The Beaufort sediments generally yield ground water of a better quality than the Ecca sediments. This will subsequently be discussed in some more detail. Comparing the Ca^{2+}-, Na^+- and Cl^--contours with one another, it is found that the Ca-concentrations of groups 1, 5 and 6 are much higher than those of group 2. However, the Cl-concentrations of the different groups are approximately the same. Groups 1 and 2 have more or less the same Na-concentrations, but they are much higher than those of groups 5 and 6. From the above discussion, it is obvious that the ground water from groups 1, 5 and 6 is enriched in Ca^{2+}, which is most likely, due to the influence of the excessive effluent mine water. The relatively low Ca-concentrations of group 2 is due to natural circumstances. The ground water in this region is naturally saline, with high Na- and Cl-concentrations and a low Ca-concentration.

Groups 1, 5 and 6 were subjected to reverse ion exchange, and therefore have a high Ca^{2+}-content and a lower Na^+-content. The Cl^--content of all the waters is basically the same, as Cl^- does not participate in ion exchange or reverse ion exchange. The reason why group 1 has a high Na-content and not low as expected, is because the ground water in that area is directly affected by Swart Pan which has a very high Na^+-content. Thus, although a large quantity of the Na^+ has been adsorbed by clay particles, sufficient Na^+ remained in solution to cause the high Na-concentrations in this area.

6.4.1.1 Comparison of water chemistries

To depict areas where possible contamination of ground-water resources occurred, a preliminary criterium was used during the reconnaissance sampling. The assumption was based on the fact that all ground waters in the area with a conductivity in excess of 250 mS/m, were possibly contaminated. At that stage, no chemical analyses of the ground water in the region were available, thus the assumption proved valuable in planning the extended sampling phase. However, as the reconnaissance survey progressed, the validity of this assumption was questioned, because boreholes with conductivities in excess of 500 mS/m were sampled relatively far away from any pollution sources. Most of these boreholes are situated to the west of Odendaalsrus and Welkom, in an area where extensive pan development has taken place. The question to be answered was, whether the ground water was contaminated by distant pollution sources or whether the ground-water quality was adversely affected by natural hydrochemical phenomena.

In order to distinguish between the natural poor quality ground water and the polluted ground water, all boreholes, within a distance of 30 m from any pollution source, were plotted on a Piper diagram (Figure 6.35). Comparing the Piper diagram, containing all surface mine water (Figure 6.1) with the above figure, a striking resemblance is observed. The mine water which is enriched in SO_4^{2-}, Cl^- and Ca^{2+}, correlates well with some of the borehole water in the region, which is also enriched in the above-mentioned ions, although the SO_4^{2-}-enrichment is not as obvious. In the anion triangle, Cl^- is the main ion, whereas in the cation triangle, Ca^{2+} represents the major cation and is also reflected in the central diamond of the figure. The group, identified in Figure 6.35, coincides with the position of calcium chloride brines, identified by Johnson (1972). The only way that the Ca^{2+}-enrichment with a resultant decrease in Na^+ can be explained is by reverse ion exchange.

To determine whether the ground water would still correlate with the surface mine water as the distance from the pollution source increases, all the boreholes within 500 m as well as 1 km from any pollution sources, were plotted on Piper diagrams. The plots are shown in Figures 6.36 and 6.37. Looking firstly at Figure 6.36, it is observed that the borehole water still correlates well with the surface mine water. However, a small group appears at the bottom right of the cation triangle where Na^+ seems to be dominant. The appearance of this group cannot be explained. Figure 6.37 shows the same tendency as Figure 6.36, except that a big group starts to appear approximately in the centre of the diamond and can be ascribed to one of two factors:

(i) The infiltrated mine water is diluted by mixing with the ground water and a gradual change in overall chemistry is observed.

(ii) The contaminated ground water has not yet spread that far and the natural composition of the ground water in the region is observed.

The new group appearing at the centre of the diamond represents a dynamic ground-water regime, in which ion exchange may take place. In contrast to the main group, the Cl^--content in this group constitutes less than 55% of the total ion content of the ground water, and the Na^+ more than 40% of the cations. This is not surprising, as ground water in this group has a low salinity and is generally of a good quality. In contrast with the other group, the CO_3^{2-}- and HCO_3^--percentages are relatively high, as can be expected in a dynamic ground-water regime.

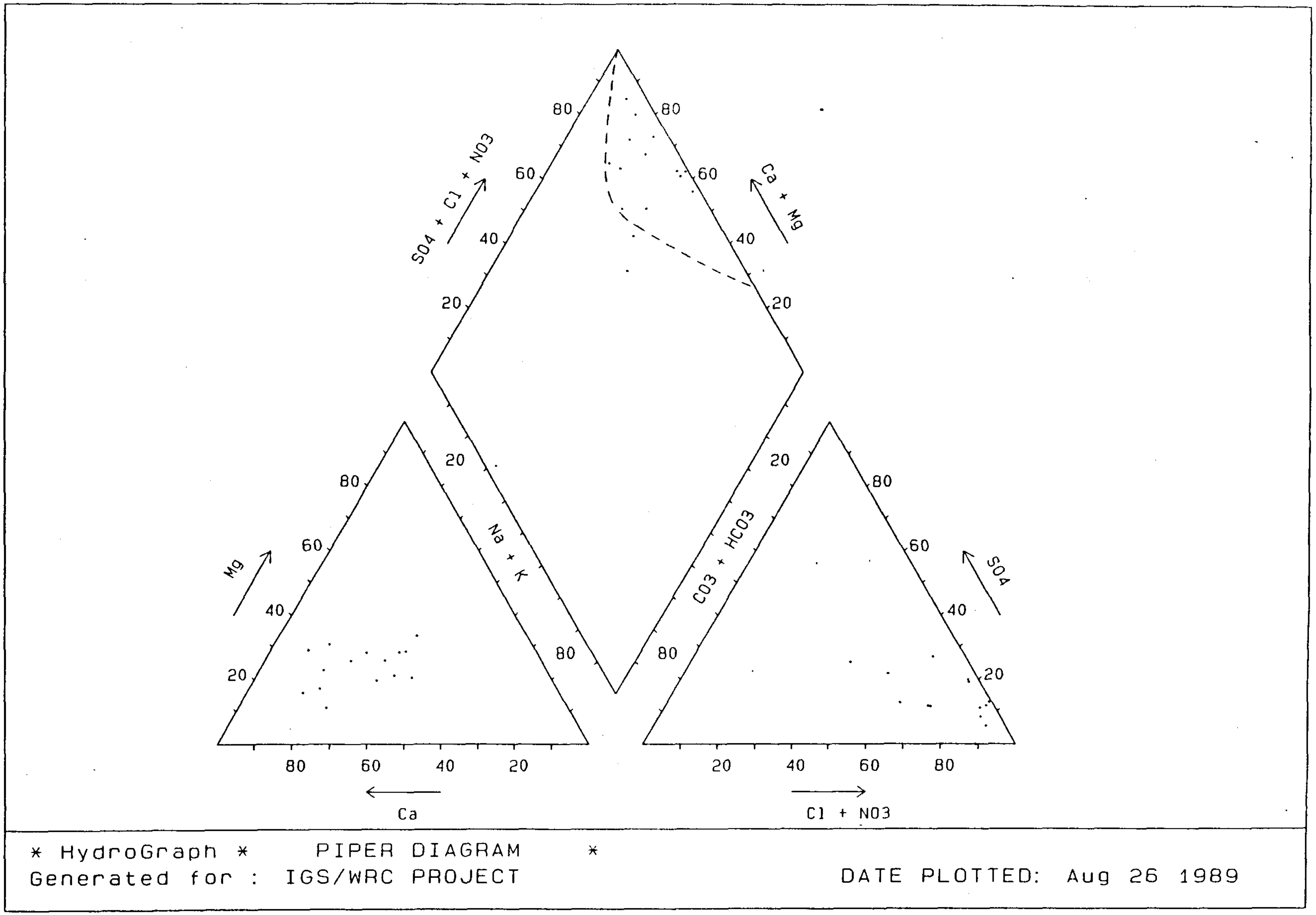


Figure 6.35. Piper diagram of ground water from the boreholes which are situated within a distance of 30 m from any pollution source.

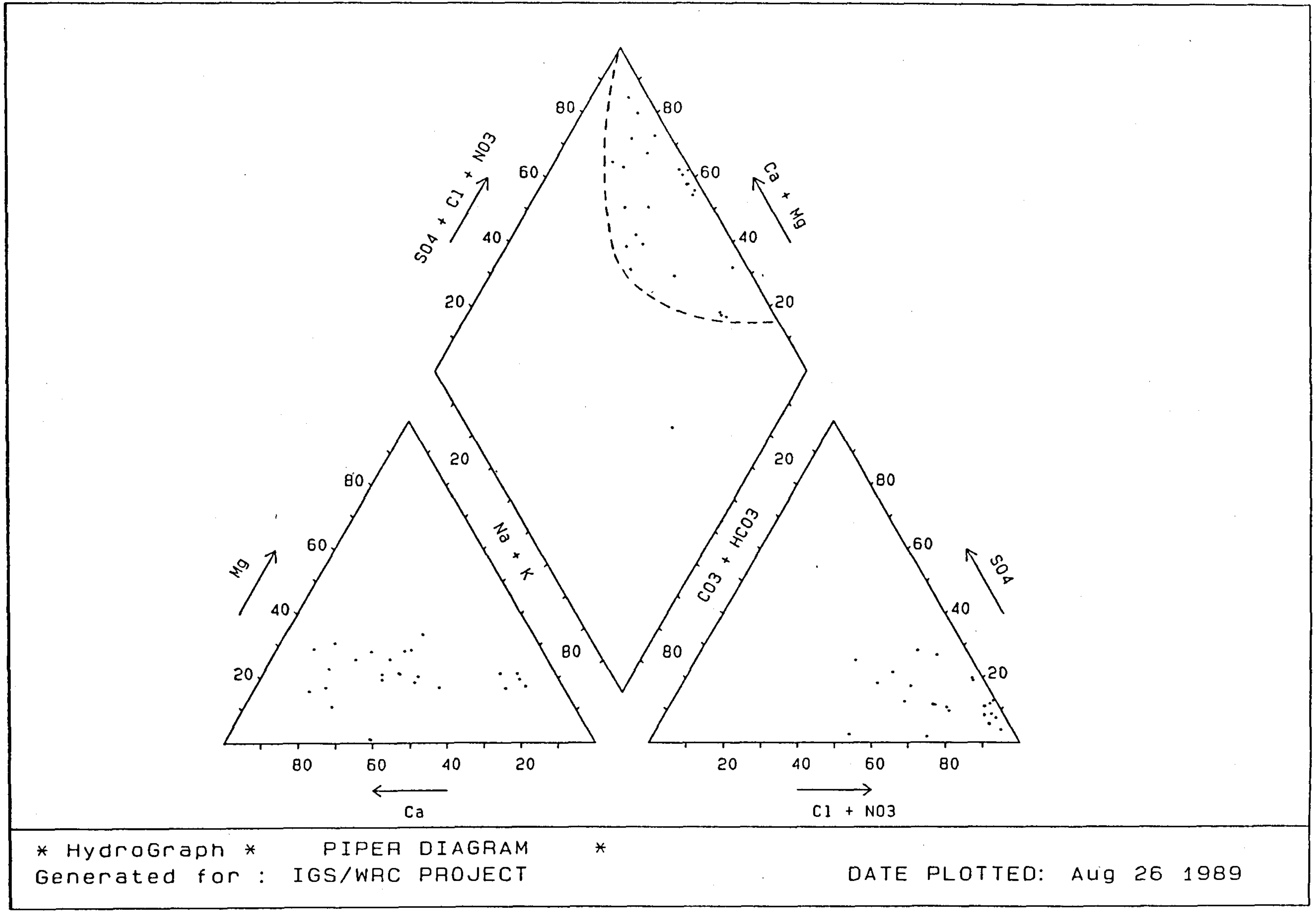


Figure 6.36. Piper diagram of ground water from the boreholes which are situated within a distance of 500 m from any pollution source.

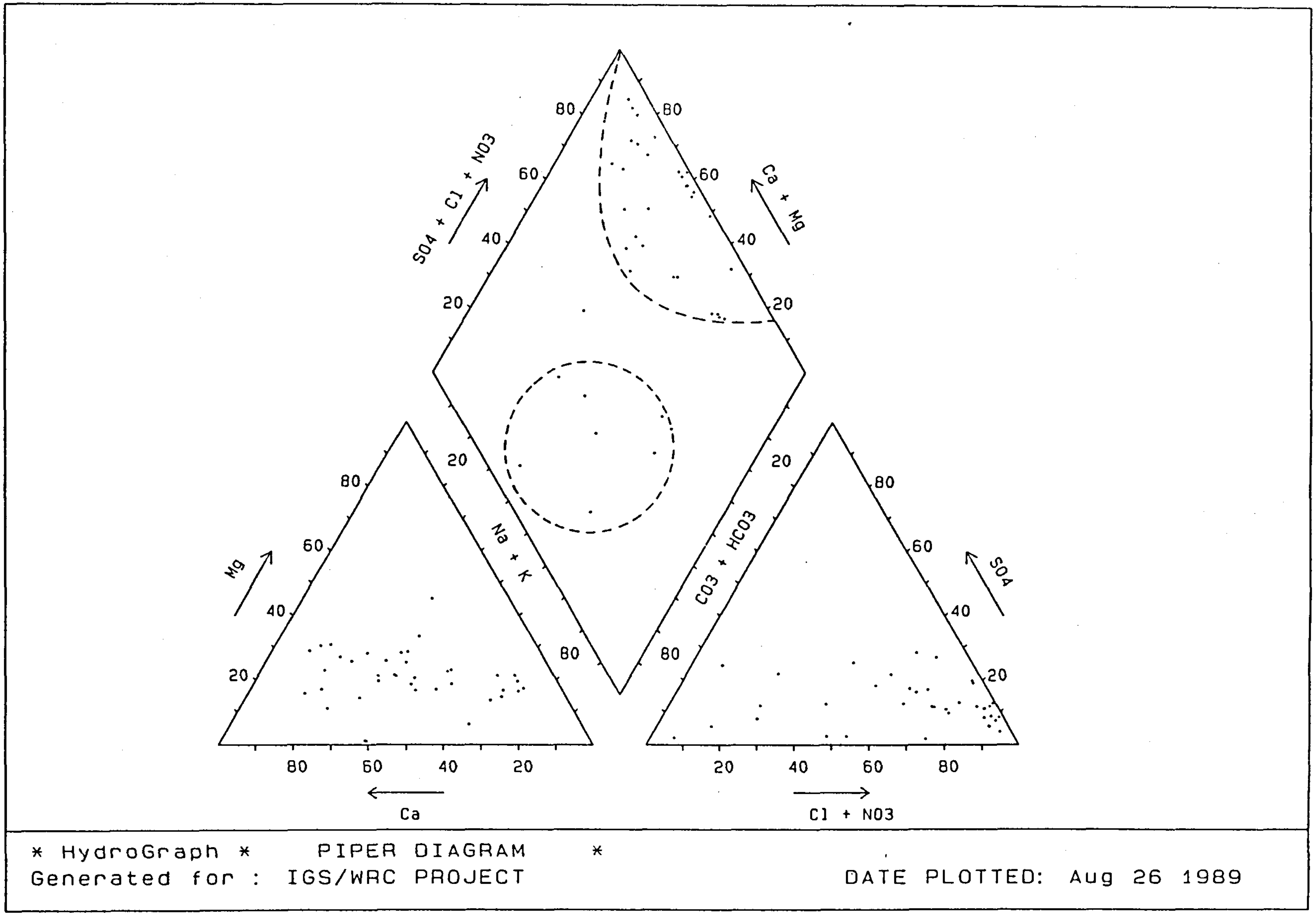


Figure 6.37. Piper diagram of ground water from the boreholes which are situated within a distance of 1 km from any pollution source.

From the above discussion, it appeared that the effluent mine water infiltrates the subsoil and eventually reaches the ground-water level.

In order to verify the above, two target areas, namely:

(i) Loraine disposal facility - Ecca sediments (old disposal site), and

(ii) Beatrix disposal facility - Beaufort sediments (new disposal site)

were selected.

Figures 6.38 and 6.39 represent some of the chemical analyses of the respective target areas. From Figure 6.38, it is evident that the ground waters from the region differ significantly and will be discussed in more detail at a later stage. The fields depicted on the triangles represent ground waters of different electrical ranges. In both cases, it is noticed as the electrical conductivity increases towards the disposal facilities, the Na^+- and Cl^--content of the ground water increases. In the case of the Beatrix facility, with increasing electrical conductivity, the Na^+ decreases, while the Ca^+ increases, which can be ascribed to reverse ion exchange. This phenomenon also occurs at the Loraine disposal complex and is illustrated by the following example.

To investigate the enrichment of Ca^{2+} in the ground water in more detail, the chemistries of borehole DC 5 and Swart Pan were evaluated. The borehole is situated about 7 m from the edge of the pan and was drilled by the owner of the farm into a shallow dolerite dyke, intersecting the pan.

Figure 6.40 shows a Piper plot of the chemistry of both the pan and the borehole. From the diagram, it is observed that the Ca^{2+}-concentration of the borehole water is considerably higher than that of the pan, indicating a possible Ca^{2+}-enrichment. This tendency is exactly the same as previously discussed (see Figures 6.38 and 6.39), where Ca^{2+} is exchanged for Na^+ in the presence of water with a high Na^+- and Cl^--content. The shift of the borehole chemistry away from the position of Swart Pan towards the top of the diamond, is similar to the position of the contaminated boreholes, shown in Figure 6.25. This can also be observed in the cation triangle, as Ca^{2+} constitutes only a fraction of the total cations in the case of the pan, while a definite shift towards the Ca^{2+}-corner of the triangle is observed in the ground-water sample.

Figure 6.41 represents a Schoeller diagram of the chemical data of the borehole and Swart Pan. Ion-concentrations of the pan are generally higher than those of the borehole water, except for the Ca^{2+}- and HCO_3^--ions. The Cl^--concentration of the borehole is slightly

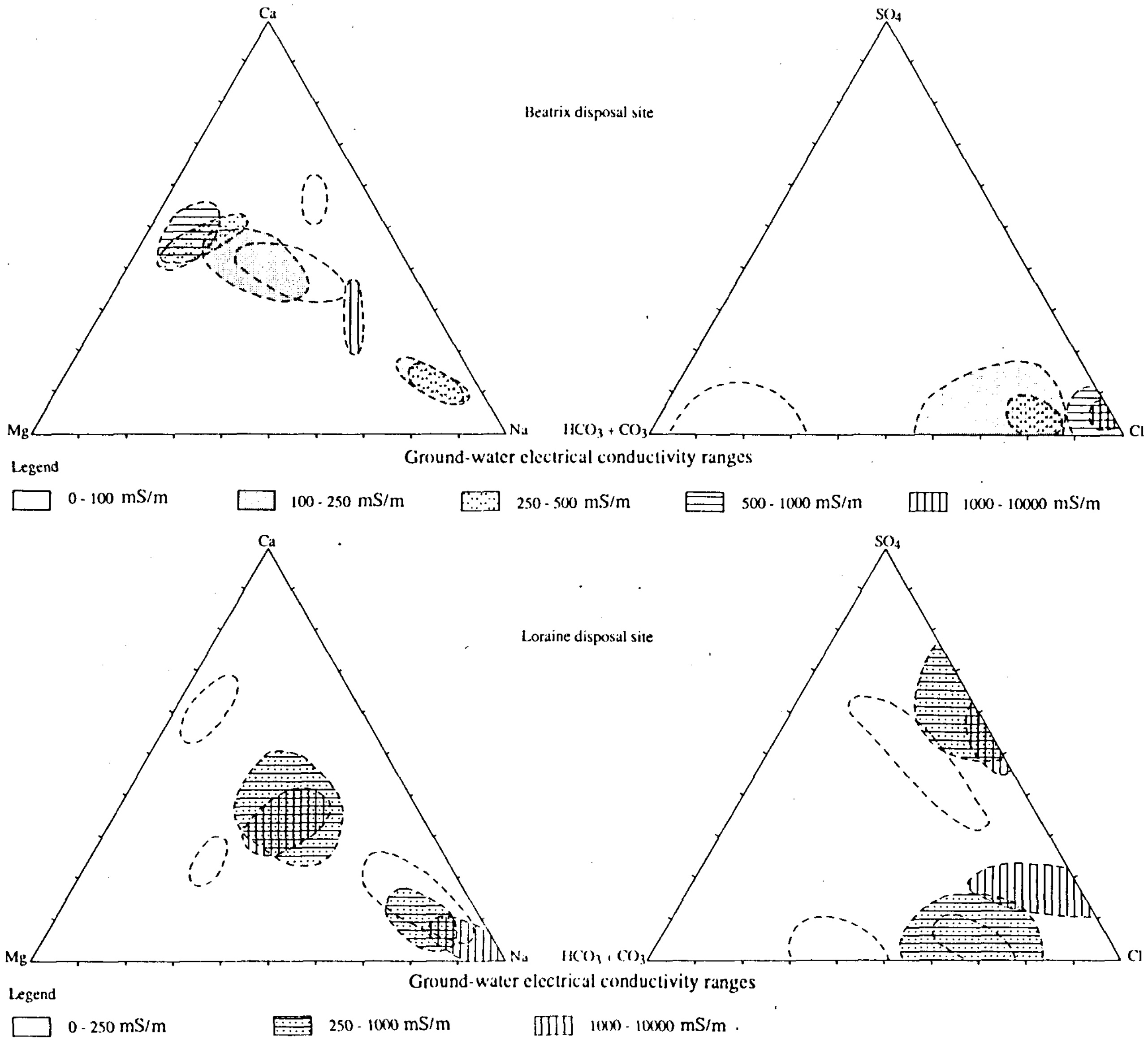


Figure 6.38. Triangular plot of the major anions and cations of borehole water in the vicinity of the Loraine and Beatrix disposal sites.

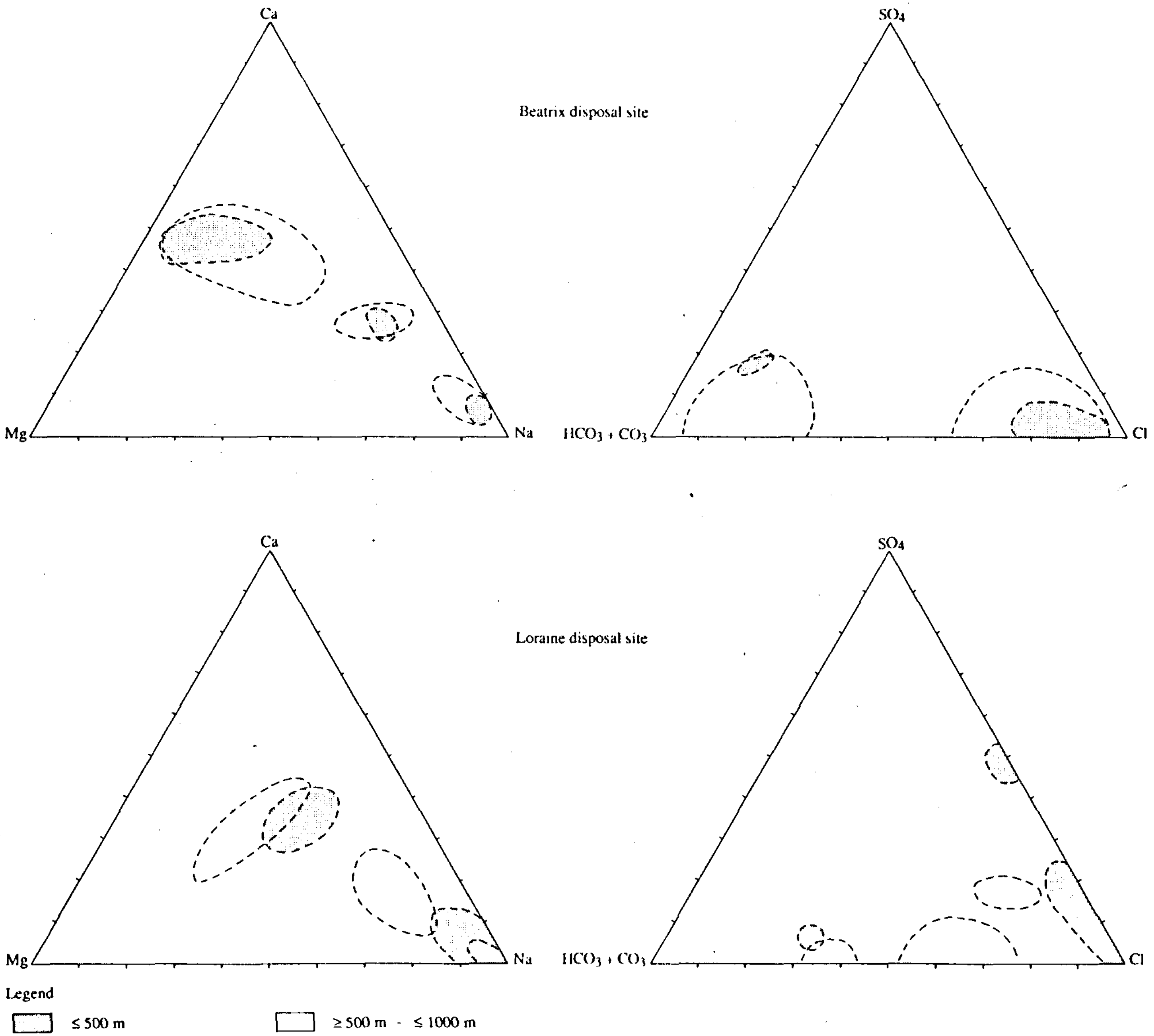


Figure 6.39. Triangular plot of the major anions and cations of boreholes within 500 m and 1 000 m from the disposal sites.

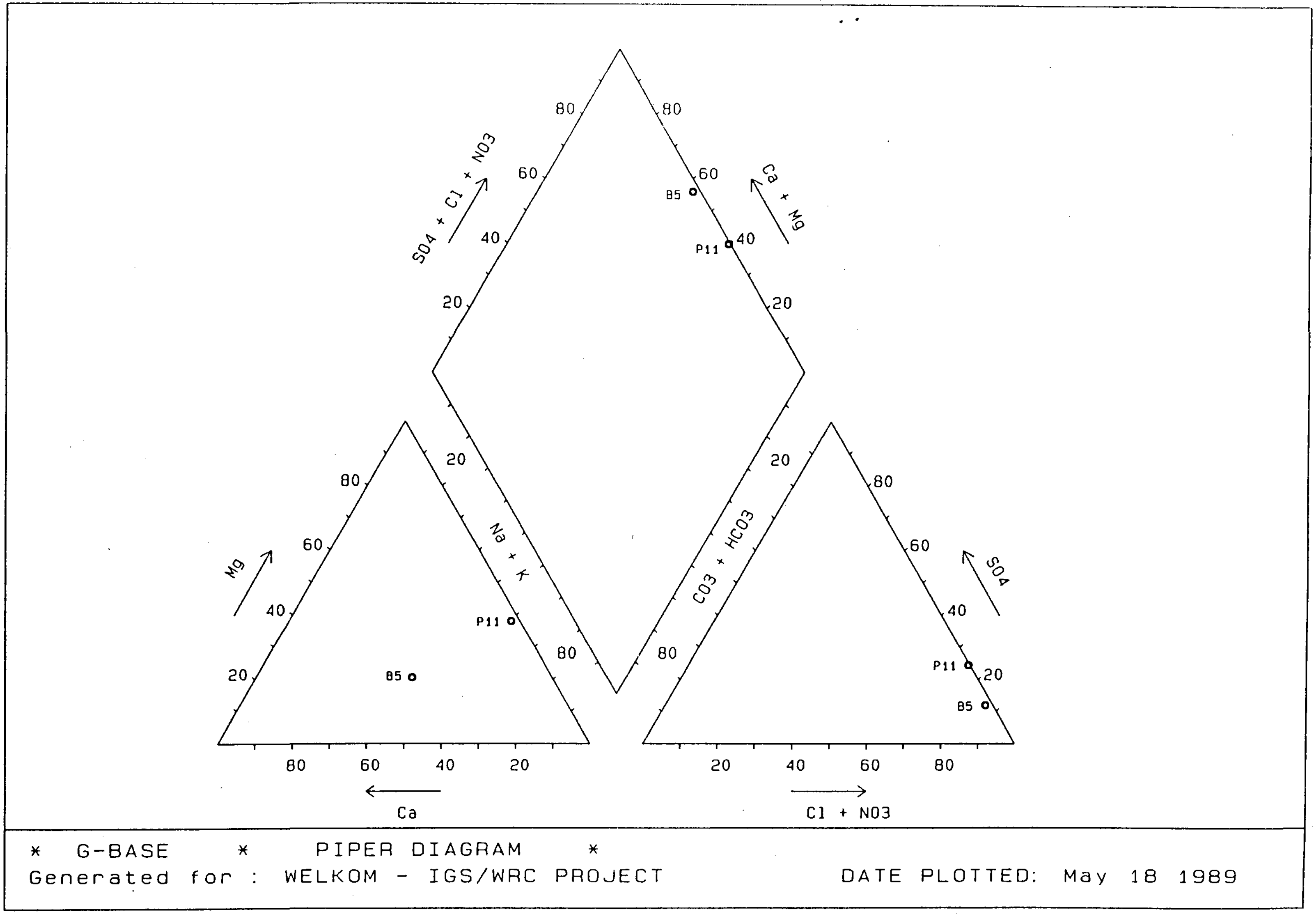


Figure 6.40. Piper diagram showing the relation between the water of Swart Pan (P 11) and borehole B 5.

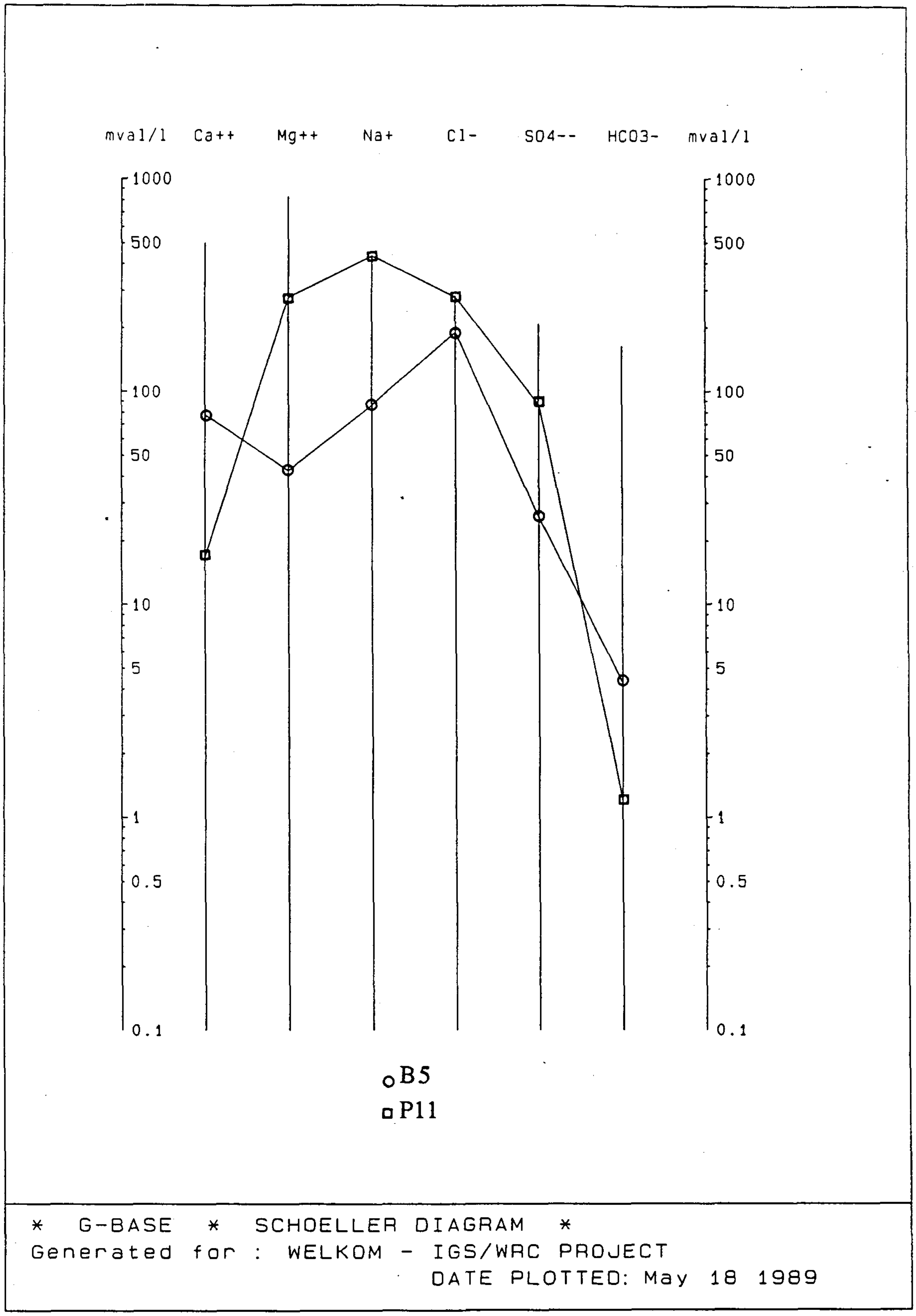


Figure 6.41. Schoeller diagram comparing the chemical data of Swart Pan (P 11) and borehole B 5.

lower than that of the pan and this can mainly be ascribed to the dilution of the water, as Cl^- is a highly mobile ion. The lower SO_4^{2-}-concentration may be due to dilution, as well as adsorption to the surrounding matrix. The higher HCO_3^--concentrations can be explained as follows: Ground water is enriched in CO_2 (gas), originating from the roots of plants and oxidized organic matter. The CO_2 (gas) dissolves into the ground water and this solution reacts with $CaCO_3$, resulting in HCO_3^--enrichment.

The above and other examples indicate that reverse ion exchange is indeed taking place in the Orange Free State Goldfields, due to the presence of large concentrations of Na^+ and Cl^- in mine effluent.

It is furthermore noticed that ground waters in the vicinity of the Beatrix facility have low SO_4^{2+}-concentrations, compared to the Loraine facility. This can be ascribed to the fact that the new mines are still dewatering significantly, while the SO_4^{2+}-production from old disposal facilities (slimes dams) has been going on for 30 to 40 years. Figure 6.39 very clearly indicates the increase of ion concentrations (especially Ca^{2+}, Na^+, SO_4^{2+} and Cl^-) closer to the respective disposal sites.

By plotting only the boreholes to the north-west of Welkom at distances > 1 km from the respective pollution sources and with an electrical conductivity > 250 mS/m on a Piper diagram, one should be able to determine whether these boreholes are polluted by mining effluent or not. Further, one should be able to determine to which extent the contamination has spread throughout the area.

According to Figure 6.42, two groups are depicted. The first group (Group I) shows a good correlation with the surface mine water. The boreholes plotting in Group II on the diagram display a dominant NaCl-character and can be classified as stagnant waters. When looking at the cation triangle, it is observed that there seems to be a linear relationship between the Ca^{2+}- and the Mg^{2+}-content. The composition of the water is typical of a stagnant water with Na^+ and Cl^- the dominant ions. This tends to coincide well with the general ground-water quality of the Ecca sediments and will subsequently be discussed in more detail.

To analyse the chemistry of the boreholes which are not situated within 1 km of any pollution source, boreholes situated a kilometre and further from the pollution source were plotted on a Piper diagram in Figure 6.43. From the figure, it is noted that although the samples plot all over the diamond, the absence of samples that plot in the polluted ground-water group is striking. Although a few samples plot on the boundary or just within the polluted ground-water group, the majority of the ground-water samples plot at the centre and the bottom of the diamond, representing dynamic and coordinate regimes where base

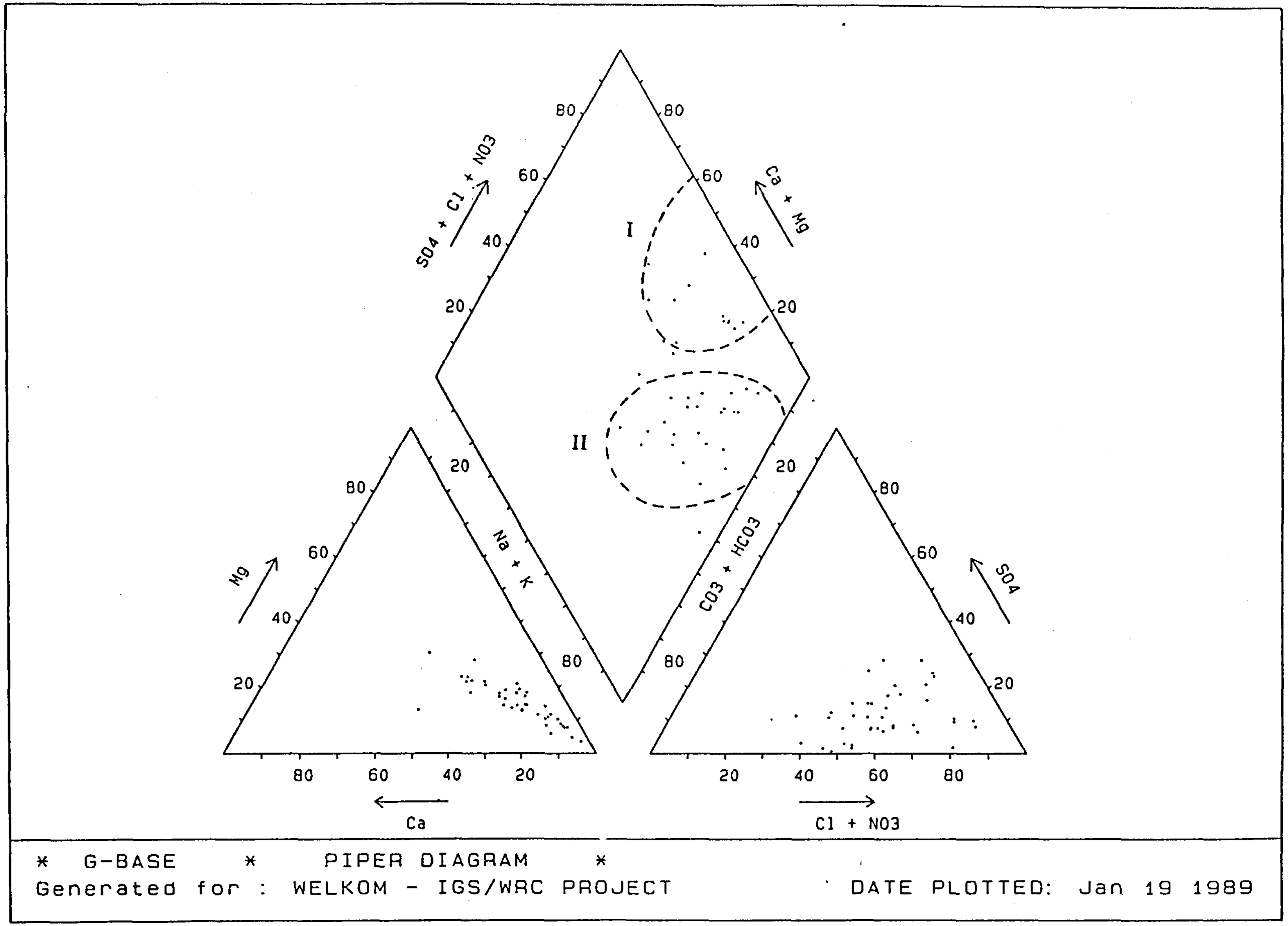


Figure 6.42. Piper diagram of ground water from the boreholes which are situated to the west of the Orange Free State Goldfields and which have conductivities in excess of 250 mS/m.

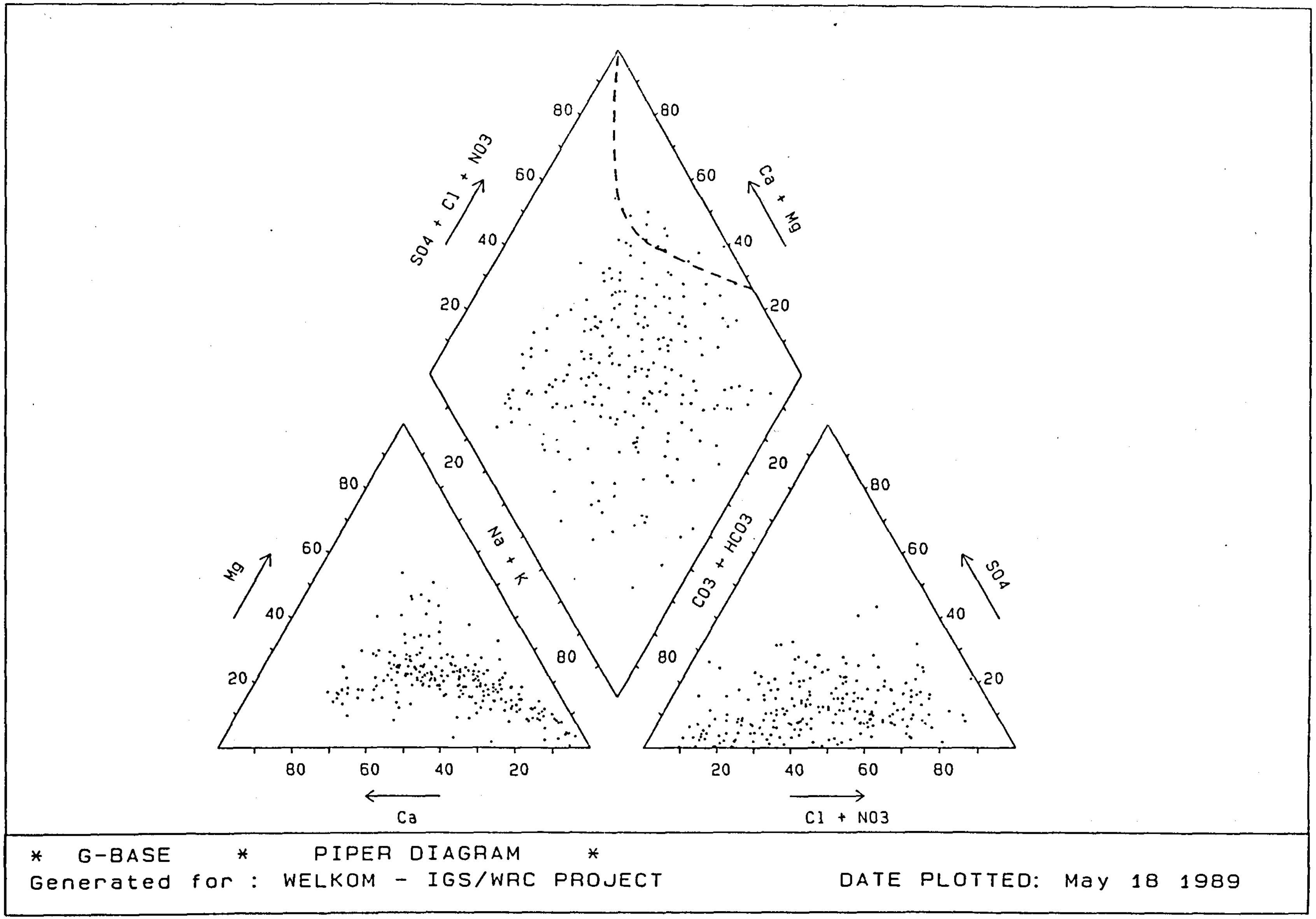


Figure 6.43. Piper diagram of boreholes which are situated further than 1 km from any pollution source.

exchange, dilution, dissolution and precipitation are taking place. *This indicates that the overwhelming majority of the ground water is unaffected by the numerous pollution sources that exist in the Orange Free State Goldfields.*

6.4.1.2 Geological influence of ground-water qualities

Tordiffe (1985) concluded that when ground water is in contact with a particular rock type, some chemical interaction can be expected which, in most cases, is unique to the particular system. Factors which have a major influence on the interaction, are the nature of the rock type involved, topography and climate.

According to Tordiffe (1978), ground water from the Ecca Group has a high salinity, with Na^+ and Cl^- the dominant ions in the water. Furthermore, he found that the ground-water quality of the Ecca Group is largely affected by the mixing of connate water of marine origin.

Figures 6.44 and 6.45 show Piper plots, as well as plots of the six major ion pairs, of boreholes situated in the Beaufort sediments and the Ecca sediments respectively. In the case of the Piper plots, only boreholes further than 1 km away from any pollution source were plotted. Looking at the Piper diagram, it can be observed that the boreholes situated in the Beaufort sediments represent a regime where recharge and base exchange are taking place. In contrast with this, the boreholes in the Ecca sediments seem to represent a regime where concentration, dissolution and mixing are taking place. From these figures, it is therefore evident that the ground water in the Beaufort sediments is of a better quality than in the Ecca sediments. Something very striking which is observed from both figures is the fact that almost no boreholes plot in the polluted ground-water group identified in Figure 6.35. *This may indicate that at a distance of 1 km from a pollution source, the majority of the ground water is unpolluted.*

In Figure 6.45, all the boreholes, located in the study area, are taken into account. Again, the ground waters are divided into different conductivity ranges. The figures verify the fact that generally the Beaufort ground water has a better quality than the Ecca ground water. As in the case of Figure 6.39, the ion concentration increases towards the pollution sources. If one looks at the individual ions and their relation to one another, in more detail (see Figures 6.46, 6.47, 6.48 and 6.49), a few interesting facts are observed. In both cases, a linear relationship exists between the Cl^- and Br^-. However, the respective concentrations appear to be higher in the Ecca sediments than in the Beaufort sediments, verifying the marine conditions under which the Ecca sediments were deposited. From the Ca/SO_4 and Na/Cl-ratios, it is evident that in the case of the Ecca sediments, the respective ions are present in almost equal quantities, whereas in the case of the Beaufort sediments, ions such as Cl^- and

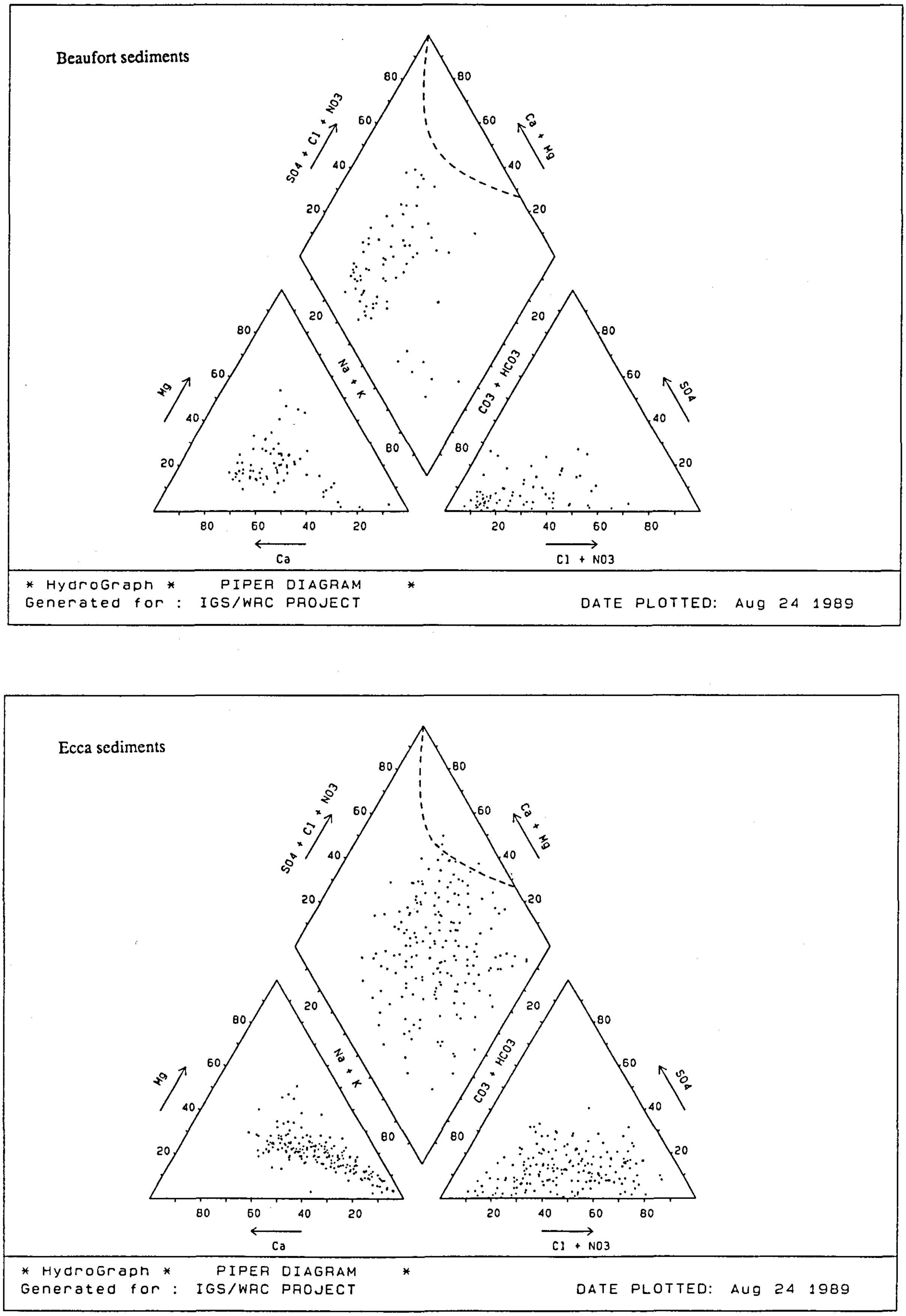


Figure 6.44. Piper plot of boreholes situated > 1 km from waste sites in the Beaufort and Ecca sediments.

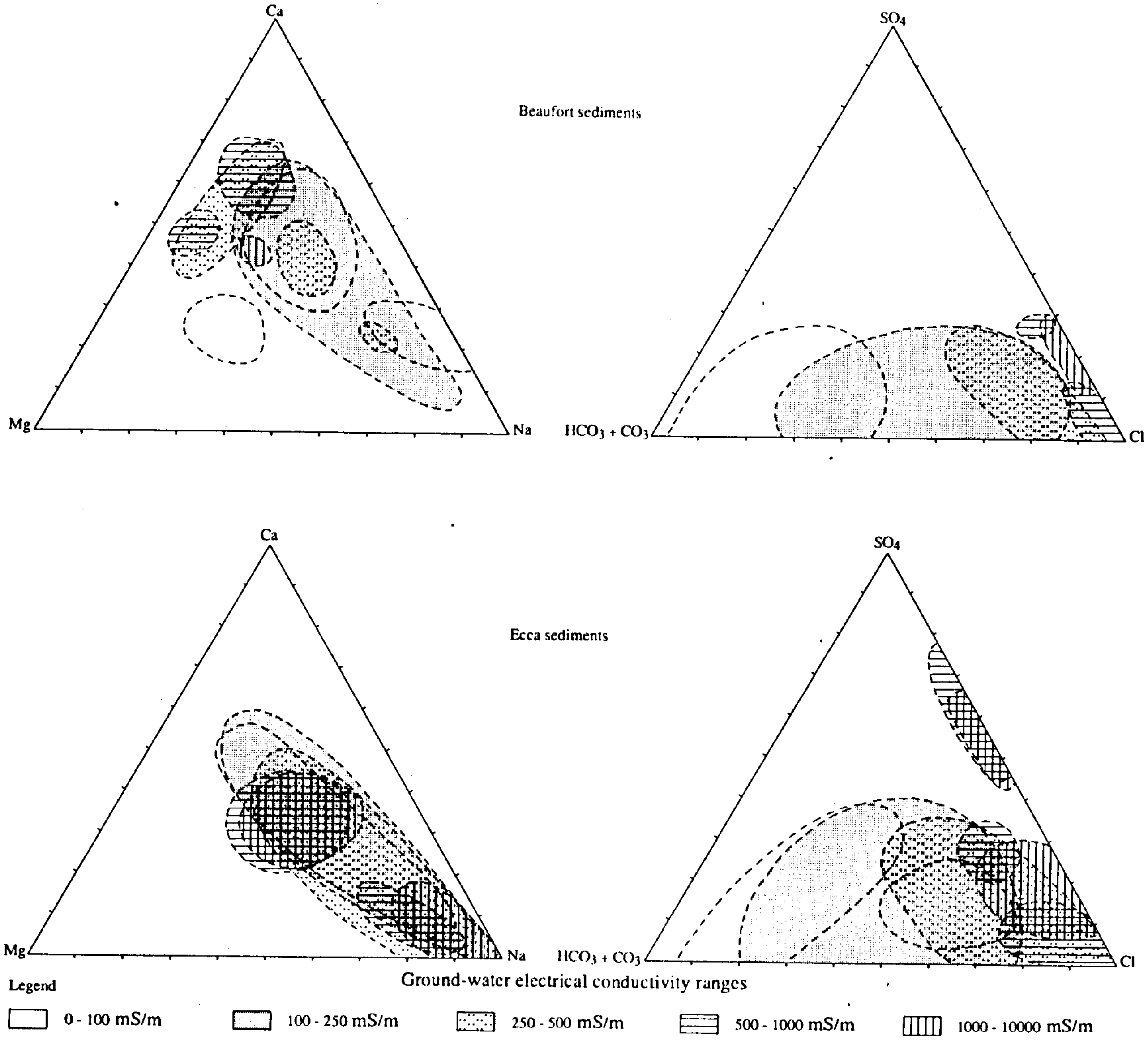


Figure 6.45. Triangular plot of major anions and cations of all boreholes situated in the Beaufort and Ecca sediments.

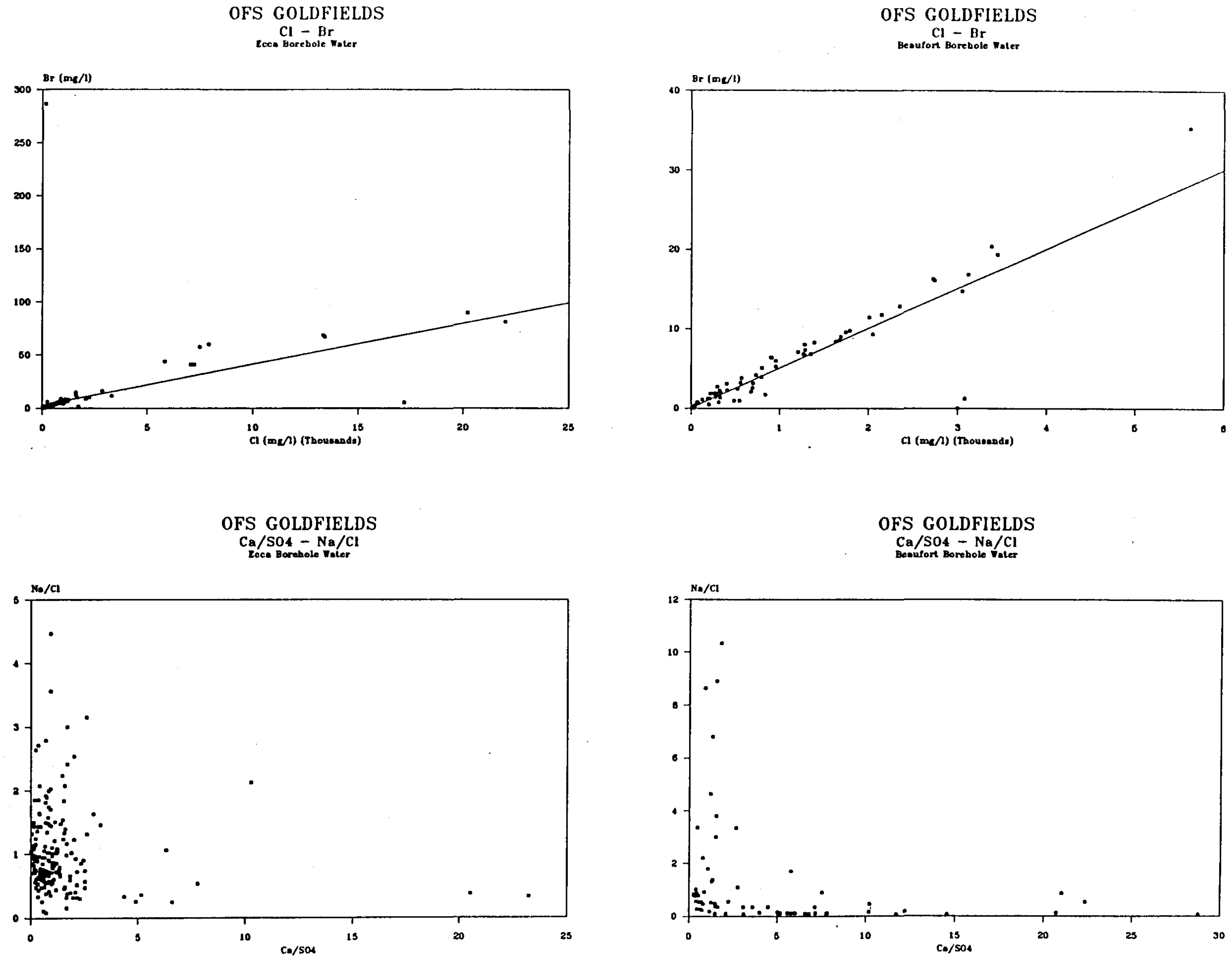


Figure 6.46. Ionic ratios and ion relations of ground water in the Beaufort and Ecca sediments (Cl - Br; Ca/SO4 - Na/Cl).

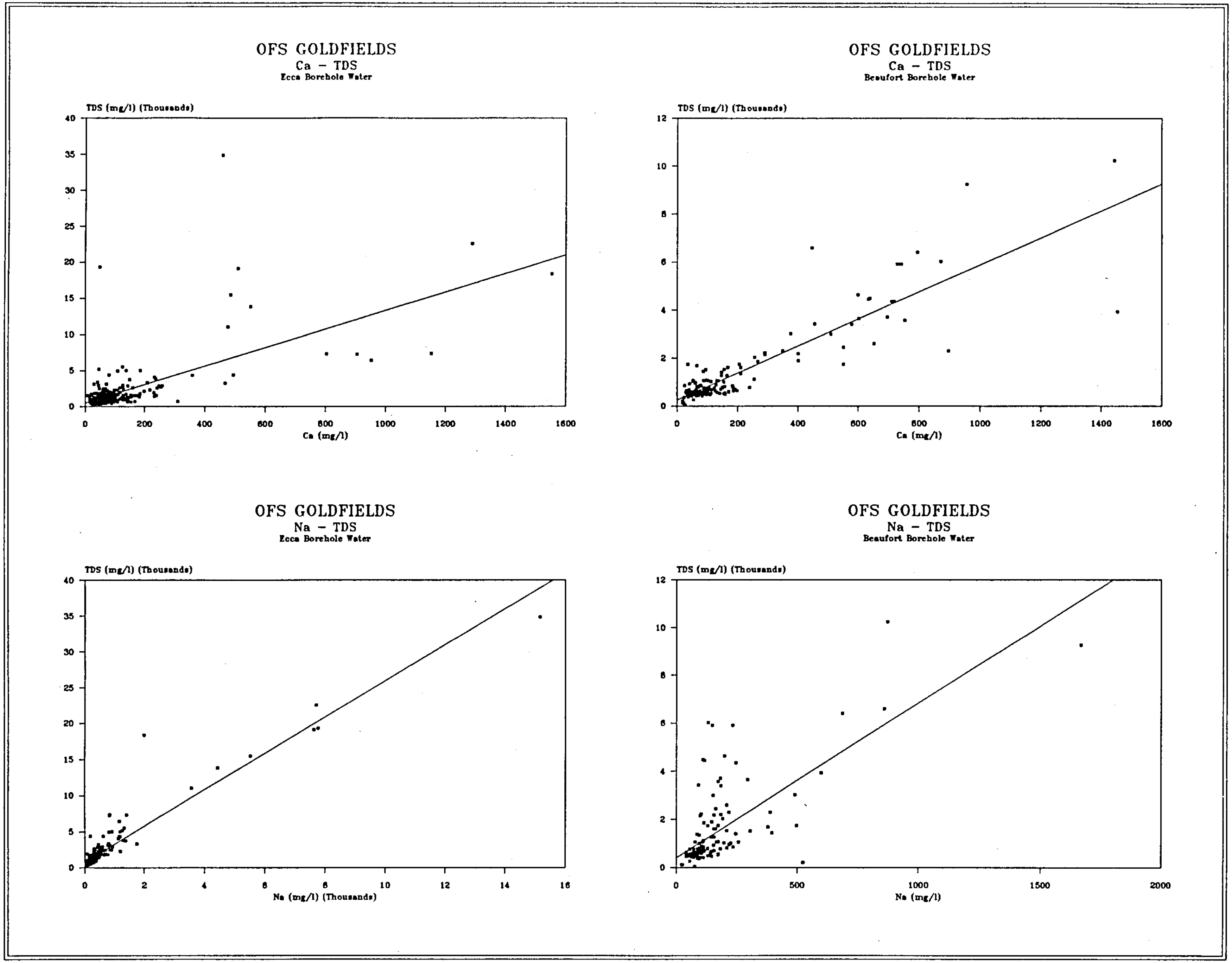


Figure 6.47. Ionic ratios and ion relations of ground water in the Beaufort and Ecca sediments (Ca - TDS; Na - TDS).

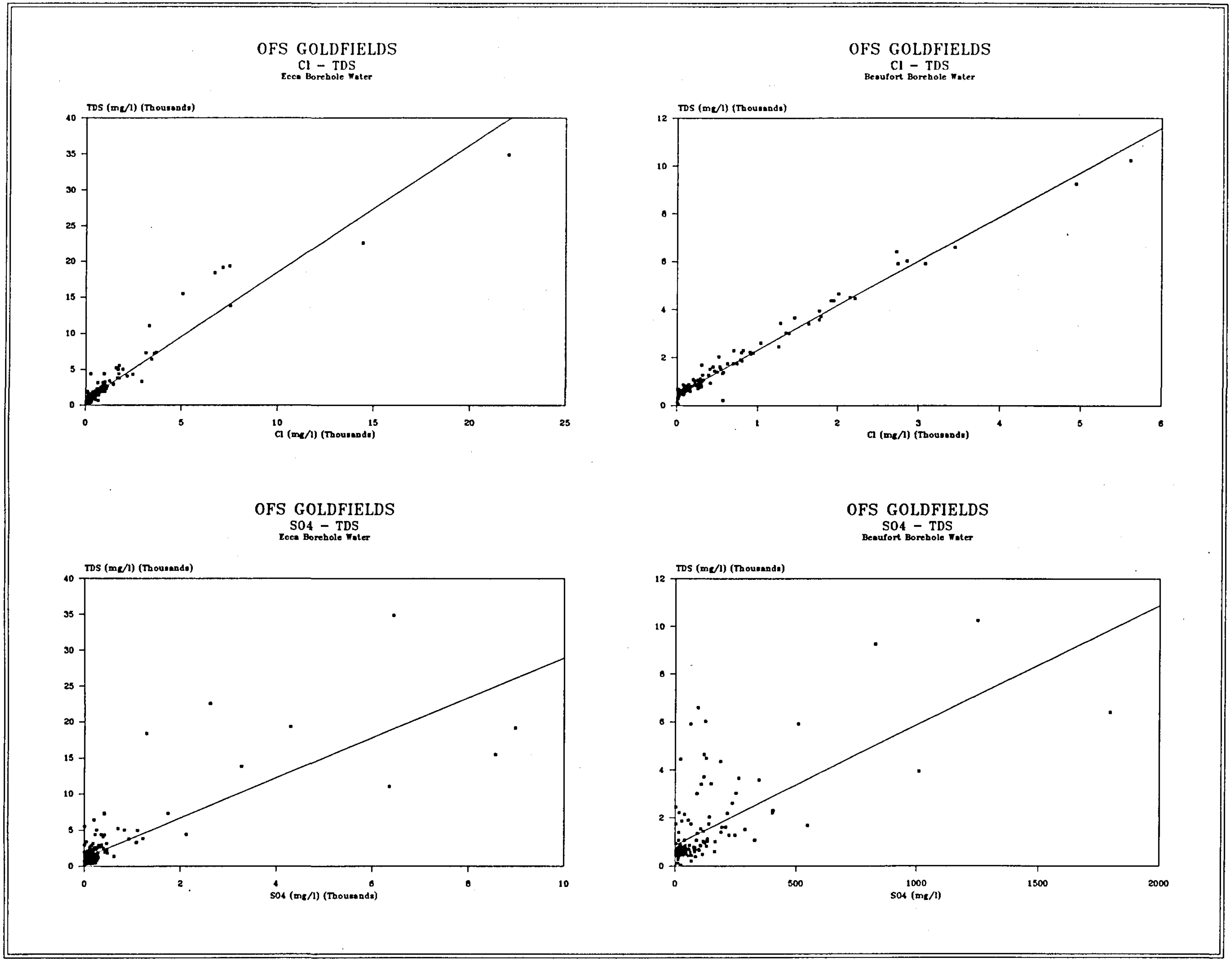


Figure 6.48. Ionic ratios and ion relations of ground water in the Beaufort and Ecca sediments (Cl - TDS; SO_4 - TDS).

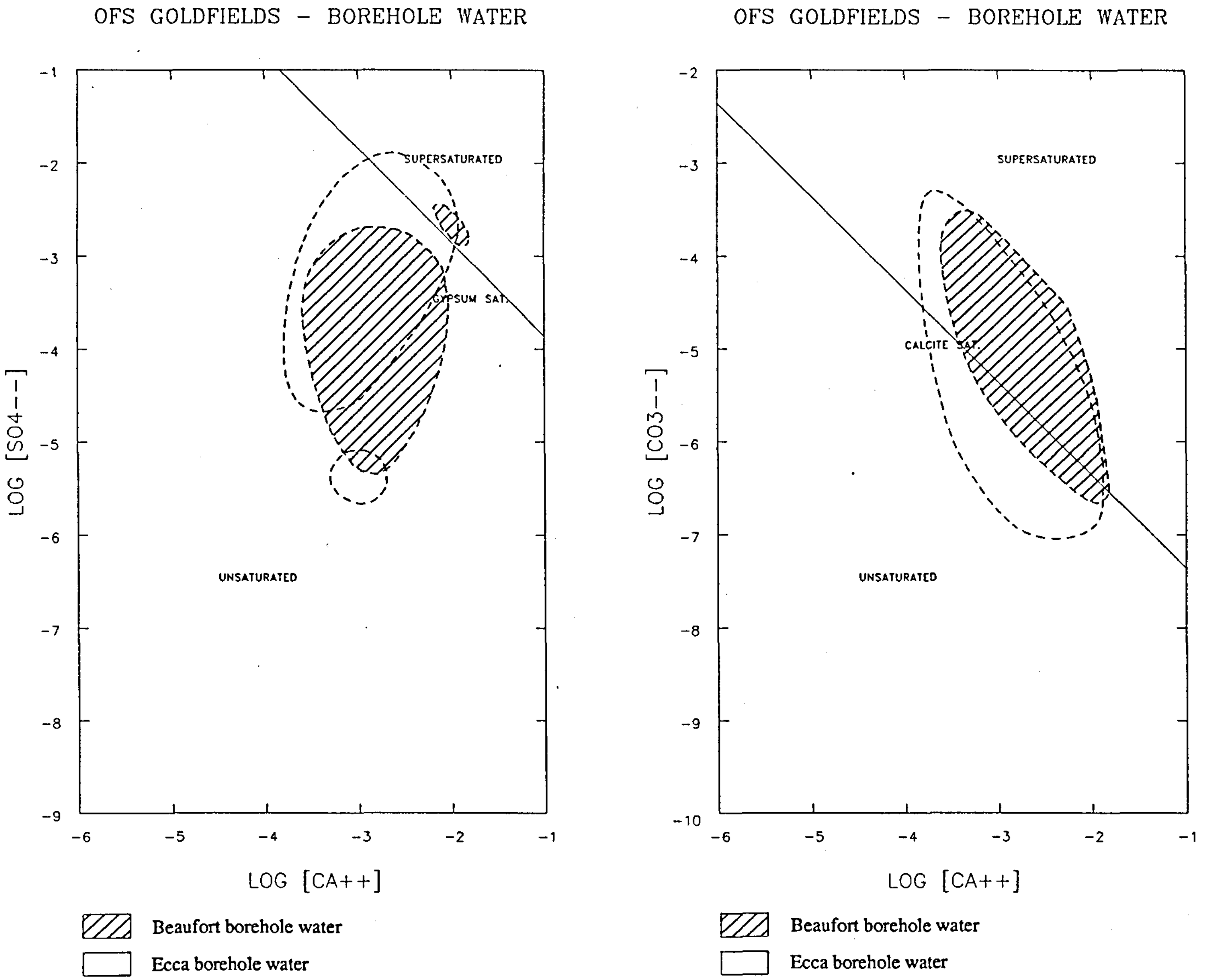


Figure 6.49. Gypsum and calcite saturation of ground water in the Beaufort and Ecca sediments.

especially SO_4^{2-} are present in smaller quantities. Furthermore, one can assume that boreholes in the Beaufort sediments, with high Na/Cl-ratios, are not situated in the vicinity of a disposal site.

If the four major ions (Ca^{2+}, Na^+, Cl^- and SO_4^{2-}) are related to the TDS, it is interesting to note that in the case of the Ecca sediments, Na^+ and Cl^- show a linear relationship towards the TDS. The Beaufort sediments, on the other hand, are linearly related to Ca^{2+} and Cl^-. The fact that SO_4^{2-} does not relate well to the TDS in any of the analyses means that in both cases, SO_4^{2-} occurs sporadically throughout the area, or in the vicinity of a slimes dam facility.

Figure 6.49 depicts the gypsum, as well as the calcite saturation of the Ecca and Beaufort sediments respectively. From these diagrams, it is noticed that a significant number of samples in the Ecca sediments are gypsum saturated, while the Beaufort sediments are undersaturated, correlating well with the above-mentioned results. In the case of calcite saturation, the sediments display a similar pattern, i.e. the majority of water samples are calcite saturated.

6.4.1.3 Ionic ratios

In order to verify the above results, ionic ratios were used to distinguish between polluted and unpolluted ground-water resources. The ionic ratios which proved to be useful in the study were:

(i) Ca/Cl-ratio.

(ii) Na/Cl-ratio.

(iii) Ca/Na-ratio.

The above ratios clearly distinguish between polluted ground water and unpolluted water of a natural poor quality, dividing each group into a specific interval of the ratio. By using the mean and the standard deviation of the samples belonging to a specific group, the respective intervals were determined. Intervals for the Ca/Cl-, Na/Cl- and Ca/Na-ratios are listed in Table 6.9.

TABLE 6.9. CLASSIFICATION OF GROUND WATER BY USING IONIC RATIOS

	INTERVALS	
Ratio	Polluted ground water	Natural poor quality ground water
Ca/Cl	0,15 - 0,75	0,0 - 0,108

Na/Cl	0 - 0,55	0,53 - 1,30
Ca/Na	> 0,30	< 0,20

If both the Ca/Cl- and Na/Cl-ratios of a water sample fall in the polluted ground-water interval, the ground water is to be regarded as polluted and vice versa. On the other hand, if the two ratios fall in different intervals, the ground water is regarded as difficult to classify, i.e. the water can either be naturally unpotable or it can be polluted.

It must be emphasized that the use of these ratios is only effective when ground water with an electrical conductivity > 250 mS/m is used. This is due to the fact that the ratios of potable ground water in the Beaufort sediments also fall within the calculated pollution interval. According to Tordiffe (1978), the reason for this being that Ca^{2+} seems to be the more dominant ion in ground water of the Beaufort sediments, with Cl^- and Na^+ to a lesser extent. However, when these waters come into contact with water which has a NaCl-character, the electrical conductivity of the water tends to increase and so will the Cl-content. As the ground water in the Beaufort sediments is of a natural good quality, all the ground water in this succession with an electrical conductivity > 250 mS/m is situated near pollution sources and is therefore obviously polluted.

By using the Ca/Na-ratio, the ground water which previously proved difficult to classify, can now be distinguished (see Table 6.8). If the ratio does not coincide with either one of the two groups, it still remains difficult to classify the ground water.

The reasons why these ratios tend to verify the results obtained by the Piper diagram are due to the fact that in the natural unpotable ground water in the region, Na^+ and Cl^- are dominant and Ca^{2+} constitutes only a fraction of the total ion-concentration. In the polluted ground water, Ca^{2+} tends to become more dominant, with a resultant decrease in the Na-content due to reverse ion exchange. Furthermore, the Cl-content of this water increases and becomes the major ion in solution, as in the case with the natural unpotable ground water. However, due to the elevated Ca^{2+}-concentration of these water, the Ca/Cl-ratio of polluted ground water will have a higher value than that of the natural poor quality ground water, and the Na/Cl-ratio will have a lower value. Furthermore, due to the increase of Ca^{2+} and the decrease of Na^+ in the polluted ground water, the Ca/Na-ratio will be greater for the polluted water than for the natural unpotable ground water.

All the ground-water samples with an electrical conductivity in excess of 250 mS/m were classified by the method. To verify the ionic-ratio classification, the same samples were plotted on Piper diagrams (Figures 6.50 and 6.51), which represent the polluted ground water and the natural unpotable ground water respectively. According to the two figures, the classified polluted ground water correlates well with the polluted ground water (see

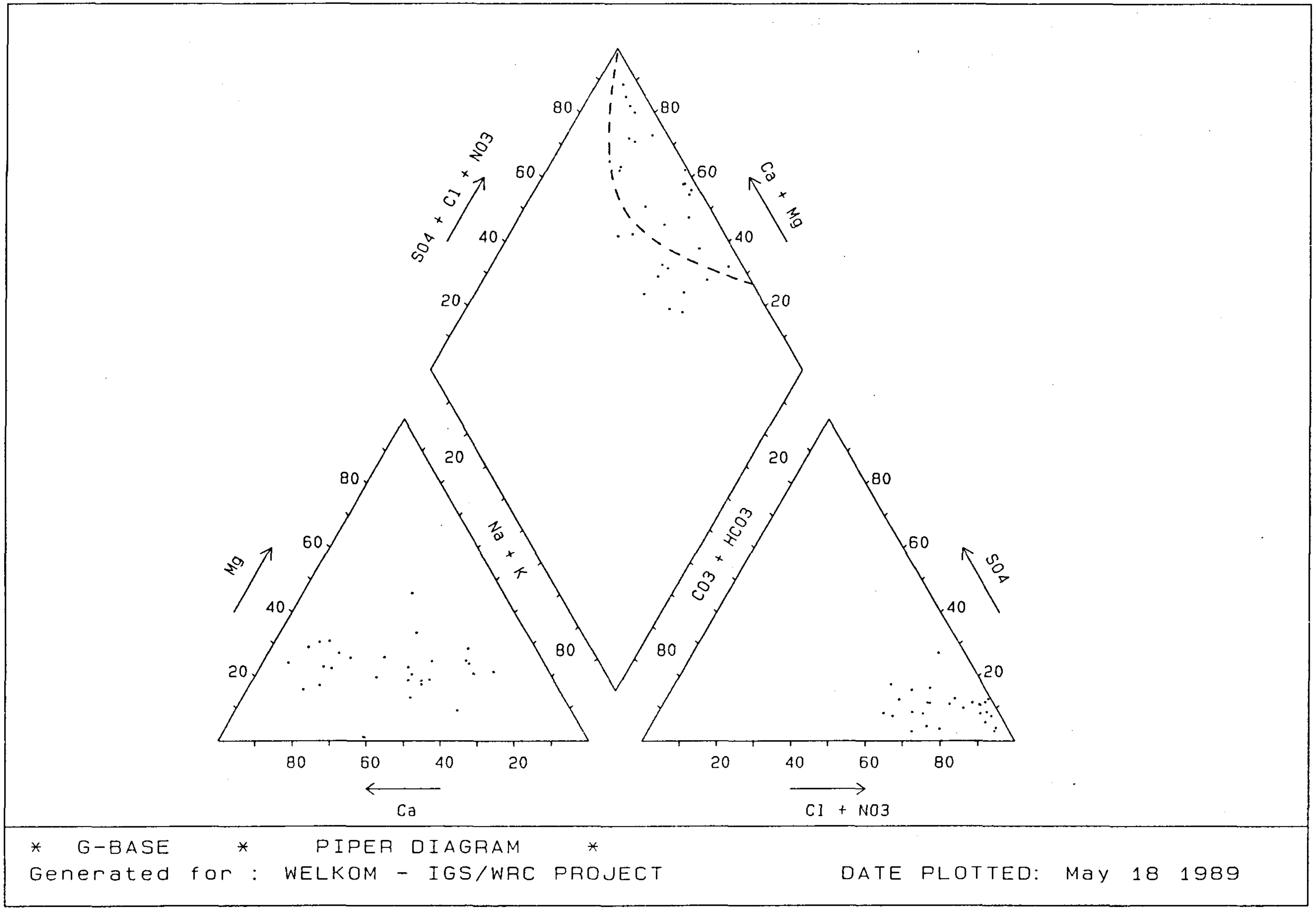


Figure 6.50. Piper diagram of the ground water that is classified as polluted, by using ionic ratios.

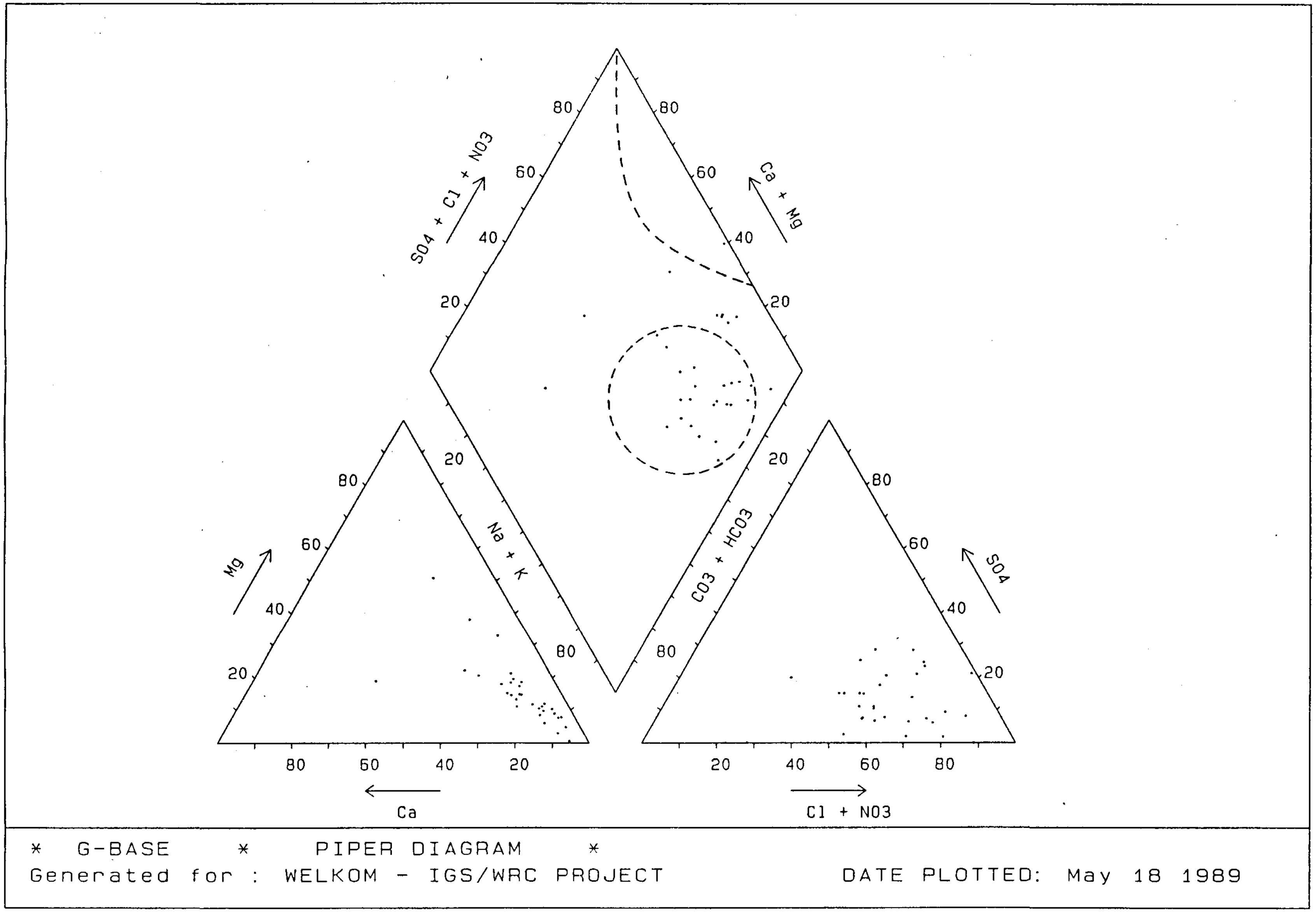


Figure 6.51. Piper diagram of the ground water that is classified as natural unpotable ground water, by using ionic ratios.

Figure 6.35) and the natural unpotable ground water (see Group II of Figure 6.42). With a few exceptions, all the water samples plot into either one of the two groups. Thus, using a Piper diagram in conjunction with the specified ionic-ratios, the ground water (with excessive electrical conductivities > 250 mS/m) can be classified as polluted or not.

In order to quantify the contribution of the different pollutants, as well as to study their dispersive characteristics, three target areas were selected:

(i) Loraine disposal complex.

(ii) Harmony disposal complex (new).

(iii) Beatrix disposal complex.

The hydrochemistry of the above-mentioned areas will be discussed subsequently.

6.4.2 HYDROCHEMICAL EVALUATION OF THE TARGET AREAS

As mentioned previously, pollutant migration and -spread mainly depend on various factors such as:

(i) ground-water gradients,

(ii) pollutant concentration gradients,

(iii) adsorption and ion exchange and

(iv) other chemical processes.

Furthermore, it should be mentioned that in general when quantifying pollutants, as well as their migration rates, one should evaluate data on a more local (detailed) scale.

Previous sections indicated that five basic ground-water pollution indicators exist, i.e. Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-} and SO_4^{2-}. Due to the fact that the Mg^{2+}-concentration can be closely correlated with the Ca^{2+}-concentration, the Mg^{2+}-concentration was not used in further evaluations. Thus, the above-mentioned ions, as well as the heavy metal concentrations in the ground water of the three target areas, are evaluated in detail in this section.

Maps depicting the sample locations, as well as the pollution sources at the respective target areas, were constructed. Contour maps of the above-mentioned ions, for each target area, were also constructed and represent a more comprehensive view of the ground-water qualities in the vicinity of the various pollution sources.

6.4.2.1 Loraine disposal complex

The Loraine mine which is situated in the north of the study area, is one of the oldest mines in the area (see Figure 6.52). Two major pollution sources were identified at this disposal facility:

(i) Slimes dam.

(ii) Return water complex.

Due to the fact that the slimes dam was constructed on sandy aeolian deposits and predates the underdrainage technology, seepage from the slimes dam poses a real problem, especially in seasons with above average rainfall. During the 1988/1989 rainfall season, excess plant effluent spilled in Swart Pan and as Swart Pan reached its full capacity, it overflowed into two adjoining natural pans. The problem is extended by a shallow dolerite dyke which intersects Swart Pan.

The influence of the disposal facility on the immediate surroundings is shown in Figures 6.53 to 6.54, which are contour maps of the above-mentioned ions. When evaluating the respective contour maps, the following observations are made:

- The ground water in the vicinity of Swart Pan and the other natural pans has a higher Na^--content than the ground water in the vicinity of the slimes dam.

- The Ca^{2+}-concentrations in the ground water is more or less the same in the vicinities of both the slimes dam and Swart Pan.

- High SO_4^{2-}-concentrations occur in the ground water around the slimes dam, which is to be expected due to pyrite oxidation in the slimes dam.

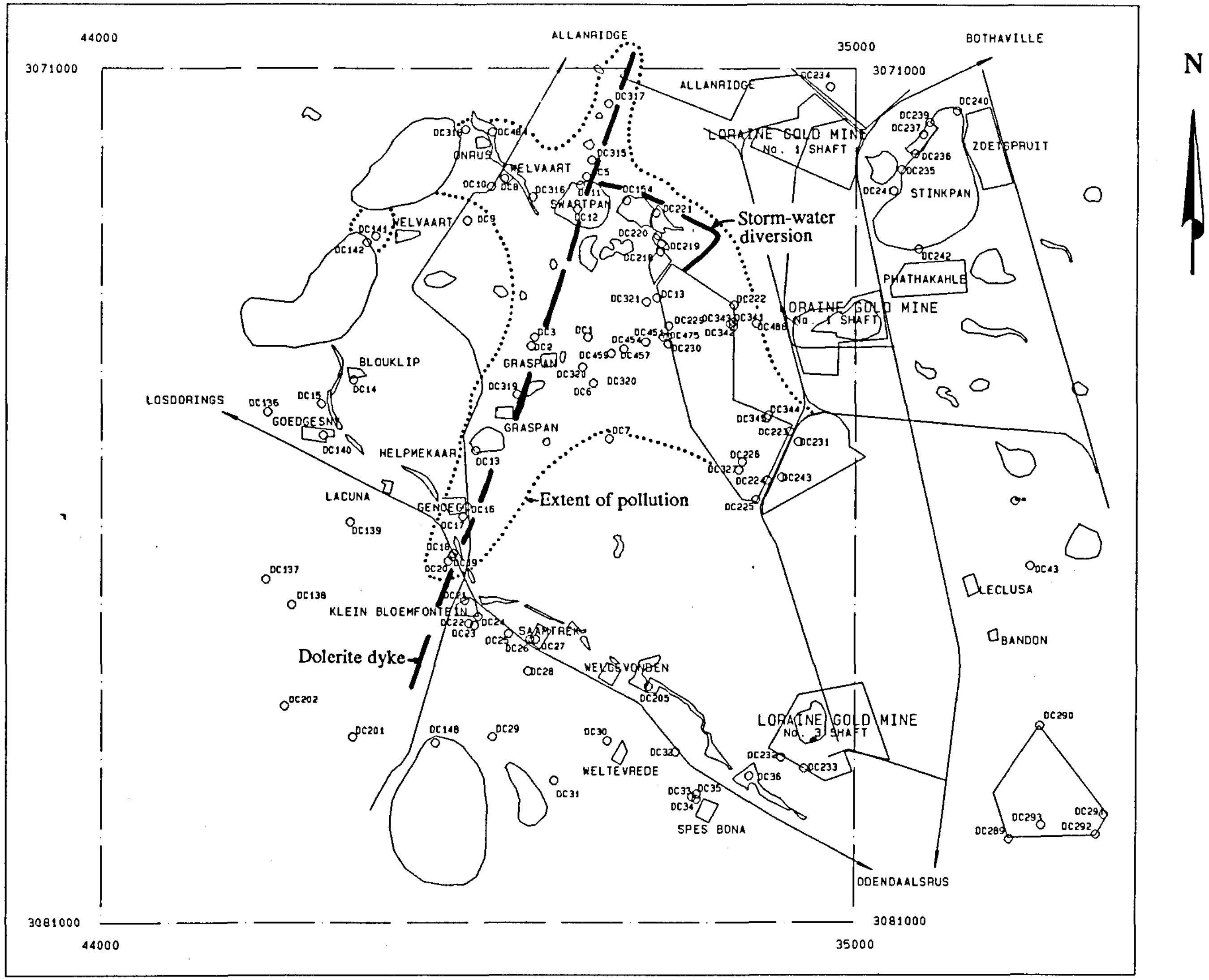
- The high Cl^--concentration in the ground water in this area is thought to originate mainly from two sources:

  (i) Ecca sediments

  (ii) Effluent mine water entering natural pans.

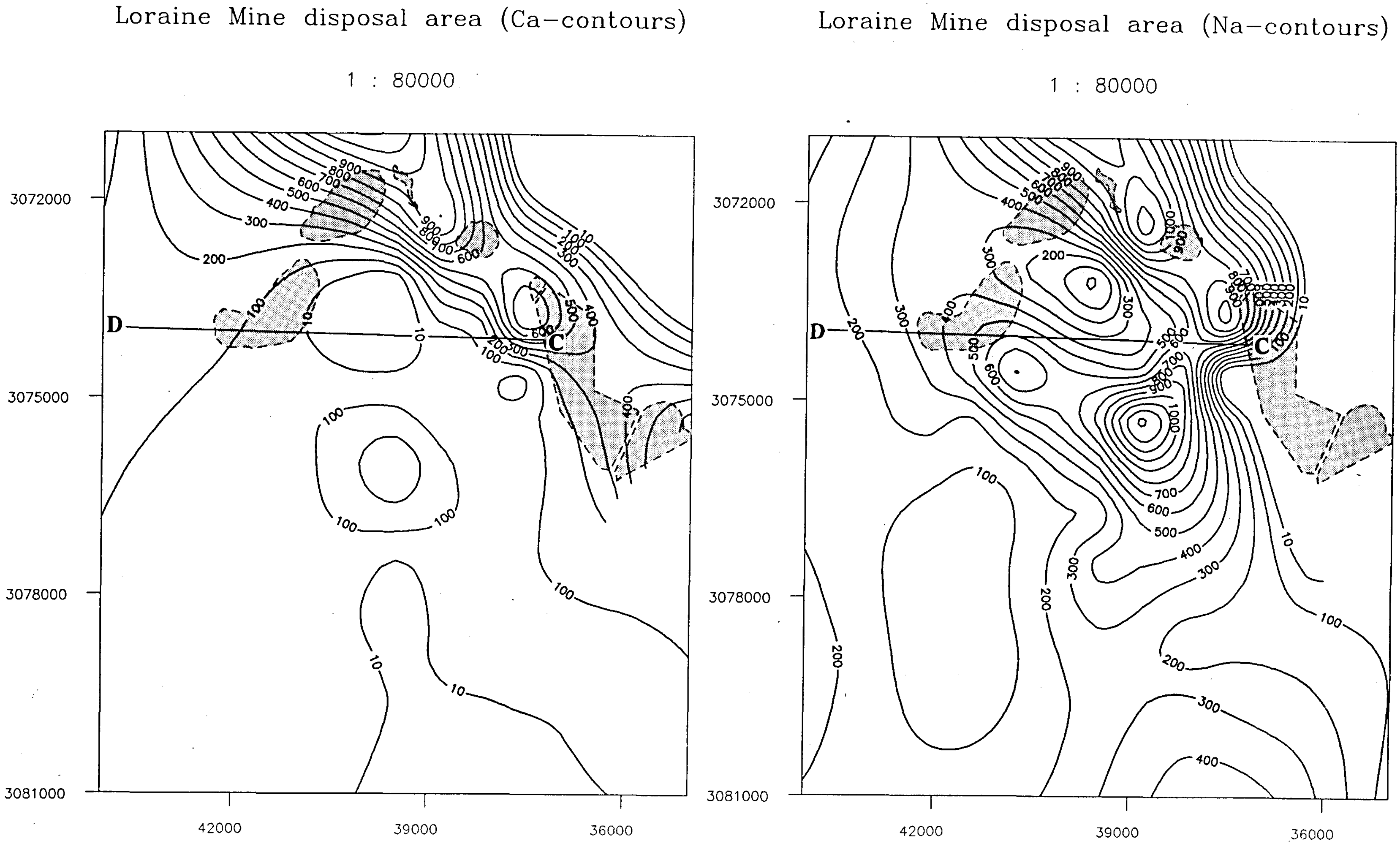
  The distribution of the Cl^- in the ground water is also of a greater extent than those of the other ions, which can be ascribed to the fact that Cl^- is classified as a conservative tracer.

- It is also evident that the dolerite dyke plays a major role in the distribution of the Na^+ and Cl^-.


Loraine Mine disposal area

1 : 80000

Figure 6.52. Loraine Mine disposal facility.


Loraine Mine disposal area (Ca–contours)

1 : 80000

Loraine Mine disposal area (Na–contours)

1 : 80000

Figure 6.53. Ca2+- and Na+-contours of the Loraine disposal facility.

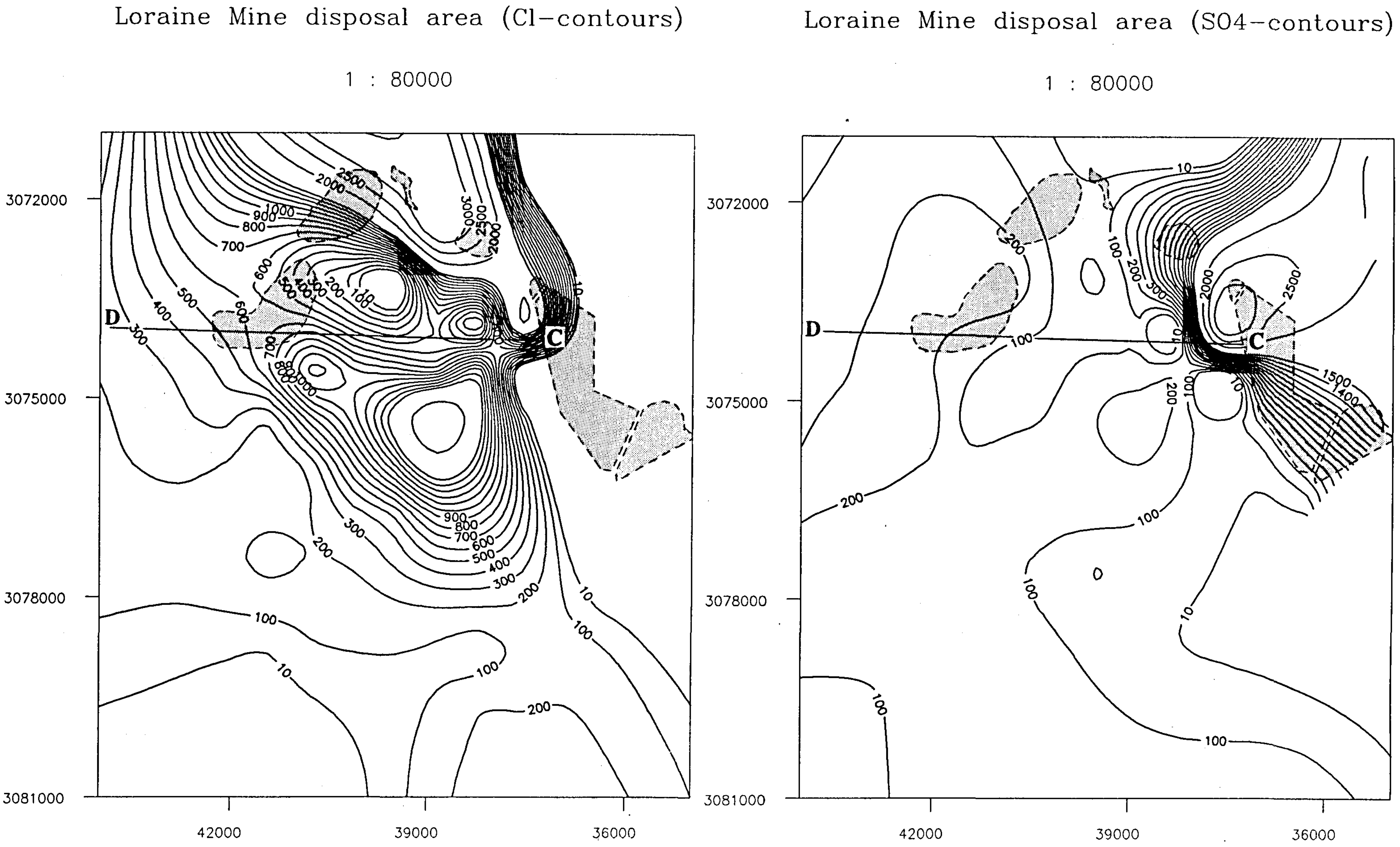


Figure 6.54. Cl⁻- and SO₄²⁻-contours of the Loraine disposal facility.

In order to determine the extent and migration rate of the respective pollutants, concentrations of the ions at different points along a profile line CD are listed in Table 6.10, as well as shown in Figure 6.55.

TABLE 6.10. ION CONCENTRATIONS AT DIFFERENT POINTS ALONG THE CD PROFILE LINE.

Position (m)	Ca^{2+} (mg/l)	Na^+ (mg/l)	Cl^- (mg/l)	SO_4^{2-} (mg/l)
C 10	500	500	900	2000
500	300	550	850	1500
1000	100	600	800	700
2000	100	700	900	100
D 5000	100	300	400	100

From Table 6.8 and Figure 6.55, it is evident that Na^+ and Cl^- stay in solution for much longer periods than Ca^{2+} and SO_4^{2-}.

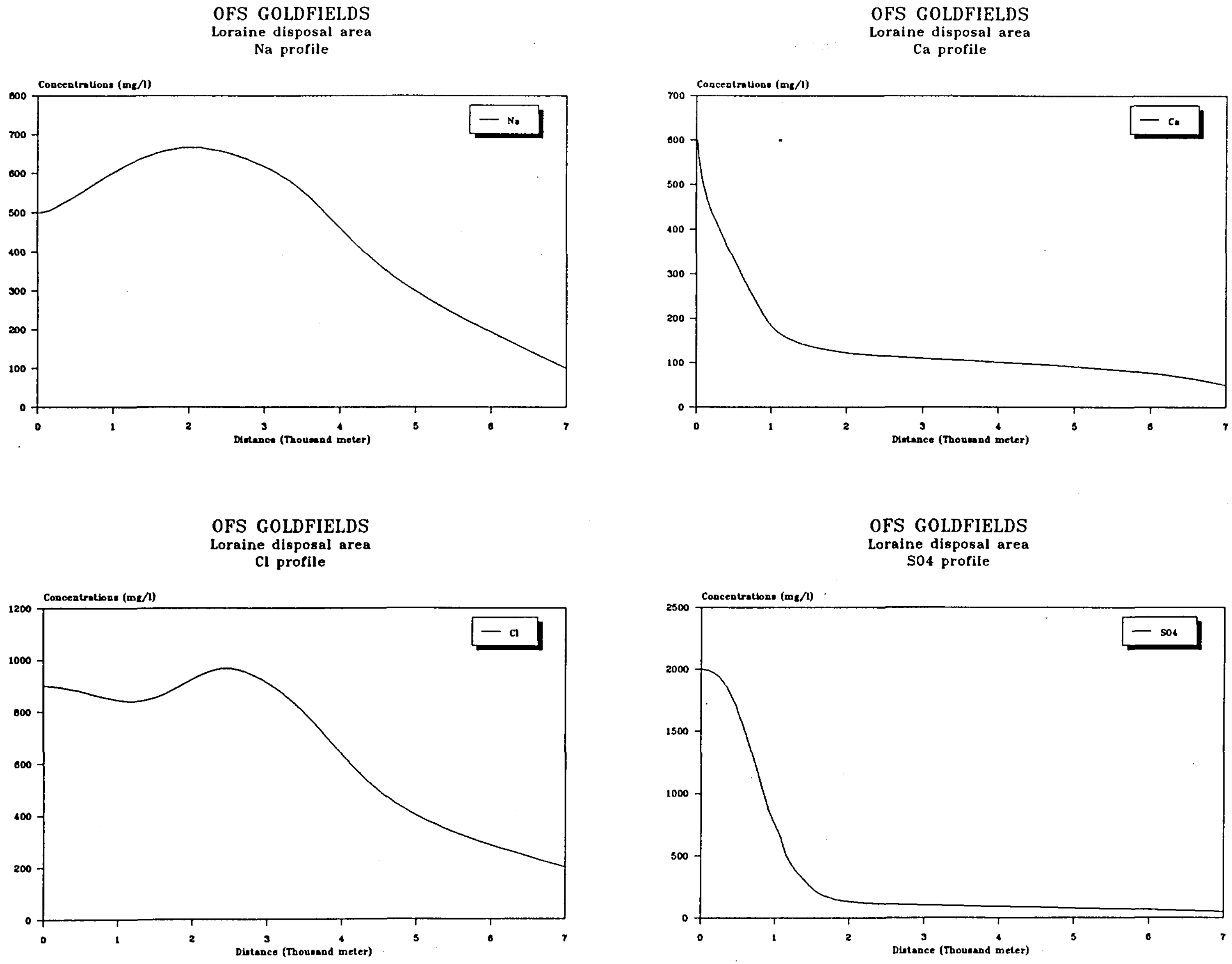
Divalent cations are generally held more strongly than monovalent cations. Therefore, Ca^{2+} is more easily adsorbed by the clay minerals than Na^+. However, from previous discussions, it was found that ground water in this area (due to its high salinity) was subjected to reverse ion exchange, explaining the high Ca^{2+}-content. The high Na^+-content of the ground water in this area is basically derived from two sources:

(i) Ecca sediments.

(ii) Mine effluent water.

Thus, although a large quantity of Na^+ has been adsorbed by clay particles, sufficient Na^+ remains in solution to cause the high Na^+-concentration in this area. It must also be kept in mind that SO_4^{2-} forms complexes with Ca^{2+} and Na^+. $NaSO_4^-$ is highly soluble, whereas $CaSO_4$ is less soluble, meaning that it will precipitate at an earlier stage. This can clearly be seen when the Ca^{2+} and SO_4^{2-}-profiles are compared to one another. The circulation of Cl^- is mostly through physical rather than chemical processes. Therefore, chloride ions tend to remain in solution and can be effectively used to determine the extent of the pollution over a period of time.

From Table 6.8 and Figures 6.53 and 6.55, it is observed that 5000 m from the pollution source the concentrations of Cl^- and Na^+ are relatively high. This could be due to the natural salinity of ground water in the region. This salinity of the ground water in the region tends to coincide well with the general ground-water quality of the Ecca sediments. The influence of the dolerite dyke, intersecting Swart Pan, as well as a series of natural



OFS GOLDFIELDS
Loraine disposal area
Na profile

OFS GOLDFIELDS
Loraine disposal area
Ca profile

OFS GOLDFIELDS
Loraine disposal area
Cl profile

OFS GOLDFIELDS
Loraine disposal area
S04 profile

Figure 6.55. Concentration profiles along profile line CD at the Loraine disposal facility.

pans in the area, is also evident in the Na- and Cl-profile 2000 to 3000 m from the slimes dam, explaining the increase in concentration on the profiles. Ground-water gradients in this region (Figure 5.8) are on average very small, mainly due to the flatness of the surface topography. *If one compares the ground-water gradients with the contours and profiles and one bears in mind the very low permeabilities of the Ecca sediments in the region, one can assume that the ground-water pollution is restricted to an area within 6000 m to the west and south-west of the disposal facility.*

Heavy metal concentrations in the vicinity of the Loraine disposal facility are shown in Figure 6.56. Table 6.11 lists the distance and the pH of a series of shallow wells that were used to observe the change in heavy metal concentrations with increasing distance from the disposal site.

TABLE 6.11. HEAVY METAL OBSERVATION WELLS.

Site Number	Distance from slimes dam (m)	pH
DC230	10	4,1
DC475	10	4,0
DC451	50	4,1
DC452	100	6,1
DC453	150	6,8
DC454	200	5,6
DC455	250	6,5
DC456	300	6,8
DC457	350	6,6
DC458	400	6,8
DC459	500	7,4

Due to acid mine drainage at the Loraine Mine slimes dam, fairly low pH-values are observed in the direct vicinity of the slimes dam. These low pH-values result in large quantities of the heavy metals being in solution in close proximity of the slimes dam. However, as the water infiltrates the surrounding sediments and moves further away from the slimes dam, the pH-values increase (due to neutralization), causing the heavy metals to precipitate.

The same phenomenon was observed at borehole DC 5 (± 7 m from the edge of Swart Pan) and Swart Pan itself. In the past, Swart Pan received considerable volumes of effluent plant water. In borehole DC 5 (mean pH = 6,9), the heavy metal concentrations are all within the "maximum permissible" limit. This is in spite of the fact that the heavy metal concentrations in Swart Pan (mean pH = 4,2) are elevated. *From the above, it would seem that the heavy*

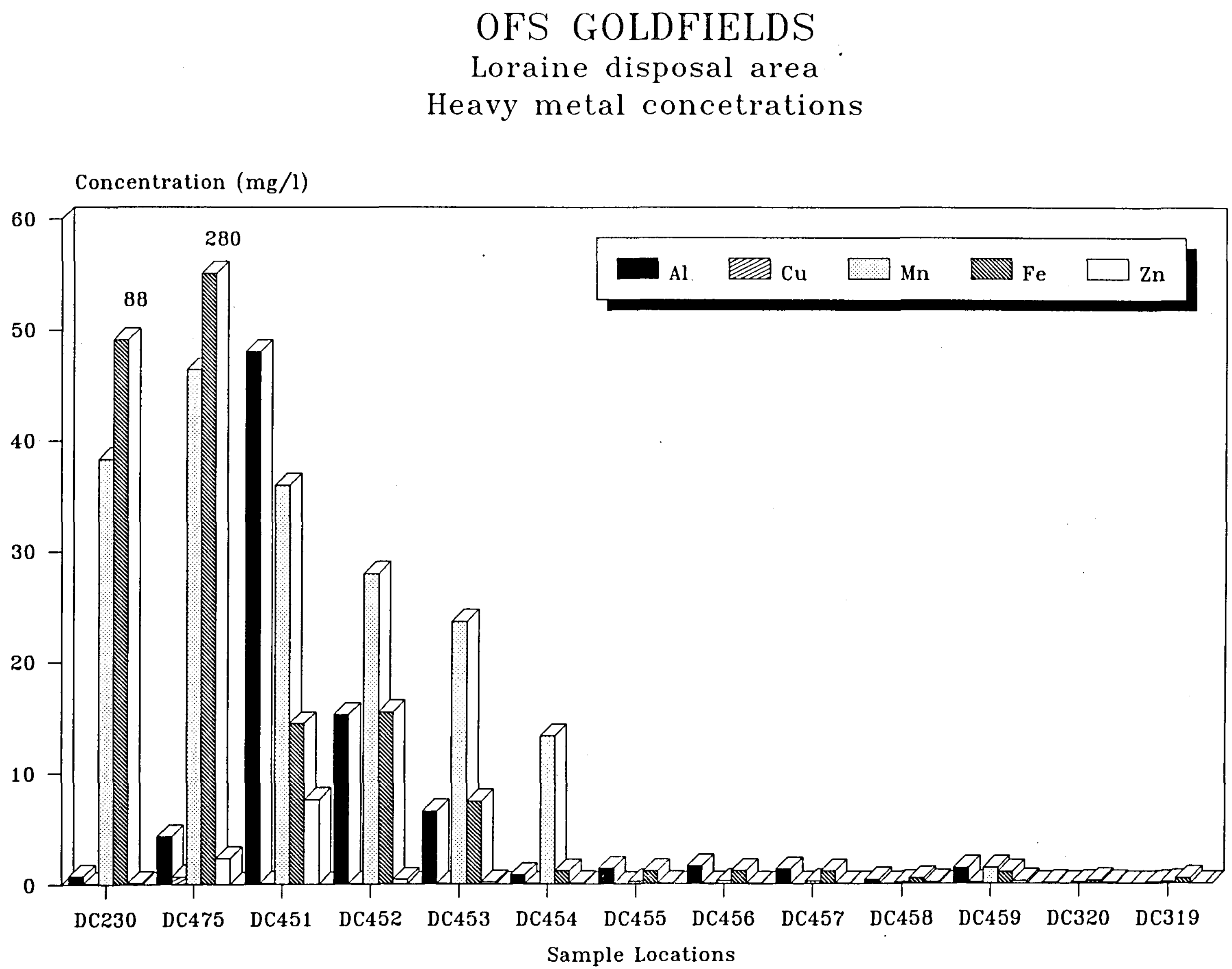


Figure 6.56. Heavy metal concentrations in the vicinity of the Loraine disposal facility.

metals do not pose a large pollution threat as high concentrations only occur very close to the disposal site. This may, however, change in future, as it is entirely dependent on the acid production potential of the slimes dam.

6.4.2.2 Harmony Mine new disposal area

This disposal complex is situated in the east of the study area, just north of Virginia, and is approximately three to four years old (see Figure 6.57). When evaluating the ion concentrations depicted in the respective contour maps (Figures 6.58 and 6.59) of this area, the following observations can be made:

- The ground water in the vicinity of the slimes and return water dams has a higher Na- than Ca-content.
- The Cl^-- and SO_4^{2-}-concentrations in the ground water are higher than the concentrations of the other ions.
- The dispersion of Cl^- in the ground water is greater than that of the other ions.
- It is also evident that the ground-water gradients (see Figure 5.10) in this area play a major role in the migrations and dispersion.

No significant reverse ion exchange has occurred in the vicinity of the disposal area. The reason being that at this stage small volumes of NaCl-water enter the system. Thus, the ion exchange takes place according to the normal selectivity of the respective ions. These phenomena are also evident in the ion profiles shown in Figure 6.60. The concentrations of the ions at different points along the profile line AB are listed in Table 6.12.

TABLE 6.12. ION CONCENTRATIONS AT DIFFERENT POINTS ALONG PROFILE AB

Position (m)	**Ca^{2+} (mg/l)**	**Na^+ (mg/l)**	**Cl^- (mg/l)**	**SO_4^{2-} (mg/l)**
A 10	400	400	700	600
500	150	200	550	200
1000	100	100	300	100
1500	50	50	100	50
B 2000	50	50	50	50

The high Cl^-- and SO_4^{2-}-content are typical of polluted ground water from mining activities as discussed in previous sections. The return water dam, however, has a greater impact on the environment and is the main pollution source.

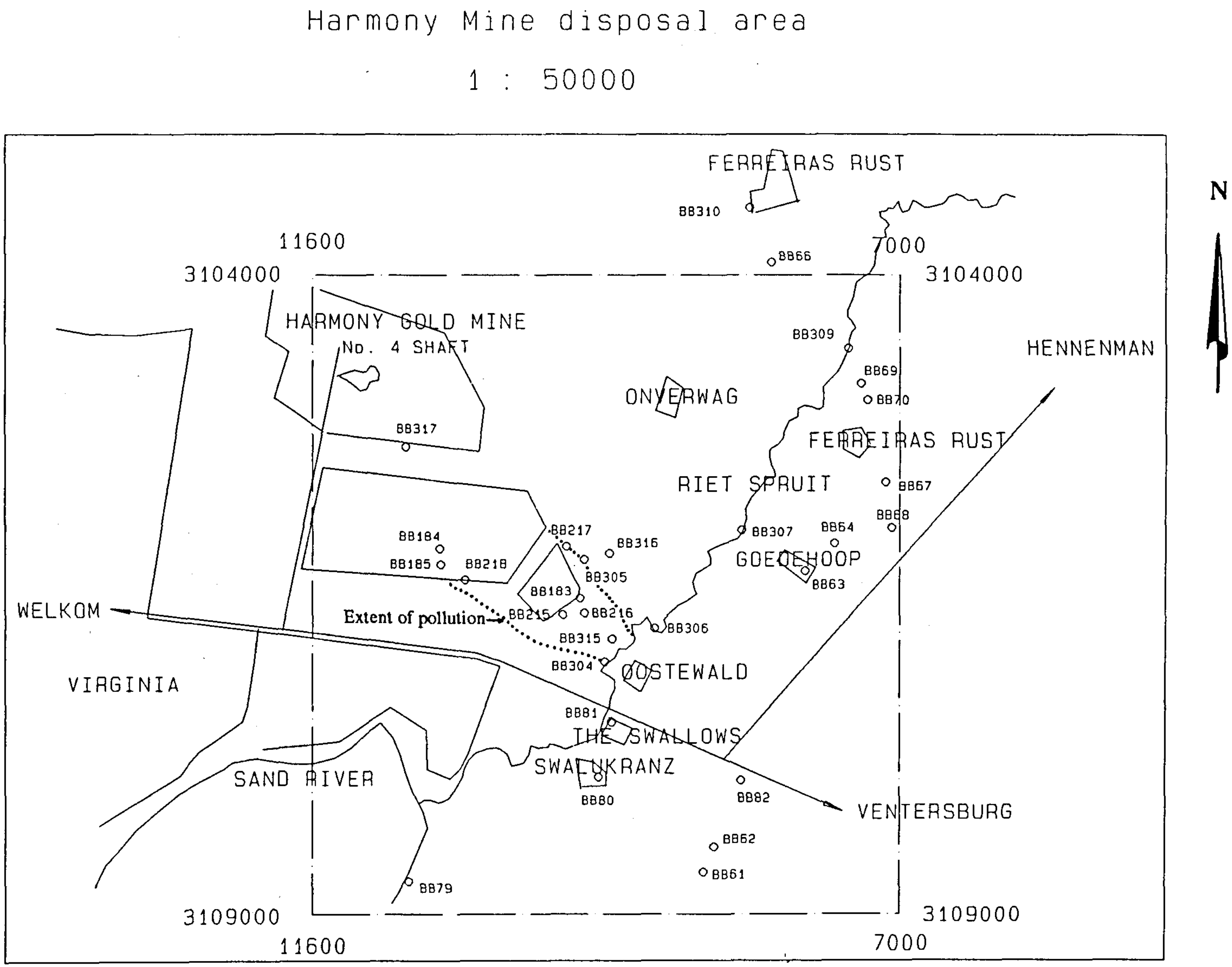
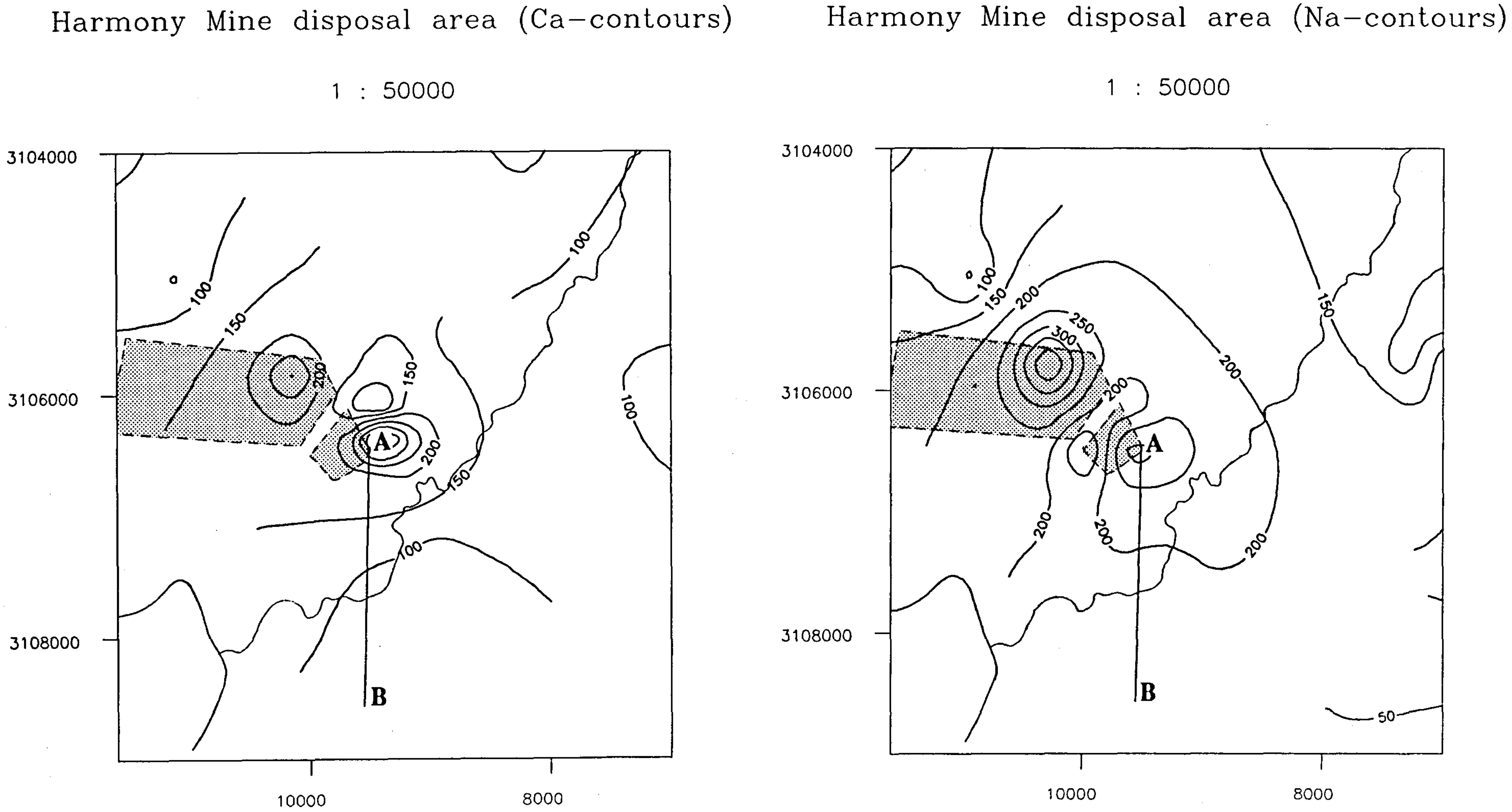


Figure 6.57. Harmony Mine disposal facility.



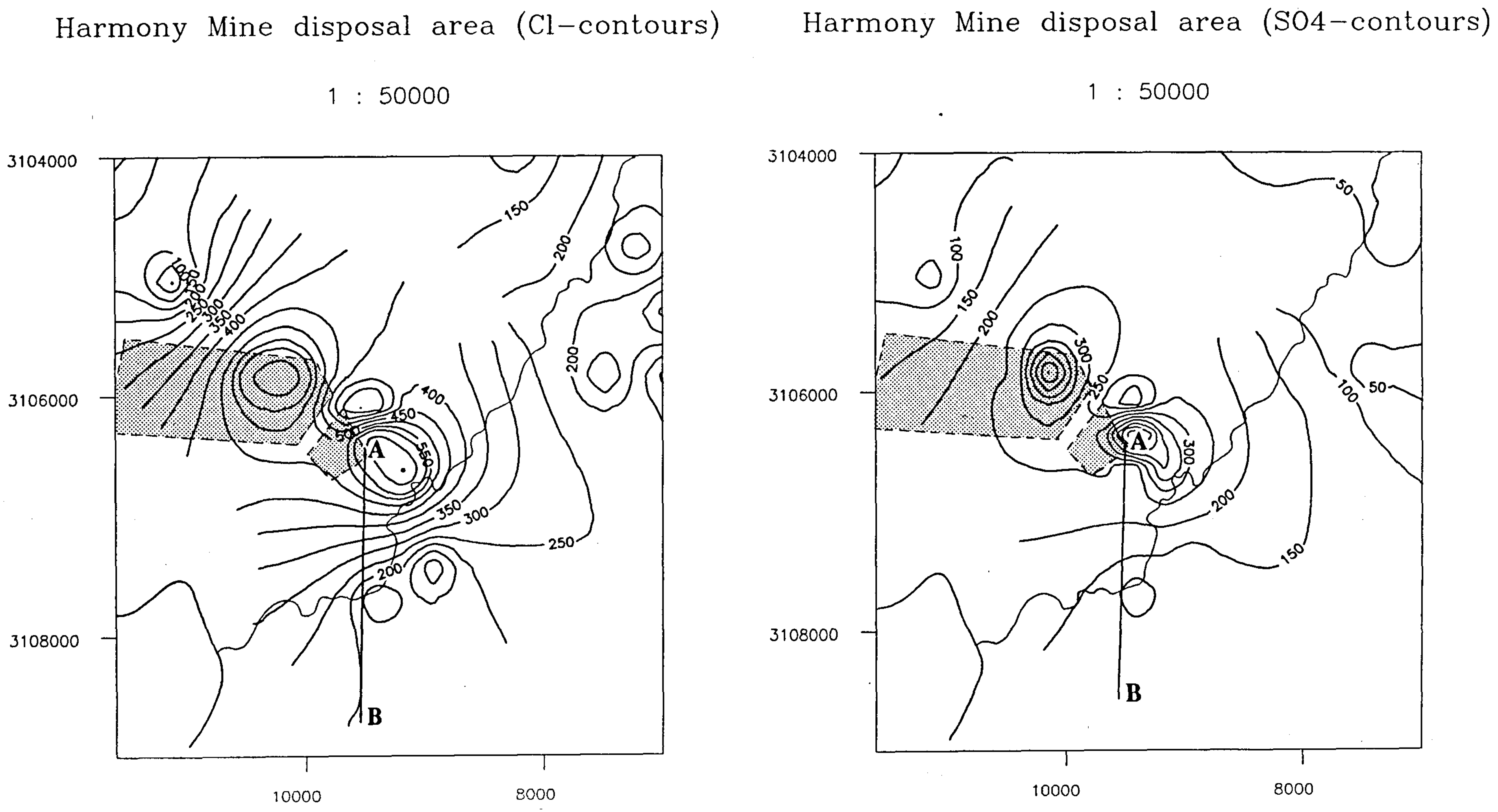
Harmony Mine disposal area (Ca–contours)

1 : 50000

Harmony Mine disposal area (Na–contours)

1 : 50000

Figure 6.58. Ca^{2+}- and Na^{+}-contours of the Harmony disposal facility.

 Harmony Mine disposal area (Cl-contours)

Harmony Mine disposal area (S04-contours)

Figure 6.59. Cl^-- and SO_4^{2-}-contours of the Harmony disposal facility.

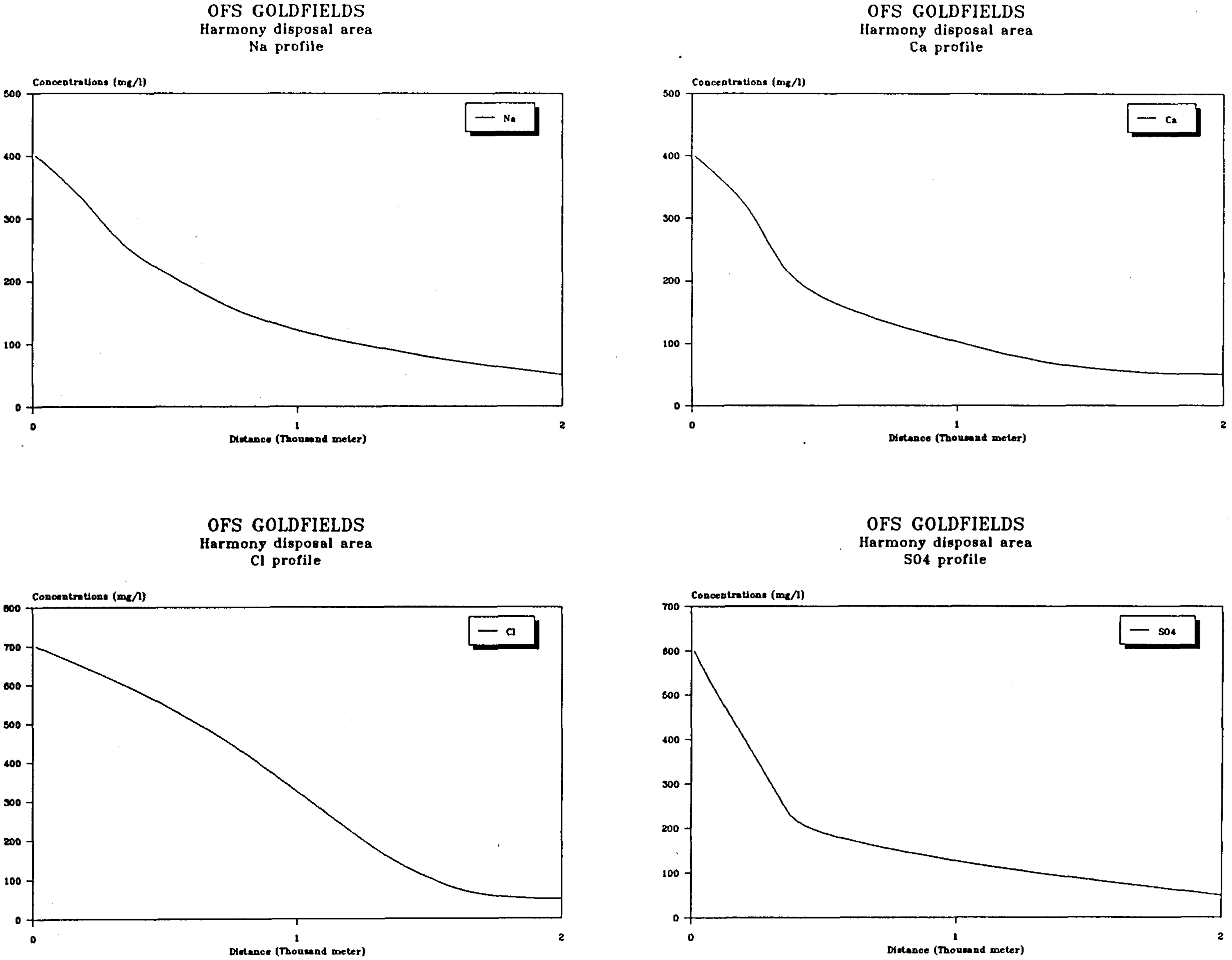


Figure 6.60. Concentration profiles along profile line AB at the Harmony disposal facility.

The contamination plume extends downstream towards the Riet Spruit, south-east of the area. It is highly unlikely that the pollution plume will cross the spruit, due to the ground-water gradients which are mainly towards the Riet Spruit and the Sand River. The Riet Spruit is a tributary of the Sand River.

Heavy metal concentrations in the ground water, in the vicinity of the disposal complex, are shown in Figure 6.61. *From the figure, one can conclude that the heavy metal concentrations are all within the "maximum permissible" limit.*

6.4.2.3 Beatrix Mine disposal area

This complex is situated to the south of the study area and is roughly 10 years old. The disposal complex comprises several evaporation areas and one slimes dam (see Figure 6.62). Two of the evaporation areas and part of the slimes dam are situated on a shallow dolerite sill. The contour maps of Na^+, Ca^{2+}, Cl^- and SO_4^{2-} show the extent of the contamination in this area (see Figures 6.63 to 6.64). When evaluating the respective contour maps, the following observations can be made:

- The Cl^-- and Ca^{2+}-concentration in the ground water is higher than the concentrations of the other ions.
- The high Cl^--concentration in the ground water in this area originates mainly from the two evaporation areas in the south of the area, which receive large quantities of NaCl-water from the mine.
- The distribution of the Cl^- in the ground water is also greater than those of the other ions.
- The low concentrations of all the ions in the vicinity of the slimes dam, identifying the main pollution sources as the evaporation areas.
- Ground-water gradients (see Figure 5.9) also play a major role in the distribution of the ions, especially towards the eastern side of the complex.
- The influence of a shallow weathered dolerite sill on the dispersion of the respective ions is also evident.

The concentrations of the ions at different points along a profile line EF are listed in Table 6.13, while the ion concentration profiles are shown in Figure 6.65.

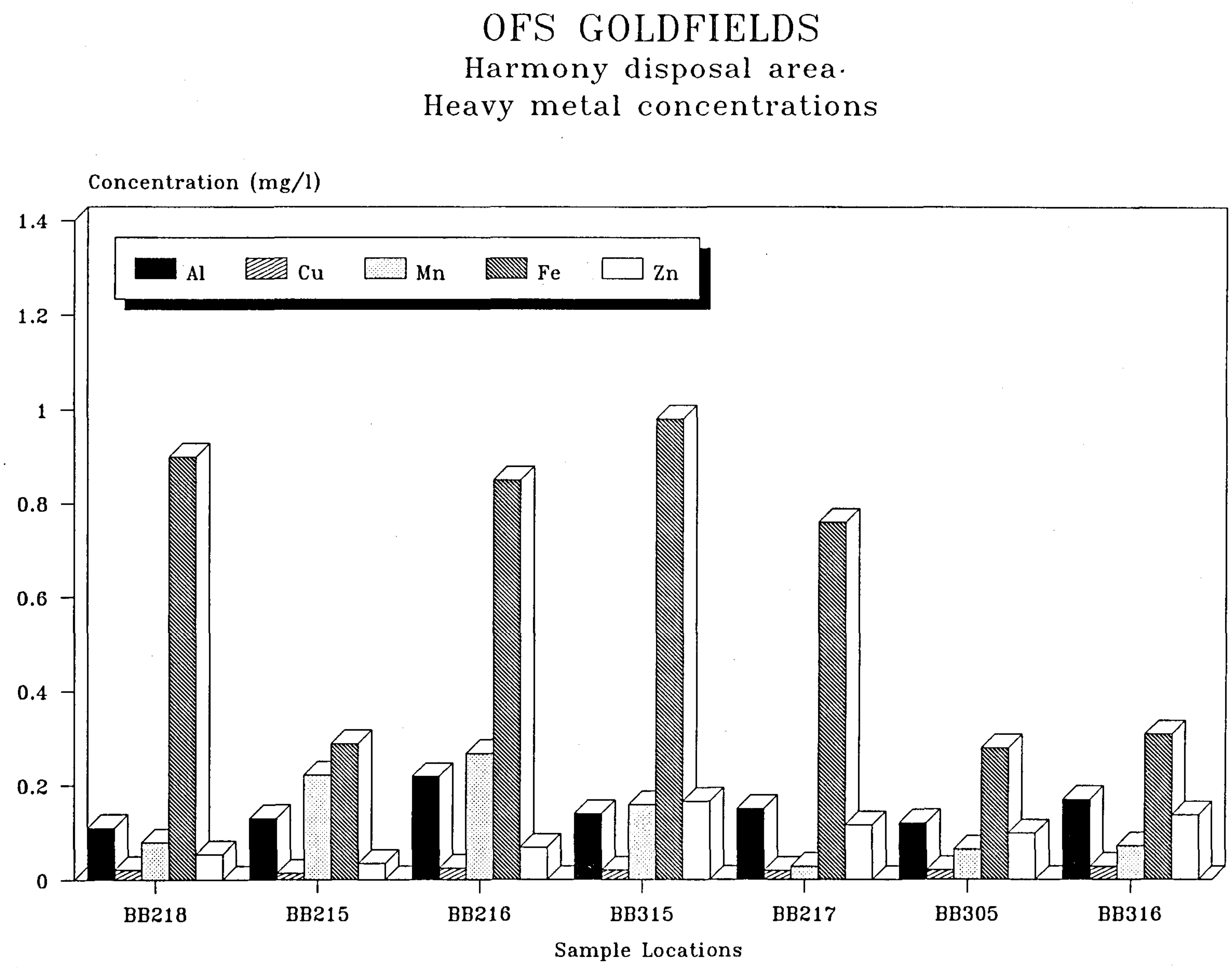


Figure 6.61. Heavy metal concentrations in the vicinity of the Harmony disposal facility.

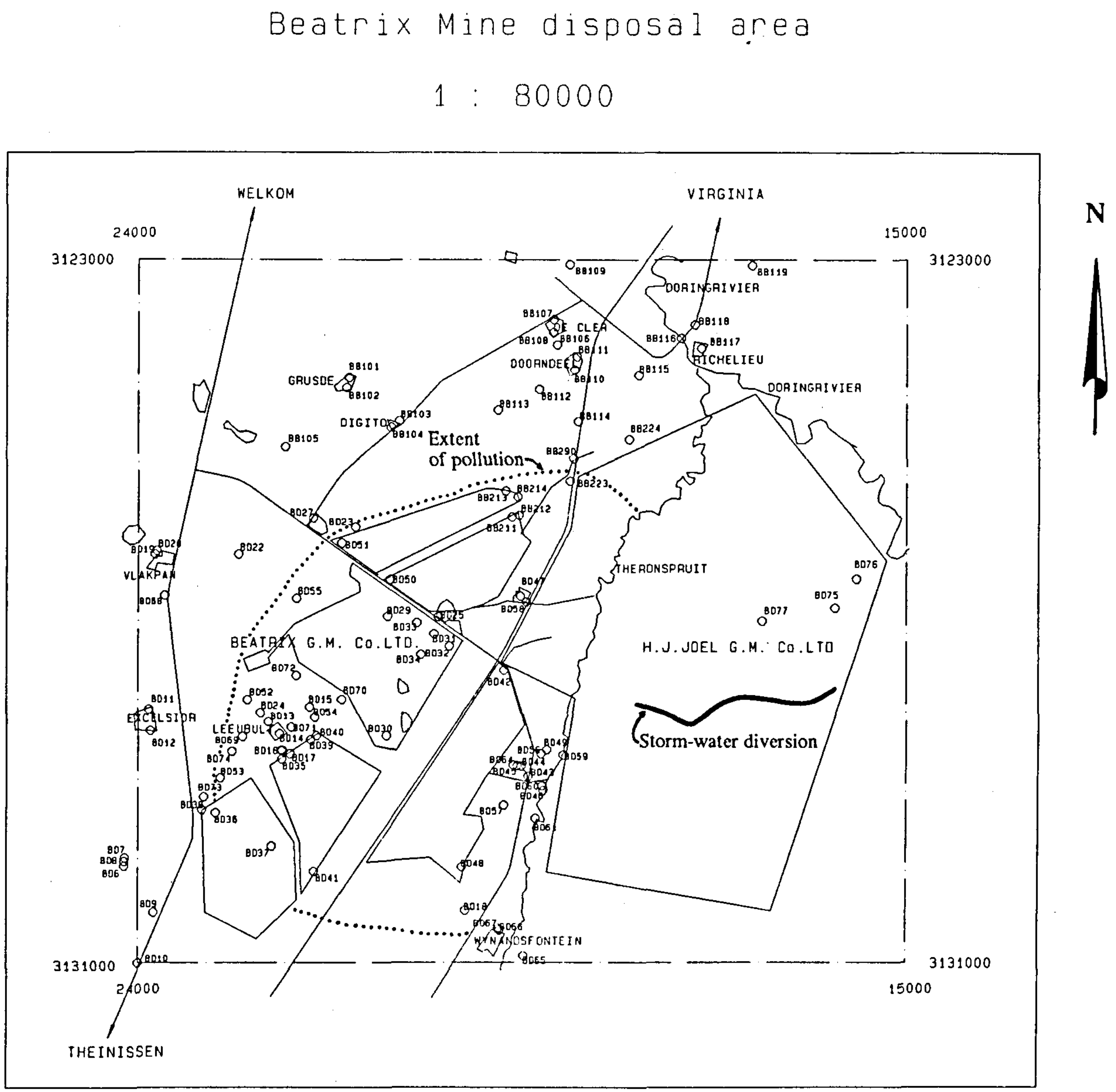
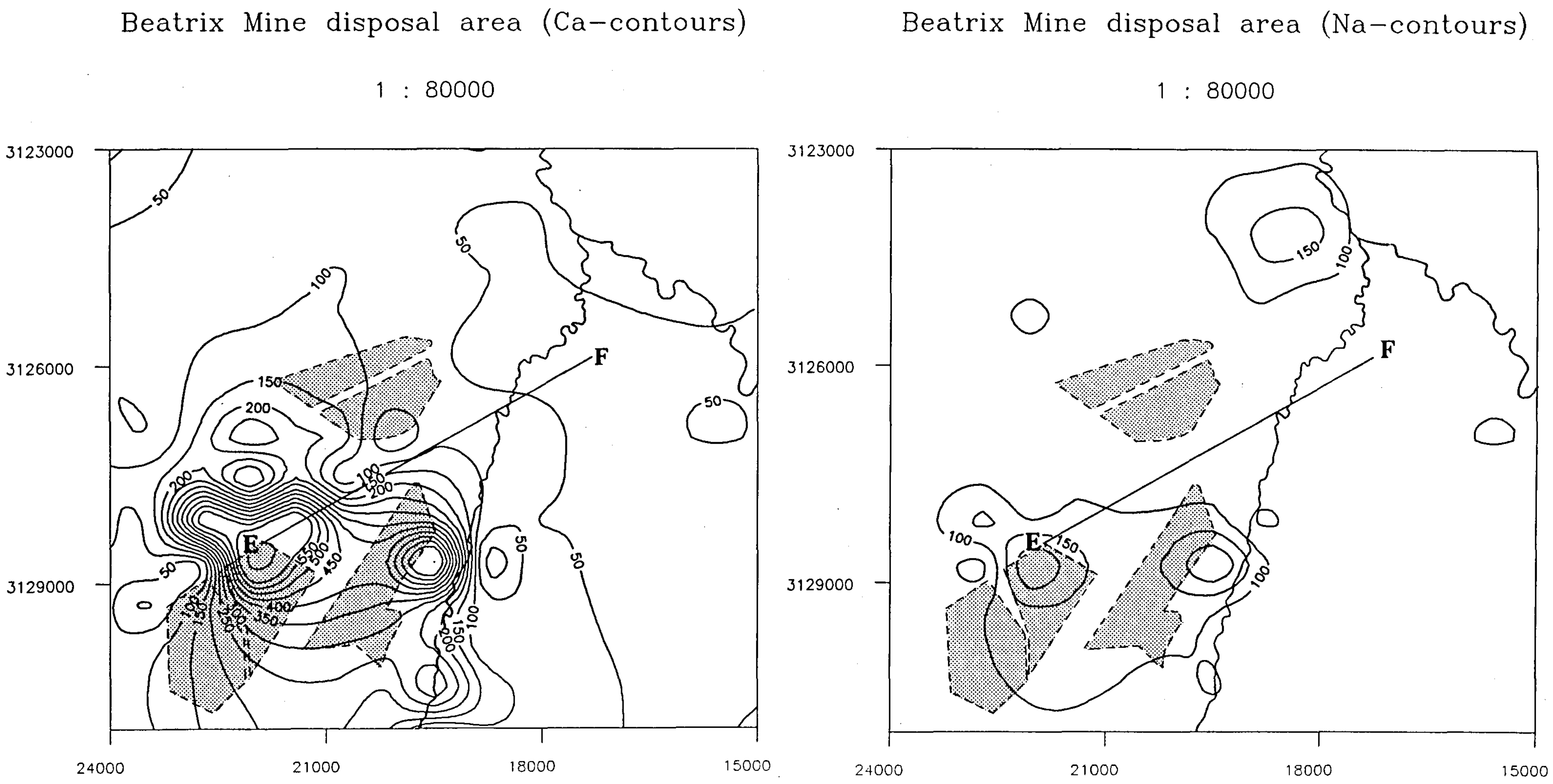


Figure 6.62. Beatrix Mine disposal facility.


Beatrix Mine disposal area (Ca–contours)

1 : 80000

Beatrix Mine disposal area (Na–contours)

1 : 80000

Figure 6.63. Ca^{2+}- and Na^{+}-contours of the Beatrix disposal facility.

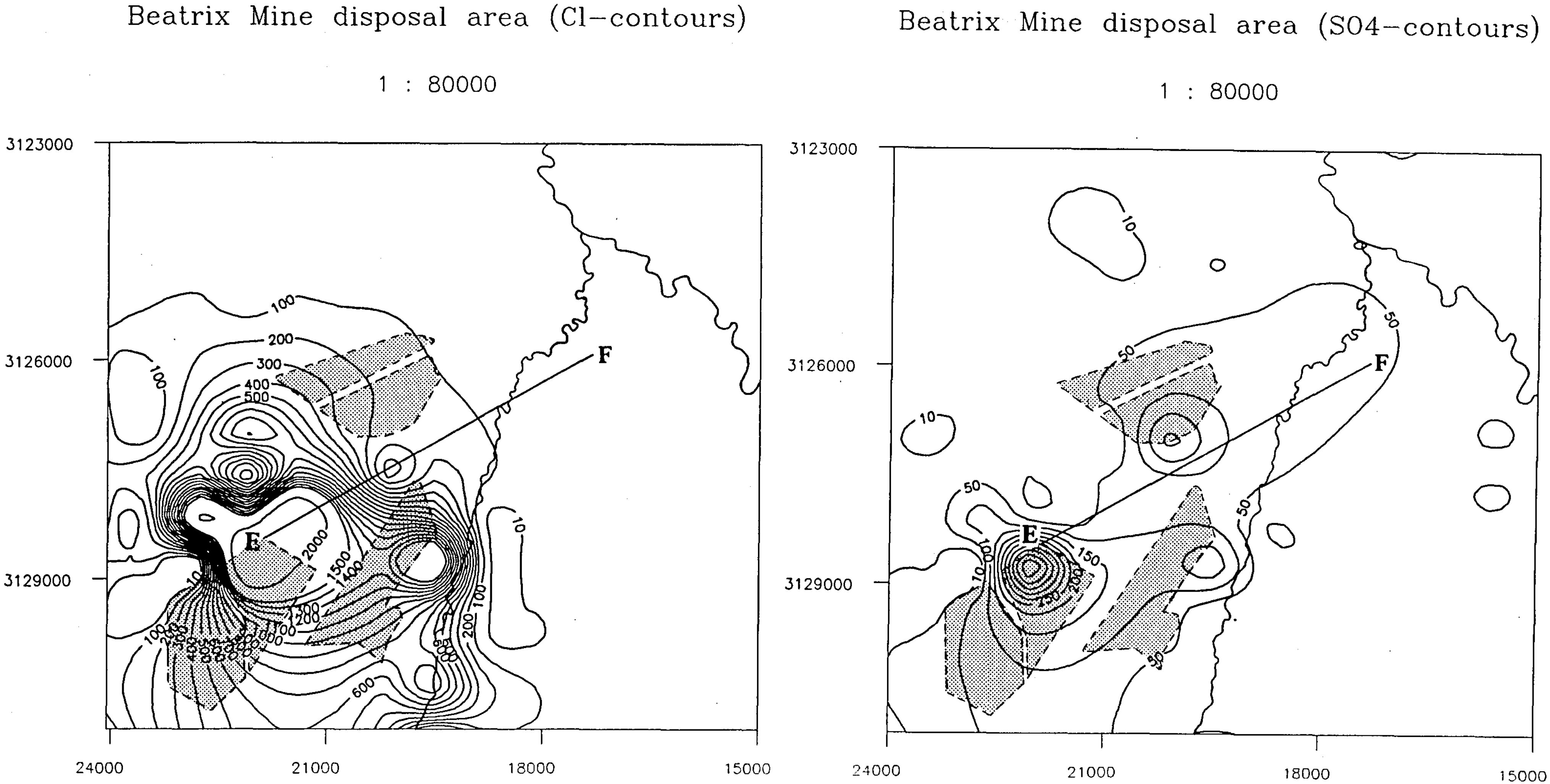


Figure 6.64. Cl⁻- and SO_4^{2-}-contours of the Beatrix disposal facility.

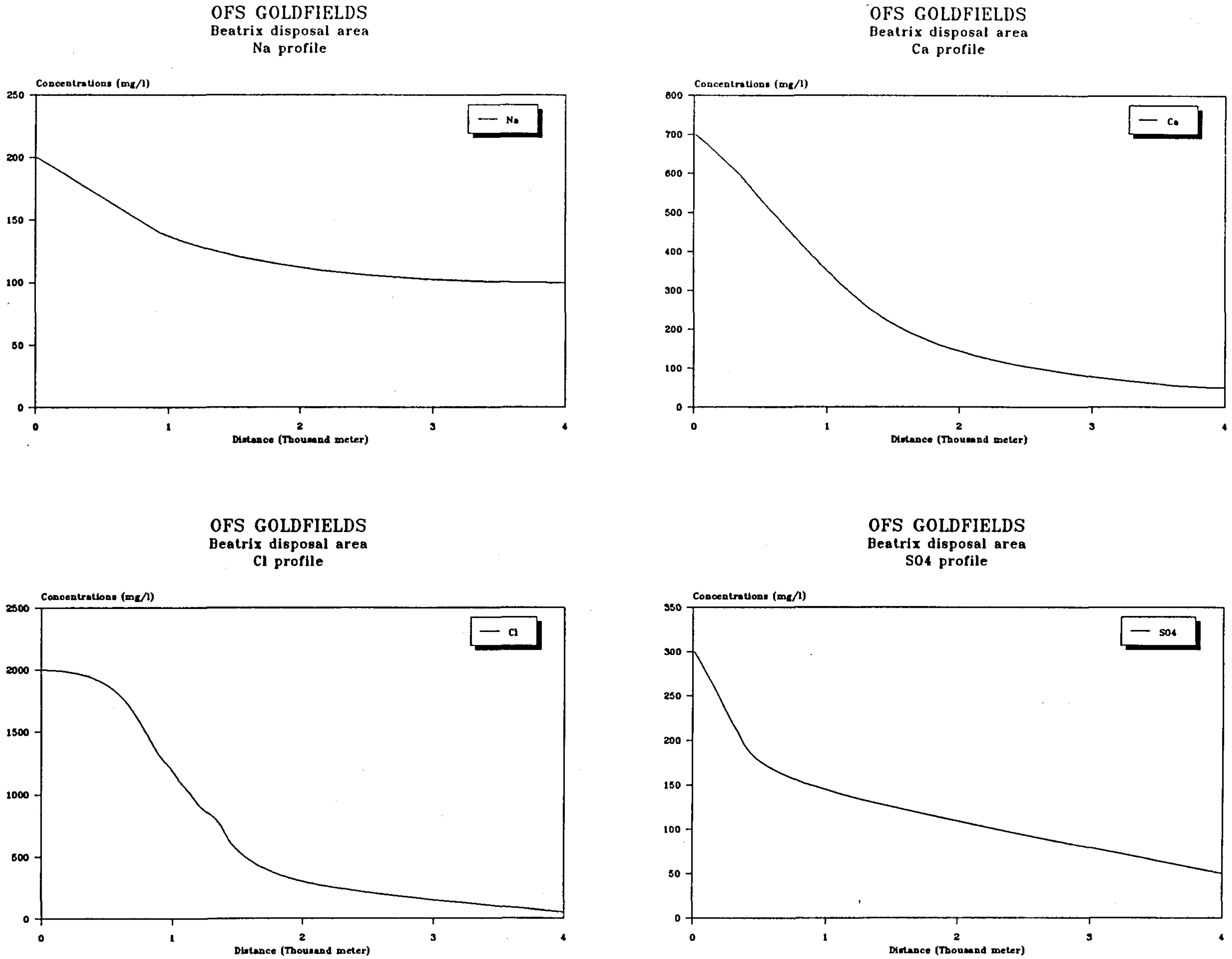


Figure 6.65. Concentration profiles along profile line EF at the Beatrix disposal facility.

TABLE 6.13. ION CONCENTRATIONS AT DIFFERENT POINTS ALONG THE PROFILE EF

Position (m)	Ca^{2+} (mg/l)	Na^{+} (mg/l)	Cl^{-} (mg/l)	SO_4^{2-} (mg/l)
E 10	700	200	2000	300
500	550	150	2000	150
1000	300	100	1200	150
2000	100	100	300	100
F 4000	50	100	50	50

It is evident from the above-listed results and Figure 6.65 that the Cl^{-} stays in solution for a much longer period than Na^{+}, Ca^{2+} and SO_4^{2-}.

Ground water in this area is also subjected to reverse ion exchange, yielding the relatively high Ca^{2+}- and lower Na^{+}-concentrations, due to the large volumes of effluent mine water (high salinity) in the evaporation areas. The Na^{+}-concentration of 100 mg/l at a distance of 4000 m from the disposal facility is probably due to normal ion exchange, which correlates reasonably well with unpolluted water in the Beaufort sediments (see section 5.4.1.2).

A shallow north-easterly to easterly dipping dolerite sill covers a large portion of the south-western part of the area. The dolerite sill which is weathered to a coarse gravel, reaching thicknesses of up to six metres, outcrops in a number of the evaporation dams, posing a considerable pollution threat downstream. The extent of this sill mainly controls the spread of the contaminant. This is clearly seen in some of the boreholes, close to the disposal site (BD 53 and BD 73), which did not intercept any dolerite, when drilled. These boreholes do not show any contamination, indicating that contaminant transport through the sediments is exceptionally slow.

At this stage, one can assume that the pollution has been restricted to an area within 2000 m north, north-east and east of the disposal facility, mainly depending on the extent of the dolerite sill.

If one evaluates the heavy metal concentrations in the area (Figure 6.66), it is seen that the concentrations are all currently within the permissible limit, depending on future acid production by the slimes dam.

To conclude, it can be said that in all the cases the spread of the contamination can be closely correlated to existing ground-water gradients, as well as the prevailing geological conditions.

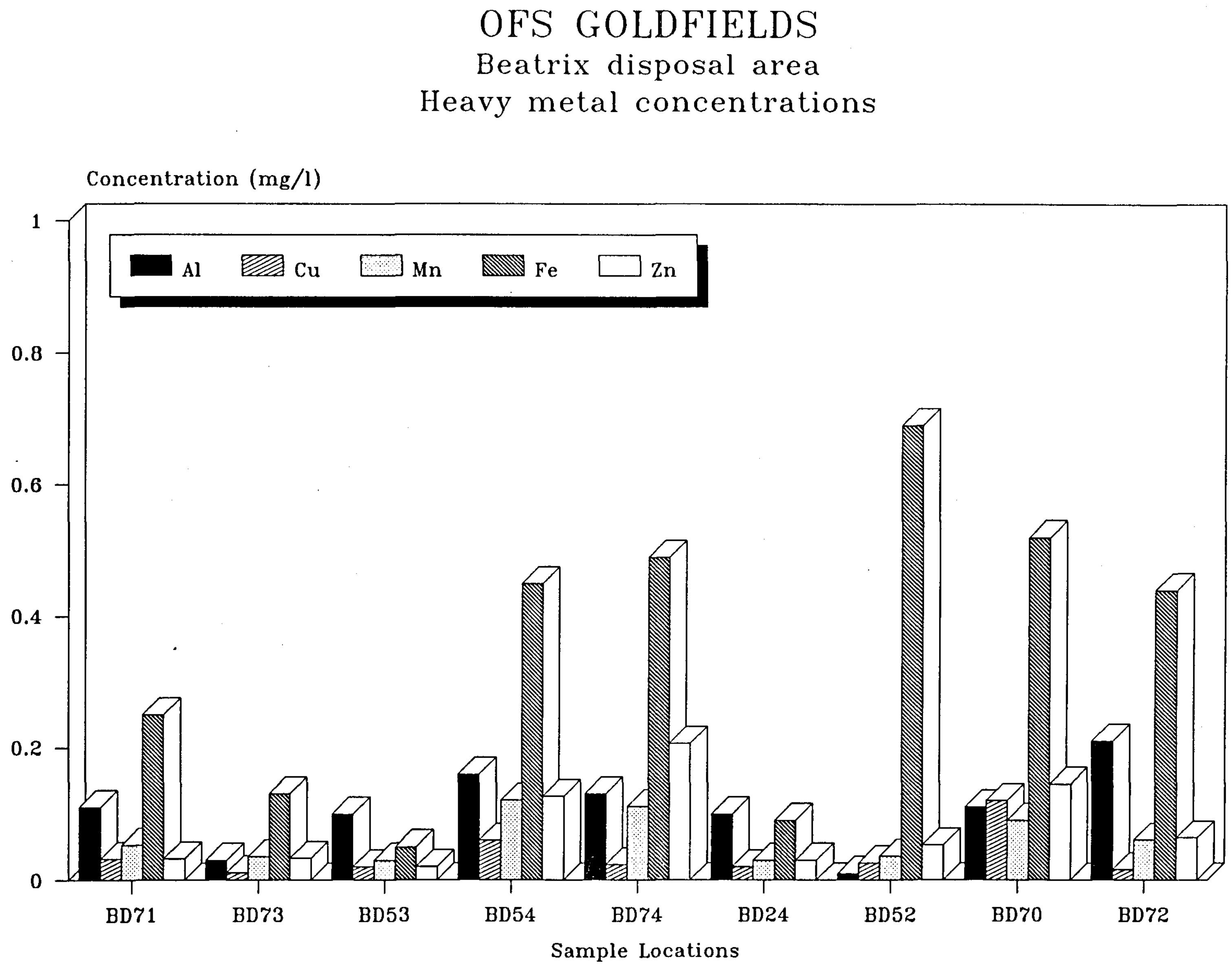


Figure 6.66. Heavy metal concentrations in the vicinity of the Beatrix disposal facility.

One can also assume that in the case of the Loraine disposal complex (± 40 years old), the contamination of the system has almost reached a steady state situation, whereas both the Harmony and Beatrix complexes are dynamic, due to their respective ages and their geohydrological characteristics.

6.4.3 AGRICULTURAL ACTIVITIES

One of the initial aims of the project was to determine the source of all possible pollutants to the ground-water regime in the study area. This would also include pollution which might arise from any agricultural activity in the region.

Agricultural activities throughout the area are limited to dry-land crop cultivation, grazing and, to a lesser extent, dairy farming. Some irrigation schemes are situated along the Sand River, as well as in the central west of the area. The water utilized for irrigation purposes is obtained from a canal system supplied by the Allemanskraal Dam.

The basic fertilizers used in the area are:

(i) NH_4^+ - Ammonium.

(ii) PO_4^{3-} - Phosphate.

(iii) K^+ - Potassium.

(iv) Zn - Zinc (in trace quantities).

(v) $(CaMg)\ CO_3$ - Dolomitic Limestone.

Depending on the crops, the quantities of the respective fertilizers may vary. Insects and weeds are generally controlled by pesticides and herbicides.

All fertilizers pose a potential pollution threat to the surrounding environment, depending on their application rate and volume. Generally, fertilizers are leached through the soil into the ground-water regime. Of all the fertilizers, $PO^{3-}{}_4$ and $NO^-{}_3$ are the most widely applied. Most phosphate fertilizers are adsorbed on soil particles, so that they seldom constitute a ground-water problem. Nitrogen, on the other hand, is only partially used by plants and is also adsorbed to only a limited extent by the soil, constituting a larger pollution hazard to the ground-water regime.

Erosion of soil by either wind or water plays an important part in the spread of pollutants from agricultural activities, especially in the case of $PO^{3-}{}_4$ and $NO^-{}_3$, adding to the eutrophication and salination of surface water systems.

The magnitude of the threat of pesticides and herbicides to the water resources depends upon the properties of the pesticide/herbicide, the volume, the state (liquid or solid) and the application rate of the particular pesticide/herbicide. Pesticides and herbicides comprise many types of organo-chemicals. Many of these compounds have chemical structures which are relatively insoluble in water, while many may be readily adsorbed on soil particles. In addition, many of the compounds may be highly resistant to physical, chemical and biological degradation, resulting in an accumulation of pollutants, persisting in the environment for a long time. These pollutants which progressively pollute the water resouces, have the potential to jeopardize many uses of water, while in some cases, their degradation products may be even more toxic than the compound itself.

Except for a few localized NO_3^- pollution sources throughout the area, no other pollution sources were observed during the reconnaissance and extended sampling phases. All NO_3^- sources could be ascribed to relatively large feeding-pens in close proximity of existing boreholes. No ground-water samples were analysed for the occurrence of pesticides and herbicides.

Bearing the above in mind, as well as the time constraint on the research project, it was decided that no further research should be devoted to this matter.

CHAPTER 7

MANAGEMENT OPTIONS

7.1 INTRODUCTION

Water pollution, at present and in the past, has been controlled by means of effluent standards. However, despite the use of these standards, the quality of the water resources in South Africa is deteriorating. This forced the Department of Water Affairs to gradually change its approach to a Receiving Water Quality Management Objective approach.

According to Best (1990), the Receiving Water Quality Management Objective approach is based on the following principles:

(i) "The desired quality of water resources is determined by its present and/or intended uses. The Department recognizes that representatives of water users and, where practically possible, the general public, should be involved in decision-making concerning the determination of the desired quality of a particular resource.

(ii) It is accepted that the water environment has a certain, usually quantifiable, capacity to assimilate pollutants without detriment to predetermined quality objectives.

(iii) The assimilative capacity of a water body is part of the water resource and, as such, must be managed judiciously and shared in an equitable manner amongst all water users for the disposal of their wastes.

(iv) For those pollutants which are considered hazardous, because they pose the greatest threat to the environment as a result of their toxicity, extent of bio-accumulation and persistence, a precautionary approach aimed at minimizing or preventing their entry into the water environment should be adopted.

(v) Water quality and water supply management have to be fully integrated. Water quality objectives cannot be determined independently from water supply objectives as a whole. Therefore, water quality management has to be done as an integral part of the overall water resource management."

Furthermore, he also stated that a water management policy needs to be applied in such a manner that the objectives of environmental conservation and economic growth become complementary to each other and for the one concept to be an incentive for the other.

One of the aims of the research project is to suggest management strategies for the Orange Free State Goldfields, whereby the influence of waste disposal can be minimized. From the previous chapters, it is evident that contamination of both the surface and subsurface water reservoirs has occurred throughout the study area. Effluent disposal has been ongoing in some instances (older mines situated in the central and northern parts) for over 40 years, while towards the southern parts of the area (new mines), effluent disposal has been taking place for the past 10 years.

Thus, when suggesting effective management strategies for the Orange Free State Goldfields, the following should be carefully taken into consideration:

- The processes associated with pollution generation and migration of pollution products from the source to the environment. An understanding of the different processes and the factors that control pollution are extremely important, if not essential, in developing effective prediction, control and monitoring methods.
- The prediction of possible pollution that might occur from different pollution sources. An understanding of the chemical processes and site specific conditions is important for the prediction of pollution in certain areas.
- Pollution control methods that could be implemented to minimize or prevent pollution. Control measures may be directed at preventing the pollution generation from occurring or may be aimed at preventing the transport of contaminants to the environment. An alternative approach is to allow pollution generation and migration to occur and then to collect and treat the effluent before releasing it to the environment.
- The design of an appropriate monitoring program is essential for the implementation of pollution management strategies. Consideration in a monitoring program includes: chemical elements to be measured, frequency, location and method of sampling.
- Due to the high cost of aquifer rehabilitation from pollution, aquifer protection policies are necessary and should be based on the degree of vulnerability of individual aquifers to different pollutants and their relative importance taking into account delayed effects.

7.2 PREDICTION OF POLLUTION OCCURRENCE

The targeting of different pollution sources for the evaluation of their potential to pollute the environment is essential for predictions of pollution. This evaluation is accomplished through the collection of representative water samples at the different sites. However, in the case of a new site, the comparison with a similar nearby site for predictions must be done to see if any pollution will occur. Such predictions, early in the planning phase of a new waste disposal site, would indicate whether pollution may be a potential concern at the site.

The above-mentioned evaluation of pollutants, as well as disposal sites, can be enhanced by numerical models, i.e. the application of either general two-dimensional flow models, if no chemical analyses are available, or coupled multi-solute transport models with sorption, ion exchange and equilibrium chemistry, if sufficient hydrochemical data exist. Furthermore, the use of models will depict shortcomings in the existing data, as well as the monitoring programme, and will ensure that data are collected accordingly.

Predictive test works will aid the design, testing and implementation of preventing/control/treatment techniques during waste disposal site operation and the creation of a monitoring program.

7.3 POLLUTION CONTROL METHODS

Methods of controlling pollution include prevention and abatement techniques. Prevention refers to measures designed before waste disposal sites are sited and with the knowledge of the potential pollution that might occur. Abatement refers to measures implemented either at waste disposal facilities where pollution is occurring and was not anticipated, or at facilities where control measures are not effective (Steffen, Robertson & Kirsten, 1989).

Prevention of pollution is the most preferred form of control and should, if at all possible, be the primary long-term approach. However, where pollution generation is not prevented, the next level of control is to prevent or reduce the migration of the pollution to the environment. Since water is the transport medium for contaminants, the management of the different water sources is essential for pollution control. Placing a waste disposal site plays a major role in the migration and distribution of pollution in the vicinity of the waste disposal site. The approach to controlling pollution therefore requires the management and investigation of one or more of the following:

(i) geological environment,

(ii) hydrology,

(iii) geohydrology,

(iv) covers and seals of a pollution source and

(v) collecting and treatment of the pollution.

7.3.1 GEOLOGICAL ENVIRONMENT

The area under investigation is underlain by Karoo sediments. Typical formations will include clay, sandstone, siltstone, shale, mudstone, alluvium and dolerite intrusions. The importance of knowing the relative distribution of the different geological formations can be found in the fact that the hydrogeological and hydrochemical characteristics of the various geological formations may differ to a large extent.

Dolerite intrusions play a significant role in Karoo aquifers, as well as in ground-water movement and, therefore, pollution migration. A knowledge of the distribution of these bodies in the study area will enhance the effectiveness of any ground-water quality monitoring and management program.

7.3.2 HYDROLOGY

When conducting an investigation in water qualities, a basic knowledge of the hydrology is necessary. This is because hydrology and geohydrology are both components of the larger hydrological cycle and can therefore never be viewed in isolation from each other.

The main hydrological components to be considered are precipitation, evaporation, drainage and run-off.

A water balance is an effective management technique to control surface water reservoirs and can be stated as follows:

water input = water output + water retained.

In this equation, each term represents a rate of accumulation or loss.

Precipitation

The significance of precipitation in terms of the design and implementation of a water quality monitoring and management program mainly lies in the following:

- Precipitation is the main source of fresh water recharge to the ground-water system.

- Extreme rainfall events may cause problems with the storage capacities of the different storage facilities where excess mine water is evaporated and recycled. Large precipitation events may also cause tailings impoundment failure. Failure during such events is also likely to result in large losses of tailings or waste fines to the environment.

In view of the above-mentioned, the identification of rainfall cycles, as well as probability analysis for flood occurrence in the Orange Free State Goldfields, can be important as excess water is one of the major issues in the area. Thus, if rainfall cycles can be identified and floods can be predicted, mines could use such information assisting them in the optimal design of their storage facilities.

Evaporation

Due to the fact that large surface areas are used for the evaporation of excess effluent water, it is essential to determine realistic evaporation figures, as well as evaporation/precipitation ratios (potential evaporation) for each month of the year. If additional evaporation facilities are needed, natural salt-pans can be utilized as evaporation areas.

The potential evaporation for the Orange Free State Goldfields reaches a maximum in June, July and August and a minimum in January, February and March.

Drainage and Run-off

A knowledge of the run-off and drainage of a certain area allows one to recognize those parts of the landscape that are major contributors to either storm-water run-off or surface water ponding, as well as potential ground-water recharge zones. Precautions may have to be taken to avoid these zones or to retain effluent water generated upon them. An understanding of storm-water run-off production and ground-water recharge may indicate the processes by which pollutants might reach streams and the ground-water table. Management techniques should be implemented to conserve these zones, so that they might continue their function instead of being polluted.

Diversion of surface flows, while easily implemented, is often difficult to maintain in the long term. The best long-term solution to such surface flows is to select a disposal site which minimizes the need for diversion. In order to be able to delineate possible surface drainage routes, a surface drainage route map of possible waste (solid or liquid) disposal sites should be compiled before deciding on the locality of a specific disposal site. However, where old disposal sites occur in surface drainage routes, diversion channels should be built to minimize the pollution potential of these sites. These diversion channels should fulfil the following conditions:

(i) Large enough to bypass all storm-water run-off, as well as when extreme flow conditions occur.

(ii) Where erosion can take place, appropriate erosion protection methods, such as concrete lining of canals, should be implemented.

(iii) The design of the channels to be such that they can be easily maintained, ensuring efficient operation.

7.3.3 GEOHYDROLOGY

Ground water serves as a transport medium for contaminants. The contamination of ground water may be prevented by the interception or isolation of polluted water before it comes into contact with the ground water, or better site selection avoiding high potential ground-water recharge areas.

Ground-water recharge from waste disposal sites can be minimized by engineered barriers, which are generally not likely to provide long-term control. Isolation can be achieved by placing the disposal site on an artificially created impermeable layer, overlying a drainage layer to remove the possible leachate that might occur. The performance and cost of different interception and isolation methods vary over a wide range, depending on hydrogeological and other site specifications.

In order to be able to determine these hydrogeological parameters and to monitor ground-water quality in a meaningful manner, good information regarding the water-bearing bodies in the monitoring area must be obtained. This information is usually obtained by the execution of a drilling program or logging of previously drilled boreholes in the area of investigation. The following information must be determined during drilling and monitoring programs:

(i) exact geological information,

(ii) aquifer characteristics,

(iii) water-level information and

(iv) ground-water quality information.

Each aquifer can be hydraulically described in terms of two main aquifer characteristics, namely permeability and storativity. Permeability is the rate at which water is transmitted through an aquifer and storativity is the volume of water an aquifer releases from or takes into storage. These two factors play a major role in the rate of ground-water migration through an aquifer.

7.3.4 COVERS AND SEALS FOR POLLUTION SOURCES

Generally, all disposal sites are susceptible to ground-water pollution, as well as wind and water erosion. The principle source of this water is precipitation. A way of controlling infiltration of precipitation is by means of low permeability covers or seals. Covers and seals offer the ability to restrict the access of oxygen and water to reactive wastes. To limit oxygen and water entry, the cover must itself have a low permeability to air or water, e.g. the restriction of water can serve to limit both the formation of acid and the subsequent transportation of the oxidation products from a slimes dam to the environment.

A variety of materials may be used to provide surface covers, mainly depending on local availability as well as site conditions. The materials include different types of soils, synthetic membranes, water and a combination of the above. In the case of acid mine drainage, the most effective means of excluding oxygen that is essential for the oxidation process and therefore the generation of acid mine drainage, is by means of a water cover (Steffen, Robertson & Kirsten, 1989). This is, however, not feasible under South African conditions, due to the limited water resources. The other cover materials are generally more effective as inhibitors of infiltration. Soil covers, in particular, are suitable for re-vegetation purposes, but not essential, as vegetation can be done directly into slimes dams.

Vegetation of slimes dams has proved to be one of the more successful means of erosion control and unnecessary spills caused by run-off. Another important aspect of vegetating slimes dams is to increase the total evaporation potential of the site, reducing ground-water transport through the structure, therefore reducing the possible leaching of the tailings.

It is not only the old inactive slimes dams that can be covered with vegetation, but also the new slimes that are still in the process of construction.

7.3.5 COLLECTING AND TREATMENT OF POLLUTION

According to Steffen, Robertson & Kirsten (1989), collection and treatment of pollution at existing facilities is often the only practical option available. Treatment measures can be either active systems which require continuous operation, such as a chemical treatment plant or passive systems which are intended to function without intervention of man, such as artificially constructed wet lands.

Chemical treatment, while it offers a secure short-term method of achieving environmental protection, may not offer a cost-effective long-term solution.

Wet lands, such as bogs, marshes and swamps, are increasingly being recognized for their ability to treat waste waters. The vegetation, water-logged organic soil and microorganisms, all contribute to the removal of dissolved substances, including heavy metals, nutrients and suspended solids, from the water. In some wet lands, the pH of the water is also buffered. In the case of the Orange Free State Goldfields, such an option is impractical, primarily due to a water shortage, as well as the absence of natural wet lands.

Collection requires collecting of both contaminated surface waters as well as ground water. Collecting of surface waters is easily achieved by means of surface ditches. The collecting of subsurface water requires the installation of collecting trenches, wells or cut-off walls to force the ground water to the surface, where it can be collected. Most collecting systems require long-term maintenance. The design of appropriate collecting systems is generally site specific and mainly depends on the location of the pollution plume, topography, precipitation and run-off properties, as well as the general geohydrology of the site.

7.4 THE DESIGNING OF AN APPROPRIATE MONITORING PROGRAM

Environmental monitoring in and around a waste disposal site is intended to define base line conditions and to identify changes in conditions during and after operation. The conditions monitored include physical processes such as water flow, water levels, precipitation, evaporation and water quality. The major objective of a monitoring program at a waste disposal site is to monitor the effectiveness of the prevention/control/treatment techniques and to detect whether the techniques are successful.

The baseline monitoring defines existing environmental conditions of the physical, chemical and biological aspects of the area (see Figure 7.1). Therefore, a report containing all the above facts should be produced and, only on the basis of the findings in this report, should a final decision on the suitability of the particular site be taken. Once the site has been established, a monitoring system should be installed on the site, gathering vital information on the impact the system has on its surroundings (see Figure 7.2).

All monitoring stations should be monitored at least biannually to detect changes in the environmental conditions. If these changes are significant, more frequent monitoring should be performed. If an adverse impact is determined, alternative control or treatment techniques should be designed, tested and implemented. If no unacceptable impacts are detected over an acceptable period of time, the site can proceed with closure.

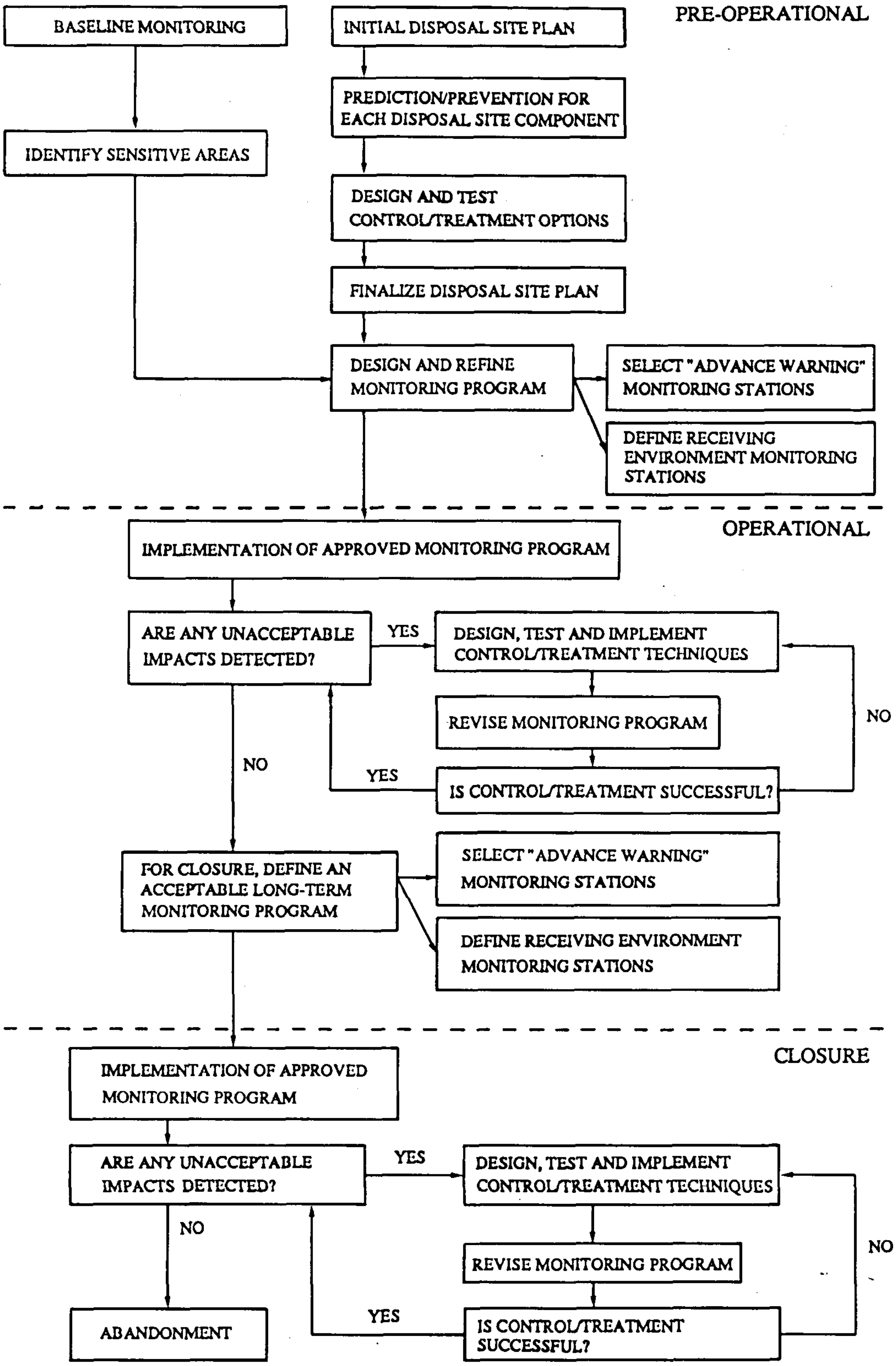


Figure 7.1. A recommended approach to environmental monitoring (after Steffen, Robertson & Kirsten, 1989).

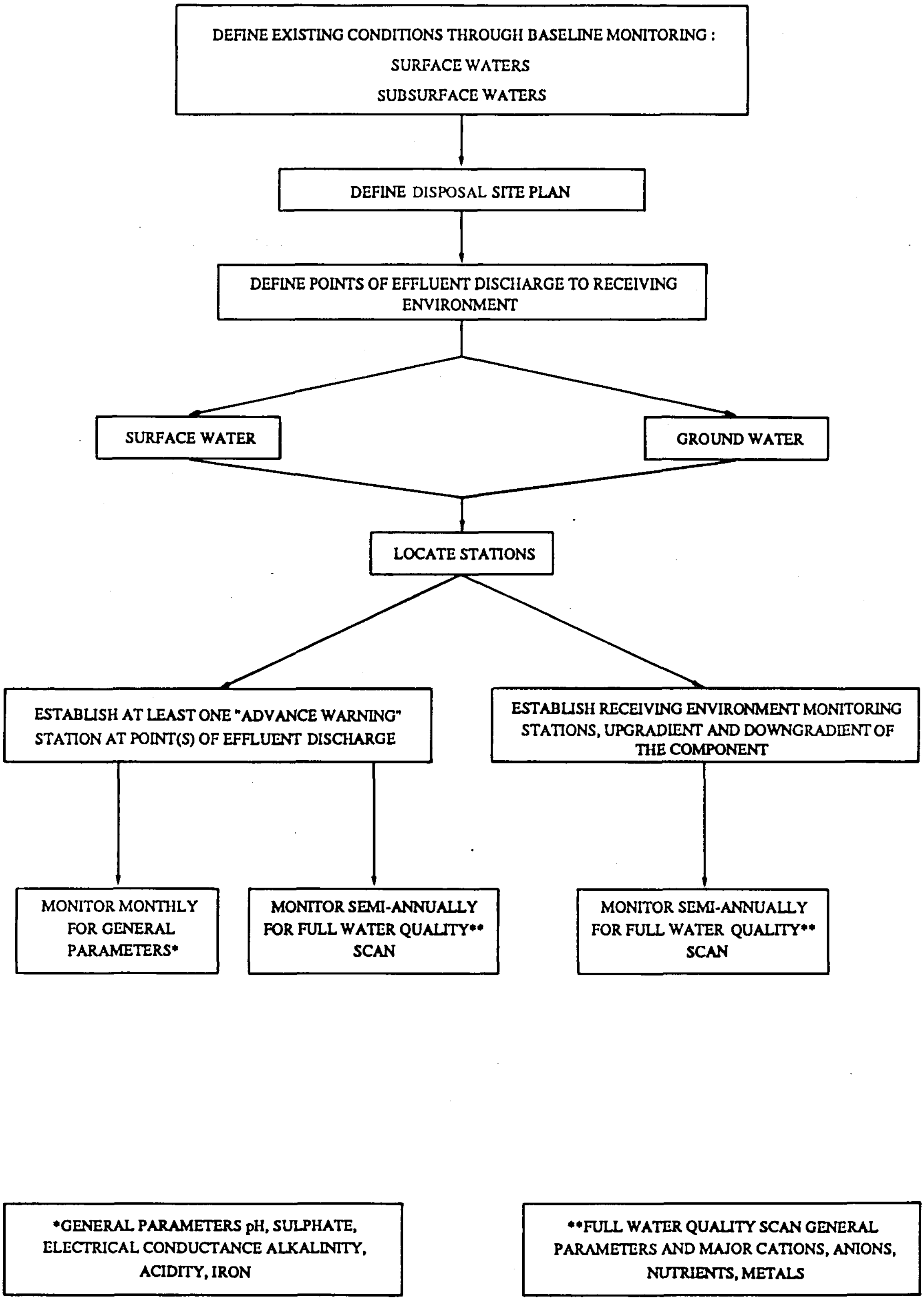


Figure 7.2. Design and refinement of an integrated on-site/off-site monitoring program (for operation and closure) (after Steffen, Robertson & Kirsten, 1989).

7.5 APPLICATION OF MANAGEMENT STRATEGIES TO THE ORANGE FREE STATE GOLDFIELDS

The Orange Free State Goldfields produce many different types of waste (solid or liquid), contributing in varying quantities to the total water quality of the Orange Free State Goldfields. Wastes found in the Orange Free State Goldfields are:

(i) *Mining:*

  (a) Solid waste

  (b) Tailings and return water dams

  (c) Evaporation areas

(ii) *Municipal:*

  (a) Urban solid waste

  (b) Urban liquid waste

  (c) Industrial effluent

The basis of any good and effective management strategy is an extensive data base. One cannot act efficiently without accurate site specific information. Through the course of the research project, such a data base has been established. Considering the size of the research area (approximately 2 100 km^2), on-going monitoring, as well as extending the present information, will be necessary. The points used for basic monitoring during the investigation were restricted to existing boreholes and available surface water reservoirs, while more detailed monitoring was carried out at selected target areas (discussed in Chapter 5.3). Ideally, this situation should be extended to more sites, however, if the present monitoring of boreholes is maintained by e.g. the Department of Water Affairs (DWA), the situation will be well in hand to prevent future, large-scale pollution problems. It should also be stressed that the co-operation of all the mining companies, as well as municipalities and farmers in the region, will have to be obtained.

7.5.1 MINING WASTE MANAGEMENT

A large portion of all the waste produced in the study area is generated by the gold mines. Three basic mine disposal facilities comprise:

(i) solid waste sites,

(ii) tailings dams and

(iii) evaporation areas

and will be discussed in more detail subsequently.

7.5.1.1 Solid Waste Management

Waste rock and old disused slimes dams can be classified as solid waste in the mining environment. Not much work was done on either of the mentioned structures, as their pollution potential is much less than that of active slimes dams or evaporation areas.

(a) Waste rock dumps

Waste rock dumps originate from two major sources, namely underground development and sorting. In both cases, however, the waste rock is mineralized to a greater or lesser extent with mainly pyrite FeS_2. This waste is conveyed to large dumps, where it is stockpiled until some use can be justified for it. Rocks on the sides of the dumps are exposed to rain and the atmosphere, oxidizing the FeS_2, producing small negligible amounts of H_2SO_4 (sulphuric acid). If, however, the base of the rock dump is constantly surrounded by water, the FeS_2 oxidation will increase, producing more H_2SO_4. It is therefore important not to establish rock dumps in low-lying areas such as natural pans or vleis.

(b) Old inactive slimes dams

Most of these structures are currently being reclaimed. However, there are a few old slimes dams which are totally disused. A major problem with disused slimes dam facilities is the fact that they get eroded by wind and water. If these structures are not effectively maintained by the respective mines, a structural deterioration of the catchment paddocks and solution trenches (see Appendix I, Figure I-2) of the slimes dam will occur. High intensity rain storms can cause excessive run-off, thus if the drainage system of such a facility is defective, the run-off can cause spills to surrounding areas. If disused structures are vegetated, run-off from tailings facilities can be sufficiently controlled to prevent unnecessary spills.

Another important aspect of vegetating disused slimes dams is to increase the evapotranspiration potential of the site, reducing ground-water transport through the structure, thereby reducing the possible leaching of the tailings.

Wind erosion also plays an important part in this region. During droughts, sandstorms frequently occur, which erode the slimes dam surface and spread the eroded slimes over vast areas downwind. Vegetation on disused slimes dams can minimize wind erosion.

7.5.1.2 Tailings and return water dams

In the study area, almost 47 km^2 of land is utilized for slimes and return water dams. Large quantities of gold tailings and water are pumped daily onto the slimes dams. Of the available water on the slimes dam, an average of 30% reaches the return water facility, while the rest remains in and on the slimes dam. Large quantities of the remaining water evaporate, while a certain quantity infiltrates the substrata, contaminating the ground water in the region. The extent of this contamination is controlled by the underlying geological strata, which in the Goldfields area limits its spread. It is, however, difficult to estimate an infiltration rate for the respective slimes dams and their return water dams.

As discussed in Appendix I, the paddock system is used to place gold tailings hydraulically. This system is also suited for the generally flat topography in the Orange Free State Goldfields. During the course of the research project, four active slimes dam complexes were investigated:

(i) Loraine slimes dam

(ii) Western Holdings slimes dam

(iii) Harmony slimes dam

(iv) Beatrix slimes dam

Boreholes were drilled at increasing distances from the respective complexes. Two of the complexes (Loraine and Western Holdings) were equipped with neutron access tubes. Monthly measurements indicated that contamination of the ground water had occurred in all cases, but in varying degrees, depending on the hydraulic conductivities of the underlying sediments and the construction of the slimes dam.

In the case of the Loraine slimes dam (± 40 years old), the structure is situated on sandy aeolian deposits. A french drain, with intermittent level control pumps, was constructed immediately next to the solution trench of the slimes dam, to intercept any seepage from the slimes dam and pump it back to the adjacent solution trench. The method was effective up to the point where, due to the sludging up of the french drain, as well as surplus run-off water from the slimes dam, due to above average rainfall occurring during the 1988 and 1989 rain season, it apparently failed. Observations suggested that this caused a significant rise in the ground-water level of the adjacent land. Furthermore, during the above period, return water (overflow from Swart Pan) spilled into a system of natural pans, contaminating a large area via surface water run-off. Figure 6.52 shows the extent of pollution in the Loraine slimes dam area. The problem is exacerbated by a shallow dolerite dyke, intersecting a pan receiving mine effluent. The influence of the dolerite in spreading the contaminant is also depicted in Figure 6.52. The problem has, to a certain extent, been addressed by the construction of a storm-water diversion channel, preventing future excess storm-water run-off to enter the disposal facility.

At the Western Holdings slimes dam, on the other hand, contamination by the slimes dam is limited due to the absence of prominent dolerite structures in the area, as well as the low hydraulic conductivities of the surrounding sediments, which are evident in low borehole yields in the vicinity (0,1 l/s). The return water dam (DC 281), however, has an greater impact on the environment. Borehole DC 323 was drilled within 50 m of the dam wall. Depending on the level in the dam, the distance of the waterfront to the borehole differed significantly. Borehole DC 323 was dry when drilled, however, after three months, it had a water level of 4.0 m. Water samples were taken from both the return water dam, as well as the borehole. Figure 7.3 shows the respective results, as well as chemical analyses from boreholes DC 85 and DC 101. The figure suggests that the chemical compositions of both DC 281 and DC 323 display a similar trend, except that the respective ion concentrations in the borehole are significantly higher. This means that although the sediments are relatively impermeable, contaminated water reaches the ground-water zone. Chemical analyses of boreholes DC 85 and DC 101, which are situated roughly 1 km from the complex, represent fairly good quality water, indicating that the low permeabilities of the local sediments contain the spread of the contaminant effectively.

To study possible seepage from the slimes dam into the substrata in more detail, the neutron density readings in conjunction with a water balance, were used. Table 7.1 reflects the results from a water balance of the slimes dam. The average annual available volume of water for this facility is about 130 Ml. Due to the form of the phreatic surface in the slimes dam, one can assume the vertical flux (q), in the slimes dam, to be 1 x 10^{-7} m/s. Thus, potentially large volumes of water are available to infiltrate the substrata. However, the amount of water, as well as the rate of infiltration, depends entirely on the underdrainage of the slimes dam, as well as the hydraulic properties of the underlying sediments. According to Kirchner and Van Tonder (1990), the recharge for Karoo sediments can vary between 1,5 and 3% of the annual rainfall.

TABLE 7.1. A WATER BALANCE FOR THE WESTERN HOLDINGS SLIMES DAM

Months	Evaporation mm	Rainfall mm	Area km^2	E Ml	P Ml	W - D Ml	L Ml
Jan	165,5	93,8	1,7	282	159	148	25
Feb	113,8	71,8	1,7	194	122	133	61

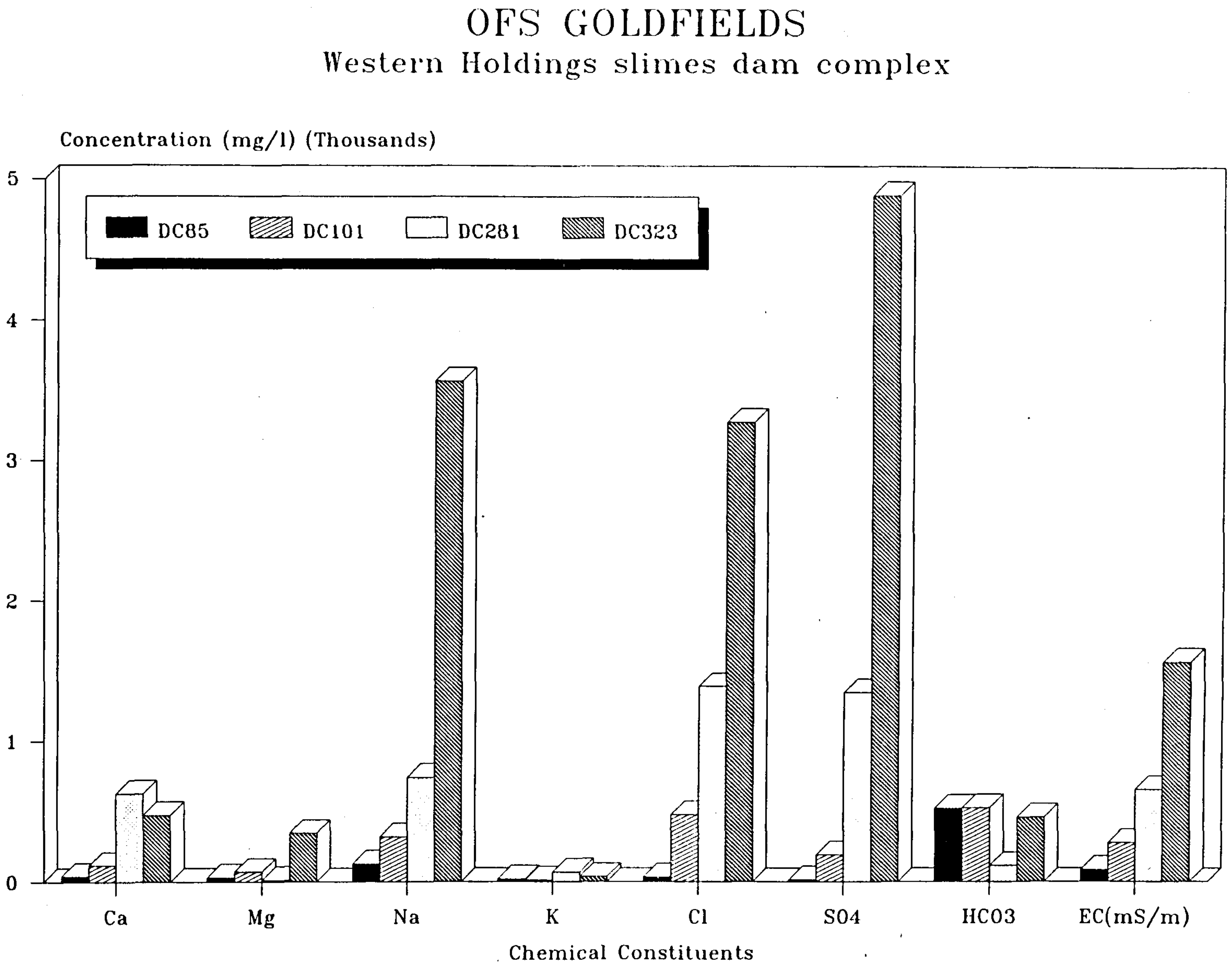


Figure 7.3. Chemical analyses of surface and borehole water at the Western Holdings slimes dam.

March	140,4	74,1	1,7	238	126	138	26
April	103,4	47,2	1,7	175	80	145	50
May	86,2	20,4	1,7	146	35	146	35
June	67,6	7,8	1,7	112	13	137	38
July	71,3	7,9	1,7	121	13	150	42
August	102,8	8,5	1,7	175	14	148	- 13
Sep	130,2	14,6	1,7	221	25	157	- 39
Oct	155,4	47,1	1,7	264	80	162	- 22
Nov	184,3	66,2	1,7	313	113	155	- 45
Dec	172,9	73,7	1,7	294	125	143	- 26
Total	1492,9	533,1		2538	906	1762	130

E - maximum potential evaporation from the slimes dam
P - precipitation on the area
W - water deposited onto slimes dam
D - decant water from slimes dam to the return water dam
L - possible leachate from slimes dam

The Harmony slimes dam complex under discussion is a very young complex. The complex is situated close to the Riet Spruit, which is a tributary of the Sand River (see Figure 6.57). Part of the complex is situated on a shallow dolerite sill, while a dolerite dyke intersects the return water dam. Figure 6.57 shows the extent of the contamination which has taken place up to date. It is seen that the contamination plume extends towards the river and that the dyke controls the spread of the contaminant. As in the case of the Western Holdings complex, the influence of the slimes dam on the ground-water quality seems less than that of the return water facility.

The Beatrix slimes dam complex is situated next to a evaporation area. The evaporation area and part of the slimes dams are situated on a shallow dolerite sill. Figure 6.62 shows the extent of the contamination in the area. However, any potential contamination by the slimes dam is dominated by the effect of the adjacent evaporation areas. Figure 7.4 depicts the chemical analyses of two boreholes at various distances from the slimes dam (BD 73 - 50 m and BD 53 - 250 m). The boreholes did not intercept any dolerite. Their chemical analyses are very similar, indicating that contaminant transport through the sediments is very slow (the age of the Beatrix complex is ± 10 years).

Any slimes dam complex poses a potential pollution hazard, if not sited, constructed and managed according to the best engineering principles. For example, the H.J. Joël Mine, which is situated to the east of the Beatrix Mine, between the Theron Spruit and the Doring River, have developed their evaporation as well as their slimes dam complex across a tributary of the Doring River. Furthermore, the slimes dam complex, as well as the evaporation areas, is situated on a highly jointed and weathered dolerite sill.

Due to the fact that the complex was constructed across a stream, it will collect all the additional run-off water originating from rain storms in the stream's catchment area. The

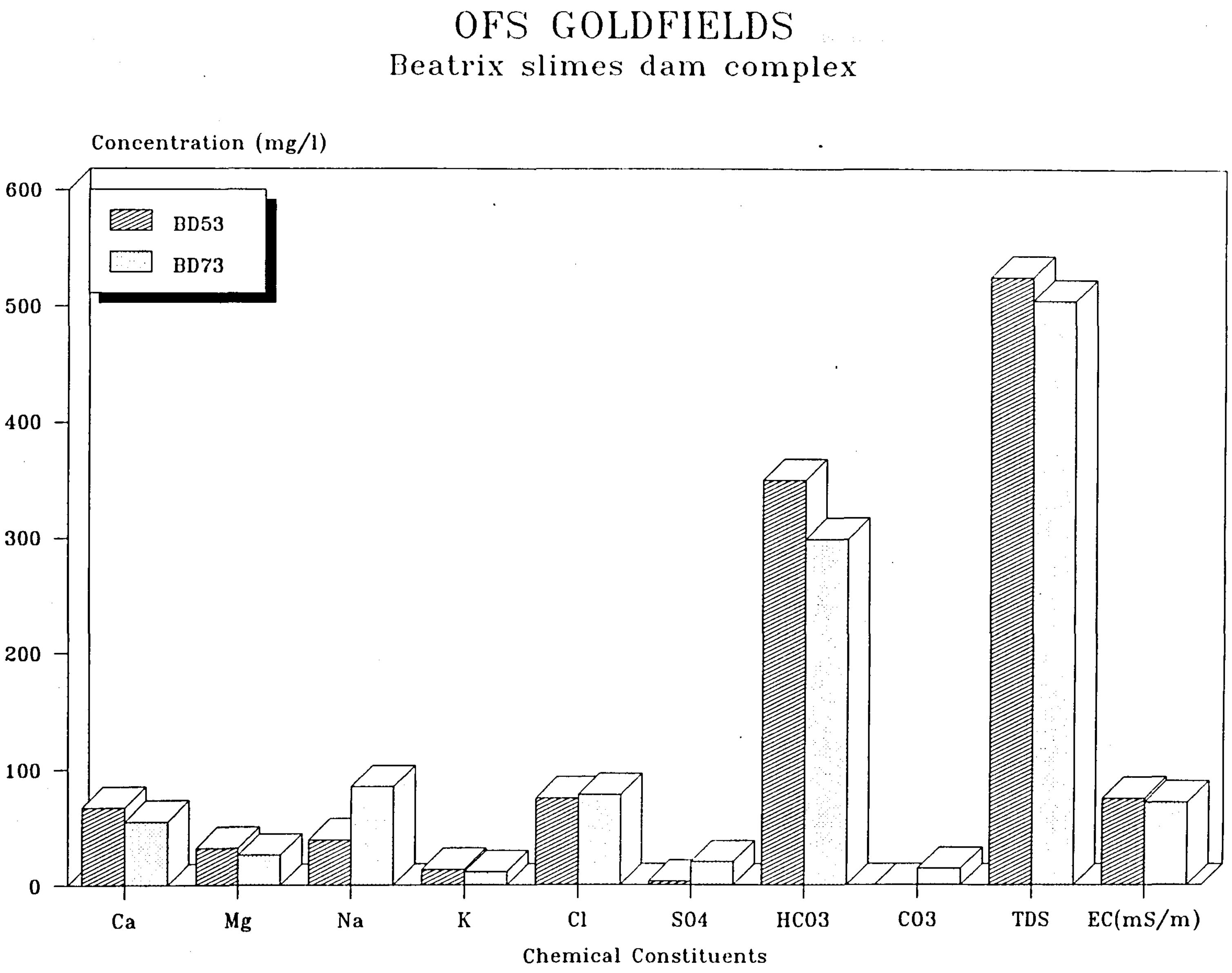


Figure 7.4. Chemical analyses of boreholes BD 53 and BD 73.

catchment area of the stream is small, in the order of 13 km^2. The rational method was used to calculate a flood peak discharge for a one in ten year rainfall event, as well as a one in fifty year rainfall event. Peak flows of 27 m^3/s and 56 m^3/s were obtained respectively. If these peak flows are transformed to volumes of water, minimum volumes of 1,458 x 10^5 m^3 and 2,862 x 10^5 m^3 of water can be expected, for the respective rainfall events. The daily run-off water from the slimes dam, which runs into the return water dam, is on average about 2,80 x 10^3 m^3/d. The capacity of the return water dam is 150 000 m^3. From the above, it is evident that the return water facility cannot cope with a one-in-fifty year flood.

Furthermore, government regulations stipulate water storage capacity requirements on the basis of a balance, which incorporates average monthly rainfall and rainfall of recurrence interval 1 : 100 years of one day duration.

The situation has, however, been addressed by the construction of a storm-water run-off diversion channel. The run-off water is diverted over a watershed to a neighbouring subdrainage system of the Doring River. Thus, in order for the system to be effective in the long term, the diversion channel has to be maintained regularly.

At this stage, the majority of slimes dams in the region do not pose a serious pollution hazard, however, it should be kept in mind that they definitely pose long-term pollution threats. The reason being that three to four per cent of the gold-bearing matrix consists of pyrite, which makes pyrite a minor but important constituent of gold residues, as it constitutes a source of both ferrous iron and sulphate. It is therefore important to maintain and monitor these structures on a regular base, even after the mine has been closed. A monitoring system for these sites, during the operational phase and after closure, can be based on the methodology depicted in the flow charts of Figures 7.1 and 7.2.

7.5.1.3 Evaporation areas

Currently, roughly 51 km^2 of land in the Orange Free State Goldfields is used as evaporation areas, for surplus mine effluent (see Appendix I, Figure I-1). Of the three basic types of mine disposal, this has potentially the largest pollution hazard. The total discharge from all the mines in the region is presently in the order of 155 Ml/d.

To see how much of the water is discharged into the available evaporation areas, a simple water balance ([P + R + W] - [O + B - E]) over the last two years was compiled (see Table 7.2). Table 7.2 indicates that an annual shortage of 2 753 Ml is calculated for the region, basically meaning that more water is lost than what is made. It should be stressed that the change in storage of the respective reservoirs could not be accounted for, as no monthly dam and pan level measurements were available.

TABLE 7.2. TOTAL WATER BALANCE OF THE ORANGE FREE STATE GOLDFIELDS RETURN WATER AND EVAPORATION DAM

Months	Evaporation mm	Rainfall mm	Area km^2	P + R Ml	W Ml	O + B Ml	E Ml	Difference Ml
Jan	165,5	93,8	51	7244	4876	2726	8441	953
Feb	113,8	71,8	51	6335	5808	2738	5804	3601
March	140,4	74,1	51	6826	6376	2769	7160	3273
April	103,4	47,2	51	3283	5635	2851	5273	794
May	86,2	20,4	51	1841	5399	2905	4396	- 61
June	67,6	7,8	51	1275	5453	2934	3448	346
July	71,3	7,9	51	888	5288	3119	3636	- 579
August	102,8	8,5	51	992	4894	3085	5243	- 2442
Sep	130,2	14,6	51	1175	5118	2950	6640	- 3297
Oct	155,4	47,1	51	4349	5316	3119	7925	- 1379
Nov	184,3	66,2	51	4805	5512	3093	9399	- 2175
Dec	172,9	73,7	51	4502	5435	2950	8818	- 1831
Total	1492,9	533,1		43514	65110	35239	76183	- 2797

P - precipitation on the area
R - run-off from external catchments
W - water deposited into the systems
O - water overflow out of the systems
B - water recircled or pumped out of the systems
E - maximum potential evaporation from the systems

Two evaporation areas were monitored in detail:

(i) St. Helena - Wolve- and Riet Pan complexes

(ii) Beatrix - evaporation complex

Figures 7.5 and 6.62 show the extent of the contamination at the respective complexes.

The St. Helena complex is situated in a region where relatively thick sand deposits, as well as palaeodrainage channels occur. Since December 1988, the evaporation area at Wolve Pan, which was initially confined only to the pans, has increased to about 300 ha. The drainage in this region is generally to the south-west, towards the Sand River. Furthermore, the complex is situated on the edge of the Sand-Vet irrigation scheme, extending to the south, south-west and west of the area. Not only is the complex situated unfavourably for the surrounding agricultural activities, due to the underlying geology, but the potential pollution hazard has increased, due to the expansion of the evaporation area, as well as an increase in the hydrological gradient.

As previously mentioned, the Beatrix evaporation complex is situated on a shallow weathered dolerite sill. The sill entirely controls the spread of the contamination in the area.

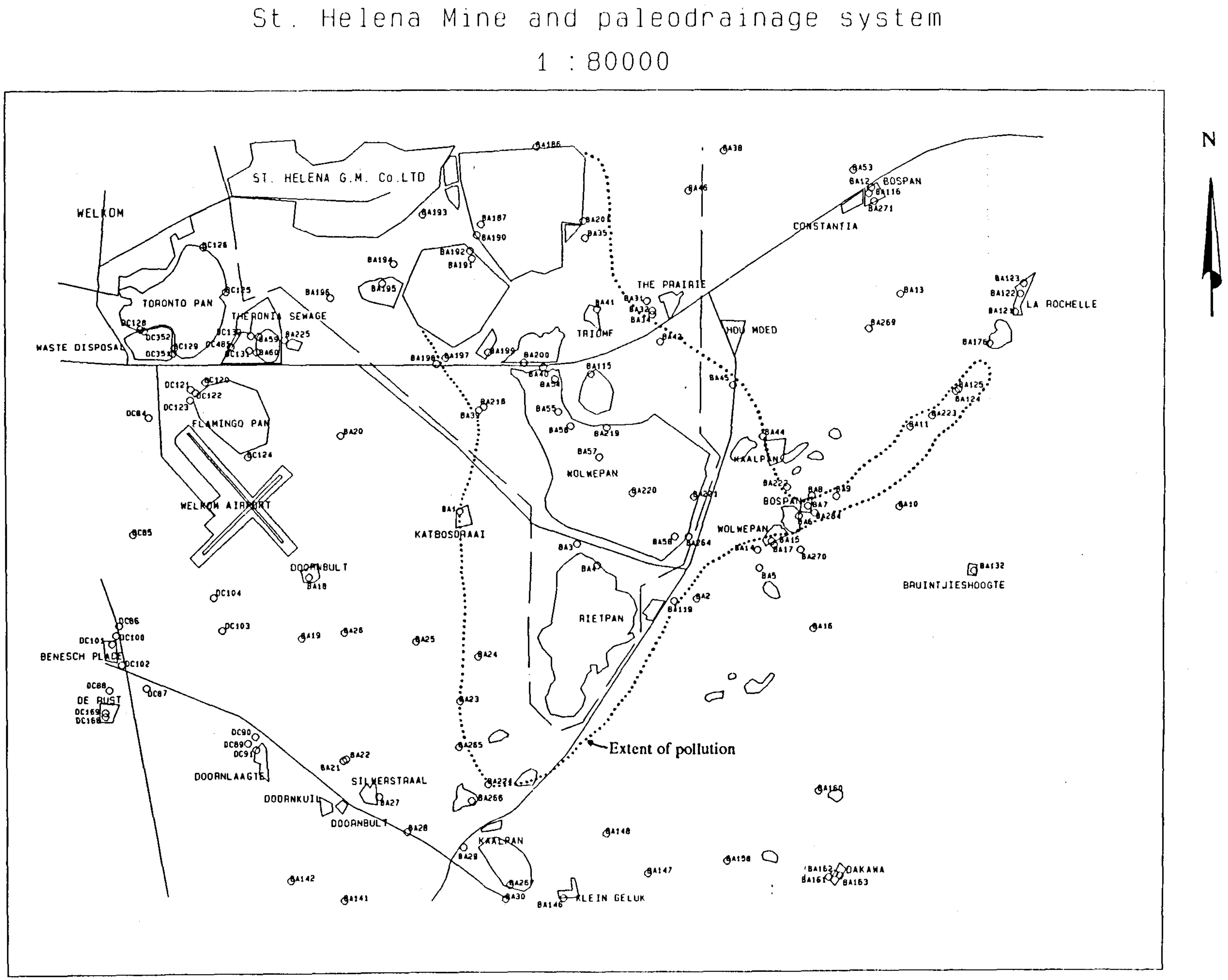


Figure 7.5. St. Helena-, Wolve- and Riet Pan evaporation facility.

Due to damming of water on this shallow structure, a number of springs have been created, directly draining into natural watercourses (such as the Theron Spruit). Even more disturbing is the fact that, at one stage, canals were constructed, spilling the surplus effluent into the Theron Spruit and Doring River. Steps limiting seepage from the evaporation areas, as well as stopping effluent discharge into the Theron Spruit, were taken by the Beatrix Mine.

From the above, it is clearly seen that currently the evaporation areas have the largest pollution potential in the Orange Free State Goldfields. It is furthermore noted that the spread of the contaminant in the ground water is generally controlled by the geological features of the underlying sediments. It is therefore of the utmost importance that proposed sites are thoroughly investigated by geohydrologists and engineers before the construction of the site is approved. Existing sites and newly constructed sites should be monitored on a regular basis to minimize possible contamination.

From the water balance (listed in Table 7.2), it is evident that no new evaporation areas need to be developed throughout the study area. Furthermore, large quantities of the water pumped to the surface (dewatering) by the new mines, can be evaporated in large (old) evaporation areas, situated in the centre of the region. This will not necessary mean the construction of a new pipeline, as such a pipeline already exists, from Beatrix via Oryx, to the central Welkom mines. If, however, additional evaporation areas are needed, natural salt-pans (which are generally classified as effluent pans) can be utilized as evaporation areas, e.g. Dankbaar Pan and Doring Pan which are used by several mines in the area to discharge their effluent water.

Blending of water is not an option, due to the existence of toxic organic and inorganic constituents in these effluents, as well as the fact that such a solution would be in violation of the DWA approach to effluent control.

7.5.2 MUNICIPAL WASTE

Of the four municipalities situated in the study area, only three (Welkom, Virginia and Odendaalsrus) can pose a significant pollution threat towards the environment. However, as discussed in Chapter 6.4.4, large volumes of especially the liquid effluent are re-utilized after treatment.

7.5.2.1 Urban solid waste

Three major sites are situated in the area (see Figure 6.20), of which two are located in natural pans (Welkom and Odendaalsrus), while the remaining site (Virginia) is located on the bank of the Sand River. Samples of the respective pans and river, adjacent to the sites, were taken and chemically analysed. No significant contamination was observed in all three cases. Due to the new legislation concerning solid waste sites, both sites located in the pans have to be closed down. It is thus important, when selecting new solid waste sites, that they are not situated near any surface water structures.

7.5.2.2 Urban liquid waste

A total of 75 Ml/d of sewage effluent is produced by the municipalities and mines throughout the area. Fairly high PO_4^- and NO_3^- values were occasionally measured in this sewage effluent. Fortunately, large volumes of purified sewage are used by the respective municipalities, as well as mines throughout the area. It is, however, suggested that the 1 mg/l PO_4^--standard is again applied to this area, as excessive algae growth is observed in some of the natural pans and streams.

7.5.2.3 Industrial effluent

At this stage, only one factory discharges a significant quantity of effluent (195 m^3/d). This effluent is discharged over an open area (see Figure 6.22), which drains into a system of vleis and pans and resulted in the killing of fish and birds. The effluent can easily be confined to a specific area by means of a dam wall, as well as a cut-off trench around the site. Another option, in this case, might be to install suitable aerobic digestors which reduce the level of contaminants, such that the effluent can be discharged through sewage purification works.

The municipal wastes do not currently pose a major pollution threat to the environment. However, as the municipalities expand, the situation may change and the pollution hazard can increase significantly.

To conclude, it must be stressed that future site selection must include a detailed geohydrological investigation, supervised by a qualified geohydrologist. Furthermore, future site selections should include a risk assessment of environmental effects and risks associated with waste management. According to Steffen, Robertson & Kirsten (1989), the principles of risk assessment can be summarized as follows:

- In analysing risk, the attempt is made to predict how the future will turn out if a certain course of action/inaction was undertaken, i.e. answering the following three questions:
  (i) What can happen? (i.e. what can go wrong?)
  (ii) How likely is it that that will happen?
  (iii) If it does happen, what are the consequences?

In 1987, Van Zyl developed risk assessment around four general steps:

(i) Hazard identification and assessment.

(ii) Exposure assessment.

(iii) Consequence or dose-response assessment.

(iv) Risk characterization.

This approach can also be applied to existing sites, especially sites which are being closed down, where such an assessment can shed some light on the future potential pollution hazard of the specific site.

Another way of assessing a future or existing site, is by means of a numerical site rating. Le Grand (1980) designed a standardized system for evaluating waste disposal sites, with special reference to ground-water contamination problems. The system is divided into 10 steps within four stages:

- Stage 1 provides a standard hydrogeological description of the site.
- Stage 2 indicates the degree of seriousness of the hazard potential, by identifying the degree of aquifer sensitivity and the degree of contaminant severity.
- Stage 3 describes the relative probability of contamination by comparing the site's numerical value with a standard value that is derived from an integration of aquifer sensitivity and contaminant severity.
- Stage 4 assesses the site, with consideration given to engineering modifications.

Figure 7.6 schematically illustrates the procedures taken in integrating site and contaminant characteristics into situations that can be compared in a standard way and graded for regulatory decisions. This system was designed for and is used by the U.S. Environmental Protection Agency.

Quite a number of the current problem areas could have been confined to a much smaller scale, had the site selection been more thorough.

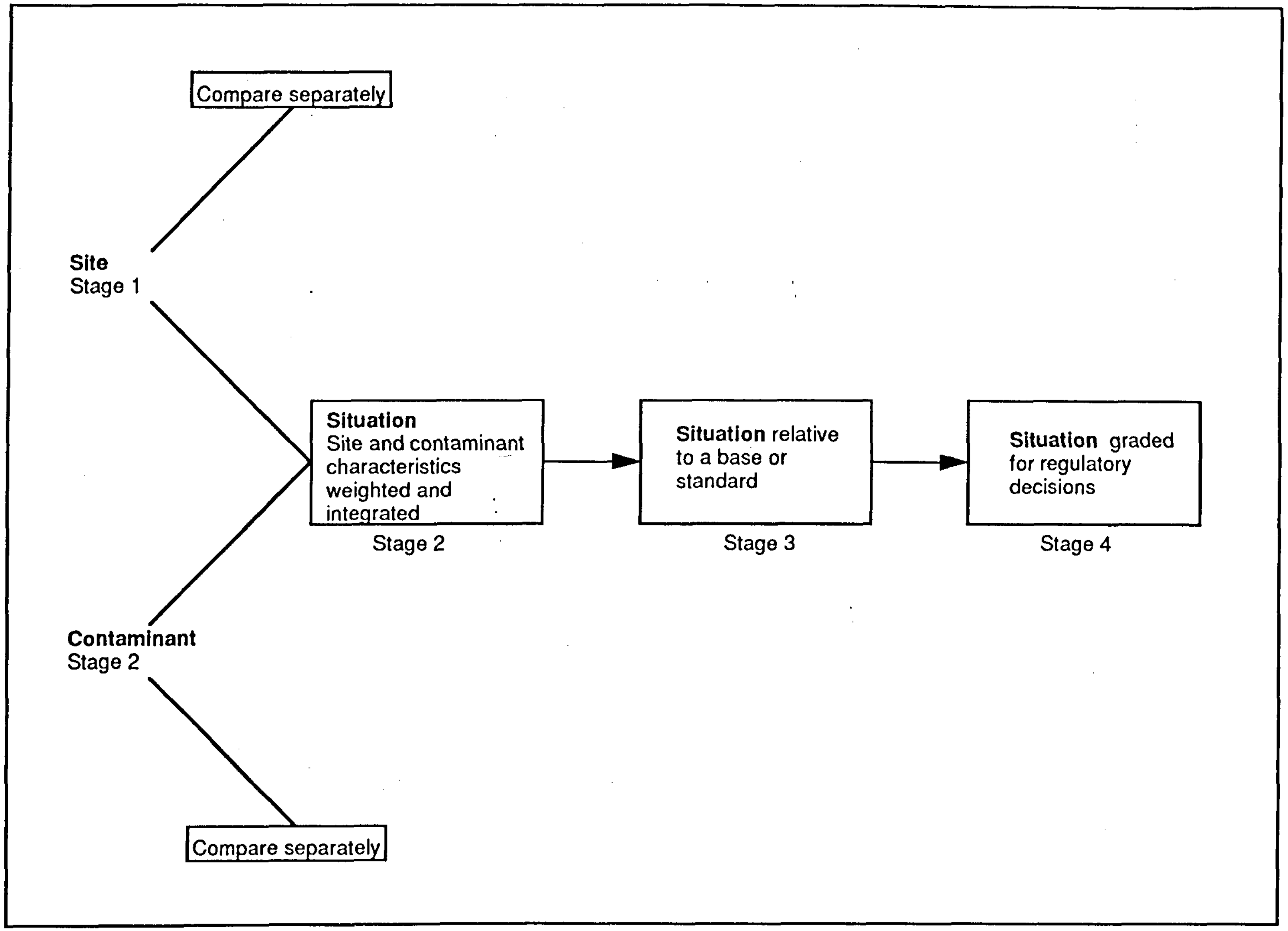


Figure 7.6. Flow chart schematically showing the integration of site and contaminant characteristics into situations, which represent entities that can be uniformly evaluated and graded (after LeGrand, 1980).

7.6 AGRICULTURE

Due to the fact that very little research regarding agricultural contaminants was done during the three-year project, it is difficult to suggest management options limiting potential pollution from agricultural sources.

Feeding-pens should not be located in close proximity of existing potable productive ground-water resources, especially in regions where the ground-water levels are shallow. If the depth to the ground-water table is large, most biological pollutants originating from the feeding-pens, are removed in the vadose zone before reaching the ground water. Furthermore, run-off from rainfall should be diverted around such a structure, limiting the water which can come into contact with the animal wastes.

Soil erosion by wind or water is an important mechanism, spreading pollutants from agricultural sources. By applying the correct ploughing, tilling and moisture conservation techniques, wind erosion can effectively be limited. If cultivated farm-land is situated on a sloping topography, ploughing and contouring techniques must be applied to limit run-off from rainfall, hence minimizing soil erosion.

A number of agricultural pollution sources, such as fertilizers and pesticides, which were not researched during the course of this study, will have to be addressed in the near future to determine their impact on the water quality of the region.

7.7 LEGISLATION AND AGREEMENTS

In the case of the Orange Free State Goldfields, a large portion of all the waste is produced by the gold-mining industry. In the light of the above fact, it is necessary to take a brief look at the current legislation concerning pollution arising from the gold-mining industry. In order to be sure that the management of existing and future disposal sites are effective as well as efficient, legislation must exist to be adhered by.

During a short course on acid mine drainage in October 1990, Van der Merwe, Director of the Directorate Water Pollution Control, DWA, summarized the relevant legislation as follows:

"Through the Water Act, 1956, legislators for the first time addressed the problem of water pollution arising from the activities of the mining industry. This legislation came into effect on promulgation of the Act, on 13 July 1956.

Before the amendment to the Act in 1984, legislation controlling pollution from abandoned mining operations was embodied in sections 21(6) and 23(2) of the Act. Talks between the Chamber of Mines and the Minister of Water Affairs during 1975 concerning the responsibility of its members with regard to mines which abandoned operations before promulgation of the Act in 1956, resulted in mutual agreement on 19 January 1976, as follows:

(1) Pollution control measures, the maintenance of such measures and all costs pertaining thereto, in respect of mines or works operations abandoned prior to 13 July 1956, will be the responsibility of the State.

(2) In respect of mines or works which abandoned operations after 13 July 1956, the company, at closure of operations, will be required to provide pollution control measures to the satisfaction of the State. The State will thereafter take responsibility for the maintenance and the betterment of pollution control measures taken.

(3) Should mining or works operations, at any stage, be resumed at a mine, previously abandoned, then the company resuming such operations will be responsible for any existing pollution control measures on the portion which is being reworked and for any additional pollution control measures which are required in respect of the resumed operations.

With publication of the Water Amendment Act, 1984, the previous sections 21 and 23 referred to above, were repealed and replaced by section 22 of the amended Act.

The implications of the new section 22 are that any person who has control over land is responsible for pollution control measures to prevent water pollution on or from such land. Problems are being experienced in respect of now non-existent mining companies which abandoned operations, without providing pollution control measures in the period following 13 July 1956 and prior to the agreement with the Chamber of Mines on 19 January 1976. As stated, these companies no longer exist and control over the land has passed to other parties.

To address this problem and to honour the past agreement with the mining sector in the implementation of section 22 of the Act, Ministerial approval was given on 11 August 1986 for exemptions to be issued in terms of section 22(2)(a) of the Act to the following categories of persons and bodies:

(1) In respect of mines or works which abandoned operations prior to the promulgations of the Water Act on 13 July 1956. In this case, the State will assume

responsibility for the provision and maintenance of pollution control measures, exempting any persons or bodies in this regard, who are at present in control of the land.

(2) In respect of mines or works which abandoned operations and the companies of which disbanded in the period following 13 July 1956 and before 19 January 1976. In cases such as these, the State will assume responsibility for the provision and maintenance of pollution control measures, exempting any persons or bodies in this regard, who are at present in control of the land.

(3) In respect of mines or works, conducted by companies which still exist and which abandoned operations in the period following 13 July 1956 and before 19 January 1976. In this case, no exemption will be given in respect of the provision of pollution control measures. Provision of these measures to the satisfaction of the State, will remain the responsibility of the persons concerned. If necessary, the State will carry out these pollution control measures and recover the expenditure involved in part or wholly, as the case may be, from the persons concerned. The State will thereafter assume responsiblity for the maintenance and improvement of the pollution control measures provided, exempting such persons in this regard.

(4) In respect of mines or works which abandoned operations after 19 January 1976. In this case, no exemption will be given with respect to the provision of pollution control measures. Provision of these measures to the satisfaction of the State will remain the responsibility of the persons concerned. If necessary, the State will carry out these pollution control measures and recover the expenditure involved in part or wholly, as the case may be, from the persons concerned. The State will thereafter assume responsibility for the maintenance and improvement of pollution control measures provided, exempting such persons in this regard."

In the case of the Orange Free State Goldfields, all the mines are currently still active, meaning that the mines in the region have to adhere to paragraph (4) of section 22(2)(a) of the Act.

A complete summary of the Water Act, Mines and Works Act, Health Act and Environmental Conservation Act is listed in Appendix II.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The potential pollution threat in the Orange Free State Goldfields seems to be quite considerable, due to the abundance of pollution sources like sewage plants, solid waste dumps, slimes dams, evaporation dams, return water dams and industrial effluent waste sites. Every one of these sources contains or generates substances that can be harmful to the environment, but the depositional environment of these pollution sources plays a vital role in the releasing of any pollution to the environment. The geological formations occurring in the area appear to effectively limit the spread of ground-water pollution, except where dolerite dykes and sills occur.

It seems that present legislation, when applied accordingly, is relatively effective in limiting water pollution. One of the major shortcomings of the present legislation is that concerning the pollution of ground water. Compulsory ground-water monitoring systems at all waste disposal sites can play a vital role in the protection of our ground-water resources.

By using the method of Dyer, the rainfall in the area was evaluated and certain tendencies observed. Definite rainfall patterns seem to occur in the Orange Free State Goldfields and wet and dry cycles were identified. These cycles seem to vary in length between 8 and 11 years. It seems that a wet cycle is presently occurring and that above average rainfall can therefore be expected for the next few years. The contents of the storage areas for excess water would, therefore, rather increase than decrease with the resultant increase in the possible pollution hazard.

The distribution of pans is mainly confined towards the western and north-western parts of the study area and seems to be geologically controlled, as most of the pans tend to occur in the softer Ecca sediments. There seems to be a close relation between the occurrence of pans and palaeodrainage and this relation was confirmed during the drilling phase when river sand and gravel were encountered in the boreholes that are situated on postulated palaeodrainage systems. The actual existence of these palaeodrainage systems is something of concern, as one of the mines' evaporation areas is situated in close proximity of such a system, posing a pollution hazard dependent on the size and extent of the particular palaeodrainage system. However, the extent and the occurrence of these systems is yet to be determined.

The borehole survey revealed that ground waters in the vicinity of pollution sources, as well as those far away, have high conductivities, mainly to the west of Odendaalsrus. To investigate this phenomenon and to determine the possible pollution potential of each source, 52 boreholes were drilled in the various target areas. During the drilling phase, it was observed that due to the relative impermeability of the Karoo sediments, fracturing of the sediments is essential for a constant water supply. Dolerite intrusions are, therefore, essential to improve the regional ground-water yield of the Karoo sediments. This is true, especially for the Ecca sediments, consisting mainly of shale. On average, the borehole yields in the Beaufort sediments tend to be about three times higher than those in the Ecca sediments and the yields are therefore, to a certain extent, geologically controlled. The higher yield in the Beaufort sediments can mainly be ascribed to the relative abundance of sandstone which has a specific yield three times that of shale and the occurrence of joints in the sediments.

Whereas the borehole yields seem to be geologically controlled, the ground-water movement seems to be topographically controlled. In the central and southern parts of the region, the general direction of ground-water movement is towards the Sand River. The western and north-western parts of the area depict localized ground-water movement, due to the flatness as well as the lack of well-developed drainage in the area. Looking at the ground-water gradients on a regional scale, ground water in the region mainly flows from east to west, coinciding with the regional surface drainage.

Due to the great volume of water present in the Witwatersrand rocks, large quantities of water are pumped from the mines to make them accessible for mining activities. To examine future dewatering, pumpage and salts to be disposed of, a computer model is required. By using a mathematical simulation model, the dewatering of the deep ground-water aquifer was simulated. The simulated water levels correlate fairly well with the few known water levels. The simulation revealed that during the past 37 years, 1239 million cubic metres of water was pumped to the surface, exposing the environment to 3,717 million tonnes of salt. For the next 20 years, the figures will be 2218 million cubic metres of water and 6,7 million tonnes of salt, providing that the mines maintain their present pumping rates and the establishment of new mines in the area continues. The simulation also shows that the large-scale pumping over the last 37 years did not have a significant effect on the deep ground-water table, as the cone of depression is limited to a small area surrounding the mining activities. Thus, when a new mine is established on the outskirts of the Goldfields, pumping water from underground will be unavoidable, increasing the potential pollution threat.

The huge quantities of unpotable water disposed on the surface in the Orange Free State Goldfields cause pollution to both the ground water and the surrounding environment. At present, approximately 155 Ml/d of water is pumped to the surface and is stored in reservoirs in the area. The water either evaporates or infiltrates into the ground. The quality of the above-mentioned water is very poor (mainly NaCl-water).

As the Sand River flows through Virginia, the water quality deteriorates as a result of various pollution sources, of which the Sand River canal seems to be the major source. Throughout the whole study period, this canal flowed continuously, even during dry periods. This is mainly due to overflow and seepage from evaporation dams on mine property. The water in the canal is of a very poor quality, with electrical conductivities ranging from 550 to 1200 mS/m. A salt load of 1194 t/d was calculated for the Sand River at the Bloudrif Bridge. As the Sand River finally flows into the Bloemhof Dam, this practice should not continue.

During the research, it was observed on various occasions that excess effluent water was disposed into streams, and natural vlei systems, other than the Sand River canal. Although it did not occur on a continuous base, it did contribute quite significantly to the increasing salt load of the surface- and ground water in the area. It should, however, be mentioned that proper measures have been taken by the respective mines, to prevent future spills of excess effluent water.

As in the case of the borehole yields and the distribution of pans, the natural ground-water quality in the Goldfields also seems to be geologically controlled. The ground-water quality in the Ecca sediments seems to be generally of a poorer quality than the ground water found in the Beaufort sediments, which can be ascribed to the mixing of connate water of marine origin, explaining the high salinity in the ground water from the Ecca Group.

If one evaluates the hydrochemistry of the region, it is observed that by virtue of its size a large portion of all the potential pollution sources is generated by the gold-mining activities in the area. Mining wastes, if not properly managed, can be detrimental to the environment, due to large volumes of effluent water with high concentrations of Na^+, Cl^-, SO_4^{2-}, Ca^{2+} and, to a lesser extent, heavy metals, CN^- and other organic constituents used in the gold extraction process.

One of the major problems encountered during this investigation was to distinguish between ground water with a natural poor quality and ground water that is polluted, due to mining and other activities. This problem arose when ground water with high conductivities was sampled to the west and north-west of the study area, far away from any pollution sources. By evaluating all the ground water with high conductivities on hydrochemical diagrams, as well as specific ionic ratios (Ca/Cl, Na/Cl and Ca/Na), two groups of ground water appeared, i.e. water with a natural poor quality and ground water polluted due to mining activities.

Due to the presence of surface effluent water with a predominant NaCl-character, reverse ionic exchange seems to take place in the vicinity of mine disposal sites. The effect of reverse ionic exchange is that the ground water seems to become enriched with calcium.

In the central, north and north-western parts of the area, mining has been on-going for more than 40 years, in some instances. Due to the fact that the disposal sites in these areas are mainly located on Ecca sediments which have low permeabilities, as well as the fact that the area is very flat, it can be assumed that pollution has reached a quasi steady state situation (within four to six kilometres (downstream) from the pollution sources). This means that although pollution might still occur, it cannot clearly be defined, due to dilution and the hydrochemical background of the particular area. In the southern parts of the area, most of the disposal sites are situated on Beaufort sediments which are more permeable than the Ecca sediments. Combining this with the fact that drainage in this part of the study area is reasonably well-developed towards the Sand River, one can say that the respective contaminants are still actively dispersing. However, the contamination levels are not as high as in the northern parts and the contaminants are generally located closer to the respective disposal sites (within 1 km), except in the case where shallow-lying geological structures control the spread of the pollution.

If specific target areas are looked at in more detail, it is observed that Cl^- has spread to a greater extent than any of the other relevant ions, due to its inherent characteristics as a conservative tracer. The spread of Cl^--contamination can therefore be used as a measure to estimate conservatively the maximum spread of the pollution. Heavy metals seem only to have elevated concentrations in close proximity of pollution sources, especially slimes dams which tend to generate acid mine drainage. If the spread of the pollution at specific disposal sites is correlated with the local ground-water gradients, it is noted that the spread of the pollution closely follows the direction of the ground-water gradients.

At a distance of 1 km (regional upstream ground-water gradient) from the pollution sources, the overwhelming majority of the ground water seems to be of a reasonable quality. The distance of 3 km that Hodgson (1987) specified at which the ground water seems to be unpolluted, proved to be valid for most cases. It should be stressed that ground-water gradients play an important part in the spread of contaminants. Generally, as the distance from the pollution source increases, the water quality seems to improve.

The contour maps of the macro elements in the ground water show that the high concentrations coincide with disposal sites. This clearly indicates the influence of the mining activities on the ground water in the vicinity of the disposal sites.

The spread of pollution in both surface and subsurface water resources was helped on by sporadic spills of effluent water into natural surface water systems, e.g. the Mahem Spruit which is polluted up to Gans Pan, near Wesselsbron.

Quantifying the contribution of the respective pollution sources is almost impossible, as this would definitely entail development of a mass transport model of the entire study area. Insufficient data exist to prepare such a model. Furthermore, such a model would be too large for the existing computing facilities. This problem can partially be overcome by constructing numerous smaller models, representing different situations in the study area. This, however, would be very time-consuming. Furthermore, almost no historical record of geohydrological and hydrochemical data of the region exist, making calibration and verification of the respective models impossible.

In the past, many of the disposal facilities were sited without proper investigations of factors such as:

(i) Geological environment.
(ii) Hydrology.
(iii) Geohydrology.
(iv) Monitoring.

Quite a number of the current problem areas could have been confined to a much smaller scale, had the site selection been more thorough. Future site selections should include all the above-mentioned aspects, as well as a risk assessment of environmental effects and risks associated with waste management.

Currently, the evaporation areas pose the largest pollution threat, due to the large quantities of unpotable water which are stored in them. It was found that enough evaporation areas existed in the study area. However, if additional evaporation surfaces are needed, natural salt-pans can be utilized more extensively due to their effluent characteristics. In the long term, however, slimes dams, if not managed according to best engineering and environmental principles, constantly pose a potential pollution threat and have to be maintained and monitored on a regular base to minimize their acid generation capabilities.

The primary aims of the research project were to:

(i) Determine the source of possible pollutants to the ground-water regime.

All the possible pollution sources throughout the study area were located, sampled and evaluated. Due to the fact that a large number of the pollution sources are duplicated throughout the area, specific target areas were selected and studied in detail. Very little research was done on possible agricultural pollution sources.

(ii) Quantify the contribution of the different sources.

Quantification of contaminant loads to which the environment was exposed, was done only to a very limited extent, in that the total salt load of the deep aquifer water, discharged by all the mines in the region, was estimated by means of a finite element model. However, to quantify the contribution of different organo-chemical species is virtually impossible, primarily due to the lack of relevant historical data for a representative water balance or mass transport model.

(iii) Study the migration rate of pollutants through the aquifers.

The spread of any contaminant is closely correlated with the migration rate of the relevant contaminant. The study of the migration rate of different pollutants in the Orange Free State Goldfields was limited to the target areas, as well as to the more important anions and cations (Ca^{2+}, Na^{+}, Cl^{-}, SO_4^{2-}) and some of the heavy metals. As in the case of the quantification of contaminants, the study of the migration rates could have been done in more detail by a multi-solute transport model with sorption, ion exchange and equilibrium chemistry. This was not done due to the lack of historical data.

(iv) Model local and regional movement of pollutants through the aquifer and predict future water qualities.

Bearing the above-mentioned in mind, no mass transport models were constructed, to predict future water qualities throughout the region, on either a local or regional scale.

(v) Determine chemical alterations to the pollutants while on surface and in the aquifer.

Infiltration of polluted effluent water into the ground-water regime will involve chemical alterations. Chemical alteration mechanisms were identified and discussed in some detail, especially in the case of the different target areas. No attention was devoted to the alteration of organic compounds, used by either the agricultural or mining sectors.

(vi) Enter information into the ground-water data base.

During the course of the research project, a ground- and surface water data base for the Orange Free State Goldfields data was created on HydroCom and was constantly updated as new information was generated and collected.

(vii) Suggest management strategies whereby the influence of disposal can be minimized.

Suggesting management options/strategies whereby the influence of waste disposal sites can be minimized was an important aim of the research project. This aspect is covered in detail by the report and should help mining companies, municipalities and industries in the location and development of future waste disposal sites, as well as in the maintenance of existing disposal facilities. The management options should also be incorporated in the waste management strategy of the Department of Water Affairs, especially relating to ground-water resources.

Although not all the initial aims of the research project were fully achieved during the course of the project, sufficient information was gathered and evaluated to suggest meaningful management options. Furthermore, suggested aims and objectives of the research project were met to such an extent that future monitoring and waste management can effectively be applied throughout the entire area, mainly due to a well-established data base, which has to be constantly maintained and updated. Future monitoring and management of all waste disposal sites in the study area should be co-ordinated by the DWA.

Finally, a number of the more important conclusions are summarized and listed below:

- Contamination of surface and subsurface water resources by municipal, industrial and mining activities, throughout the area, has taken place in the past and is currently still taking place. This is, however, at a significantly reduced scale, due to the preventive actions taken by the responsible organizations.

- Contamination of ground-water resources is generally contained within close proximity of the disposal site, depending on the age of the site, as well as the local ground-water gradients in the vicinity of the site. Thus, although the pollution risk in the Orange Free State Goldfields is relatively large due to the abundance of pollution sources, the vulnerability of ground-water resources in this region is relatively small, due to favourable geological conditions.

- The Karoo sediments (Ecca/Beaufort) in the study area are relatively impermeable, limiting the spread of possible pollution within the close proximity of the disposal facility. However, in the case where shallow dolerite structures intersected disposal facilities, the spread and extent of the pollution were almost entirely controlled by the size and extent of the dolerite structures.

- Spillages of effluent water into natural river and vlei systems, spread the contaminants over relatively large distances.
- Of all the waste disposal structures, evaporation pans and dams currently pose a large pollution potential. Currently, the spread of the pollution around the slimes dams appears to be limited. However, unless these structures are vegetated and managed according to sound environmental and engineering principles, they will pose a long-term pollution threat.
- No new evaporation areas need to be developed in the area. Large volumes of water pumped to the surface (dewatering) by the younger mines, can be evaporated in some of the older, under-utilized evaporation facilities, situated in the centre of the region. This will not necessarily mean the construction of a new pipeline, as such a pipeline already exists. If, however, additional evaporation areas are needed, natural salt-pans can be utilized as evaporation areas.
- Excessive algae growth is observed in some of the natural pans and streams. It is thus suggested that the 1 mg/l PO_4^--standard is applied to especially municipal effluents in the study area.
- Detailed geohydrological investigations, as well as a risk assessment of environmental effects and risks associated with the waste management of each future waste disposal site, will have to be done.

The cooperation of all the concerned organizations throughout the whole duration of the research project was very good, especially in the case of the mining companies. As problem situations were identified to them, they, in almost all cases, initiated remedial actions curbing the situation.

8.2 RECOMMENDATIONS

As the mining and industrial activities in South Africa increased from the turn of the century, so did the contamination of surface- and subsurface water resources. In future, managing water resources will largely involve the prevention of pollution of the limited water resources in Southern Africa. Preventive measures should include identification and control of polluted run-off from urban, industrial and mining areas. Such measures can include the following:

8.2.1 MANAGEMENT

- Better planning for example, before establishment of a mine, is required to prevent possible pollution from e.g. evaporation areas, situated on a shallow dolerite sill, as well as where large quantities of water are disposed on unconsolidated deposits. Prevention of situations, like these, can reduce the pollution hazard considerably.

- Better water budgeting at mines, e.g. in dry periods, the mines use all their excess water, but during wet periods rain water can cause problems as is presently experienced. This can be avoided, if better planning is done by the mines, for example, to budget for more storage capacity (e.g. utilize natural salt-pans) or to cut down on other water sources during periods of high rainfall, while old and new mines can also share evaporation facilities, due to an interconnecting pipeline.

- Implementation of present legislation concerning ground-water pollution has proven to be difficult. A complicating factor is the fact that water resources in South Africa are divided legally into public and private water. Ground water is generally classified as private water, whereas almost all surface waters are public water. However, ground water and surface water are hydrologically connected, thus making it difficult to separate them legally. This complicates the management of ground-water resources in South Africa. Thus, more effective legislation should be promulgated. Such legislation has to include compulsory monitoring of waste disposal sites and a detailed geohydrological investigation to prevent the establishment of any disposal site on unsuitable geohydrological structures.

- The current legislation concerning mine, municipal and industrial effluent seems to be sufficient. If the current application of legislation is performed in conjunction with the "Receiving Water Quality Management Objective" approach of the DWA and the current monitoring program is continuously revised and maintained, future potential pollution can be minimized.

During the research, quite an extensive data base was created. This data should be available to the DWA for future monitoring of the region. The monitoring program must include all the respective disposal facilities in the area. Special attention should be given to a monitoring program on the Sand River and its tributaries. The rivers should be monitored on a regular base to determine the salt load that is finally flowing into the Bloemhof Dam.

This monitoring program should also include boreholes to determine the variation of water quality with time, as well as water-level variations throughout the area.

Currently, the evaporation areas pose the largest pollution potential in the study area, due to the large quantities of unpotable water which are stored daily in them. In the event of closing any of the older mines in the region, this surplus water can be stored in such a mine. Precautions, however, have to be taken to seal off the old mine workings, such that the danger of flooding neighbouring active mines is minimized.

8.2.2 RESEARCH

A number of pollution sources, especially agricultural sources, such as:

(i) fertilizers and
(ii) pesticides (herbicides and insecticides).

have not been studied in any detail during the course of the project. It is suggested that such research is conducted in the near future, hence estimating the impact on the environment by the agricultural sector.

Insufficient historical data have prevented the research team from quantifying the contribution of the different pollutant sources. The investigations which have been done up-to-date, can be regarded as a firm basis for the development of a solute transport model, which can be used to quantify the contribution as well as predict future water qualities in the region.

A matter of concern is the existence of palaeodrainage channels in the central-western parts of the region. This particular area forms part of the Sand River Irrigation Scheme. The regional ground-water gradient is from east to west. Large evaporation areas are situated in close proximity of such a palaeodrainage system. For future waste management to be effective, these structures have to be identified and investigated in detail, in order to determine their influence on the spread of pollution. Such an investigation would necessarily involve a detailed geophysical and drilling program.

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APPENDIX I

In this Appendix, the possible pollution sources in the Orange Free State Goldfields are identified. Their composition, as well as the possible pollution they may cause, is discussed. The relative positions of the different sources are given in Figure I-1.

I-1 MINING WASTE DISPOSAL

Of particular importance in this region, is the gold mining industry. Due to the nature of this industry, it has vast quantities of residue, which have to be disposed of. The bulk of the residue will, however, always be disposed of on the surface, posing an immediate pollution threat to the surrounding area.

The residues mainly consist of:

(i) residues,

(ii) excess mine- and plant water, and

(iii) waste rock,

and are usually disposed of in surface structures such as:

(i) slimes dams (residue dams),

(ii) return water dams,

(iii) evaporation areas, and

(iv) rock dumps.

The nature and pollution hazard of each of the above structures will be discussed subsequently.

I-1.1 SLIMES DAMS

The residues contained in slimes dams (also referred to as residue dams) consist essentially of slime from the gold- and/or uranium extraction processes. The grain size of this slime is between 65 and 80% minus 75 μm and the gold values vary between 0,1 and 0,5 g/t (Stanley, 1987). Figure I-2 illustrates a typical layout of a slimes dam.

It will be useful to list the components of a slimes dam and briefly describe their purpose. According to Stanley (1987), the different components are:

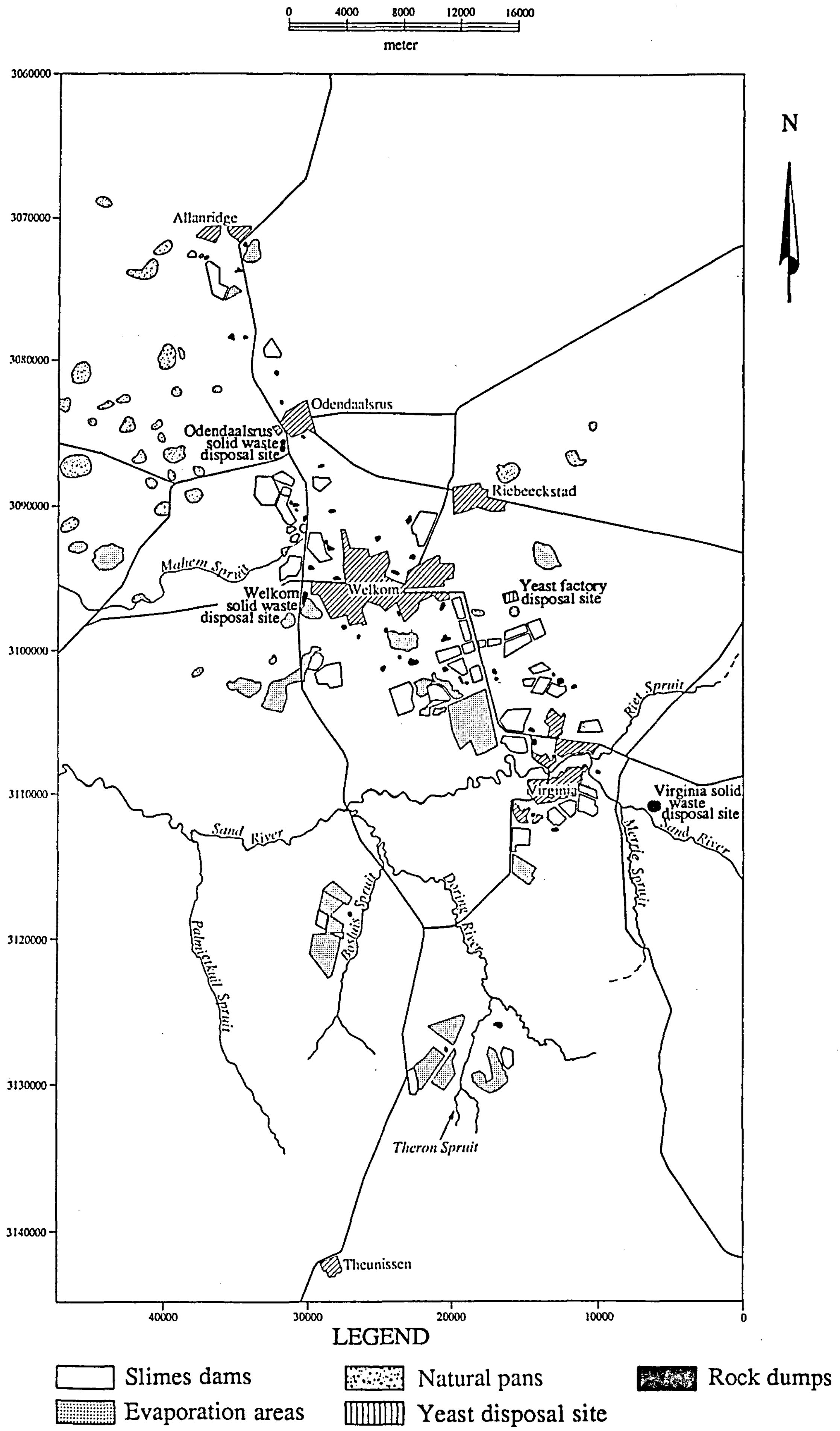


Figure I-1. Localities of the possible pollution sources in the Orange Free State Goldfields.

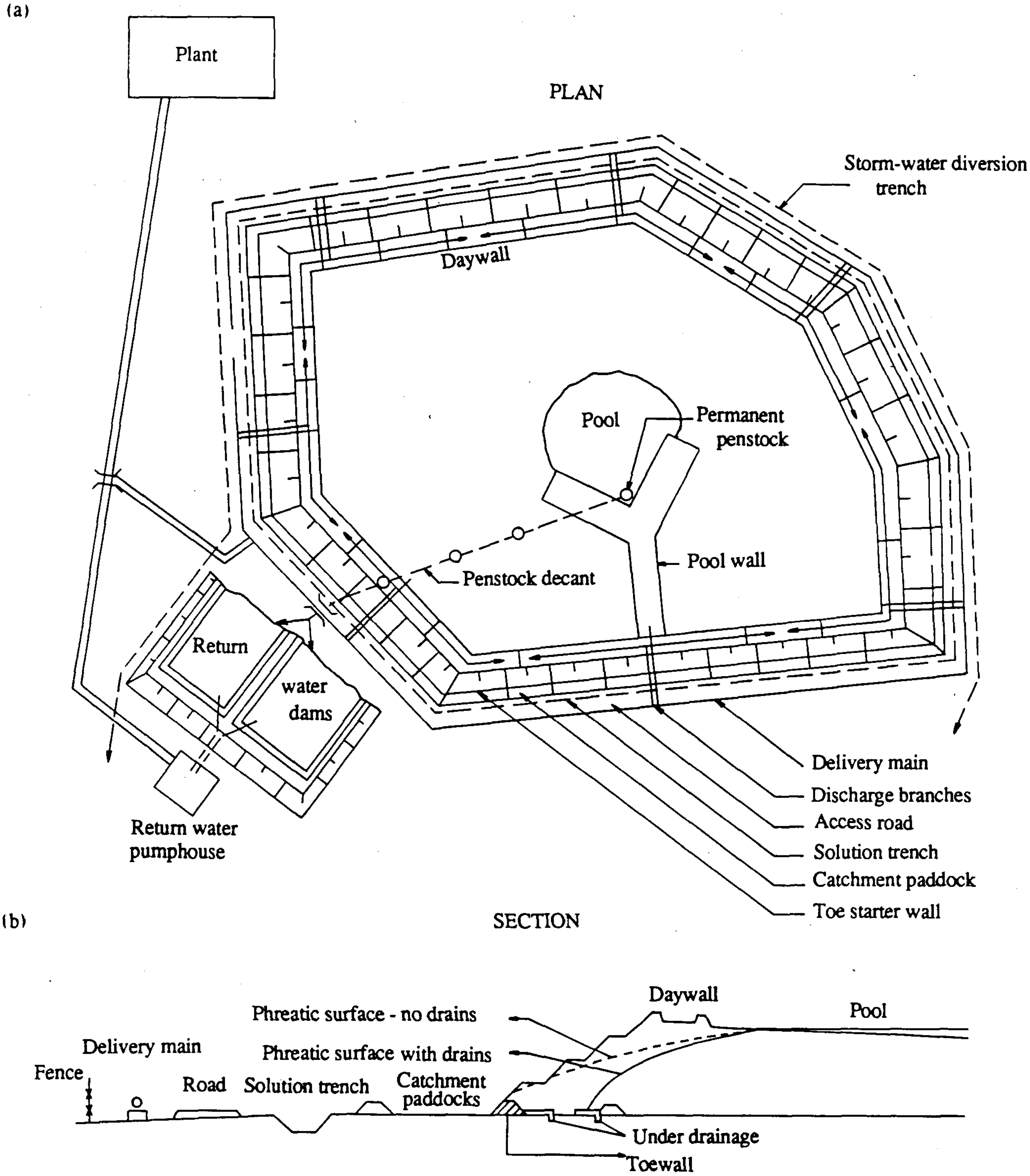


Figure I-2. The typical layout of a slimes dam (after Stanley, 1987).

(i) **Toe wall** - a wall, usually of compacted earth, to contain the tailings either during the early development of the structure or as a total confining structure.

(ii) **Underdrainage system** - a system of filter drains to control seepage within the structure.

(iii) **Decant penstock system** - a pipe system to remove clarified- and storm water which accumulate on the structure.

(iv) **Delivery system** - a network of pipes, valves and discharge points to convey the slime to, around and onto the structure.

(v) **Return water system** - a network of dams, sumps, pumps and pipes for storing and transporting excess effluent and storm water from the slimes dam to the plant.

(vi) **Storm-water control system** - a system of trenches to control and divert external storm water.

(vii) **Storm-water catchment system** - a system of paddocks around the toe of the structure to control and store storm water and sediments eroded from the sides of the slimes dam.

When designing an effective water management system, the mining industry tries to meet two important objectives, namely:

(i) Minimizing the loss of water, which minimizes the water costs.

(ii) Eliminating pollution caused by discharge of effluents, not complying with the statutory requirements.

According to Stanley (1987), the cost of water has not yet reached the level where it is a significant portion of the cost of gold production. This implies that the second objective must be accepted as a responsibility, which cannot always be justified economically.

However, in order to run an effective water management program, a clear understanding of the effluent generation and mine reticulation must be obtained. This can be achieved by using hydrological models, comprising elements such as:

(i) Inflow: tailings water, precipitation and disposals such as sewage or concentrated effluents.

(ii) Outflow: re-use of return water, evaporation, seepage losses and interstitial water.

Figure I-3 schematically illustrates all the components and functions required for a hydrological water balance model.

Before continuing any further on the topic of residue disposal on slimes dams, it might be of some importance to briefly discuss the stability of slimes dams. The stability of all slimes dams depends primarily on the stability of the slopes of the slimes dam. The parameter to which slope stability is the most sensitive is the position of the phreatic surface. If the phreatic surface rises too high in the slimes dam, it can cause major stability problems, which can lead to total failure of the structure. Such an event can lead to large-scale pollution of the whole environment surrounding the structure. Figure I-2(b) illustrates how a blanket drain underneath the slimes dam can draw down the phreatic surface and improve the stability of the structure.

A number of methods exist for placing gold mine tailings hydraulically:

(i) The paddock system.

(ii) The cyclone system.

(iii) The spigot system.

(iv) Opened discharge behind a mechanically formed containment wall.

The method generally used by the gold mines in the Orange Free State Goldfields is the paddock system, which is more suited for a flat topography. Such a system is illustrated in Figure I-4. During the day time, slimes are being deposited sequentially into the paddocks, subdividing the daywall to a depth of about 150 mm. During night-time, the slimes are deposited in the interior of the slimes dam (night wall). The paddocks are left to dry and crack up for about three weeks, before the next deposition. This drying is essential for the construction of the slimes dam, as the drying results into densification, giving the tailings the required strength. Furthermore, the cracks tend to fill up with coarser material which improves the vertical drainage. It is also important that the rate of rising of the slimes dam is controlled, to ensure optimal desiccation of the respective paddocks.

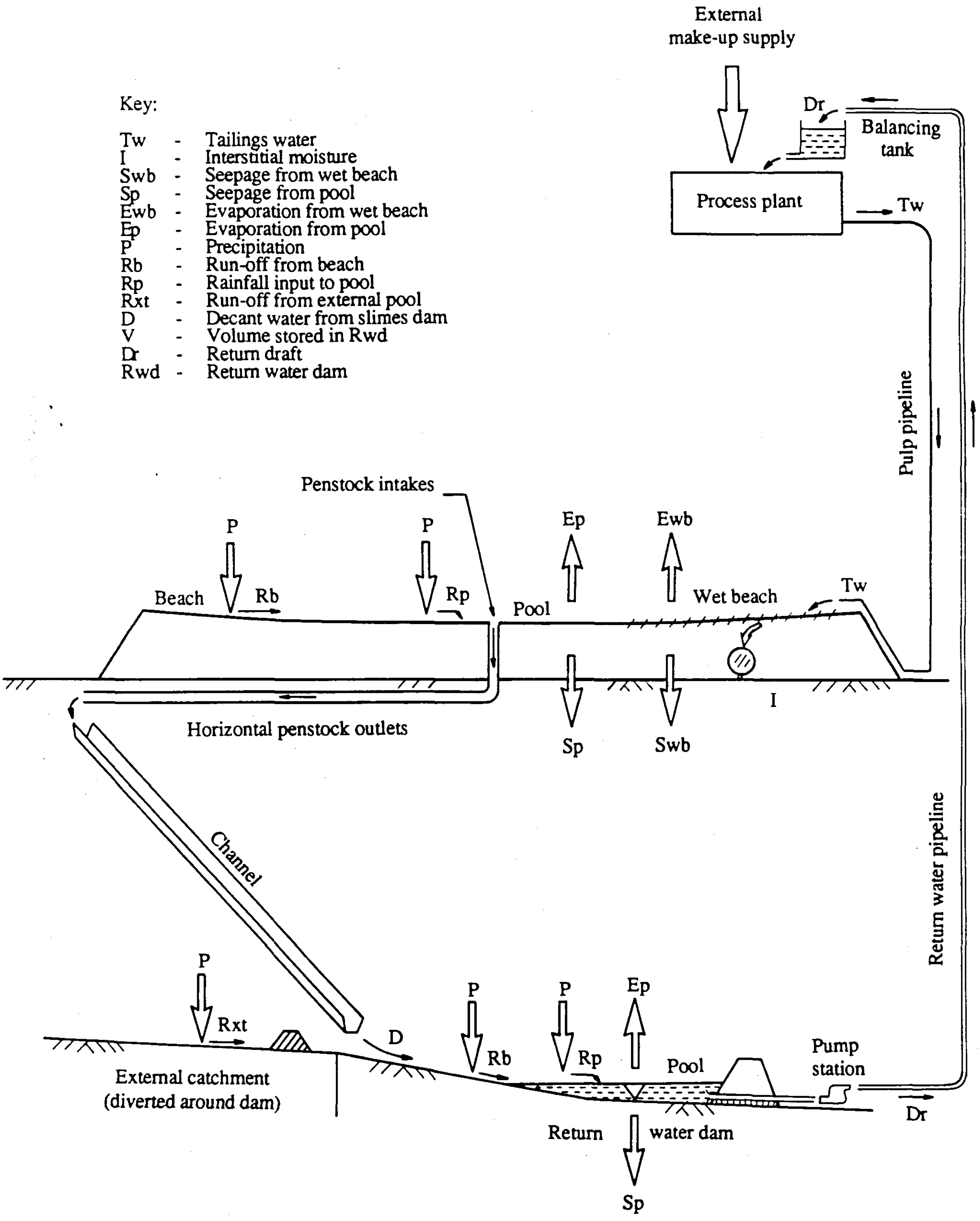
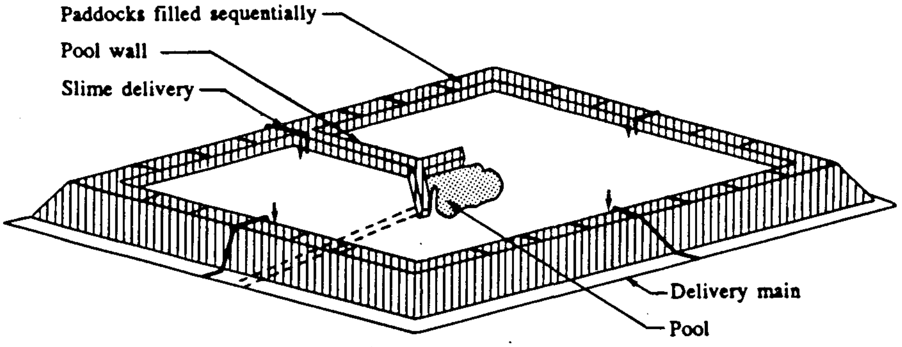
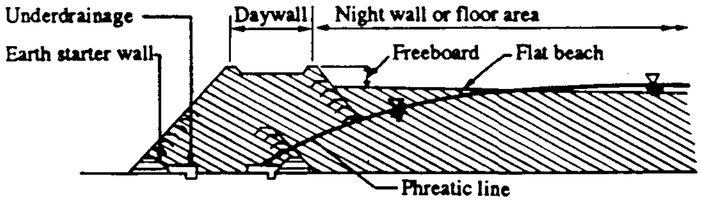


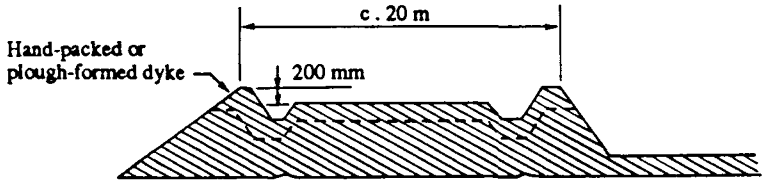
Figure I-3. The tailings system network (after Stanley, 1987).



a) Perspective view



b) Typical section



c) Typical daywall section

Figure I-4. Paddock system of slimes dam construction (after Stanley, 1987).

I-1.1.1 Types of slimes dams

Slimes dams tend to leach as water percolates through the structure. Thus, to be able to form an idea of the possible leachates originating from a slimes dam, the type of slimes must be identified.

Slimes dams are classified according to the type of slime that is deposited upon it. Certain minerals may or may not have been extracted during the extraction process. The following slimes dams are present in the area:

(i) Au, U_3O_8 and Fe_2S extracted.

(ii) Au and U_3O_8 extracted.

(iii) Au and Fe_2S extracted.

(iv) Only Au extracted.

Together with the above-mentioned minerals, a combination of the following reagents will generally also be present in the slimes dams:

Cyanide - $CaCN_2$, NaCN

Lime - CaO

Zinc and lead nitrate - $ZnNO_3$ and $PbNO_3$

Sulphuric acid (neutralized) - H_2SO_4

Hydrochloric acid - HCl

Sodium hydroxide - NaOH

Calcium hydroxide - $Ca(OH)_2$

Solvent organics, i.e. Kerosene, alamine, isodecanol

Flotation reagents, i.e.:

Copper sulphate - $CuSO_4$

Senkol 50 - sodium mercaptobenzathiazole

Dowfroth 200 - polypropylene glycol

Polyacrylamide flocculants

Antiscalent

As can be seen from the above-mentioned list, water in the slimes dams will be enriched in Ca^{2+}, Na^+, SO_4^{2-}, Cl^-, cyanide, heavy metals and certain organics. Furthermore, many of the mines in the region use purified sewage effluent in the gold extraction process, leading to a high NO_3^--content in some of the mine waters. Due to the recirculation of water in gold plants, the concentration of certain of these chemicals and elements tends to increase. As these elements and chemicals move through the slimes dams, certain physical and chemical processes may reduce or increase the concentrations of these elements and chemicals. Their ability to withstand these processes, will determine whether they are present in the seepage from the slimes dam.

I-1.1.2 Pyrite oxidation in slimes dams

The solubility of the remaining metals in the slimes dams is due mainly to bacterial action. The bacteria responsible for this are referred to as chemolithotropic micro-organisms. They obtain their energy from the oxidation of materials such as sulphides, sulphur and ferrous iron.

The gold-bearing conglomerate encountered in South Africa is always intimately associated with a matrix and therefore crushing and grinding are essential for the recovery of gold. According to Förstner and Wittmann (1976), the conglomerate essentially consists of the following minerals: quartz (70 - 90%), phyllosilicates (10 - 30%) and primary minerals (1 - 2%). The pyrite (sulphide) content of the gold ore varies between 0,85% and 1,60%.

Exposure of pyrite (FeS_2) and of other sulphide minerals to atmospheric oxygen and moisture results in one of the most acidic of all known weathering reactions. The pyrite is oxidized to ferrous sulphate ($FeSO_4$) and sulphuric acid (H_2SO_4) and the reaction proceeds as follows (after Krenkel and Novotny, 1980):

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2FeSO_4 + 2H_2SO_4$$

Flowing water then leaches away the ferrous sulphate and sulphuric acid. The leachate which is formed in the process is called acid mine drainage. The ferrous sulphate can be oxidized further to ferric sulphate [$Fe(SO_4)_3$] and the ferric sulphate hydrolyses to form insoluble ferric hydroxide [$Fe(OH)_3$] and more sulphuric acid as follows:

$$4FeSO_4 + 2H_2SO_4 + O_2 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O$$

$$Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4$$

It is a well-known fact that bacterial action, for example by the *Thiobacteriaceae* family, can assist the oxidation of pyrite under moist conditions. These bacteria are motile, non-capsulated rods (0,6 to 1,6 µm) with a viable pH range of 1 to 4,6, but an activity range limited to pH 2,4 to 3,5 (Mitchell, 1978). Differentiation between two species, namely

Thiobacillus thiooxidans and *Thiobacillus ferrooxidans* has been based upon their ability to catalyse sulphur or iron oxidation. *T. Thiooxidans* is an iron bacteria and *T. ferrooxidans* can catalyse both iron and sulphur oxidation (Mitchell, 1978). Under ideal conditions, the presence of these bacteria can speed up the rate of oxidation by several orders. Favourable conditions for the bacteria have been established as follows (Förstner and Wittmann, 1981):

(i) Large surface area, small particle size.

(ii) Temperature between 30° - 35° C.

(iii) Sufficient nutrients, e.g. for *T. ferrooxidans,* organic carbon, iron sulphate, pyrite, calcium nitrate and ammonium sulphate.

(iv) Aeration.

The above-mentioned reactions are major contributors to the fact that mine drainage has a low pH and a high sulphate content. A consequence of the low pH of mine drainage is the fact that metal salts become very soluble at low pH. This results in heavy metal enrichment in the water.

According to Marsden (1986), the maximum depth of oxidation into a slimes dam is 3 m, due to its very fine and highly compacted structure. He states that the oxidation interface lies between the 2 and 3 m horizons and that at the 3 m horizon, sulphur is still present as sulphide, which means that oxidation has not occurred.

Oxidation is limited to the depth to which oxygen can gain access. The air that occurs in the pores of the slime deposit is stagnant, except for changes in temperature and pressure that will cause expansion and contraction. He also stated that to a depth of 0,1 m, complete oxidation occurs in a month, after which the rate of oxidation declines rapidly with depth. Only, after two to three years, complete oxidation to the 1 m horizon would have taken place.

Although oxidation may have occurred to a depth of 2 - 3 m, considerable quantities of the sulphate then produced, are still present in the deposit. This means that the rate of leaching of the sulphate is low and thus the rate of pollution is also low. The fact that the sulphate is still present, implies that the deposit is only slightly permeable to rain.

It is necessary to stress that the residue deposits contain tens of millions of tons of sulphur. However, owing to the inability of oxygen to penetrate more than 2 to 3 m into the deposit, the rate of oxidation and pollution are low.

I-1.1.3 Possible pollution hazard

The gold mines in the Orange Free State Goldfields produce in excess of 5 million tons of slime and 2 million tons of rock per month (Gowan, 1987). If a ratio of 1 : 1 water to solids is accepted, it is evident that large volumes of water are pumped onto the slimes dams every month.

A certain fraction of this water will reach the ground-water table by seeping through the unsaturated zone directly beneath the slimes dam. The majority of the water will nevertheless reach the solution trenches on its way to the return water dam. The fact that the trenches are earth- and not concrete trenches and almost constantly filled with water, will further propagate seepage into the underlying strata.

Table I-1 illustrates some effluent compositions for gold and uranium tailings of South African mines. This table gives an indication as to what chemical constituents may be expected in the nearby ground-water regime.

TABLE I-1. WATER QUALITY OF GOLD AND URANIUM TAILINGS (After Wagner and Van Niekerk, 1987)

	GOLD TAILINGS		URANIUM TAILINGS	
	MINE A	MINE B	MINE A	MINE B
Total Dissolved Solids	3960	2931	2530	36290
pH	9,8	8,2	9,8	7,3
Conductivity (mS/m)	387	461	249	3790
Sodium as Na	390	460	430	210
Potassium as K	49	50	60	21
Calcium as Ca	510	600	160	550
Magnesium as Mg	13	69	00	130
Kjeldahl Nitrogen as N	83	47	44	38
Ammonia Nitrogen as N	36	37	24	37
Nitrate & Nitrite Nitrogen as N	5	10	50	13
Nitrate Nitrogen as N	2	1		1
Silicon as Si	10	1	11	1
Sulphate as SO_4	1700	2100	590	2400
Total phosphate as P	0	0		0
Ortho-phosphate as P	0	0		0
Chloride as Cl	400	340	370	145
Total alkalinity as $CaCO_3$	384	74	240	31

Chemical oxygen demand	344	109		28
Methylene Blue Active Agents (LAS)			,01	
Aluminium as Al	4	,2	,5	0
Fluoride as F	0,3	,5	,2	,6
Cyanide as CN	3,6	1,2	510	,001
Mercury as Hg	0,02	0		,009
Silver as Ag	0	,04		0
Arsenic as As	,07	,005	0	0
Selenium as Se	0	0	0	,02
Gold as Au	0,4	,2	,04	,08
Nickel as Ni	8,4	11,2	2,7	,2
Cobalt as Co	4,0	4,3	,8	,2
Cadmium as Cd	,007	,007	0	,008
Chromium as Cr	,04	,03	,03	,04
Copper as Cu	5,1	4,8	8,9	,03
Iron as Fe	,03	0	0	0
Manganese as Mn	,08	6,8	0	25
Lead as Pb	,06	,05	,04	,05
Zinc as Zn	2,9	1,9	37	0
Organic carbon as C		,02	,04	,01

* All units are in mg/l

Additional pollution in the immediate vicinity of the slimes dam may be caused by wind- and storm-water erosion. The rehabilitation of old slimes dams by establishing vegetation on it will, however, reduce the erosion, and therefore minimize any pollution originating from erosion.

I-1.2 RETURN WATER DAMS

Return water dams are provided in all modern slimes dam complexes. These small water dams provide a service of great importance to the long-term stability of the slimes dam. In South Africa, the slimes dam is not usually designed as a water-holding structure, but in terms of the Act, it has to retain all water falling on it, including a 1 : 100 year storm. This water and the usual excess pool water, as well as the run-off from the sides, cannot be released into the nearest watercourse, but is generally stored in a return water dam. The water may be recycled for use, whenever possible, or evaporated in evaporation dams.

I-1.2.1 Possible pollution hazard

It is evident from the above discussion that the water reaching the return water dam will have a very high salt load. Since water is stored in the dam and the dam contains water most of the time, a constant seepage of water into the ground will occur. The amount of water penetrating, will be determined by the permeability of the underlying strata.

Noteworthy is the fact that every dam has an emergency spillway. By law, return water dams must have a 0,5 m freeboard for a 1:100 year storm event.

I-1.3 EVAPORATION DAMS

Evaporation dams are large surface area dams which are relatively shallow and can contain large amounts of redundant water. The dams must be relatively shallow to increase the temperature of the water and consequently the evaporation rate.

The water that has to be contained in the evaporation dams is basically of two kinds:

(i) Underground water from the mines that is predominantly stagnant (NaCl-water). This water shows conductivities of up to 500 mS/m.

(ii) Water from the return water dams that cannot be recycled. This water may also include considerable quantities of purified sewage water, used in the gold extraction process. However, the majority of this water will have the same composition as that of the slimes dams and return water dams.

I-1.3.1 Possible pollution hazard

If taken into consideration that the surface area of these dams (for one mine's excess water) can extend over 8 km^2 and that it can store up to 6 000 million litres, the seriousness of the problem is realized.

It is quite obvious that not all this water will evaporate. A substantial quantity of the water will penetrate the underlying strata and finally reach the ground-water table. The permeability of the substrata will determine the rate of contamination.

In the vicinity of a river, a slope generally exists towards the river. If evaporation dams occur near the river, the slope will cause the water to seep towards the river and the river water may eventually be contaminated. Direct flow into the river may also take place when the dams reach their full capacity and overflow.

I-1.4 ROCK DUMPS

Waste rock originates from two main sources, namely sorting and underground development. Rock pieces rejected by sorting are those mineralized to a lesser extent than the cut-off grade for gold extraction.

The pyrite content of these rocks is generally less than that of the ore. Because rock dumps are very permeable to air and water, the oxidation of pyrite and the leaching of soluble oxidation products by rain water can proceed freely. Although the rock dump as a whole is very permeable, the individual rock pieces are mostly impermeable. Most of the oxidation will therefore take place on the outer surface of the rock pieces, excluding the majority of pyrite from the oxidation process. It should also be mentioned that a considerable quantity of the rock dump is crushed to a relatively fine material, making more pyrite available for oxidation. If the base of the rock dump comes into contact with water, the oxidation process may be accelerated.

I-1.4.1 Possible pollution hazard

It seems that the pollution threat from rock dumps is not as severe as in the case of the previously discussed sources, due to oxidation being limited to the surface of the coarse waste rock particles and the finer crushed fraction of the rock dumps.

I-2 URBAN WASTE DISPOSAL

Due to the ever-increasing urbanization, as well as the growth of industries in and around urban areas, the amount of urban waste seems to escalate. Liquid urban waste (sewage) and industrial effluents have been identified as the main contributors to the phosphate load in surface waters in Southern Africa. Solid wastes, on the other hand, if in contact with water, tend to produce leachates enriched in inorganic constituents, as well as numerous harmful heavy metals.

With the exception of a yeast factory, which produces a considerable amount of effluent, no other major industrial effluents are found in the Orange Free State Goldfields, although the urban liquid and solid wastes still pose a pollution hazard to the surrounding environment. The nature and impact of these urban waste sources, on their surroundings, will subsequently be discussed in more detail.

I-2.1 URBAN LIQUID WASTE DISPOSAL

Sewage is a complex mixture of inorganic and organic substances as well as man-made materials, which is collected in a sewage system and conveyed to a treatment plant for processing. In most communities, the storm-water run-off is collected in a separate system and is usually conveyed to the nearest natural watercourse for disposal without treatment. Municipal waste water refers to liquid material collected from residences, businesses and institutions, and frequently contains industrial effluents from dairies, laundries, bakeries, garages and other factories. Only 0,1% of sewage consists of dissolved salts and other materials, such as soap, plastic, grease, fats, oil, food particles and laundry detergents, while the remaining 99,9% consists of pure water (Best and Ross, 1977).

(a) Sewage treatment

The main method of sewage treatment today is based on the digestion of the organic matter by bacteria. This digestion can take place both under aerobic and anaerobic conditions and the rate of decomposition is dependent on many factors. Under aerobic conditions, the availability of oxygen is the limiting factor, whereas under anaerobic conditions the pH and the temperature are more important. The modern biological methods of sewage purification consist mainly of the following methods:

Percolating filter method.

Activated sludge method.

Oxidation ponds.

The activated sludge consists mainly of an active community of various types of bacteria and protozoa. The sludge and the sewage are aerated, either by bubbling air through the mixture or by stirring vigorously. After the sewage has become biologically oxidized by the sludge organisms, the mixture is allowed to settle, whereafter the clear effluent flows into the river and most of the sludge is returned to be mixed with the sewage entering the aeration tanks. The excess activated sludge is disposed of in drying beds.

Oxidation ponds are shallow lagoons which are large enough for the sewage to be retained in the ponds for varying periods, so that the waste water in the ponds can be purified by the action of bacteria and algae. The first step is the breakdown of the biodegradable organic matter by the bacteria to products such as carbon dioxide, ammonia and nitrate salts. Together with sunlight, the algae (chlorella pyrenoidosa) then utilize these materials to make new cells and oxygen (photosynthesis). The oxygen is then used by the bacteria to break down more organic waste. Therefore, there exists a mutual relation between the bacteria and the algae (Pelczar *et al.*, 1970).

As all the main sewage purification works in the Orange Free State Goldfields use the percolating filter process, this process will therefore be discussed in more detail.

The incoming sewage flows through a grid to remove the large objects and then into settling tanks, where a large portion of the solid matter settles out and is collected as sludge. This sludge is then digested by anaerobic bacteria in the absence of oxygen in digestion tanks. The anaerobic digestion process consists of two steps which are mutually dependent:

Complex organic compounds are hydrolysed by enzymes and micro-organisms to simpler organic compounds. These compounds are converted by bacteria to acetic, propionic and buturic acids. These acids are then converted by methane bacteria to stable organic forms and carbon dioxide and methane are liberated.

This digestion is carried out by two main groups of micro-organisms, i.e. hydrolytic and methane organisms. Hydrolytic bacteria are very abundant in sewage and waste sludge and are also capable of reproducing very rapidly. Unfortunately, the methane bacteria are few in numbers and reproduce very slowly. They are also very pH sensitive, with a pH range of between 6,5 and 8,0. This may have the effect that the organic acids may form faster than they can be catalysed by the limited population of methane bacteria. The proper environment for both types of bacteria requires a delicate balance between the population of the bacteria, the supply of food, pH, temperature and the accessibility of the food (Nemerow, 1978).

The product of anaerobic digestion of sewage is given in Table I-2.

TABLE I-2. PRODUCTS OF ANAEROBIC DIGESTION OF SEWAGE
(After Best and Ross, 1977)

Carbon	→	methane (CH_4)
Nitrogen	→	amines, ammonia
Sulphur	→	organic sulphur compounds, sulphides
Phosphorus	→	organic phosphorus compounds, phosphine

Anaerobic digestion also destroys viruses and pathogens significantly, but does not destroy a large proportion of endoparasite eggs which remain and can be viable in soil for up to two years.

This breakdown organic matter is then dried on drying beds. The supernatant liquid from the settling ponds is sprayed on the percolating filter, also called the biological filter. This biological filter consists of a bed of media, which is usually a granular material such as crushed stone, over which supernatant liquid from the settling tanks is sprayed and through which it percolates. Slime, containing a large number of organisms, forms on the surface of the media, i.e. protozoa, algae, aerobic bacteria and fungi.

Larger organisms like insects, larva of the insects, spiders, earthworms and snails also occur between the openings of the rocks. As the sewage flows over this slime, a series of complex biochemical reactions takes place by which organic matter is removed from the sewage by the bacteria and organisms.

Organic material in sewage water mainly consists of carbohydrates, proteins, fats, soap and detergents. Carbohydrates exist mainly as sugars, like glucose and cellulose, and these sugars are broken down into simple sugars, which in turn are converted into carbon by the organisms in the slime. Proteins have large molecular structures and are built up of amino acids. Proteins are finally degraded into amino acids, fatty acids and a variety of nitrogenous compounds, as well as organic phosphates and sulphides. Soaps are manufactured from fats, sodium and potassium, and are converted to simple fatty acids by the organisms. Detergents consist mainly of polyphosphates, which are broken down to simpler phosphates at the sewage works. The oxidation products of sewage are given in Table I-3.

TABLE I-3. OXIDATION PRODUCTS OF TREATED SEWAGE
(After Best and Ross, 1977)

Carbon → CO_2, HCO_3^- (bicarbonates), CO_3^{2-} (carbonates)
Nitrogen → NH_3 (ammonia), NO_2^- (nitrites) and NO_3^- (nitrates)
Sulphur → SO_4^{2-} (sulphates)
Phosphorus → PO_4^{3-} (phosphates)

Autotrophic bacteria, which are of the greatest significance in sanitary engineering, are the nitrifying, sulphur and iron bacteria. According to Clark *et al.* (1971), nitrifying bacteria perform the following reactions:

$$NH_3 \text{ (ammonia)} + O_2 \text{ (oxygen)}\ ^{\text{Nitrosomonas}}\ NO_2^- \text{ (nitrite)} + \text{energy}$$

$$NO_2^- \text{ (nitrite)} + O_2 \text{ (oxygen)}\ ^{\text{Nitrobacter}}\ NO_3^- \text{ (nitrate)} + \text{energy}$$

Sulphur bacteria, like *Thiobacillus*, perform the following reaction:

$$H_2S \text{ (hydrogen sulphide)} + O_2 \rightarrow H_2SO_4 + \text{energy}$$

By performing reactions as the above-mentioned, the bacteria oxidize the organic compounds in the water which are sprayed on the biological filter and the rest of the liquid passes through the filter and is collected at the base of the filter.

The filter performance is generally related to the filter volume, while the quantity of the micro-organisms present is more dependent on the surface area of the media in the filter. The removal of organic load appears to be dependent on the surface area of the bacterial slime and clogging of the filter tends to reduce the microbial efficiency. When this slime gets too heavy, it will slow down and resettle, therefore increasing the efficiency of the filter.

The liquid collected at the base of the filter will therefore contain the breakdown products of organic matter, dead microbial cells and some waste products from the larger organisms in the biological filter. These materials are settled out of suspension in final humus tanks and returned to the anaerobic digesters. The supernatant liquid may again be sprayed on the biological filter, to improve the quality of the effluent, or it can flow into maturation ponds from where it is extracted by mines, municipalities or gravitated into dams or rivers.

Figure I-5 gives a schematic representation of the sewage purification system, used in the study area.

Table I-4 shows the quantity and the use of purified sewage effluent of the major sewage works in the Goldfields.

TABLE I-4. QUANTITIES OF PURIFIED SEWAGE EFFLUENT DISPOSED IN THE GOLDFIELDS

Sewage purification works	Influent	Effluent	Use of effluent
	megalitres/day		
Welkom Theronia	20	19	Winter: 8 Ml/d re-used by municipality. 11 Ml/d flow into Flamingo- and Toronto Pan. Summer: Everything re-used by municipality.
Welkom Wit Pan	30	29	23 Ml/d re-used by mines. 6 Ml/d flow into Wit Pan.
Odendaalsrus	4	3,9	Everything re-used by mines.
Virginia	20	17	Biggest proportion re-used by mines. The rest by municipality. A portion flows into the Sand River.

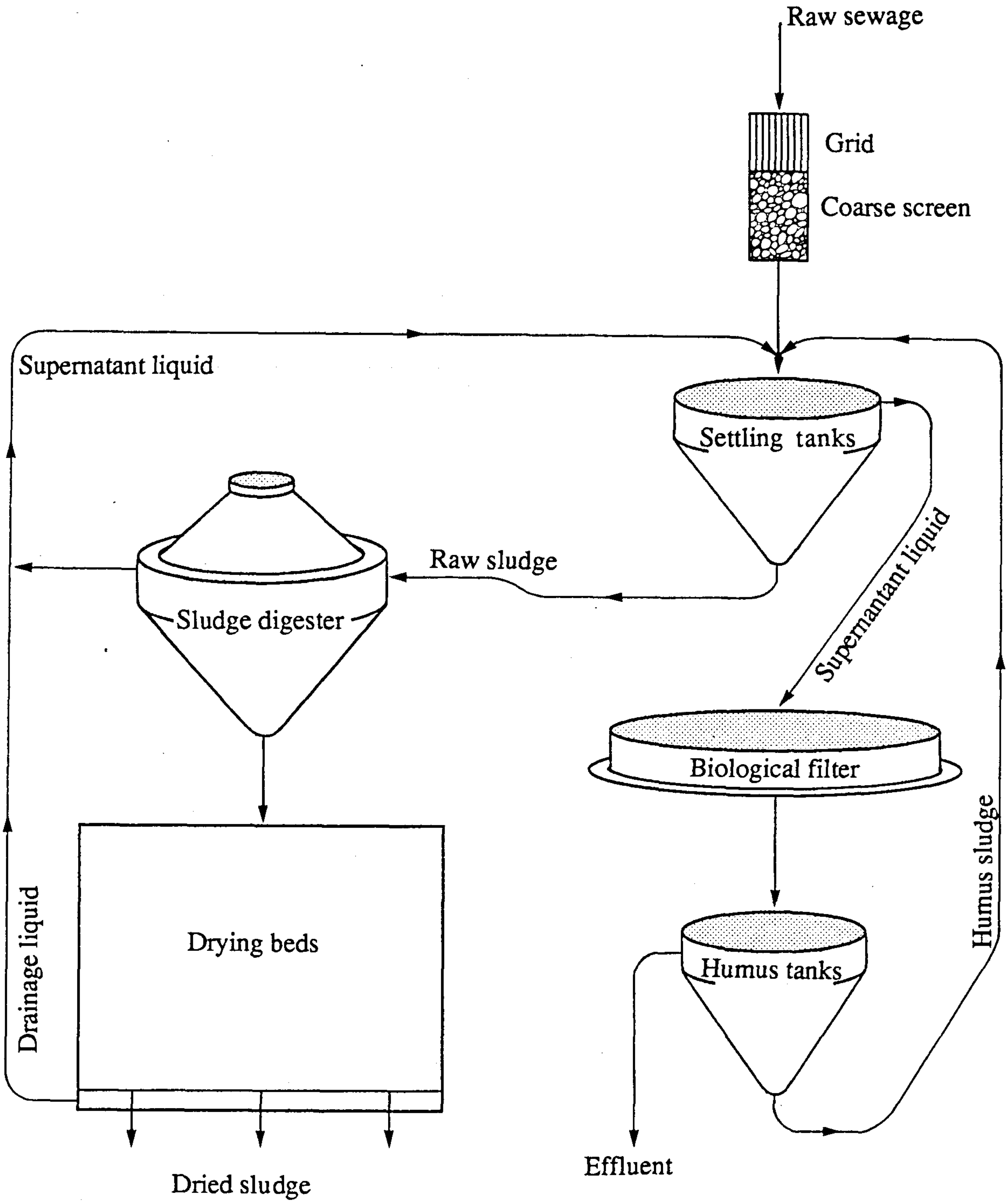


Figure I-5. Schematic representation of a sewage purification system.

As can be seen from the table, the greater part of the effluent is being re-used, either by mines or by municipalities in the Goldfields.

(b) Possible pollution hazard

If sewage works do not function effectively, an effluent is produced which does not comply to the general effluent standards. This could lead to a health hazard, as much of the treated effluent is discharged into rivers and natural surface water reservoirs which are being used for recreational purposes. The health hazard is due to the possible presence of bacteria and viruses in the effluent.

The enrichment of our streams and dams with nutrients, i.e. phosphorus and nitrogen, is also something of great concern. Man's activities result in municipal, industrial and agricultural waste waters rich in these nutrients. Much of this waste water, whether purified or not, is returned to natural watercourses and pans, resulting in the enrichment of these waters with nutrients. This process is called eutrophication and it results in water quality characteristics undesirable for man's use of the water. In South Africa, several signs of eutrophication began to appear in certain impoundments, receiving purified effluents as long ago as 1950. In these early years, both the Vaal and the Hartebeespoort Dams were troubled with algal blooms.

Plant growth, in the forms of microscopic algae and water plants, is generally limited in nature by a lack of nutrients. Eutrophication therefore leads to the sudden and rapid growth of undesirable water plants, like blue green algae, water grasses, water hyacinth and Kariba weed. The rapid growth of these plants can have several secondary effects, like the rapid uptake of oxygen, resulting in anaerobic conditions and the excluding of sunlight and heat from the lower waters, which causes the water to become stratified both with respect to oxygen and temperature. Certain algae species are toxic and plants may also alter the chemical quality of the water. Floating plants are very undesirable for water sport and the recreational potential of a dam can be severely affected.

Algae can also clog filters, import odours and taste to the water and toxic algae may require special water purification processes. Toxic algae can also cause cattle deaths.

It is obvious that sewage effluent is not the only source of nutrient enrichment in the natural waters. Other sources are (after Rudd, 1979):

(i) Point sources such as fertilizers or explosive factories.

(ii) Diffuse sources like storm run-off from urban areas and run-off from intensively farmed agricultural areas.

(iii) The capture of atmospheric pollution by rainfall.

Sludges also contain high levels of manganese, iron and aluminium, but these elements will not normally limit sludge application to soil. As plants adsorb heavy metals into their systems, it is apparent that heavy metals such as cadmium, copper mercury, nickel, lead and zinc, present the most serious hazards to plants and animals.

In extreme cases, the high chemical oxygen demand (COD) of a poor quality effluent may cause the complete effacement of water life in streams and dams.

I-2.2 URBAN SOLID WASTE DISPOSAL

The routine solid waste is produced in residences and commercial establishments and includes waste resulting from the preparation of serving food and general dry rubbish. All other kinds of waste originating in a community include garden refuge, industrial wastes, used building materials and house furnishings (Clark *et al.*, 1978). Most solid waste exists in the form of complex organic materials, but these materials are slowly degraded by micro-organisms to more stable compounds. This microbial degradation of solid waste proceeds at a much lower rate than that of other biological treatment systems, i.e. activated sludge, anaerobic digestion, etc.

The complex organic compounds are catalysed primarily by aerobic or facultative bacteria and fungi. Facultative bacteria are of great importance in the degradation of solid waste, since they can survive in both aerobic and anaerobic environments. This is very important, since the penetration of air into a well-compacted landfill is very limited and oxygen inside the landfill is utilized rapidly by aerobic bacteria as they decompose organic wastes. Initially, facultative bacteria degrade the complex organic wastes under anaerobic conditions to simple organic acids. These acids are then converted either anaerobically to methane or aerobically to carbon dioxide and water. The composition of the solid waste will largely determine the rate of degradation, as starches, proteins and sugars are easily decomposed, whereas cellulose, lignin and other carbohydrates are very resistant to biological degradation. Fortunately, fungi are active in decomposing the major constituents of plants like cellulose and lignin, and therefore play an important role in the degradation of solid waste. Algae, like the green algae and the blue-green algae, play only a minimum role in the degradation of solid waste. Protozoa, like the amoeba, act primarily as destroyers that prey on bacteria and play an important role in maintaining the equilibrium of microbial flora in solid waste systems.

Bacteria, e.g. Nitrosomonas, Nitrobacter and *Thiobacillus*, perform the same reactions as described in section I-2.1 (a). These reactions are very important in the oxidizing and reduction of nitrogen and sulphur compounds. Carbon dioxide is also utilized by autotrophic bacteria, as carbon dioxide represents the only source of carbon for these organisms. Carbon dioxide is transformed to carbohydrates by the following reduction reaction (after Hagerty *et al.*, 1973):

$$CO_2 + 2H_2 \rightarrow (CH_2O)_x + H_2O$$

Whereas complex organic compounds are degraded, inorganic compounds like sulphate and phosphate are being produced. This process is referred to as mineralization. The acids resulting from the degradation of solid waste may dissolve minerals and the result is a highly mineralized leachate. The quality of the leachate from a solid waste disposal site is determined by factors such as the age of the dump, the composition of the solid waste and the geohydrological characteristics of the underlying strata (Wagner and Van Niekerk, 1987).

Table I-5 lists the substances which are associated with leachate from solid waste disposal, as well as a concentration range for the respective constituents, from a South African landfill site.

TABLE I-5. ACTUAL AND RANGE VALUES FOR LEACHATE COMPOSITION (After Ball, 1984)

Parameters	**Range of Composition**		**Actual Value**
mg/l	**Low**	**High**	
COD	28	89 520	440
BOD	8	33 360	-
TOC	256	28 000	-
pH	3,7	8,7	7,1
TDS	584	44 900	-
Conductivity (mS/m)	2 810	16 800	646
Alkalinity	0	20 850	1 440
Total Hardness	0	22 800	-
Calcium	60	7 200	202
Magnesium	50	1 500	114
Ammonia	0,1	1 106	52
Nitrate	0,2	40	-
Chloride	4,7	3 000	540
Sulphate	0	2 000	204
Phosphate	0,1	130	4,7
Iron	0,2	5 500	2,4
Copper	0	10	-
Nickel	0	0,8	0,2
Zinc	0	370	0,2

Solid waste contains a wide range of pollutants, but these pollutants will vary from landfill to landfill, depending on the type of material being accepted at the disposal site. The industrial base of the surrounding area will also determine the variety of pollutants (Everett *et al.*, 1984).

It must be emphasized that water is essential for the biological degradation of solid waste. Solid waste containing less than 60% moisture will, therefore, be very difficult to decompose. Ground water often serves as a water source to moisten solid wastes and can therefore also become contaminated with the leachate. However, an excessive amount of water may fill the air voids, therefore making aerobic metabolism impossible (Hagerty *et al.*, 1973).

Possible pollution hazard

Surface water that is analysed for possible pollution from solid waste disposal sites should be analysed for COD, the major inorganic constituents, total nitrogen, dissolved oxygen, iron, manganese, lead, silver, chromium, cadmium and zinc. Ground water in the area should be analysed for the major inorganic constituents, iron, manganese, chromium and cadmium (Everett, 1980).

It must be stressed that leachate from solid waste can easily pollute ground- and surface water. However, a source of water through the fill material is required. Possible sources of water can be precipitation, moisture content of the refuse and surface- or ground water in contact with the solid waste. By excluding water from solid waste, the forming of leachate can be reduced drastically. If solid waste can be compacted to prevent the infiltration of water into the solid waste, the possible pollution threat to both surface- and ground water will be significantly reduced.

By carefully choosing a site for waste disposal, e.g. above the flood-mark, not nearby any standing water and not on very permeable material, the pollution threat can be reduced even further.

APPENDIX II

I-1 LEGAL ASPECTS

The use of any water in the Republic of South Africa is subject to the requirements of the Water Act of 1956. The aim of this law is to ensure the utilization of the limited water resources to the best advantage of the nation. Thus, the Water Act, 1956, together with a few pieces of legislation and uncodified common law, represents the law that forms the framework within which the demands on the available water resources can be regulated and utilized (Department of Water Affairs, 1986).

In South Africa, water occurs in varying quantities on the surface and in the subsurface. As water resources are developed and utilized, their applications are incorporated into the law. Because surface waters are generally the easiest to utilize, they are regulated quite strictly. On the other hand, regulations concerning ground water are totally insufficient. However, although the Water Act has afforded the State adequate powers to develop and control the water resources, it has become apparent that further development of the Water Act will be required to meet the future demand (Department of Water Affairs, 1986).

Presently, there are numerous Acts of Parliament in force, which either directly or through regulations, control industrial and mining waste management. The acts that control waste disposal, for environmental control, will be briefly described in this section. In Table II-1, the acts and the appropriate regulations are listed.

II-1.1 MINING WASTES DISPOSAL

(a) Water Act

(i) The eroding of mining waste dumps due to rain must be prevented.

(ii) The flow and seepage of effluent, including water pumped from underground, beyond the boundary of a mine or works, must be prevented.

(iii) External storm water must be diverted around mining waste and dumps. Provision must be made for the maximum precipitation to be expected over a period of 24 hours, with a return period of a hundred years. A freeboard of at least 0,5 m shall be provided.

(iv) Internal storm water to be retained. Any run-off water must also be retained by barrier dams and evaporation dams.

(v) French drains and seepage drains shall be constructed at all tailings dams where seepage occurs.

(vi) Mining waste dumps and evaporation dams must be practically located and designed to minimize damage.

(vii) Mining waste dumps and evaporation dams must not be located near any spring or less than 45 m away from the one in the fifty year's flood mark.

(viii) Mining waste dumps and evaporation dams not to be located on waterlogged ground or on ground liable to become waterlogged.

(ix) Any person removing material from mining waste dumps is responsible to reinstate pollution prevention works.

(x) Authority is required to dispose of surplus underground water beyond the boundary of a mine.

(xi) The safety of slimes dams must be ensured.

(b) Mine and Works Act

(i) The Minister may make regulations for the prevention and combatting of any pollution, the making safe of any slimes dam, etc. and the conservation at or near any mine or works.

(ii) Mine managers must ensure the safety of any dump constructed.

(iii) Liquid waste must be rendered harmless before it is permitted to escape.

(iv) Waste dumps must be covered to prevent dust pollution.

(v) Waste disposal sites must be demarcated with the approval of the Inspector of Mines. Every site must be controlled to ensure that the environment is not polluted.

(vi) Waste material from a mine to be disposed of in workings, wherever practicable, after consultation with the Department of Water Affairs.

(vii) No sand dump or slimes dam shall be established on the bank of any stream, river, dam, pan or lake, without written permission of the Inspector of Mines.

II-1.2 INDUSTRIAL WASTE DISPOSAL

(a) Health Act

The Minister may make regulations for:

(i) The protection of the catchment areas of rivers, watercourses, dams, etc. and of the feeding areas of underground water against pollution.

(ii) The requirements in respect of quality to which treated or purified waste, any product reclaimed from waste or the effluents, sludge or other products resulting from any process of treatment or purification of waste shall conform before its disposal or utilization.

(iii) The regulation, control, approval, restriction or prohibition of methods or disposal of sludge or any other waste product of water purification or water treatment.

(iv) The control or restriction of rubbish, night-soil, sewage or other waste originating from residential, industrial or commercial premises.

(b) Environment Conservation Act

(i) From a date promulgated by the Minister, all waste disposal sites must be registered.

(ii) The Director-General may refuse a permit if he is of the opinion that the waste disposal site cannot be operated or maintained with the view of the protection of the environment.

(iii) The permit holder shall create monitoring points which the Director-General may determine in respect of that waste disposal site. He shall also undertake such monitoring, recording and reporting as determined by the Director-General.

(iv) All flood water from a one in fifty year's flood which may originate during a period of 24 hours, to be diverted from the waste disposal site.

(v) All run-off arising from that waste disposal site during a 24-hour storm to be retained on that waste disposal site.

(vi) A record must be kept of the origin, quantity and nature of waste products salvaged.

(vii) Immediately after operations of that waste disposal site have been abandoned, cover the surface of the waste disposal site with a layer of suitable material so that (a) no ponding of precipitation occurs, (b) free drainage of rain water is ensured and (c) monitoring of the waste disposal site continues.

(c) Water Act

(i) Water used or effluent produced for industrial purposes must be purified in accordance with the SABS, before discharging it into any public stream or any other area.

(ii) Purified water must be discharged into the stream or origin.

(d) Hazardous Substance Act

(i) The Minister may declare any substance or mixture of substances, any product or material to be Group I, Group II, Group III or Group IV hazardous substance.

(ii) The Minister may make regulations authorizing, regulating, controlling and restricting the dumping of any grouped hazardous substance.

II-1.3 GENERAL

(a) Water Act

(i) Any person who has control over land on which anything was or is done which involved or involves a substance capable of causing pollution, must take steps to prevent the pollution of any public, private or underground water.

(ii) Any person who wilfully or negligently does any act which could pollute public or private water, including underground water, in such a way as to render it less fit, shall be guilty of an offence.

(iii) The Minister may make regulations relating to the prevention of the pollution of water.

II-1.4 DISCUSSION

When all the acts and regulations are taken into account, it seems like the present legislation is quite effective in combatting the pollution of the environment. However, there are a few subjects that are not covered very effectively by the legislation.

The Water Act states that no mining dumps and/or evaporation dams must be located near any spring, but no distance is specified. Whether the distance is 50 m or 500 m, is debatable. This distance will be vital in the long-term survival of the spring to produce fresh water. Distances must also be specified to prevent slimes dams, etc. being established near rivers or watercourses. The present legislation only prohibits the establishment of slimes dams, etc. on the bank of any river or dam without permission.

The legislation for the prevention of ground-water pollution is very vague. The pollution of ground water must be prevented, but specific steps that must prevent it, are not discussed. No geological survey of the underlying strata is required before the establishment of, for example, evaporation dams on a certain site. This means that these dams can be located on top of very permeable material, without even knowing about it, and this could be disastrous for the ground-water quality in the area.

The Water Act also states that the flow and seepage of any effluent beyond the boundary of a mine or work must be prevented. The surface flow beyond the boundary of a mine can easily be determined by observation, but seepage into the ground and then flowing beyond the boundary of the mine cannot be determined purely by observation. The only way that this can be done is by monitoring boreholes beyond the property of the mine.

TABLE II-1. ACTS AND REGULATIONS THAT CONTROL WASTE DISPOSAL (Modified after Best, 1987)

ACT AND APPROPRIATE SECTION	REGULATIONS AND APPROPRIATE SECTION	MAIN REQUIREMENTS
Water Act, 1956 (Act 54 of 1956)		
96	GN R1559 of 25.07.86	Safety of slimes dams.
21	Not required.	Control over liquid wastes disposal.
22	Regulations pending	Prevention of water pollution on any land or under any land.
23	Not required	Pollution of water to be an offence.
26(c) and (d)	GN R287 of 20.02.76 6.1 and 15	The flow and seepage of any effluent beyond the boundaries of a mine to be prevented.
	7 and 14	Eroding of mine dumps to be prevented.
	8	External storm water to be diverted around any source of pollution.
	11.1	Internal storm water to be retained on mining waste dumps.
	11.3	French drains and ditches to catch seepage around tailings dumps to be constructed.
	12, 16.1 and 16.2	Location of waste dumps and evaporation dams.
	21.2	Any person removing material from mining waste dumps is responsible to reinstate pollution prevention works.
Mines and Works Act, 1956 (Act 27 of 1956)		
12(1)(a)		The Minister can make regulations for:
g(A)		The prevention and combatting of any pollution arising from mining operations.
g(B)		The making safe of any undermined ground or any mining waste dumps or trenches, etc.
h(A)		Conservation of the environment near any mine.

12	GN R992 of 26.06.70 2.10.15	Safety of any slimes dam or any dump to be ensured.
	5.9.2	Liquid waste to be rendered harmless, before permitting to escape.
	5.10	Waste dumps must be covered to prevent dust pollution.
	5.13.1	All mining waste disposal sites to be demarcated and controlled to prevent pollution.
	5.13.4	Waste material from a mine to be disposed of in workings, wherever practicable.
	5.14.3	Location of slimes dams or sand dumps in relation to rivers, etc.
Health Act, 1977 (Act 63 of 1977)		
37	No regulations yet	Control over waste products of water purification and water treatment.
38	No regulations yet	Regulation, control or restriction of waste originating from residential, industrial or commercial premises.
Environment Conservation Act, 1982 (Act 100 of 1982) 12(2)(a)	Notice 591 of 1988	All waste disposal sites must be registered. Monitoring points shall be created and monitored. External storm water to be diverted around and internal storm water to be retained on the waste disposal site. Keep record of the waste products salvaged. Surface of the waste disposal site to be covered after dumping at the site had ceased.
Hazardous Substances Act, 1973 (Act 15 of 1973) 2	Not required	The Minister may declare any substance to be a Group I - Group IV hazardous substance.
29(1)(a)(vi)	No regulations yet	The Minister may make regulations in connection with the disposal of any hazardous substance.

APPENDIX III

III-1 SIGNIFICANCE OF SOME MAJOR CONSTITUENTS IN WATER ANALYSES

Aluminium

Although aluminium is the third most common element in the earth's crust, it is usually only a minor constituent in water. Aluminium is normally regarded as non-toxic, because it is relatively insoluble. This situation can change as aluminium tends to go into solution under strong acid or alkaline conditions (Kempster *et al.*, 1980). Thus, in the acid environment of slimes dams, high aluminium concentrations can be expected.

The normal dietary intake of aluminium is 20 to 30 µg/day, deriving from fruit and vegetables.

Boron

According to Kempster *et al.* (1980), the normal dietary intake of boron is 3000 µg/day. The toxicity of the element depends on the form in which it occurs. Certain forms of boron are relatively toxic to man, but plants are more sensitive to high boron levels, although it is essential for plant growth.

Bromide

The normal dietary intake of bromide is 8 - 24 µg/day. Bromide in natural concentrations is not known to affect the health of plants and animals.

Cadmium

Cadmium is found in nature in the form of sulphate, and although it is readily soluble in water, it precipitates at high pH-values. The normal dietary intake is around 70 µg/day. Excessive cadmium concentrations may cause high blood pressure. High concentrations of cadmium may be present in sewage effluent.

Calcium

Calcium is dissolved from practically all rocks. Calcium carbonate forms a protective coating on pipes, therefore reducing the corrosion of the pipes. At low calcium concentrations (soft waters), heavy metals are more toxic. Neutralization of acid mine waters may lead to very high calcium values, as calcium oxide is used in the neutralization process.

The normal dietary intake is 1400 mg/day.

Chloride

Chloride is very soluble and usually occurs together with sodium and bears relation to the salinity of the water. To certain plants, chloride may be toxic. The high chloride content originates from the deep stagnant water in the area.

The dietary intake of chloride is not specified.

Copper

Copper is an essential nutritional element and the normal dietary intake is around 3 mg/day. Copper is only toxic at very high concentrations and at these concentrations has a disagreeable taste. High concentrations of copper may be due to mining activity or the leaching of solid waste in the area.

Cyanide

Although cyanide does not freely occur in nature, water may be contaminated with cyanide due to mining and industrial activities. Cyanide is more toxic at low pH than at high pH, but is decomposed rapidly by bacterial action. A cyanide dose of more than 50 mg can be fatal, but less than 10 mg is non-injurious (Kempster and Smith, 1985). By chlorination of cyanide, the cyanide is converted to cyanogen chloride, which is an order of magnitude less toxic than cyanide. Cyanide is more toxic to fish than to humans.

Iron

Iron is the fourth most abundant element on earth and is an essential element. It is an essential part of the red blood pigment, haemoglobin, which is responsible for carrying oxygen in the blood. At high concentrations, iron may be toxic, especially to infants. Iron concentrations above 300 µg/l may cause stains and have an unpleasant taste.

The recommended total dietary intake is 10 mg/day (Kempster and Smith, 1985). High iron concentrations in the water may be caused by the oxidation of pyrite in the slimes dams.

Lead

Lead is an accumulative poison in both humans and animals. Lead is highly toxic and is a poison which affects nerve tissue. The toxicity of lead is inversely related to the calcium content of the water. Lead is more toxic at low calcium concentrations than at high concentrations. Lead is a common industrial and mining pollutant. Lead nitrate is used in the gold extraction process and will thus be present in the reduction works water pumped to the evaporation dams.

The normal dietary intake of lead is 300 µg/day (Kempster and Smith, 1985).

Magnesium

Magnesium is relatively abundant in the earth's crust and the weathering of sedimentary rocks is considered to be the main source of magnesium in natural waters. Magnesium sulphate and magnesium chloride are both very soluble and several thousands milligram per litre of magnesium can be held in solution in equilibrium with chloride and sulphate. High concentrations of magnesium may cause scouring diseases among livestock.

Magnesium is an essential element and the normal dietary magnesium intake is 250 mg per day. Water with a magnesium concentration which exceeds 100 mg/l may have an unpleasant taste. Although magnesium is non-toxic, it can cause diarrhoea in new users (Kempster and Smith, 1985).

Magnesium, together with calcium, tends to flocculate soil colloids and tends to maintain good soil structure and permeability (Hodgson, 1987). Magnesium is not normally added in the gold reduction process.

Manganese

Manganese is an essential nutritional element and the normal dietary intake is around 4000 µg/day. The limit for drinking water is not based on toxic, but on aesthetical considerations. Due to its staining ability (Kempster and Smith, 1985), high amounts of manganese and iron may occasionally occur in good quality ground water, if high amounts of organic matter are introduced into the soil near the recharge area (Krenkel and Novotny, 1980). High amounts of manganese may occur in mining and industrial effluent.

Nitrate

Although nitrate is non-toxic to adults, it may cause mucous membrane irritation in adults, if occurring in concentrations greater than 100 mg/l in water. Nitrate concentrations in excess of 10 mg/l (as N) may cause fatal methaemoglobineamia to infants (Kempster and Smith, 1985).

Nitrate is the final product of bacterial oxidation of organic matter, and sewage effluent as well as fertilizers, is thus the main sources.

Phosphate

Phosphorus is relatively abundant in the earth's crust, being found as phosphate. Phosphates are a very essential nutritional necessity for all forms of life on earth. Man requires large quantities of phosphates and calcium to form bone. Whereas phosphate is non-toxic, free yellow phosphorus is very toxic. The normal dietary intake of phosphate is around 2 g/day.

High phosphate concentrations in water may be derived from sewage effluent and fertilizers and cause excessive algae and water plant growth. The presence of phosphate is nearly always an indication that other, less desirable pollutants, are also present. No drinking-water standard for phosphate is proposed by Kempster and Smith (1985). The special phosphate standard for industrial effluent is 1 mg/l.

Potassium

Potassium is a relative abundant element in the earth's crust. Because potassium occurs in rocks in a form that is not easily brought into solution, the potassium content of natural waters is normally low. Potassium is an essential nutritional element, but in large doses it can be toxic, as it disturbes the electrolyte balance. At concentrations above 340 mg/l, potassium gives an unpleasant taste. Potassium salts can also have an cathartic effect.

The normal dietary potassium intake is 2,8 g/day (Kempster and Smith, 1985).

Sodium

Sodium is mostly ingested by man as sodium chloride (table salt). This ingestion of sodium chloride varies between 0,5 g/day to as much as 30 g/day. High sodium intake leads to serious health problems, one of which is high blood pressure. The normal dietary intake is about 500 μg/day. The taste threshold for sodium in drinking water is 290 mg/l for the bicarbonate salt and 135 mg/l for the chloride salt. The sodium limit of 100 mg/l is based on health implications and not on any taste effects (Kempster and Smith, 1985).

Sodium tends to disperse the soil colloids and this results in the loss of good tilth and permeability. The sodium-absorption-ration (SAR) is a useful index of the sodium hazard of irrigation water.

Sodium in the effluent water in the Orange Free State Goldfields originates from the deep ground water pumped to the surface, and also from chemicals added in the gold reduction process.

Sulphate

Most sulphate compounds are readily soluble in water and are readily dissolved from sedimentary rocks. At sulphate concentrations of more than 250 mg/l, water may have an adverse taste. At sulphate concentrations above 250 mg/l, the corrosivity of water, especially towards cement, is increased. Sulphate has traditionally been regarded as non-toxic, but there is some doubt as to the validity of this assumption, as animal data reveal that sulphate can be injurious and may lead to deficiencies of essential trace elements such as copper and selenium, with resulting health effects in the long term. The normal dietary intake of sulphur is about 3 g/day (Kempster and Smith, 1985).

High concentrations of sulphate may occur in the excess mine water due to the oxidation of pyrite by bacteria (see section 2.2.1.3 for the mechanism of pyrite oxidation).

Zinc

Zinc is abundant in rocks, but it is only a minor constituent in natural waters because the free metal and its oxides are only slightly soluble (Hodgson, 1987).

Zinc gives an astringent taste to water at concentrations that exceed 5 mg/l. Zinc is an essential nutritional element and the normal dietary intake is around 15 mg/day. Zinc is moderately toxic to fish, but non-toxic to humans. Water, having a high concentration of zinc, should be screened for the highly toxic element cadmium, which is normally associated with zinc.

Zinc is added in the gold reduction process and high concentrations may be present in acid mine waters.

Electrical conductivity

Generally, ions occur in a dissociated form in waters and are able to move under the influence of an electrical potential, due to their respective charges. The ability of water to conduct a current is a function of the concentration and the charged ions and the rate at which the ions can move under the influence of the potential (Lloyd and Heathcote, 1985). Furthermore, the ionic activity is dependent on the temperature. As the temperature increases, the electrical conductivity also increases. Any measurement should be reported at a specific temperature, which is normally 25°C, under laboratory conditions. According to

Lloyd and Heathcote (1985), an approximate correlation between the electrical conductance (EC) and the total dissolved solids (TDS) exists and can be used:

$$\mathrm{TDS} = k_c \, \mathrm{EC}$$

where TDS is expressed in mg/l and EC in mS/m at 25°C. The correlation factor k_c varies between 0,55 and 0,80 for ground water and should be determined specifically in each study.

Electrical conductivity measurements can be used as a monitoring parameter, both on an areal and a time basis. Furthermore, electrical conductivity measurements can be used to determine sampling frequency, as well as to support hydraulic observations at the groundwater/surface-water interface or in pumping tests.

Temperature

Temperature measurements at the specific sites are important for thermodynamic calculations, related to the hydrochemistry, as well as to support hydraulic and other chemical measurements.

pH

The negative logarithm of the hydrogen ion activity in a solution is generally called the pH of the solution. When ground water is removed from an aquifer, the physical controls governing the hydrogen ion activity are changed and thus the pH changes. However carefully water is sampled, once it is allowed to stand, the pH might change to such an extent that the laboratory measurements bear little relevance and it is important that it be measured at the site (Lloyd and Heathcote, 1985).

Total dissolved solids (TDS)

The total dissolved solids in water include all solid material that is in solution, whether it is ionized or not. However, it does not include suspended sediments, colloids or dissolved gases.

Reported livestock tolerances range from 3000 - 15000 mg/l, whereas for fresh-water fish, about 7000 mg/l of sodium chloride can be expected to be lethal. People accustomed to high mineralized water may complain that less concentrated water seems to be flat. Gastric disturbances may rather be caused by a change in the concentration of dissolved solids of the drinking water than in the original concentration of dissolved solids in the water itself (Hodgson, 1987).

Calcium, magnesium, sodium, potassium, bicarbonate, sulphate, chloride and silica are usually available in ground water. Iron, aluminium, nitrogen and carbonate, in addition to the previous constituents, may be found in soil and geological materials. There are important precipitation reactions for calcium, magnesium, bicarbonate and sulphate, resulting in the precipitation of calcite, aragonite, gypsum and magnesium carbonates.

When sodium has been brought into solution, it tends to remain in that status, because there are no important precipitation reactions which can keep sodium concentrations low in natural waters. Sodium can only be kept in the solid phase by the adsorption on mineral surfaces, especially by clay minerals which are present in solid and sedimentary rocks (Tordiffe, 1978).

Hem (1970) states that equilibria involving carbonates are the major limiting factor concerning the solubility of calcium in natural waters. The two crystalline forms of calcium in sedimentary rocks are calcite and aragonite, both having the formula $CaCO_3$. Cation exchange has a considerable influence on the calcium concentrations in natural waters. Divalent cations are generally held more strongly than monovalent cations. Therefore, Ca^{2+} is easily adsorbed by clay minerals and is not so mobile as Na^+.

Ion exchange reaction, where adsorbed Na^+ is exchanged for Ca^{2+} which is in solution, occurs in the presence of clay minerals which are abundant in the Ecca shales and weathered dolerite. The clay minerals will thus become enriched in Ca^{2+} and the water with Na^+, until chemical equilibrium is reached. The reverse effect can also occur, when water with a high salinity (high Na^- and Cl^--content) percolates through ferruginous clays.

In most natural fresh water, the magnesium concentration is much lower than the concentration of calcium, and the magnesium concentration is normally less than the sodium concentration (Hem 1970). However, Tordiffe (1978) comes to the conclusion that in ground water, calcium is the least mobile cation, that the magnesium ion is only slightly more mobile than calcium and that the sodium ion is the most mobile of the cations. Magnesium ions are smaller than sodium or calcium ions and, therefore, have a stronger charge density, a greater attraction for water molecules and magnesium, as in the case with calcium, readily replaces sodium on the exchange material (Walton, 1970). However, Mg^{2+} can also be released, which means that the ground water may become enriched with Mg^{2+} (Matthess, 1982). Thus, in the vicinity of large quantities of mine effluent with a very high salinity, the ground water can become enriched with Ca^{2+} and Mg^{2+} and not with Na^+, as is generally the case.

Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes with other ions, do not form salts of low solubility, are not significantly absorbed on mineral surfaces and play a few vital biochemical roles (Hem, 1970). The circulation of Cl^- in the hydrological cycle is mostly through physical rather than chemical processes. Therefore, chloride ions remain in solution and have the ability of withstanding the processes which reduce the concentration of the other ions in solution.

Chloride usually occurs together with sodium and bears relation to the salinity of the water. The high chloride concentrations in the study area originates from the deep stagnant waters that are dumped in evaporation dams on the surface.

It is important to note that reducing environments can convert dissolved sulphate to sulphide and dissolved nitrate to nitrogen gas. Nitrogen, phosphorus and potassium can be removed from the environment by crop uptake. Chemical constituents that can be lost as a gas, are the following: sulphate, nitrate, mercury, arsenic and selenium.

According to Stanley (1987), 3 to 4% of the gold-bearing reef matrix consists of pyrite, which makes pyrite a minor but important constituent of gold residues, as it constitutes a source of both ferrous iron and sulphate. Most sulphate compounds are readily soluble in water and easily dissolved from sedimentary rocks. Oxidation and reduction are frequently bound up with biological processes. Sulphate reduction, in particular, involves the assistance of micro-organisms. Sulphides (FeS_2) are oxidized to yield sulphate ions (SO_4^{2-}) and sometimes free sulphur ions (S^{2-}), which are carried off in the water. Therefore, high concentrations of sulphate may occur in the excess mine water from slimes dams, due to the oxidation of pyrite by bacteria. Microbiological reduction can cause a lower SO_4^{2-} concentration. The sulphate ion could also be adsorbed onto clays.

The sulphate ion is a complex with a strong tendency to form further complexes. The most important complexes in natural waters are the ion pairs, $NaSO_4^-$ and $CaSO_4$, which increase with increasing sulphate concentration. The strongest ion pairs form with divalent and trivalent cations (Matthess, 1982). In reducing waters with $pH < 7$, undissociated H_2S may be expected, whereas in alkaline conditions HS^- is predominant. The S^{2-}-ion requires such a high pH that it seldom occurs in natural conditions. H_2S and HS^- form insoluble heavy metal sulphides that are precipitated (Hem, 1970).

Nitrate is the final product of bacterial oxidation of organic matter, sewage effluent, as well as fertilizers. High nitrate concentrations in shallow ground water, in places where large numbers of animals are confined, can be attributed to leachings from livestock corrals. Nitrogen can occur at all oxidation states.

Trace constituents, such as aluminium, barium, cadmium, copper, fluoride, iron and lead also have important precipitation potentials. Trace elements usually precipitate at high pH-values and tend to go into solution under strong acid conditions (Kempster *et al.*, 1980).

III-2 HYDROCHEMICAL PROCESSES AND THEIR SIGNIFICANCE TO GROUND-WATER QUALITY

Water is the most common substance on earth and, because of its dipole nature, the most effective solvent for many types of solids, liquids and gases. The geochemical properties of ground water generally depend on those of the recharged water (atmospheric precipitation and surface waters) and on the subsurface geochemical processes. These control the water quality during the course of its underground movement by raising or lowering the amount and kind of the dissolved solids. The scale of these changes is dependent on the chemical and physical properties of the surrounding rocks, the degree of diagnesis in sediments, the water temperature, the chemical content of the water, the volume of water in movement, its velocity and human influence.

The following processes play an important role during the chemical evaluation of ground water, polluted or unpolluted:

- dilution,
- filtration,
- mineral dissolution, solubility and chemical precipitation,
- adsorption,
- ion exchange,
- buffering,
- oxidation reduction,
- volatilization and
- biological degradation and assimilation.

Dilution

Dilution is caused by fresh water derived from rainfall, seepage from streams and canals and artificial recharge, and mainly depends on the chemical composition of the dilutant. Furthermore, dilution of water may not be seen as representing a general dilution in terms of the entire chemical composition of the specific water. According to Everett (1980), the dilution of pollutants occurring in the saturated zone is generally determined by the following factors:

(i) The volume of waste water reaching the water table.
(ii) The waste loading, i.e. the weight per unit area of pollutant reaching the water table.
(iii) Areal hydraulic head distribution.
(iv) Transmissivity of aquifer materials.
(v) Vertical hydraulic head gradients and vertical permeabilities through confining beds.
(vi) Quality of the native ground water.
(vii) Quantity of recharge reaching the water table from other sources at the land surface.
(viii) Quality of the recharge reaching the water table from other sources.
(ix) Well construction.
(x) Pumpage volumes and patterns.

When evaluating the dilution of any contaminant in the saturated zone, one requires a considerable hydrogeologic judgement and experience gained from other case histories.

Filtration

Filtration essentially removes virtually all the suspended materials from either polluted or unpolluted water. This process is generally not effective fro most of the inorganic species, except for iron and manganese (Everett, 1980). However, in ground water certain chemical species may precipitate due to oversaturation, which may be effectively filtered out as the water moves through the substratum.

Mineral dissolution, solubility and chemical precipitation

Generally, when water comes into contact with the substratum, the dissolution of certain minerals begins. This process will continue until equilibrium concentrations are attained in the water or until the minerals are consumed (Freeze and Cherry, 1979). The solubility of minerals may vary over many orders of magnitude, which may result in the fact that some ground water may only be marginly higher in dissolved solids than rain water, while other ground water may become more salty than sea water.

Some minerals dissolve congruently, meaning that the products of the dissolution reaction are all dissolved species. However, the most minerals that affect the chemical composition of the ground water dissolve incongruently, meaning that some of the dissolution products occur as solid mineral substances. The latter dissolution reaction is applicable for the most alluminium silicates (clay minerals). Furthermore, it is important to note that mineral solubilities in pure water are lower than those in waters with a high salt content. This is due to the fact that the increased solubility is caused by decreases in activity coefficients as a result of the increased ionic strength (Freeze and Cherry, 1979) and is also known as the ionic strength effect. The latter can play a very important role in the chemical evolution of polluted and unpolluted ground water.

Another effect which may influence the solubility of minerals is known as the common ion effect. This process takes place when the addition of ions by dissolution of one mineral influences the solubility of another mineral to a greater extent than the effect exerted by the difference in activity coefficients. Both the ionic strength effect and common ion effect are depicted in Figure III-1, i.e. for a given NaCl-content. The presence of each mineral calcite or gypsum causes a decrease in the solubility of the other. However, due to the ionic strength effect, both minerals increase in solubility at higher NaCl-concentrations (Freeze and Cherry, 1979).

If the ground water becomes saturated with regard to specific chemical species, precipitation may take place. Thus, chemical precipitation can occur, if the necessary chemical species for chemical reactions are present in sufficient quantities.

The extent of dissolution or precipitation reactions for systems that attain equilibrium can be derived from the equilibrium constants (Stumm and Morgan, 1981):

$$bB + cC \underset{\text{precipitation}}{\overset{\text{dissolution}}{\rightleftharpoons}} dD + eE$$

The relationship between reactants and products, in a condition of disequilibrium, can be expressed as:

$$Q = \frac{[B]^b\,[C]^c}{[D]^d\,[E]^e}$$

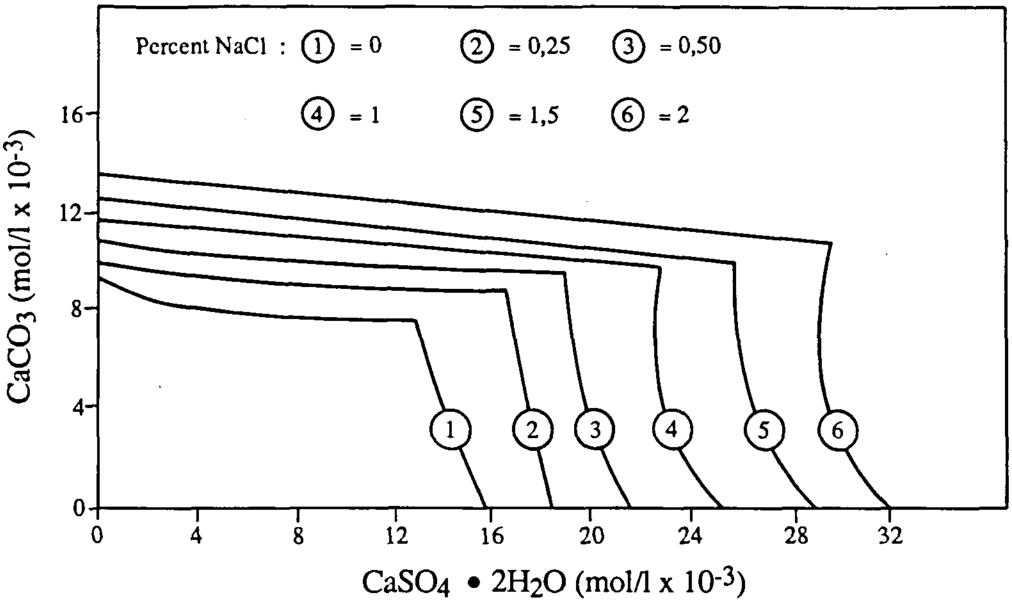


Figure III-1. Solubility of gypsum and calcite in water with various concentrations of dissolved NaCl, 25°C, p_{CO2} = 1 bar (after Shternina and Frolova, 1945).

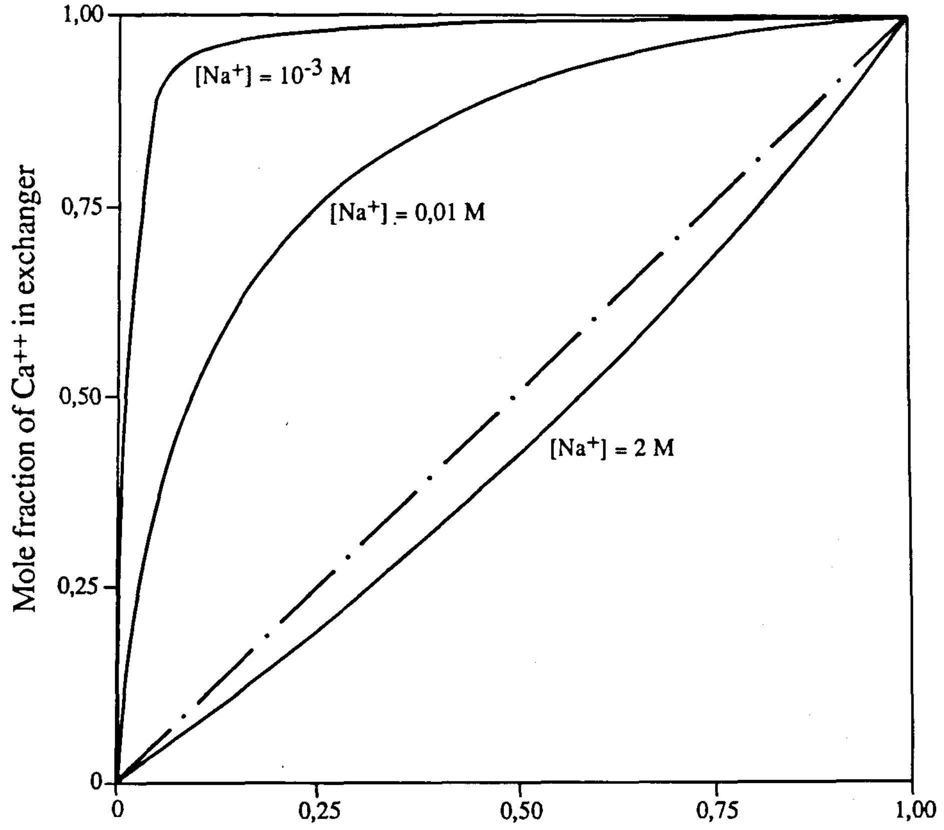


Figure III-2. Typical exchange isotherms for the reaction $Ca^{2+} + 2\,(Na^+ R^-) \rightleftharpoons (Ca^{2+}R_2) + 2Na^+$ (after Stumm and Morgan, 1981).

where

Q = the reaction quotient
B,C,D and E = the chemical constituents
b,c,d and e = the number of moles of chemical constituents

To determine when precipitation will take place, a ratio, comparing the status of the dissolution-precipitation reacting at a specific point in time, and the thermodynamic equilibrium (K_{eq}) are used, namely:

$$S_i = Q/K_{eq}$$

where S_i = the saturation index.

When $S_i > 1$, the water is supersaturated with respect to specific ionic constituents, which implies that the reaction must proceed to the left, requiring mineral precipitation. If, on the other hand, $S < 1$, the water is undersaturated with respect to specific ionic constituents, requiring mineral dissolution (Freeze and Cherry, 1979).

Adsorption

All minerals have, on the surface, lattice defects that attract polarized water molecules and H^+ and OH^- ions. Adsorption is probably one of the most effective processes for attenuating ground-water pollution. Clay minerals may have an important function in natural water systems, because of their large surface area per unit weight. In effect, clay minerals may operate as adsorbents for dissolved chemicals in water and the adsorption depends on a complex set of physico-chemical conditions. Most of the clay surfaces contain a net charge deficiency which is negative. There is also evidence that the edges of clay minerals contain positive charges.

In acid solutions, the surface of the clay minerals may become positive through adsorbed hydrogen or other cations along with the exposed cationic sites created from breaking of bonds, while lattice defects can explain the negative charges along the surface of the clay minerals in the particular solution. As the surface area increases, the total charge density and ion exchange capacity also increase (Faust & Hunter, 1967). Adsorption phenomena are most readily explicable on the basis of inequities or unbalanced forces at an interface, arising among solids, liquids or gases. Surface tension of a liquid enables a surface to assume a minimum area that is caused by molecular cohesive forces. Surface molecular forces tend to be attracted inward to the bulk of a liquid at a greater rate than their escaping tendency at the surface. This effect produces unbalanced forces at the interface and therefore the surface tension of a liquid can be lowered through the adsorption of a surface-active agent at the interface. The adsorbate is mainly bound to the adsorbent by two forces, i.e. Van der Waals forces, which are very weak, and covalent bondings, where the ions are not only adsorbed onto the surface, but in some minerals they become fixed into the crystal lattice.

Ion exchange

This phenomenon arises from the adsorption behaviour of charged surfaces. When exposed to water, the charged sites or layers are changed surface hydroxide groups that control the charge on the mineral surface. Depending whether the OH^--group dissociation is predominantly acidic or basic, the net charge on clay minerals is normally negative, though sites of both negative and positive charges may exist (Freeze and Cherry, 1979).

Thus, the nature of the surface charge is a function of the pH, i.e. at low pH-values the charge surface is predominantly positive, while at high pH-values, the charge surface is predominantly negative. This implies that the adsorption of cations and anions depends mainly on the pH of the solution. When a clay particle is in a dilute solution of water containing both ions of similar (-) and opposite (+) charge, the (+) ions would tend to adsorb near the surface at which point the electrical potential, developed at the solid liquid interface, is a maximum and the (-) ions would be found in the diffuse layer at lower electrical potential, resulting in an electrical double layer. This means that cations would tend to be adsorbed at the clay surface, while anions are repelled. However, if more positive sites become available along the surface, the reverse would occur (Faust and Hunter, 1967).

The probability that adsorption or ion exchange may occur through surface tension effects is naturally dependent on the dimensions of the internal and external surfaces. Thus, on the magnitude of the density, grain size, porosity, as well as the extent of the subsurface materials. The ion exchange capacity increases with an increase in pH and surface area (Faust and Hunter, 1967). Furthermore, they stated that ions with a large charge/ionic size ratio, would be adsorbed more readily. Therefore, the maximum adsorption should occur at a high charge and small ionic size. Ionic replacement follows the series monovalent < divalent < trivalent and therefore, the higher the valence of the ion, it seems to be more difficult to remove the ion from a clay mineral and the affinity for adsorption seems to be greater. However, for ions of the same valence, the affinity for adsorption decreases with decreasing ionic size, and increases with increasing atomic number (Matthess, 1982). Hydrogen is an exception, because it behaves as a divalent or trivalent ion most of the time.

The relative replacing power for negative surfaces is given by the following Hofmeister series:

$$Li^+ < Na^+ < K^+ < H^+ < Mg^{2+} < Ca^{2+} < Sr^{2+} < Ba^{2+}$$

Barium is thus held by a much stronger force than for example lithium. It must be emphasized that the order is not fixed for all minerals and is subjected to natural variations (David and De Wiest, 1966).

According to Stumm and Morgan (1981), the double-layer theory predicts qualitatively correctly that the affinity of the exchanger for bivalent ions is larger than that for monovalent ions and that this selectivity for ions of higher valency decreases with increasing ionic strength of the solution. In ground water, the exchange between Na^+ and Ca^{2+} is very important. The relative ion affinity during the exchange process may be defined by applying the principle of mass action to the particular reactions, e.g. where Ca^{2+} is exchanged for Na^+:

$$2\ \{Na^+ R^-\} + Ca^{2+} \rightleftharpoons \{Ca^{2+} R_2^{2-}\} + 2Na^+$$

and

$$K_{Na\ -\ Ca} = \frac{[Ca^{2+}]_E\ [Na^+]_S^2}{[Na^+]_E^2\ [Ca^{2+}]_S}$$

where

-R = the exchange site, i.e. the negatively charge network of the cation exchanger
E = the exchange phase
S = the solution phase

Thus, for any ion exchange reaction, K depends on the mole fractions of the ions involved, meaning that the activity ratio of the involved ions can be expressed in terms of molality and the activity coefficients:

$$\frac{[Ca^{2+}]}{[Na^{+}]^2} = \frac{\gamma_{Ca}\,(Ca^{2+})}{\gamma_{Na}^2\,(Na^{+})^2}$$

where

γ_A, γ_B = the activity coefficients.

A selectivity coefficient for the relevant exchange reaction can be defined by:

$$Q_{(Na-Ca)} = \frac{\gamma_{Ca}\,(Ca^{2+})}{\gamma_{Na}^2\,(Na^{+})^2} \bullet \frac{X_{Ca}}{X_{Na}^2}$$

where

X_{Ca}, $X_{Na}{}^2$ = the mole fractions of Ca^{2+} and Na^+.

Figure III-2 shows the typical exchange isotherms for the above-mentioned exchange reaction. From the figure, it is evident that in dilute solutions the exchanger shows a strong preference for Ca^{2+} over Na^+, correlating well with the ion exchange observed in unpolluted potable ground water. However, as the ion concentration increases, the selectivity of the exchanger decreases and the exchanger shows a strong preference towards Na^+ (Stumm and Morgan, 1981). The latter is generally known as reverse ion exchange.

Buffering is the resistance to a pH change of the soil solution. If the pH of the discharged water is between six and nine, the extent of buffering in most cases will be relative unimportant. The following aspects regarding buffering are important:

- The basis of the buffer capacity lies in the adsorbed cations on the exchange complex of the soil.

- The higher the ion exchange capacity, the greater the buffer capacity will be.

- The portion of the cation exchange capacity occupied by the exchangeable bases, is termed as base saturation.

- Higher base saturation correlates with higher pH and vice versa.

- The degree of buffering is lowest at the extremes of base saturation and higher at intermediate base saturation values.

Oxidation and reduction

Oxidation of organic matter in the topsoil and other surface deposits is an important pollutant attenuation mechanism. Together with reduction reactions, oxidation often works in conjunction with other pollutant attenuation mechanisms. Many of the attenuation processes which occur in the unsaturated zone, can also occur in the saturated zone, but in a somewhat different or modified manner. The lower oxygen content in the saturated zone reduces the possibility of oxidation of organic materials. Because organic matter is virtually absent in the saturated zone, the extent of adsorption is decreased.

In the usual ground-water system, surface areas of solid minerals are exposed to slowly moving water. The nature of mineral alteration products and the composition of the solution of the aquifer are controlled by the total environment. Thus, near sources of recharge, ground water contains dissolved oxygen and CO_2, which tend to dissolve carbonates and oxidize iron minerals. In the saturated zone, which is not in close contact with the atmosphere and where organic matter consumes the dissolved oxygen, reducing conditions are expected. Thus, transitional zones and the seasonal rise and fall of the water table impose oxidizing conditions on reduced minerals and vice versa. Generally, in redox reactions there are no force electrons, meaning that an electron balance is always maintained.

According to Lloyd and Heathcote (1985), the most important oxidizing agents in ground water are dissolved oxygen, oxo-anions such as nitrate and sulphate and water itself. Reducing agents in ground water include a wide variety of organic compounds, such as carbohydrates, humic substances, inorganic sulphides, such as pyrite, and iron silicates. Furthermore, they also state that most aquifers contain some reducing agents, while most water entering the aquifer contains oxidizing agents. Thus, as the ground water passes through the aquifer, the oxidizing agents are reduction agents, the most powerful oxidizing agents reacting first (e.g. DO $\rightarrow NO_3^- \rightarrow SO_4^{2-}$).

A very important reaction encountered in the study area is the oxidation of pyrite, which stems from the mining activities in the region. The following overall stoichiometric reactions characterize the oxidation of pyrite:

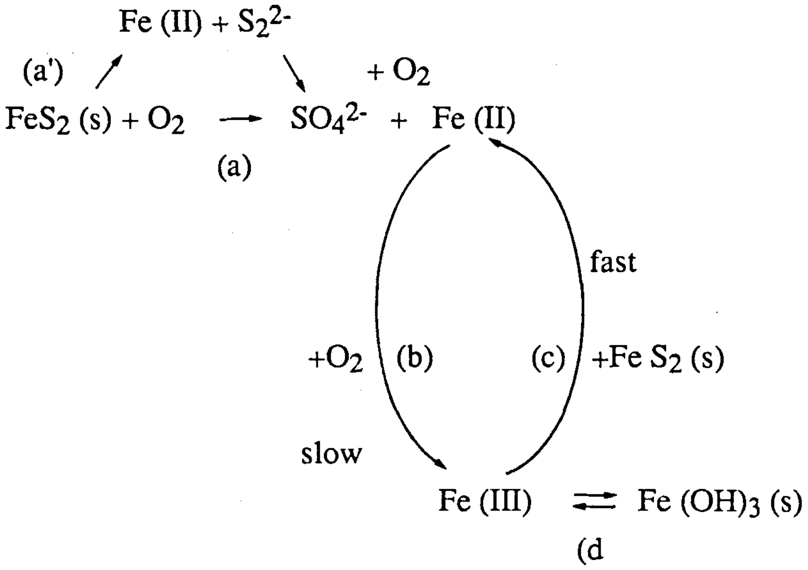
$$FeS_2\ (s) + 7/2\ O_2 + H_2O = Fe^{2+} + 2SO_4 + 2H^+$$

$$Fe^{2+} + 1/4\ O_2 + H^+ = Fe^{3+} + 1/2\ H_2O$$

$$Fe^{3+} + 3H_2O = Fe(OH)_3\ (s) + 3H^+$$

$$Fe\ S_2\ (s) + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

To explain the above oxidation process of pyrite, the following model (Stumm and Morgan, 1981) is used:



Pyrite is either oxidized directly by oxygen (a) or is dissolved and then oxidized (a'). The ferrous (Fe II) ion formed is further oxidized, very slowly (b) to ferric iron (Fe III), which is rapidly reduced by pyrite (c), releasing additional acidity and new Fe (II) to enter the reaction through (b). Precipitated ferric hydroxide serves as a reservoir for soluble Fe (III) (d). If the regeneration of Fe (III) by reaction (b) is halted, so that the concentration of soluble Fe (III) decreases, it will be replenished by dissolution of the solid Fe $(OH)_3$ and will be free to act again, should it come into contact with additional FeS_2.

Important to note is that micro-organisms influence the overall reaction rate by mediating the oxidation of ferrous iron. More detail about the biological degradation will be discussed subsequently.

Volatilization

Volatilization is when chemical constituents are lost as a gas. According to Everett (1980), no quantitative procedure is proposed to evaluate the extent of this phenomenon and it is therefore of more importance to be aware of the chemical constituents that may be affected.

Biological degradation and assimilation

Biological degradation and assimilation are extremely important in the removal of organic and biologic constituents. Many organic chemicals can be removed or attenuated by biological activity in the vadose zone. Some chemical constituents are strongly assimilated and concentrated by plants, while other chemical constituents can be removed by crop uptake.

Microbial metabolism is of great importance to the quality of surface and ground water. As previously mentioned, the micro-organisms do no affect the direction of any reaction, but they do affect the rate of reactions (Matthess, 1982). Three main groups of micro-organisms are generally found in surface- and ground-water systems:

(i) Bacteria.
(ii) Actinomycetes.
(iii) Fungi.

An environmental factor controlling the presence of specific type of organisms, is the absence or presence of oxygen. Micro-organisms can be divided into anaerobic and aerobic types.

It is a well-known fact that bacterial action, for example by the *Thiobacteriaceae* family, can assist the oxidation of pyrite under moist conditions. These bacteria are motile, non-capsulated rod (0,6 to 1,6 µm) with a viable pH range of 1 to 4,6, but an activity range limited to a pH of 2,4 to 3,5 (Mitchell, 1978). Differentiation between two species, namely *Thiobacillus thiooxidans* and *Thiobacillus ferrooxidans* has been based upon their ability to catalyse sulphur or iron oxidation. *T. Thiooxidans* is an iron bacteria and *T. ferrooxidans* can catalyse both iron and sulphur oxidation (Mitchell, 1978). Under ideal conditions, the presence of these bacteria can speed up the rate of oxidation by several orders. Favourable conditions for the bacteria have been established as follows (Förstner and Wittmann, 1981):

(i) Large surface area, small particle size.
(ii) Temperature between 30° - 35°C.
(iii) Sufficient nutrients, e.g. for *T. ferrooxidans,* organic carbon, iron sulphate, pyrite, calcium nitrate and ammonium sulphate.
(iv) Aeration.

The above-mentioned reactions are major contributors to the fact that mine drainage has a low pH and a high sulphate content. A consequence of the low pH of mine drainage is the fact that metal salts become very soluble at a low pH.

Although techniques by which to quantify the chemical changes as they move through the vadose zone do exist, the matter usually becomes very complicated and therefore do not warrant further attention for the purpose of this investigation.