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# PREDICTION TECHNIQUES AND PREVENTATIVE MEASURES RELATING TO THE POST-OPERATIONAL IMPACT OF UNDERGROUND MINES ON THE QUALITY AND QUANTITY OF GROUNDWATER RESOURCES

by

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# PREDICTION TECHNIQUES AND PREVENTATIVE MEASURES RELATING TO THE POST-OPERATIONAL IMPACT OF UNDERGROUND MINES ON THE QUALITY AND QUANTITY OF GROUNDWATER RESOURCES

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### EXECUTIVE SUMMARY

### 1 BACKGROUND INFORMATION AND SCOPE OF INVESTIGATION

Over the past ten years, the issuing of closure certificates has dwindled to a point where very few closure certificates have been issued. Uncertainties in terms of the long-term water quality in these mines are often too great for the Government to issue closure certificates with confidence.

This research was initiated in view of this difficulty in issuing closure certificates. The scope of the investigation was as follows:

- To evaluate and document the current impact of closed underground mines on the quality and quantity of groundwater resources, in order to select suitable sites for further detailed investigation, thus generating an impact rating system that could also be applied to operating mines.
- To evaluate, with the aid of field observations, various credible preventative
  options to minimise the undesirable impacts of water quality deterioration
  and influx relating to underground mining.
- To select or design reliable tools for the prediction of water qualities and quantities during the post-closure phase, to provide information for closure and to assess the applicability of these tools to South African conditions.

The first research objective dealt with the evaluation and documentation of the current impact of closed underground mines on the quality and quantity of groundwater resources. This work formed part of the development of a risk assessment procedure. It provided a broad overview of the problems associated with mine water management, identifying the issues that could, in the long run, present serious problems when applying for closure of the mines.

The second objective stated the use of field trials to identify credible management options. Field trials are ongoing at all of the mines through variations in mining methods, monitoring and different solutions that have already been implemented. These solutions may be in terms of water and salt minimisation, impact prediction, alternative water supply for affected parties, desalination and use of mine water. In terms of achieving this aim of the investigation, three existing systems have been investigated. Aspects that should be explored in greater detail have been identified. A selection has been made of issues that will have a positive impact on water quality and quantity.

The third objective related to predictive tools. A wide selection of these tools is generally available. Most of these require expert knowledge of hydrochemical processes and flow dynamics. These tools have been used to model and understand the systems in question. A high priority in this research was the development of alternative and simplified methodologies that can be used as general tools by the mining community. These simplified methodologies are based on sound principles of flow dynamics, hydrochemistry and geology. They should go a long way in providing a better understanding of the systems investigated.

### 2 APPROACH

The first step in this research was to develop a risk assessment procedure that could be used to evaluate the risk of groundwater pollution from a mining operation. This enabled the classification of mines and mining activities according to their potential impact on groundwater resources in their vicinity.

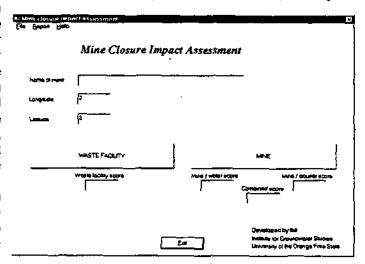
Following this and based on the outcome of this risk classification, three issues were selected to be investigated in greater detail. These are:

- Underground high extraction of coal in the Mpumalanga Coal-field.
- · Mining in coal outcrop areas of KwaZ ulu-Natal.
- · Gold mining in the West Rand

### 3 RISK ASSESSMENT

A software package, called RISKY, has been developed as part of this research, to be used by the mining industry. The software should be used on various levels to screen mining activities in terms of its potential impact on groundwater resources. This evaluation takes place on three levels, namely the

risk associated with surface disposal, the mine water character and the aquifer character. The software calculates a numeric score, called risk factor. The higher these factors, the greater is the risk terms of potential long-term impact. As a trial study, the software has been applied to the collieries in the Mpumalanga area.



The following are the main conclusions from the application of the RISKY procedure:

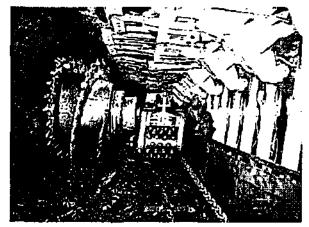
- Categories and classes used for the evaluation of the mines are sufficiently general to be used for mines where a minimum of information is available. The evaluation may therefore be used as a first approximation, to either decide between various options or to evaluate the performance of one mine against another.
- As more information becomes available at mines, the quantification procedures used to evaluate each category or class can be refined. The RISKY software does not need to change, but accommodates input from more sophisticated systems.
- The weighting between categories and classes and the facility to fit non-linear distributions across classes should be sufficient to accommodate most situations. If these facilities prove to be inadequate, it is possible to program a suitable equation into the evaluation, so that the RISKY procedure does not become invalid.

- In the event that additional categories or classes need to be added to the system, this can also be done without jeopardising the operational simplicity of the RISKY software.
- The combination of the RISKY procedure with a Geographic Information System and the possibility of displaying any of the scores in each of the categories as GIS coverages, significantly enhance the applicability of the system. The power of spatial visualisation of specific issues has been extensively demonstrated in this research.
- It is recommended that the database on which these evaluations have been based, should be refined to incorporate information for all mines in South Africa. The quality of the information used for the Mpumalanga mines should also be verified. Through the introduction of this procedure to the industry and government departments, a common denominator will be created which may be used during mining, as well as after closure, to evaluate performances on a regional and in a comparative way.

### 4 UNDERGROUND HIGH EXTRACTION OF COAL

Underground high extraction of coal has been performed for many years in South Africa. The impact that this has on groundwater and surface water resources has been investigated in most instances, and this information is available as part of EMPR applications.

Much of this information is of a historic kind and does not allow prediction with confidence of the final



geohydrological and hydrochemical outcomes of such systems. This complicates matters when applying for closure of a mine. Uncertainties associated with future water quantities and qualities are often too great. In view of these uncertainties, the investigation is aimed to:

- Provide a summary of the status quo for groundwater in underground high extraction areas.
- Investigate, through modelling, the recovery and decanting phases after mining has ceased.
- Provide recommendations into ways and means that the impact of underground high extraction can be minimised.

The following conclusions are drawn from this investigation:

- Underground high extraction of coal is a well-established practice in the South African Coal-mining Industry. For the next 30 years, some 40000 ha have been earmarked for extraction by this mining method.
- Underground high extraction of coal collapses the overlying strata and drains the groundwater from it. A typical projected influx rate is 15 ML/d for a mine of 12000 ha.

- This water is contaminated in mines to the extent that it cannot be disposed
  of in streams without special considerations. Neither can this water be used
  for agricultural purposes, predominantly because of its high sodium content.
- Operating high extraction mines encounter significant problems in underground water management, because of the large volumes of water involved. It has been demonstrated in this research that these problems are mainly the result of the sequence of mining. It is suggested that all mines should, on average, be able to cope with the influx of water on condition that they commence high extraction in the deepest part, retreating to higher ground.
- One of the current options for mine water handling is to pump it to surface, where it is desalinated. The disposal of the brine from the desalination process presents a problem for which there is currently no solution.
- It is suggested that longwall mining, as a mining practice, should seriously be re-evaluated. Of all high extraction mining methods, it inflicts the greatest impact on overlying aquifers. Longwall mining is also the least flexible mining method in terms of manoeuvring around structural discontinuities on the coal-seam horizon. Streambeds are often undermined for the sake of continuity in the development of a longwall panel. If at all possible, longwall mining should be replaced by shortwalling or, better still, stooping. The most environmentally friendly option would obviously be bord-and-pillar mining. Streambeds should not be undermined by high extraction unless the mining company can prove that this would have no impact on surface run-off and water infiltration.
- To date, mines have seriously neglected the importance of surface rehabilitation above collapsed high extraction areas. The importance of minimising rain-water ingress through collapsed areas cannot be stressed sufficiently. Surface cracks should be destroyed by ploughing across collapsed areas. In areas of rock outcrop, cracks should be filled in and surface run-off should be diverted around these areas.



 All mines performing underground high extraction should do proper planning for the post-closure phase. The quality of the water that will decant from these mines will be site-dependent and can be managed to some extent. Systems for water management should be based on current and proven technologies, which subscribe to the current objectives of water quality management by the DWA&F.

Based on our current knowledge of water ingress into areas of underground high extraction of coal, the following recommendations are made:

- Mines should seriously revise and motivate their life of mine plan for high extraction in the light of results obtained.
- Mines should do their utmost in minimising water influx into high extraction areas by instigating an active programme of surface rehabilitation, the most important of which should be:
  - > A soils map of the total surface area above underground high extraction should be prepared.

- After collapses have occurred, areas with sufficient soil cover should be ploughed over as deeply as possible to destroy any cracks that penetrate to surface.
- Areas with insufficient soil cover should be inspected for cracks and these should be filled in. Rock outcrops are usually along slopes and surface run-off should be diverted around these areas, thus minimising the possibility of water cascading into the mines.
- Pans that develop above areas of high extraction should be provided with outlets by trenching. No water should be allowed to accumulate in the pans.
- Streams should, under no circumstances, be undermined by underground high extraction.
- Annual inspections should be made of rehabilitated areas to ensure that these areas are operating as was originally intended.
- Mines should submit a post-closure plan for water management during and after the recovery phase of the water levels. This plan should form part of their EMPR.
- Mines should have at least one dedicated, well-trained person in charge of mine water management. His job description should be the management of underground water to minimise volumes and pollution; plan and supervise surface rehabilitation; perform groundwater investigations and verify predictions. He should enter data into a database, process this data and extract information in a way that allows the identification of trends. He should understand processes - both chemical and hydraulically, and be able to report in a format acceptable by the DWA&F.

### 5 COAL MINING IN OUTCROP AREAS OF KWAZULU-NATAL

Significant topographic differences are present in the KwaZulu-Natal Coal-fields. Coal deposits have, in many instances, only been preserved within the mountains. Outcrops of coal are therefore plentiful along many of the mountain slopes. In these instances, the depth of the coal seams below surface typically ranges from 0 m to more than 100 m below surface. Access to these coal deposits has been gained by tunnelling into the mountainside. This is typical of the Vryheid Coal-field, but also applies to the Utrecht and Newcastie areas.

Mining in these areas has dominantly been of the bord-and-pillar type, followed by pillar extraction in many instances. As a result, the overlying strata have, in most instances, collapsed. The severity of these collapsed structures varies from area to area.





Many of these mines have very little holding capacity for water with the result that mine water often flows freely from the mines via adits into valleys below.

The Department of Water Affairs and Forestry extensively monitors water quality in streams of KwaZulu-Natal.

The area of particular interest to this study is the Vryheid Coal-field and the tributaries leading away from mines in this area. The results suggest that:

- . The acid-generating potential of the coal mostly exceeds its base potential.
- The base potential, if any, is present in a variety of mineralogical forms, such
  as sodium carbonate, calcium/magnesium carbonate and iron carbonate.
  The latter only has a temporary neutralising impact. In many of the instances
  examined, most of the sodium and calcium/magnesium carbonate have
  already been depleted through leaching and reaction with acid water.
- In aerated environments, acid generation starts on the outer surface of a mine work face, boulder, rock or grain. Carbonates on the outer surface counteract acidification until they are depleted. Acidification of outer surfaces is therefore fairly rapid, while the inner portions are still unchanged. In flooded areas, water is in constant contact with the coal. Here, water siphons along fractures into and through the coal. Carbonate minerals are present in the fractures and react with the acid water. It is often observed that sections of mines that have historically been acid during mining, become alkaline when they are flooded. Whether or not this is a permanent change in the pH will depend on the amount of neutralising agent available, the degree of flooding and flow dynamics. In areas that are not flooded, reaction between the acid water and the carbonate veins cannot occur.
- In the Nkongolana area, only about 5 20% of the underground workings can be flooded with water. Only a small portion of the mines therefore has a potential to convert back into an alkaline phase. The neutralising potential of the coal in these areas is therefore inade quate for sustained neutralisation of all acid produced in the rest of the mines. The conclusion is that at some stage in the future, current alkaline sections of the mines are likely to become acid. To postulate about the time that this will take is not meaningful without significantly more information.
- To rehabilitate the top of the mountain, filling all cracks is not possible. The
  mountains are inaccessible over much of the area. Suitable material to fill
  the cracks is not available. Recharge as experienced in the past will
  therefore continue indefinitely.
- Therefore, very little remains that can be done to improve the long-term chemistry of the mine water in the Nkongolana area. Mining methods applied and the intensity are the main reasons for the current situation. In new mining areas: (1) Pillar extraction should not be allowed unless the mining company can guarantee minimal and manageable impacts on water quantities and qualities; (2) Access to underground workings should be from the highest topographic position, with the mine floor sloping away from the entrance. These recommendations are, however, too late in many respects, because most of the coal in mountainous and outcrop areas of KwaZulu-Natal has already been extracted. Many small fringe areas of coal still exist that can mainly be mined by opencast methods. It is important that the GME and the DWA&F keep proper control on mining in these areas thus limiting local environmental impacts.
- Apart from the fact that very little can be done to minimise mine water
  pollution at the source, other innovative schemes may be implemented
  where and when required. Lime dosing, wetlands, anoxic drains, dilution or
  mixing of mine waters or disposal into the sea are but a few possible

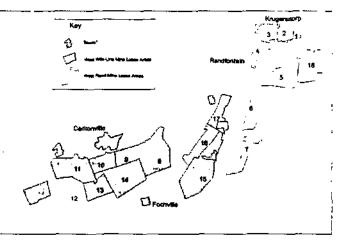
solutions. The detailed discussion of these is beyond the scope of this report.

- In terms of mine closure, it would not be reasonable for the authorities to
  insist that mining companies should take indefinite responsibility for water
  management at these collieries. The problems at this coal-field are clearly a
  legacy of circumstances born from ignorance in terms of the potential
  environmental impact. Legislative requirements have also become
  considerably tighter over the period in question. A workable solution should
  include responsibility on the part of the Government.
- It will be almost impossible for a single company to implement workable solutions on their own for mine water management in the Nkongolana Catchment. It is suggested that a collaborative approach should be adopted. This collaboration should include the authorities, without whose sympathetic and imaginative approach no solution will be forthcoming
- The quality of monitoring by the mines has improved tremendously over the past two to four years. They all have electronic databases (HydroCom) and process this information using the WISH software package. The development of both these packages was partially sponsored by the WRC. Individuals from the relevant mining houses have been on training courses at the IGS and are capable of performing monitoring and data processing themselves. It is recommended that monitoring should continue along the lines set by the mines during the past four years. Of particular interest would be the investigation of trends at the two VCC adits, at the Vrede Gap, discharge from Hlobane through the wetlands and from Wintershoek. From a compliance point of view, other localities will also have to be monitored.

### 6 GOLD MINING IN THE WEST RAND

### 6.1 Introduction

This research focussed on the post-operative hydrogeological impacts of the two gold-mining areas. west Johannesburg, referred to as the West Rand and West Wits Line. The study investigated an area of over 2500 km<sup>2</sup>, a large portion of which. has been influenced by mining activity. At this scale, the investigation is an



overview of the situation. There are many variables that could not be considered at this scale as their influence would require detailed investigation that was not possible within the constraints of this project.

Seventeen mines have been established in this area. They have varying lifespans and impacts on the groundwater resources in the area.

VII

The principle aquifer under consideration is the dolomitic aquifer of the Malmani subgroup which has been compartmentalised by several north-south trending syenite dykes of Pilanesberg age. Groundwater moves rapidly in large volumes through large solution cavities in the dolomites. This groundwater flow, along with the Wonderfontein Spruit, forms a continuous link between the mining areas. These areas may warrant special protection due to the very valuable groundwater resource that they contain.

Due to the dolomites which occur across the area, problems have been experienced with water in the mines. Consequently, the mines pump out large volumes of water from the compartments to dewater the dolomites.

### 6.2 Mined Out Volume and Rewatering Rates

The method of volume estimation is based on mine production figures:

The wettest mines in this area were overlain by dolomite. Enslin *et al.* (1967) showed that rainfall recharge of the system was equal to the average annual flow of springs issuing from the dolomite. Thus after mining, recharge of the mine openings and the dewatered dolomites will be at the rate of the original springs flowed. The time to fill can be calculated from the mined volume and the steady state spring flows as shown in Table 1.

Additional time will be required to fill the dewatered karst. (This is given in Table 2.)

Table 1.	Rewatering til	me estimates.
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Mine Groups	Mined volume	Spring	Spring Flow	Time to Fill	
	(ML)		ML/day	Short (years)	Long (years)
Old West Rand (Champ D'Or, Luipaardsviel etc.)	48221				
West Rand Randfontein	44402		30.0	8.4	
West Rand WAGM and		Gemsbokfontein			
REGM (Cooke and Doornkop)	114256	(Zuurbekom leakage?)	8.9		36.9
West Wits Kloof	99511	Venterspost	21.2	6.1	13.1
		Bank	47.9		
West Wits Carltonville	217106	Oberholzer	55.0	15.5	22.3

Table 2.	Storage in the dolomites and additional time required to rewater the
	storage.

Compartment	Total Volume Removed		Dynamic volume from mine records		Dynamic volume from DWA records		Storage in compartments (ML)		Time to rewater Dolomites (years)	
	Period	(ML)	Constant dewatering rate (ML/day)	(ML)	Eye yields (ML/day)	(ML)	Mine Records	Eye Flows	Mine Records	Eye Flows
Bank	1969-1996	1009810	70	690323	47.9	472362	319488	537448	18.2	30.7
Oberholzer	1952-1996	1108150	50	803550	55.0	883884	304600	224265	15.1	11.1
Venterspost	1968-1996	412320	40	409080	21.2	216871	3240	195448	0.4	25.2
Gemsbokfontein	1986-1996	219000	?		8.9	42348		176651		54.2

### 6.3 Sinkhole development

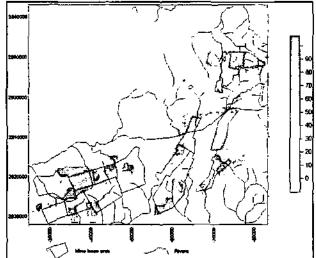
The stability of the dolomites was affected by dewatering. This resulted in catastrophic sinkhole development in the 1960's. Upon rewatering, the karstic caverns should fill with water allowing stability to increase. Under normal recovery and normal rainfall, the metastable conditions will be unaffected.

### 6.4 Sources of contamination

Many of the mine waste dumps are on the dolomites, because their underdrain characteristics increased dump stability. Mine waste disposal has allowed significant leachate to infiltrate the dolomite. Along with development of the area domestic and industrial wastes have been disposed of so adding another threat to the water resources of the dolomite. Water in the mines is of reduced quality. In some mines, it will discharge into the karst aquifer thus adding an additional pollution load.

## 6.4.1 The most important conclusions relating to water contamination in post-mining times are:

- The surface water entering the West Wits Line Area is, in many cases, contaminated before entering the area.
- Water polluted by leachate from mine dumps, so called acidmine drainage, shows characteristically high sulphate concentration and high dissolved salts.
- Surface and groundwater show the same classification thus confirming what the hydrogeology suggests, i.e. that the



waters are intimately related. This relationship and high recharge of groundwater from surface streams are relatively unique in this area and are due to the karst topography.

- The Boskop Dam, the receiving water body for the Wonderfontein Spruit, shows deteriorating quality. Salinity and sulphate are mainly responsible.
- Conditions exist for uranium to be transported in solution in these waters.
  Thus radiogenic material may be migrating, dissolved in groundwater, to be
  consumed at some other point where radioactive contamination may not be
  expected.
- The mine waste sites, the source of this pollution plus other wastes are difficult to identify, isolate or control, thus the pollution is diffused. Because of this, pollution will continue even when the mines have ceased operations.
- Due to the presence of the dolomites, the final discharging water will have a neutralised pH but could have a high salinity
- Pollution which occurs while mining is in progress will, in spite of environmental concerns, continue or get worse after responsible authorities (owners or mining companies) have left the area.
- 6.4.2 The most important conclusions relating to the concerns about dolomite dissolution and instability in post-mining times are
  - The mines influence on surface water is to increase all total dissolved solids as shown by the EC values; sulphate is increased by additional of acid water, a rise in chloride and sodium. Other constituents for example calcium and magnesium are characteristically high because of the dissolution of dolomite.
  - Increased salinity and lowered pH of acid-mine drainage will increase the waters' ability to dissolve dolomite.
  - Initially oxidising conditions will exist in the mine openings. The initial water will be of poor quality. The system will be dynamic preventing stratification. If this water recharges the dolomites significant dissolution of the dolomite could occur. If the water quality were that of the Blyvooruitzicht fissure and the rewatering rate was 60ML/day (an average between the dynamic records and the original eye flow), more than 6000 m³ dolomite/year will dissolve. This will have two major implications:
    - Significant widening of preferred pathways causing greater overall transmissivity in the dolomites and greater storage volumes.
    - Possible stability problems, should excessive karstification result.

The karstic aquifer that exists in this area and widening of existing solution openings have implications for groundwater flow that follows preferred pathways. This has serious implications for any modelling that assumes that the dolomites are a porous medium<sup>1</sup>.

### 6.5 Modelling

### 6.5.1 Modelling pollution from surface sources

Distribution and directions of mine waste-derived pollutant migration, with and without pumping, were modelled. The pollutants form a diffuse source that influences most of the catchments in this area. The pollution migration patterns

corresponded closely with migration postulated by Coetzee *et al.* (1996), based on remote geophysics sensing and GIS modelling of a portion of this area.

Modelling of the West Rand mines was reported on by Krantz (1997) and gave predicted filling times of the mines between 4.2 and 7.2 years. His predictions correspond well with figures found in this investigation which gave estimates for the same area of 8.5 years. This independent approach confirmed the "expected time to fill" calculations by volume methods given in this report.

A three-dimensional model of the Bank compartment was developed to establish an approach and evaluate the aquifer parameters. The model was able to generate water levels that matched measured values for both deep dewatering and recovered water levels (or pre mining levels). The recovery of water in the system gave a recharge period of 21 years after pumping stops. This compared well with the calculations shown previously. Having achieved realistic results with the Bank model, the approach could be applied to neighbouring data poor compartments. This was done with success and the usefulness was applied in the scenario models.

### 6.5.2 Modelling pollution from rewatering

The possibility that water in the mines might pose a problem was considered. Conceptual, visual and numeric models were used to evaluate this section. Due to insufficient measured or known parameters, the conceptual model drives numeric models, and results obtained are a function of the conceptual model.

Two main models, synchronous and compartmentalised water rise, were envisaged with a third, thermal convection, modifying the two end members.

### 6.5.2.1 Impacts of Model 1

Some of the contaminated mine water is mixed with recharging water by the U-tube like flow. This continually contaminates the dolomites with the high salinity water.

### 6.5.2.2 Impacts of Model 2

All the original karst is recharged. The groundwater is stratified with the poorest quality, dense water at the bottom. Thus contaminants from the mine excavations do not affect the water quality of the aquifer. If leakage through the dykes occurs, the deep contaminated water will only affect the mines. Shallow leakage is between karst and has always occurred.

### 6.5.2.3 Impacts of Model 3 on 1 and 2

If thermal convection were to modify the Model 1 situation it would add to the Utube effect, ensuring more complete mixing of mine water and the water in the dolomitic aquifer. This would ensure that the worst mine water continually moved into the aquifer. Thermal convection would work against density stratification so that good quality water exchange above the mines would be contaminated by thermally driven poor quality water rising from the shafts.

### 6.5.2.4 Feasibility of Model 3

This was evaluated using empirical relationships and graphical presentation. The temperature density driver is greater than the salinity stratification driver.

However, thermal convection is reduced by the porosity in the formation. An empirical calculation showed that thermal convection was unlikely.

### 6.5.2.5 Calculation of the impact

From the chemistry of the system it was shown that acid production and hence water degradation should stop after flooding of the mine openings. Thus the water trapped in the system at completion of rewatering will be the worst. Further exchange will dilute the water and concentrations will decrease logarithmically. From first principles and the average values given by large scale steady state pumping from the mines, loads and renewal times could be calculated. These are given in Table 3.

Table 3. Loads and renewal times.

	Original discharge load (kg/day)	Load after 6 <sup>th</sup> renewal (kg/day)	Renewal Time (years)
Bank	2.80E+04	4.38E+02	222
Oberholzer	1.58E+04	2.47E+02	393
Venterspost	1.50E+04	2.34E+02	37

The long renewal times imply that an ongoing problem might exist. In reality far less of the contaminated water will be flushed out due to incomplete mixing and dead end mine voids, thus the renewal time would be shorter. Three dimensional model results were in line with the conceptual and calculated results.

### 6.6 Scenario management

There are two option groups

- · Full recovery of water levels and natural water passage through the system.
- Control of water recovery and discharge from the system by pumping.

The first option is appealing as it is self-managing and therefore sustainable. The second option offers an engineered type of control but has many disadvantages, including:

 The long-term (endless) pumping costs and responsibility would be impossible for any of the mines to take on. Mine-closure approval would be extremely difficult to obtain, as the state would have to be sure that pumping costs would never revert to them.

The continued pumping option could only be accepted if it were self-sustaining and cost-effective. Options to achieve this for the West Rand mines are part of a project that is currently being investigated.

Several permutations within each of these option groups were considered.

### 7 EVALUATION OF RESEARCH OBJECTIVES AND ACHIEVEMENTS.

The following are opinions of the authors as to the degree to which the research objectives have been met:

7.1 To evaluate and document the current impact of closed underground mines on the quality and quantity of groundwater resources, in order to select suitable sites for further detailed investigation, thus generating an impact rating system that could also be applied to operating mines.

A mine risk assessment procedure has been developed which runs under Windows 95/98 or NT has been developed and demonstrated. It is user-friendly and has been applied with success to mining in the Mpumalanga area. This software is available free of charge from the IGS Web site (www.uovs.ac.za/igs). The rating system is based on the evaluation of 22 parameters, information generally known by mines. They should, without any difficulty, be able to calculate risk factors for specific situations.

7.2 To evaluate, with the aid of field observations, various credible preventative options to minimise the undesirable impacts of water quality deterioration and influx relating to underground mining.

Field trials on many levels are ongoing in the mining industry. Mines willingly participated by contributing their data and providing assistance in the generation of additional information. Three typical scenarios were investigated, all three being pressing issues in terms of their potential long-term regional impact. It is our opinion that information generated during this investigation contributes significantly to a better understanding of these systems and quantifies the long-term potential impacts.

7.3 To select or design reliable tools for the prediction of water qualities and quantities during the post-closure phase, to provide information for closure and to assess the applicability of these tools to South African conditions.

Many models are available for the prediction of pollution transport and chemical reactions. In this research, the focus has been on the understanding of processes, the extraction issues that really matter and the explanation of these issues in a way that the mining community can understand. Finite element models have been reduced to displays and graphs that can be used for first order evaluations. The power of this work lies in the simplification of the tools. If necessary, these can be supplemented by the sophistication of numerical and chemical modelling.

### 8 RECOMMENDATIONS FOR FURTHER WORK

The most important issue emanating from this study is that insufficient data is often available to evaluate the regional and long-term impact of mines, particularly for the period after closure. The details in the EMPR documents are mostly of a descriptive nature and insufficient for a scientific regional impact assessment. The following recommendations are made for further work:

Establish regional information systems

Regional information systems that combine relevant information from the mines should be established and maintained. The RISKY software, coupled with GIS, is a first step. The Intermine Flow Project, currently under way, would also serve as a sound basis for the establishment of such a regional information system.

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### investigate areas of insufficient information

Regional risk factors should be extracted from the regional information system. Investigations should be launched into areas of insufficient information. These should be researched to the extent that they could serve as guide-lines for granting closure. The regional information system should be populated with relevant time series and other data that can be used for extrapolation purposes.

### Integrate data

Integration of the numerous bits of information should be done. Water is an interrelated discipline. Many studies have been done to date on mine water deterioration. This information should be integrated to identify data deficiencies and allow the definition of solutions.

### Define solutions

Definition of solutions at a very early stage is essential. The industry and the government should tackle problems from a futuristic point of view. Solutions that would be valid in 50 years from now should be identified, researched and implemented as a combined strategy.

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### 1 INTRODUCTION

### 1.1 Background information and scope of investigation

South Africa is a country blessed with an abundance of minerals. Most of these occur subterranean and underground mining is necessary to extract them. Associated with mining is usually a deterioration in mine water quality. This could, depending on the exact hydrodynamics of these systems, impact on surface and groundwater resources in the vicinity of the mines.

Some mines, particularly those that contain sulphide-bearing minerals, list among a high risk to pollute water resources. This is due to oxidation of the sulphides after mining comences, producing sulphuric acid. Many such mines exist in South Africa. These are, for instance, the gold, base metals and coal mines.

Once all economically mineable minerals have been extracted from a mine, they are left to fill up with water. As the water level in these mines rises, a level is reached where mine water starts seeping into adjacent strata, thus polluting aquifers. At higher levels, water will decant from the mines to enter directly into streams.

Under current legislation, mines that cease production, remain the property of the original owner until a closure certificate has been obtained. Owners are responsible to manage any environmental impact, whether it is surface subsidence or contamination of water to the satisfaction of the Departments of Mines, Water Affairs and Forestry and Environment and Tourism.

Over the past ten years, the issuing of closure certificates have dwindled to a point where very few closure certificates have been issued. Uncertainties in terms of the long-term water quality in these mines are often too great for the Government to issue closure certificates with confidence.

In view of this difficulty in issuing closure certificates, this research has been initiated. The scope of this investigation is as follows:

- To evaluate and document the current impact of closed underground mines on the quality and quantity of groundwater resourcies.
- To select and demonstrate, with the aid of field trials, various credible management options, thus minimising undesirable impacts of water influx and water quality deterioration in underground mining.
- To select or design reliable tools for the prediction of water qualities and quantities during the post-closure phase.

### 1.2 Approach to the research

The first step in this research was to develop a risk assessment procedure that could be used to evaluate the risk of groundwater pollution from a mining operation. This enabled the classification of mines and mining activities according to their potential impact on groundwater resources in their vicinity.

Following this and based on the outcome of this risk classification, three issues were selected within the mining industry, to be investigated in greater detail in terms of their potential to pollute groundwater resources after closure. The scope of these investigations was threefold:

- To demonstrate our current understanding of the potential outcome and the complexity of these systems.
- To propose and discuss management options that would lessen the potential environmental impact over the long term.
- To provide sufficient knowledge on a regional basis for the mining companies and the DWA&F, in order to quantify the extent of the potential impact and act thereupon.

The areas that were selected for detailed investigation are:

- Underground high extraction of coal in the Mpumalanga Coal field.
- · Mining in coal outcrop areas of KwaZ ulu-Natal.
- · Gold mining in the West Rand

Apart from these, many other water-related issues of importance also exist in the mining industry. Most of these have already been detailed in previous investigations. Examples are the East and Central Rand (Scott, 1995), the Free State Goldfields (Cogho *et al.*, 1992) and the Mpumalanga opencast mining (Hodgson and Krantz, 1998). Relevant information from these studies will be incorporated in this investigation.

### 1.3 Structure of this report

This report consists of eight chapters. The first chapter is an introduction to the scope of the research. Chapters 6, 7 and 8 contain the overall conclusions, recommendations and list of references.

The rest of the document, namely Chapters 2 - 5, contains the crux of this investigation.

Chapter 2 explains the reasoning behind and the development of the risk assessment for the potential impact that mines may have on groundwater occurrences. Chapter 3 details the impact of, and possible solutions to, underground high extraction of coal. Chapter 4 discusses, by way of using the Vryheid Coal-fields as an example, the status of coal mining in Natal and its potential impact on water resources. Chapter 5 investigates the potential long-term impact of gold mining in the West Rand on the groundwater in the dolomite aquifer.

### 1.4 Research objectives and interpretation thereof

The first research objective deals with the evaluation and documentation of the current impact of closed underground mines on the quality and quantity of groundwater resources. This work forms part of the development of a risk assessment procedure. It provides a broad overview of the problems associated with mine water management, identifying the issues that could, in the long run, present serious problems when applying for closure of the mines.

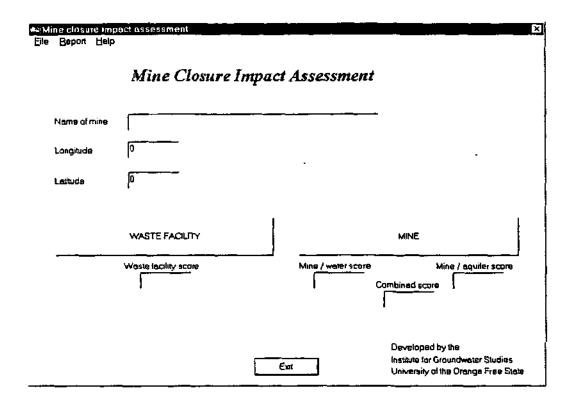
The second objective states the use of field trials to identify creditable management options. Considering the scale of mining in South Africa, field trials are ongoing at all of the mines, through variations in mining methods, monitoring and different solutions that have already been implemented. These solutions may be in terms of water and salt minimisation, impact prediction, establishing alternative water supply for affected parties, desalination and use of mine water. In terms of achieving this aim of the investigation, three existing systems have been investigated. Aspects that should be explored in greater

detail have been identified and a selection of issues that will have a positive impact on water quality and quantity has been made.

The third aim relates to predictive tools. A wide selection of these tools is generally available. Most of these require expert knowledge of hydrochemical processes and flow dynamics. Although these tools have been used to model and understand systems in question, a high priority in this research was the development of alternative and simplified methodologies that can be used as general tools by the mining community. These simplified methodologies are based on sound principles of flow dynamics, hydrochemistry and geology and should go a long way in providing a better understanding of the systems investigated.

The overall conclusion is drawn that this investigation has covered essential ground that was previously not researched on this scale and documented. It should serve as a guideline for the mining industry and the DWA&F in terms of the *status quo* of what should and could be done to minimise water pollution within the mining industry.

# 2 RISK ASSESSMENT FOR GROUNDWATER POLLUTION FROM MINES IN SOUTH AFRICA



Chapter by

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# 2 RISK ASSESSMENT FOR GROUNDWATER POLLUTION FROM MINES IN SOUTH AFRICA

### 2.1 Scope of investigation

Mining, as the name implies, is a non-renewable activity and the inevitable fact of starting a mine is that it will stop some time in the future. In South Africa, mines that stop working are required to submit an application for closure to the Government Mining Engineer in terms of the Minerals Act No. 50 of 1991, Sections 12, 39 and 54. In spite of this, the mining industry in South Africa has experienced considerable difficulty in obtaining a permit for closure. This has often been because insufficient information was available to confidently predict the long-term impact that the mine may have on groundwater resources in and around these mines.

Many mines have the potential to impact on groundwater or surface water either by the water that collects in the mined cavities or from water interacting with surface dumps. The National Water Act No. 36 of 1998, Part 4, deals with the prevention and remedy of water pollution. The Environmental Conservation Act No. 54 of 1989, Sections 19 (1) and (2), deals with the management of surface pollution sources. Although mining waste is currently excluded from the Environmental Act, sufficient legislation is in place to ensure that the post-operational impact of mines on water resources in and around defunct mines can be controlled. Apart from these Acts, the Environmental Management Programme Report (EMPR) which all mines have to produce, is a legal commitment, once it is approved by the Government, by which the mines should abide.

In view of the requirements by these Acts and the EMPR, mines are required to demonstrate to the satisfaction of the Government that the long-term impact of mining activity, after closure, will be within acceptable criteria.

This investigation has been initiated to assist the mines and the authorities in the process of evaluating possible pollution risks during and after mining operations have ceased.

The scope of this work is to:

- Identify, evaluate and rank mine sites which may be responsible for groundwater pollution during or after operations have ceased.
- Develop this evaluation process into a computer programme, that could be used by both the mining industry and authorities in assessing the pollution risk for a specific mine or group of mines.
- Link the risk assessment evaluation with a geographic information system which may be used over a region to perform intermine comparisons.
- Identify the major unknowns with respect to the risk assessment and suggest investigations that should be performed to eliminate these uncertainties from the risk equation.
- Select one of these issues and through in-depth study, demonstrate how greater certainty, with regard to the possible long-term impact of this issue, may be obtained.

### 2.2 Background information

Intensive mining in South Africa started more than a hundred years ago in the early 1870's. During the initial development and resulting urbanisation it was thought that South Africa had sufficient water resources to cope with all water demands. No attention was paid to the possible pollution of surface and groundwater resources from mining or from waste products in the mining environment. Even severe droughts such as experienced during the midnineteen thirties, the early fifties or mid sixties did not awaken a sense of water conservation nor the prevention of pollution from these sources.

In 1970, for the first time, South Africa was described as a country which would, by the turn of the century, run into serious water-supply problems. Through the development of ingenious water supply and catchment transfer schemes (Tylcoat and Forster, 1987, Department of Water Affairs and Forestry, 1980, Merensky and Hopkins, 1979, Vanderriet, 1975, Res Nova, 1984) sufficient provision has been made to meet South Africa's needs in sectors that needed it most. The predicted catastrophe in terms of water supply has, therefore, been postponed for at least a decade.

Through detailed investigation, particularly since 1970, a much clearer understanding has been obtained on all aspects of water in South Africa and how this relates to the mining industry. Work during the mid-seventies by several researchers, including Dyer (1976, 1979, 1982), Howes & Dyer (1982), Gillooly & Dyer (1979), Dyer and Tyson (1978), Tyson (1970, 1980, 1981, 1990), Muller and Tyson (1988) and Cockcroft *et al.* (1987) have demonstrated that South African rainfall, though irregular in space and time, does exhibit a degree of cyclicity. Droughts occur, the periodicity of which appears to follow a pattern. Even so, timing and amplitudes of dry or wet spells respectively are difficult and impossible to predict. In view of this, South Africa has largely adopted a cautionary approach in terms of water supply and it has become generally accepted that water restrictions are part of life in cities and towns.

Work on catchment run-off modelling has advanced significantly during the past 20 years, to such an extent that run-off models currently exist for all major catchments in South Africa (Brown and Van Niekerk,1991; Hughes, 1985; Jakubczyz, 1991 and Pitman and Kakabeeke, 1991). Consultants and authorities in South Africa model aspects of run-off and water supply.

The importance of groundwater as a resource has increased over the past 20 years. Some reasons for this are:

- Developing a groundwater supply is cheaper than building a dam and its associated infrastructure.
- Groundwater requires little or no treatment before use for domestic supply.
- · There are no evaporation losses from groundwater resources.
- Groundwater resources may be developed in the vicinity where the water supply is required, dams can only be constructed in streams with assured flow and may be a long distance from the demand.
- Groundwater resources are not as easily polluted as surface water resources.
- Groundwater resources do not take up valuable agricultural (or other) land. Due to these factors in favour of the development of groundwater resources, the use of groundwater has increased in South Africa from about 3 % of the national requirement in 1970, to an estimated supply of 13 % of the national requirement in 1980 (DWA&F, 1980).

Some groundwater resources have either been over-exploited or polluted to such an extent that they no longer meet the original requirement for which they were developed. This has largely been due to ignorance and lack of guidance on groundwater matters. There are many examples within and outside the mining industry. Examples of over-exploitation of groundwater resources are given in Orpen *et al.* (1991), citing Dendron and similar schemes in the Northern Province where, through excessive extraction for irrigation, aquifers in granitic rocks have temporarily been exhausted. This investigation focuses on the potential of groundwater degradation caused by the mining industry.

### 2.2.1 The influence of mining on groundwater

Groundwater affected by mining is commonly subdivided into shallow and deep systems. Although different authors use different terms to describe the two systems, they amount to a natural near-surface system and a deep mining induced system. Fractures and partings in the rock sequence, natural or enhanced by mining, convey water into the mine openings from where it must be pumped to allow mining to continue.

The shallow systems are usually recharged directly from rainfall and the water is of good quality. Examples of where the shallow groundwater system has been dewatered, to allow mining, are found in the West Rand area (Booysen, 1981; Kleywegt and Pike, 1982; Morgen and Brink, 1984; Schwartz and Midgley, 1975 and Warwick *et al.*, 1987). Here, a dolomitic aquifer has been dewatered in order to mine safely and unhindered by water inrushes at depth below this stratum. Dewatering problems are not unique to underground mines. At Sishen (an opencast, iron ore mine), the related carbonate aquifer has been dewatered.

Water abstraction from these aquifers has been at rates that would have been sufficient to significantly supplement the domestic requirement of major cities in South Africa. The water from these mines is currently discharged into streams and much of the potential of the aquifers in both of these examples is not utilised.

### 2.2.1.1 Gold mining

Gold Mining has had a significant influence affecting both groundwater quantity and quality. The nature or the scale of the activity could be instrumental in the problem.

Dewatering of the West Rand dolomite aquifer that has been cited is an example of a serious influence of gold mining. It has resulted in large volumes of groundwater being wasted, and destabilising of the surface, sometimes with catastrophic results.

The West Rand aquifer has been significantly polluted by the disposal of mining related waste on surface (Fleischer, 1981). Slimes dams from the gold mining industry are the main contributors of sulphate to the groundwater in this area. In the years before sufficient understanding of aquifer mechanics in this area was available, it was thought to be sound practice to place slimes dams on top of dolomitic aquifers. This ensured stability of the dams, as much of the retained water drained vertically through the slimes dam into the aquifer below. In areas around the Klerksdorp Gold-fields, the West Rand as well as the East Rand Gold-fields, many slimes dams are located directly on dolomitic aquifers. Many of the current problems associated with water quality deterioration in the

Blesbok Stream on the East Rand are derived from the mining related waste products on surface (Scott, 1995).

In the Free State and Evander Gold-mines, the gold-bearing reefs are overlain by a significant thickness of impermeable strata, which separates the gold mining horizons from the upper aquifers. Even though vast quantities of water are being pumped from the underground workings (Cogho, 1988) and the dewatering impact on the Witwatersrand sediments has extended tens of kilometres from the areas of mining, there is no measurable dewatering impact on the upper aquifer. In some of the coal-mines, more than 10 km from the Evander Goldfields, a water level difference of more than 100 m between the deep and shallow aquifers exists.

Another contrasting feature between the deep and shallow waters of these Gold-fields is the large difference in water quality. Natural water which enters the gold-mines, has high dissolved sodium and chloride with concentrations often more than 2 000 mg/L (Cogho, 1988). The shallow water in the Karoo sediments above the mines is potable with calcium and magnesium bicarbonate being the main dissolved salts and the total salinity is usually less than 500 mg/L (Vegter, 1995). A possible reason for this difference is the direction of movement of the water. Extracted water, from the shallow aquifer, will be held in the Ecca sediments that are predominantly arenaceous. Water that accumulates in the mines will have moved through the full Karoo sequence before entering fractures in the Witwatersrand sediments and so into the mines. Thus the water will have passed through the argillaceous Beaufort sediments which yield brack water in many places.

In the Free State and Evander Gold-fields, mine dewatering does not measurably impact on the usable volume of groundwater. However, the water pumped from the mines is disposed on surface, most often, in contoured evaporation areas or pans. It has been demonstrated by Cogho (1988) that significant contamination of the upper aquifer has occurred in the Welkom Gold-fields, because of mine water disposal. In mitigation of these actions, Cogho concluded that the hydraulic conductivity of the upper aquifer is so low that pollution of groundwater is restricted to the immediate areas around the pans. However, in view of the vast volumes of water which have been pumped from these mines and the shortage of evaporation or containment areas on surface, vast areas, often quite far from the mining activities, have been used for mine water disposal. The latter is an example of a situation where mining has little impact on groundwater volumes, but where the disposal methods contribute to groundwater contamination.

Through the knowledge that has been acquired during the past 20 years, much better provision can be made at future gold-mines to curtail pollution migration from mining and particularly from surface waste disposal.

### 2.2.1.2 Coal mining

The coal-mines in KwaZulu-Natal are another example of mining impacts on water resources. The coal-mines are situated in a topographically dissected area, where coal seams outcrop above the valley bottoms. In most of the collieries, high extraction mining methods were used; bord-and-pillar, followed by pillar extraction and longwall mining (at one mine). The result of the high extraction mining at all of these mines has been the collapse of the overlying strata.

Rain-water easily moves through the mining induced fractures in the collapsed strata. The water is contaminated (acidified) through oxidation of pyrite in the

rocks and loose material left in the mines. Because of the limited water retention in the mine openings, most of them decant water from sub-outcrop areas or shafts, into the valleys below. Coal discard dumps have been left on surface at the coal-mines in Natal, in various states of rehabilitation, adding an additional source of water pollution.

As a result of this, the Department of Water Affairs and Forestry (DWA&F) had to review their catchment water quality standards for some of the catchments. Sulphate concentrations of up to 1000 mg/L in the Black-Mfolozi and the Nkongolana Rivers are allowed.

Some of the larger coal-mines have closed or are in the process of applying for closure certificates. Many other mines have simply been abandoned and very little information is available regarding conditions in the mine or their possible impact on the water resources.

### 2.2.2 Legal aspects

All mines that were abandoned before 1956, are the responsibility of the State. All mines belonging to companies that were liquidated before 1976, are also the state's responsibility. Mines that stopped mining operations after 1976, are the responsibility of their respective owners who must apply for closure in terms of the Minerals Act No. 50 of 1991, Sections 12 and 39 (1), (2) and (3).

### 2.2.3 Closure applications

The Government has turned down many applications for closure, especially in the last 10 years. The biggest concern is the possible uncontrolled pollution of water resources in the vicinity of these mines, after they have filled up with water. Most of the mines that applied for closure were required to monitor the water conditions at the mine for a number of years. In spite of this period of monitoring and the data so generated, the Government was still not in a position to grant closure with confidence.

The lack of confidence is due to:

- A lack of information or a lack of understanding of the system with respect to its long-term behaviour.
- A lack of understanding of the possible regional impact.
- Reliance on the part of the Government to accept responsibility for these mines.
- A lack of specifically formulated evaluation techniques and procedures that can be applied to ensure that closure can be granted with confidence.

Many of the past pollution management strategies applied by mines or Government have been reactive. Strategies were developed as needed, rather than viewing the total problem, with the aim of managing the long-term effects.

Under the present circumstances, it is unlikely that closure permits for many of the post-operative mines or mines seeking closure will be issued in the next decade or two. There is an inherent danger that mining companies and the authorities may not develop the necessary co-ordinated approach to solve problems over the regions that will be impacted.

Such a structured and co-ordinated effort is important and will comprise many facets and involve many disciplines. Of these geohydrology, which will provide a proper understanding of the groundwater regime and its interaction with the

mine and surface water environments, is probably one of the more important disciplines.

The current status of knowledge about groundwater systems in South Africa is of a high standard. Extensive knowledge has been acquired during the past 20 years on the nature and distribution of aquifers. This has been summarised in a series of maps by Vegter (1995). These maps depict aspects which are valuable to groundwater management, such as the potential for the development of aquifers, the depth to groundwater occurrence, the recharge characteristics from rainfall and the natural water quality distribution. It should therefore be a simple task to relate the geohydrology and possible impact of specific mining operations to the information already available and published by Vegter (1995). This could provide a preliminary impact assessment of the mine involved.

There have also been numerous geohydrological and water quality investigations at many mines during the past 20 years. The Environmental Management Programme Report forced mining companies to gather information and make it available in one document. Thus significant amounts of information have become available at several mines, regarding the pre-mining geohydrological conditions, as well as the expected geohydrological conditions after mining operations have stopped.

Geohydrological and hydrochemical computer models can be used to predict the outcome of groundwater pollution from almost any mining operation (Hodgson and Krantz, 1995; Parkhurst *et al.*, 1980; Parkhurst, 1995; Pinder and Gray, 1977 and Pinder and Wood, 1984). It would appear that to issue a closure certificate would be a matter of conducting the necessary environmental impact assessments, instigating the necessary precautionary measures and submitting application for closure based on a sound understanding of the history of mining. One of the main reasons why this is not the case, is probably the lack of standardisation of the methods used for assessing environmental impacts.

Numerous companies and environmental consultants use a range of methods for impact assessments in South Africa. Often the results of these assessments cannot be compared with one another, because of different methods, scale, time intervals or inaccuracies. It is currently impossible for Government Departments to draw comparisons between mines, in terms of performance and long-term possible impacts, and they can therefore not be blamed for their apparent inability to grant closure to mines that have ceased operations.

### 2.2.4 Aims

Existing risk assessment procedures such as WASP or DRASTIC (to be amplified later in this document), were never intended for a detailed risk assessment within a mining industry.

Based on this introduction and background information to the problem, the current research is intended to:

- Identify the main geohydrological, hydrochemical and related conditions that should be considered in the application for mine closure.
- Arrange these issues in a logical way.
- Provide a numerical scale for the evaluation of each of these issues, as they relate to the potential overall impact on the groundwater system.

- Identify those issues where insufficient information is available and which could, in future, be stumbling blocks when applications for mine closure are submitted.
- Research the issues of uncertainty with the view of providing sufficient information and defining proper methods to evaluate these issues, thus providing a comprehensive approach which may be used by the mines in preparing the closure application and by the Government in evaluating it.

### 2.3 Considerations for risk assessment

### 2.3.1 Introduction

Risk assessment has been developed in a variety of ways and the method that is used depends on such factors as the object of the assessment, the availability of data and the requirements of the analysis. No provision has been made for management attitude, their commitment and the quality of their technical staff.

Some forms of risk assessment are statistically determined while others are based on more deterministic procedures. The statistical approach would preferably be used when data is available, for example, the Monte Carlo simulations have been applied with significant success in the geohydrological situation by Bair *et al.* (1991), Janse van Rensburg (1994) and Loomis and Warner (1987).

As geohydrology is a young discipline (in place in South Africa since 1973), many mines have not accumulated suitable data for statistically valid evaluation. Most geohydrological evaluations are done through analytical methods in which aspects of flow through porous and fractured media, chemical reactions, dispersion and mass transport are considered. For analytical methods to be applied, equations governing the processes that are operating within the system must be developed, the parameters (variables) must have been measured or determined and the boundary conditions should be set. For many of the processes, these equations are not defined and the variables have never been measured, thus these techniques cannot be applied. In situations of so many variables and unknowns, deterministic procedures have been used. For example, evaluating waste disposal sites where ranking and scores are given, based on an understanding of the conditions at the site. This is a method of non-parametric evaluation that is common in decision analysis.

These methods are well-established and often used in environmental assessment. An example of such a deterministic procedure is the so-called WASP procedure, developed by Jolly and Parsons (1991) and Kuczera and Diment (1988). An example of a system, that has been developed in the United States for their Environmental Protection Agency is the so-called DRASTIC procedure (Aller *et al.* 1985 and Jolly and Parsons 1991).

### 2.3.1.1 Establishment of risk assessment procedures

Risk assessment procedures could be based on statistical (stochastic, e.g. At Risk, Monte Carlo) or deterministic (e.g. WASP, DRASTIC) techniques. The deterministic approach that uses order and ranking to evaluate multiple options is the most obvious choice. Specific variables will not be measured, but rankable variables such as rock type, climatic regime and size of operation will be available.

For this investigation, the threat will be the possible pollution of groundwater resources. The source of threat will be mining operations (underground mining or surface mine waste disposal) and the risk will be given as a ranking<sup>1</sup> that certain operations possess, because of how, where, or the nature of the minerals that were recovered. Thus some operations will have a greater probability to contaminate groundwater resources than others.

The first step in the establishment of a risk assessment procedure, is the identification of the parameters that should be considered. The variety of factors in the mining industry that could impact on water quality, means that several components need to be considered before a meaningful risk assessment can be made.

Mining exposes rock to air and water. In this disturbed environment, minerals are out of equilibrium and reactions between the minerals, water and air lead to degradation of the water quality. The reactions are usually related to sulphide minerals which oxidise in the atmosphere, acidifying water that comes into contact with them, at the low pH so formed metals are found in solution. These are predominantly iron but could also include other metals such as arsenic, cadmium, selenium, copper and nickel, depending on the mineral association. The metals may have a variety of toxicity from neurotoxicity to carcinogenity.

Other variables relate to where degradation takes place, for example in the mine, or on surface where rock and water from the mine are disposed. The pathways that the degraded water follows may also have an effect. Some rock associations contain minerals that are useful in neutralising the acid water. These may be part of the waste material or may be available in the environment that the polluted water passes through.

The mechanisms through which the polluted water can migrate from the mine, or from surface pollution sources, are also variables that must be considered.

The risk assessment will therefore have to be able to consider all these parameters when evaluating the possible risk from underground mines versus sources of pollution on the surface. Many of these parameters are common to both scenarios. Rainfall, for instance, could impact on surface waste material as well as on underground mines.

Pollution, once it is in the aquifer, behaves similarly for either surface pollution sources or underground mines.

### 2.3.1.2 Parameters to be considered in risk assessment

A risk assessment procedure should be capable of extracting the similarities between situations and also evaluate differences between various situations.

In terms of mine wastes, material that is stored on surface either temporarily or permanently, nine parameters have been identified to be considered in a risk assessment. These are:

- The composition of the waste material.
- · The reactivity of minerals in the waste.
- The surface area of the waste facility.
- · The size distribution of the waste material.
- The state of management of the waste facility.

<sup>&</sup>lt;sup>1</sup> Note this risk has no statistical basis, the distinction between the different sources could be linear or based on a power relationship. There is no way of determining the relationship, based on the tests given in this document.

- · The quality of leachate which emanates from the waste facility.
- The degree of toxicity to the most sensitive user who is likely to be exposed to leachate from the waste facility.
- · The characteristics of the soil and rock which underlie the waste facility.
- The development potential of the aquifer which is likely to become polluted.

Each of these categories may contain several subclasses, which would need to be evaluated by the procedure to define the risk. A risk assessment procedure developed around these categories should be able to accommodate input from a variety of data and information sources or models.

In terms of a risk assessment with respect to the potential pollution of groundwater resources from the mines, the parameters to be considered have been classified into two groups. The first group contains parameters which depict the relationship between the mine and the water which flows into the mine. The second group of parameters relate to the relationship between the mine and the water-bearing strata around the mine.

For the first group, the following eight parameters have been identified as the main issues:

- The mineral mined.
- The composition of the reactive minerals in the mine.
- · The extent of the surface area mined.
- · The rock type in the mine.
- · The mining method.
- The mine status, e.g. operating, closed, abandoned.
- · The quality of the water in the mine.
- The potential toxicity of the mine water in the event that it should migrate from the mine.

The second group considers the mine/aquifer relationship and are:

- The mineral mined.
- The dewatering rate of the mine during full production.
- The position of the mine relative to the main water-bearing strata.
- The interconnectivity between the mine and the water-bearing strata.
- The nature of the topography in the area above the mine.
- The amount of rainfall in the vicinity of the mine.
- Access for surface water to and from the mine, i.e. the decant point(s).
- The development potential of the main aquifer at the mine.

Each of the above categories may contain subclasses which will need to be considered in the overall evaluation of the pollution risk from the mines.

When comparing these lists with the parameters considered by existing procedures such as WASP or DRASTIC, it is clear that the latter procedures were never intended for a detailed risk assessment in a mining industry. As far as a Monte Carlo simulation is concerned, it is unlikely that sufficient information will be available in many of the categories to evaluate these parameters statistically.

As an example, the parameter that deals with the toxicity of the leachate can be considered. Apart from the fact that insufficient scientific information is available for the accurate evaluation of its impact on humans, vegetation, animals and aquatic life, most of the mine situations will be site-specific and detailed investigations will be necessary before conclusive answers can be

given. In this research, the parameters are grouped in such a way that an expedient mechanism for decision-making is put in place.

When studying the categories, it is clear that an approximate outcome can be selected, without doing additional research. A statistical risk assessment may be used when more information becomes available.

### 2.3.2 Evaluation of risk assessment procedures

Since two risk assessment procedures, namely WASP and DRASTIC, were available at the start of this investigation, the logical step was to investigate these procedures' applicability to the mining situation with the possible view of adapting either, if necessary. The following is therefore a critical review of the two procedures.

### 2.3.2.1 WASP

The WASP evaluation was developed by Jolly & Parsons in 1994. The acronym WASP stands for Waste-Aquifer Separation Principle. The procedure is a systematic method for evaluating a site's suitability for waste disposal, based on geohydrological criteria. It calculates a numeric score on a scale of 0 - 10, which is the site-suitability index. This index can also be regarded as a risk criterion, because the higher the index, the greater the risk of pollution migration to the aquifer. The criteria used by WASP fall into three categories:

- The characteristics of the waste with respect to leachate generation referred to as the Threat Factor.
- The characteristics of the unsaturated zone underlying the waste facility also referred to as the Barrier Factor.
- The characteristics of the aquifer itself.

These categories conform to the requirements of risk assessment as far as surface waste deposits at mines are concerned. A closer inspection of the subdivisions in each of these categories and the calculations behind them is, however, necessary to decide on required adaptations.

### 2.3.2.1.1 The Threat Factor

The threat factor deals with the waste itself. Two factors are considered, the composition and volume of the waste.

Calculations are based on the assumption that wastes of different compositions will have different impacts on groundwater beneath the waste site. A threat factor score nomogram (Figure 2-1) has been suggested by Jolly & Parsons (1994). In this nomogram, wastes are classified into five categories, namely:

- Garden and building rubble.
- Domestic waste.
- Dry industrial waste.
- Effluent and sludge.
- · Hazardous waste.

Since the WASP evaluation was specifically developed for domestic and hazardous waste disposal, mine waste is not included in the nomogram.

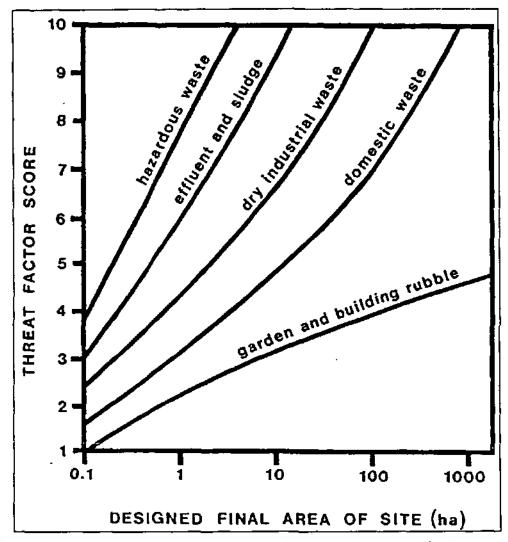


Figure 2-1. Threat factor score nomogram (Jolly and Parsons, 1994).

Mine waste comprises different rock types with mineral composition, ranging from inert to reactive. Mine waste could be accommodated on the nomogram, with inert mine waste corresponding to the Garden and Domestic Waste category. The reactive mine waste, depending on the leachable constituents and chemical composition of leachate from this waste, will correspond to the other categories, from the Dry Industrial Waste category to the Hazardous Waste category.

The actual chemistry in reactive environments in mines is, however, far more complex than just the five classes indicated on the nomogram. Although it should, in theory, be possible to accommodate all the scenarios by means of lines on the nomogram, it will in practice leave too many options open and interpretation will become impossible.

The size of the waste facility is considered in the calculation of the threat factor. This variable is known at all mine waste facilities and can thus be included. In the mining industry, the most severe pollution is derived from oxidation of pyrite in waste dumps. Oxygen availability is therefore important. The main source of oxygen is from daily ingress of air, due to barometric fluctuations, thus its impact is greatest on the outer few metres of the waste. For that reason, the

size of the waste site is directly proportional to the tonnage of the sulphate produced and the x-axis on the Threat Nomogram should be linear for mining waste. The concentration of sulphate in the leachate derived from a mine waste dump is unrelated to the size or height of the waste, as only the upper few metres of the waste are involved in the reaction. The logarithmic scale suggested by Jolly & Parsons for the size of the waste facility is not necessarily applicable to the mine waste situation.

#### 2.3.2.1.2 The Barrier Factor

The term "Barrier" is referred to by Jolly & Parsons (1994) as the soil and rock underneath a waste facility, from surface to the groundwater. They suggested three variables to be considered in the calculation of the barrier factor. These are:

- The thickness of the barrier zone (also referred to as the unsaturated zone).
- Its hydraulic conductivity.
- · Its effective porosity.

From this information, using Equation (1), the travel time that a pollutant will take to travel through the barrier to reach the aquifer is calculated:

$$t = KS/n$$
....(1)

#### where

t = the time in days

K =the hydraulic conductivity in  $m^3/m^2/d$ 

S = the gradient in m/m

n = the effective porosity. In the evaluation of the barrier, Jolly & Parsons use a Barrier Factor Score Nomogram (Figure 2-2) which provides a barrier factor score. The higher the score, the less the barrier acts as a retarding agent.

Although it is interesting to know the travel time, this parameter is not relevant, except in radioactive waste in the assessment of the pollution potential from a waste site. A more relevant approach would be to calculate the volume of leachate that passes through the barrier zone into the aquifer below, and the salt tonnage. This could be done by using Equations (2) and (3):

$$Q = KAS....(2)$$

#### where

Q =the volume of leachate ( $m^3/d$ )

K = the hydraulic conductivity of the strata in m³/m²/d

A = the area underneath the waste dump through which seepage of leachate takes place (m<sup>2</sup>)

S = the hydraulic gradient (m/m)

and

$$m = QC/1000....$$
 (3)

#### where

m = the mass of salt leaching into the aquifer blow in kg/d

Q = the volume of leachate (m³/d)

C = the concentration of salts in the leachate in mg/L

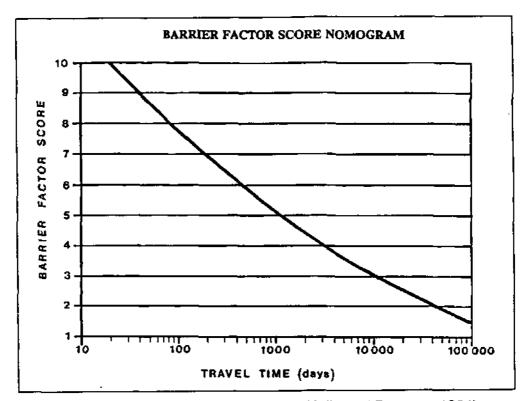


Figure 2-2. Barrier Factor Score Nomogram (Jolly and Parsons, 1994).

When calculating the pollution impact of leachate on an aquifer below the waste site, it is the mass of contaminant that matters and not the travel time, as specified by Jolly & Parsons. This is due to the fact that all groundwater systems are dynamic. All of them therefore have a dilution effect as groundwater flows through the aquifer underneath the waste sites. This must be remembered when determining the potential for a waste facility to pollute the underlying groundwater system. In a monitoring series by the Department of Water Affairs and Forestry (1994), the "Expected Environmental Concentration Principle" (EEC), has been established to allow for this dilution effect.

To use WASP in its current form, not allowing for the calculation of the EEC, is therefore not in line with commonly used geohydrological principles. This method would also not be in line with the prescribed methods to be accepted by the DWA&F. Significant modifications will therefore be necessary to WASP, to accommodate these required changes.

### 2.3.2.1.3 Resource Factor

The resource factor, as identified by Jolly & Parsons, has been subdivided into two categories, namely:

- The groundwater usage component.
- The groundwater potential component.

Each of these components is subdivided into three levels, as illustrated in Table 2.1. This section of WASP is in line with that suggested above for the mining industry, namely examination and consideration of the aquifer potential.

Table 2.1. Resource factor score nomogram	(Joll	y & Parsons,	1994).
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Data Reliabil Lev	<b>*</b> .	Level 2	Level 3
Groundwater usage	Certain - based on full hydrosensus, records and reports.	Based on partial hydrosensus and discussions with local residents, driller or geohydrologist.	Uncertain - based on estimations.
Groundwater potential	Certain - based on full geohydrological investigation and detailed study.	Based on extrapolation of information from other areas, discussions with local geohydrologists familiar with the area etc.	Uncertain - based on estimations, interpretation of regional and national geological and geohydrological maps

### 2.3.2.1.4 Applicability of WASP to the mining situation

The WASP evaluation has specifically been developed for site suitability evaluation for domestic and hazardous waste disposal. Evaluation of WASP with information from the mining industry suggests that adaptation of WASP for use at mine waste sites will require major modifications to this procedure. Shortcomings of WASP are:

- The mine waste will have to be classified into categories ranging from inert to toxic, before a threat factor can be calculated.
- The nomograms used in WASP are subjective and a new set of curves will have to be developed and tested for the mining industry.
- The barrier factor as calculated by WASP does not consider the salt load that passes through the barrier into the aquifer. The impact on the underlying aquifer and the Expected Environmental Concentration (DWA&F, 1994) cannot be calculated by using the WASP evaluation.
- WASP can only be used to evaluate the impact of surface waste on groundwater resources and not for the evaluation of the risk associated with groundwater pollution from underground mining.
- WASP does not have the flexibility to include additional parameters which may be important to the mining situation, such as rainfall and leachate concentration.
- WASP does not link to a Geographic Information System. Regional performance comparisons between issues or mines can therefore not be established.

In view of these WASP shortcomings, it was decided not to adapt it for groundwater pollution risk assessment in the mining industry.

### 2.3.2.2 DRASTIC

A standardised system for evaluating groundwater pollution potential using geohydrological settings, called DRASTIC, was developed by Aller *et al.* (1985). This method allows the systematic evaluation of the pollution potential of any geohydrological setting.

Geohydrological considerations form the basis of the DRASTIC system and most of the major geohydrological factors that impact on groundwater movement are incorporated in this evaluation. These are:

Depth to the groundwater level (D).

- · Net Recharge to the aquifer (R).
- Aquifer media (A).
- Soil media (S).
- Topography (T).
- Impact of the vadose zone media (I).
- · Hydraulic Conductivity of the aquifer (C).

Through considering these factors in combination with different waste types, numerical values called DRASTIC indices are extracted. DRASTIC indices may, thereafter, be combined with geohydrological settings and be displayed on maps. The advantage of using a system like DRASTIC therefore lies in the final product which is usually in the form of a map.

Many variations of DRASTIC have been developed and published since its introduction in 1985. Jones *et al.* (1987) has, for instance, modified the DRASTIC scheme to apply it to the evaluation of pesticide pollution in agriculture. Further work by Daniels and McTernan (1989) developed a pesticide risk index based on the original DRASTIC index. Barrett and Williams (1989) and Durnford *et al.* (1990) worked in the agricultural field also related to pesticide pollution.

From these references, it is clear that the DRASTIC system can be adapted with success to be used under a variety of conditions. It is suggested that the DRASTIC system is best suited to the regional evaluation of aquifer pollution potential and that site-specific issues, such as waste disposal and mining, can better be evaluated through the consideration of a wider selection of parameters.

It was consequently decided to develop a risk assessment procedure specifically for the South African situation. Requirements for this system were:

- It should be in the form of a computer code, running under Windows 95/98 and Windows NT/2000, as these were operating systems available at the time of investigation.
- It should be able to evaluate any number of variables.
- It should be able to apply weighting factors amongst variables and also between variables.
- It should provide output in the form of numeric values that could without modification be drawn into GIS systems, such as Arc/Info or Arc/View.
- It should be user-friendly.

# 2.4 The development of the mine closure impact rating system "Risky"

### 2.4.1 Introduction

The development of a risk rating system for the South African mining situation requires:

- A system that is based on sound scientific principles and the best available information.
- A system that is flexible and that can be adapted as more information becomes available.
- A user-friendly system that can be used for first approximations, but which will also allow integration of information from sophisticated models.

The first step in the development of such a system has already been taken in the previous chapter. This constitutes the separation of surface waste facilities from underground mining activities, so that these risks are evaluated separately.

# 2.4.2 Overriding considerations

The next step in this development was the identification of overriding factors. Overriding factors are issues that dominate the outcome of the risk assessment. In the authors' opinion, only one such factor exists, which applies to both the surface waste disposal as well as the underground situation. This is the final pH of the leachate that emanates from the facility. Mine effluents of low pH are problematic because:

- The acid effluents have to be neutralised before they can be disposed of into public systems.
- The heavy metal content of acid systems is likely to exceed accepted groundwater quality standards.
- Aquatic life, in particular, is sensitive to high concentrations of heavy metals, such as aluminium, copper, lead and zinc.

Many of the mines in South Africa contain rocks that generate acid leachate. The acidity stems from the oxidation of minerals in the rock, when exposed to water and air. All the gold, platinum and base metal mines fall in this category. Collieries in South Africa generally have both acid and base potential. The base potential counteracts acidity, but it is often insufficient to permanently maintain the pH of the mine water on the alkaline side.

Mines that do not acidify may still have salinity problems. At some of the coalmines, for instance (Hodgson and Krantz, 1995), sufficient base potential is available in the rock to counteract acidification of the water for many years. At these localities, all heavy metals, except manganese, precipitate as they are released from the rock. The toxicity of the leachate from such mines is therefore much lower than in the case of acid mines.

Opposed to mines with acid-generating potential, are mines whose rocks do not release significant amounts of salt. Typical examples are quartz, calcite, limestone, dolomite and mica quarries. These mines must obviously be allocated a very low risk of polluting groundwater. A list of mines, classified according to their pollution potential, based on their potential to generate acid and also in terms of the reactivity of the rocks in the mines, has been compiled and is included in Appendix A.

Based on the above discussion, a logical step in the development of the pollution risk rating system would be to classify mines according to the reactivity of the minerals from the mines. A four-tiered classification is suggested, namely:

- · Mines that produce acid leachate.
- Mines that currently produce alkaline leachate from waste facilities, but
  which will, at some stage in the future, have insufficient natural base
  potential to neutralise all the acid that is produced. This can be determined
  through, inter alia, acid-base accounting procedures. Effluents from mines
  in this category usually have a high total dissolved solids content.
- Mines that have sufficient natural base potential to counteract all acid that will be produced through oxidation processes at the mine.
- Mines that have rocks that are generally non-reactive and that will not significantly pollute water as it passes into the aquifer.

### 2.4.3 Subordinate considerations

The next step, though not essential in the development of the risk rating system, is to identify and rank other considerations in order of importance. This is done separately for surface waste facilities and underground mines.

#### 2.4.3.1 Surface mine waste facilities

Surface mine waste facilities usually comprise discard rock, slimes and water. At some mines effluents or other wastes from various sources may be co-disposed, for example, process and sewage water.

The impact that these facilities have on the underlying groundwater is, to some degree, variable and depends on considerations such as the chemical composition of the leachate, the volume of leachate, the character of the soil below the site and the nature of the receiving aquifer. Eight issues have been identified to evaluate the potential risk that surface mine waste disposal may have on the receiving aquifer. These are:

- · The composition of the waste material.
- The area of the waste facility in hectares.
- · The particle size of the waste material.
- Management practices at the waste sites.
- The salinity of leachate which is likely to impact on the receiving aquifer.
- The toxicity of the leachate at the point where it emanates to the receiving environment.
- The character of the barrier between the bottom of the waste facility and the aquifer below.
- The development potential of the aguifer.

Each of these categories has been subdivided into four classes. A schematic presentation of the categories with the classes is included in Figure 2-3. Detailed descriptions of the various classes are provided in the discussion in Chapter 2.5.

# Screen layout for impact assessment of mine waste on groundwater

	Waste material:	Coal	
Reactive minerals in waste			
Acid	Alkaline then acid	Alkaline	Non-reactive
Area of waste facility (ha)			
>10	4 - 10	1-4	<1
Size of waste material			
Coarse	Medium	Fine	Very fine
Management of waste and	leachate		
Unmanaged	Managed but neglected	Managed, berms, vegetation	Liners, capping, return water system
Electrical conductivity of le	eachate (mS/m)		
>300	150 - 300	75 - 150	<75
Toxicity of leachate			
Radiogenic or toxic	Harmful	Limited impact	No impact
Barrier between waste and	aquifer		
Insignificant	Marginal protection	Significant protection	Excellent retardation
Aquifer development poter	ıtial		
High	Significant	Marginal	Insignificant

Figure 2-3. Screen layout for impact assessment of mine waste on groundwater.

Behind each of the categories and classes are several sets of equations, which allow for weighting as well as skewing. Weighting and skewing can be controlled through a formula editor view, as part of the computer programme (Figure 2-4).

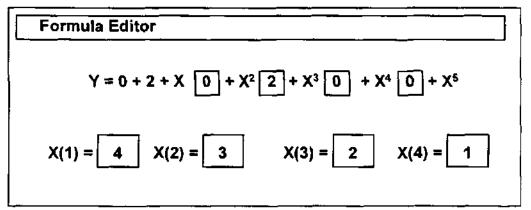


Figure 2-4. Formula editor, available for entering weights and equations into the risk assessment procedure.

It is possible to assign new relationships between categories and classes as new information becomes available, without having to redesign the evaluation system. Through the use of the weighting facility, outputs from models that have been run outside the risk assessment may be accommodated. The polynomial equation that may be defined across the classes in each category allows emphasis to be placed on certain issues, if so desired.

### 2.4.4 Computer software for surface waste facilities

The evaluation has been developed into a computer code, named RISKY. This software runs under Windows 95 or Windows NT. In this code, the weights for the different classes have been fixed, based on the best available information at the time of developing the software. The polynomial facility has not been used, although available in the programme, because sufficient definition could be achieved through the use of the weighting factors.

In the development of a national system, it is essential that the same rules apply to all evaluations. The use of different weighting factors or polynomial equations by different companies/agencies can therefore not be allowed. The development of a computer code is an ideal way to ensure standardisation. As more information becomes available, the computer code, weighting factors and polynomial equations can be adapted.

During the evaluation with RISKY, selecting an applicable class makes a single choice in each category. The selection gives a composite score in the left corner of the computer screen. High scores indicate potential high impacts.

The following interpretation should be attached to these scores:

Score	0 - 25	25 - 50	50 - 75	75 - 100
Risk	Very low	Medium	High	Very High

A general observation regarding the use of this scheme:

- Some of the categories provide for exact selection of the correct category because numeric values define the categories. Examples are the area of the waste facility in hectares or the electrical conductivity of the leachate.
- In the other categories, the input is, to a certain extent, subjective. A
  detailed explanation of the exact meaning of specific words used in the
  classes is discussed in Chapter 2-5. Problems may, for instance, arise in
  the classification of the physical size of the waste material. Rock and coal
  discard is classified as "Coarse", irrespective of whether it has been slightly
  crushed during compaction. Slimes from a crusher or washing plant are
  classified as fine.
- Another example is the management of waste and leachate. Although the
  categories are descriptive, they do not present problems, as it is usually
  evident where waste sites are managed well and where they have been
  neglected.
- Selecting the appropriate class for subjective choices such as the toxicity of the leachate or the description of the barrier between the waste facility and the aquifer, do not usually present problems as the classes are relatively broad.

Input for the aquifer development potential may be extracted from the map by Vegter (1995). This information can be made available through the use of GIS, or can be manually included by comparing the locality of a mine with the information provided on the map. For the purpose of manual interpretation, the following information is provided is provided in Figure 2-5:

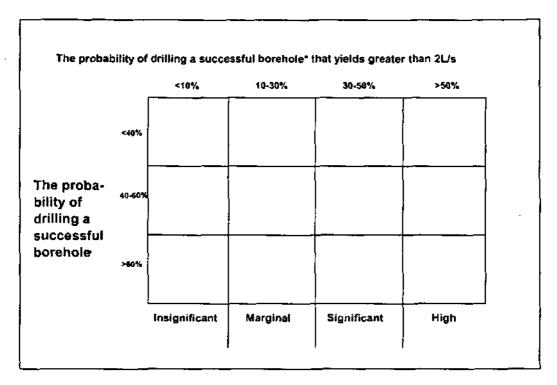


Figure 2-5. Interpretation of Aquifer Development Potential (after Vegter, 1995).

# 2.4.4.1 Underground mining

The risk of groundwater pollution from underground mining is determined by considering two sets of variables. Two forms have been developed for impact assessment relating to the mine/water and the mine/aquifer relationship (Figures 2-6 and 2-7). These have also been programmed as computer input screens in the RISKY software.

The overriding factor is the reactivity of the environment that is dealt with, as was the case in the impact assessment for surface waste facilities. In this respect, the classification; viz. acid, alkaline, becoming acid with time, alkaline and non-reactive have been retained in the calculations.

Items that are considered for the mine/water relationship are:

- The mineral mined.
- · The reactivity of the rock in the mine.
- The final area to be mined in hectares.
- The nature of the rock in the mine, i.e. porous, fractured or solid.
- The mining method, i.e. whether supported or collapse methods were used.
- The mine operating status, i.e. whether it has been abandoned, operations ceased or still operating.

	Mineral mined:	Coal	
Reactive minerals in mine	·		
Acid	Alkaline then acid	Alkaline	Non-reactive
Area to be mined (ha)			
>1 000	400 - 1 000	190 - 400	<100
Rock type in mine	· · · · ·		
Porous and fractured	Parous	Fractured	Impervious
Mining method			
>20% of area collapsed to aquifer or to surface	5 - 20% of area collapsed to aquifer or to surface	0 - 5% of area collapsed to aquifer or to surface	None of area collapsed to aquifer or to surface
Mine status			
Closed before 1956	Closed 1956 - 1976	Closed 1977 - present	Still operating
Electrical conductivity of m	ine water (mS/m)		
>300	150 - 300	75 - 150 <sup>1</sup>	<75
Toxicity of mine water			
Radiogenic or toxic	Harmful	Limited impact	No impact

Figure 2-6. Screen layout for impact assessment on mine/water relationship.

	Mineral mined:	Coal	
watering rate of mine (m3	/d)	<u>-</u>	
>10 000	1 000 -10 000	100 - 1 000	<100
ine relative to aquifer			
Within aquifer	Through aquiler	Balow aquiler	Above aquifer
terconnectivity between m	ine and aquifer		
Major	ı Significant ;	Minor	Insignificant
opography			
Intersecting seepage	Indirect connections	Impact unlikely	No impact
ainfail (mm)			
>1 000	500 - 1 000	200 - 500	<200
ccess for water to and from	n mine		
Direct openings	Partly blockaded	Blockaded	No connection
quifer development potent	)a/		
High	Significant	Marginal	Insignificant

Figure 2-7. Screen layout for impact assessment on mine/water relationship.

 The electrical conductivity of the mine water that is likely to seep from the mine.

The toxicity of the mine water at the point where it will seep from the mine.

In terms of the mine/aquifer relationship, variables under consideration are:

- The average calculated dewatering rate for the whole of the mine.
- The mine position relative to the aquifer, i.e. above, below or in the aquifer.
- The degree of interconnectivity between the mine and the aguifer.
- The possibility of water from the mine seeping out on surface due to topographic variations.
- The annual rainfall.
- The accessibility of water to and from the mine through man-made conduits.
- The aquifer development potential (this is the same as for the waste disposal menu).

Two computer screens have been developed for the evaluation of the groundwater pollution risk from the mine. The same principles as in the evaluation of the surface waste apply. Once the information on the Mine/Water has been provided, the next button should be selected on the computer screen, this will activate the Mine/Aquifer menu.

As in the case of the surface waste, the reactivity of the mining environment dictates the outcome. Acid systems will return significantly higher scores than alkaline or inert systems.

After the required input has been provided for both the Mine/Water and Mine/Aquifer screens, returning to the Main Screen will display the risk ratings for all three systems. The two scores for the mine are averaged to give a combined score. A combined score for the waste facility and the mine is not calculated because mines exist that have practically no waste. For instance, the coalmines whose coal is consumed by power stations.

The information entered and the calculated scores can be saved by selecting the 'save option' under the file menu on the main screen.

# 2.4.4.2 Geographic Information System (GIS)

Scores for the individual categories as well as the combined score for each of the mines can be converted to GIS format by running the programme RISK2ARC. This software converts all the information in the current directory to a spreadsheet format. This information, together with the maps provided with the software, can be accessed through the use of ArcView3. Discussion of the procedures to accomplish this is presented with the software.

# 2.5 Examples of application of the RISKY evaluation

The functionality of the RISKY evaluation can best be illustrated by examples.

### 2.5.1 Example 1: Coal mining in Mpumalanga

Coal mining in Mpumalanga Province has been chosen as the main example for the following reasons:

- · Readily available information.
- It is topical as the two major catchments Olifants and Vaal Catchment, have received news coverage during the past 10 years.

 Major dams, namely the Witbank, Loskop, Grootdraai and Vaal derive water from these two catchments. A drainage map of the area is included in Plate 1 (Appendix B). Plate 2 shows the mining industry superimposed onto these catchments.

The information used in the evaluation is public domain, such as shareholders plans, conference proceedings or visual appearance. As this might not be the most appropriate information to have used, the values assigned to the mines should be regarded as first approximations.

The illustration of the RISKY evaluation involves two distinct procedures. The first is the entry of the necessary information for all the mines into the RISKY database. The second procedure involves presenting the data. In this case the data has been spatially represented on maps using a Geographic Information System.

### 2.5.1.1 Data entry Into RISKY

The Risky software is available from www.uovs.ac.za/igs. The programme starts with a blank screen on which data entry may be made. The entry of data into the software is interactive with a user-friendly graphics interface. The main screen allows entry of the name of the mine, a mine number and the longitude and latitude to define position. Figures 2-8(a), (b), (c) and (d) show these options as they appear on the computer screen.

The next step is the selection of the Mine Waste option on the screen. This opens a second screen for the evaluation of the RISK potential of mine waste on surface. The waste material composition is selected from a list of class options in a category. Hereafter, selections may be made from each of the categories. The selected class is highlighted and a score applied. The score is shown at the bottom of the screen. As further classes are selected, the score is updated. Definitions of the exact meaning of the short descriptions in each of the classes are included in further discussions. After all categories have been selected, the user is allowed to return to the main menu.

The next step is the selection of the Mine/Water/Aquifer option from the main menu. This activates two menus in succession. The principle of providing information for these two menus is exactly the same as that for the Mine/Waste menu. Upon completion of both menus, the user can return to the main menu. Scores for the completed menus are reflected on the main menu. In the case of the Mine/Water/Aquifer menus, a combined score for the mine as a whole is also displayed.

RISKY can be used by mining companies to evaluate the influence of the two mining options on the final impact. For example, assume that the coal-seam in this area is at a depth of approximately 100 m below surface. The classes in each of the categories selected with respect to bord-and-pillar mining are illustrated in Figures 2-9 (a) and (b). As opposed to bord-and-pillar mining, the classes which have been selected for longwall mining for the same mine, are illustrated in Figures 2-10 (a) and (b).

A comparison between the last two figures clearly reveals that a switch from bord-and-pillar mining to high extraction underground mining impacts on many of the categories which are used in this evaluation. The arguments behind the categories which have changed are as follows:

	npact assessment	·		×
File <u>R</u> eport <u>H</u> e		Impact Assessn	nent	
Name of mine				
Longitude	Ō			
Letitude	0			
	WASTE FACILITY  Waste facility score	Mine / water	MINE  Scare Mine / aquifer  Combined scare	<u>sco</u> re
		Exit	Developed by the Institute for Groundwater St University of the Orange Fr	

Figure 2-8(a). Mine closure impact assessment - Main Screen.

Reactive minerals in waster		Mine	nd mineral
rupacive minerals in waster C Acid	C Alkaline then acid	C Alkeline	○ Non-reactive
Area of waste facility that			. (10111940010
C > 10	C 4-10	C 1-4	C <1
Size of waste material			
Coarse	← Medium	← Fine	← Very fine
Management of waste and le	Bechate		
C Unmanaged	C Managed but neglected	_ Managed, berms, vegetation	Liners, capping, return water system
Electrical conductivity of lea	chate (mS/m)		Tool John
C > 300	C 150-300	C 75-150	C <b>∢</b> 75
Toxicity of leachate			
○ Radiogenic or toxic	C Hamful	C Limited impact	C No impact
Barner — — — —	·····		
⊂ Insignificant	C Marginal protection	C Significant protection	C Excellent retardation
Aquiter development potent	ial ————————————————————————————————————		
← High		○ Marginal	C Insignificant

Figure 2-8(b). Mine closure impact assessment - Mine/water screen.

Reactive Minerals in waste — —		Mineral	mined;
← Acid	C Alkaline then acid	C Alkaline	C Non-reactive
Area to be mined (htt)	C 400 - 1000	C 100 - 400	C < 100
Rock condition in mine	C Paraus	← Fractured	C Impervious
Mining method	5-20 % of area collapse aquifer or to surface	ed to _ 0-5% of area collapsed to aquiler or to surface	No collepse to equifer or to surface
Mine status — Clased before 1956	C Closed 1956 - 1976	← Closed 1977 - present	ି Still operating
Electrical conductivity of mine w	rater (mS/m)		
C > 300	C 150 - 300	C 75-150	C < 75
Toxicity to most sensitive users	C Harmfull	C Limited impact	C No impact

Figure 2-8(c). Mine closure impact assessment - Mine/aquifer screen.

		м	lineral mined;
ewatering rous of mins (m3/ ^ > 10000	(d) ~ 4000 - 1 0008	C 1000 - 4000	C <1000
rafiupo ot evitales eni			
Within aquiter	C Through aquiler	C Below equiter	Above equifer
terconnectivity between mit	ne and aquifer-		
Mejor	C Significant	○ Minor	C Insignificant
ородторку			
Intersecting saapage	C Indirect connections	<ul> <li>Impact unlikely</li> </ul>	○ No Impact
ainfall (mm / year)			
>1000	C 500-1000	← 20B-50Q	C < 200
ccess of water to and from	mine		
Direct openings	<ul> <li>Partly blockaded</li> </ul>	○ Blockeded	C No connection
quiler development potenti	aJ		
High	C Significant	C Marginal	C Insignificant
	<del>,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,</del>	·	
•			

Figure 2-8(d). Mine closure impact assessment - Mine/water screen.

leactive Minerals in waste	والمساوة المساوس المساوس المساوس المساوس المساوس	Minerai	mined: (Coal
C Acid	C Alkaline then acid	€ Alkeline	○ Non-reactive
Area to be mined (ha) > 1900	C 400 - 1000	C 100-400	< 100
Rock condition in mine	C Porous	C Fractured	Cimpervious
Mining method	5 - 20 % of avea collapsed to aquifer or to surface	0-5% of area collapsed to aquiler or to surface	No callapse to aquiler or to surface
Mine status ————————————————————————————————————	C Clased 1956-1976	Closed 1977 - present	€ Still operating
Electrical conductivity of mine we	oter (mS/m) · · · - · ·		
← > 300	C 150 - 300	€ 75-150	C <75
Toxicity to most sensitive users	- · · -		
C Radiogenic toxic	C Harmfull	C Limited impact	No Impoct

Figure 2-9(a). Screen layout for impact assessment on mine/water relationship for bord-and pillar mining at 100 m depth.

		• • • • • • • • • • • • • • • • • • • •	lineral mined:
= :	/d)		
> 10000	ে 4000 - 10000	(* 1 שעט - 4 שע	C < 1000
Mine relative to aquiler			
C Within aquifer	<ul> <li>Through aquifer</li> </ul>	<ul> <li>Batow aquiler</li> </ul>	C Above aquiler
Interconnectivity between mi	ne and aquifer		
C Major	C Significant	← Minar	<ul> <li>Insignificant</li> </ul>
Topography —		· · · · · · · · · · · · · · · · · · ·	
C lutersective seebade	· · C Indirect connections	C Impact unlikely	<ul> <li>No impact</li> </ul>
Rainfall (mm / year)			
C ≯1000	@ 500-1000	C 200-500	C < 200
Access of water to and from	mine ———		
○ Direct openings	C Partly blockaded	○ Blockaded	<ul> <li>No connection</li> </ul>
Aquifer development potenti	a		
○ High	← Significent	Marginal	C Insignificant

Figure 2-9(b). Screen layout for impact assessment on mine/aquifer relationship for bord-and-pillar mining at 100 m depth.

			Mineral	ulțu	ed: Coal
Reactive Minerals in waste C Acid	© Alkaline then sold		Alkaline	<u>ر</u>	Non-reactive
Area to be mined (ha)	C 400-1000		100 - 400	<u></u>	< 100
Rock condition in mine  Porous and fractured	C Porous	· ·	Fractured	<u></u>	impervious
Mining method	5-20 % of area collapsed to aquifer or to surface	۰	0-5% of area collapsed to aquifer or to surface	<u> </u>	No collapse to aquiler or to surface
Mine status Closed betare 1956	C Closed 1956 - 1975	<u></u>	Closed 1977 - present	e	Still operating
Electrical conductivity of mine v	vater (mS/m)	==			
C > 300	<b>ほ 150 - 300</b>	۲	75 - 150		< 75
Taxicity to most sensitive users  Rediogenic, toxic	€ Hermfull	·-·	Limited impact	- ~·-	No Impact

Figure 2-10(a). Screen layout for impact assessment on mine/water relationship for longwall mining at 100 m depth.

	М	ineral mined:
#)		
C 4000 - 10000	C 1000 - 4000	C < 1000
Through aquiter	C Below aquiter	C Above aquiler
e and aquiter —		
C Significant	C Minor	C Insignificeat
C Indirect connections	C Impact unlikely	C No Impact
<del></del>		· · · · · · · · · · · · · · · · · · ·
€ 500-1000 T	C 200-500	C < 200
ins		······································
<ul> <li>Partly blockaded</li> </ul>	C Blockaded	C No connection
ļ		
C Significant	@ Marginal	C Insignificant
	<ul> <li>← 4000 - 10000</li> <li>← Through aquider</li> <li>← and aquifer</li> <li>← Significant</li> <li>← Indirect connections</li> <li>← 500 - 1000</li> <li>← Partly blockeded</li> </ul>	C 4000 - 10000 C 1000 - 4000  Through aquiter  Below aquiter  Significant C Minor  Indirect connections C Impact unlikely  500 - 1000 C 200 - 500  Partly blockeded C Blockeded

Figure 2-10(b). Screen layout for impact assessment on mine/aquifer relationship for longwall mining at 100 m depth.

# 2.5.1.1.1 Reactive minerals in mine

Sulphide minerals are stable in reducing environments. Mining exposes these minerals to atmospheric conditions (air and water); an environment in which they are unstable. They react to form oxidic phases that are in equilibrium in the new environment. In doing so, sulphur is released and reacts with the water to form sulphuric acid. This may lower the pH of mine waters to around 2. At pH below 5, many toxic metals go into solution in the acid water so the concentration of metals in solution increases.

### 2.5.1.1.2 Mining method

An underground coal-mine that is mined by bord-and-pillar methods at a depth of 100 m below surface, can be flooded with water after mining operations have ceased, without any danger to the adjacent environment. The mine is too deep to allow ingress of oxygen into the workings and also too deep to allow water to flow from the mine, after it has filled up.

IN contrast, in the case of high underground extraction of coal, numerous cracks are created from the mining level all the way to the surface. Ingress of fresh water containing oxygen and also ingress of air are possible. The probability of the mine water becoming acid over a period of time is therefore significantly greater for high underground extraction mining than for bord-and-pillar mining.

### 2.5.1.1.3 Chemistry of mine water

Water in a bord-and-pillar mine does undergo limited degradation. After the mine has been flooded, no further degradation of the water in the mine is expected, since oxygen will have been excluded from the system.

Groundwater undergoes significant changes in its chemical composition as it flows towards areas of underground high extraction, enters these areas and accumulates in the mine. These reactions have been discussed in detail by Hodgson and Krantz (1995). Water contained in high extraction areas usually has a high sodium content; the sulphate, calcium and magnesium content also increase with time. The water is unsuitable for irrigation or for disposal into public streams.

### 2.5.1.1.4 Dewatering rate of mine

Influx of water into underground high extraction mining areas in South Africa ranges from 500 - 3 000 m<sup>3</sup>/day, per area mined (Hodgson and Krantz, 1995). Typical influx rates for a whole mine could be 10 - 20 ML/day. This is significantly higher than what is usually encountered at bord-and-pillar mines, where the whole mine would usually experience an influx of 2 ML/day or less.

#### 2.5.1.1.5 Mine relative to aguifer

In Mpumalanga, three aquifers have been described by Hodgson and Krantz (1995).

The uppermost aquifer is in weathered strata. This groundwater is unaffected by coal mining.

In fractured unweathered Ecca formations, water is found in:

- Fractures.
- The coal-seam.
- Associated with dolerite intrusion contact zones.

Bord-and-pillar mining usually only impacts on water in the coal horizon, the other groundwater resources are left intact.

Fractures that extend below the Karoo sediments are usually closed and yield little water. Occasional exploration intersections of these fractures have yielded water under pressure which enters the mine. These sources of water are usually low-yielding and are sealed if they present a problem to mining operations.

As high extraction mining methods cause all the strata above the coal-seams to collapse, all aquifers in and above the coal-seam are affected.

# 2.5.1.1.6 Interconnectivity between mine and aquifer

Fracturing due to collapse of strata above high extraction areas is usually most severe immediately above the mined out area, with distance crack densities decrease and on surface, circular cracks usually appear. Connection between aquifers and underground high extraction areas should be classified as major.

In some places, the fractures have silted up and perched water tables in the weathered aquifer occur above some of the collapsed areas. Thus the connection between the aquifers and underground high extraction areas could diminish with time.

For bord-and-pillar mining, there are very few instances known where aquifers overlying bord-and-pillar mining in Mpumalanga have been dewatered. Although farmers have made allegations to this regard, in almost all instances these were due to equipment failure.

#### 2.5.1.1.7 Access for water to and from mine

Some mining methods allow direct access of water to or from the mine workings. For example, surface run-off could flow directly into surface workings.

Recharge water from the mine could decant from an open pit, rise up a shaft or recharge local groundwater via mining induced fractures.

Thus the mining method has a significant impact on the risk potential to the groundwater system.

# 2.5.2 Example 2: Mineral mining

The potential impact of a quarry for industrial mineral recovery such as quartz, used for fillers, filter sand or glass manufacture; calcite or dolomite, used for fillers in paints and plastics and in agriculture, steel and mining industry, resorts here. The selected categories for a typical small-scale operation are illustrated in Figures 2-11(a) and (b). It is clear from the individual as well as combined scores for an operation of this kind, that there is no threat to the environment.

Reactive Minerals in waste		Mineral	mined: Silica
C Acid	C Alkaline then acid	C Alkaline	€ Non-reactive
Area to be mined (ha)		•	
C > 1000	C 400-1000	C 100-400	€ <100
Rack condition in mine			
C Parous and fractured	C Porous		← Impervious
Mining method  > 20 % of area collapsed to aquiler or to surface	5 - 20 % of area collapsed to aquifer or to surface	©-5% of area collapsed to	e Na collapse to aquifer or to surface
Mine status			10 00,0101010101010101010101010101010101
Closed before 1956	€ Closed 1956 - 1976	Closed 1977 - present	≪ Still operating
Electrical conductivity of mine w	ster (mS/m)		
C > 300	€ 150-300	C 75-150	G <75
Toxicity to most sensitive users	A AMERICAN SERVICE STREET	<del></del>	
□ Radiogenie, toxic	⊂ Harmfull	C Limited impact	No Impact

Figure 2-11(a). Screen layout for impact assessment on mine/water relationship for silica mining.

Novemboring rate of mine (m. 2	(-T		lineral mined:
> 10000 c > 10000	/d) ← 4000-10000	<b>№ 1000 - 4000</b>	C < 1000
line relative to aquiler		· · · · · · · · · · · · · · · · · · ·	CO VALUE CONSTRUCTION IN THE RESERVE THE SECTION OF THE SECT
Within equifer	C Through equifer	◆ Below aquiler	C Above aquifer
nterconnectivity between mi	ne and aquiler		PRINCE
C Major	C Significant	C Minor	← Insignificent
opography-			
Intersecting seepage	C Indirect connections	○ impact unlikely	© No Impact
tainfall (mm / year)			
C > 1000	€ 508-1000	C 200 - 500	€ < 500
ccess of water to and from (	mine ————————————————————————————————————		
C Direct openings	<ul> <li>Partly blockaded</li> </ul>	C Blockaded	♠ No connection
quiler development potenti	<u> </u>		
∩ High	C Significant	Marginal	C Insignificant
··········			

Figure 2-11(b). Screen layout for impact assessment on mine/aquifer relationship for silica mining.

# 2.5.3 Example 3: Gold mining

A further example is drawn from a comparison between gold mining in the West Wits area and that in the Free State gold-fields. Both mining operations are deep, but dewatering of the overlying aquifers is only necessary in the West Wits area. In contrast, the Free State mine dewatering has no perceptible impact on the aquifer that is generally used for household and farming. In both areas though, waste disposal on surface, for instance, rock, slimes, water and effluents from reduction plants, have significant impacts as illustrated by the Mine/Waste menus. The results from these evaluations are included in Figures 2-12(a) and (b). The conclusions drawn from these two figures are that the risk for pollution of the aquifer is significantly greater in the West Rand area because of the presence of the dolomite, than in the Free State where Karoo rocks are encountered.

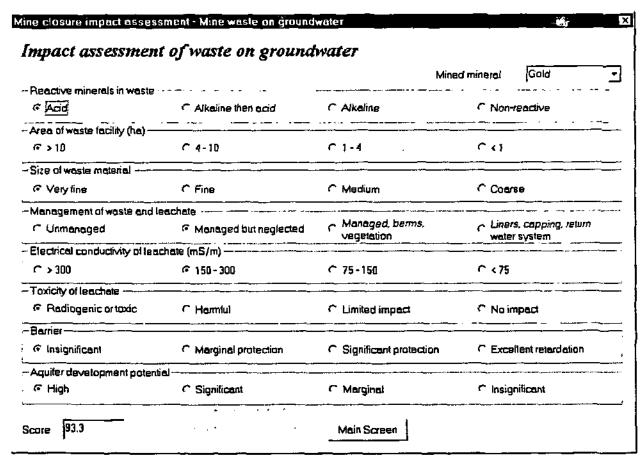


Figure 2-12(a). Screen layout for impact assessment of mine waste on groundwater at the West Witwatersrand Gold-mines.

			nad minaral Gold
Reactive minerals in waste: Acid	C Alkaline then acid	C Alkaline	○ Non-reactive
Area of waste facility (ha)			
<b>€</b> > 10	C 4-10	C 1-4	C K1
Size of waste material			
© Very line	C Fine	C Medium	C Coarse
denagement of waste and I	eachale		
CUnmanaged	← Managed but negleded	<ul> <li>Managed, berms, vegetation</li> </ul>	Liners, capping, return water system
lectrical conductivity of lea	chate (mS/m)		
C > 300	₱ 150-300	C 75-150	C <75
oxicity of leachate -			them a probable of the control of th
• Radiogenic or toxic	C Harmful ,	C Limited impact	○ No impact
larner — — — — —			
C Insignificant	<ul> <li>Marginal protection</li> </ul>	C Significant protection	C Excellent retardation
quiler development potent	jal	-	and the contract of the contra
∩ High	C Significant	Marginal     Marginal	C Insignificant

Figure 2-12(b). Screen layout for impact assessment of mine waste on groundwater at the Free State Gold-mines.

# 2.5.4 Regional evaluation using GIS

#### 2.5.4.1 Introduction

The initial description of the method treats each mine as a point. The next step in this investigation was to assign values to each of the categories for all the major coal mines in Mpumalanga and to evaluate this information spatially by means of a Geographic Information System (GIS).

Arc/Info GIS software was used because:

- It is used by the Department of Water Affairs in South Africa.
- Many coverages of regional and local information are available from the Department.

Coverages required for this study were:

- · Surface drainage systems.
- Catchment boundaries.
- Infrastructure.
- · Mine boundaries.
- Mine holding companies or owners.
- Current operating status of the mines.

These coverages can be superimposed through the use of Arc/Info software.

ArcView 3 was used for coverage manipulation and to produce maps. An interface between RISKY results and ArcView 3 was developed. The scores of

any of the categories in RISKY, as well as the composite scores calculated by the program, could be spatially mapped with ArcView 3.

The results of this example are plotted in Plates 3 - 20 which are shown in the Appendix. Some discussion of the results is given in the next sections.

#### 2.5.4.2 Surface area of waste facilities

The majority of the mines in Mpumalanga have accumulated significant tonnages of mine waste, particularly at mines where coal washing plants are used. The waste material can be 20 - 30% of the total coal production. At some of the larger collieries more than 30 Mt of coal discard is already stored and projected tonnages for the life of these mines are about 60 Mt.

Such volumes of coal discard are almost impossible to manage properly and they will have a significant impact on the groundwater resources in their immediate vicinity. Plate 3 shows that the majority of the collieries fall in the high risk range when it comes to the surface area of their waste facilities. In fact, almost all collieries rank above the 50% risk of having an impact on groundwater.

At some of the collieries shown in Plate 3, water disposal or other waste byproducts have also resulted in elevated risks for these mines.

# 2.5.4.3 Waste management

The classes for waste management used in this evaluation range from unmanaged (highest risk) to managed with liners, capping and return water system (lowest risk).

Due to the scale of waste storage at the collieries, it is impossible to economically provide the coal discards, for instance, with liners below the dumps. None of the waste facilities in the Mpumalanga area therefore fall in the low risk category (Plate 4).

Only one of the collieries currently falls in the second category, namely well managed with berms and vegetation even though, at many other collieries, berms and vegetation are present. Obvious signs of seepage from these facilities are evident on close examination and these facilities have been classed into the next category, namely managed but neglected. This does not imply that the remainder of the collieries is not doing anything to prevent pollution emanating from waste facilities. It simply suggests that management options exercised at the mines are currently not sufficient to curtail migration of pollution. About 60 percent of the collieries fall in the high-risk category for waste management.

### 2.5.4.4 Electrical conductivity of leachate

In the coal-mining industry, pyrite oxidation is usually followed by neutralisation by the natural base potential of the rock. This leads to high salinities, which are reflected by high electrical conductivity values.

The high-risk areas, in terms of electrical conductivity shown in Plate 5, are due to a combination of factors. Usually, it is a result of waste products having been placed in areas where air and water can easily ingress into the waste, thus causing significant deterioration of water quality in the waste piles. At more than 80% of the collieries in the Mpumalanga area, leachate from the mine waste products have electrical conductivities between 150 - 300 mS/m.

### 2.5.4.5 Toxicity of leachate

The toxicity of the leachate is often intimately associated with the electrical conductivity. Under alkaline conditions, there is a direct correlation between toxicity and salinity. Where the leachate is acid, the toxicity of the leachate increases, mainly because of its potential impact on aquatic life. At all the sites in the Mpumalanga area, leachate is neutralised before it passes into public water systems. For that reason, the rating of the mines in Plate 6 is the same as in the previous figure; i.e. the risks for toxicity and electrical conductivity are the same for the collieries. In the event that the base potential from coal discard dumps becomes depleted through oxidation processes, the possibility exists that neutralising agents cannot be added at the source in each instance, in which case the toxicity diagram will show higher risk ratings.

### 2.5.4.6 Aquifer development potential

The aquifer development potential for South African Aquifers has been published by Vegter (1995). This information has been combined with the information generated during the mine pollution risk assessment. The result is presented in Plate 7. It is concluded that the aquifers in the Mpumalanga area are generally low yielding and that the impact of aquifer pollution would be low, except perhaps to farmers who lose their only water supply.

#### 2.5.4.7 Area to be mined

The area to be mined has been selected as a category for the evaluation of the risk associated with the mine/water relationship. The argument usually applied is that the larger the area, the larger the volume of water expected in mine environments. In this respect, the mines have been subdivided using a logarithmic scale, with mines smaller than 100 ha considered to have a small total impact, provided that mining is done according to recognised standards.

Unfortunately, most of the smaller mines in South Africa belong to individuals or small mining organisations. They are often less inclined to consider environmental implications in pursuit of short-term profits. The RISKY evaluation can, however, not accommodate mines that do not adhere to the required standards. These mines should be evaluated according to the situations encountered on site. In the RISKY evaluation, it is therefore assumed that sound management practices are applied at all mines in South Africa irrespective of size. The size of the mines therefore only relates to the volume of water and finally the potential impact that it could have on the surrounding environment, in terms of possible seepage of this water into adjacent aquifers.

Several mines in Mpumalanga have merged. This development has not been shown in Plate 8. The risk assessment result would be different if the mines were considered as merged.

Most of the older mines classify in the low risk category in terms of their scale of operations. These mines usually score unfavourable in terms of most other categories. This is due to a legacy of pollution as a result of unacceptable practices during the early years of mining. This one redeeming category is therefore available for old mines.

### 2.5.4.8 Mining method

Mining methods have changed significantly during the past 20 years in Mpumalanga. Bord-and-pillar mining was the predominant technique before

1975. In 1976, the first longwall operations were planned and pillar extraction had been performed on a limited scale at several collieries. Opencast mining was also developed into a profitable technique, with more than five collieries planning large-scale operations at that stage.

Of these mining methods, opencast collieries have the greatest potential to pollute surface water resources (Hodgson and Krantz, 1995). This is followed by underground high extraction of coal, because of the scale on which it is done and the fracturing of the overlying strata.

Bord-and-pillar mining is generally considered to be less of an environmental risk, provided the overlying strata do not collapse. Collapse of the strata has occurred in the area west of Witbank and significant pollution currently flows. from these mines into the Olifants- and Klip Rivers. The RISKY evaluation does not distinguish between stable bord-and-pillar mining and collapsed bord-and-pillar systems. Thus class selection in this category must take the collapse into account. It is recommended that collapsed bord-and-pillar mining should be grouped in the same class as underground high extraction mining. This has been done for the compilation of Plate 9.

The conclusion is drawn that where bord-and-pillar-mining methods were used at depths below surface that prevented collapse, this mining method did not interfere with aquifers or surface run-off. The method therefore has low risk of causing groundwater pollution. Mines which used underground high extraction methods, received the highest scores.

### 2.5.4.9 Mine status

Plate 10 is a depiction of the risk of pollution for mines in terms of their operating status. Mines that have closed before 1956 have been assigned the highest risk potential. This is due to the fact that these mines are the responsibility of the Government and any pollution that is derived from these mines will have to be remedied from public funds.

Mines that have been abandoned or that stopped operations between 1956 and 1976, could also be the Government's responsibility if the companies responsible, during that time, have subsequently been placed under liquidation.

Mines that closed after 1976, are placed in a lower risk category, since the owners of these mines can usually be held responsible for pollution that originates from these mines.

The lowest risk in this category represents those mines that are currently operating. Most of these mines or mining groups currently have funds that have been set aside for rehabilitation purposes. Whether these funds are adequate is another matter. The creation of national funds is still under investigation. In other countries, particularly in the United States (Sorensen et al., 1975), the principle of reserving funds for rehabilitation and management after closure has been established. Through contribution to such a fund, the after closure responsibility is taken care of, ensuring that the mines do not become a problem. If such a system is instigated in South Africa, this category will have to be reviewed and the necessity for its inclusion in this risk assessment will be reconsidered. In Plate 10, and in view of a lack of sufficient information, none of the mines have been classified in the category of closure before 1956. The remainder of the mines that have closed, have been separated into two groups, depending on the year of closure. It is clear that more than 80% of the mines are still operational in the Mpumalanga area.

### 2.5.4.10 Electrical conductivity of mine water

Water from underground mines in Mpumalanga usually has electrical conductivity in the range 150 - 300 mS/m. There are few exceptions, as indicated in Plate 11. In cases with water of better quality, it is usually due to active circulation in these mines.

The long-term water quality is expected to remain within the range indicated in Plate 11. After operations have stopped, the mines will be allowed to flood, after which significant water quality deterioration is not expected in most of the deeper mines.

### 2.5.4.11 Toxicity of mine water

The toxicity of the mine water is linked to the electrical conductivity of the water (Plate 12) in the same way that was done for leachate from surface wastes. The toxicity may fall in a higher risk class than the electrical conductivity, but only in cases of low pH. Most of the mine waters have neutral pH-levels. Crop irrigation tests are being done with these waters.

In exceptional cases, acid water flows from individual mines and affects aquatic life in the receiving water. This is particularly the case in the area west of Witbank.

### 2.5.4.12 Dewatering rate

The dewatering rate is directly related to the mining method. Underground high extraction of coal causes collapse in the overlying strata. Mines where this mining method is used, get a high risk rating (Plate13).

### 2.5.4.13 Mine position relative to the aquifer

In all examples in Mpumalanga, the mines are below the aquifers.

In deep underground mines using bord-and-pillar methods, there is little risk of dewatering the overlying strata. Prospect boreholes and shafts do, however, pass through the upper strata and local dewatering is possible.

In areas of high extraction, fracturing of the overlying strata is so intense that most of the water is drained from the overlying strata into the mines. Aquifers are depleted so that farmers often have to be supplied with alternative water sources.

High risks in this category are directly related to high underground extraction mining (Plate 14).

#### 2.5.4.14 Interconnectivity between mine and aquifer

This category is, to some extent, an overlap of the previous category in which the mine position relative to the aquifer has been considered. It does, however, provide another view of this aspect as can be seen from the different ratings that have been obtained (Plate 15).

# 2.5.4.15 Access of water to and from mine

Access of water to the mine is an important consideration during mining operations. Large volumes of water that flow into the mines increase the risk of pollution, since this water has to be disposed of.

After mine closure and after the water level in the mine has fully recovered, the mine water becomes part of the regional groundwater regime. If interconnections exist between the mine and surface or between the mine and aquifers, a danger exists that polluted water from the mine will flow into surface watercourses or recharge aquifers along these pathways. In this category, shallow underground mining, irrespective of the mining method, and high extraction underground mining would both receive high scores (Plate 16).

### 2.5.4.16 Overall risk of contamination from waste on surface

Plate 17 has been obtained by combining the individual scores for the surface waste disposal categories. If the mine, south-east of the Grootdraai Dam, is ignored because it is no longer operational, then the conclusion is that surface waste facilities at collieries in Mpumalanga are poorly managed. All mines fall in the high to very high risk classes. It is clear that special attention will have to be given to all aspects of surface waste disposal in the mining industry, to ensure sustainable, environmentally acceptable, conditions after mine closure.

### 2.5.4.17 Mine/water quality risk assessment

Plate 18 shows the risk of groundwater contamination spreading from collieries in the Mpumalanga stream as a result of mine/water interrelationships. It is clear that mines in the south are generally performing better than the mines in the north. This is due to the mines in the south being generally deeper and newer than those in the north, and more advanced water management strategies are practised.

### 2.5.4.18 Mine/aquifer risk assessment

The north/south distinction also occurs for aquifer risk assessment, although the collieries in the south register higher risks (Plate 19). This is mainly due to several of the collieries in the south practising underground high extraction mining. The collieries in the north are classed as having the highest risk, because of their proximity to surface.

#### 2.5.4.19 Total mine risk assessment

When combining the information on the previous two Plates, a total mine risk assessment is obtained. The conclusion is that more than 50 percent of the mines fall in the low risk category of 25 - 50% (Plate 20). The mines that fall into a higher category are all located in the north, where shallow mining or specific mining practices increase the risk of groundwater pollution.

# 2.6 Conclusions

The following are the main conclusions from the application of the RISKY evaluation:

- Categories and classes used for the evaluation of the mines are sufficiently broad to be used for mines where a minimum of information is available.
   The evaluation may therefore be used as a first approximation, to either decide between various options or to evaluate the performance of one mine against another.
- As more information becomes available, the quantification procedures used to evaluate each category or class can be refined. The RISKY

- software does not need to change, but accommodates input from more sophisticated systems.
- The weighting between categories and classes and the facility to fit non-linear distributions across classes should be sufficient to accommodate most situations. If these facilities prove inadequate, it is possible to program a suitable equation into the evaluation, so that the RISKY procedure does not become invalid.
- In the event that additional categories or classes need to be added to the system, this can also be done without jeopardising the operational simplicity of the RISKY software.
- It stands to reason that the selection of classes in each of the categories will need to be substantiated by the provision of documentary proof by the mines.
- The combination of the RISKY procedure with a Geographic Information System and the possibility of displaying any of the scores in each of the categories as GIS coverages, significantly enhance the applicability of the system. The power of spatial visualisation of specific issues has been adequately demonstrated in this research.
- It is recommended that the database on which these evaluations were based, should be refined to incorporate information for all mines in South Africa. The quality of the information used for the Mpumalanga mines should also be verified. Through the introduction of this procedure to the industry and government departments, a common denominator will be created which may be used during mining, as well as after closure, to evaluate performances on a regional and in a comparative way.

As far as the sensitivity of the RISKY evaluation is concerned, scores between 0 - 100 are possible for each of the main evaluation screens. Distribution graphs of the scores obtained for the mines with respect to each of the main evaluation screens have been plotted in Figure 2-13.

The values for the mine risk assessments range from 20 - 90%, while in the case of surface waste disposal, they range from 50 - 93%. This is excellent in terms of sensitivity, considering that only coal mining has been considered. If the risk assessment had included examples of mining with environments ranging from inert to highly reactive, scores between 0 - 100% would be possible.

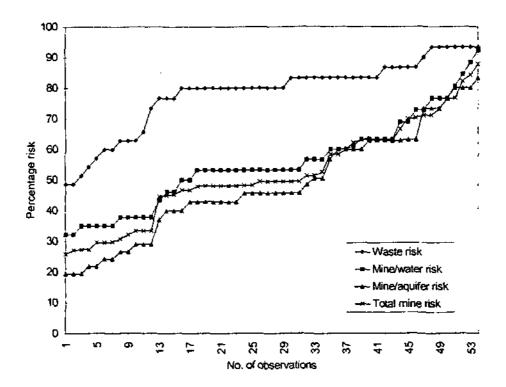


Figure 2-13. Scores obtained for the mines and with respect to each of the evaluation screens.

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Appendix A
Classification of constituents mined and their associated risk
in terms of waste reactivity

Classification		Product	Type deposit	Rank
	ł	Diamonds	Pipes	2
Precious stones	2	Diamonds	Alluvial	0
	3	Diamonds	River Gravels	-1
	4	Emeralds		0
	- 5	Gold	Placer	10
	6	Gold	Banded ferruginous chert	22.5
Precious metals	7	Gold	Gold/quartz veins	13.5
	8	Gold		22.5
	9	PGM	Magmatic differentiation -	13
	,	1 0.00	Merensky Reef	
	10	PGM	Magmatic differentiation -	- 11
	10	FOM		11
			Chromite Bands	
	1 [	Соррег	Replacement bodies	7
	12	Copper		9
	13	Copper		9
	14	Соррет	Breccia bodies,	9
		}	(hydrothermal?)	
	15	Соррет	Alkaline intrusive	.9
	16	Nickel	Ultrabasic pipes	0
Base metals	17	Zinc	V	2
Dage metala	18	Lead		2
	19	Tin	Replacement controlled by:	24.75
	19	110		24.73
			structures, fractures and porous	
			bedded zones	
	20	Iron Ore	Chemical ppt	-0.5
	21	Iron Ore	Banded ironstone	1.5
	22	Iron Ore	Alkaline intrusive	-4
	23	titanium iron	Magmatic differentiation -	-3
			Magnetite Bands	
	24	Manganese	Residual	-0.5
Ferrous metals	25	Manganese	Chemical ppt	0.5
	26	Chrome	Magmatic differentiation -	. 5
		Cinonic	Chromite Bands	_
	27	)   Vanadium	Magmatic differentiation -	-6
	21	Atmadinin	Magnetite Bands	-0
	70	7	Iviagnetite Bands	
	28	Tungsten		-1
	29	Antimony		24.75
Minor Metals	30	Titanium	Beach Placer	-2
	31	Zirconium	Alkaline intrusive	-1
	32	Tantalite		0
Fissionable Metals	33	Uranium	Placer	18
	34	Thorium	Alkaline intrusive	1
	35	Andalusite	Metamorphism (Bushveld	-l
		<b>\</b>	aureole)	
	36	Asbestos	Metamorphism	l
	37	Asbestos	Metamorphism	i
	38	Asbestos		i
	39	Attapulgite		-l
	40		İ	0
		Barytes		
	41	Bentonite		-1
	42	Beryl	i	-1
	43	Calcite		-1
	44	Fluorspar		0

<u>Classification</u>		Product	Type deposit	Rank
Industrial Minerals	45	Gypsum		0
•	46	Feldspar		1- [
	47	Graphite		1
	48	Kieselguhr		-1
	49	Limestone		0
	50	Mica		-1
	51	Perlite		-1
	52	Pyrophyllite		-2
	53	Mineral Pigments		-1
	54	Vermiculite		-1
	55	Wollastonite		[ 0
	56	Silica		-1
	57	Sillimanite		-1
	58	Talc		-1
	59	Silcrete		-1
	60	Kaolin _		
	61	Clay		-1
	62	Fireclay		-1
	63	Flintclay		-1
Ceramic Raw	64	Magnesite		-1
Materials	65	Montmorillonite		-1
	66	Nephiline		] -t
	67	Refractory Schist		
	68	Granite		-1
	69	Marble		0
Dimension Stone	70	Quartzite		-1
	71	Siltstone		-i
	72	Slate	_	
	73	Coal		7
Energy Materials	74	Phosphates		-2.5
	75	Salt		[_ 0_
	76	Rose Quartz		0
Semi-precious stones	77	Tigers Eye		Ò
F	78	Verdite		ا أ

The magnitude of the rank values has no meaning; their relative sizes only are important, giving a ranking rather than a rating.

Negative values are used to identify surface or opencast operations; some mineral commodities are related to both types and are treated separately. The absolute values are equivalent for ranking purposes.

The Rank has been calculated using the following approach:

Values were assigned to a mining type that generated wastes in the following way:

Waste or stockpile	Sand	Slim e	Rock	Slag	Process Effluent	Result Wr
Assigned value	1	0.5	0.5	1	1	Σ

The cumulative result was multiplied by a Resultant Factor that is determined on the basis of the ore or waste containing reactive minerals or phases. The factors are listed as follows:

Reactive material/ phase	Sulphides	Arsenides	Other leachables	Oxides	Resultant Factor
Factor	2	2.5	2	1.5	Σ

The Rank (R) listed in the table is determined from the waste result multiplied by the reactivity resultant factor:

$$R = W_r R_{rf}$$

This approach only takes waste and reactivity into account. Many other factors also contribute and should form part of this evaluation, such as, climatic region and scale of the operation. These will give the evaluation a more reliable multidimensional base.

The arithmetic manipulation of the assigned values can also be revised to produce a better relative rank value.

Risk	Assessment	Procedure

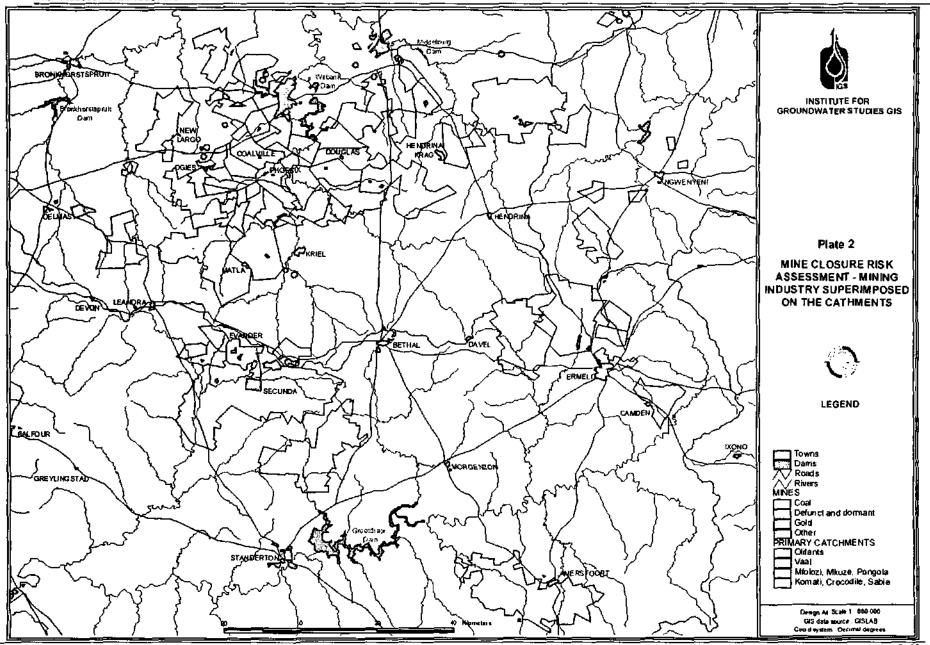
The maps on the following pages were compiled by calculating the risk factor for each of the components and each of the mines. Thereafter, this information was entered into an Arc/Info database, from which the scores were extracted, using groupings, represented by different colours. Other software, such as WISH could also have been used.

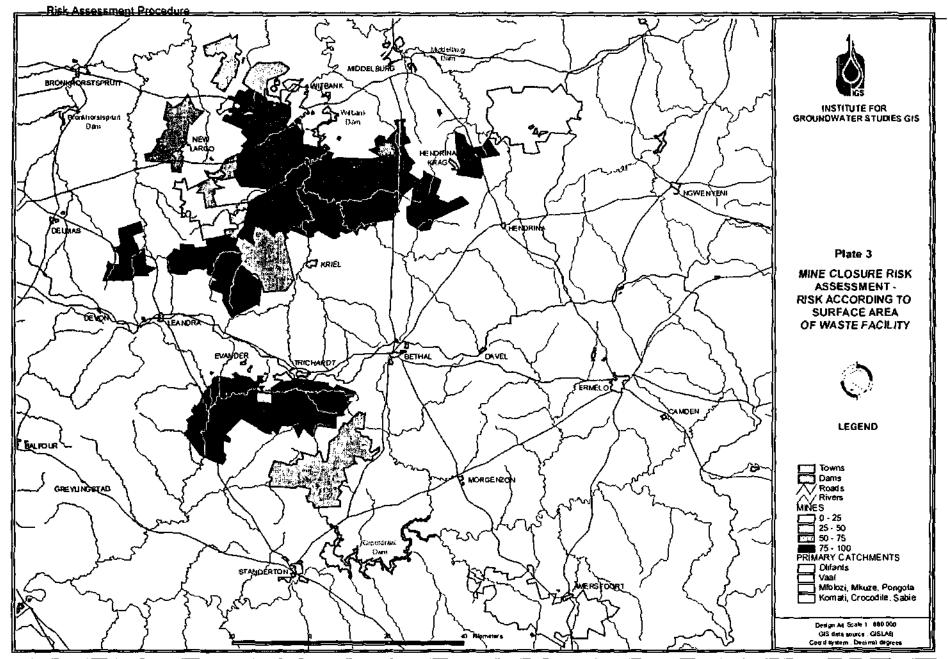
#### Risk Assessment Procedure BROWN HORST SPRUIT Downtors (spini) 100 Dam INSTITUTE FOR - DARGO GROUNDWATER STUDIES GIS BYTAITE TA $\mathcal{D}$ 4 COUGLAS HENDRINA OGIES KRAG PHOENIX ( DELINAS HENDRINA Plate 1 KRIEL MINE CLOSURE RISK ASSESSMENT -SURFACE DRAINAGE AND INFRASTRUCTURE EAHORA BETHAL DAVEL EVANDER <u>TRICHARÓT</u> SRMELQ CAMDEN LEGEND Towns Dams Rivers MORGENZON Roads CHEYLINGSTAD PRIMARY CATCHMENTS Olifants Vaal Komati, Crocodile, Sabie

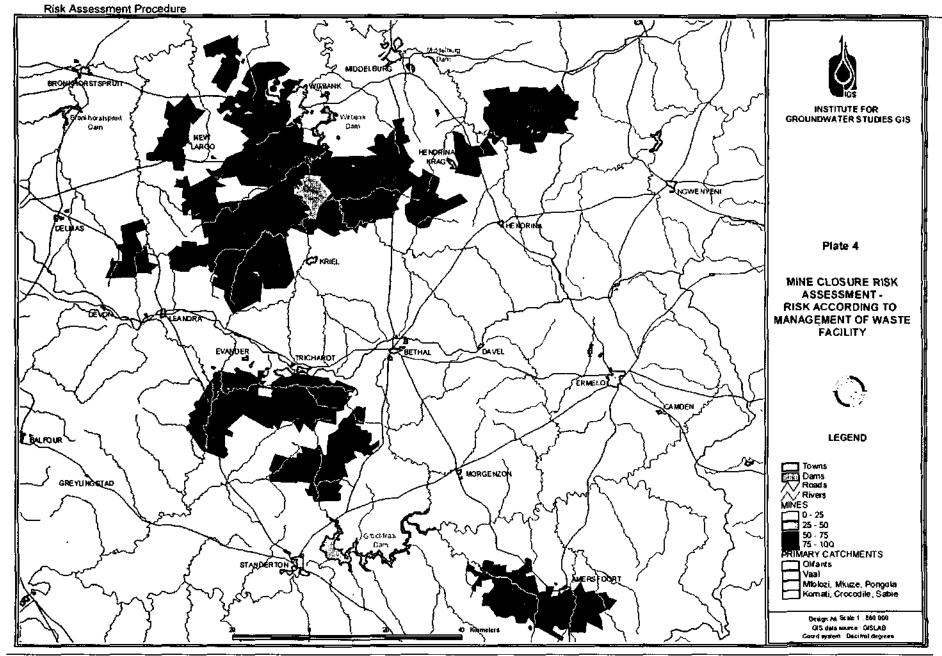
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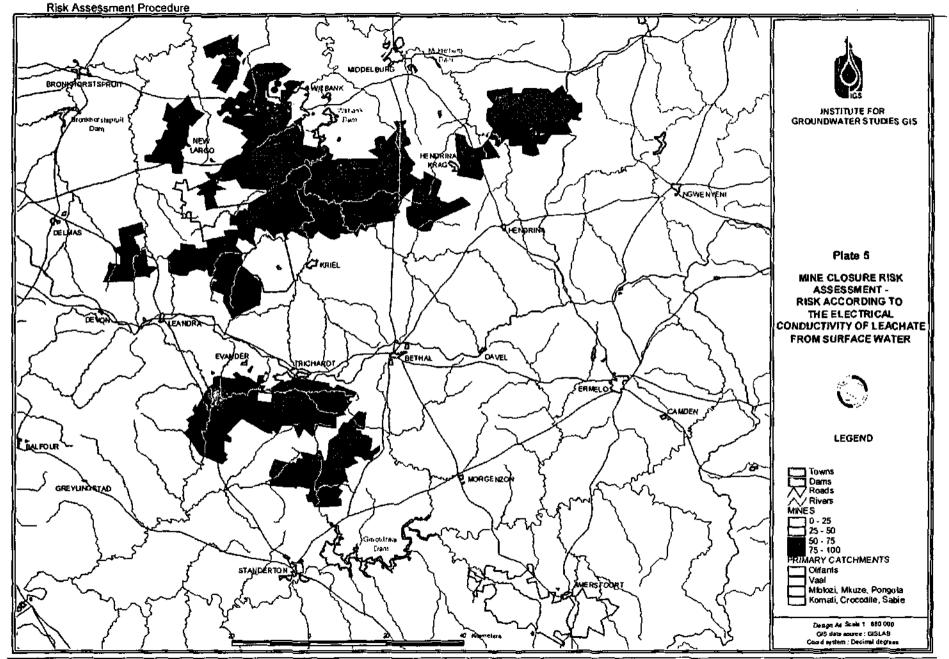
Coard system , Decimal degrees

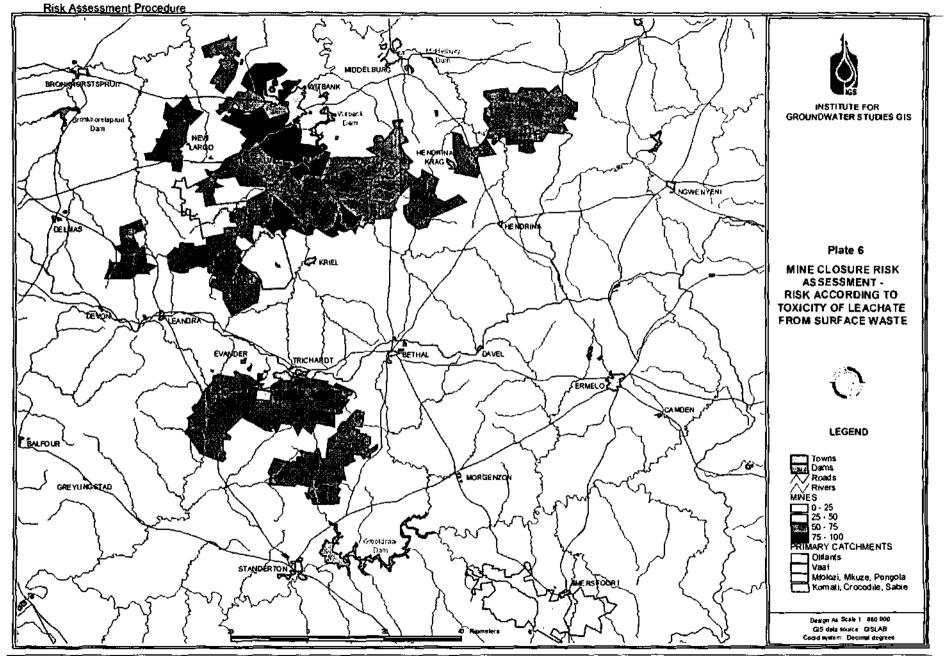
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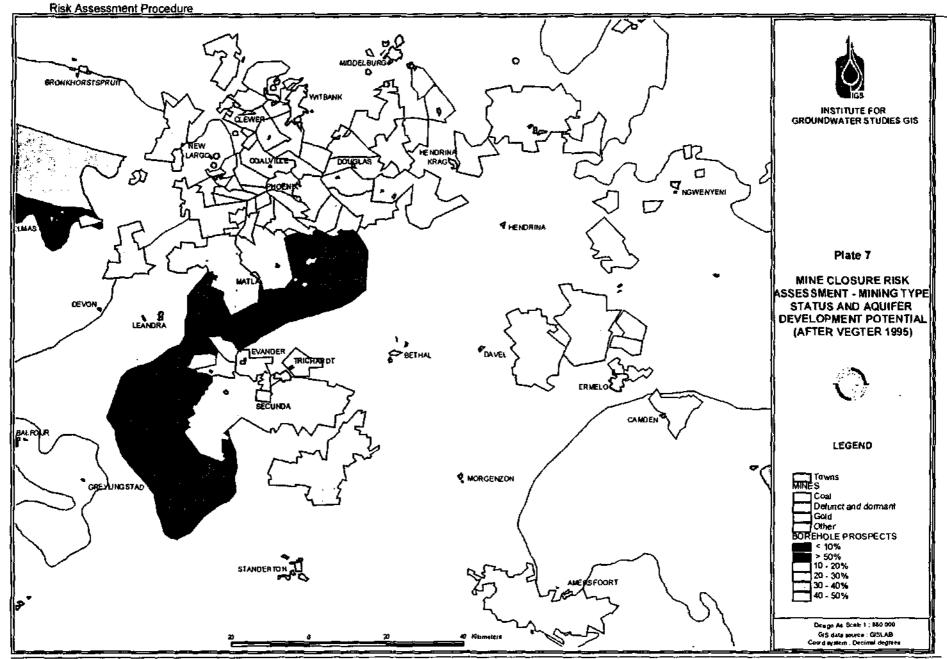


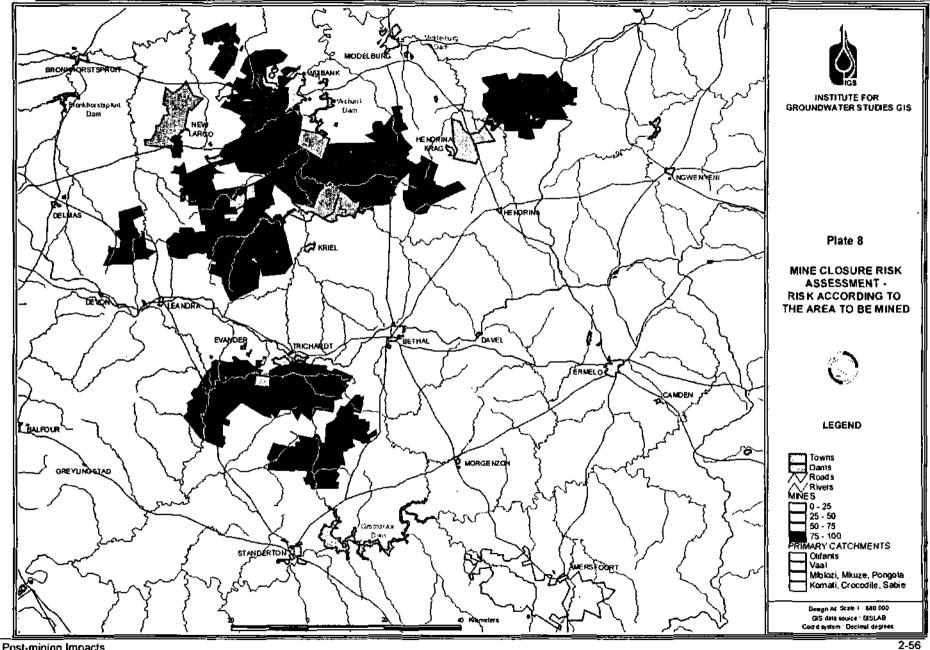


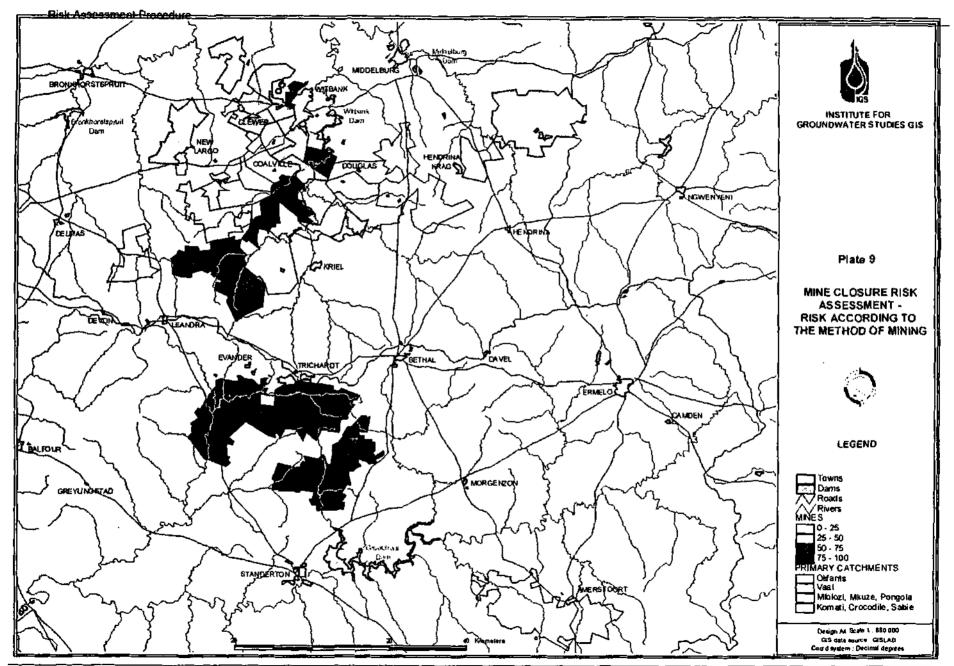


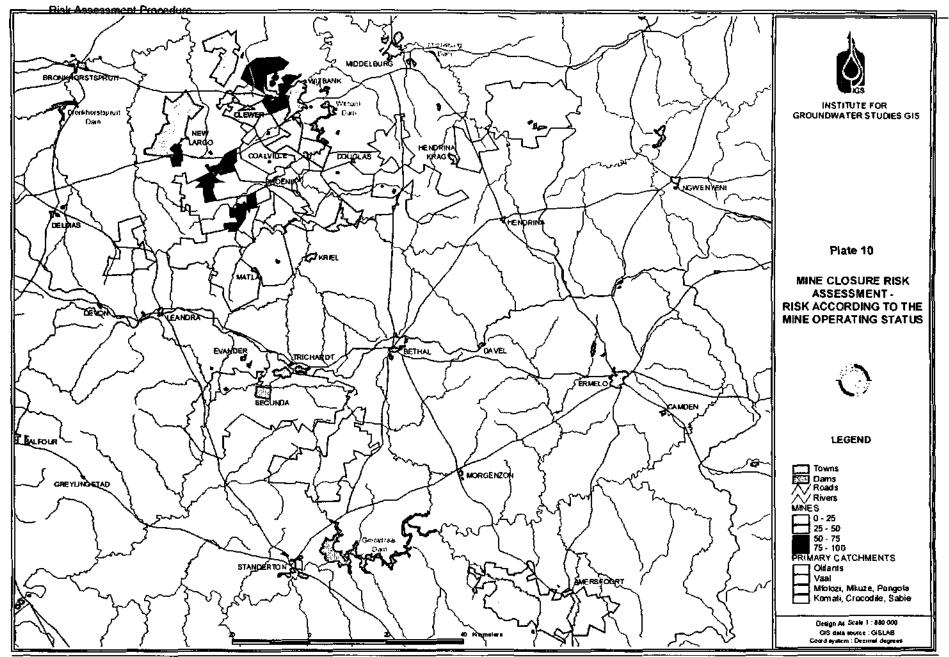


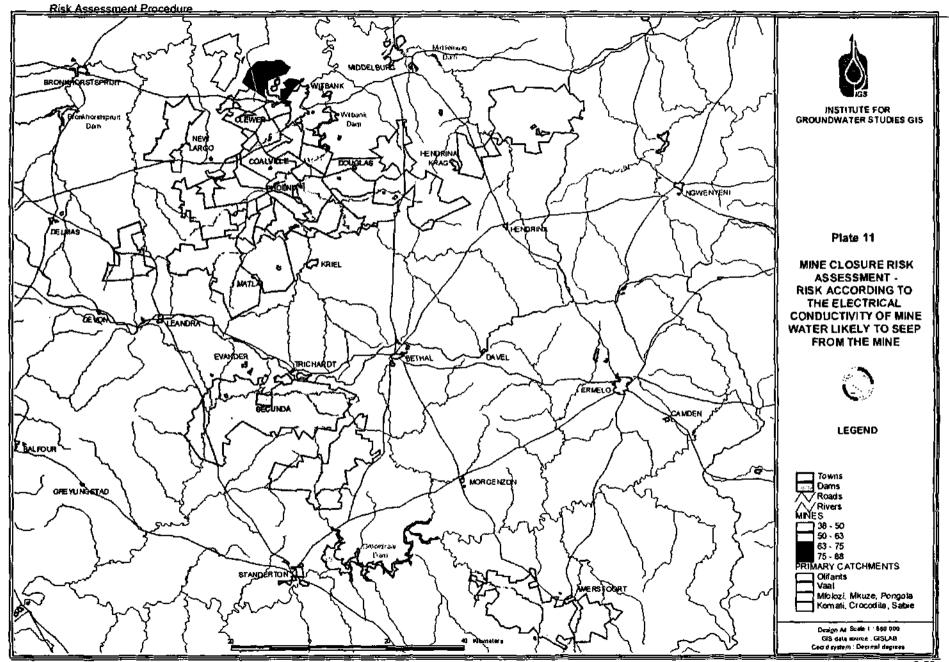


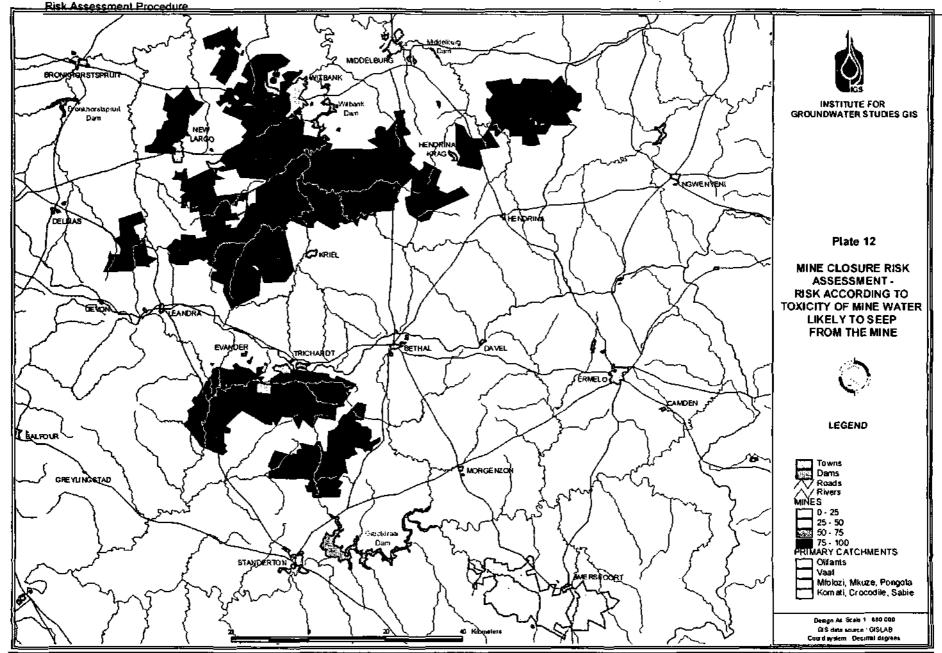


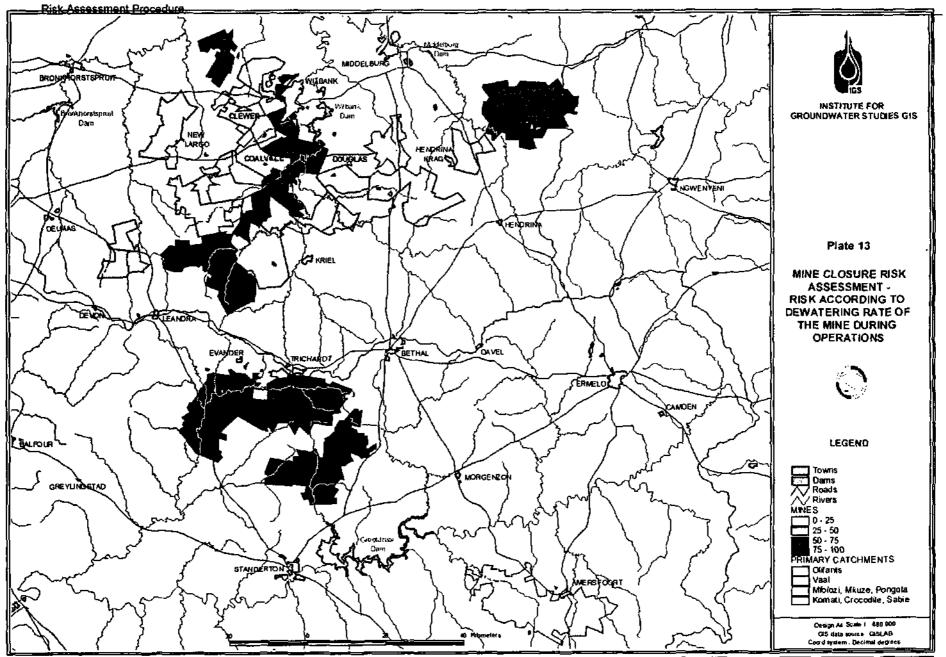


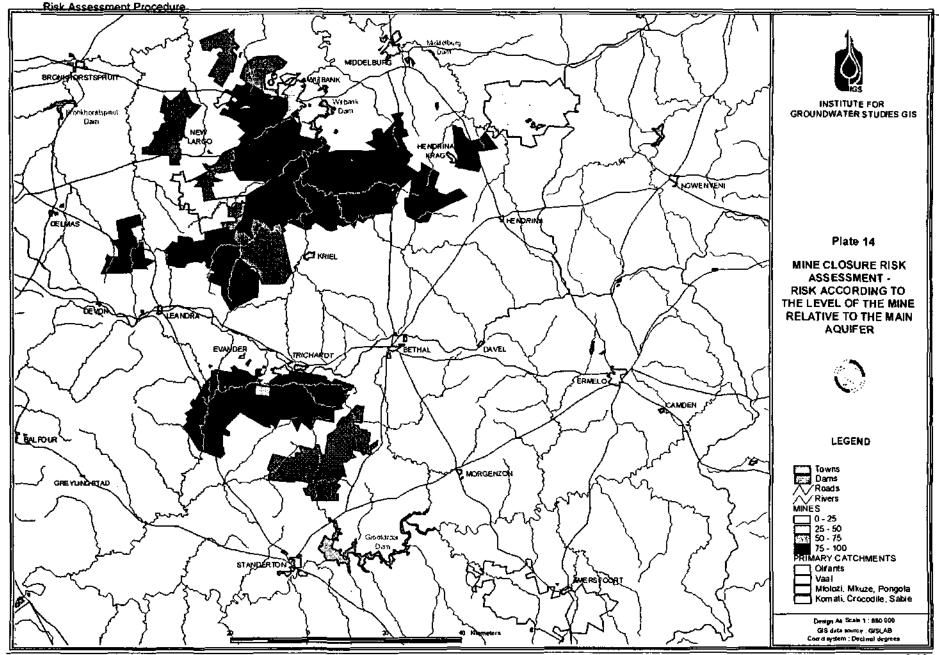


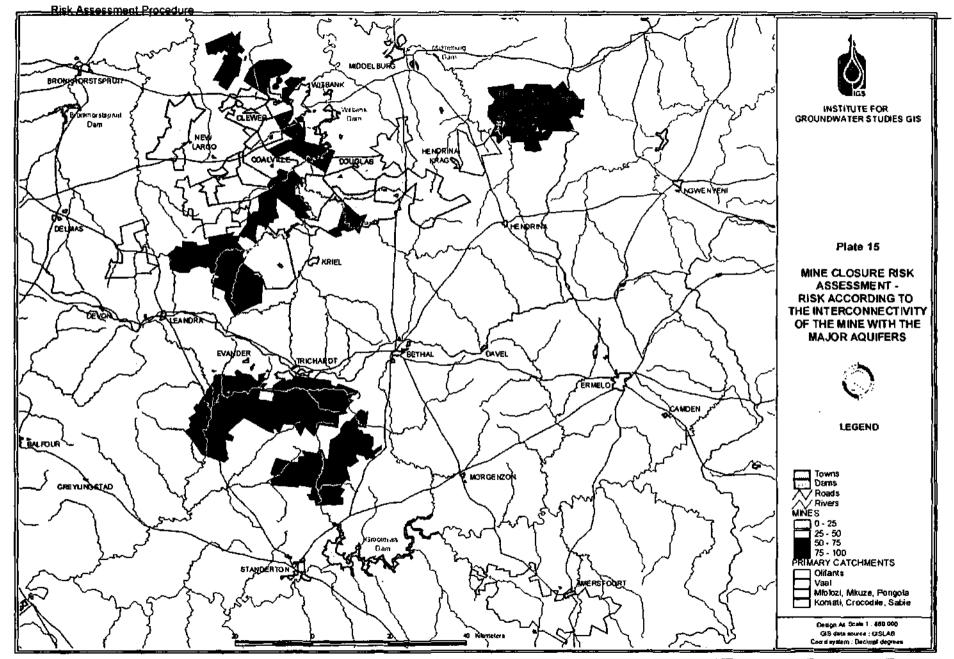


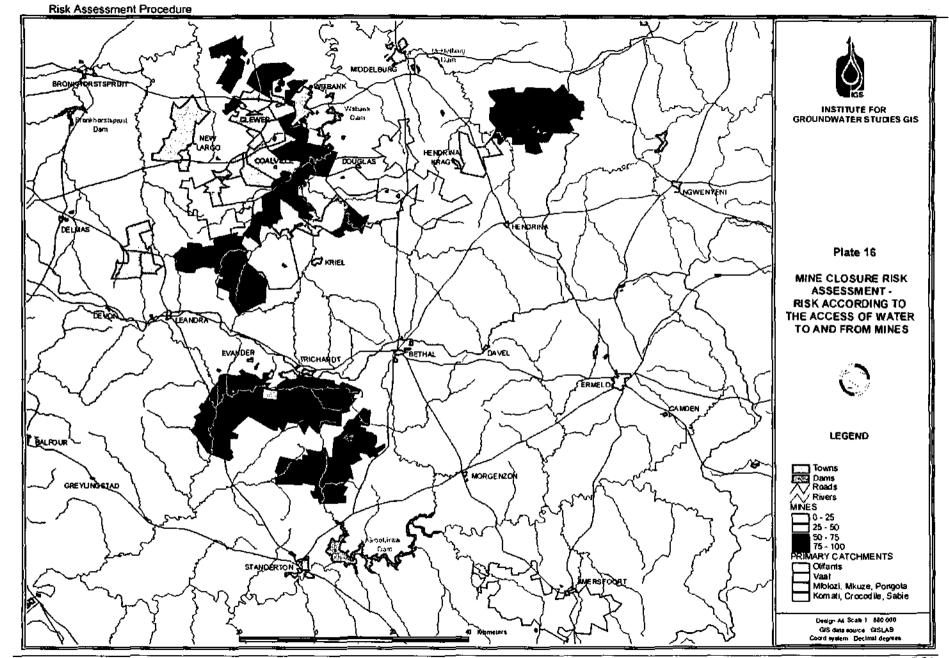


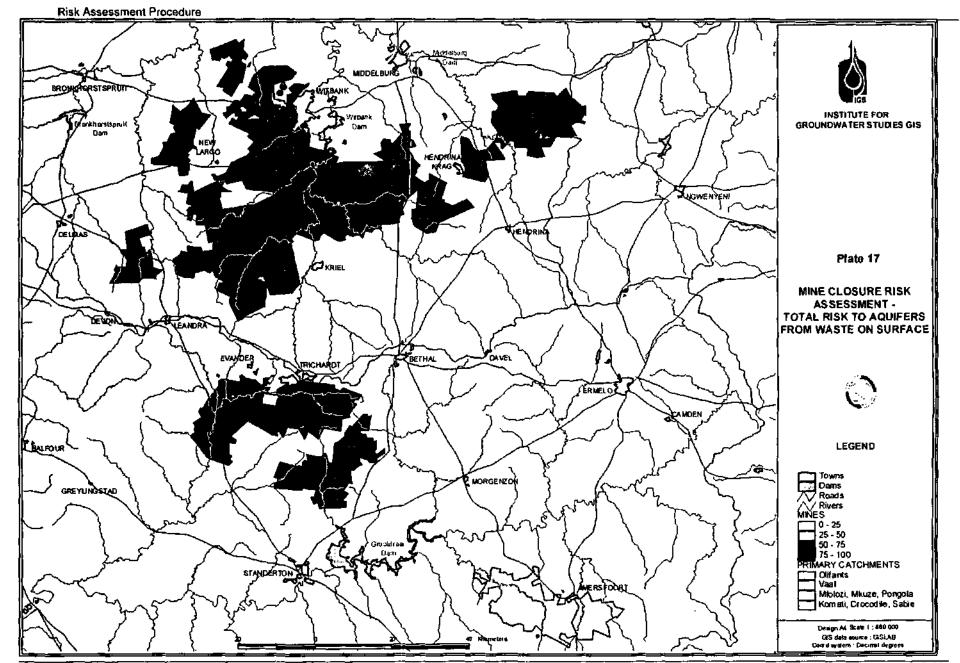


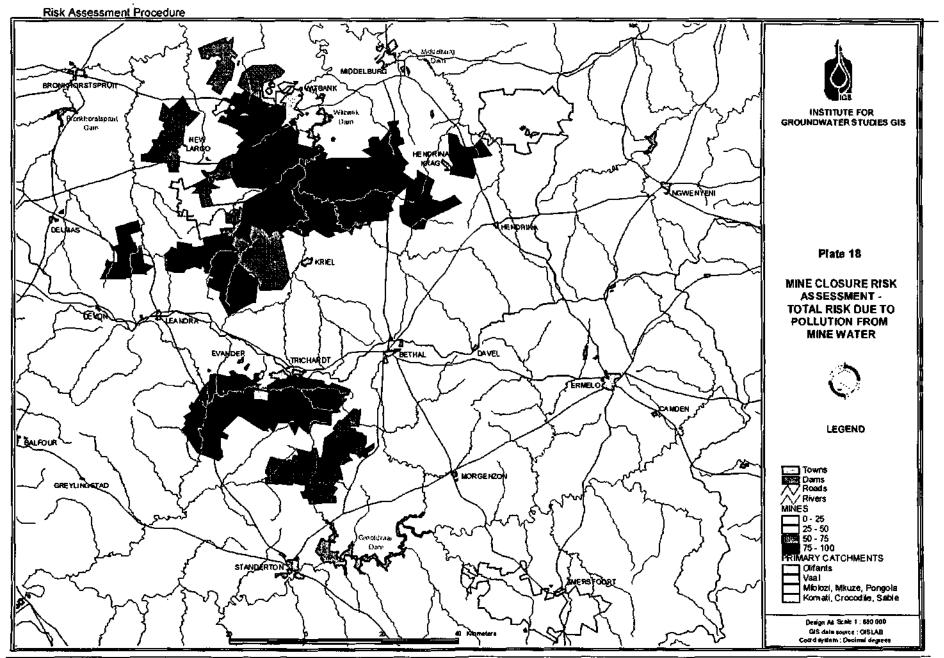


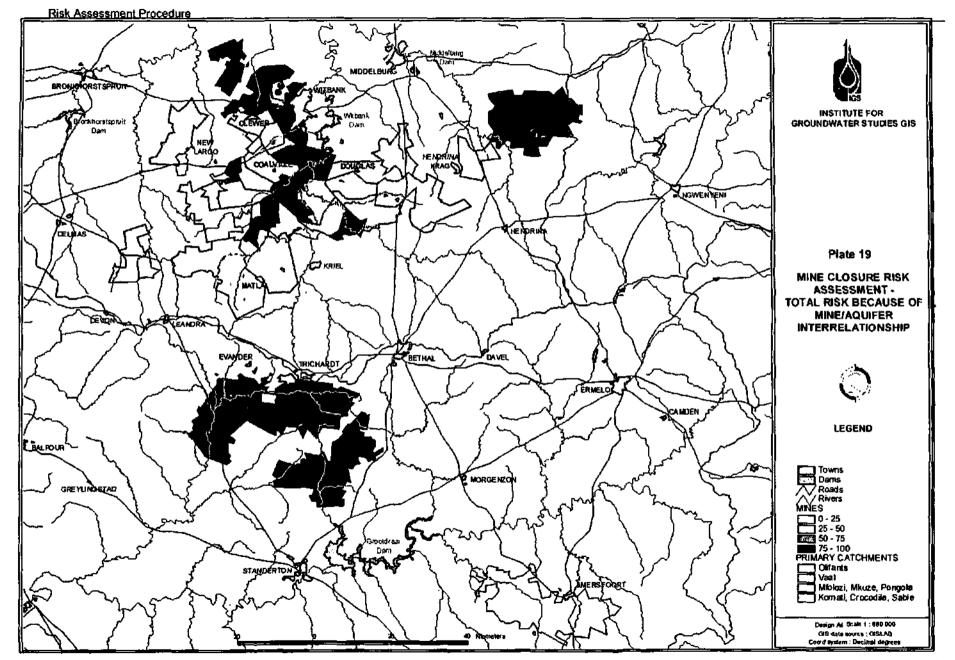


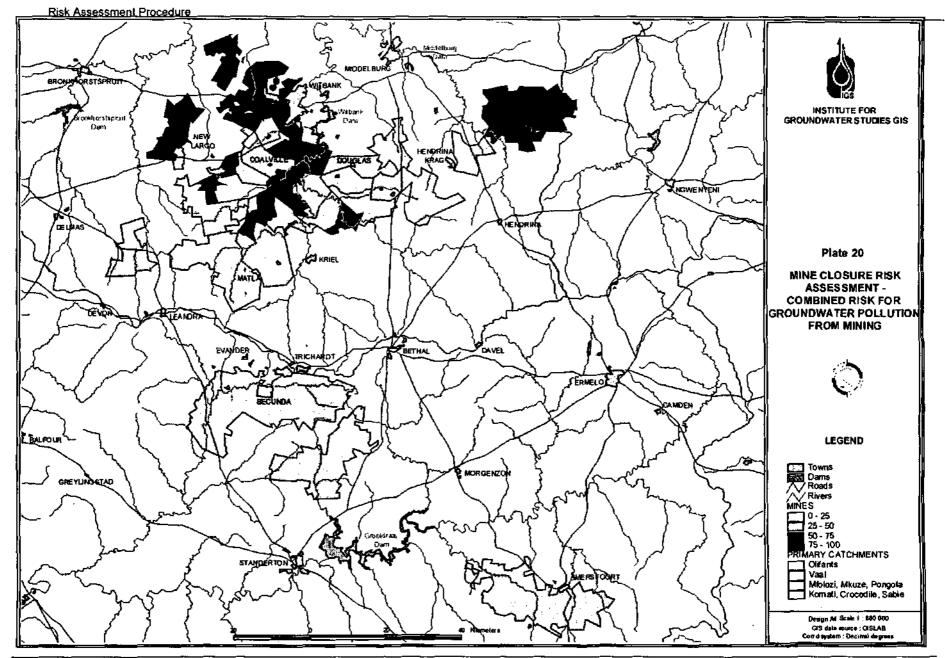












# 3 UNDERGROUND HIGH EXTRACTION OF COAL AND ITS IMPACT ON GROUNDWATER



Chapter by
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Institute for Groudnwater Studies

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## 3 UNDERGROUND HIGH EXTRACTION OF COAL AND ITS IMPACT ON GROUNDWATER

#### 3.1 Introduction

Underground high extraction of coal has been performed for many years in South Africa. The impact that this has on groundwater and surface water resources has been investigated in most instances, and this information is available as part of their EMPR application.

Much of this information is of a historic kind, unable to predict with confidence the final geohydrological and hydrochemical outcome of such systems. This complicates matters when applying for closure of the mine, because of uncertainties associated with future water quantities and qualities. In view of these uncertainties, the current investigation is intended to:

- Provide a summary of the status quo for groundwater in underground high extraction areas.
- Investigate, through modelling, the recovery and decanting phases after mining has ceased.
- Provide recommendations into ways and means that the impact of underground high extraction can be minimised.

#### 3.2 Status quo at underground high extraction of coal

Two mining methods for underground high extraction of coal are generally used in South Africa. These are:

- Pillar extraction, also referred to as stooping.
- Longwall mining, with a shortwall variation.

To date, stooping has been performed at many collieries. The extent of this may vary from experimentation in a single area to stooping over most of the mine.

Longwall and shortwall mining, in view of its significant initial capital outlay, has only been implemented at a few collieries. These are the Eskom tied mines, such as Coalbrook, Matla, New Denmark and Arnot; the Sasol mines at Sasolburg and Secunda and Durnacol in KwaZulu-Natal. In view of the fact that Chapter 4 of this document deals with mining in KwaZulu-Natal, this chapter will deal only with underground high extraction in Mpumalanga.

#### 3.2.1 Stooping

Stooping is the process whereby pillars from bord-and-pillar mining areas are extracted. Continuous miners are generally used for this extraction process, cutting sections into pillars until most or all of the pillars have been removed from specific areas. Pillar extraction usually commences at the furthest point, retreating to the entrance of an area. The roof in areas where pillars have been extracted is left to cave in, which it usually does. This caving often causes subsidence on the surface. Subsidence cracks may penetrate to surface, allowing groundwater and surface water to drain into the collapsed mine workings.

The amount of subsidence at surface and the severity of cracks depend on:

- The depth of mining and nature of overlying rock.
- The coal seam thickness mined.
- The area stooped and panel geometry.
- The degree to which pillars have been left in the stooped area, thus still supporting the coal roof.

Examples of the variations in stooping patterns applied in a single colliery are shown in Figure 3.1.

The following interpretation is relevant to water flow:

- The intensity of stooping varies tremendously from area to area.
- The stooping method applied also varies, removing anything from a small portion of a pillar to removing all of it.
- Information on whether or not the roof in stooped areas has collapsed, and
  if so, whether the impact extends to surface, is not available.

#### 3.2.2 Longwall mining, including shortwalling

Longwall mining is done along panels, usually 200 m wide. Shortwall panels are usually 100 m wide. Mechanised equipment (Figure 3.2) extracts the coal. Behind the shields, the roof is allowed to cave. Due to the significant dimensions of longwall panels, caving of the overlying strata occurs up to the surface (Figure 3.3). As a rule of thumb, subsidence at surface is usually in the order of 50% of the mining thickness. This may be more extreme in shallow high extraction areas and where two or more panels overlie each other. A typical mining height for longwall equipment is three metres.

At shortwall panels, caving usually extends only some distance into the overlying strata.

The length of longwall panels is usually limited by:

- Practical considerations.
- Geological constraints, such as dykes, faults and seam thickness and quality of coal.

Areas extracted to date by longwall mining are extensive. Future areas planned for mechanised underground high extraction are even greater. Planned underground high extractions typically range from 5000 – 12000 ha for the larger mines.

The depth of longwall mining ranges from 50 – 200 metres below surface. Only one seam is usually mined. In one instance, No. 5 and No. 4 Seams have been extracted through longwall mining in overlying areas. Surface subsidence here was extensive, totally more than 3 metres in some areas.

#### 3.3 Impact on water quantity

Fractures from underground high extraction areas intersect groundwater and surface water in the overlying aquifers. The impact on both these resources and on the mines could therefore be severe. Before investigating the actual impacts, a description of the pre-mining geohydrology and hydrology is necessary.

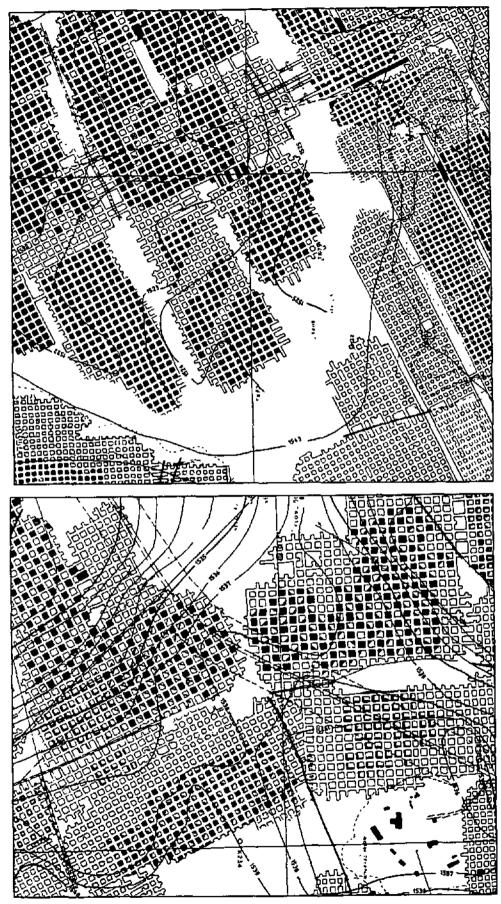


Figure 3-1 Examples of bord-and-pillar mining (open squares) and stooped areas (black).



Figure 3.2 Mechanised longwall mining equipment, courtesy of Coalbrook Colliery.



Figure 3-3 Surface crack above shallow underground high extraction.

#### 3.3.1 Pre-mining groundwater occurrence

Three distinct superimposed ground-water systems are present within the Olifants Catchment. They can be classified as the upper weathered Ecca aquifer, the fractured aquifers within the unweathered Ecca sediments and the aquifer below the Ecca sediments.

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#### 3.3.1.1 The Ecca weathered aquifer

The Ecca sediments are weathered to depths between 5 - 12 metres below surface throughout the Mpumalanga Area. The upper aquifer, typically perched, is associated with this weathered zone and water is often found within a few metres below surface. This aquifer is recharged by rainfall. The percentage recharge to this aquifer is estimated to be in the order of 1 - 3% of the annual rainfall, based on work by Kirchner et al. (1991) and Bredenkamp (1978) in other parts of the country.

Observed flow within the Mpumalanga Area confirmed isolated occurrences of recharge values as high as 15% of the annual rainfall. It should, however, be realised that within a weathered system such as the Ecca sediments of the Olifants Catchment, highly variable recharge values can be found from one area to the next. This is due to variations in the composition of the weathered sediments, which range from coarse-grained sand to fine clays.

Generally speaking, the north-western portion of the coalfield is characterised by coarser grained sandstone and higher recharge values are expected there. It is concluded from the above information that a recharge value in the order of 3% of the annual rainfall is feasible. In terms of the catchment size for the Witbank Dam (3 256 km²) for instance, this amounts to 60 Mm³ recharge per annum. In comparison with the Witbank Dam, this amounts to about half of the holding capacity of the dam. Further south, dolerite sills often occur at surface. These are weathered or fractured and rain water recharges with ease.

Rainfall that infiltrates into the weathered rock soon reaches an impermeable layer of shale or dolerite, underneath the weathered zone. The movement of ground water on top of this layer is lateral and in the direction of the surface slope. The groundwater reappears on surface at fountains where the flow paths are obstructed by a barrier, such as a dolerite dyke, paleo-topographic highs in the bedrock, or where the surface topography cuts into the groundwater level at streams. It is suggested that less than 60% of the water recharged to the weathered zone, eventually emanates in streams. The rest of the water is evapotranspirated or drained by some other means.

The aquifer within the weathered zone is generally low yielding (range 100 - 2000 L/hour), because of its insignificant thickness. Few farmers therefore tap this aquifer by borehole. Wells or trenches, dug into this upper aquifer, are often sufficient to secure a constant water supply of excellent quality.

The excellent quality of this water can be attributed to the many years of dynamic ground-water flow through the weathered sediments. Leachable salts in this zone have been washed from the system long ago and it is only the slow decomposition of clay particles, which presently releases some salt into the water.

#### 3.3.1.2 The fractured Ecca aquifers

The pores within the Ecca sediments are too well cementated to allow any significant permeation of water. All ground-water movement is therefore along secondary structures, such as fractures, cracks and joints. These structures are better developed in competent rocks such as sandstone, hence the better water-yielding properties of the latter rock type.

It should, however, be emphasised that not all of the secondary structures are water-bearing. Many of these structures are closed because of compressional forces that act in the earth's crust. The chances of intersecting a water-bearing

fracture by drilling decrease rapidly with depth. At depths deeper than 30 m, water-bearing fractures with significant yield were observed in opencast coal mines to be spaced at 100 m or greater. Scientific siting of water-supply boreholes is necessary to intersect these fractures. The conclusion is drawn that boreholes have insufficient yields for organised irrigation. This is confirmed by a survey of the catchment, during which no irrigation from this aquifer could be found.

Coal seams are often fractured and have some hydraulic conductivity. Underlying the coal, is the Dwyka tillite. It is impermeable to groundwater flow due to its massive nature and fine matrix, forming a hydraulic barrier between Pre-Karoo aquifers and those high up in the succession.

In terms of water quality, the fractured Karoo aquifer always contains higher salt loads than the upper weathered aquifer. This is ascribed to the longer residence time of the water in the fractured aquifer.

Although the sulphate, magnesium and calcium concentrations in the Ecca fractured aquifer are higher than those in the weathered zone, they are well within expected limits. The occasional high chloride and sodium levels are from boreholes in areas where salt naturally accumulate on surface, such as at pans and some of the fountains.

#### 3.3.1.3 Pre-Karoo aquifers

In only a few instances drilling has intersected basement rocks underneath the Karoo Supergroup. Very few, if any, of the farmers tap water from the aquifer beneath the Dwyka Formation. Reasons for this are:

- The great depth.
- Low-yielding character of the fractures.
- Inferior water quality, with high levels of fluoride, associated with granitic rocks.
- Low recharge characteristics of this aquifer because of the overlying impermeable Dwyka tillite.

In the southern portion of the catchment, dewatering of this aquifer has occurred, to some extent, because of the pumping in the Evander Goldfields. This does not impact on the Ecca Aquifer due to the presence of the Dwyka tillite.

#### 3.3.2 Pre-mining surface hydrology

Annual rainfall in the areas where underground high extraction is done ranges from 650 - 760 mm per annum. Surface slopes are gentle. Run-off is in the order of 8%.

Surface water in streams gains from groundwater seepage. Seepage into streams is mainly from the weathered aquifer. This is generally not sufficient to cause significant flow in the streams.

#### 3.3.3 Impact of mining on water influx

#### 3.3.3.1 Extent of dewatering

Cracks above high extraction intersect overlying aquifers. Groundwater drains into the mine below and the aquifer is locally dewatered. The dewatering cone

commonly extends less than 500 m away from these areas because of the low transmissivity of the aquifer. Along fracture zones, the impact of dewatering may extend up to 1,5 km from collapsed areas. During the initial stage of dewatering, the shape of a dewatering cone is very much dependent on the presence or absence of high transmissive zones. For the purpose of illustrating this impact, finite element simulations of a hypothetical situation have been done. The resultant development of the dewatering cone is illustrated in Figure 3-4.

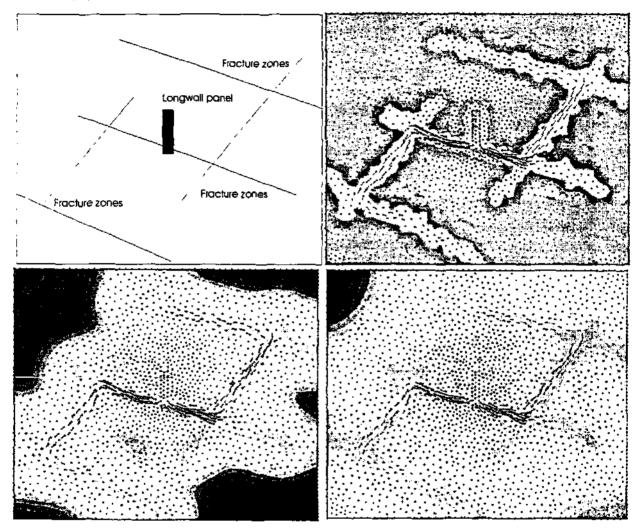


Figure 3-4 Typical fracture pattern intersecting a longwall panel, followed by dewatering of the adjacent strata, after 10 days, 100 days and 365 days. Scale from left to right for each diagram is 4000 m.

Discussion of this information follows:

- Fracture zone often have hydraulic conductivities up to 4 6 orders of magnitude greater that the Ecca sediments.
- If such a fracture zone is intersected by a longwall panel, then the resultant dewatering along the fracture zone is fast, often noticeable over distances of up to 1,5 km.
- The dewatering effect along the fracture zones will extend until a balance is obtained between seepage from the matrix, recharge from rainfall and the transmissivity of the fracture zone.

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- It is important to note that boreholes along fractures will be impacted upon over great distances, but that boreholes in the solid rock, almost right next to a longwall panel, will not be impacted upon during the early stages of dewatering.
- Irrespective of the presence or absence of fracture zones, the net amount
  of water available per unit area of rock remains the same in the long term.
  This amount is dependent on the recharge from rainfall. In the
  quantification of the long-term yield of the aquifer, only the recharge
  pattern and the extent of the dewatering cone therefore need to be
  considered.

In the real life situation multiple aquifers should be considered as illustrated in Figure 3-5. Each of these aquifers will adopt their own dewatering pattern, depending on hydraulic constraints such as transmissivity, recharge and vertical seepage.

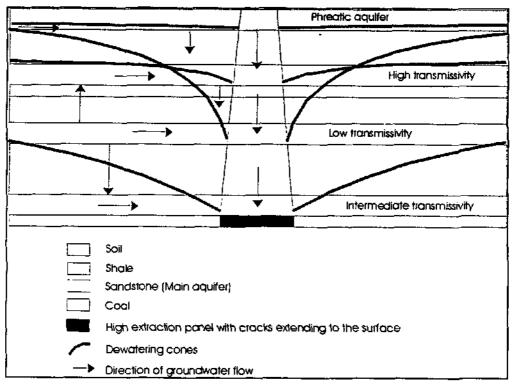


Figure 3-5 Schematic presentation of dewatering cones and vertical interaction between aquifers intersected by fractures from underground high extraction.

Vertical seepage between aquifers is also possible, depending on the hydraulic conductivity of the rock separating the two aquifers. Situations may even arise that water will seep downwards in some areas and upwards in other areas between the same aquifers. The possible combinations are endless. Through pumping tests and detailed observation only small portions of aquifers may be tested in the field.

In the prediction of the behaviour of the groundwater systems under conditions of underground high extraction, logical assumptions therefore have to be made and simplifications are accommodated within the regional context. This has been done in the previous examples.

#### 3.3.3.2 Recharge from rainfall

In areas of extensive underground high extraction, it can be safety assumed that all recharged water will migrate downwards to enter into the collapsed mine workings. Under undisturbed conditions, 3% of the annual recharge would be an acceptable average value. Under disturbed conditions above longwall panels, recharge is likely do be greater and 5% of the annual rainfall would be a good first estimate. Applying this to a mine of 12000 ha, yields 11500 m³/d (Figure 3.6).

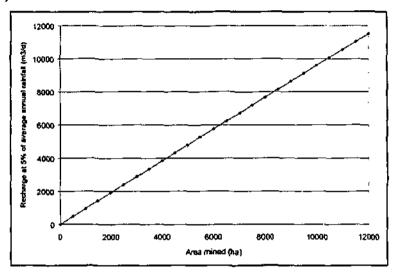


Figure 3.6 Relationship between 5% recharge and area mined.

Under field conditions a linear relationship would not apply since surface gradients are disrupted by subsidence and more water will be available for recharge in these areas. Recharge from rainfall will also vary significantly depending on the actual amount of rainfall and the intensity thereof. The actual recharge would therefore be site- and occurrence dependent, with 3% of the rainfall as a conservative minimum value.

Figure 3.7 shows a relationship that has been established through correlating water ingress with rainfall at one of the collieries, where limited stooping has been done.

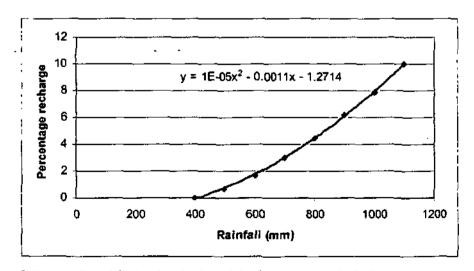


Figure 3.7 Established relationship between rainfall and recharge in an underground coal mine.

The first step in the application of variable recharge values, lies in the generation of a rainfall sequence. For the purposes of this demonstration, a random sequence between 400 - 1000 has been generated for a period of 40 years (Figure 3.8).

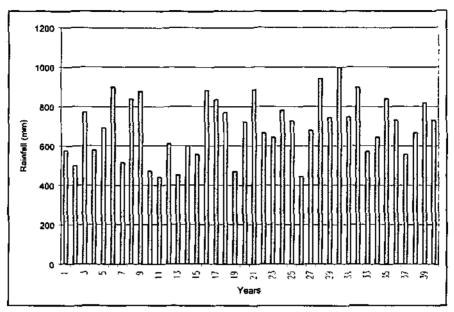


Figure 3.8 Random rainfall sequence between 400 – 1000 mm.

Following this, the recharge equation (Figure 3.7) was applied for an operating mine of 12000 ha over a period of 40 years (Figure 3.9).

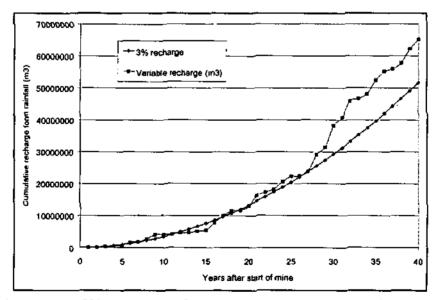


Figure 3.9 A 3% recharge factor versus variable recharge over a random sequence of rainfall event between 400 - 1000 mm/annum.

The variable recharge shows some deviation from the 3% recharge curve due to a greater incidence of high rainfall events during the latter part of the rainfall series. The importance of considering high rainfall episodes in recharge calculation is emphasised since a single high rainfall year could contribute up to three times as much recharge as a normal rainfall year.

#### 3.3.3.3 Regional groundwater flux

The rate flow of groundwater to collapsed areas is a function of the transmissivity of the rock adjacent to the collapsed area, the hydraulic gradient and the area of throughflow. For the purpose of demonstrating the relative contribution of groundwater during underground high extraction, a transmissivity of 10 m²/d and a hydraulic gradient of 0,01 will be assumed. These are logical average values for the Mpumalanga Area. The additional contribution of groundwater over and above that from rainfall recharge is demonstrated in Figure 3.10.

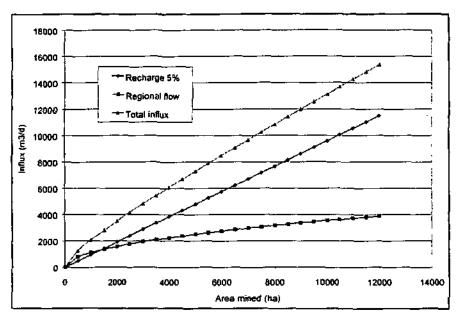


Figure 3.10 Recharge and groundwater flow towards a collapsed underground high extraction area.

The important issue here is that groundwater flow initially contributes most of the water but as the size of underground high extraction increases, recharge from rainfall becomes the dominating contributor.

Variable recharge, based on different rainfall amounts per annum, can also be combined with the regional groundwater flow. Figure 3.11 summarises this information as a progressive volume of water that will have to be dealt with during the life of the mine.

Recharge from rainfall directly above areas of high extraction clearly introduces a greater variability into the equation than regional groundwater flow. This is because groundwater flow is limited by the transmissivity of the undisturbed rock adjacent to high extraction and the hydraulic gradient. During dry spells, the gradient will flatten slightly, but not significantly enough to seriously impact on regional flow.

These illustrations demonstrate the influx of water under homogeneous geological and topographic conditions. This is never the case in the real life situation. Many heterogeneities, that could significantly impact on the groundwater flow, exist. Two of these that would have the greatest impact and which should be considered are transmissive zones such as faults, fissures and dykes, and the recharge from streams.

Transmissive structural discontinuities such as faults, fissures and dykes can collect and convey groundwater over large distances and at great rates. Dewatering cones could easily extend over kilometres along these structures,

collecting water from other fractures and aquifers that they intersect. Such structures exist in all South African Coal Mines, though at a low frequency. Its impact, if intersected by underground high extraction, is reflected in a high initial and sustained influx of water. To date, only one such a transmissive zone has been intersected. The initial inrush of 3000 m³/d has been sustained ever since, i.e. for more than 10 years. As high extraction moved laterally away from such an area, the amount of influx does not increase significantly. This confirms the limited availability of groundwater due to a low transmissivity of the rock. Only once mining progressed beyond the influence sphere of the dewatering cone, will the rate of influx increase again.

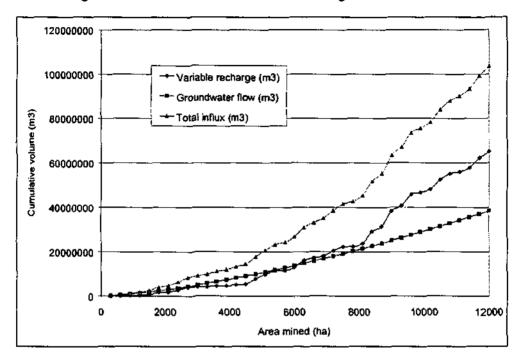


Figure 3.11 Progressive volumes of water to enter into an underground high extraction mine.

The statement can therefore be made that the overlying controlling factors of water flux into underground areas of high extraction are the average transmissivity of the rock and the recharge rate to the aquifer. This is true if the recharge rate exceeds the rate at which groundwater can flow through the aquifer. The latter is the case for all South African Collieries in the Mpumalanga Area. The localities of transmissive zones therefore need not be known if cumulative influxes are to be predicted. The error introduced by not allowing for such a transmissive zone evens out as mining progresses.

The above examples have been based on certain assumptions. These results may or may not be valid for specific circumstances, mainly depending on the regional transmissivity of the aquifers adjacent to the mines, mining configuration and recharge characteristics from rainfall. The only one of these not dealt with up to now, is the mining configuration.

All examples up to now have assumed a single area of underground high extraction and thus the development of a single dewatering cone. If two separate areas are to be mined through high extraction and they are sufficiently far apart not to interfere with each other's dewatering cones, then they can be treated as separate entities. The closer they are to each other, the more they will interfere with each other's dewatering cone and the less water will be derived from the area between two mining operations. The calculation of this

interference is complex and can best be done through numerical modelling. However, as a rule of thumb the interference is of a logarithmic nature and is illustrated in Figure 3.12.

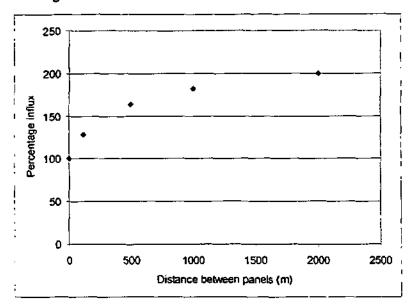


Figure 3-12 Distance versus influx relationship between two underground high extraction areas of identical dimensions.

#### 3.4 Impact on water quality

The chemical character of water from a mine that performs underground high extraction can perhaps best be illustrated through an examination of its discharge water quality (Figures 3-13a, b and c). Discharges by this mine were made during the period 1985 – 1992 and 1998 onwards.

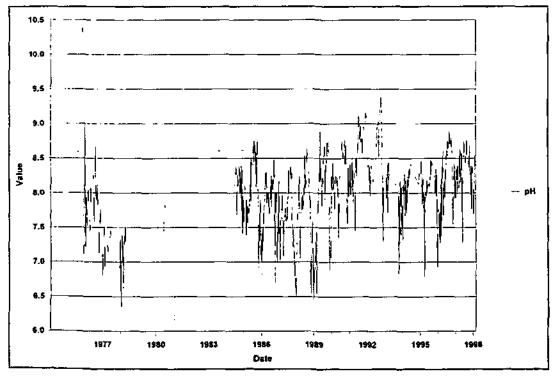


Figure 3-13(a) pH-values in a stream receiving water from an underground high extraction colliery.

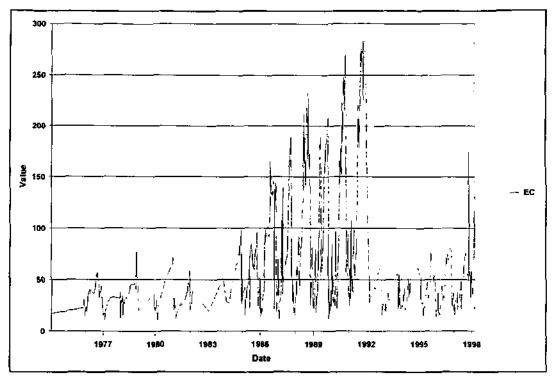


Figure 3-13(b) Electrical conductivity values (mS/m) in a stream receiving water from an underground high extraction colliery.

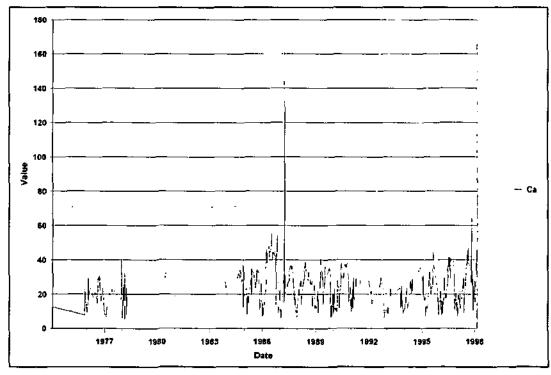


Figure 3-13(c) Calcium concentrations (mg/L) In a stream receiving water from an underground high extraction colliery.

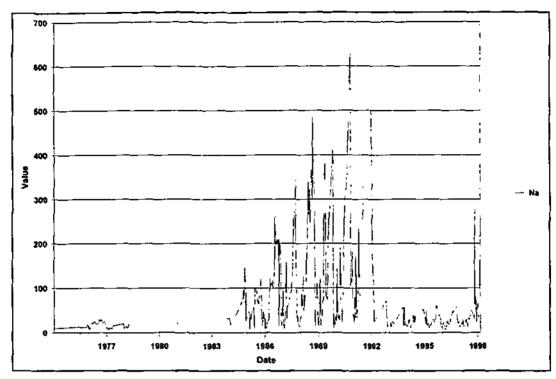


Figure 3-13(d) Sodium concentrations (mg/L) in a stream receiving water from an underground high extraction colliery.

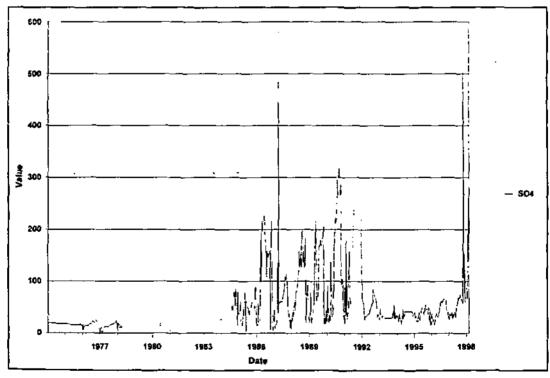


Figure 3-13(e) Sulphate concentrations (mg/L) in a stream receiving water from an underground high extraction colliery.

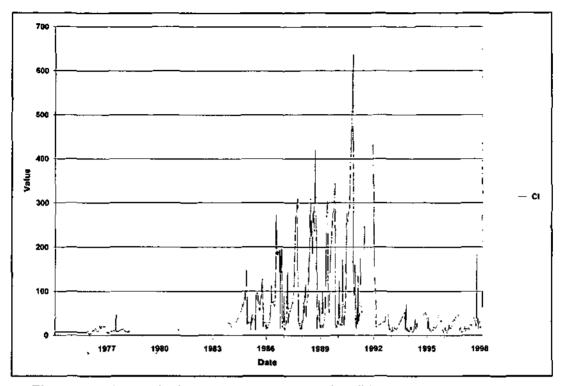


Figure 3-13(f) Chloride concentrations (mg/L) in a stream receiving water from an underground high extraction colliery.

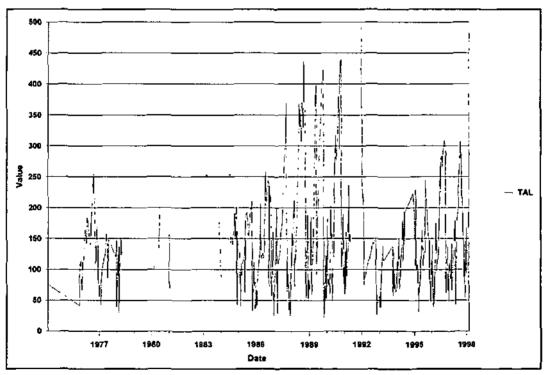


Figure 3-13(g) Total alkalinity values (mg/L) in a stream receiving water from an underground high extraction colliery.

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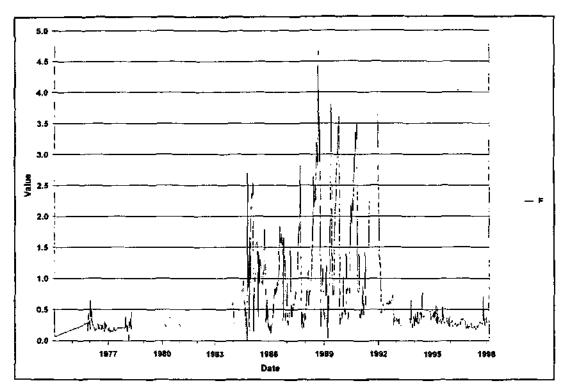


Figure 3-13(h) Fluoride concentrations (mg/L) in a stream receiving water from an underground high extraction colliery.

It can be concluded from these presentations that water quality in high extraction underground mining has a unique and complex chemistry. To explain this chemistry, the following environments are identified:

- The original groundwater in the aquifers tapped by the farmers before mining, is mainly of a calcium/magnesium bicarbonate composition.
- As groundwater flows towards collapsed mining areas, cation exchange takes place. This results in water enriched in sodium and relatively low calcium and magnesium concentrations.
- In the fractured columns above underground high extraction, dissolution of sodium carbonate and sodium chloride occurs. This results in a rise in the pH of the water, pH-levels between 8,5 and 9,5 are not uncommon at this stage with alkalinity values in the range of 200 – 500 mg/L. Generally speaking, the southern Mpumalanga Collieries have higher alkalinities due to sodium carbonate dissolution than those further north.
- In the mines, water is left to accumulate in the collapsed areas. Here a
  gradual deterioration of the water quality occurs as pyrite is oxidised in the
  fractured column and on the coal seam horizon. An increase in sulphate is
  the result.
- The acid that is produced is neutralised by the alkalinity of the water. Only
  after the sodium alkalinity diminishes, will calcium and magnesium
  alkalinity come into play. At that stage, the pH of the mine water will drop to
  around 6,5. By monitoring the sodium and pH-levels, a clear definition of
  the phase in which the mine water is can be made.
- If pyrite oxidation continues and if the base potential of both sodium and calcium/magnesium is inadequate to neutralise all the acid that is

produced, the mine will eventually acidify. To date, sporadic instances of acidification have been reported.

Having sketched the scenarios under which mine water in underground high extraction mines undergo chemical changes, the discharge water quality in Figures 13(a – h) will now be examined.

- The pH-, alkalinity, sodium, chloride and fluoride levels of the stream water have been elevated since the introduction of mine water into the stream.
- If the assumption is made that all chloride occurs as sodium chloride, then about half of the sodium is available as sodium carbonate, i.e. about 10 meg/L Na.
- Sulphate levels have lately been around 200 mg/L, which translates into 4 meq/L SO<sub>4</sub>. The conclusion is drawn that sufficient sodium carbonate is available at this stage to neutralise all acid production from pyrite oxidation.
- Calcium levels have been unaffected. The presence of some calcium in the
  water is mostly attributed to dissolution and not to reaction with the pyrite.
  Almost all the calcium/magnesium carbonate base potential should
  therefore still be in the mine and available for neutralisation of the acid, if
  necessary.

Mining at this locality has been in progress since the mid eighties. Through accurate monitoring of water from different collapsed panels, it should have been possible to plot sodium and sulphate concentrations to determine:

- The possible life span of sodium neutralisation.
- The possible escalation of sulphate production due to the intervention of bacterial oxidation as the pH of the water drops.

Unfortunately, this kind of information is not available, since the importance of detailed and complete data sets is only realised by the mining community nowadays.

## 3.5 Proposed water management strategies

### 3.5.1 Underground storage of water during mining

Mines that perform underground high extraction of coal have historically done very little advance planning in terms of mine water management. This is mostly due to an underestimation of the severity of the problem. Although most collieries perform geohydrological investigations to predict the potential groundwater influx into underground areas of high extraction, the initial influx is often low and remains unnoticed in the collapsed areas. This false security leads to crisis situations where emergency dewatering of panels becomes necessary. The quality of water from panels is mostly not in line with requirements for disposal into streams and special permits have to be obtained.

Influx of water into mines that currently practice underground high extraction of coal range from 1000 – 17000 ML/d. This influx is in line with that predicted in Section 3.3. The water is currently stored underground or pumped to surface if necessary.

Underground storage of mine water presents a problem because of its large volumes. Panels in which water can be left to accumulate, mostly become available only after mining has been completed. The ideal situation would be

that underground high extraction should commence from the deepest portion of the mine, retreating to higher ground. Although this may seem unfeasible at first glance, it has been implemented by one mining group with significant success. A typical example of coal floor contours showing the suggested idealised mining sequence is included in Figure 3-14. If high extraction is done in the sequence indicated by the numbers, this would ensure that:

- Areas are available for flooding.
- Mine water will often naturally drain towards low-lying areas.
- Oxygen is eliminated in the flooded areas, thus eliminating further decay of the water quality due to pyrite exidation.

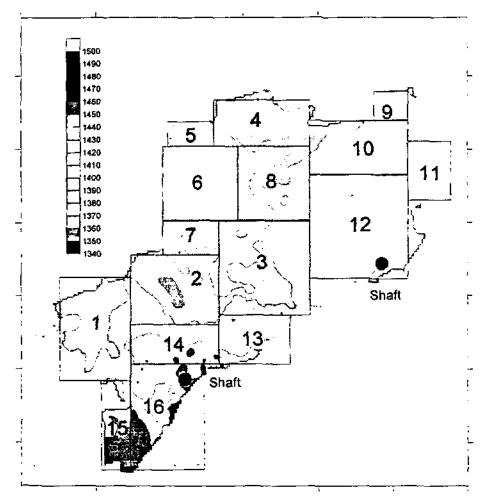


Figure 3-14 Floor contours and the idealised mining sequence for underground high extraction (Scale from left to right is 30 km).

Once the basic sequence of mining has been established, shafts should be sited. These should obviously be located in high areas, e.g. in compartments 11 and 14. The main underground development should be along ridges of the coal floor, e.g. along the south-eastern perimeter of the mine.

An analysis of basic data yields the following:

- Mining at a large colliery produces approximately 10 Mt of coal per annum.
- This creates 6,25 Mm<sup>3</sup> underground space.
- If 75% of this is in collapsed areas, then the space available for mine water accumulation is in the order of 10 ML/d.

 If this space creation is planned properly, then over a period of 40 years for a mine area of 12000 ha, the space created should be in the order of 120 Mm³ and the cumulative influx should be 100 Mm³ (Figure 3-15).

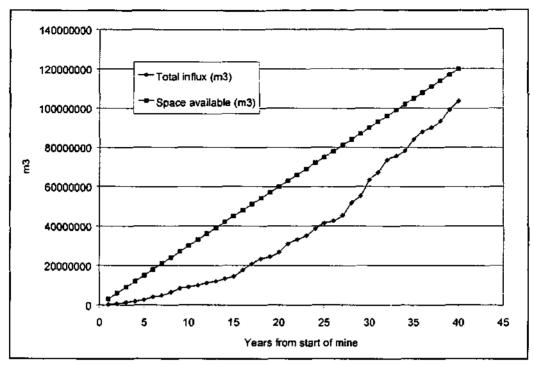


Figure 3-15 Availability of underground space for water storage and projected water influx.

- It is noteworthy that the projected influx is equal to the capacity of the Witbank Dam. From a strategic point of view, the possibility of utilising an underground reservoir with such a large capacity should be investigated
- It is clear that the mine should be able to cope with most of the influx for the full duration of mining, on condition that proper planning is done at the start of the mine.

Despite this knowledge, very few mines are currently coping with the influx of water. Examples are plentiful where mine water has been disposed of in streams in the past. Sometimes the mine water is mixed with clean water to dilute the impact on downstream users. In other instances, desalination units that can handle up to 12 ML/d have been built. Both these actions would probably have been unnecessary if proper mine scheduling had been done.

Another action that could be implemented, is the rehabilitation of the surface above areas of underground high extraction.

#### 3.5.2 Rehabilitation of the surface

Rehabilitation of the surface is a word synonymous with mining. This is, however, only true for opencast mining. Underground mining has, to date, done very little surface rehabilitation above collapsed mining areas. Most of the work relates to emergency situations, such as the sealing of cracks where surface water obviously cascades into the mines. In terms of influx minimisation, this is totally unacceptable.

The following actions are suggested as standard practice:

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- A soils map of the total surface area above underground high extraction should be prepared.
- After collapses have occurred, areas with sufficient soil cover should be ploughed over as deeply as possible to destroy any cracks that penetrate to surface.
- Areas with insufficient soil cover should be inspected for cracks and these should be filled in. Rock outcrops are usually along slopes and surface runoff should be diverted around these areas, thus minimising the possibility of water cascading into the mines.
- Pans that develop above areas of high extraction should be provided with outlets by trenching. No water should be allowed to accumulate in the pans.
- Streams should under no circumstances be undermined by underground high extraction.
- Annual inspections should be made of rehabilitated areas to ensure that these areas are operating as was originally intended.
- Any deviation from the above precautionary measures should be motivated in detail by the mining company, proving the deviation is as environmentally acceptable or better.

### 3.5.3 Utilisation of mine water after closure

The utilisation of mine water after mine closure is a possibility that every farmer in these areas have contemplated from time to time. The Mpumalanga Coalfields is an area with limited groundwater resources. Any additional source of water would be welcome.

Two possibilities of mine water utilisation after mine closure exist. Both of these require that the mine should fill up with water, before they can be implemented.

The filling up of mines with water could be left to natural inflow, in which case mines will slowly fill over many years. Those mines that followed the mining sequence suggested in Section 3.5.1 would almost be full of water by the time they close. Others will take many more years to fill.

The best water quality is expected in those mines that were progressively allowed to fill up as mining continued. Nevertheless, this water will still be saline, high in sodium and chloride. The conclusion is drawn that irrespective of which natural filling up sequence has been implemented, the quality of the water will be such that the mine water cannot be used as such for irrigation or be discharged into streams.

Another possibility of filling up mines would be the redirection of surface water into the mine. This has been done in opencast mining, but not yet in underground mines. The intention would be to interconnect mine workings with boreholes to surface water bodies such as dams in the catchment. This will introduce clean water flooding the mine before significant pyrite oxidation can occur. Soluble constituents such as sodium chloride and sodium carbonate will still contaminate the mine water. The feasibility of this artificial flooding would be site-dependent.

Once a mine is flooded, flow into the mine will not cease. Groundwater influx will be reduced because of the hydrautic pressure within the mine. The final resting level of the water table will be determined by the lowest overflow where

water from the mine will spill onto surface. In the case of the example used in Figure 3-14, the lowest point will be as indicated in Figure 3-16. This suggests that as much as 100 m of certain columns above high extraction areas will not be flooded. In these areas, the influx rate from groundwater will almost be the same as during mining. This water, in combination of recharge from rainfall, will move vertically into the mine, then horizontally along the coal seam and finally decant with the rest of the mine water at the lowest topographic point.

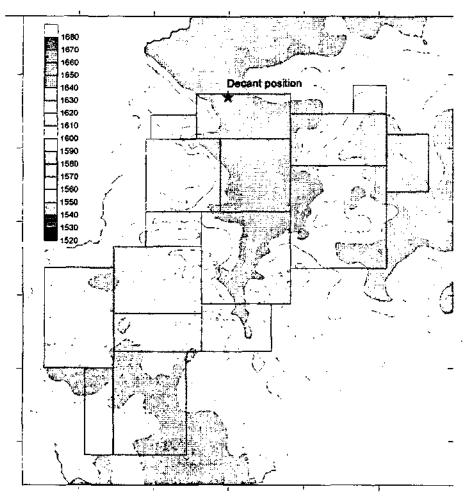


Figure 3-16 Surface contours of the area to be mined, showing the decant elevation and position.

In view of these different recharge points that will continue to supply water into the mine, there can be no question of stratified flow. Piston action flow, with the clean water driving the polluted mine water ahead of it, will be the case. The exact interaction between recharge, mine water displacement and mine water dilution will depend on the specific nature and amount of recharge at each locality. If homogeneous dilution is assumed, then a logarithmic decay relationship for the salt concentration in the mine should be the case (Figure 3-17).

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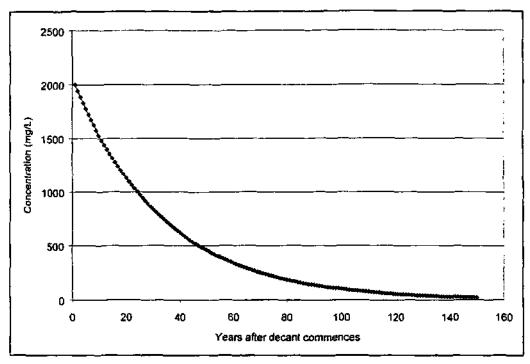


Figure 3-17 Decay curve for salt concentration in a high extraction mine (12000 ha), assuming an influx of 10 ML/d and an initial concentration of 2000 mg/L.

It is important to realise that concentrations will decrease by about 50% within the first 25 years after decanting has commenced. Treatment of the water, if necessary, will therefore only have to be done for a finite period of time.

In reality, the system will not behave ideally and deviations from this decay curve should be expected. These will probably average out in the long term. It is expected that preferred pathways will be established in some instances that will leach faster than in other areas. This could result in faster recovery of the water to an acceptable quality.

Several possibilities to manage water during the cleansing phase exist. Two of these are:

- Flood release of polluted mine water in streams. This would require a surface storage facility from where the mine water that decants can be released.
- Desalination and utilisation of the mine water. This would require great expense, maintenance of such systems for 25 - 50 years and a use for the water. A question is also what to do with the brine from the desalination plant. With present-day technology and limited finances available, treatment is less viable that flood release.

Once the mine water quality has improved to such an extent that it can be used in agriculture, utilisation of water from a mine may be considered. The available amount of water will be limited by the amount of recharge. Induced recharge could become an important component of water management. This would entail:

- Lowering the water table in the mine to below the decant level though abstraction from boreholes.
- Introduction of excess surface run-off into the mine through boreholes in dams.

## 3.5.4 Other possible management options

Other management options that have been tried in the past or which could be applicable on a limited scale are:

- Planting eucalyptus trees, either upstream or downstream of where the decant is going to occur; or above high extraction panels.
- To minimise influx by not undermining high transmissive aguifers.
- Redesign extraction panels so as not to collapse the surface.
- · Using vertical intrusions as barriers.
- Limiting the size of the mine.
- Using the best mine water of best quality for suitable purposes.

### 3.6 Conclusions

The following conclusions are drawn from this investigation:

- Underground high extraction of coal is a well-established practice in the South African Coal Mining Industry. For the next 30 years, some 40000 ha have been earmarked for extraction by this mining method.
- Underground high extraction of coal collapses the overlying strata and drains the groundwater from it. A typical projected influx rate is 15 - 25 ML/d for a mine of 12000 ha.
- This water is contaminated in the mines to the extent that it cannot be disposed of in streams without special considerations. Neither can this water be used for agricultural purposes, predominantly because of its high sodium content.
- Operating high extraction mines encounter significant problems in underground water management because of volumes of water encountered. It has been demonstrated in this document that these problems are mainly the result of the sequence of mining. It is suggested that all mines should, on average, be able to cope with the influx of water on condition that they commence high extraction in the deepest part, retreating to higher ground.
- One of current options for mine water handling is to pump it to surface, where it is desalinated. The disposal of the brine from the desalination process presents a problem for which there is currently no solution.
- It is suggested that longwall mining as a mining practice should seriously be re-evaluated. Of all high extraction mining methods, it inflicts the greatest impact on overlying aquifers. Longwall mining is also the least flexible mining method in terms of manoeuvring around structural discontinuities on the coal seam horizon. Streambeds are often undermined for the sake of continuity in the development of a longwall panel. If at all possible, longwall mining should be replaced by shortwalling or, better still, stooping. The most environmentally friendly option would obviously be bord-and-pillar mining. Streambeds should not be undermined by high extraction unless the mining company can prove that this would have no impact on surface run-off and water infiltration.
- To date, mines have seriously neglected the importance of surface rehabilitation above collapsed high extraction areas. The importance of

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minimising rainwater ingress is stressed in this document. Surface cracks should be destroyed by ploughing across collapsed areas. In areas of rock outcrop, cracks should be filled in and surface runoff should be diverted around these areas.

 All mines doing underground high extraction should do proper planning for the post closure phase. The quality of the water that will decant from these mines will be site-dependent and can be managed to some extent. Systems for water management should be based on current and proven technologies, which subscribe to the current objectives of water quality management by the DWA&F.

### 3.7 Recommendations

Based on the current status of our knowledge of water ingress into areas of underground high extraction of coal, the following recommendations are made:

- Mines should seriously revise and motivate their life of mine plan for high extraction, in line of suggestions made in this regard in the current report.
- Mines should do their utmost in minimising water influx into high extraction areas by instigating an active programme of surface rehabilitation along lines suggested in this report.
- Mines should submit a post closure plan for water management during and after the recovery phase of the water levels. This plan should form part of their EMPR.
- Mines should have at least one dedicated, well-trained person in charge of mine water management. His job description should be the management of underground water to minimise volumes and pollution; plan and supervise surface rehabilitation; perform groundwater investigations and verify predictions. He should enter data into a database, process this data and extract information in a way that allows the identification of trends. He should understand processes – both chemical and hydraulic and be able to report in a format acceptable by the DWA&F.

## 4 COAL MINING IN OUTCROP AREAS OF KWAZULU-NATAL



Chapter by

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Institute for Groundwater Studies

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## 4 COAL MINING IN OUTCROP AREAS OF KWAZULU-NATAL

### 4.1 INTRODUCTION

Significant topographic differences are present in the KwaZulu-Natal Coal-fields. Coal deposits have, in many instances, only been preserved within the mountains. Outcrops of coal are therefore plentiful along many of the mountain slopes. In these instances, the depth of the coal seams below surface typically ranges from 0 m to more than 100 m below surface. Access to these coal deposits has been gained by tunnelling into the mountainside. This description is typical of the Vryheid Coal-field, but also applies to the Utrecht and Newcastle areas (Figure 4-1).

Mining in these areas has dominantly been of the bord-and-pillar type, followed by pillar extraction in many instances. As a result, the overlying strata have, in most instances, collapsed. The severity of these collapsed structures varies from area to area, depending on the:

- · Mining depth.
- Extend of high extraction and geometry.
- · Overlying rock type.

Generally speaking, fractures are more severe along perimeter of the mined areas, where high extraction borders onto unmined ground. Here, fractures on surface are often open and range from a few centimetres in width, to more than 0,5 m in exceptional instances. Run-off from rainfall cascades into these structures, recharging the mine workings below.

Many of these mines have very little holding capacity for water with the result that mine water often flows freely from the mines via adits into valleys below. The Department of Water Affairs and Forestry (DWA&F) extensively monitors water quality in streams of KwaZulu-Natal (Figure 4-2). These results have kindly been made available to be used as background information in this report.

The area of particular interest to this study is the Vryheid Coal-field and the tributaries leading away from mines in this area. An examination of water qualities within these streams will set the scene in terms of historic and current water contamination from this area.

### 4.2 REGIONAL SURFACE WATER QUALITY

Two major rivers collect run-off from the Vryheid Coal-field. These are the Mkuzi and Black Mfolozi Rivers (Figure 4-3). Of local importance at the Vryheid Coal-field is also the Nkongolana River, which is a tributary of the Mkuzi River.

Statistics on chemical analyses from DWA&F observation points along these rivers have been plotted in Figures 4-4 - 4-11. The box-and-whisker plots follow in the downstream sequence for each of these drainage systems. The average values recorded at each of these localities are shown in Figures 4-12 - 4-16. Specialised chemical diagrams of water samples from these rivers are plotted in Figures 4-17 - 4-19.

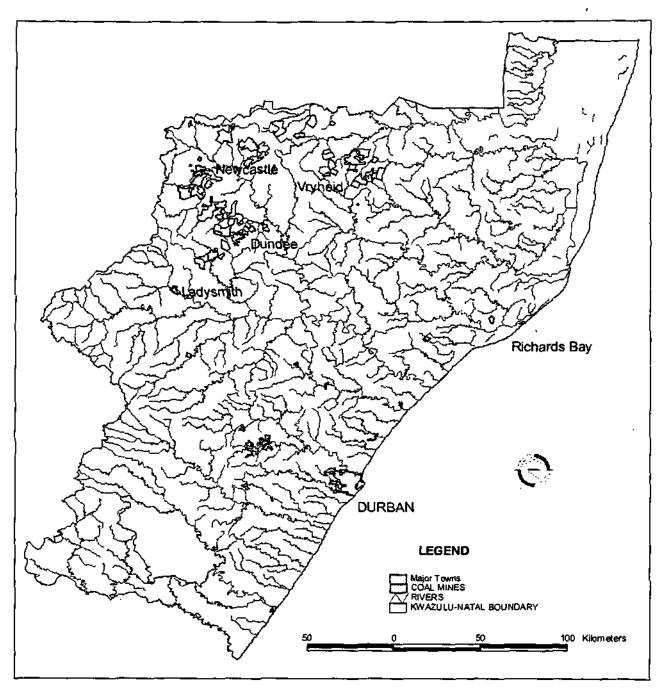


Figure 4-1. Map of KwaZulu-Natal, showing coal-mining areas.

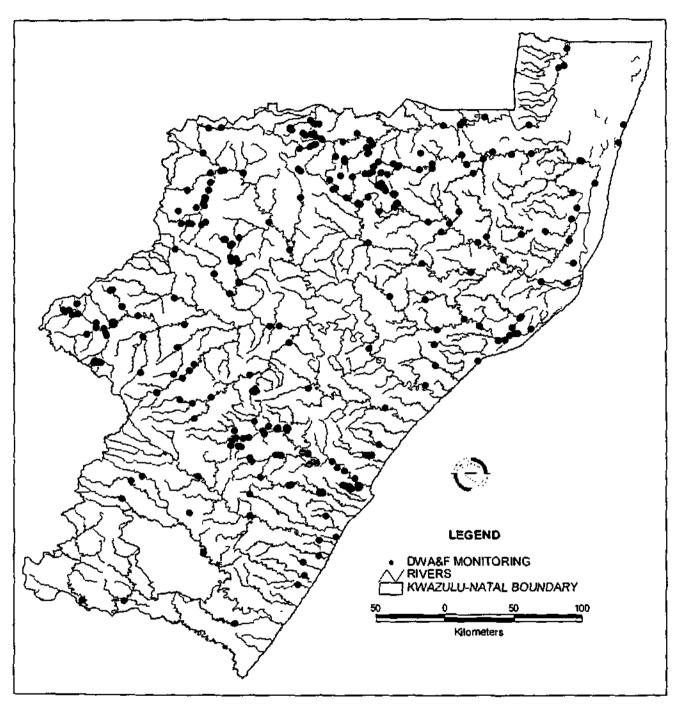


Figure 4-2. Map of KwaZulu-Natal, showing surface water quality monitoring localities of the DWA&F.

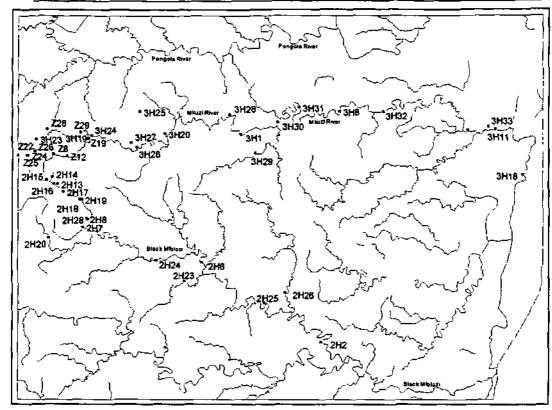


Figure 4-3. Map of northern KwaZulu-Natal, showing surface water quality monitoring localities of the DWA&F along the Mkuzi and Black Mfolozi Rivers.

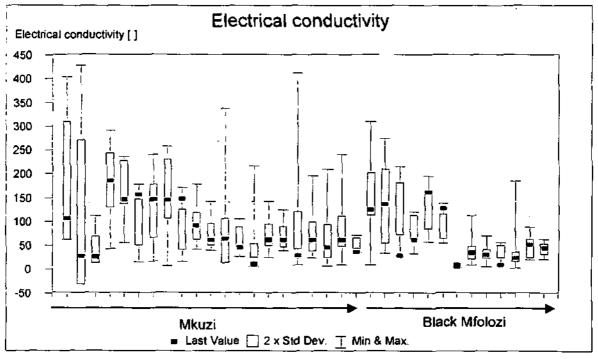


Figure 4-4. Statistics on electrical conductivity values (mS/m) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

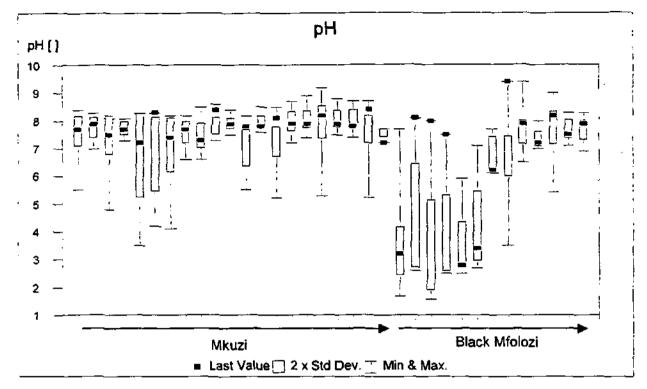


Figure 4-5. Statistics on pH- values from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

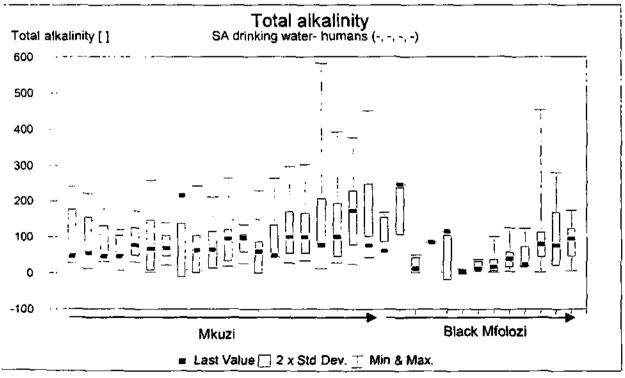


Figure 4-6. Statistics on total alkalinity values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

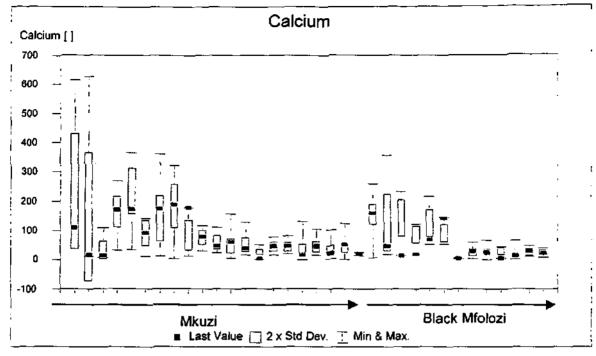


Figure 4-7. Statistics on calcium values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

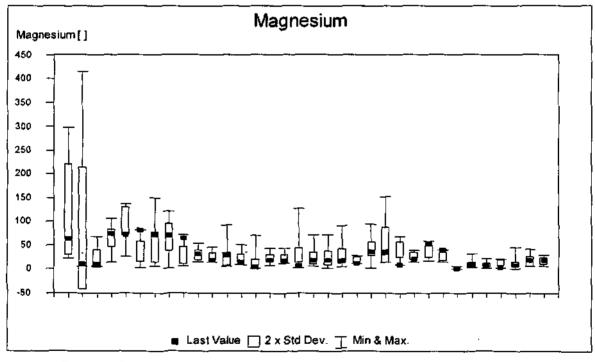


Figure 4-8. Statistics on magnesium values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

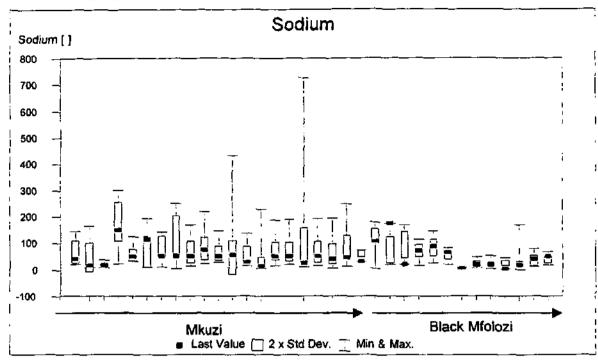


Figure 4-9. Statistics on sodium values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

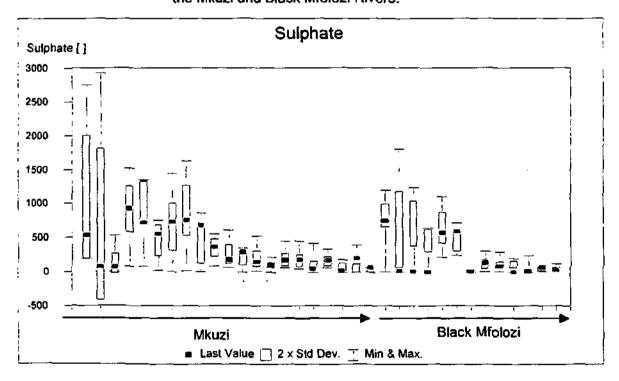


Figure 4-10. Statistics on sulphate values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

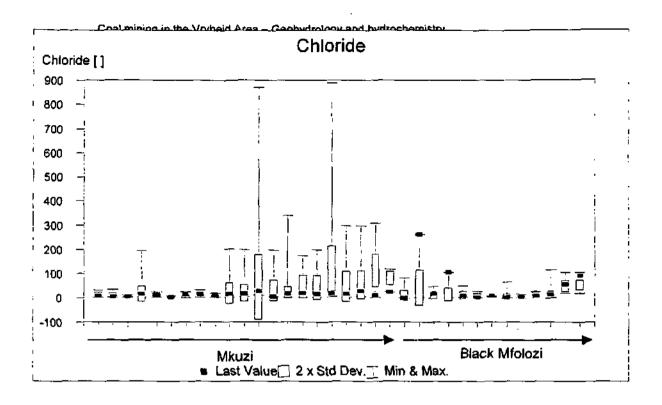


Figure 4-11. Statistics on chloride values (mg/L) from DWA&F monitoring for the Mkuzi (Z- and 3H-numbers) and Black Mfolozi (2H-numbers) Rivers.

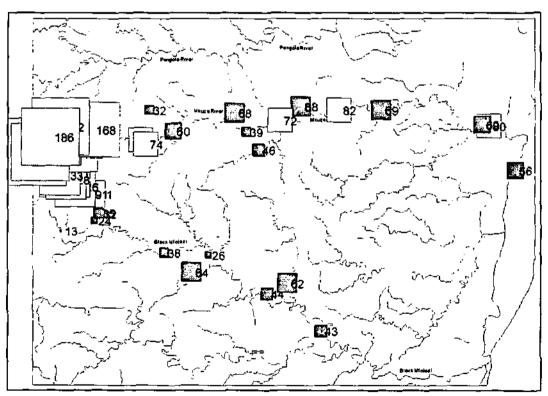


Figure 4-12. Average electrical conductivity values (mS/m) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

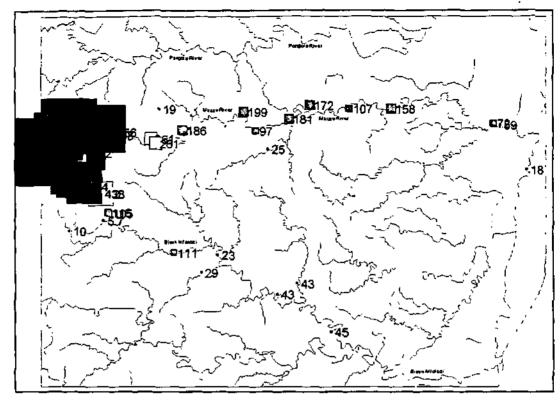


Figure 4-13. Average sulphate values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

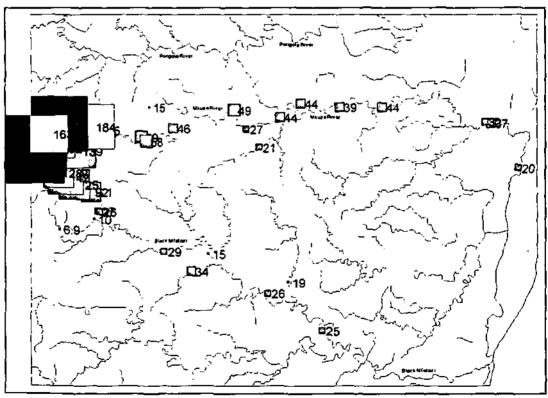


Figure 4-14. Average calcium values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

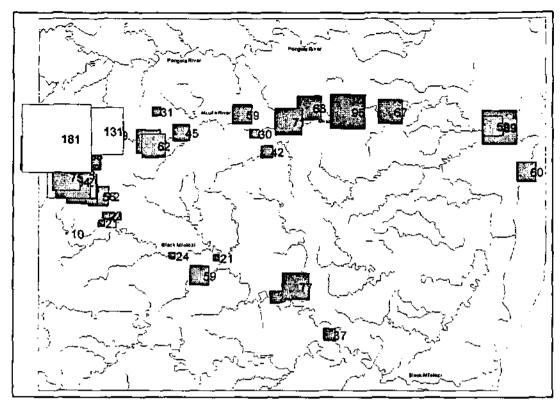


Figure 4-15. Average sodium values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

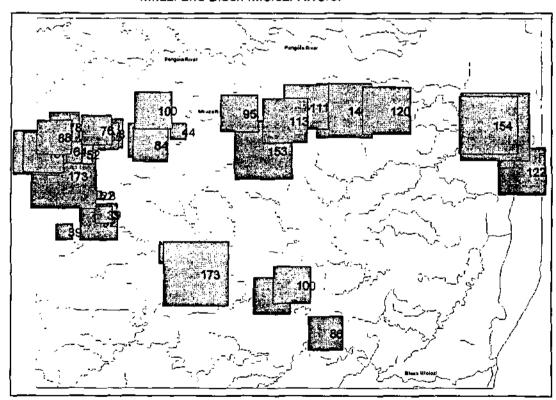


Figure 4-16. Average alkalinity values (mg/L) from DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

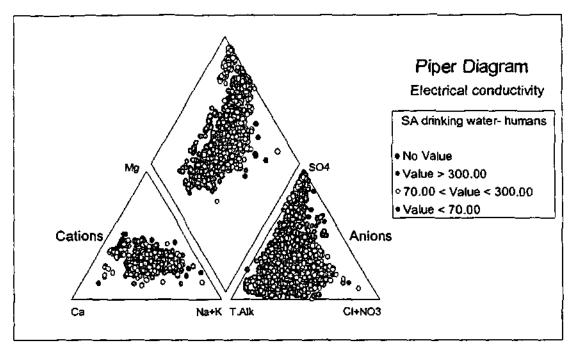


Figure 4-17. Piper Diagram of DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

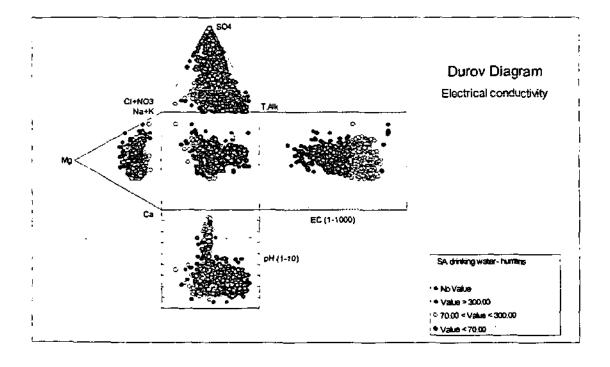


Figure 4-18. Durov Diagram of DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

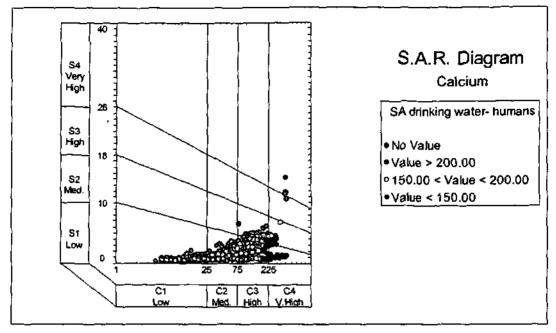


Figure 4-19. Irrigation Diagram of DWA&F monitoring for the Mkuzi and Black Mfolozi Rivers.

The following conclusions are drawn from this information:

- Mining in the Vryheid Area has an obvious impact on both the Black Mfolozi and Mkuzi Rivers. Locally elevated salinities and low pH-levels are the main characteristics.
- These impacts diminish downstream in both rivers, mainly due to dilution. In general, the Black Mfolozi River recovers faster from this pollution than the Mkuzi River.
- The main constituents released from the mines are sulphate, calcium, magnesium and sodium. A drop in the alkalinity of the stream water is also noticeable in the upper reaches of these stream s.
- On the assumption that all sulphate above natural levels are derived from mining, the Piper Diagram (Figure 4-17) demonstrates the degree to which sulphate contamination has impacted on many of the water samples in these two catchments.
- The Durov Diagram (Figure 4-18) shows the relationship between sulphate concentrations and pH-levels, as well as a trend towards sodium chloride enrichment. The origin of sodium is twofold, namely from mining and from natural leaching from the Karoo sediments across which the rivers run for most of their route.
- The Irrigation Diagram (Figure 4-19) indicates that high salinities are the main concern if these waters are to be used for irrigation. A steady increase in the sodium content is present with an increase in the salinity. The potential impact of this sodium, much of which is of natural origin, is dampened by the release of calcium and magnesium from the mining area.

The above examples and conclusions are considered to be sufficient to set the scene in terms of current and past pollution of surface water resources from coal mining at Vryheid. The next step is to examine local details relating to mining.

## 4.3 THE NKONGOLANA AREA

### 4.3.1 Mining methods and extent

Coal mining in the Vryheid Area occurs in three distinct areas (Figure 4-2). Of these, the north-eastern group is of particular interest to this investigation. This constitutes Hlobane, Vrede, Cliffdale and Vryheid Coronation Collieries (Figure 4-20). Here, mining has ceased altogether during the past five years.

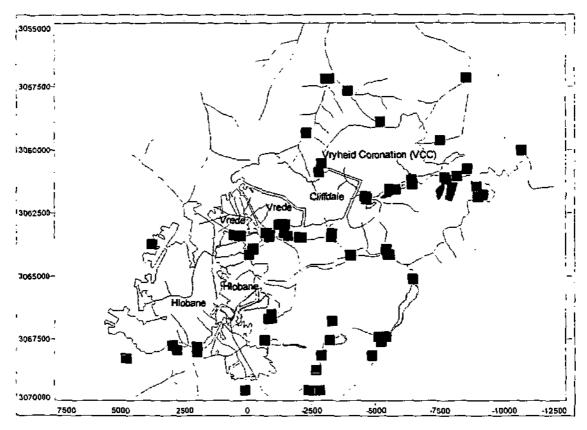


Figure 4-20. Outlines of the mining extent within the Nkongolana Catchment, also showing surface drainage systems and water quality monitoring points.

Mining has mainly been by underground methods. Up to three overlying seams have been extracted. Bord-and-pillar mining was used for development along the coal seams, whereafter pillars were removed over most of the area. The coal seams are thin, with mining width in the order of 1,7 m. Despite this thin extraction height, subsidence above areas of total extraction has been significant. Cracks penetrate to surface. These cracks are best developed in areas where high extraction borders onto unmined areas. Influx of surface water run-off through the cracks occurs freely. The cracks are so extensive that it would be impossible to fill all of them. In addition, much of the mountainous area can only be reached by helicopter.

Structurally, the coal seams have been disrupted extensively by faulting and intrusion of dolerite dykes. The complexity of the system is demonstrated in Figure 4-21.

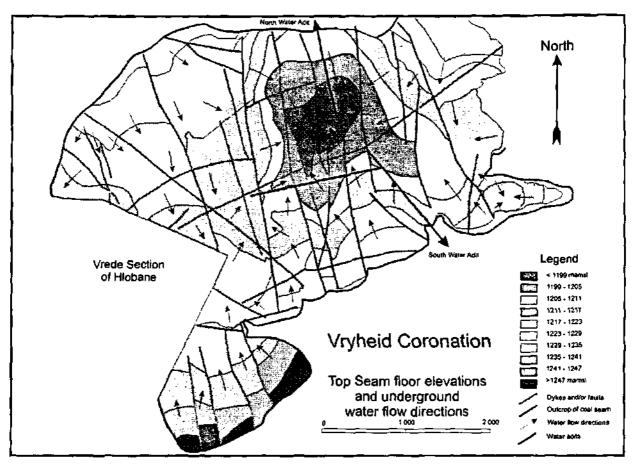


Figure 4-21. Structural disturbances, floor contours, mine water flow directions and water control adits at Vryheid Coronation Colliery (Information supplied by D.A. Salmon).

Even the information in Figure 4-21 is a vast over-simplification of the real situation. The full complexity of the geology and geohydrology is only appreciated through examination of the large mine plans. Underground visits to the mine are mostly impossible nowadays, because most of the mine roof has collapsed.

The main conclusion from the information in Figure 4-21 is that most of the mine water drains towards the central part of the mine. This has also been the case during mining operations. As a result, two adits were installed to drain water from the mine workings. After mining had been completed, the water level within the mine has risen to approximately 1 205 mamsl. Apart from this accumulation of water, many other smaller accumulations should also be present in the mine. These typically dam against faults and unmined portions of seams. It is estimated that not more than 20% of VCC has been flooded.

Over the whole of the Nkongolana Area, the dip of the mine floor varies significantly from mine to mine (Figure 4-22). To the west of VCC, at Cliffdale, the dip of the coal floor is to the north. Further west, at Vrede, it swings around to the south. At Hlobane Colliery, the dip is mainly to the east. Secondary drainage systems are present in the north and west of Hlobane.

The main conclusion in terms of the dip of the coal floor is that VCC is the only mine that has some capacity to store water underground. Hiobane has rather

limited storage facilities and it is estimated that less than 10% of the mine can be flooded upon closure of the mine. Mining operations have, in fact, ceased at Hlobane colliery during 1998. Cliffdale and Vrede have almost no underground storage capacity for water.

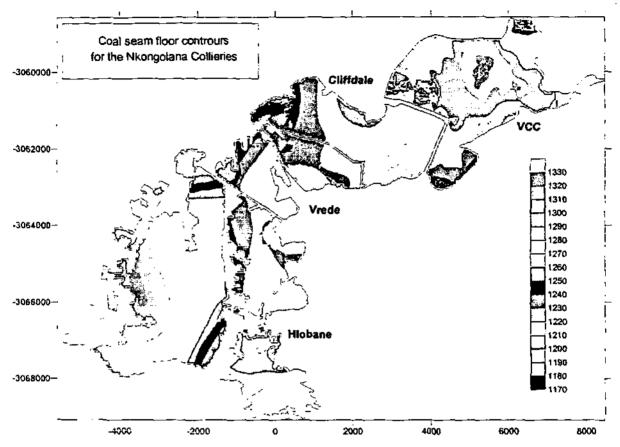


Figure 4-22. Coal-seam floor contours (mamsi) for the Nkongolana Area.

Apart from underground mining, small-scale opencast mining has also been done along the peripheral coal outcrop areas. Many such small excavations existed, most of which have been rehabilitated. In some instances, the water levels in these pits have risen to decant on surface. An example of such mining with its associated water problem is shown in Figure 4-23. This photograph shows a rehabilitated portion of an opencast mine. The water level within this pit has risen to surface within three years after mining has ceased. The water is saline and acid. Iron precipitation is evident. Flow from this pit is in the order of 0,4 l/s (Figure 4-24), which translates to an approximate recharge of 12% of the rainfall.



Figure 4-23. Water seeping from a rehabilitated opencast mine in the Nkongolana Area.



Figure 4-24. Net result of water flow from an opencast section in the Nkongolana Area.

### 4.3.2 Water quality

Analyses of water samples have been done for many years by the mines. Some of this information has dated and is not considered reliable. In recent years, special efforts have been made by both VCC and Hlobane to acquire accurate and sufficient data. All water quality information generated since then has been entered into a computerised database (HydroCom) and is processed by them or their environmental services section. This study has greatly relied on this information to depict local water quality conditions. These sources of valuable information are gratefully acknowledged. A selection of these results is presented in Figures 4-25 - 4-33 and in Table 4-1.

The box-and-whisker diagrams show two series of samples. It starts with water from the area between Hlobane and Vrede Collieries, showing results in a downstream direction up to the final monitoring point at V13 (Figure 4-25). The

second series of results were drawn from the stream passing south of VCC colliery (C12 to 2130/2).

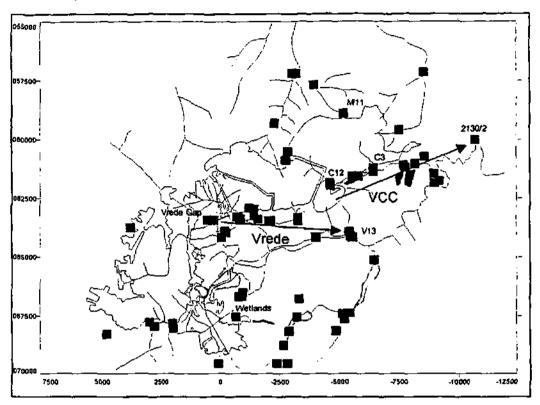


Figure 4-25. Series selected for box-and-whisker plots.

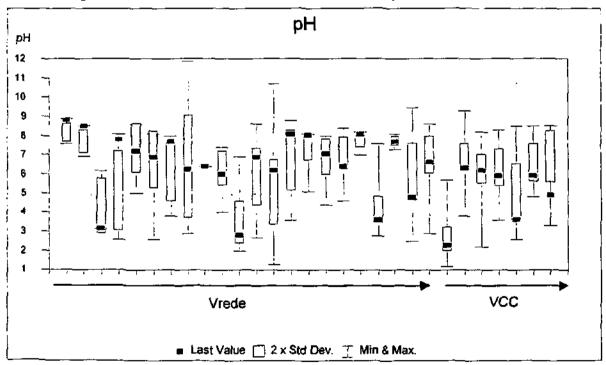


Figure 4-26. Box-and-whisker plot of pH-values along streams indicated in Figure 4-25.

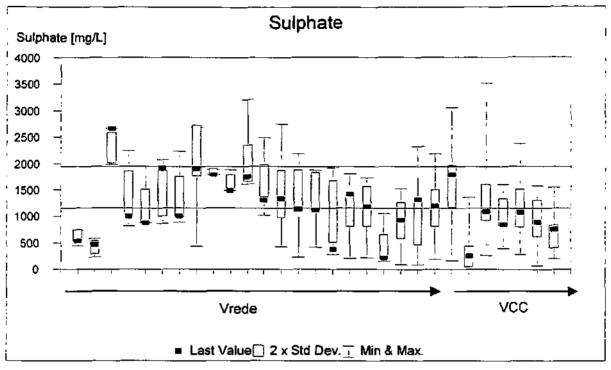


Figure 4-27. Box-and-whisker plot of sulphate values along streams indicated in Figure 4-25.

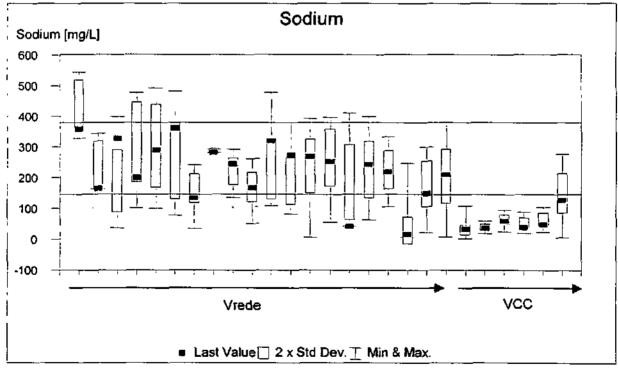


Figure 4-28. Box-and-whisker plot of sodium values along streams indicated in Figure 4-25.

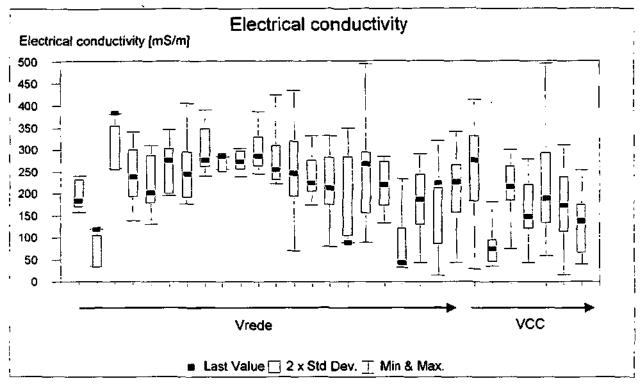


Figure 4-29. Box-and-whisker plot of electrical conductivity values along streams indicated in Figure 4-25.

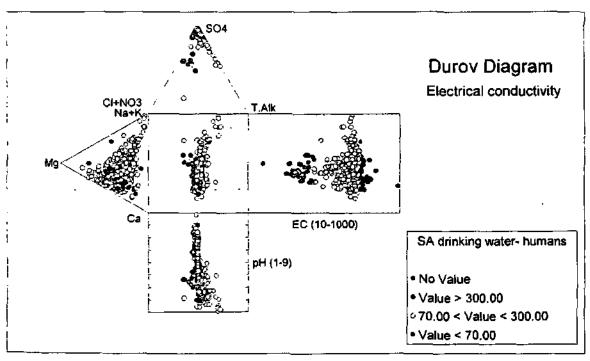


Figure 4-30. Durov Diagram of water samples from the two streams indicated in Figure 4-25.

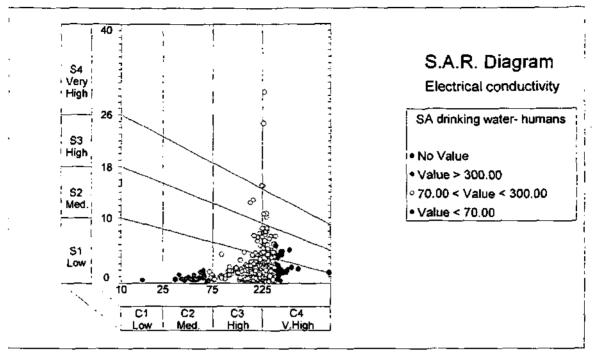


Figure 4-31. Wilcoxen Diagram of water samples from the two streams indicated in Figure 4-25.

Table 4-1. Detailed chemical results of water from selected localities at Hlobane Colliery

Normer	рН	EC	Ca	Mg	Na	K	PAIk	MAIK	<u>a</u>	504
HLB Vrede	7.64	235	138	38	431	7.6		344	4.4	1024
B/L, Sec 104	7.83	247	17.4	3.6	580	6.4	Ó.	465	11	843
Tshoba Sec 367	7.61	252	255	103	309	125	0	141	25	1522
	NO3 as N	F	NO2	PO4	Br	Al	Fe	Mh		
	<b>-</b>						i i			
HLB Vrede	0.14	0.52	0	0.33	0	0.01	0.015.	1.82		
B/L Sec 104	0.26	1.1		0	0	0.018	0.084	0.339		
Tshoba Sec 367	0.47	0.41	0	a	0	0.009	0.007	0.002		
	Ag	As	(Ba	Be	Q.	Cd	Co	Cu	Hg	La
18 531 . 1			<u> </u>	<u> </u>		— <u> </u>				0.004
HLB Vrede	1 0	D)	0	neg	0	0.	0.017	0.002	neg	0.001
B/L Sec 104	O	0		neg	0	0	0.005	0.002	neg	0
Tshoba Sec 367	0	Q		neg	û	ā	0	0.002	neg	0
	L	Мо	Ni	Pb	Sb	Se	Sn	Sr	٧	
	]				- 1	i	Ī			
HLB Vrede	0.186	0.001	0.049	0	neg.	0	neg	5.08	0	
B/L Sec 104	0.355	0.005	0.012	0	neg	0.	neg	1.42	0	
Tshoba Sec 367	0.226	0	0.017	0	neg	0	nea.	9,77	0	

The following conclusions are drawn from this information:

The pH of the mine water is high as the water leaves the HLB Vrede Gap.
 This is due to the presence of sodium carbonate (Table 1) in Hlobane

- Colliery. The relatively low sulphate level confirms dynamic throughflow of water in this section of Hlobane Colliery.
- At Vrede Colliery, acid water from Vrede joins the Hlobane water and pH levels below 3.0 have been recorded. Sulphate levels are in the range of 1000 2000 mg/L, still not reaching saturated conditions. Sodium levels decrease downstream, confirming the lower availability of sodium carbonate as a neutralising medium in the other collieries.
- In the case of the Notshelwa River past VCC, it starts off at C12 with very high acidity and low pH-values. Sulphate concentrations are in the same order as that at Hlobane and Vrede. Sodium levels are lower than what would be expected under natural conditions for the Karoo sediments. This suggests active circulation which has leached most of the sodium from VCC. Through chemical reaction, all of the calcium/magnesium carbonate from the coal has also been leached at this locality. The acid chemistry of this water is attributed to local geohydrological conditions and not to differences in the original coal chemistry. Factors locally in favour of acid generation are: (1) Shallow and outcrop conditions; (2) Aerated mining environment; (3) Insufficient capability to flood the underground workings.
- In contrast to the area around C12 at VCC, most other historic sampling has
  yielded neutral pH-levels. Noticeable is the chemistry of the water that drains
  from the mine along the South Adit (C3). The near absence of sodium and
  the lower than usual sulphate concentrations (800 1600 mg/L) suggest
  dynamic throughflow of water. Details on time series for specific chemical
  parameters from the South Adit (C3), North Adit (M11) and C12 are
  presented in Figures 4-32 and 4-33. These will be discussed later.

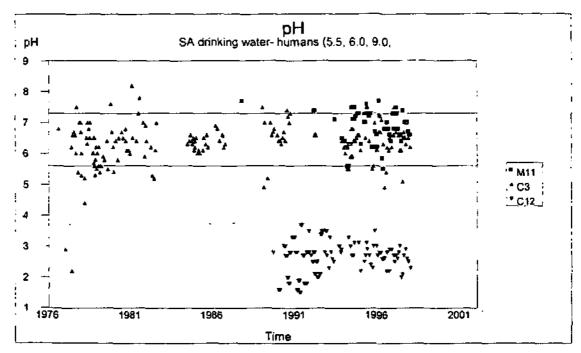


Figure 4-32. Time series of pH-values for the South Adit, North Adit and C12.

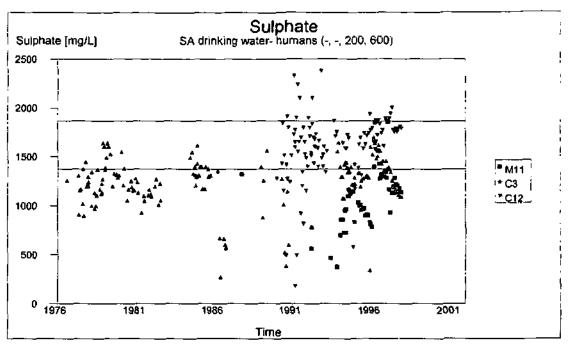


Figure 4-33. Time series of sulphate values for the South Adit, North Adit and C12.

- The plot on the Durov Diagram (Figure 4-30) differs significantly from that of the Mkuzi and Black Mfolozi (Figure 4-18). Pronounced sulphate domination, associated with acidification of a significant number of samples is present on the local mining scale. The degree to which this water is able to recover and re-establish itself in usable form, becomes clear from Figure 4-18.
- Water with high salinities exhibit the same tendency as in the regional study, having medium to high sodium hazards. On the local scale, the elevated sodium is associated with mining but on a regional scale, sodium is introduced through natural leaching, especially as rivers cross semi-arid areas closer to the sea.

It suffices to state that the constituents and parameters that contribute to a change in the catchment water quality can be traced back to mining activities and sometimes even to individual mines. Elevated sodium levels are currently derived from Hlobane Colliery, while acid water is typically, though not exclusively, associated with water from Vrede, Cliffdale and sometimes VCC. In the latter respect, a closer examination of the VCC water is warranted.

Three dominant sources of mine water are derived from VCC. Two of these are from adits, draining water from the accumulated mass of water in the mine and the third from the C12 outcrop area. The chemistries of these waters, over periods up to 22 years, are demonstrated in Figures 4-32 and 4-33. The most obvious difference lies in the pH of these waters. Sulphate levels also differ, but not as significantly.

The difference in pH-levels is totally dependent on the local hydrodynamics. Water in the central portion of the mine is derived from about 80% of the mine surface area. Of this, only 20% of the mined out area has been flooded. Approximately 3 Mm³ water has accumulated here. As water drains from the rest of the mine, whether acid or alkaline, it mixes with the accumulated water, resulting in a well-mixed system. Here, the water comes into contact with the

remaining coal and rock. If acid, the water is neutralised through reaction with base minerals. Calcium/magnesium carbonate would typically be present, which buffers the water at a pH of 6.5. The oscillation of pH-values for the adit water around this value confirms this reaction and that calcium/magnesium carbonate is still available in the coal and rock. The rate of calcium/magnesium carbonate consumption can be calculated from the sulphate concentrations and recorded flows. Based on measurements at the adits, approximately 3.6 t calcium/magnesium carbonate is consumed daily.

At C12, practically no accumulation of water can occur. No chance for the acid water to settle and be neutralised exists. The contact time, as well as the contact surface area, is inadequate.

These two examples that explain vastly different pH-values in one mine can be extended to the entire Nkongolana Area. Conditions that are favourable for acid water neutralisation are:

- Internal drainage and water accumulation in the mines.
- · High concentration of sodium carbonate, as in the case of Hlobane Colliery.
- High concentration of calcium/magnesium carbonate.

It is clear that only VCC and to some degree Hlobane Colliery, conforms to these requirements. Both Cliffdate and Vrede Collieries have hardly any underground water storage capacity. Higher incidences of acidity are therefore expected at the latter two mines.

A question that arises from this information, is whether or not sufficient base potential is available within the coal at VCC and Hlobane to neutralise future acid generation. This can be tested through acid-base accounting.

#### 4.3.3 Acid-base accounting

Many procedures for acid-base accounting are in use in the world. It suffices to state that two main classes of these procedures are available, namely static tests and humidity cell tests. Both procedures hold certain advantages above the other and both have a place in the prediction of the long-term chemical outcome through pyrite oxidation in the coal-mine situation. The main advantages of static tests are that they are quick to perform (3 weeks) and quantitative results on acid, base and leaching parameters are obtained. Humidity cells, also referred to as dynamic testing, are mainly used to predict a sequence of events, from the oxidation and neutralisation phase, right through the acid and finally up to the inert phase. Oynamic testing, though very valuable, takes a long time (>20 weeks usually). For that reason, static tests were performed on samples from VCC and Hlobane mines.

The results of these tests are presented in Figures 4-34 - 4-36. The following conclusions are drawn from this information:

• The initial pH-values for many of the coal samples were below the buffering levels of calcium/magnesium carbonate (pH of 6,5). This suggests that very little, if any, calcium/magnesium carbonate is still present in this coal. The fact that many of the initial pH-levels are around 5.5 could suggest that iron carbonate is still present, though this has not been verified through laboratory testing. Iron carbonate, in any case, does not contribute to the permanent base potential of the coal and should therefore be ignored in acid-base calculations.

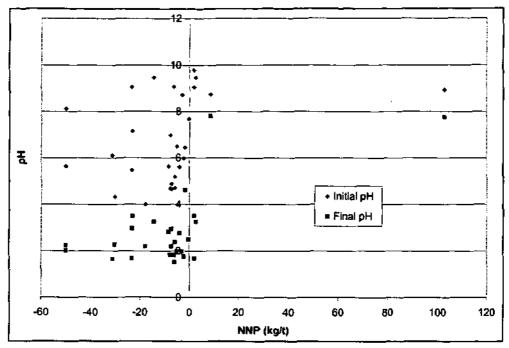


Figure 4-34. Initial and final pH-values for coal samples from VCC, Vrede and Hlobane, before and after complete oxidation under laboratory conditions.

- Seven of the samples have initial pH-levels in the order of 9.0 and above. These samples are mainly from Hlobane Colliery and suggest the presence of sodium carbonate. This is favourable, since sodium carbonate is soluble and easily mobilised from the coal to neutralise acid at source. It is concluded that the sodium carbonate alkalinity will be exhausted first, whereafter pH-levels will drop to around 6.5. This is the buffering level for the calcium/magnesium carbonate. Only after exhaustion of the latter mineral, will the pH of the coal in the mine drop to lower levels.
- The final pH-levels in Figure 4-34 indicate the potential final outcome. This
  assumes an isolated system, which is not the case in the mines. The final
  pH-levels in Figure 4-34 are therefore higher than would be the case in the
  mines. Nevertheless, the conclusion is drawn that all coal samples, except
  two, acidified significantly during the oxidation tests. pH-levels below 2.0
  were recorded in a significant number of cases.
- The overall conclusion is that acidification of the coal at these mines is well
  under way. The acid potential exceeds the base potential and acidification
  over a matter of time is inevitable. The time scale over which this will take
  place cannot currently be predicted with accuracy.

In addition to pH measurements, the actual acid and base potential of the coal have been determined. These results are presented in Table 4-2.

Two significant issues come to light from this information. These are:

- The acid potential exceeds the base potential of the coal in many instances.
- Initial pH-levels are higher at Hlobane than at the other mines. This is due to the presence of sodium carbonate in the coal at Hlobane Colliery. Despite this, acidification did take place in four out of five samples for Hlobane Colliery.

Table 4-2. Results from acid-base calculations.

Samples	Initial pH	Final pH	Acid	Base	NNP	Base/Acid
			kg/t	kg/t	kg/t	
VCC T/S - 1R	5.63	2.24	51.48	1.51	-49.97	0.03
VCC M/S - 1R	7.69	2.49	3.36	3.10	-0.26	0.92
VCC B/S - 1R	8.74	7.81	3.26	11.83	8.56	3.62
VCC T/S - 4R	4.65	2.21	5.66	-1.59	-7.25	-0.28
VCC M/S - 4R	5.47	2.96	17.83	-5.35	-23.18	-0.30
VCC M/S - 7R	5.64	2.83	5.26	-3.16	-8.41	-0.60
VCC T/S - 3F	8.93	7.76	15.05	117.82	102.77	7.83
VCC M/S - 3F	6.45	4.63	1.61	-0.13	-1.74	-0.08
VCC B/S - 3F	4.33	2.28	22.10	-8.06	-30.16	-0.36
VCC T/S - 6F	4.87	2.95	4.99	-2.35	-7.34	-0.47
VCC M/S - 6F	5.19	2.38	4.92	-0.86	-5.78	-0.17
VCC M/S - 9F	5.60	2.76	3.62	-0.43	-4.06	-0.12
VCC T/S - 2C	6.98	1.85	15.60	7.91	-7. <u>6</u> 9	0.51
VCC M/S - 2C	4.71	1.53	5.11	-0.83	-5.94	-0.16
VCC B/S - 2C	6.50	1.99	9.29	4.28	-5.01	0.46
VCC T/S - 5C	7.15	3.49	23.40	0.35	-23.05	0.02
VCC M/S - 5C	6.11	1.66	31.44	0.33	-31.11	0.01
VCC M/S - 8C	5.98	1.77	2.40	0.16	-2.24	0.07
VCC Random	4.00	2,20	18.91	1.23	-17.68	0.07
VCC Channel	4.69	1.85	9.09	1.32	-7.77	0.14
					L	
Vrede 1	8.72	1.99	6.57	3.58	-2.99	0.54
Vrede 2	9.07	1.83	7.70	1,39	-6.31	0.18
Vrede 3	8.12	2.02	50.07	0.20	-49.87	0.00
Hlo, Floor Sect. 104	9.46	3.25	1.85	4.42	2.58	2.39
Hlo. Bottom Coal Sect 104	9.05	1.69	2.18	4.17	1.99	1.91
Hlo. Midstone Sect 104	9.78	3.51	1.01	2.84	1.84	2.82
Hlo. Top Coal Sect 104	9.05	1.69	27.46	4.17	-23.29	0.15
Hlp. Roof Sect 104	9.46	3.25	18.77	4.42	-14.34	0.24

Chemical analyses on leachate from the oxidation tests were also performed on some of the coal samples. Figures 4-35 and 4-36 present these results. These are plots for concentrations of constituents versus their oxidised pH-levels. Conclusions from this information are:

- Plots of this kind enable the visual evaluation of constituent availability at the full range of available pH-levels.
- Most constituents exhibit significantly higher solubility as pH-levels drop.
  This indicates that their availability from the coal is greater than actual
  concentrations would suggest. These plots are therefore valuable in
  determining expected concentrations of constituents under equilibrium
  conditions at different pH-levels.
- Certain constituents, such as sodium and potassium, as well as calcium and
  magnesium to some extent, exhibit no real increase in concentration with a
  drop in the pH. This suggests that these constituents are available in very
  limited quantities and that saturation levels will not be reached. This is
  significant because it again demonstrates the insufficient presence of base
  minerals to neutralise sulphate production.

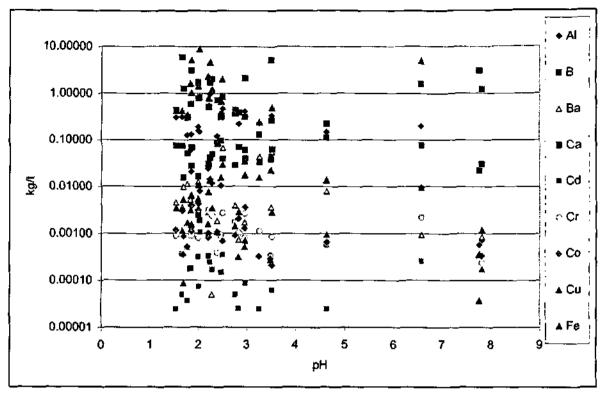


Figure 4-35. Concentration of selected constituents leached from coal samples during complete oxidation.

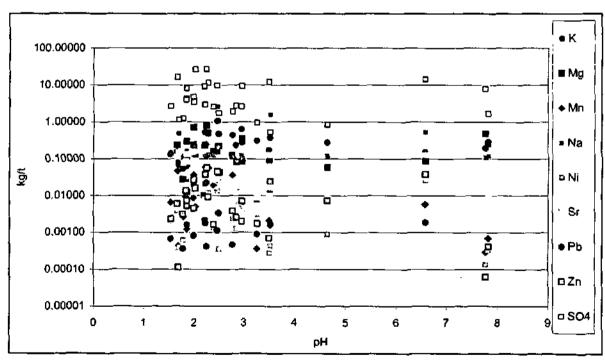


Figure 4-36. Concentration of selected constituents leached from coal samples during complete oxidation.

- The presence of these heavy metals should not raise undue concern.
   Through lime treatment, most of them can be precipitated.
- The acid-base accounting confirms trends observed in water samples from the mines. Occurrences of alkaline versus acid water in the mines can therefore be explained through a combination of coal mineralogy and hydrodynamics.

#### 4.3.4 Mine water balance

Accurate flow rates into or from the mines are not available. The best set of data is that recorded at VCC, at the two adits. In addition, rainfall for the area is available from the CCWR. Rainfall for the Vryheid area has been contoured in Figure 4-37. Conclusions from this presentation are:

- Most of the rainfall occurs from October to March. Winter months are dry.
- Rainfall events above 200 mm per month are relatively common. High rainfall months are significant in terms of higher influx into the mines.
- Successive years of drought occur, such as that between 1925 to 1932 and 1940 to 1952. Since 1952, drought periods have been relatively insignificant.

The rainfall information was correlated with the recorded flow from the mine, adjusted to represent recharge to the mine and expanded over the whole period for which rainfall records are available (Figure 4-38). Calculated annual recharge values for the same time span are shown in Figure 4-39.

The following conclusions are drawn from this information:

- The calculated minimum and maximum annual recharge to VCC, based on 80 years' rainfall history, range from 0.35 to 6.9 ML/day. This is a considerable spread of values. Considering that almost all recharge occurs between the months of October March, the flow from the mine during summer should therefore be at least double these amounts. If a safety factor is built into the system, flows as high as 15 20 ML/d can be expected from VCC at high rainfall events and for periods up to one month.
- All of the mines are currently filled to their maximum capacity with water.
  There is no reserve holding capacity. Recharge to VCC will therefore report
  to the streams north and south of the mine. In the event that treatment is
  considered as an option for the mine water, the treatment plant should be
  designed to cope successfully with the extreme variations in flow, including
  the mine water through the North Adit.

Assuming similar conditions for the rest of the Nkongolana Area and projecting this information to these areas, the results in Table 4-3 have been obtained. This amounts to a total influx of 4 - 22 Mt. per day over a whole year. Generalisations of this kind should at least be refined for summer and winter conditions. It has, for instance, recently been reported by Hlobane Colliery that their flow during summer has been as high as 35 ML/d. This still has to be confirmed through monitoring over longer periods.

These flows have been expressed as average daily flow over a period of a year. In view of the short residence time of the water in the mines, flow from the mines will react almost immediately upon rainfall events. A rainfall event of 200 mm/month will, for instance, yield a combined flow of 75 ML/day for that month. The relationship applicable between the amount of annual rainfall and recharge is demonstrated in Figure 4-40.

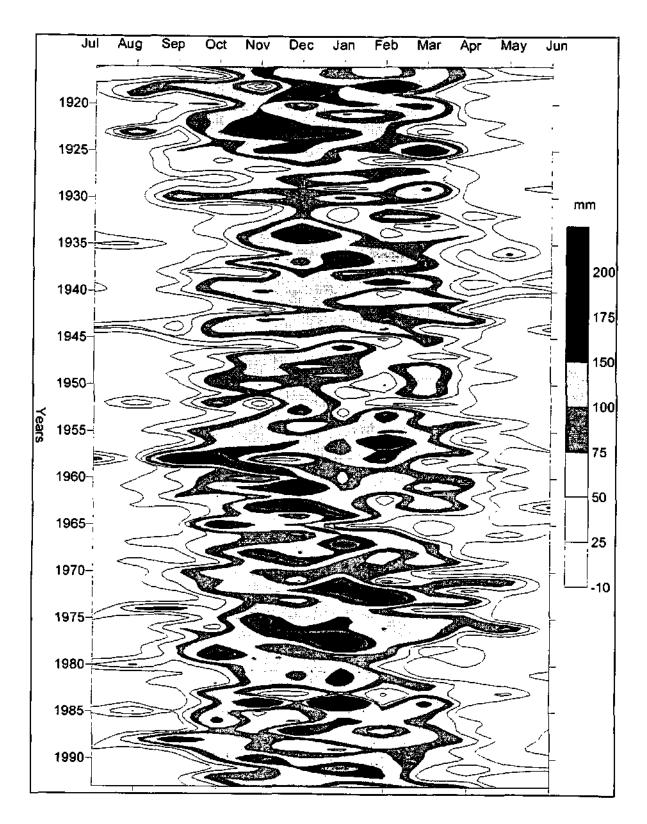


Figure 4-37. Contours of monthly rainfall for the Vryheid area.

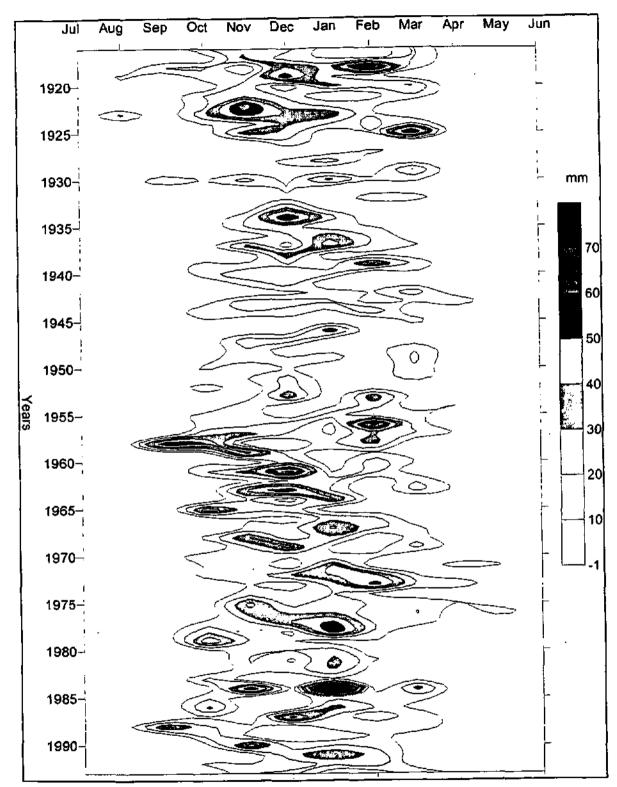


Figure 4-38. Contours of calculated monthly recharge to VCC.

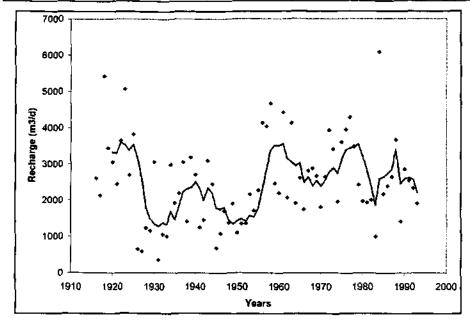


Figure 4-39. Calculated annual recharge to VCC, based on the historic rainfall data, with a five-year moving average curve fitted to the data.

Table 4-3 Projected annual recharge for collieries of the Nkongolana Area.

_	•	Rain 1000 mm	Rain 600 mm	Rain 400 mm
Colliery	Area (ha)	Recharge 20%	Recharge 15%	Recharge 9%
<b>Hiobane West</b>	1335	7315	3292	1317
Hlobane East	690	3781	1701	681
Vrede West	216	1184	533	213
Vrede East	221	1211	545	216
Cliffdale	646	3540	1593	637
VCC	1017	5573	2508	1003
Total	4125	22603	10171	4068

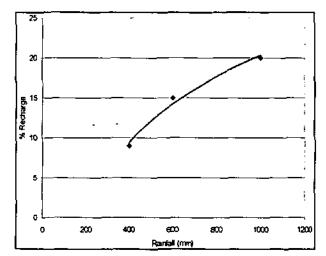


Figure 4-40. Relationship between annual rainfall and recharge to VCC, as established during this investigation.

### 4.4 APPLICATION TO NATAL ANTHRACITE COLLIERY

Based on information obtained from the study in the Nkongolana Area, available information from NAC, which is located about 10 km to the south-east, has also been interpreted. Sampling points at NAC are shown in Figure 4-41. The layout of the mine is shown in Figure 4-42. Selected results from the monitoring programme are shown in Figures 4-43 - 4-48.

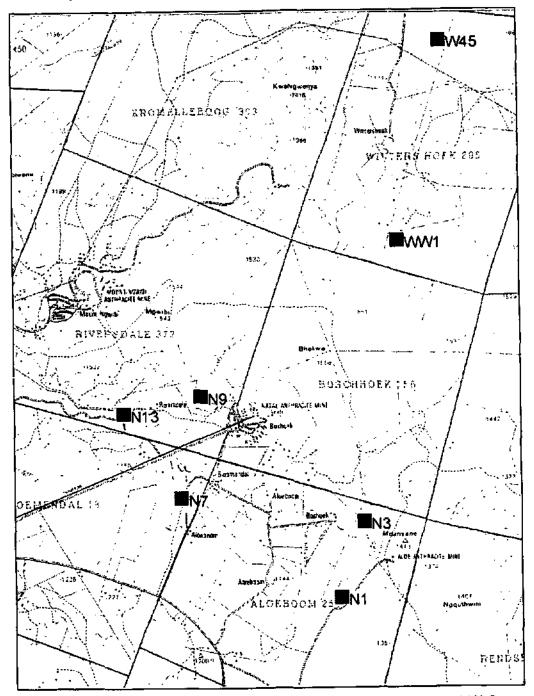


Figure 4-41. Plan showing water quality monitoring positions around NAC.

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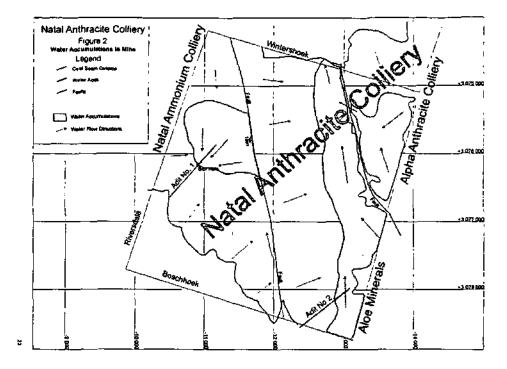


Figure 4-42. Coal outcrop and water accumulation in the underground workings of NAC.

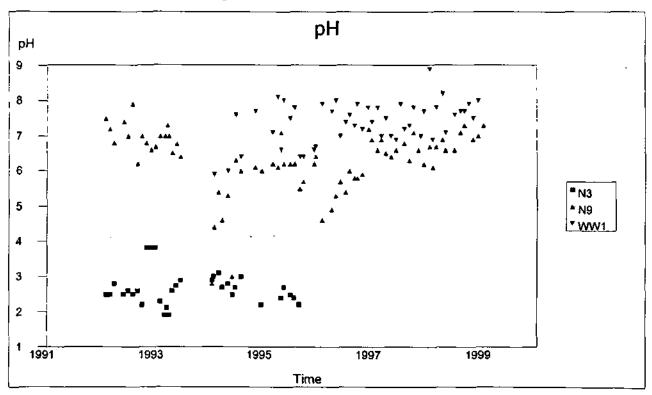


Figure 4-43. pH-values for monitoring points at NAC.

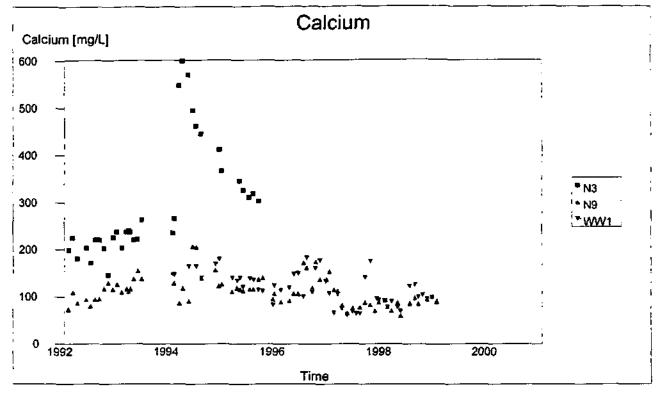


Figure 4-44. Sulphate values from monitoring points at NAC.

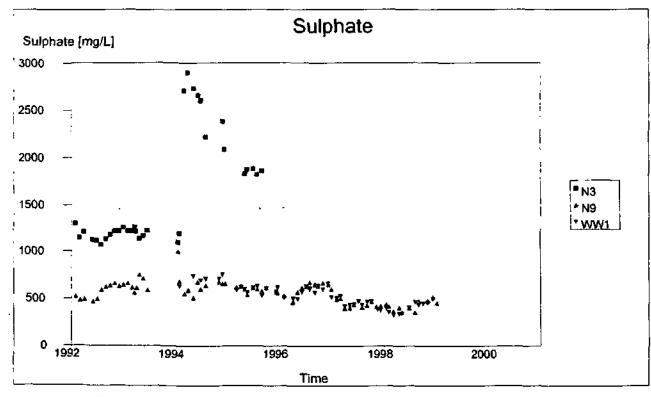


Figure 4-45. Calcium values from monitoring points at NAC.

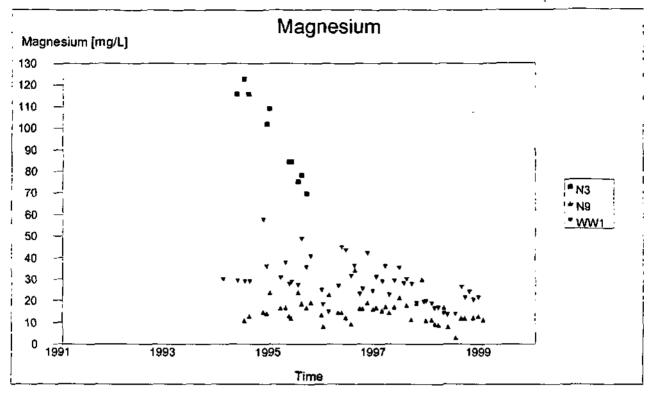


Figure 4-46. Magnesium values from monitoring points at NAC.

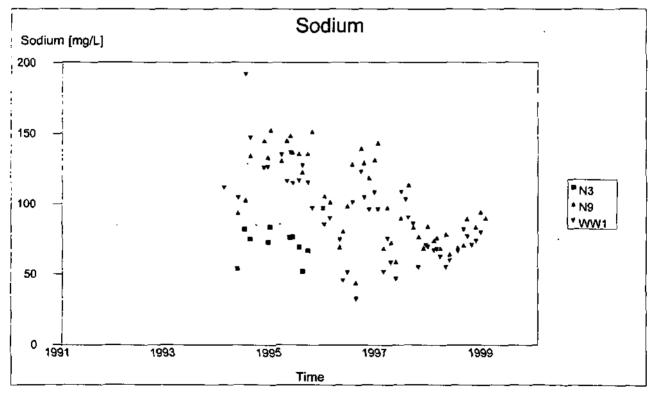


Figure 4-47. Sulphate values from monitoring points at NAC.

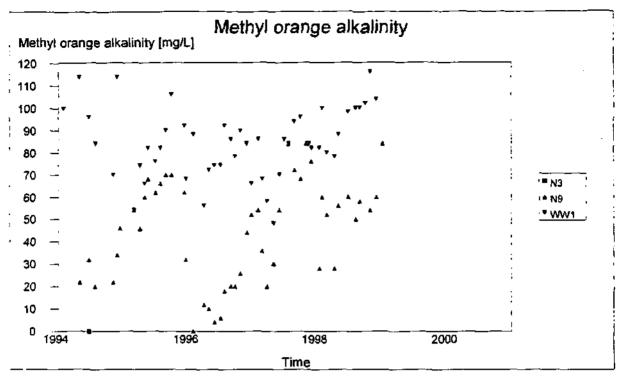


Figure 4-48. Total alkalinity values from monitoring points at NAC.

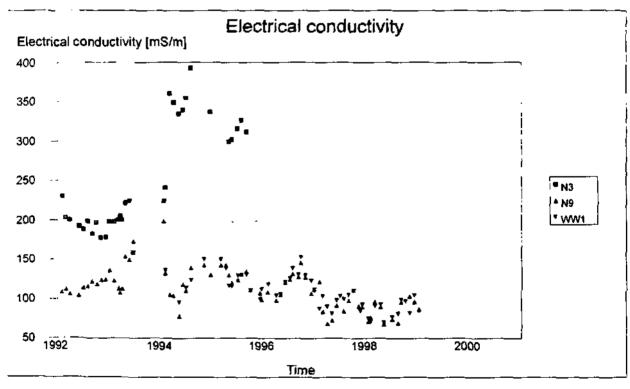


Figure 4-49. Electrical conductivity values from monitoring points at NAC.

Conclusions from this information are:

- Monitoring at N3 ceased in 1995 when the adit was sealed.
- About 33% of NAC has been flooded. According to the theory developed for partially flooded mines, water from the totally flooded portions of the mine should be alkaline while water from unflooded and fringe areas should be acid.
- A significant improvement in the mine water quality is present over the past eight years. This is reflected in all the parameters shown in the preceding figures.
- The pH of the mine water is significantly above the buffering level of calcium/magnesium carbonate. The total alkalinity is also high by comparison to that at VCC, for instance. This suggests that sodium carbonate is present in the coal and rock and that this is sufficient to neutralise current acid production. The decrease in sodium concentration in the mine water, from 140 to 70 mg/L suggests that it is being depleted through active circulation of water in the mine. Once the availability of sodium drops below that required for neutralisation of the acid, the pH of the mine water will drop to around 6,5, where it will be buffered by calcium/magnesium carbonate in the rock and coal.
- Sulphate levels are low by comparison to the collieries in the Nkongolana Area. This is ascribed to high through flow of water at NAC and elimination of pyrite oxidation in flooded areas. Flow of water has historically averaged 10 ML/d. This is three times the volume of water flowing from VCC.
- It is concluded that the model suggested for pyrite oxidation and acidification
  for the Nkongolana coal-mines also fits NAC. NAC has the advantage of
  elevated sodium carbonate in the coal and rock, which, in the interim, acts
  as a neutralising agent. To express an opinion on whether or not the base
  potential at NAC will be sufficient to neutralise all acid that will be produced
  is premature. Only through proper acid-base accounting will an answer on
  this matter become available.

#### 4.5 CONCLUSIONS

Coal mining in mountainous areas of KwaZulu-Natal has often created conditions that favour oxygen and water ingress into the mines. Many collieries outcrop along the slopes of mountains with the result that water can seep from them to enter into surface streams.

The results from this study suggest that, for the Vryheid Coal-field:

- The acid-generating potential of the coal mostly exceeds its base potential.
- The base potential, if any, is present in a variety of mineralogical forms, such
  as sodium carbonate, calcium/magnesium carbonate and iron carbonate.
  The latter only has a temporary neutralising impact. In many of the instances
  examined, most of the sodium and calcium/magnesium carbonate has
  already been depleted through leaching and reaction with acid water.
- In aerated environments, acid generation starts on the outer surface of a
  mine work face, boulder, rock or grain. Carbonates on the outer surface
  counteract acidification until they are depleted. Acidification of outer surfaces
  is therefore fairly rapid, while the inner portions are still unchanged. In
  flooded areas, water is in constant contact with the coal. Here, water siphons
  along fractures into and through the coal. Carbonate minerals are present in
  the fractures and react with the acid water. It is often observed that sections

of mines that have historically been acid during mining, become alkaline when they are flooded. Whether or not this is a permanent change in the pH will depend on the amount of neutralising agent available, the degree of flooding and flow dynamics. In areas that are not flooded, reaction between the acid water and the carbonate veins cannot occur.

- In the Nkongolana Area, only about 5 20% of the underground workings can be flooded with water. Only a small portion of the mines therefore has a potential to convert back into an alkaline phase. The neutralising potential of the coal in these areas is therefore inadequate for sustained neutralisation of all acid produced in the rest of the mines. The conclusion is that at some stage in the future, current alkaline sections of the mines are likely to become acid. To postulate about the time that this will take is not meaningful without significantly more information.
- To rehabilitate the top of the mountain, filling all cracks is not possible. The
  mountains are inaccessible over much of the area. Suitable material to fill
  the cracks is not available. Recharge as experienced in the past will
  therefore continue indefinitely.
- Therefore, very little remains that can be done to improve the long-term chemistry of the mine water in the Nkongolana Area. Mining methods applied and the intensity thereof should take the main blame for the current situation. In new mining areas: (1) Pillar extraction should not be allowed unless the mining company can guarantee minimal and manageable impacts on water quantities and qualities; (2) Access to underground workings should be from the highest topographic position, with the mine floor sloping away from the entrance. These recommendations are, however, too late in many respects, because most of the coal in mountainous and outcrop areas of KwaZulu-Natal has already been extracted. Many small fringe areas of coal still exist that can mainly be mined by opencast methods. It is important that the GME and the DWA&F keep proper control on mining in these areas thus limiting local environmental impacts.
- Apart from the fact that very little can be done to minimise mine water
  pollution at source, other innovative schemes may be implemented, where
  and when required. Lime dosing, wetlands, anoxic drains, dilution or mixing
  of mine waters or disposal into the sea are but a few possible solutions. The
  detailed discussion of these is beyond the scope of this report.
- In terms of mine closure, it would not be reasonable for the authorities to
  insist that mining companies should take indefinite responsibility for water
  management at these collieries. The problems at this coal-field are clearly a
  legacy of circumstances born from ignorance in terms of the potential
  environmental impact. Legislative requirements have expanded considerably
  over the period in question. A workable solution should include responsibility
  on the part of the Government.

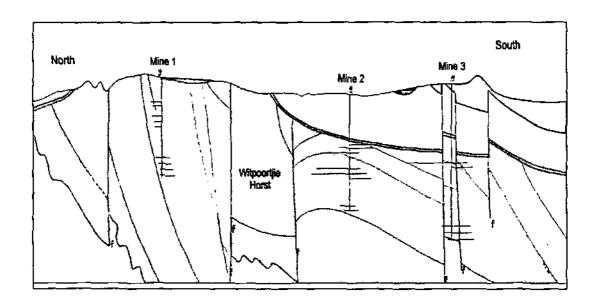
#### 4.6 RECOMMENDATIONS

It will be almost impossible for a single company to implement workable solutions on their own for mine water management in the Nkongolana Area. It is suggested that a collaborative approach should be adopted. This collaboration should include the authorities, without whose sympathetic and imaginative approach no solution will be forthcoming.

The quality of monitoring by the mines has improved tremendously over the past two to four years. They all have electronic databases (HydroCom) and process this information using the WISH software package. The development of

both these packages was partially sponsored by the WRC. Individuals from the relevant mining houses have been on training courses at the IGS and are capable of performing monitoring and data processing themselves. It is recommended that monitoring should continue along the lines set by the mines during the past four years. Of particular interest would be the investigation of trends at the two VCC adits, at the Vrede Gap, discharge from Hlobane through the wetlands and from Wintershoek. From a compliance point of view, other localities will also have to be monitored.

# 5 POST MINING IMPACTS OF GOLD MINING ON THE WEST RAND AND WEST WITS LINE



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#### 5.1 Introduction

#### 5.1.1 Background to the project and scope

One of the most important aquifers in South Africa is the dolomitic aquifer of the West Rand and Far West Rand area. Due to the anthropegenic influences from both mining and industrial sources, this aquifer is increasingly under threat of becoming a vast unexploitable reserve of no use as a groundwater resource.

Gold mining is the principle economic activity in the West Rand and Far West Rand regions. This industry is the basis of the economy and socio-economic development of the region. Gold mining on the West Wits Line contains of the biggest and richest mines in the entire Witwatersrand basin (Robb, et al, 1997). Unfortunately, associated with all the economic and social benefits arising from gold mining there are several negative impacts on the environment. This investigation will concentrate on the hydrogeological impacts and attempt to predict the long-term post-operative impacts of gold mining on the groundwater resources.

#### 5.1.1.1 Project Origin and Objectives

Due to the multitude of problems experienced in the past when closure was applied for, it was deemed appropriate to launch a project that would facilitate closure methodologies acceptable to both the mining industry and the various state departments. The Mining Industry and Department of Water Affairs thus initiated research into the post-operational impacts of mines on groundwater resources, in a project funded by the Water Research Commission.

As an initial phase, the project sought to identify areas where such research was most needed. Four different areas were identified of which the gold-mines of the West Rand and West Wits Line form the focus of this report.

#### 5.1.1.1.1 Objectives

The objectives of the project are as follows:

- Identify aspects to be researched in collaboration with the mining industry and the DWAF.
- Investigate these issues to quantify long-term potential impact.
- Investigate ways to minimise impacts.
- Negotiate acceptance of these methodologies by the industry and the DWA&F.

These aims were refined and the aspects and areas to be researched identified, using an impact rating system whereby the mines are rated, using a simple input system where the different aspects are given different weights. Based on this, the West Wits Line was rated as being an important area to be researched.

#### 5.1.1.1.2 Impact rating system

Zeelie (1996) did research into the development of impact rating systems to assess long-term potential impacts. Her findings, relevant to this report, are outlined below.

In the past most applications for closure have been denied by the government agencies. A major concern is often the possible uncontrolled pollution of water resources in the proximity of these mines after water levels have recovered. Mines applying for closure have had to monitor the performance of the system for a number of years, after which closure was still not granted with confidence.

The lack of confidence and denial of closure stem from:

- Insufficient information or lack of understanding of the long-term behaviour of the system.
- Regional basis impacts not sufficiently quantified.
- · Government not wanting to accept responsibility for these mines.
- Lack of specifically formulated mechanisms and procedures which can be applied to ensure that closure can be granted with confidence.

Previous pollution management strategies within mines and by the Government have been of a responsive nature, formulated to meet a specific problem, rather than viewing the problem in totality.

Unless the situation is altered, it is unlikely that closure permits for many of the dysfunctional mines will be issued within the next decade or two. This holds the inherent danger of mining companies and the authorities not developing coordinated approaches to solve problems on a regional basis ( Zeelie, 1996).

Groundwater related research, specifically at the mines, over the past few years has increased the knowledge and understanding of the interactions involved when mines reach closure. Furthermore, the nature and distribution of aquifers in South Africa have been characterised by numerous investigations. The most prominent of these has been a summarised series of maps by Vegter (1995). These maps depict many aspects that are valuable to groundwater management, such as the potential for the development of aquifers, the depth to groundwater occurrence, the recharge characteristics from rainfall and the current natural water quality distribution.

It should therefore be a simple task to relate the geohydrology and possible impact of specific mining operations to the information already available and published by Vegter and others.

With the introduction of the Environmental Management Programme Report, significant amounts of information have become available at all mines with regard to the pre-mining geohydrological conditions, as well as the expected geohydrological conditions after mining operations have ceased.

Through the use of computers, advanced geohydrological and hydrochemical models have become available, which are capable of predicting the outcome of groundwater pollution from almost any mining operation (Hodgson and Krantz, 1995; Parkhurst *et. al.*, 1980; Parkhurst, 1995; Pinder and Gray, 1977 and Pinder and Wood, 1984). To issue a closure certificate should thus be a simple

matter of conducting the necessary environmental impact assessments, instigating the necessary precautionary measures and application for closure based on a sound understanding and history of mining (Zeelie, 1996). This is, however, not the current state of affairs in South Africa, largely due to the lack of standard methodologies for assessing environmental impacts.

Numerous companies and environmental consultants are currently active in South Africa, employing a wide diversity of methodologies for impact assessments. The results from these investigations are diverse and the methodologies applied are often not comparable. There are therefore mitigating circumstances to government agencies' apparent inability to grant closure to mines which have ceased operations.

Based on this introduction and background information to the problem, Zeelie's research was intended to:

- Identify the main geohydrological and related conditions that should be considered in the application for mine closure.
- · Arrange these issues in a logical way.

In terms of mine waste material which is stored on surface in a temporary or permanent capacity, nine parameters have been identified which should be considered in a risk assessment (Zeelie, 1996). These are:

- · The composition of the waste material.
- The reactivity of minerals within the waste.
- The surface area of the waste facility.
- The size distribution of the waste material.
- The state of management of the waste facility.
- The quality of leachate which emanates from the waste facility.
- The degree of toxicity to the most sensitive user which is likely to be exposed to leachate from the waste facility.
- The characteristics of the soil and rock which underlie the waste facility.
- The development potential of the aquifer which is likely to become polluted.

In terms of a risk assessment with respect to the potential pollution of groundwater resources from within the mines, the parameters to be considered have been classified into two groups. The first group contains parameters depicting the relationship between the mine and the water which flows into the mine, concentrating on interactions and influences. The second grouping is for parameters which relate to the relationship between the mine and the water-bearing strata around the mines, concentrating more on physical attributes.

For the first grouping, the following eight parameters have been identified as the main issues:

- The mineral mined.
- The composition of the reactive minerals within the mine.
- The surface area to be mined.

- The rock type within the mine.
- The mining method to be employed.
- The mine status.
- The quality of the water within the mine.
- The potential toxicity of the mine water in the event that it should migrate from the mine.

The second group, which considers the parameters with respect to the mine/aquifer relationship, is:

- The mineral mined.
- The dewatering rate of the mine during the full production.
- The position of the mine relative to the main water-bearing strata.
- The interconnectivity between the mine and the water-bearing strata.
- The nature of the topography in the area above the mine.
- The amount of rainfall in the vicinity of the mine.
- Access for surface water to and from the mine.
- The development potential of the main aguifer at the mine.

Zeelie (1996) draws a comparison between gold mining in the West Wits area with that in the Free State gold-fields to illustrate the effect of these issues. Although both mining operations occur at great depths, dewatering of the overlying aquifers is necessary in the West Wits area, whereas in the Free State area the mining as such has no impact on the aquifer that is generally utilised for household and farming purposes. In both areas though, waste disposed of on surface in the form of rock, slimes, water and effluents from reduction plants has significant impacts. The conclusions drawn from this are that the risk for pollution of the aquifer is significantly greater in the West Wits area with associated dolomites than in the Free State, where Karoo formations form the surface geology.

The developed rating system thus considered the following in a methodology of simple user interface entries:

- · Reactive minerals in mine.
- Mining method.
- · Electrical conductivity and toxicity of mine water.
- Mine relative to aquifer.
- Interconnectivity between mine and aquifer.
- Access for water to and from mine.
- · Regional evaluation using GIS.
- · Surface area of waste facilities.
- Waste management.
- Electrical conductivity of leachate.

- Toxicity of leachate.
- Aquifer development potential.
- Area to be mined.
- Mining method.
- Mine status.
- Electrical conductivity of mine water.
- · Toxicity of mine water.
- · Dewatering rate.
- · Mine position relative to the aquifer.
- Interconnectivity between aguifer and mine.
- Access of water to and from mine.
- Overall risk of contamination from waste on surface.
- Mine/water quality risk assessment.
- Mine/aquifer risk asses sment.

These factors provide a total mine risk assessment, giving a measure of the potential post closure impact. As will be shown in the following chapters, the gold-mining operations along the West Wits Line and West Rand are of such a nature that the associated risk is fairly high, based on all the individual components mentioned above.

Some 50 kilometres west of Johannesburg, mines were developed in outcrops that were separated from the continuous line of reef outcrops of the Central Rand by structural discontinuities. The reefs were found to continue to the south under a cover of younger sediments. Mining developed in this area soon after the discovery of gold in South Africa in 1886, and is still developing, with the youngest gold-mine in South Africa being in this area.

The mining areas are referred to as the West Rand and West Wits Line. Some of the mines have closed down, many have changed owners and mining style so that underground mining, opencast mining and reclamation of sand and slimes dams have been done here. Some of the richest, biggest and deepest (4 km) gold-mines in the world (Robb *et al.*, 1997) are located in this area. The gold-bearing reefs contain an array of minerals such as native gold, uranium oxides, traces of platinum and an array of sulphide minerals with pyrite being the most abundant. Most of the mines have produced uranium as well as gold.

The gold-mining industry is the basis of the economy and socio-economic development of the region. Unfortunately, in contrast to all the economic and social benefits derived from gold mining, there are several negative impacts on the environment. This investigation focuses on the hydrogeological impacts with the aim of predicting the long-term post-operative impacts of gold mining on the groundwater resources.

The southern and western parts of the area have thick sequences of dolomite underlying the soil horizons and overlying the gold-bearing rocks. These dolomites are part of the most important aquifer in South Africa. Unfortunately, in association with deep underground mining, their water-bearing properties

have not been appreciated, as they have been the cause of significant water inrushes into the mine workings. These were extremely troublesome to mining and the dolomites were dewatered to improve the safety of mining conditions. Karst formation in the dolomites was destabilised by dewatering and many sinkholes and dolines have developed as a result.

Mine waste disposal has added to the plight of the aquifer with significant leachate and even neat mine wastes finding their way into the dolomite. The development of the area also means that domestic and industrial wastes have been disposed of, adding another threat to the water resources, in the dolomite.

#### 5.1.2 Gold Mining

Despite the claim by Robb *et al.* (1998) that the gold-mining industry is generally proactive in ensuring that mining (does) not impact unreasonably on the environment, there are still several aspects that are adversely affected by mining. Wells *et al.* (1992) list the most important factors to be considered:

- · Mining method.
- · Nature of minerals.
- · Management of solid waste.
- · Mine dewatering.

To investigate the post-mining influences of mining areas in South Africa, information was requested from mining companies with the initial aim at closed and abandoned mines. In the initial phases of the project, the companies were requested to complete a list of information. There were no responses for the following possible reasons (Scott, 1997):

- . The mine was abandoned, thus there is no traceable responsible authority.
- The mine is listed as abandoned, but has actually been amalgamated into a larger company, sections of which are still active. For this reason, the holding company does not consider the mine to be closed.
- Many of the mines listed as closed have changed ownership, and with the change are still operating, perhaps mining different reefs or doing reclamation work under a new name.
- The holding company is unwilling to submit information. There may be numerous reasons for this; the most probable being the effort required is seen as unprofitable.

For these reasons, the emphasis of the project was shifted to include operating mining areas. This is justified since the operating mining areas are intimately associated with orphaned mining areas as described in two of the above points. In operating mining areas, the mine authority is identifiable; thus information and co-operation are more likely to be available. Operating mining areas are also the abandoned or closed mines of the future and the potential to generate pollution must therefore be investigated (Scott, 1997).

To assess the possible future impact of these mines, the historical and current trends were evaluated and are presented in this report. Aspects such as dewatering of the mines, waste disposal and pollution sources were included in an attempt to quantify the current influence of the mining industry on the geohydrological environment in the West Rand and West Wits Line. The Institute for Water Research at Potchefstroom University has conducted

investigations into radiation pollution. Due to the specialised requirements for these investigations, they have not been dealt with at length in this chapter.

To predict the future impact, use was made of empirical and computer modelling techniques. From these, scenario and management options were assessed.

From the assessment of the current situation, predictions were made as to the possible long-term impacts of the mines after closure. The final modelled output will thus give an indication of the likely scenarios, and the impacts that could occur.

#### 5.1.3 West Rand and West Wits Line Gold Mining

This report will focus on the gold mining in the West Rand and West Wits Line. There are seventeen mines in this area, each with a different life-span and impact on the groundwater resources of the area. The principle aquifer under consideration is the dolomitic aquifer of the Malmani subgroup which has been compartmentalised by several north-south trending syenite dykes of Pilanesberg age. This aquifer has great potential as a future water resource for South Africa, provided measures are implemented to preserve the quality of its water.

#### 5.1.3.1 Definition of the investigation area

Some 50 km west of the centre of Johannesburg two mining areas have developed. Their historical development is related to their geological expression, these aspects are thoroughly described by Toens and Griffiths (1964), De Kock (1964), Lednor (1986) and Engelbrecht (1986). These authors refer to the mining areas as the West Rand Gold-field and the West Wits Line.

These two mining areas have been enormously important in the South African economy and some of the richest gold reefs in the world have been mined here.

The mines form four separate groups, which are distinct from each other due to geological structure and differences in the geological formations that are being mined.

Figure 5-1 shows the distribution of mines in these areas. The mine names are listed in Table 1, which links the name and reference number used in Figure 5-1.

Table 5-1. Mines of the West Rand and West Wits Line.

West Rand Mine Lease Areas	West Wits Line Mine Lease Areas
East Champ D'Or	8. East Driefontein
2. Luipaardsvlei	9. West Driefontein
3. West Rand Cons (First Wesgold)	10. Blyvooruitzicht
4. Randfontein Estates (REGM)	11. Doornfontein
5. Western Areas N and S (WAGM)	12. Deelkraal
6. REGM Cooke	13. Elandsrandt
7. REGM Doornkop	14. Western Deep Levels
	15. Libanon (including Venterspost)
	16. Kloof
	17. Leeudoorn

18. Durban Roodepoort Deep (Shows Relationship to Central Rand Gold Mines)

In spite of the geological separation, surface and groundwater flows are able to link the mines. These links are part of the focus of this investigation.

The predominant surface water link is the Wonderfontein Spruit; the various ways that it links these mining areas will be shown in later parts of this chapter.

The most important aquifer in South Africa, the Malmani dolomites of the Transvaal sequence, is fairly pervasive and groundwater moves rapidly in large volumes through large solution cavities in the dolomites. This, along with the Wonderfontein Spruit, forms a continuous link between the mining areas. These connections are shown in Figure 5-2.

#### 5.1.3.2 Extent of the problem

Geohydrological maps of the Department of Water Affairs (Vegter, 1995) show that the area is underlain by formations that have a very high potential to yield groundwater of good quality. These areas may warrant special protection due to the very valuable groundwater resource that they contain.

The area has been actively mined since the last century. Compartments in the dolomites have been dewatered, thus changing the geohydrologic regime, and, in many instances, mine wastes have been dumped on the dolomites, because their underdrain characteristics increased dump stability.

Related studies undertaken in the area include:

- Studies to investigate the influence of mine dewatering on dolomite stability.
   These arose due to the catastrophic collapses that occurred in the dolomites during the 1960's. Examples are Fleisher (1981) and Wolmerans (1984).
- Studies to investigate the influence of waste disposal were undertaken by Coetzee (1996), Stoch (1996) and Kempster et al. (1996).

This study investigates an area of over 2 500 km², a large portion of which has been influenced by mining activity. On this scale the investigation is, necessarily, an overview of the situation. There are many variables that cannot be considered at this scale. These could cause divergence in the results on a local scale and would require detailed investigation that is not possible within the constraints of this project. Some of these influences include:

- The aguifers have been subjected to extreme dewatering stresses.
- Mining and industrial development are extensive.
- · Population density is high.
- Mining, industrial and human wastes have been disposed of in this area.
   These have created surface and groundwater pollution sources and related problems.

Within this large area, most of the mining and many of the human and industrial activities are impacting on the quality of surface and groundwater. There are certain realities that ensure that the extent of the problem remains obscure (Scott, 1997):

 There has been no overall monitoring program and much of what is feared about pollution in the area relates to individual perceptions, for example fears about refuse sites which may be polluting. Many of the mines are in the process of establishing such monitoring networks.

- There are also aspects of water pollution relating to radiogenic contamination which have not been studied in any detail. Indeed information relating to the monitoring, analysis techniques and toxic concentration guidelines is still developing.
- Much of the area is underlain by Karst and this results in the surface drainage disappearing underground. Thus a continuous downstream monitoring program is not possible everywhere.
- The mines are dewatering. This causes local, deep cones of depression and draws groundwater into the mine, thus the subsurface water pathways have been altered and may be complicated, making it even more difficult for a reliable monitoring program to be established.
- An encouraging aspect is that a Mooiriver Forum has been established. This
  connects all role players in an attempt to identify where problems are being
  experienced and in an integrated way, with communication, will address
  these problems and hopefully find solutions.

The forum's mission statement is:

To ensure that the water in the Mooi River is fit for all users.

The aims of this investigation were therefore to:

- Highlight the potential sources of pollution relating to mining practice, and to attempt by means of a model to show where these influences may migrate.
   This should provide targets for more detailed study and control.
- Investigate the potential influence of recovered mine water, assuming that the mines have stopped operating.

#### 5.1.3.3 Method of investigation

This investigation has used existing information from published and unpublished reports, EMPR reports as submitted to the DWA&F and published and unpublished maps and plans. In this regard, the investigators are indebted to the Department of Water Affairs, Geohydrology Division, the Department of Water Affairs, Pollution Control Division, the Council for Geosciences, JCI Projects and Goldfields of South Africa for co-operation and supplying information.

A brief overview of the system under investigation in terms of situation, climate, geology and geohydrology will be given. This will be followed by an in-depth look at the current situation, concentrating on the major impacts that gold mining has on the geohydrological environment as far as pollution sources and dewatering as well as their influences are concerned. The in-depth investigation focuses on the West Wits Line Mines, where information was more readily available.

Empirical and numerical predictive techniques were employed in an attempt to gauge the long-term influence of these operations on the groundwater resources of the area. The West Wits Line series of mines have been modelled under different scenarios, while the West Rand situation has been investigated by Krantz (1997).

Different scenarios were modelled to compensate for the lack of reliable information throughout the research area and the range of predictions gives rise to the different management options that were considered. In this way, a qualitative guide to the optimal management procedures should be obtained.

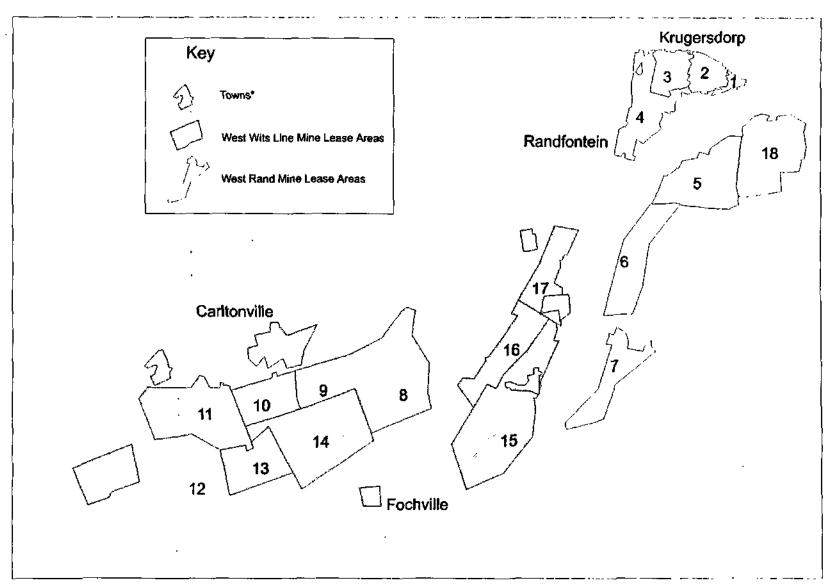


Figure 5-1. Mines of the West Rand and West Wits Line Mining Areas.

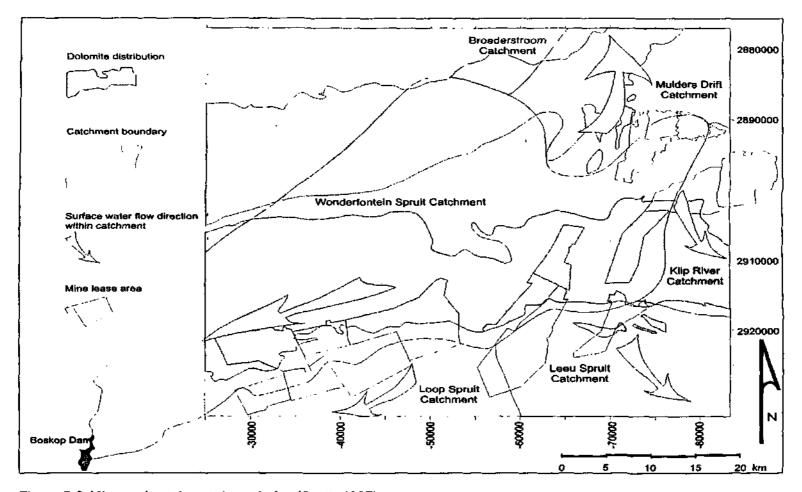


Figure 5-2. Mine and catchment boundaries (Scott, 1997)

#### 5.2 Geography

#### 5.2.1 Area investigated

The investigation area extends from Krugersdorp in the north to Fochville in the south (Figure 5-1). This area is bounded by 27° to 28° longitude and 26° to 26° 45° latitude. This describes a surface area of approximately 2 500 km².

This area includes 17 gold-mines and parts of the towns Krugersdorp, Randfontein, Westonaria, Carltonville and Fochville in the provinces of Gauteng and North-west.

The introduction stated that more emphasis will be placed on what has been called the West Wits Line; this is the southerly portion of the area shown in Figure 5-1, making up the mines numbered 8 - 17. Details of this area are shown in Figure 5-3.

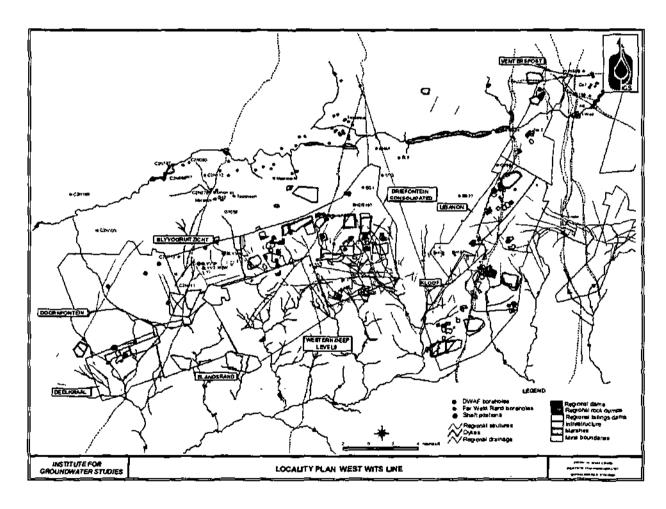


Figure 5-3. Locality plan of the West Wits Line showing salient features.

#### 5.2.2 Physiography

The physiography of the region is referred to as the Highveld of South Africa with elevations of 1 500 m - 1 700 m above sea level. The terrain is generally flat or slightly undulating, with the Pretoria group on the northern and southern fringes of the dolomite, forming the hilly topography. A digital elevation model is shown in Figure 5-4 and a contour map in Figure 5-5.

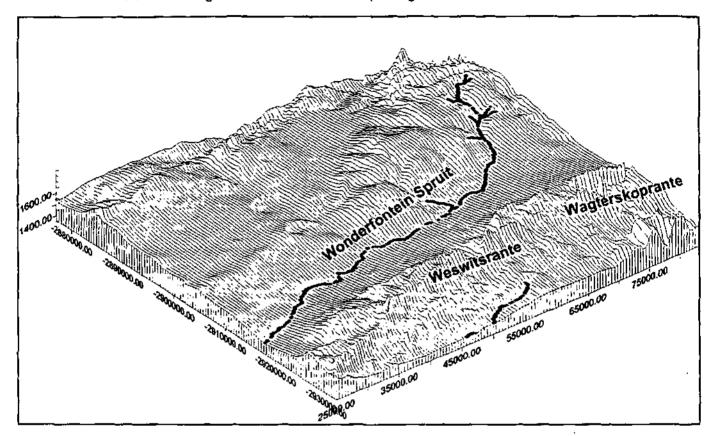


Figure 5-4. Illustrated topography of the area.

#### 5.2.3 Climate

The area experiences a warm sub-humid climate. Rain occurs in summer, mostly between November and February in the form of thunderstorms. The mean annual precipitation is about 630 mm. The area has a very high mean annual evaporation of about 1 700 mm.

The monthly average rainfall for Kloof Mine is shown in Figure 5-6.

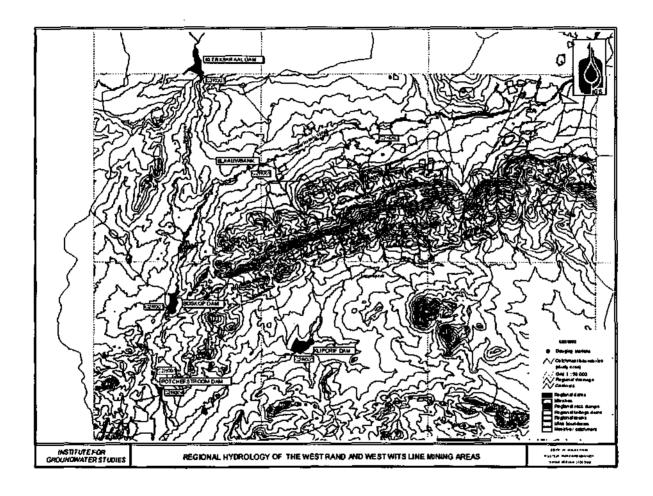


Figure 5-5. Topography and associated drainage pattern of the area.

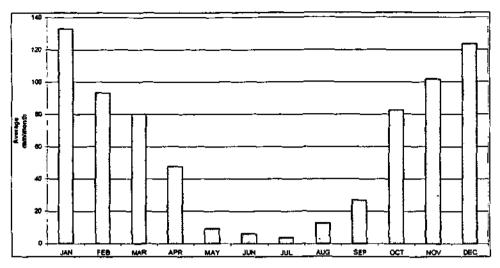


Figure 5-6. Mean monthly rainfall at Kloof Gold-mine.

There are many rainfall gauging stations in the area. These were used to make site-specific comparisons between the precipitation, groundwater levels and mine dewatering pumping. The positions are shown in Figure 5-7.

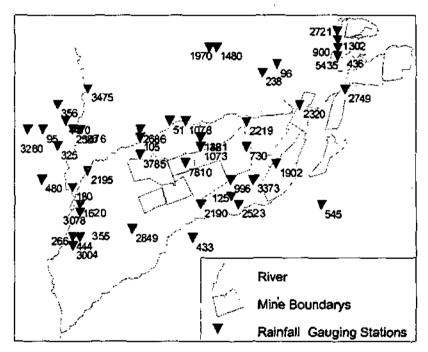


Figure 5-7. Rainfall gauging stations in the West Rand showing number of daily records (from the CCWR).

# 5.2.4 Vegetation

The vegetation of the study area consists of undulating grasslands, indicative of the Bankenveld type. Remnants of native vegetation, shrubby Karee and thorn-tree species occur mainly on hilly ground where there has been no disturbance from mining, urbanisation or clearing for cultivation.

# 5.3 Geology

#### 5.3.1 General Description

After years of geological exploration, mining and geotechnical investigation in this area, the geology is well-understood. The geology is described by Toens and Griffiths (1964), De Kock (1964), Lednor (1986) and Engelbrecht (1986). The points important to this investigation will be given in the following brief summary.

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Figure 5-8 General stratigraphic section of the West Wits Line (after Els, 1987).

The geological sequence consists of sediments that have been deposited onto basement granites and greenstones. The stratigraphic column of the sediments is shown in Figure 5-8.

The Witwatersrand sediments containing the gold bearing conglomerate layers (Reefs) consist of interbedded shale and quartzarenite (quartzite) with numerous conglomerate bands. These sediments are unconformably overlain by andesitic lavas of the Ventersdorp Supergroup which, in turn, are unconformably covered by approximately 1 200 m of Transvaal Supergroup dolomite, the dolomite thickens toward the south. The dolomite is finally covered conformably by shales and quartzites of the Pretoria Series.

Tectonic activity resulted in open folds and block faults. The pre-dolomite formations have been fairly extensively faulted; these faults followed by erosion are responsible for the main distribution of these formations and hence the position of the mines. In the north-eastern part of the area, Witwatersrand sediments outcrop due to a combination of faulting and folding. There are three major faults: The Witpoortjie, Panvlakte and Bank faults.

Although much of the faulting was pre-dolomite there are faults that continue into the dolomite either due to rejuvenation of the pre-existing faults or continued activity. It is these faults and, sometimes, open joints that connect the water bearing features in the dolomites to the mine openings, which have been developed at depth. In most cases, there is a considerable thickness of impervious strata between the mines and the water-bearing features in the dolomites.

Dykes of younger age than the previously described features have intruded the area; many are roughly parallel with north-south orientation. These dykes have divided the dolomites into compartments and controlled groundwater

movement in pre-mining times. Since mine development and dewatering, the dykes still affect the movement of groundwater, but have been mined through in many places. Thus it is suspected that the pre-mining groundwater conditions will never be repeated, even when the mines have stopped operation and are flooded.

Karst topography and cave systems have developed within the dolomite. This has caused significant subsurface secondary porosity which has been traced and mapped using geophysical techniques by Kleywegt *et al.* (1973). The development of karst has been described by Fleisher (1981) and Foster (1989) who show that it is related to water-table levels, both historic and present, the nature of the sediments and relationships to intrusions. Since water levels are related to the topography studies of the paleo-topography have been used to understand the karst distribution.

Mining on the West Wits Line has developed along the southern limb of a wide anticline. As a result of transgression of the younger formations across the underlying Witwatersrand beds the depths to the sub-outcrops of the gold-bearing horizons vary from east to west - the shallowest mining being at a depth of approximately 600 m. The dips of the gold-bearing horizons are of the order of 25° and the deepest mining is approximately 3 900 m below surface (Wolmerans, 1976).

A geological map of the West Wits Line is shown in Figure 5-9.

The legend for this map is shown below.

[~]	Alluvium
	Sand and soil cover
	Shale, sandstone, day, conglomerate, limestone, mari and coal seams
	Tillite and shale
$\overline{}$	Syenite and diabase
	Diabase, gabbro, epidiorite, norite, pyroxenite and granophyre
1960	Shale, horrifels, sporadically interbedded quartzite and chert
	Quartzite with iron ore bands
	Shale with iron ore bands
	Andesite
	Quartzite
-	Shale, ferruginous in places
1	Quartzite, somewhat femuginous
	Shale
	Quartzite
	Chert breccia
	Dolomite, dolomitic limestone, locally marble, with interbedded quartz and sporadic chert brecci
	Quartzite, shale, grit and conglomerate
	Shales magnetic in places with some subordinate quartrite bands
_	Quartzite with some interbedded magnetic shales, grit and conglomerate
	Shale with interbedded quartzite
200	Quartzite with interbedded shales
100	

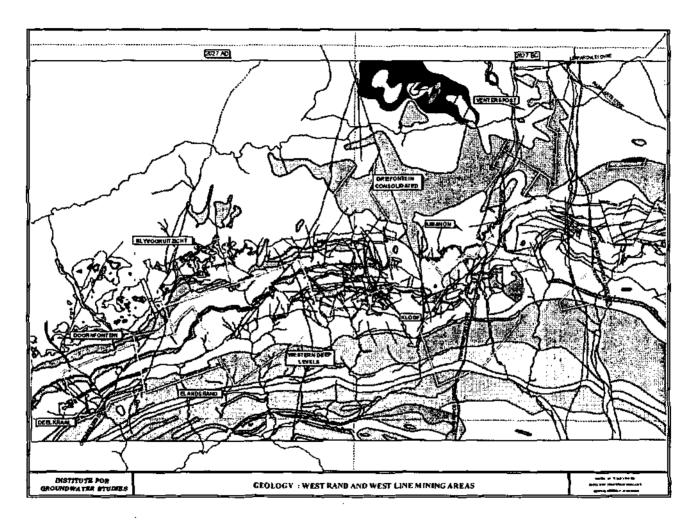


Figure 5-9. Geology of the West Wits Line (Goldfields 1995).

#### 5.4 Mining

## 5.4.1 Mining history

Mines were developed in this area soon after the discovery of gold in 1886. Mining began from surface on the outcrops that occur in the northern part of the area on Champ D'Or, West Rand Cons. and Randfontein Estates Mines, mines (REGM) which worked reefs that are covered by younger rocks were developed subsequently. There has been a fairly consistent development of mines up to the present, with WAGM South Deep being the youngest gold mine in South Africa (Table 5-2).

Some of the mines are already closed, but in spite of this, there is still activity on these properties in the form of dump reclamation and opencast mining. For example, Lindum Reefs and West Wits are both opencast mines that are operating on the old (closed) REGM property.

Table 5-2. Expected life of the mines in this area.

	Mine Name	Date Started	Expected End Date
1	Blyvooruitzicht	1937	No Reference
2	Champ D'Or	1894	1964
3	Deelkraal	1980	2018
4	Doornfontein	1954	Short (2 Shaft already closed)
5	East Driefontein	1972	Not Predicted
6	West Driefontein	1952	Not Predicted
7	Elandsrandt	1981	2011
8	Kloof	1968	2021
9	Leeudoorn	1990	2041
10	Libanon (incl. Venterspost)	1932	2005
11	Luipaardsviei	1888	1970
12	REGM	1895	1967
	Lindum Reefs		2002
	West Wits		2010
13	REGM Cooke	1971	Before 2023
14	REGM Doomkop	1983	2023
15	WAGM N and S	1960	2019
16	WAGM South Deep	1991	2054
17	West Rand Cons	1887	2006
18	Western Deep Levels	1957	
	South Mine		2033
	West mine		2002
	East Mine		2010

Up to 10 different reef horizons have been mined, mainly for gold, but some of the horizons also contain significant uranium and were worked for this metal particularly since 1950. In recent years, there has been little demand for uranium and many mines have stopped production. The reefs are still, however, mined for gold, and as a result, it is possible that uranium and radiogenic daughter products may be disposed of onto the mine dumps.

The ore bearing horizons have been worked to depths greater than 1 700 m below surface in the northern older mines and up to 3 900 m below surface in the southern mines.

# 5.4.2 Mine influences in the area

The geological section of Figure 5-10 highlights the relationship of the different mining areas to potential water inflows from the dolomites:

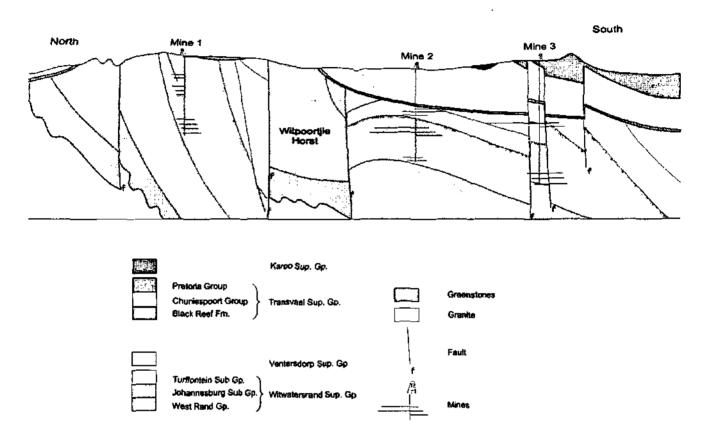


Figure 5-10. Idealised geological section from north of Krugersdorp to South in the vicinity of Fochville.

Mine 1. Represents mines in the northern part of the West Rand group of mines such as West Rand Cons. There is no direct relationship with large water-bearing formations, although this has been postulated to occur via fractures connecting dolomites in the north. These mines have developed from surface and are associated with opencast mines, inclined shafts and shallow surface workings. Recharge to the mines could therefore be derived from direct recharge, seepage from weathered and secondary aquifers and from liquid and slime waste disposal. The shallow mining and surface disturbance ensure that a high proportion of rainfall is rapidly conducted into the underground workings.

Many of these sites have been covered with dumps, backfilled with industrial and municipal wastes and the water quality in these mines is

poor. The deepest workings were some 1500 m below surface. The deepest workings are now flooded, the water level is approximately 800 m below surface and is maintained by pumping.

Mine 2. Represents mines that have experienced significant inflows from the dolomites. The dolomites above such mines have significant karst development. These mines occur in the West Wits Line group of mines, such as Leeudoorn and the northern parts of West Driefontein.

Uncontrollable volumes of water were encountered in these mines and they were granted permission to dewater the dolomites. This led to surface subsidence in the form of broad depressions (dolines) and sharp, often rapid and catastrophic collapses (sinkholes). The sinkholes are direct water connections between the surface and the mines, as shown by Vegter et al. (1989). Mining wastes have been disposed of in this area, many on the dolomites. Many of these have sinkholes in the waste dam, allowing liquid losses to the subsurface and increasing the waste dams stability.

The deepest workings are some 2200 m below surface and the shallowest workings are some 400 m below surface.

Mine 3. Because of the stability problems encountered at many of the type two mines more recent mines were situated further south on the Pretoria Group sediments. In some of these mines, the dolomites were overlain by a considerable thickness of younger deposits and karst development is not as pervasive. Thus many of these mines are relatively dry, for example, Western Deep Levels.

The deepest workings are up to 3 900 m below surface.

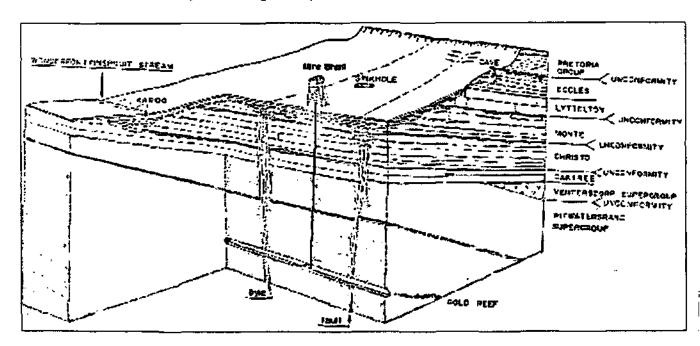


Figure 5-11. Schematic representation of aquifer conditions along the valley of the Wonderfontein Spruit (after Vegter *et al.* (1989)).

## 5.5 Geohydrology

The principal aquifer is the dolomitic aquifer of the Malmani group.

Vegter's (1995) geohydrological maps that are reproduced as Figures 5-12 - 5-15 show broad trends in water level, average recharge, aquifer potential and average borehole yield. It can be seen that mean water levels are fairly deep for the area. This is in contrast with the pre-mining conditions where water levels were fairly shallow (Fleisher, 1976). Average water levels are deepest in the Oberholzer compartment with shallower values further south in formations of the Pretoria group. The maps show that there is higher recharge on the dolomites (75 - 110 mm) compared with 50 - 75 mm further south where the Pretoria group outcrops. Predictably average yields in the dolomites are significantly higher than in other rock types. These maps give very general distributions; local conditions could be quite different. The maps do highlight the importance of the dolomites as a water resource.

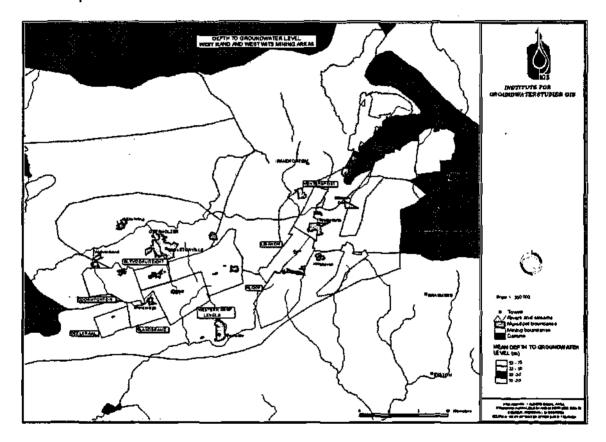


Figure 5-12. Average depth to groundwater.

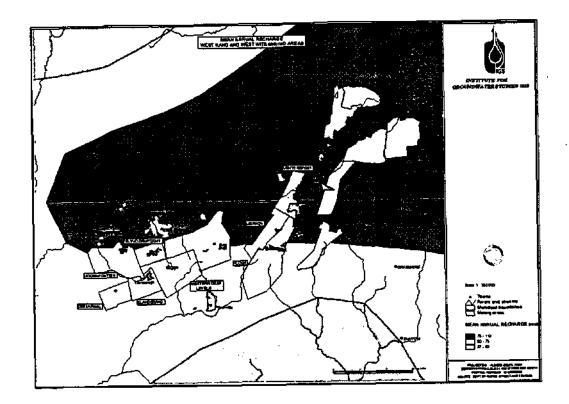


Figure 5-13. Average recharge.

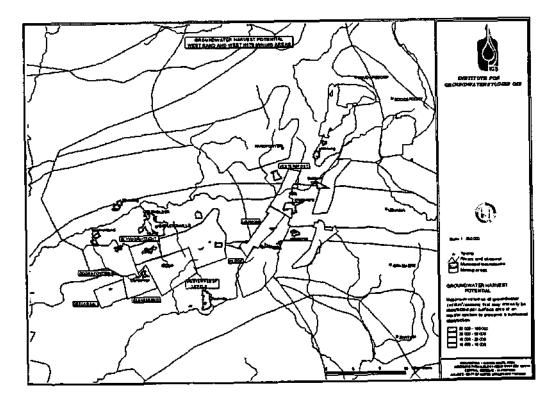


Figure 5-14. Groundwater harvest potential.

5-23

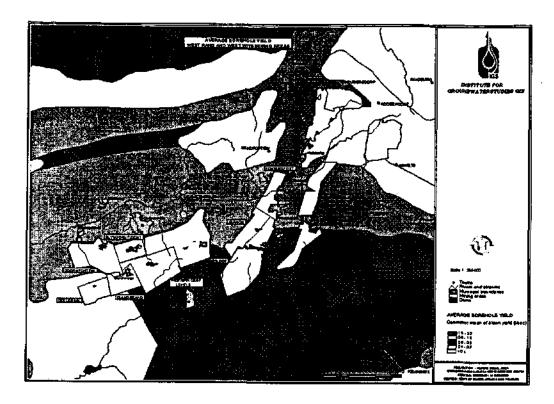


Figure 5-15. Average borehole yield.

## 5.5.1 Compartmentalisation

Major intrusions, apparently of similar age as the Pilansberg feature, radiate from the feature and are traceable over large areas in eastern Gauteng and North-west Province. Geological mapping of these intrusives in the area shows that they are roughly parallel, trend north - south, and are spaced five to sixteen kilometres apart. The dykes divide the dolomites into a number of compartments through which, it has been thought, little or no water exchange could take place.

Surface and subsurface water flow is from east to west. Under natural conditions, the subsurface flow was arrested by the dykes and forced to emanate as a spring - locally known as an "eye". The eyes and their associated compartments are important sources of water to such an extent that, like other major water bodies, they have been named. Their distribution is shown in Figure 5-17. Table 5-3 shows the volume of water that flowed from the "eyes" before mining operations started.

Table 5-3. Springs associated with compartmentalising dykes in the West Witwatersrand area (after Scott, 1997).

Compartment	Surface area (m²)	Name of spring(s) at outlet of compartment	Average flow of spring before mining (m³/d)	Average volume of rain on compartment (m³/d)	Proportion of rainfall that flows from eye %
Zuurbekom	100232000	Kiip River	Dry <sup>1</sup>	190000	
Gemsbokfontein	84951000	Gemsbokfontein	86000	162000	5.3%
Venterspost	54389000	Venterspost	209000	104000	20.1%
Bank	156690000	Wonderfontein	490000	301000	16.3%
Oberholzer	153845000	Oberholzer	540000	295000	18.3%
		Turffontein	184000		
Boskop-Turffontein	704476000	Gerhardminnebron	527000	1349000	5.6%
•		Boskop	45000		

The eyes have been considered to represent the amount of water that replenishes each compartment, but this is unlikely to be the whole situation as suggested by the column showing the proportion that each eye represents of rainfall. The high variability shows that either recharge is very variable between compartments (an unlikely situation) or that the compartments have other in- and outflows. The most probable solution is that the compartments have variable leakage and subsurface groundwater losses. This could be due to the structure of the dykes, their weathering integrity and thickness. Vast quantities of water are, however, stored in the various compartments ( Scott, 1997).

An elementary water balance for such a system might consist of the components listed in Table 5-4.

Table 5-4. Components of a water balance.

In	Out
Rainfall recharge	Evapotranspiration
Surface water losses including water from eye	Discharge at eye
Groundwater leakage through dyke	Groundwater leakage through dyke
	Use
	Mine dewatering

These components are depicted as a conceptual model in Figure 5-16.

Abstraction from the mines has caused steep drawdown around the dewatering points and has lowered the water table in the dolomites, so that the eyes no longer flow.

<sup>&</sup>lt;sup>1</sup> Groundwater abstraction has been happening in this compartment since the turn of the century, Enslin et al. have estimated an original eye flow for the area-see text.

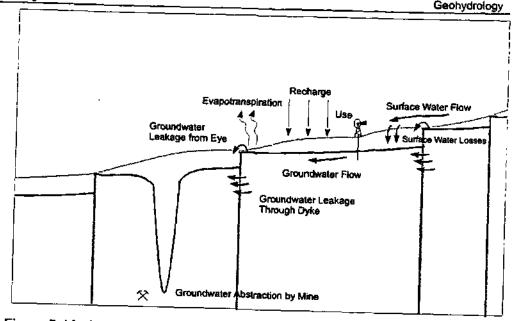


Figure 5-16. Components of the water balance.

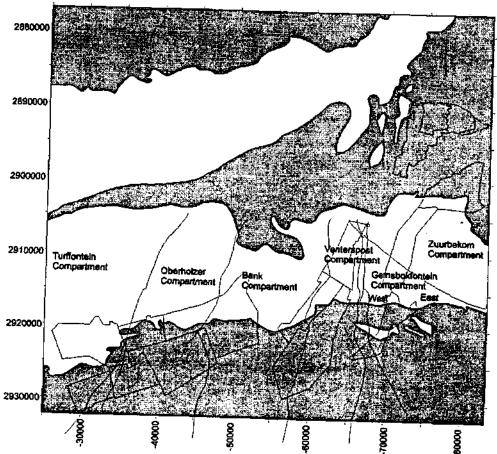


Figure 5-17. Compartmentalisation of the dolomites by syenite dykes.

Wolmerans (1984) has shown that mine development has taken place through compartment-forming Pilansberg dykes. He also shows that mining close to the dykes can destroy their integrity, thus all compartments between the Klipriversberg dyke and the Turffontein dyke will act as one compartment as

they are rewatered. Thus the Turffontein eye will control the final water level in the compartments of the study area. This is shown in Figure 5-18. The elevation of the Turffontein eye is 1 417 mamsl.

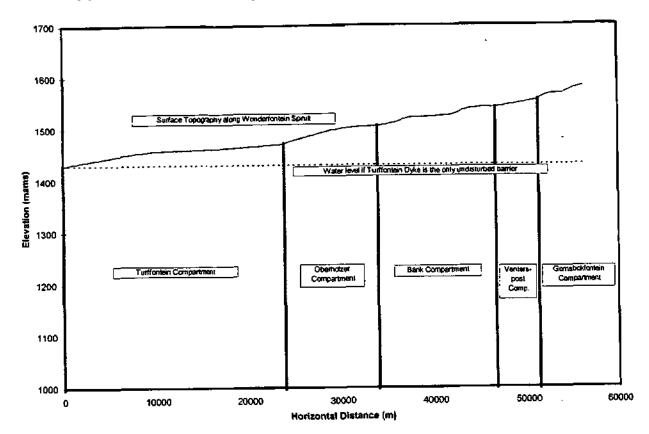


Figure 5-18. Recharged water level and outflow elevation along the Wonderfontein Spruit (after Wolmerans).

# 5.5.2 Aquifer characteristics

The hydraulic characteristics of the compartments vary and Fleisher's (1981) findings will be summarised to give an indication of the range.

In the Zuurbekom compartment, Rand Water abstracts vast volumes of water. Enslin (1967) estimated the original Klipriver eye flow to be 13 689 m³/d before abstraction, while in 1980 the flow from this eye varied between 7 200 and 12 000 m³/day. Replenishment has been calculated to be between 27379-35600 m³/day, 15% of which is estimated to be percolation from surface sources and mine effluents are thought to contribute 4% of the inflow. Transmissivity can range from very low in unweathered dolomite to extreme in the karst. Storage coefficients for the compartment are estimated at 3%.

The Gemsbokfontein compartment has complex flow characteristics including significant recirculation of water and leakage through several of the dykes (Bredenkamp, 1993). The eye originally flowed at around 8 214 m³/d. Recharge estimates vary from 7 - 13%, with storage calculated to be about 2.26%.

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Venterspost derives water from rainfall recharge, influx from its eastern boundary and surface water seepage. An estimated 34 223 m³/day recharges the compartment. About 20% of this influx is derived from compartments to the east. This leaves a rainfall recharge percentage of around 27% which by comparison to Enslin's *et al.* (1967) estimate of 13% is high. Prior to 1977 an additional source was overflow from Donaldson Dam and seepage from the Wonderfontein catchment's marshy areas. Surface water losses need to be taken into account when assessing the recharge conditions. If these had been consistently included, the difference in recharge estimate may not be as large.

Bank compartment has storage of greater than 38 million cubic metres or around 1.2%. Transmissivities are variable, but can be as large as 7000 m<sup>2</sup>/day. Recharge to this compartment has been estimated at between 5% and 27% by different authors (see Table 5-5). The original eye flow was around 50000 m<sup>3</sup>/day which suggests a recharge of between 16 - 20%.

Various authors using different methods have investigated the aquifer characteristics of storage and recharge, thus giving a range of values. Table 5-5 summarises the findings for recharge.

Table 5-5.	Recharge	comparisons.
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	Fleisher (1981)	Wolmerans (1984)	Bredenkamp (1993)	Enslin & Kriel (1967)	Foster (1989)
		F	Recharge	%	
Turffontein		5.6			
Oberholzer		18.3		3.6	12.9
Bank	24	16.3		5.8	27.3
Venterspost	27	20		8.5	54.6
Gemsbokftn	12.8	5.3	27	7.5	•
Zuurbekom	16.8	15	15.8	13	

For the same reasons reported values for storage and permeability also show ranges. Pumping tests in the dolomites give transmissivity values from 20 m²/day to 5 000 m²/day, depending on conditions encountered in the bore such as penetration, karstification and geological structures. Simonic (1993) derived storativity between 0.01 and 0.03 and transmissivity between 25 and 2500 m²/day by calibrating a numerical model in the Zuurbekom compartment. Because of the nature of karst, these variations cannot be assigned to specific areas or zones and conditions can vary greatly over very short distances.

Bredenkamp (1995) shows that water balances yield more representative S-values than pumping tests in the dolomites, because pumping tests in the dolomite measure S-values that represent the storage co-efficient of the fractured matrix rather than the specific yield of the fracture.

Factors such as these make any hydrogeological deductions and predictions (e.g. about flow rates) very difficult. This should be borne in mind when predictions, dealt with in Section 9, are read.

## 5.5.3 Surface hydrology

The surface hydrology is dominated by the Mooi River Catchment. The principal streams and rivers in the catchment are the Mooi River, Wonderfontein Spruit and Loop Spruit. Dams including the Klerkskraal, Boskop and Klipdrift have been constructed.

Geohydrology

The flows, in the Wonderfontein Spruit are complicated by losses to the karstic subsurface geology. The principal relationships between rainfall (Mean Annual Precipitation) and run-off (MAR) for the larger catchments are given in Table 5-6 (CCWR, 1997).

Table 5-6. Hydrological information of subcatchments in the study area.

Catchment Code	Approximate Stream Relationship	MAP mm/year	MAR m³	MAR4Q
C23D	Wonderfontein Spruit	663	29.5	15.1
C23E	Wonderfontein Spruit	630	25.9	22.0
C23F	Mooi River	605	23.5	31.1
C23G	Mooi River/ Wonderfontein Spruit	597	22.9	14.0
C23H	Mooi River	603	23.4	10.6
C23J	Loop Spruit	620	38.3	34.1
C23K	Loop Spruit	606	35.1	13.9
Total in these C	atchments		198	140
Total in C23			252	

The surface drainage and most important features are shown in 5-19.

Water losses to the dolomites find their way into the underground mine workings. According to Wolmerans (1978), water is fed into underground mining excavations through fracture planes within the arenaceous Witwatersrand beds from the overlying dolomite by post-dolomitic faults. These fractures have roughly the same orientation as the syenite dykes that separate the compartments.

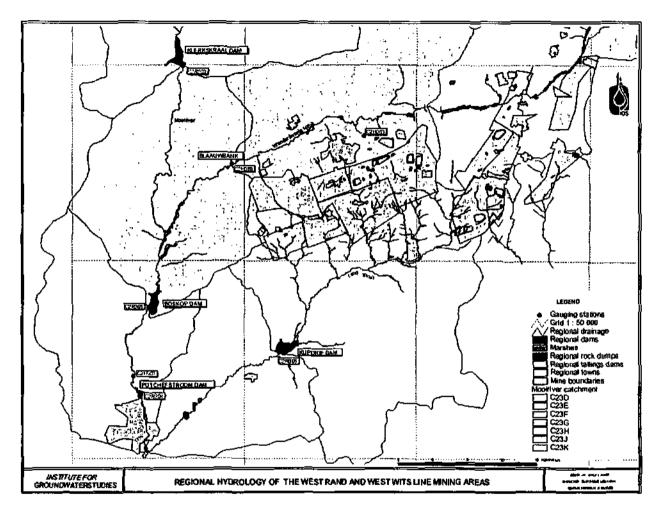


Figure 5-19. Fourth order catchments in Mooi River System.

## 5.5.4 Evolution of the aquifer

The Malmani Subgroup is composed of dark grey dolomite with variable proportions of interbedded chert and quartzite. Unweathered dolomite is a finely crystalline, massive rock with very little primary porosity. Weathering of dolomite is referred to as solution weathering, as most of the rock goes into solution leaving very little residue (wad). Thus weathering produces enlargement of fractures and joints and, in some places, interleading holes or caves develop, this is called karst. Secondary porosity of this type can allow large volumes of water to be stored and can produce large, rapid moving groundwater flow. Such groundwater conditions are unique to karst.

Van Biljon (1996) listed three aquifer types in the area:

- A fractured aquifer system that could occur in any of the geological formations and is the usual form of groundwater occurrence in rock types other than dolomite.
- The dolomitic aquifer which refers specifically to the karst development in the dolomites.
- A deep artificial aquifer that has formed from mine excavations and the stress fractures that are associated with the mine excavations.

In their description of the groundwater conditions in EMPR reports, SRK (1996) describe two aquifers, an upper perched aquifer and a lower weathered aquifer. Although this seems to be a generalisation, there are other references to perched water tables above ferricrete layers, but these are not pervasive.

The fractured aquifers are usually of local importance; however, in this situation they influence mine inflows and can be recharged from slimes dams. They may also in some places impact on the water quality in the dolomites.

The flat topography, along with the extensive karst development also ensures that the recharge percentage of rainfall is high. The absence of surface drainage in some places and disappearance of streams in others, above the dolomites, also show that high recharge occurs.

Below this, faults and joints provide hydraulic conductivity between the weathered karstic dolomites, through otherwise unweathered (almost impervious) formations, to the mine openings. Hydraulic conductivity and storage decrease with depth below the water table; thus if the inflows could be sealed off, no further water would be encountered at depth.

Flows into the mines generally increase with stope advance. Their occurrence is also determined by the number of post-dolomite faults and associated fractures which are intersected by the workings. Inflow rates are determined by the hydrological characteristics of the individual fault zones and the hydrostatic pressure of the water. Wolmerans (1978) showed that the delivery from a single fissure could exceed 250 m³/hour at a mining depth of 1 000 m. Grout curtains have been used around stope areas to limit inflow volumes, but these have short-term benefits as they break down with stope collapse.

The occurrence of "wet" and "dry" mines is another characteristic of the area. Venterspost, West Driefontein and Blyvooruitzicht mines have, historically, had the greatest water influxes on the West Wits Line. Mines such as Doornfontein and Libanon have not experienced water inflow of the same magnitude, yet they are the most intensely faulted mines in the area (Wolmerans, 1978).

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The explanation for this apparent anomaly lies in differences in crustal stress. Fractures in Venterspost and West Driefontein mines are so-called "dirty fissures", gouge-filled faults formed by tensional stresses. Libanon and Doornfontein are characterised by a large number of mylonite-filled faults which show compressional rock stresses with the mylonite forming impervious seals along the fault planes (Wolmerans, 1978). Thus the potential water delivery of a particular fissure is governed by the depth of intersection and the crustal stresses that have caused the fracture, as these determine the nature of the material which fills the fracture plane (Wolmerans, 1976).

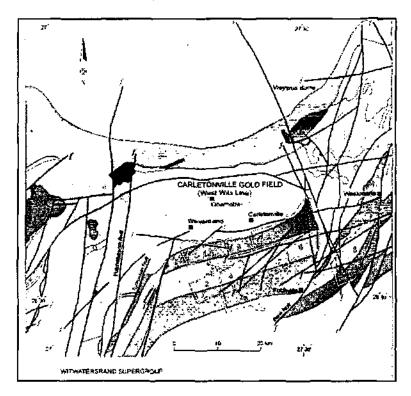


Figure 5-20. Prominent faults on the West Wits Line, after Pretorius (1986). Despite the intensive faulting, shown in Figure 5-20 from Pretorius (1986), there is little evidence from other investigations (Fleisher, 1976 and SRK, 1996) that this faulting has a significant impact on either the flow patterns or the water-level response to pumping. They may, however, provide preferred pathways for the vertical movement of the recharging waters.

Post-mining Impacts

# 5.6 Hydrochemistry

The introduction section showed that there are two areas of concern related to mining; the potential for valuable water resources to be polluted and danger related to sinkhole development. These aspects are interrelated with each other and with hydrochemistry. In this section some theoretical aspects will be dealt with and evidence and interpretation will be given in the next section.

Dolomite related hydrochemistry has been studied in some detail. This area may not be a textbook case because of anthropogenic influence, nevertheless many aspects can be understood when compared with the theory.

The main chemical processes in hydrochemistry are solution/precipitation, leaching, oxidation and reduction reactions and surface processes. These processes are evident in dissolution of the dolomites, leaching and ion exchange in the clayey sediments of Karoo outliers and the Pretoria subgroup producing more saline groundwater. Oxidation of sulphide minerals produce acid-mine drainage with associated high heavy metal concentration. Movement of such water into the dolomite enhances the dissolution process. Classic texts referring to these processes include Stumm and Morgan (1981), Garrels and Christ (1967), Drever (1994) and Lloyd and Heathcote (1985). Models that describe solution/precipitation and surface chemistry processes, assuming equilibrium, have been developed and are described by Parkhurst *et al.* (1995), Plummer (1991) and Loewenthal (1986). These models will be used in the evaluation of some of the water chemistry results.

#### 5.6.1 Dolomite dissolution

Dolomite dissociation is given as:

$$CaMg(CO_3)_2 = Ca^{2+} + Mg^{2+} + 2CO_3^{2-}$$

The solubility product for this reaction in pure water at 25°C is 1.995\( \text{l}10^{-17} \). This very small number shows that, in pure water, dolomite is virtually insoluble.

In de-ionised water, solubility is 14 mg/L but increases with  $CO_2$  hydration, for example, with  $P_{CO_2} = 10^{-3}$  and  $10^{-1}$  bar, solubility is 90 mg/L and 480 mg/L respectively (Roques, 1962, 1964). This is due to the reaction:

$$CaCO_3 \cdot MgCO_3 + 2H_2CO_3^{*2} \Leftrightarrow Ca^{2*} + Mg^{2*} + 4HCO_3^{-1}$$

This indicates the importance of carbon dioxide in natural karst development. CO<sub>2</sub> solubility decreases with increasing temperature as shown in Table 5-7 from Ford and Williams (adapted from Bogli, 1980).

Table 5-7. Equilibrium solubility of CO<sub>2</sub> (mg/L).

		Solubility of CO₂ (mg/L)			
P <sub>CO2</sub>	Temperature	0 <sub>6</sub> C	10ºC	20ºC	30°C
0.003		10.10	7.01	5.21	3.88
0.01		33.6	23.5	17.2	13.1
0.05		168	117	86	65.3
0.10		336	235	172	131

<sup>&</sup>lt;sup>2</sup> This is dissolved CO<sub>2</sub> according to the reaction CO<sub>2</sub> +  $H_2O$  =  $H_2CO_3$ 

Other acids also result in charged metal ions in solution, for example the reaction of dolomite with sulphuric acid:

$$2H_2SO_4 + CaCO_3.MgCO_3 = Ca^{2+} + Mg^{2+} + 2H_2O + 2CO_2 + 2SO_4$$

Thus lowered pH is an important factor in dolomite dissolution.

Solubility also increases with ionic strength, i.e. as the salinity of the water increases, so the solubility of dolomite will increase. This is due to solution non-ideality. In lay terms this means that when there are a number of ions in solution it is possible that some ions may be so surrounded by others that, as far as the solution chemistry is concerned, they do not exist and more of that ion can go into solution.

Thus in natural karst development dolomites' solubility will be controlled by chemical factors along with physical factors such as rainfall and physiography.

Published chemical analyses of dolomite rock are listed in Booysen (1981). These are repeated in Table 5-8 with minor correction to reflect the same species.

Investigator	% CaCO₃	% MgCO₃	% Si <sup>4+</sup>	% (Fe <sub>2</sub> O <sub>3</sub> +Al <sub>2</sub> O <sub>3</sub> +MnO <sub>2</sub> )	Total <sup>3</sup>
Basson	53	43	2	1	100
Toens	27	20	40	10	96
	55	45	8	1	110
Bond	54	45	3	3	104
	54	45	4	3	106
Theoretical stoishiometric ratio	54	46			

Table 5-8. Composition of dolomites (after Booysen, 1981).

The ratios of CaCO<sub>3</sub> to MgCO<sub>3</sub> given in these analyses are what would be expected from dolomite's stoichiometric composition. Silica is a common co-precipitate with dolomite during its formation and often occurs in discrete chert bands in the dolomite. The iron and manganese oxides are present from small amounts of siderite (FeCO<sub>3</sub>), rodochrosite (MnCO<sub>3</sub>) and from ionic substitution in the dolomite lattice. These oxides give the dolomite its deep redbrown weathered colour and are the main constituents of wad. Aluminium reflects the presence of clay minerals that are ubiquitous in many weathering environments. Their source could be colluvial or from phyllosilicates that are ubiquitous in many sedimentary and tectonic environments. These analyses show that on weathering most of the material will go into solution (these samples give an average of 85% or excluding Toens' somewhat spurious analysis 94%).

#### 5.6.2 Acid-mine Drainage

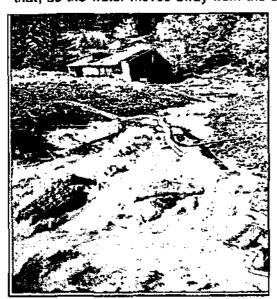
The theory of this process is described in many sources; detailed arguments are given in Stumm and Morgan (1981), so this discussion will be descriptive.

Pyrite (FeS<sub>2</sub>) is an ubiquitous but trace mineral in many rock types. It is concentrated in many types of ore deposit by natural processes, so that it may be the pervasive (but usually useless) mineral in the ore seam. In this context,

<sup>&</sup>lt;sup>3</sup> Ideally a whole rock analysis should add up to 100%.

it is referred to as a gangue mineral as opposed to the valuable minerals in the ore. Its presence and oxidation products have served as an exploration tracer for many ore prospecting techniques. In many instances, that is where its usefulness ends and it is disposed of with the other mineral wastes.

When exposed to the atmosphere and with bacterial catalysis, pyrite reacts with oxygen and water to form sulphuric acid and iron in solution. The result is water with low pH and high dissolved iron. The low pH-water is aggressive so that, as the water moves away from the source of pollution, other minerals go



into solution; this neutralises the acidity but adds dissolved ions to the solution, some of which may be toxic to organisms using the water, e.g. Al and heavy metals. Thus the TDS increases.

Iron which is in solution (as Fe2+) at pH and under reducing low conditions. oxidises under atmospheric conditions to form Fe(OH)<sub>3</sub>. This precipitates as an amorphous sludge which coats the stream bed, killing most organisms Its formation also that it covers. consumes oxygen adding to the COD of an already stressed system. Such a stream is shown in Figure 5-21 from Miller (1996).

Figure 5-21. Fe(OH)<sub>3</sub> (*Yellow boy*) coating the bed of a stream flowing from an abandoned mining area in Canada.

The presence and availability of oxygen is an important factor in all redox processes. In the absence of oxygen, under reducing conditions, sulphate is reduced to sulphide and precipitates as metal sulphides. Thus sulphate can appear to be attenuated compared to more conservative ions such as chloride. Pyrite framboids are common in many sediments, showing that reducing conditions are attained during diagenisis. *Pressed petal-like* marcasite crystals (so-called wood pyrite) are common in joints, bedding planes and slaty cleavage, as evidence of reducing conditions in these rock partings.

#### 5.6.2.1 Sources of AMD

The potential for AMD generation from sand dumps is high as they contain significant pyrite; their coarse grain size allows deep (+10 m) penetration of oxidising conditions and rapid circulation of water. Thus surface and subsurface seepage from sand dumps will be an aggressive, polluting solution.

The potential for AMD from rock dumps is relatively high, since they are coarsegrained and allow free circulation of oxygen and water.

The potential for AMD from slimes dams depends on the age<sup>4</sup> of the dam. Those dams emplaced before 1940 will contain significant fine pyrite which will

<sup>&</sup>lt;sup>4</sup> This is because, subsequent to 1940 and until 1980 there developed an increasing demand for uranium which was found in the *Monarch Reefs* of this area. Part of the Uranium extraction process involves leaching with sulphuric acid. Therefore, during this period there was a high demand for H<sub>2</sub>SO<sub>4</sub>.

have potential to oxidise and so generate acid. Dams emplaced after 1940 and up to approximately 1980 may contain very little pyrite and thus will have little potential to generate acid. Recent slime disposal contains pyrite.

#### 5.6.2.2 Neutralising potential

Buffering agents in the water and rocks counteract acidification. As indicated by Hodgson and Krantz (1995), these buffering agents consist of:

The alkalinity of the water.

Minerals contained within the waste or subsurface.

The buffering pH-levels of the common acid-consuming minerals have been included in Table 5-9.

Table 5-9. Buffer pH-levels for a selection of acid-consuming minerals, after Steffen, Robertson and Kirsten (1989).

Mineral	Composition	Buffer pH
Calcite	CaCO <sub>3</sub>	5.5 - 6.9
Dolomite	CaMg(CO <sub>3</sub> ) <sub>2</sub>	5.3 - 6.8
Siderite	FeCO <sub>3</sub>	5.1 - 6.0
Kaolinite	Al <sub>2</sub> Si <sub>2</sub> O <sub>5</sub> (OH) <sub>4</sub>	3.7 - 4.3
Gibbsite	Al(OH) <sub>3</sub>	3.7 - 4.3
Ferric Hydroxide	Fe(OH) <sub>3</sub>	3.3 - 3.7
Goethite	FeO(OH)	2.1 - 2.2

In the rock types of this area, the principal buffers are dolomite, and to a lesser degree, calcite.

Acid leachate from all dumps located above dolomites is neutralised as it passes through the dolomite. Thus the low pH is rapidly raised, heavy metals precipitate but sulphate calcium and magnesium ions will increase the salinity giving the water a characteristic composition.

#### 5.6.2.3 Radioactive contamination

Since the ores in this mining area contain significant amounts of uranium, mine wastes that were disposed of without uranium recovery will have potential to generate a radiogenic hazard. Uranium is a radioactive metal; it occurs in four oxidation states from +3 to +6. Its compounds, which include solids and salts in solution, depend on the oxidising, reducing and pH-conditions of the environment for their speciation. The relationship of uranium species with these environmental variables is shown in Figure 5-22. Table 5-10 lists the solubility of the various uranyl compounds.

Table 5-10. Uranium compounds found in natural water (After Johnson, 1994).

Compound	Uranium valeпсе	Dissolved state	Remarks
U <sup>3+</sup>	+3	Soluble	Oxidises to U <sup>4+</sup>
UO₂	+4	insolubi <del>e</del>	Uraninite
U <sup>4+</sup>	+4	Soluble	
UOH³⁺	+4	Soluble	
U <sup>5</sup> *	+5	Soluble	Laboratory conditions
UO₂*	+5	Soluble	Laboratory conditions
UO₂(OH)₂H₂O	+6	Insoluble	Schoepite
UO <sub>2</sub> CO <sub>3</sub>	+6	Insoluble	Rutherfordine
UO <sub>2</sub> 2*	+6	Soluble	
UO₂OH*	+6	Soluble	
UO <sub>2</sub> (CO <sub>3</sub> ) <sub>2</sub> 2H <sub>2</sub> O <sup>2</sup>	+6	Soluble	Uranyl dicarbonate
UO <sub>2</sub> (CO <sub>3</sub> ) <sub>3</sub> <sup>4</sup>	+6	Soluble	Uranyl tricarbonate
Oxidation 1.0	i	=	]

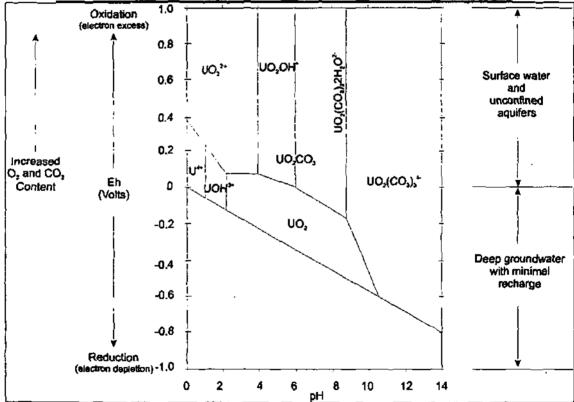


Figure 5-22. Eh - pH diagram for the U -  $O_2$  -  $H_2O$  -  $CO_2$  system at 25° C, 1 atm., and a constant  $CO_2$  partial pressure of  $10^{-3.4}$  atm. (Jennings and Leventhal, 1978).

From this theoretical information, it is evident that associated with natural groundwater, uranium would occur as insoluble uraninite or rutherfordine. At low pH in oxidising conditions, a number of soluble species would exist. At high pH, a urany! (UO<sub>2</sub><sup>2+</sup>) di- and tri-carbonate are the dominant complex ion forms. Generally, U<sup>6+</sup> bearing ionic forms are soluble and therefore mobile, while U<sup>4+</sup> are immobile. Stewart *et al.* (1976) show that, apart from pH and redox, SO<sub>4</sub><sup>2-</sup> and HCO<sub>3</sub> availability also increases the mobility of uranium.

The danger associated with uranium is due to its radioactivity in the form of I, I and I emissions that may be derived from any of the isotopes of uranium or daughter products in the uranium decay series. Thus pathways connecting uranium or its daughter products to unprotected animal or human tissue are of great concern. For example, if dissolved in groundwater after ingestion the radioactive material will be in intimate contact with sensitive tissue. Radon, a gas and one of the uranium decay series products, may be inhaled and via this pathway has intimate contact with animal tissues. Since radon dispersion occurs in the unsaturated zone and the atmosphere, its study is not part of this investigation.

Uranium, when compared with other major dissolved ions such as Cl, NO<sub>3</sub>, SO<sub>4</sub> and F, is retarded by clay minerals (Racon, 1973.). Uranium has a distribution coefficient of 39 ml/g on clays and around 7m ml/g on carbonate minerals. Soil development and the existence of clay minerals are very limited in dolomites due to their solution weathering, thus the predominant aquifer in this area will have little protection from natural retarding processes.

# 5.6.3 Water pollution sources

The possible pollution sources include industrial and mining sources. This report focuses on the mine waste sources. The positions of the mines and their waste sites are shown in Figure 5-23. More details, including shafts and water sampling positions, are shown in the maps in Appendix 1.

Other investigators (Krige, 1989) have indicated that there are many point pollution sources in the upper portion of the catchment. These sources include mine waste disposal sites such as tailings dams and waste rock dumps and once-off dumping of waste. The investigators used the example of "Klein Kariba" where the waste disposal sites were generating significant quantities of salt, which migrated via a dug canal into the Wonderfontein Spruit. Quantifying the salt loads from these sources has not been possible, so collectively these point pollution sources are a diffuse source of pollution. The difference being that point sources can usually be stopped or removed while diffuse sources must be managed. This means remediation and introduction of measures to lessen or control pollution, or learning to live with the result.

Mine waste disposal has three forms:

1. Sand heaps. These are only associated with the older mines and are therefore predominantly found associated with mines in the northern part of the West Rand group of mines. Jackson (1961) shows that they were deposited predominantly pre-1922, before the sliming process was introduced. Although after this time, some of the older plants continued to produce sand and in 1961, when Douglas et al. (1961) described gold recovery processes, they state that there were still three plants producing sand. Because these dumps relate to the early period of mining when less sophisticated metallurgical techniques were used and higher-grade ores were mined, they often contain significant residual gold values. Many are therefore targeted for reworking and are thereby removed. Their environmental influence is therefore only significant in the short term.

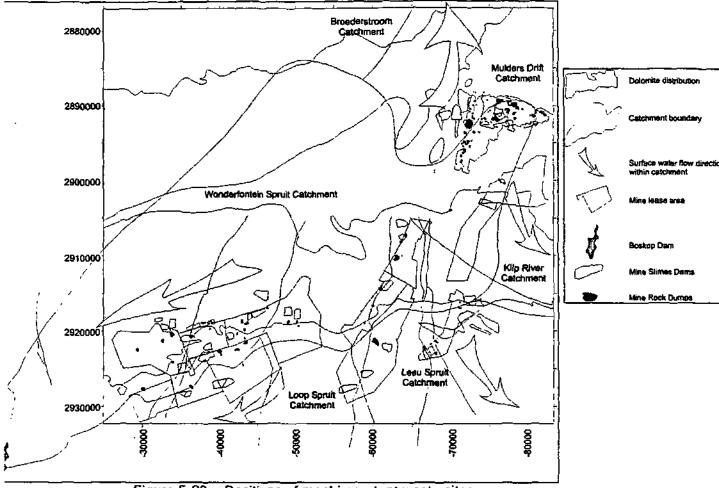


Figure 5-23. Positions of most important waste sites.

2. Rock dumps. Off-reef development such as shafts and underground access routes generate coarse rock waste. Such waste is accumulated in a dump at each shaft. In spite of there being no ore in these wastes, the rocks do contain a certain proportion (usually well below 1%) of pyrite. It is exposed to the atmosphere in the rock dump and will oxidise, thus generating small amounts of acid. Some suitably sited (close to demand and road transport) rock dumps have been used as a source of aggregate for road metal and other building applications.

At some rock dumps, as the area is considered to be spoilt, other waste disposal takes place. This is uncontrolled and a range of waste types, such as domestic and industrial waste, may be deposited at such sites.

Slimes dams. These are associated with all the metallurgical plants that have recovered metals in this area. Since the fine metallurgical residues are disposed of wet (hence the term slime), the dams have potential to generate significant seepage to underlying formations.

The slime is confined in a dam where water evaporates, is siphoned off, or seeps away. If the supporting walls or the daily disposal is not dried sufficiently the dam may become unstable and slump. Such occurrences have happened with disastrous effects, thus it is important to reduce the moisture as efficiently as possible. The dolomites form natural underdrains

and many of the slimes dams in this area have been purposely constructed so that seepage into the dolomites will enhance their drying, thereby reducing the area necessary for evaporation and increasing the stability of the dam.

Newer dams are constructed with design for environmental protection. This includes underdrains for leachate collection and toe drainage dams to collect lateral seepage. Collected seepage may be treated by evaporation at the collection points, downstream from the collection points in evaporation paddies or may be pumped back onto the slime dam. At some sites the collected water is used in the metallurgical recovery process, thus the water is used and disposed of in a partly closed system, losses being pure water evaporated to the atmosphere and the concentrated leachate to the subsurface or collection system.

## 5.7 Observations in the investigation area

In the area being investigated, the quality of surface water, groundwater and water in the mines is of interest. The Department of Water Affairs surface water monitoring data and groundwater data from the National Groundwater Database, as well as information from the mines, were used for the evaluation of water quality. Of the non-government sponsored monitoring, the sewerage works monitor effluents. The mines attempt to monitor but the industries have no data.

Sample sites cover the Wonderfontein Spruit, its tributaries and water impoundments in the West Wits Line area, the Mooi River above the confluence with the Wonderfontein Spruit and below to the Boskop Dam. Monitoring positions are shown in the figures in Appendix 1.

## 5.7.1 Surface water chemistry

### 5.7.1.1 Upper Wonderfontein Spruit (West Rand)

Mining, industries and other potential pollution contributors in the West Rand area have influenced surface water entering the West Wits Line area. Water quality is traced through the area in Figure 5-24. This shows that the water entering the area has already been degraded.

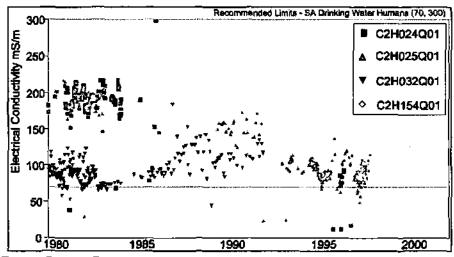


Figure 5-24. EC along Wonderfontein Spruit.

In the upper Wonderfontein Spruit, Krige (1998) has identified 13 possible sources of contamination. These include:

- Storm-water from mining, domestic and industrial areas.
- Leachate from old slimes dams and dumps.
- Leachate from domestic waste.
- Treated sewerage water, which improves the quality through dilution (the flip human sewerage works releases ~ 24 ML/d of treated effluent).
- Mine water.
- · Process water.
- Agricultural run-off.

The water quality series for the Vaal Barrage and Gold Mining published by the Department of Water Affairs and Forestry (1995) gives monitored values for water quality and flow. The only measured flow was done in the 1 000 mm pipeline; the others are estimates.

Based on this and more recent monitoring, Krige (1998) quantified salt loads for the upper parts of the catchment. He used the sulphate to TDS ratios to obtain a measure of the origin of the pollution. He found pollutants upstream of the Flip Human sewerage works were predominantly of mining origin, while lower down other factors predominate. An important finding was a decrease in flow rate in the area where the stream crosses the Witpoortjie Fault. This suggests the possibility of significant ingress into the underlying aquifer via the fault, thus allowing poor quality water to enter the aquifer.

The summarised salt loads from the upper Wonderfontein Spruit where the Donaldson Dam discharges into the 1000 mm pipeline are given in Table 5-11. The average flow for this pipeline is given as 16 400 m<sup>3</sup>/d

Table 5-11. Water quality and loads from the West Rand mining area (after Krige, 1998).

Parameter	Average from 4/95 to 8/97 mg/L	Salt load kg/d		
pH	7.92	<u> </u>		
Electrical Conductivity	96			
TDS	655	10742		
Orthophosphate as PO <sub>4</sub>	0.46	8		
COD	37			
NH <sub>3</sub>	0.65	11		
Na	92	1519		
Cr	0.12	2		
Cu	0.06	1		
Mn	0.21	3		
Zn	0.09	1		
Pb	0.17	3		
Cd	0.03	0.5		
SO₄	229	3771		
U (as μg/L)	23	0.37		

Thus a daily salt load of 10.7 tons is transported from the upper Wonderfontein Spruit catchment into the West Wits Line area. Should the Randfontein Estates

Mine start decanting (see Section 5-9), this will add an additional 33000 m<sup>3</sup>/day to push up the total salt load to 139 tons a day. As a result of this, approximately 50 000 m<sup>3</sup>/d will have to enter the 1 000 mm pipeline and a salt load of 139 t/d will be transferred to the water users in the lower catchment.

Compared to the mine influenced water in the upper catchment, the dolomitic waters in the same catchment are fresh. The classification plot (Figure 5-25) shows that most of these waters plot in a region associated with dolomitic waters. Those samples plotting with different classification have very low dissolved solids (usually below 60 mg/L). Classification is difficult for such water as even rounding errors can affect the interpretation.

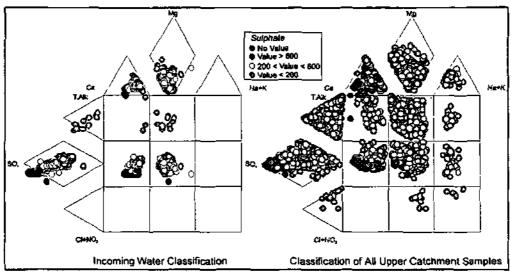


Figure 5-25. Expanded Durov for upper catchment.

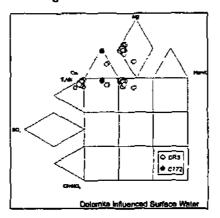
## 5.7.1.2 Lower Wonderfontein Spruit and Mooi River (West Wits Line)

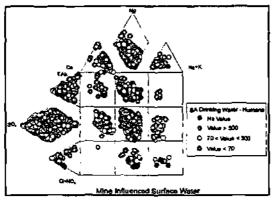
#### Water Classification

Hydrochemical plots were used to classify different types of waters and ascertain the influences on the water quality. Lloyd and Heathcote (1985) describe groundwater classification techniques using Piper and expanded Durov diagrams. In this report, the techniques have been used for surface water classification. This form of classification assumes that groundwater reacts in natural environments due to normal chemical processes. Their use for surface water may not be entirely appropriate but they are used, so that a comparison can be made with similar plots for groundwater. The intimate association of groundwater and surface water in karstic areas is also some justification.

The classification plots are shown in Figure 5-26. The majority of samples plot either in a field with HCO<sub>3</sub>\*, Mg<sup>2</sup>\* and Ca<sup>2</sup>\* dominant, described as typical of dolomitic waters by Lloyd and Heathcote (1985), or in a field with no dominant cations or anions. The higher SO<sub>4</sub><sup>2</sup> of some samples is probably due to exposure to sulphate or sulphide minerals. These are typically mining related. Some samples plot outside these fields. Those with high sodium are possibly influenced by the Karoo or Pretoria sediments or by industrial sources.

Water samples derived from dolomitic association do plot in the expected areas with the mining influenced samples exhibiting a higher sulphate. Natural hydraulic mixing processes give rise to water with a mixed character.





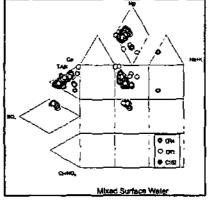


Figure 5-26. Durov classification of surface water.

The classification thus yields three groups that are referred to as: dolomitic water, mine water or mixed. The classification was checked against the sample positions and relationships with geology and pollution sources.

#### Measured Values

Average values for these three groups are listed in Tables 5-12 to 5-14<sup>5</sup>.

The mine waters have higher dissolved salt concentrations and are also more variable than surface waters that have not been influenced by mine water.

Table 5-12: Dolomitic surface waters.

	Са	Mg	рΗ	CI	Na	SO₄	NO <sub>3</sub> N	HCO <sub>3</sub>	EC
	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mS/m
Max	54	36	10	60	69	96	9	310	69
Min	5	2	5	2	1	1	0	15	7
Mean	24	13	8	14	11	19	1	116	28
Median	21	11	8	13	9	16	1	101	26
Stddev	11	7	1	8	_ 7	13	1	62	10

<sup>&</sup>lt;sup>5</sup> <u>Caution</u>. Average values can be misleading as, without flow measurements, they give no indication of the pollution load.

Table 5-13. Mine related surface waters.

	Ca	Mg	рН	Ci	Na	SO <sub>4</sub>	NO <sub>3</sub> -N	HCO₃	EC
	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mS/m
Max	420	146	11	1343	735	1383	77	522	497
Min	9	3	3	1	1	13	0	1	11
Mean	100	42	8	78	90	391	6	112	117
Median	93	39	8	53	74	349	4	109	105
Stddev	43	11	1	82	54	196	6	60	48

Table 5-14. Mixed surface waters.

	Ca	Mg	pН	Cl	Na	SO <sub>4</sub>	NO <sub>3</sub> -N	HCO₃	EC
	mg/L	mg/L		mg/L	mg/L	mg/L	mg/L	mg/L	mS/m
Max	81	51	9.1	46	40	159	4.6	330	87
Mín	6	2	5.4	2	1	2	0.0	33	8
Mean	47	41	8.2	21	19	101	0.3	225	61
Median	47	42	8.3	21	19	101	0.2	226	61
Stddev	10	5	0.4	6	5	28	0.3	31	8

These statistics and the plot of the values given in Figure 5-27 illustrate the hazard associated with these types of waters.

The maximum values for all the parameters in the non-mine related waters are within the water quality standards set by the Department of Water Affairs and Forestry (1997). The mine waters often exceed the standards; even the mean sulphate value is above the maximum permissible value for domestic use.

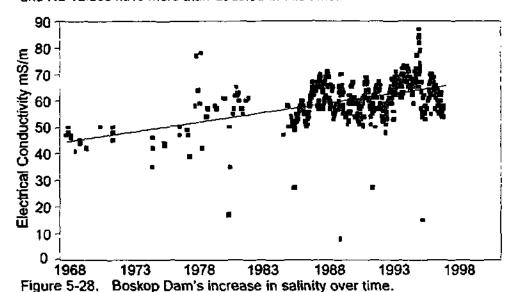
Table 5-15 compares the relative distribution values and indicates the influence of mining on the water quality.

Table 5-15. Percentile composition of different waters.

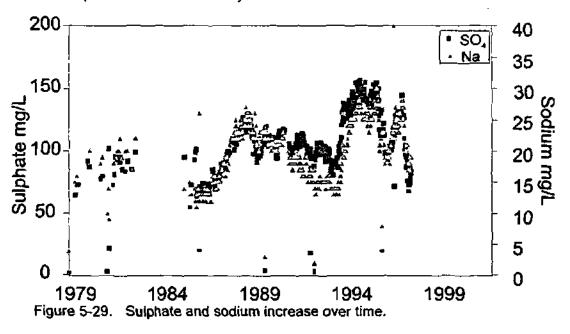
	Dolomitic		Mixed		Mine	
	95%	50%	95%	50%	95%	50%
EC (mS/m)	45	1	68	1	147	95
SO₄ (mg/L)	12	4	145	101	512	289
CI (mg/L)	2	3	29	21	96	43
Na (mg/L)	6	3	27	19	116	60

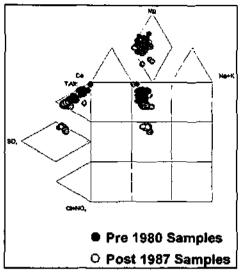
#### 5.7.1.3 Receiving Water Body

The Boskop Dam in the Mooi River is the receiving water body for most of the mining influenced water that drains from the area. It also receives water from the upper Mooi River, a catchment unaffected by mining. The water from this catchment is fresh and dilutes the mine pollution influence in the dam. Despite this the salinity concentrations have increased over the last 30 years as shown by electrical conductivity, sulphate and sodium in Figures 5-28 and 5-29. SO<sub>4</sub>-and Na-values have more than doubled in this time.



The Expanded Durov plot of Figure 5-30 also indicates the change in the overall composition of the water. Prior to 1980, the water plotted in a position typical of waters of dolomitic association. Recent samples show a change toward waters with high sulphate content; a classification for waters which are contaminated by acid rock drainage. The influence of the mining industry on the composition of this water body is thus evident.





Bredenkamp (1993) and Fleisher (1981) have indicated that the Wonderfontein Spruit which is the most important surface water conduit for the mine effluents and mining related surface waters, disappears and reappears, in a manner common of streams in karst topography. Thus this stream must also have a significant influence on the dolomitic aquifer.

A mixing model using PHREEQC (Parkhurst 1995) and STASOFT (Loewenthal *et al*, 1986) suggest that 70% of the water is derived from dolomitic sources, with the rest from mining. Accurate discharge figures are needed to confirm this.

Figure 5-30. Expanded Durov plot for Boskop Dam.

The acid/neutralising capability (ANC) of the dam was calculated using the method given by Jefferies *et al.* (1986), as reported by Thomas, Meybeck and Beim. The relationship to calculate ANC is:

ANC =  $\Sigma(Ca,Mg,Na,K)$  equivalents -  $\Sigma(SO_4,NO_3,Cl)$  equivalents

By applying this approach, the acid neutralising capacity of the Boskop Dam was found to vary between 2.9 and 5.5 equivalents with a slight decrease over time. It is thus unlikely that the dam will become acid.

# 5.7.2 Groundwater chemistry

#### 5.7.2.1 Previous work

Fleisher's (1981) thesis on the Malmani Dolomites deals with origins of groundwater and trends in quality. Pertinent points from his work relating to each compartment are:

#### Gemsbokfontein:

- Significant percolation of water from Donaldson Dam into groundwater
- A large proportion of water is recirculated; this influences water quality.
   Therefore, a serious threat of contamination can be expected.
- Flow occurs from Gemsbokfontein compartment into Venterspost Compartment.
- Possible flow of groundwater from Zuurbekom Compartment around the eye.

#### Venterspost:

- Donaldson Dam influenced the water quality up to 1977.
- Steady state conditions could have developed by 1978.
- Significant inflow from Zuurbekom and Gemsbokfontein compartments influences the hydrochemistry.
- Water quality ranges from contaminated (SO<sub>4</sub> >300 mg/L) to mixed dolomitic (SO<sub>4</sub> <70 mg/L).</li>

#### Turffontein:

Water quality is influenced by surface effluents, acid mine drainage and waste disposal.

Three water sources have been identified:

Effluent. Composition can range between

Ca≈Mg>Na with HCO₃/SO₄ high to SO₄ high,

- · Groundwater. Three types:
  - a) TDS <300mg/L, HCO<sub>3</sub> up to 150 mg/L. Found at upstream boundary of aquifer
  - b) TDS 300-500 mg/L, HCO<sub>3</sub> 150-350mg/L
  - c) TDS> 500mg/L, HCO<sub>3</sub> >350 mg/L

#### Mixed

- A number of influences are affecting the water quality in different compartments.
- Springs are mixed and contaminated waters.
- The 1000 mm diameter pipeline limits the influence from surface waters.
- The spatial distribution of groundwater quality based on interpretation of water monitoring results is given in Figure 5-32.

### 5.7.2.2 Pollution from waste disposal.

The range of pH-values recorded at monitoring points in this aquifer is plotted in Figure 5-31. The pH of these waters plots in a range between 6 and 8, but there are a number of points where the pH is higher or lower, some of which are within a range where uranium mobility can be expected.

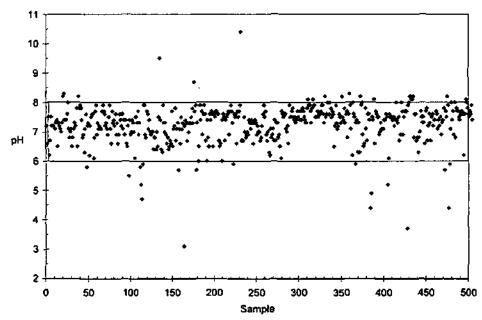


Figure 5-31. pH-values recorded in the National GW Data Base for the West Rand Area.

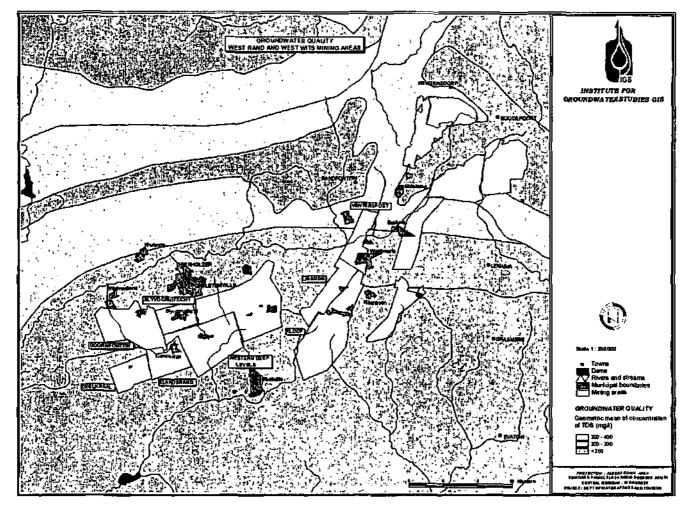


Figure 5-32. Spatial Distribution of groundwater composition.

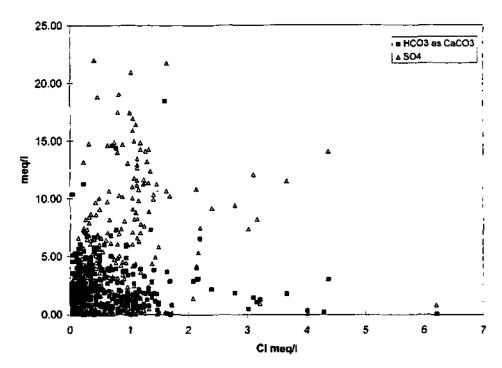


Figure 5-33. Bicarbonate and sulphate values recorded in the National GW Data Base for the West Rand Area.

Figure 5-33 shows relationships of bicarbonate and sulphate, assuming that chloride is a conservative species. The plot shows that these species are freely available and antipathetic, i.e. the increase in one is accompanied by a decrease in the other.

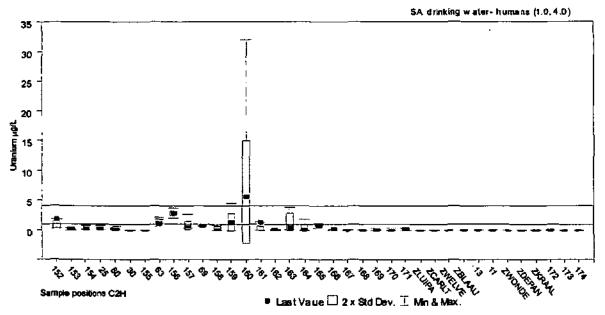
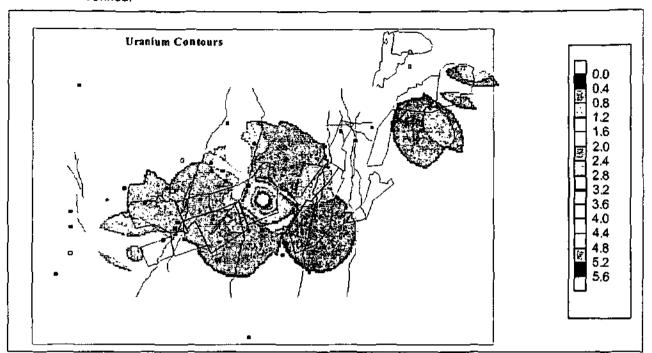


Figure 5-34. Uranium concentrations in groundwater.

Figure 5-34 shows that the current guidelines for dissolved uranium, as defined by the DWA&F for domestic use, are exceeded. Figure 5-35 shows the



possible spatial distribution of uranium in solution. The values have not been verified

Figure 5-35. Dissolved uranium contours in groundwater.

Domestic and industrial wastes are also disposed of in this area. Many of these waste sites are located on old mine property; the motivation presumably being that these already spoilt areas would not be degraded much more by further waste disposal. It is difficult to properly control such unofficial waste disposal sites and clandestine dumping of toxic, often liquid, wastes takes place.

Leachate generated within the municipal waste sites has rapid, often direct, access to the subsurface because of:

- Topsoil removal.
- Outcrop mining and exploration trenches.
- Open pit mining; the pits are later licensed as waste disposal sites.

There is little evidence from the data set that contaminants derived from municipal waste disposal are affecting groundwater quality at the regional scale of this study. More specific monitoring data would be required to show this. Although Figure 5-36 shows that many samples have nitrogen levels above recommended and maximum limits, apart from domestic wastes, there are other sources of nitrogen; for example, fertiliser application or commercial explosives as used in the mines. Most of the data points suggest that nitrogen and chloride sources are independent of each other.

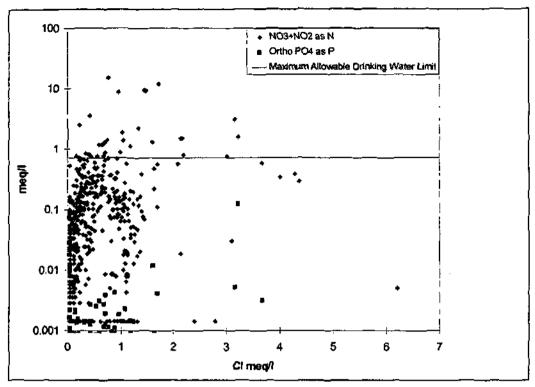


Figure 5-36. Nitrate and phosphate values against chloride (from NGWDB).

### 5.7.2.3 Classification of West Wits Line groundwater

To classify these waters, their chemical analyses were plotted on Expanded Durov plots. The result shows two hydrochemical groupings that are interpreted as two water types. The first type is calcium-magnesium-bicarbonate water that is typical of water derived from dolomitic aquifers. The second water type has sulphate as the dominant anion. It is possible that this is related to mining activity. A check on the sample positions showed that these samples are usually located close to mining operations and mine waste disposal sites. Samples taken in auger holes near slimes dams by GFSA indicated depressed pH-values with elevated sulphates occurring, while Pulles et al. report seepage from below a waste rock dump at Deelkraal as having a pH of 3.5 and conductivity of 990 mS/m. Run-off from Kloof #1 tailings dam shows sulphate values up to 2638 mg/l and pH-values as low as 3.3.

The NGWDB samples show a range of compositions from pure dolomitic waters to waters with a sodium-chloride composition. The sodium could be derived by natural hydrochemical evolution, (Chebotarev, 1955), which includes dissolution and ion exchange along a flowpath. Ion exchange, taken to its conclusion, results in enrichment of sodium relative to calcium and magnesium. For the sodium-potassium-bicarbonate waters, the shale horizons in the Pretoria sequence can often provide sites for such cation exchange. Some of the sulphate dominated water may have been influenced by mining. An additional factor to bear in mind is the fact that no uniform sampling method has been used across the area. Factors such as pH-change due to degassing of CO<sub>2</sub>, as has been observed in the area, can therefore not be quantified.

The sampling positions are shown on Figure 5-37.

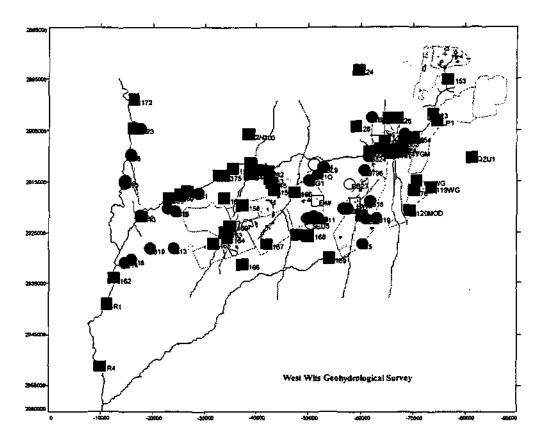


Figure 5-37. Sites used for interpretation.

in each diagram, some samples plot in positions interpreted as being the result of mixing or sulphate enrichment. Older samples or samples unaffected by mining are typically dolomitic in classification. Comparison with the surface water plots reinforces the hydrogeologic evidence of the close relationship between surface and groundwater. These plots are shown in Figure 5-38.

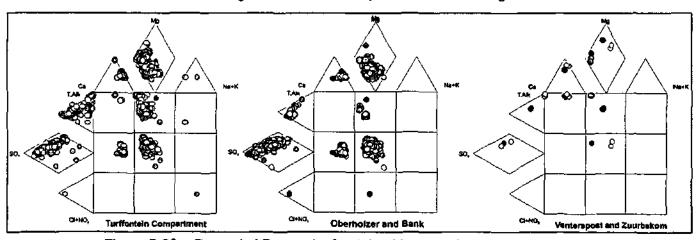


Figure 5-38. Expanded Durov plot for dolomitic groundwater compartments.

### 5.7.2.4 Mine Water Quality

A list of recent mine water quality is given in Table 5-16.

Table 5-16. Fissure water compositions.

Site id number		C2H155Q01	C2H158Q01	C2H159Q0	C2H160Q01
Description		West Driefontein	Blyvooruizicht	Doornfontein	Doornfontein
	ı	Downstream of North shaft	Fissure discharge pipe	Excess fissure pipe	#3
Date		1997-06-25	1997-06-25	1997-06-2	1997-06-25
рН		8.2	7.5	7.9	6.8
Electrical conductivity	(mS/m)	61	118	171	524
Total alkalinity	(mg/L)	191	94	74	49
Calcium	(mg/L)	54	87	112	478
Magnesium	(mg/L)	39	49	57	179
Sodium	(mg/L)	24	95	163	664
Sulphate	(mg/L)	109	381	516	1932
Chloride	(mg/L)	27	63	169	817
Nitrate as nitrogen	(mg/L)	0.9	4.1	0.8	22.9
Ammonia as nitrogen	(mg/L)	0.01	0.43	1.27	0.24
Bicarbonate	(mg/L)	229	114	89	60
Calcium hardness	(mg/L)	135	217	280	1194
Fluoride	(mg/L)	0.2	0.2	0.3	0.6
Potassium	(mg/L)	1.7	10.2	4.8	16.6
Silicon	(mg/L)	7	7.3	6.5	19.3
Total diss. solids (EC*7)	(mg/L)	427	826	1197	3668
Total diss. solids (sum)	(mg/L)	457	805	1106	4256

Equilibrium modelling of water in dolomite

Fleisher (1976) indicated that for the Zuurbekom compartment up to 4% of the annual recharge was derived from mining effluents. He also noted that other sources could contribute to the contamination. In contrast, Parsons (1997) suggests that the mines are bounded off to prevent contamination of the entire compartment, especially toward the pumping station in the south-west. Fleisher also estimated that between 25% and 33% of all outflows from Gerhardminnebron springs were derived from mining effluents from the West Wits Line. The result is that sulphate and overall satinities have shown a steady increase over time. Results from underground monitoring by GFSA indicate that the average conductivity of the underground water at Venterpost has increased by almost 70% from 1967 to 1996. Pulles *et al.* (1996) report that at Deekraal AMD waters with pH-values at 2.9 and Conductivity of 530mS/m were found underground in the mines, and at REGM, a sample was found with a pH of 2.1.

The method used by Scott (1995) on the East Rand was followed to estimate expected worst quality waters. The fissure water from Doornfontein's No. 3 Shaft was used as the worst expected water. The scenarios used were:

The rising water was assumed to equilibrate under cavernous conditions in the dolomite or mine aquifers. It was thus saturated with oxygen and all oversaturated minerals were removed by precipitation.

The water was allowed to react with dolomite to equilibrium, oversaturation was again removed by precipitation. The chemical modelling program, PHREEQC

(Parkhurst, 1996) which is based on the equilibrium theory of chemical reactions, was used for the simulations (Table 5-17).

Table	5-17	Modelled	final water	qualities.
1 4010	J- 1 .	14100001100	mich Waler	UUUMIICA.

	Fissure Water	Recharged	Equilibrated
Ca	478	475	475
Mg	17 <del>9</del>	141	178
SO <sub>4</sub>	1932	1775	1780
K	16	109	12
AI	0.3	0	0
Fe	0.2	24	0
CI	817	813	752
Mn	1.6	1.5	1.5
рΗ	6.8	5.9	6.5
ρE	6.8	-0.4	11

The model predicts that the final water chemistry will not be overly acidic due to reaction with the dolomites and other carbonate species. The model assumes that oxygen will not be replenished when iron precipitates, thus the recharging water will be reducing (negative pE) - this will limit pyrite oxidation. The 'recharged' water will have a lower pH, with associated higher metal content. The water in the mine will probably be somewhere between the recharged and equilibrated extremes.

This modelling is an oversimplification of the true conditions and gives an expected order. As many of the reactions are quite slow and may never reach equilibrium, kinetic modelling should be used. Due to data limitations and cost requirements, it is beyond the scope of this report.

To investigate the processes occurring in the "enrichment" or deterioration of the water the programs NETPATH (Plummer et al.) and inverse modelling in the PHREEQC program (Parkurst, 1995) were used. The endpoint waters required for this modelling were: the worst water quality (Deelkraal 3 shaft) and an unpolluted, typically dolomitic sample. Using these values, the change from dolomitic water type to contaminated water was modelled with the most likely participating phases included in the calculations. Several iterations were run using the different variations, but the best-modelled "inverse reaction" to describe the degradation showed that the most important reacting minerals are ferric hydroxide, dolomite, pyrite and oxygen.

# 5.7.3 Discussion

The most important conclusions relating to the concerns about water contamination in post mining times are:

- The surface water entering the West Wits Line Area is, in many cases, contaminated before entering the area.
- Water polluted by leachate from mine dumps, so-called acid-mine drainage shows characteristically high sulphate concentration. This will form the greatest threat to groundwater quality after closure. The processes and consequences of acid-mine drainage from the dumps have been discussed by researchers such as Scott (1995), Jones et al., (1988) and Kempe, (1983).
- This polluted water also has high dissolved salts.

- Surface and groundwater show the same classification thus confirming
  what the hydrogeology suggests, i.e. that the waters are intimately
  related. This relationship and high recharge of groundwater from
  surface streams are relatively unique in this area and are due to the
  karst topography.
- Due to significant losses from the Wonderfontein Spruit to the dolomite aquifer, the poor quality surface waters is impacting on the aquifer.
- The Boskop Dam, the receiving water body for the Wonderfontein Spruit, shows deteriorating quality. Salinity and sulphate most distinctly show the increases.
- In spite of dilution from the upper Mooi River and seasonal fluctuations, there is a continuing upward salinity trend in the dam.
- Conditions exist for uranium to be transported in solution in these waters. These are low or high pH, high dissolved concentrations of sulphate or carbonate.
- Thus it is possible that radiogenic material may be migrating, dissolved in groundwater, to be consumed at some other point where radioactive contamination may not be expected.
- Limited monitoring confirms these suspicions, thus continued monitoring and technique development are encouraged.
- Pollution is occurring while mining is in progress, in spite of environmental concern. When the responsible authorities (owners or mining companies) are removed, it will continue or get worse.
- Present attempts at prevention may stop or fall into disrepair after closure. For example erosion of mining wastes could contaminate water.
- The most important conclusions relating to the concerns about dolomite dissolution and instability in post-mining times are:
- The mines' influence on surface water is to increase all total dissolved solids, as shown by the EC-values. Sulphate is increased from the acid water, chloride and sodium through dissolution, and other constituents for example calcium and magnesium are characteristic because of the dissolution of dolomite. Thus the chemistry shows that water is dissolving dolomite.
- Increased satinity will increase the waters ability to dissolve dolomite.
- Lowered pH of acid-mine drainage will also dissolve dolomite.
- Initially oxidising conditions will exist in the mine openings, the initial water will be of poor quality. The system will be dynamic preventing stratification. If this water recharges the dolomites significant dissolution of the dolomite could occur. If the water quality was that of the Blyvooruitzicht fissure and the rewatering rate was 60ML/day (an average between the dynamic records and the original eye flow) more than 6000 m³ dolomite/year will dissolve. This will have two major implications;
  - 1) Significant widening of preferred pathways causing greater overall transmissivity in the dolomites and greater storage volumes.
  - 2) Possible stability problems should excessive karstification result.

## 5.8 Dewatering

# 5.8.1 Implications of dewatering on the dolomite compartments

The term dewatering tends to create a concept of completely dry mines or aquifers. This is not the case as dewatering is a state where the inflow to the mine is reduced by removing water that is in storage in the dolomites. When the compartment is dewatered the mine still experiences a continuous inflow, often very significant, with inflow rate equal to the recharge rate.

Dewatering is achieved when Pumping rate = Recharge rate

Thus even when a compartment is dewatered, substantial volumes of water must be pumped from the mines.

For example: In the Oberholzer compartment, dewatering began in September 1955 and was accomplished in April 1973. During this period maximum pumping rates reached 170 ML/day while the steady state pumping, after dewatering, is 50 ML/day. The advantage of dewatering is that under steady state conditions the water inflow to the mines is controlled and predictable. Sudden catastrophic inflows are not likely to happen.

Bredenkamp (1993), shows that the Gemsbokfontein compartment has been dewatered by WAGM since 1986, while in the Bekkersdal compartment north of the Gemsbokfontein compartment and separated by the Panvlakte dyke, water levels are apparently unaffected. The eastern Gemsbokfontein compartment leaks through the Magazine dyke, to prevent drawdown from occurring to a level where sinkholes may develop. This compartment is artificially recharged with dewatered water. The Zuurbekom compartment is affected by dewatering.

Bredenkamp's (1993) study confirms leakage from Gemsbokfontein east Compartment and suggests that a substantial amount of recirculation is taking place. The recharge is estimated to be 24% of the average rainfall of the preceding 12 months. Water levels in the Gemsbokfontein West Compartment are declining at 0.375 m/month.

## 5.8.2 Pumping rates and water levels

The available data on pumping rates has been recorded in a database allowing digital evaluation of the data. Despite gaps in the data, as some mines kept more complete records than others, the flooding of West Driefontein in 1968 is evident, and the stabilisation in pumping can be seen in Figure 5-39, for the mines when dewatering was achieved.

The mine dewatering pumping is equivalent to a large scale pumping test, the evaluation of which could yield crucial information about the aquifer parameters including hydraulic conductivity and storage characteristics. The response of water levels or pumping rate to rainfall also gives indications of the recharge characteristics. The results of such evaluation are important for making predictions about future water levels, rates of water rise and when considering management options for the system. Unfortunately not all the mines have kept suitable records and indirect techniques have to be used.

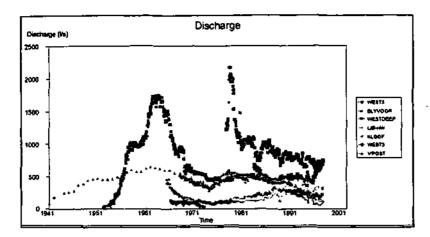


Figure 5-39. Dewatering rates at different mines over time.

Comparison between pumping rate and rainfall is an indirect indication of the water-level response to rainfall and shows the type of recharge that may be happening. Evaluation of the data in this way gave no clear relationships, although other investigators show a lag time of between two and four months on the West Rand mines, and six months in the Bank compartment (Fleisher 1981 and Krantz 1997). These investigators suggest that the lag time show two methods of recharge.

- 1. Immediate recharge happens when the mines have direct connection to the surface.
- 2. Delayed recharge happens when water is derived via recharge of aquifers and from these, flow to mine workings via fractures.

The mining companies, particularly GFSA, have monitored groundwater levels. Monitoring sites include: shafts, monitoring bores adjacent to shafts and monitoring and production bores in other parts of the catchment. The main influence is a steep drawdown near the pumping shafts and minor variation in regional water levels.

Figures 5-40 - 5-50 show the comparison between pumpage, rainfall and water levels at different monitoring points, over time. Figures 5-49 - 5-50 show the variations in estimated water level at different periods.

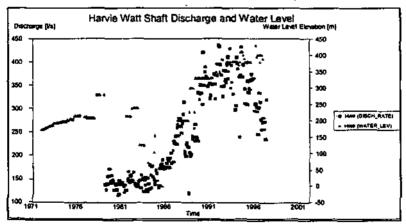


Figure 5-40. Time Series Plot of Pumping Rate and Water Elevations at Harvie Watt Shaft.

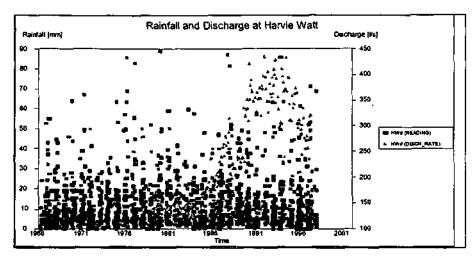


Figure 5-41. Time series plot of pumping rate and rainfall at Harvie Watt Shaft.

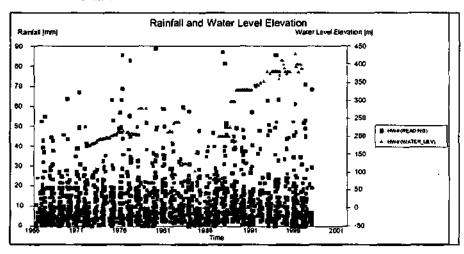


Figure 5-42. Comparison between rainfall and water level.

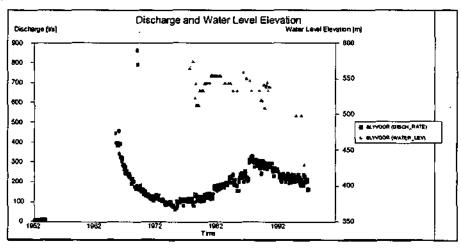


Figure 5-43. Time series plot of pumping rate and water elevations at Blyvooruitzig Mine.

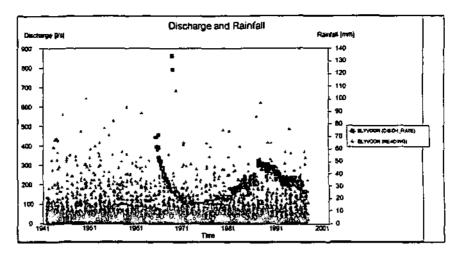


Figure 5-44. Time series plot of pumping rate and rainfall at Blyvooruitzicht Mine.

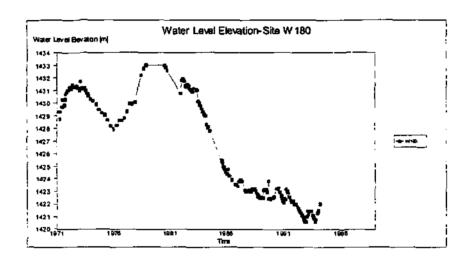


Figure 5-45. Decrease in water level over time at W180.

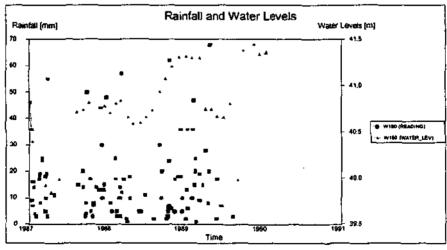


Figure 5-46. Rainfall and water levels at Site W180.

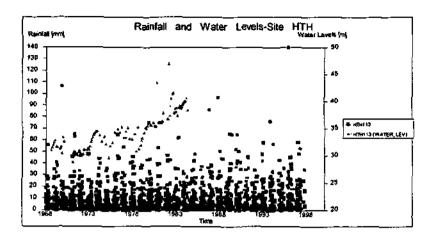


Figure 5-47. Rainfall and water levels at site HTH 113.

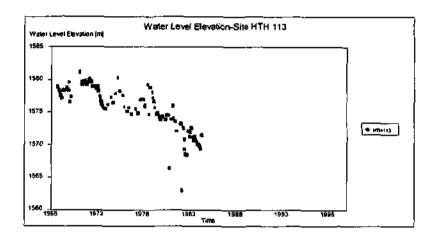


Figure 5-48. Decline in water-level elevation over time.

From these evaluations, no correlation can be drawn between specific rainfall events and changes in abstraction. The decrease in water-level elevations is very clear.

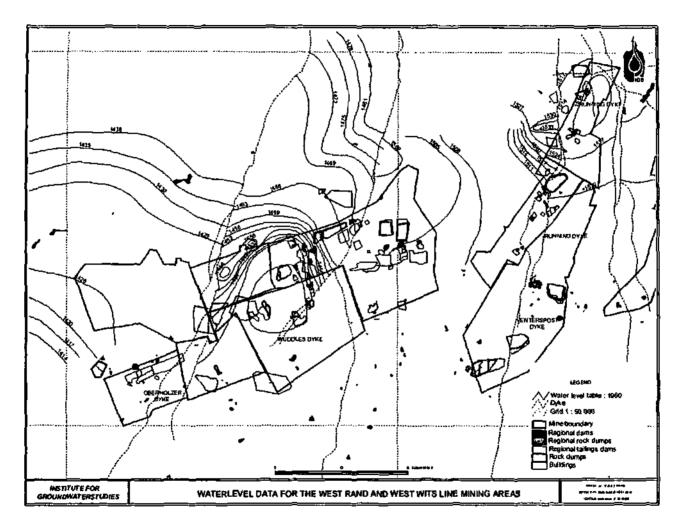


Figure 5-49. Premining groundwater elevations in the West Wits Line Area.

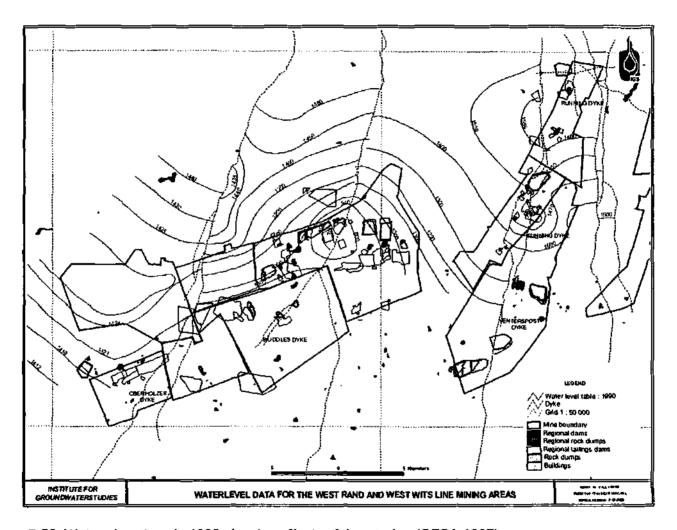


Figure 5-50. Water elevations in 1990 showing effects of dewatering (GFSA,1997).

The water elevation plots are interpretations of measured data by GFSA (1997) and show the effect that dewatering at East Driefontein has had on the regional water table. Figures 5-49 and 5-50 give estimated water levels for different time periods throughout the area.

Dewatering data from Bank compartments for the years 1994 -1997 gives a pumpage percentage of rainfall from 26 - 36%. This is higher than the recharge estimation and suggests that some of the water in the compartments is derived from neighbouring compartments by leakage through the dyke. Fleisher gives the total annual recharge of the Venterspost compartment as being in the order of 12.5 $10^6$  m³/y. He estimated that almost 20% flowed into the compartment from neighbouring compartments to the east.

### 5.8.3 Rewatering

#### 5.8.3.1 Mined out volume

Calculation of the mined out volume in this area has certain challenges:

- Numerous reef horizons have been mined; some sporadically while others have been extensively mined. Thus an approach that uses mine plans to measure the mined area and convert it to volume would be very timeconsuming and probably rather inaccurate, due to plan "up-to-dateness" and the ability to trace the fine detail.
- The mine openings close due to depth of mining, geological structure and extent of development, the controlling factors are spatially variable, so it is difficult to quantify the effect on volume.
- The lithology of the sequence controls whether closure or widespread increases in porosity occur. This can be variable over short distances (tens of metres).
- Backfilling is practised by many of the mines in this area. This has advantages such as increasing the stability and thus safety of the mines, helping to improve air flow and cooling in active areas. Backfilling reduces the open volume underground. Numerous factors affect the backfilled material's porosity and the volume it occupies, e.g. balking of milled rock.
- Some of the older mines are already partly flooded.

In the light of these uncertainties and parameter estimation difficulties, an alternative method of volume *estimation* is presented. The approach is based on mine production figures published by the Chamber of Mines as well as other production figures, given in Antrobus (1986) and various EMPR reports, and is valid up to the end of 1997.

The calculation is based on the following technique:

Tonnages of tailings disposal are given for gold and uranium mining. Since the gold grade is very low, the tonnage added by the extracted material is insignificant but can be added to complete the calculation. Tonnages of waste rock from off-reef development, such as mine shafts, are also recorded, as are

<sup>&</sup>lt;sup>7</sup> This is not an attempt to question the ability of mines to keep up to date plans; the investigators are aware that many mines kept these meticulously. However, these plans are not always available and the easy option of using shareholder plans is tempting. Shareholder plans were prepared as part of a brochure available to investors. Their aim was to show where reserves were, not necessarily where mining had been. They were never intended to be a source of scientific data.

tonnages of backfilled tailings. Thus the total tonnage that has been removed from underground can be calculated:

Total tonnage removed = Tailings + Ore + Waste rock - Backfilled tailings

The average density of such rock was assumed to be the density of quartz (2.75) as it is the predominant mineral (Feather and Koen, 1975). Since density is derived from mass/volume, the volume can be calculated from:

The results of such calculations are given in Table 5-18.

Table 5-18. Results of calculations to estimate mined volume.

	Total tonnage removed	Mined volume (m³)	Partly filled with water	Mined volume (ML)
Old West Rand	248600000	90400000	48210000	48000
West Rand Randfontein	122100000	44400000	<u> </u>	44000
West Rand WAGM and REGM	330890000	120320000		120000
West Wits Kloof	280960000	102160000		100000
West Wits Carltonville	623780000	226830000		220000
Totals	1235630000	449320000		440000

### 5.8.3.2 Rewatering rates

It has been shown that the wettest mines in this area are overlain by dolomite. The dolomite was compartmentalised and prior to mine dewatering springs issued from the lowest points along the compartmentalising dykes. The spring flows have been monitored, starting before dewatering began, thus giving the best available measure of flow rates. Enslin *et al.* (1967) showed that rainfall recharge of the system is equal to the average annual flow of the spring. Thus after mining, recharge of the mine openings and dewatered dolomites will be at the rate of the original spring flow<sup>8</sup>.

### There are uncertainties:

- Some of the mines straddle compartments and thus derive their inflow from more than one compartment.
- The volume flowing into the REGM mines from the Zuurbekom compartment.
- The volume that can move through the compartmentalising dyke.

By assigning proportionately different values due to possible contribution from neighbouring compartments, time bounds are given (short and long). The proportions are not statistically based and are derived by subjectively assigning water. More intensive research needs to be done on this aspect to give it an appropriate scientific base. It is felt that this approach gives an order of

<sup>&</sup>lt;sup>8</sup> This ignores climatic changes due to global warming and urbanisation.

magnitude to the rewatering rates and is therefore worth reporting on. Thus the estimates are given in Table 5-19.

Since the mined volume is known and the inflow rate is known if the uncertainties relating to the water distribution could be overcome, calculating the time of filling of the mines is straightforward. Johnson (1985) has used a similar approach to calculate mine filling in Northern Michigan.

There is less uncertainty in the Old West Rand Mines made up of: West Rand Cons, Champ D'Or, Luipaardsvlei, French Rand, Lancaster West, Randfontein, East Champ D' Or. Require 30 ML/day dewatering to maintain a constant water level in the flooded part of the mines (Horak, 1996).

Table 5-19. Rewatering time estimates.

Mine Groups	Mined	Spring	Spring Flow	Time	Time to Fill		
	volume (ML)		ML/d	Short (y)	Long (y)		
Old West Rand (Champ D'Or, Luipaardsvlei etc.)	48000			<u></u>			
West Rand Randfontein	44000						
West Rand WAGM and REGM (Cooke and Doornkop)	114000	Gemsbokfontein (Zuurbekom leakage?)	8.9		37		
West Wits Kloof	99000	Venterspost Bank	22 8	6.2	13		
		Oberholzer	55				

When the mine excavations have flooded, the dewatered storage in the dolomites will be recharged. This volume can be estimated from the difference between the total volume of water that has been pumped since dewatering of the different compartments started and the volume of water that would have issued from the springs over the same period of time, had the mines not been dewatering.

Storage = total volume pumped by mines - total flow from springs over same period.

The results of this estimation are shown in Table 5-20.

Maximum and minimum storage values are based on differences between reported pumping rates. Only pumping figures from steady state conditions were used. Under these conditions the pumping rate would be equal to the inflow rate which would be the same as recharge. A similar calculation can be done using the flow rates of the springs (before dewatering) the difference gives bounds <sup>10</sup> for the values of dolomite storage.

<sup>&</sup>lt;sup>6</sup> Similar calculations were carried out by Krantz (1997) who obtained a figure of 5.25 years for rewatering. Krantz used different techniques and computer modelling to arrive at his result. It is felt that the difference is insignificant given the difference in approach and in interpretation regarding the influence of the Sterkfontein dolomites. This independent "verification" of this result adds credibility to these figures.

<sup>&</sup>lt;sup>10</sup> These cannot be precisely fixed as the method assumes no other losses from the compartments, e.g. leakage through dykes.

	****									
Compartment	Total volume removed		Dynamic volume from mine records		fror	Dynamic volume from DWA records		Storage in Time compartments rewat dolomi (Total volume removed - dynamic volume)		ater nites
	Period	(ML)	Constant dewatering rate (ML/d)	(ML)	Eye yields (MUd)	(ML)	Mine records	Eye flows	Mine records	Eye flows
Bank	1969 - 1996	1000000	70	690000	48	470000	310000	530000	18.3	30
Oberholzer	1952 - 1996	1100000	50	800000	55	880000	300000	220000	15.2	11
Venterspost	1968 - 1996	410000	40	400000	21	210000	3240	190000	0.42	25
Gemsbokfontein	1986 - 1996	220000	?		8.9	42000	->	170000	5 fun 17%	54

Table 5-20. Storage in the dolomites and additional time required to rewater the storage.

The problem of apportioning this water, due to connections between compartments having been created and mines straddling compartments, is also relevant here. This would require a detailed study of the water balance in this area.

Western Areas Gold Mines began dewatering the Gemsbokfontein compartment in 1986. They artificially recharge the neighbouring East Gemsbokfontein compartment with dewatered water to prevent drawdown from occurring to a level where sinkholes may develop. According to Bredenkamp (1993), the Eastern Gemsbokfontein compartment leaks through the Magazene dyke, thus there seems to be some recirculation and a constant dewatering rate has not yet been achieved. For this reason, the calculation is not complete for the Gemsbokfontein compartment.

The idea development and data in this section are largely based on information given in the following references: De Freitas *et al.* (1978), Engelbrecht (1986), Lednor (1986), Wolmerans *et al.* (1978) and Enslin *et al.* (1968).

#### 5.8.3.3 Discharge points

When all the dewatered volumes (mine openings + storage in dolomites) have been rewatered, a pre-mine dewatering situation in the dolomites will never again be achieved. The springs that issued as a result of compartmentalising dykes occurred at points along the Wonderfontein Spruit where the dykes cut the valley. The mines have now destroyed the compartmentalising effect of all but the Turffontein dyke. Thus the water will recharge to the level of the Turffontein dyke over the whole area underlain by dolomites. An idealised section showing this result of rewatering is given in Figure 5-51. It is idealised because there will always be some gradient in the groundwater level.

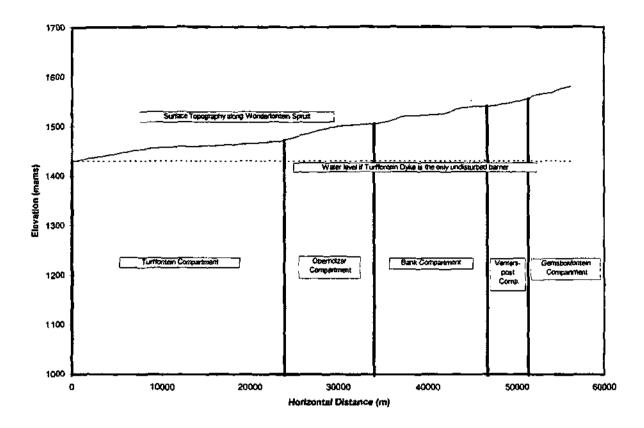


Figure 5-51. Recharged water level and outflow elevation along the Wonderfontein Spruit.

### 5.8.4 Sinkhole development

Catastrophic sinkhole development occurred in this area in the 1960's, and thus a great deal of work was undertaken to understand the reasons for sinkhole development and to be able to predict which areas were most susceptible to this phenomenon. Enslin (1969) did the pioneering work in developing geophysical techniques that would reliably show areas of potential sinkhole development, while the development of sinkholes is described by Fleisher (1981) and Brink (1979).

The stability of the dolomites was affected by dewatering, this is documented by Buttrick (1992) and Brink (1979).

In his discussion of the stability problems in the Venterspost compartment, Beukes (unknown) showed that dewatering had been complete from the early 1970's. During the period 1975 to 1978, the area received higher than normal rainfall and partial recharge of the dolomites occurred. The period over which this happened was prolonged by water flowing from the undewatered Gemsbokfontein compartment into the Venterspost compartment via the Gemsbokfontein eye. Water level rises of up to 100 m were experienced. Beukes recorded renewed movement in some of the filled sinkholes, new sinkhole formation in known paleo-sinkholes and renewed movement in areas of doline formation. Thirty percent of the levelling points in Westonaria that showed movement during the dewatering period, showed movement during this rewetting period.

It is therefore clear that rising water levels are responsible for destabilising the metastable conditions that have developed during the dewatered period. According to SRK (1996), this has serious implications for the prospect of rewatering after mine closure. The threat may not be as serious as SRK suggests because as Buttrick indicated that a mobilising agency is necessary. In the example this was present in the form of *excessive* rainfall. Under normal recovery conditions the groundwater will recover without abnormal rainfall, and the mobilising agency will not exist. Thus the metastable conditions will be unaffected and stability will increase as the dewatered zones are rewatered.

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

Enslin *et al.* (1976) discuss the necessity for recharge of the compartment to maintain stability. Recharge of the Gemsbokfontein compartment via 10 boreholes sited in highly leached fault and fracture zones, sinkholes and dry "eyes", has taken place. An average rate of about 6.3 ML/d per borehole is recharged. This is limited by the borehole construction rather than the aquifer properties. This was done in an attempt to keep the water levels within the critical - 6 m level.

In the Far West Rand, ground movement is monitored because of the subsidence and sinkhole history. Figures 5-52 and 5-53, based on records kept by gold-fields of South Africa, show the frequency of these movements.

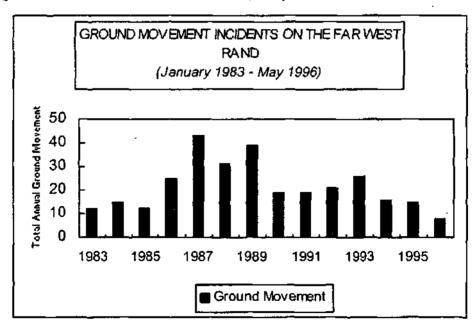


Figure 5-52. Total number of ground movements on the Far West Rand.

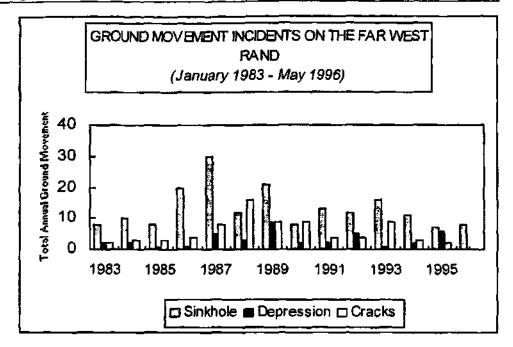


Figure 5-53. Type of ground movements on the Far West Rand.

At present, where sinkholes occur (Figure 5-54), attempts have been made to remediate them. This entails pumping a mine tailings cement mixture into the sinkholes and covering with topsoil followed by revegetation (Robb *et al.*, 1998). According to Erasmus (pers. comm., 1997), a study is under way to assess the results of these methods on the surrounding environment.



Figure 5-54. Slimes injected into a sinkhole (Coetzee and Chevrel, 1996).

## 5.9 Modellina

To understand the interactions occurring within the compartments, numerous considerations have to be considered simultaneously. To enable consideration of these processes numerical groundwater modelling was undertaken. Groundwater modelling entails the organisation, quantification and interpretation of large quantities of geohydrological data (Pinder, 1998)

Various processes influence groundwater pollution migration, such as:

- · Advection.
- · Diffusion.
- Dispersion.
- · Reaction.
- · Adsorption and desorption.
- · Other sources and sinks.
- Oxidation reduction.

These components are required to solve the mass transport equation which is a mathematical model depicting how the variables controlled by these components change in time and space. A one-dimensional mass transport equation can be written as:

$$\frac{\partial}{\partial t}(n_{\epsilon}RC) = \frac{\partial}{\partial x}(n_{\epsilon}v_{x}C) + \frac{\partial}{\partial x}(n_{\epsilon}D)\frac{\partial C}{\partial x} + \frac{\partial}{\partial x}(D_{m+\epsilon})\frac{\partial C}{\partial x} + S$$

where:

 $n_e$  - effective porosity.

R - adsorption/retardation factor.

c - solute concentration.

 $V_x$  - Groundwater flow velocity.

x - dimension.

D - dispersion coefficient.

D<sub>mee</sub> - molecular and effective diffusion coefficient.

S - sink/source.

A point solution to this equation could be analytical and exact, as a great deal of detail may be known at a point. Over a large area these components change in space. The best solution is numeric, however numeric solutions are not exact. Finite difference or finite element methods have been developed, finite element methods are somewhat more flexible in terms of spatial discretisation.

Thus to show the possible distribution of pollutants from surface dumps across this area, a two-dimensional finite element model was developed using AquaMod for WINDOWS (Van Tonder *et al.*, 1995).

# 5.9.1 Modelling pollution from surface sources

The conceptual model on which this two-dimensional model was based is derived from the rewatering and area description discussions. It entails:

 Groundwater upon recharge will remain below the surface elevation of the shafts.

- The highly transmissive dolomites will form the predominant path for groundwater flow with little exchange between them and the mines are usually situated more than 600 m below.
- The area is large over 2500 km<sup>2</sup>. Relative to this, groundwater movement is shallow and a two-dimensional model is sufficient.
- The predominant pollution threat upon closure and rewatering will be pollution migration from the mine waste heaps, many of which are located on dolomite as shown in Figure 5-23.

For this area, typical parameters have been assigned based on the geology. This and limitations of the conceptual model highlight the fact that the results should be regarded as indicative of possible trends and should be used to highlight areas where further work is required. The model details are listed in Table 5-21.

Table 5-21, Parameters used for the development of the West Witwatersrand groundwater model.

Nodes	6368	The widest node spacing was 1000 m.
	{	Two levels of refinement were defined around mine tailings sites with spacing of 600 and 300 m in order to minimise numeric errors.
Elements	12565	The bandwidth was 115.
Constant Head Nodes	405	Defined along the major water divides, around the perimeter of the area and at some of the large active mine tailings dumps.
Constant Concentration Nodes	666	Defined (as far as the coarse network would allow) at the mine waste disposal sites.
Drain Nodes	322	Defined along the major watercourses.
Zones	8	Defined to correspond to the major geological units.

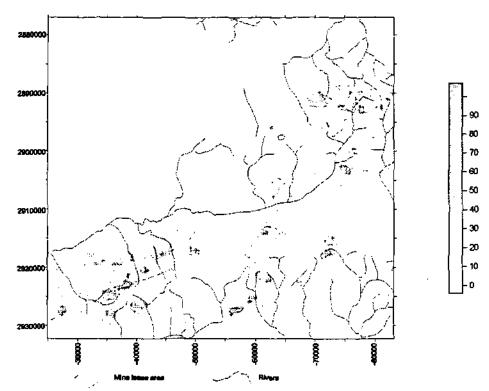
These were defined to correspond to the major geological units. The following parameters were used:

Zone	Geology	Transmissivity	Storativity	Porosity
Zone 1.	Black Reef	15	0.0001	0.01
Zone 2.	Dolomite	1000	0.0100	0.10
Zone 3.	Pretoria Group	10	0.0001	0.01
Zone 4.	Witwatersrand	15	0.0002	0.01
Zone 5.	Archaean	5	0.0005	0.05
Zone 6.	Karoo	10	0.0001	0.05
Zone 7.	Rock dumps	20	0.0010	0.30
Zone 8.	Tailing dams	_ 5	0.0100	0.30

The model was run for 10 years, and with these parameters, a steady state was obtained that bore a strong resemblance to the original groundwater topography that had been defined by Bayesian interpolation from the surface contours. The model was run in two forms:

- 1. With deep dewatering from nodes representing the major dewatering mines in the area: Venterspost, Driefontein and WAGM. This simulated the spread of contaminants under active mining conditions.
- With no dewatering, simulating the spread of contaminants that would be possible some time after the system has been rewatered. This simulated the spread of contaminants post mining.

The results of these simulations are given in Figures 5-55 to 5-57.



Figures 5-55 (top). Pollution migration at start of simulations and

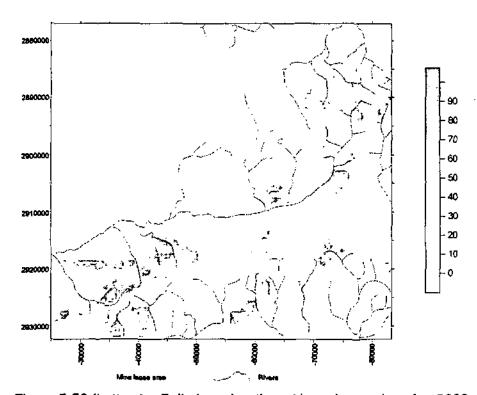


Figure 5-56 (bottom). Pollution migration with no dewatering after 3600 days.



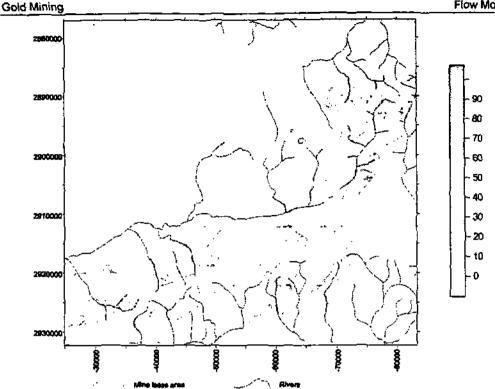


Figure 5-57. Pollution migration with mine dewatering after 3600 days.

The migration shown in Figure 5-57 corresponds closely to migration postulated by Coetzee et al. (1996), based on remote geophysics sensing and GIS modelling of a portion of this area.

### 5.9.2 West Rand groundwater model

This section reports on the groundwater model developed by Krantz (1997) for the West Rand area. This was supplied by the mines in response to a request for information regarding geohydrology, pollution sources and influences of the mines on the West Rand.

## 5.9.2.1 West Rand geology

Witwatersrand Supergroup rocks outcrop in this area due to uplift by block faulting, thus the outcrop is bordered by major faults beyond which younger rocks are juxtaposed against the Witwatersrand sediments. There are dolomitic outcrops of the Sterkfontein compartment to the west and north-west of this area. The geological cross section in Figure 5-10 shows the subsurface condition. (Mine 1 in that figure represents these mines.)

## 5.9.2.2 Modelling investigation

The most important aspects of the investigation by Krantz (1997) are:

The study was commissioned by JCI, the owners of Randfontein Estates Gold Mine (REGM). Because there is significant connection between REGM and neighbouring mines above 19 level, West Rand Cons and Luipaards Vlei were included.

The main objectives of the modelling were to:

1. Identify the geohydrological boundaries and conduits for water in the region.

- Assess the water level rise in REGM.
- 3. Determine likely decant points in the area.
- 4. Determine the potential decant water quality.

It is thus evident that the solutions to points 2, 3 and 4 of their findings have relevance to this post mining impact study.

### 5.9.2.3 Water-level rise

The model used an influx of 17.7ML/day (previous investigators had used a calculated value of 16.3 ML/d). Krantz (1997) digitised the shareholder plans of the workings and converted the areas so generated into volume using an average stope height. This was converted into a daily volume increase based on a constant influx of water. The recovery predicted that the mines would take between 4.2 and 7.2 years to fill, depending on whether a rainfall of 725 mm/year, 1068 mm/y or pumping at West Rand Cons at 7 ML/d were applied. The predictions show insignificant deviation from a straight-line recovery that was used by Scott (1996), which gave estimates for the same area of 8.5 years.

The water levels measured in Central Vent Shaft from 1993 were used to calibrate the model and the simulated values were found to mimic the observed values sufficiently after various iterations.

The cumulative departures for groundwater influxes were compared to the cumulative departures of sulphate in the Central Vent shaft and show a good correlation, with the SO<sub>4</sub> content increasing as inflows increase. This can be explained by reaction from the local influx with pyrite oxidation products. During drier periods when the inflow of the overlying strata is proportionally less, the quality is better since the dolomitic influx remains constant and so forms a greater proportion of the influx. This trend is also discernible in the plots of pH against total inflow and was used to interpret the percentage of dolomite influx.

#### 5.9.2.4 Decant points

As these workings are from outcrop, there are no significant overlying geological formations that could be recharges; so when the mines have filled, the mine shafts are possible decant points. Ten possible decant points are listed in Table 5-22.

Table 5-22.	Possible	decant	points.
-------------	----------	--------	---------

Decant Point	Mine Property	Elevation (mamsl)
Shaft 18 Winze	REGM	1649
Open Pit Lindum	REGM	1659
Main Reef Outcrop	REGM	1663
Lindum/Kimberly Outcrop	REGM	1679
Turk Shaft	LVE	1680
Deep Shaft	WRC	1682
Possible Open Pit Lindum	REGM	1682
Open Pit	West Wits	1684
Monarch Shaft	WRC	1691
Main Reef	WRC	1691

Shaft 18 Winze is the lowest point which will cause decant into the Twee Lopie Spruit. The effective base of the West Wits Pit is, however, around 1614 m., This site has been proposed as a landfill, rewatering of mines would flood the

base of this landfill. At the time of writing, the choice of site was to be re-evaluated.

### 5.9.2.5 Possible water quality

Simple chemical mixing and equilibrium modelling were used to ascertain likely decant concentration. By application of different mixing volumes and recharge rates, the final water quality will have sulphate values between 852 mg/L and 1558mg/l.

### 5.9.3 Modelling of Bank compartment

A three-dimensional model was developed to incorporate the ideas given on dewatering, rewatering and the surface pollution model. The Bank compartment was selected as it is data rich and it represents other mining influenced compartments in the area.

### 5.9.3.1 Conceptual model

The salient points regarding the Bank compartment are given in the next paragraphs; details are in previous sections of this report.

The compartment covers an area 160 km² and according to Fleisher (1981) impermeable boundaries delineate the compartment on all sides. Syenite dykes occur along the eastern and western boundaries while the impervious Black Reef formation forms an irregular boundary to the north. Fleisher suggested that the Pretoria shales to the south formed an impervious southern boundary.

Recharge occurred through rainfall infiltration, leakage from the Wonderfontein Spruit which crosses the compartment and overflow from the Venterspost compartment. Karoo outliers are areas of diminished recharge.

The geohydrology was changed by large volumes of water that were pumped from the mines; thus these were included in the model.

### 5.9.3.2 Three-dimensional model results

The model was calibrated by checking against pre-mining conditions of original eye flow and groundwater levels which were required to be the same as the pre-mining levels given by Fleisher (1979). The modelled eye flow was 47 ML/d compared with 49 ML/d the reported Wonderfontein Eye flow.

Once it was felt that the pre-mining simulation was verified by field conditions, the model was used to simulate dewatering of the compartment A dewatering rate of 70 ML/day was used in the model. Three pumping positions were used; Driefontein North Shaft, Harvie Watt shaft and Libanon 1 shaft. The water balance for this model showed that recharge could not account for all the water that was being pumped. The model was therefore further developed with leakage through the dykes.

The simulation was run for 20 years until water levels showing the steep gradient around the pumping shaft, similar to those reported by SRK, were obtained. This is shown in Figures 5-58 - 5-60.



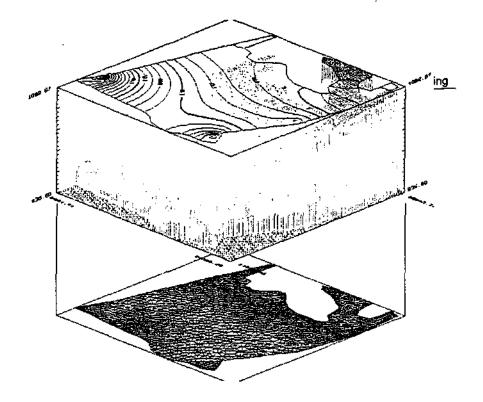


Figure 5-58. Three-dimensional view of dewatering cone viewed from Venterpost Dyke.

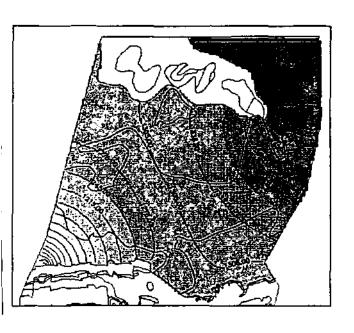


Figure 5-59. Modelled groundwater elevation contours showing dewatering cone.

Figure 5-60. Groundwater elevation contour interpretation showing cone of dewatering in 1993 (SRK, 1994)

Having achieved realistic dewatering, the model was used to evaluate recovery of water in the system. This gave a recharge period of 21 years after pumping stops. By comparison, Scott's (1997) calculations using flow differences gave values between 17 and 31 years (depending on inflow) for rewatering of the Bank compartment, thus giving independent evidence that the model was realistic. Having achieved realistic results with the Bank model, the approach

could be applied to neighbouring data poor compartments. This was done with success and the usefulness was applied in the scenario models.

The recovered water levels can be compared with Fleisher's (1981) model of water levels based on field measurements in Figures 5-61 and 5-62.

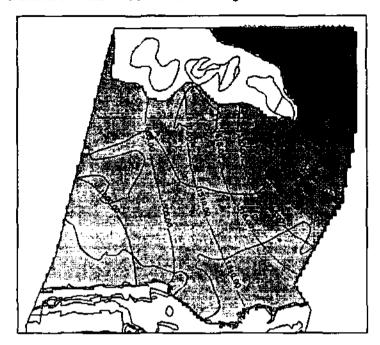


Figure 5-61. Recovered water levels after 21 years.

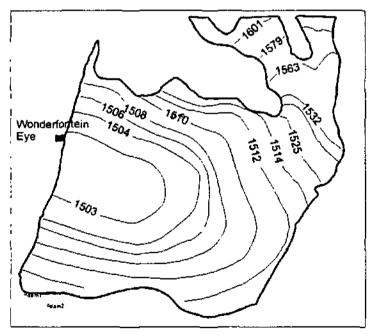


Figure 5-62. Water levels in 1963 (after Fleisher, 1981).

# 5.9.4 Modelling pollution from rewatering

So far this investigation has defined what will happen on cessation of mining from the point of view that the mines have flooded and that the water in the mine does not pose a problem. This assumption was based on three possibilities:

- 1. Water that is pumped from the mine is of usable quality; it is used for irrigation and even for domestic use in some places.
- Water will stratify in the mine with poor quality water trapped in the deepest parts of the mines.
- The water exchanging in the recharged karst aquifers is only influenced by surface contamination sources.

Using these possibilities, the distribution of mine waste derived pollutantmigration, with and without pumping, as modelled. The pollutants form a diffuse source that influences most of the catchments in this area.

Other influences of mine closure could be renewed instability in the karstic dolomites. These possibilities have also been considered.

What has not been considered, because the assumptions excluded the possibility, is that the rising mine water will have an influence on the water resources of the area.

Thus in this section, the possibility that water in the mines might pose a problem will be considered.

# 5.9.4.1 Conceptual modelling

We don't know what will happen on rewatering and there is no easy way of finding out. In this report, what is known and how the surface water, groundwater and mine water systems operate has been described. From the descriptions, a conceptual model, tested by numeric modelling, shows that there are only a few possible ways that rewatering could have an impact. These options will be described in the following sections.

Each description will:

- · Define the conceptual rewatering model.
- · Give evidence for and against the model.
- Define what the likely results might be if this were the way that the system will react when the mines have filled up.
- List some of the gaps in knowledge that might help with any further work that
  might be done. These gaps should direct such work, identifying them is
  what modelling is most useful for.
- List management options. All management options must be measured against certain criteria. These criteria will include technical and economic viability, effectiveness and that they do not allow diffuse pollution to occur.

Each of the rewatering models uses the dewatering model that was described in Chapter 8 of this report, viz. mine voids and karst is dewatered but there is still flow into the mines. This means that the normal permeability of the rock matrix, i.e. fractures and other partings, is saturated and water is moving through them into the mine openings.

The models assume that rewatering starts over the whole area at the same time. This may not be realistic, as we know that some of the mines are near the

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end of their lives while others are still active. Dewatering must be assumed to continue until all mines have stopped working.

## 5.9.4.2 Model 1 Synchronous water rise

### Defining the conceptual model

The mines have excavated through the compartmentalising dykes so there is free passage of water between compartments, even though via a deep, indirect, contorted U-shaped route that includes karst, fractures and mine openings.

Significant groundwater leakage occurs through the dykes. This could be enhanced by mining induced fracturing, by weathering of the dykes in the unsaturated conditions that prevailed during dewatering (i.e. adjacent to the karst) or leakage associated with other geological structures.

Because of these pathways, groundwater will not completely recharge all the compartments and some of the karst will remain dewatered. Groundwater levels will not return to the pre-mining condition. This is shown in a rather idealised section (Figure 5-18). The original springs, which have dried up due to dewatering, will stay dry. The last dyke "Turffontein" which was unaffected by dewatering will contain the water and the Turffontein spring will flow once more.

Water is sourced from rainfall recharge, some from surface water flow and an undefined amount is derived from neighbouring compartments. Thus water enters the dewatered karst and moves down fractures or shafts into the mine openings.

On cessation of pumping, the following sequence of events will happen:

- The mine openings (including shafts) fill up (estimated times are given in Table 5-18 and 5-19).
- The karstic dolomite is recharged incompletely in all compartments, except Turffontein (Figure 5-18).
- Recharge rate differences between compartments are equalised due to the mine tunnels and leaking dykes. Thus the rate and level of water rise in all compartments are the same, i.e. synchronous water rise.

#### Give evidence for and against the model

- Mines have tunnelled through the compartmentalising dykes
- ✓ Fracture and fracture systems connect mines so that water levels in one mine affect those in a neighbour.
- The dykes allow some groundwater through, enhanced in some places by mining induced fracturing.
- Interpretations of water-level information show that the compartments are independent (Figure 5-50).
- Dewatering is independent in individual compartments.

# Defining the likely impacts of the water

Some of the contaminated mine water is mixed with recharging water by the U-tube-like flow. This continually contaminates the dolomites with the high salinity water. The impact will be greatest in the Turffontein compartment.

Some water moves through the Turffontein Dyke and diffuse groundwater pollution occurs.

### Knowledge gaps

- · Where the holes through the dykes are.
- Where areas of mining have encroached on the dykes so that mine induced fracturing may affect them.
- Which mines are hydraulically connected, i.e. which mines' dewatering affected neighbouring mines.
- In the flooded system will acid still be produced.
- Monitored water quality of rising water in dormant mines. (Dynamic water quality as opposed to stagnant water that may be trapped in the mine excavations.)

### Management Options

All flow emerges at one point, so no pumping is required and water treatment could be initiated, if necessary.

Before flooding, holes through the dykes could be plugged thus limiting the U-tube flow.

A hidden advantage would be if the water quality were good as no management would be required.

### 5,9.4.3 Model 2 Compartmentalised water rise

#### Defining the conceptual model

The compartments are intact and will fill up independently. Some compartments fill faster than others depending on surface area, volumes to be filled and recharge rate.

The original groundwater levels will be restored and each spring will flow again.

Water is sourced from rainfall recharge, some from surface water flow and an undefined amount (much less than in Model 1) is derived from neighbouring compartments. Thus water enters the karst in the dewatered parts and moves down fractures or shafts into the mine openings.

On cessation of pumping, the following sequence of events will happen:

- The mine openings (including shafts) fill up.
- The karstic dolomite is recharged completely in all compartments.
- Recharge rate differences between compartments exist and the water rises faster in some than in others.
- Springs from the early filled compartments can contribute to filling of neighbouring compartments in a cascade-like arrangement.

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<sup>&</sup>lt;sup>11</sup> Probably not because the inflowing water from the recharging dolomites will be neutralised if it had been acid. At high pH (above pH 3), Fe<sup>3+</sup> cannot occur in solution unless extreme oxidising conditions exist, so without oxygen and no Fe<sup>3+</sup> acid production will be limited until the dissolved oxygen is consumed, after which it will stop.

### Give evidence for and against the model

- ✓ Interpretations of water-level information show that the compartments are independent.
- ✓ Dewatering is independent in individual compartments.
- Some of the springs flowed when the mines were dewatering albeit with decreased flow.
- Mines have excavated through the compartmentalising dykes.
- \* Fracture and fracture systems connect mines so that water levels in one mine affect those in a neighbour.
- The dykes do allow some groundwater leakage.

### Defining the likely impacts of the water

All the original karst is recharged.

The groundwater is stratified with the poorest quality, dense water at the bottom. Thus contaminants from the mine excavations do not affect the water quality.

if leakage through the dykes occurs, the deep contaminated water will only affect the mines. Shallow leakage is between karst and has always occurred.

### Knowledge gaps

- · Where the holes through the dykes are.
- Where areas of mining have encroached on the dykes so that mine induced fracturing may affect them.
- Which mines are hydraulically connected, i.e. which mines' dewatering affected neighbouring mines.
- The long-term effectiveness of shaft grouting in allowing water to recharge via shafts.
- In the flooded system will acid still be produced.
- Monitored water quality of rising water in dormant mines. (Dynamic water quality as opposed to stagnant water that may be trapped in the mine excavations.)
- Mine volumes.
- · Distribution and orientation of karst development.

### Management Options

The water quality is stratified, therefore water movement in the recharged system is shallow, thus the mines do not contribute to water degradation and no management is necessary.

# 5.9.4.4 Model 3 Thermal convection

This option could affect either Model 1 or 2 by superimposing the influence of thermally driven convection.

### Defining the conceptual model

Over the mining depths used in the area, temperature differences between the water in the deeper parts of the mine and fresh, recharging groundwater could be up to 40°C. The hotter water has a lower density than cool water and will be driven upwards where it will constantly mix with shallower water.

### Defining the likely impacts of the water

If thermal convection were to effect the Model 1 situation it would add to the Utube effect, ensuring more complete mixing of deeper water and the water in the dolomitic aquifer.

In Model 2, this would work against density stratification.

### Give evidence for and against the model

Theoretical arguments.

Salinity related and thermal density variations in water are shown in Figure 5-63.

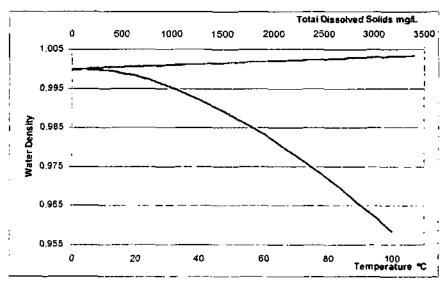


Figure 5-63. Water density relationship with temperature and salinity.

The grey band in Figure 5-63 shows the mine temperature range, while the salinity covers an expected range in mine water. The relationship shows that temperature related density variation would override salinity induced density stratification.

A complication in this consideration is that the water is not a free body but water movement will be restricted by dead end mine openings and preferred water passage through low permeability fractures.

For thermal convection to occur in a porous medium, the temperature gradient must be much higher than what is required in a water body. In a porous medium, the temperature gradient must be:

$$\frac{\partial T}{\partial z} \left( 16 / \frac{H^2}{27 \pi^2 \kappa_e \rho_o} \right) > \frac{4 \pi^2 \lambda^2 \mu}{\kappa_e \rho_o g \alpha_t H^2}$$

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There are empirical equations that could be used to show this, for example:

 $N_{RA} = \frac{g\rho_o(c_w\rho_w)Hk\alpha_t\Delta T}{\mu\kappa_b}$  This gives  $N_{RA}$ , the Rayleigh Criteria which, for thermal convection in a porous medium to occur, must be greater than 40.

A calculation of this type for this area gave the result shown in Table 5-23.

Table 5-23. Evaluation of Raleigh Number for a West Wits Line mine.

Symbol	Explanation	Units	West Wits Line
9	Gravity acceleration	cm/sec	980
ũ <sub>o</sub>	Reference density	1 g/cm	1
C <sub>w</sub>	Specific heat per unit volume of water	cal/cmºC	1
ĺw	Fluid density	g/cm	1
н	Thickness of the formation	cm	80000
k	Permeability	cm <sup>2</sup>	5.2E-18 to 5E 11
Ū₁	Coefficient of thermal expansion	\Cō	2.00E-04
<b>∄</b> T	Temperature gradient	<sup>©</sup> C/cm	0.0005
C	Fuld viscosity	g/cms	6.00E-03
Q <sub>e</sub>	Effective thermal conductivity	cal/cmsec <sup>o</sup> C	4.00E-03
N⁄ <sub>RA</sub>	Raleigh Number		1.55e-07 to 1.29

- \* The Raleigh Number so derived is very small. This suggests that thermal convection will not be possible in this system. The maximum value given above is using the assumption of a high permeability which would translate to a hydraulic conductivity of 5 m/d across the entire system. This implies that density stratification may still be a possibility. These figures suggest that permeabilities and thermal gradients have to be very high for free heat convection to occur. It is possible that the conditions could occur in the shafts but are unlikely to occur in the rest of the system.
- No occurrences have been reported in this area, in spite of relatively deep exploration geological drilling.

### Knowledge gaps

Water density at the sali nities predicted for mine water.

Water density at the temperature proposed.

#### 5.9.4.5 More detailed modelling requirements

Models 1 and 2 do not need further modelling at this level as a model would be driven by the conceptual model, due to a lack of measured or known parameters; thus the model results are the conceptual model. The only advantage would be to produce graphical presentation.

The possibility of thermal mixing in the shaft only and implications for density stratification should be investigated.

### 5.9.4.6 Possibility of pollution from rewatering

Two models, with or without thermal effects, are possible. However, in each model when the water has recovered, it will move through karstic dolomite which exists in the upper 100 - 200 m of the Malmani formation.

A review of the conceptual model of the way water enters the subsurface will be useful, as in the next section some of the possible remediation scenarios will be considered. Whether these are feasible or not will have to be evaluated against the reality of the total system. Thus the sections shown in Chapter 4 and Figures 5-64 and 5-65 which are modified (Fleisher, 1981) should be considered.

Water is derived from surface precipitation and migrates into the subsurface via a thin soil cover and relatively well-developed karst, thus streams go underground. The underlying rocks are impervious but have been faulted and fractured. Water fills the fractures and fault planes and can move through some of them.

Mining has opened voids in the rocks at levels associated with Black Reef (base of dolomites), Ventersdorp Contact Reef (Top of Witwatersrand Supergroup) and at various levels within the Witwatersrand Supergroup rocks. Where these openings intersected major faults or fractures, water inrushes were encountered. Water was pumped out, thus generating a gradient between the surface saturated conditions and the subsurface pumped out conditions. Pumping is essential as long as mining continues. Compartments have been dewatered; this means that water has been removed from storage and pumping is now at a steady state. The water removed from storage means that the significant storage volume of the karst has been dewatered. The steady state flow shows that what is recharging is moving underground to be pumped out. Thus, in spite of the term dewatered, the underground pathways are still saturated.

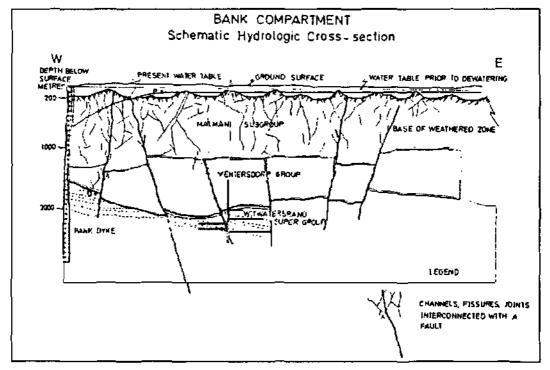


Figure 5-64. Model of subsurface conditions (Fleisher, 1981).

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When mining stops, the mined out volume will be flooded and water will rise in the mine excavations. As this happens, successively more water inflows to the mines will be stopped by water inflow and the rate of water rise will decrease with time. This water rise will not affect the fractures in any of the rocks as these are already saturated, so the only effect will be to rewater the karst caverns when the water reaches that level.

The models described in this section cover the possible final water levels. Whatever these may be, i.e. whether they are depressed and the Turffontein dyke controls all water, or whether the compartments fill up and discharge takes place from each of the eyes once more, is not really the important question. The really important issue will be whether that water is significantly contaminated or not.

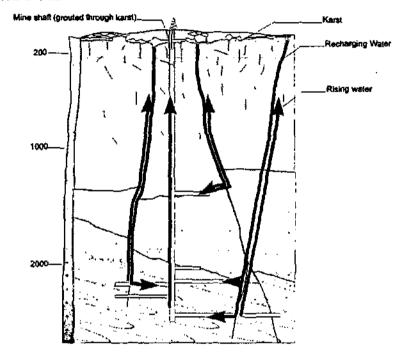


Figure 5-65. Conceptual model of mine rewatering.

The contamination issue will be the important one to consider when selecting the management option. If the dolomites are allowed to be recharged by contaminated mine water, this will constitute an additional source of diffuse pollution, adding to the mine waste pollution and industrial related pollution loads being carried by the system. If additional diffuse pollution cannot be accepted, then the only way to control it is to remove the water from the mines before it reaches the karst.

Some of the ways that this could be achieved will be considered in the next chapter.

## 5.9.4.7 Influence of pollution from rewatering

In Chapter 7, the water quality in the mine was shown to be slightly contaminated, the main contaminants being sulphate, increased salts and the potential for dissolved radiogenic species. The water therefore has potential to add to the pollution load of the system. Calculations to obtain an idea of likely impacts of such additional loads are presented and discussed in this section.

It is assumed that the poorest water quality will be that given in Section 7. This water will initially fill the created mine void and as rewatering occurs, its level rises in shafts and other secondary porosity as described in Section 9.1.6. Upward migration and rewatering will terminate inflows and mix incoming and rising water.

The conceptual model of this scenario illustrates the different options which might occur. These vary from a best case, where the water will not influence the quality in the dolomites, to the case where due to a combination of head differences causing gradients, thermal influences and structural weaknesses in shafts, the water is flushed into the transmissive portion of the dolomitic aquifer.

To obtain an average hydraulic conductivity (K) in the compartments, the steady state dewatering rates, area of the compartment and the depth to mining, were used to satisfy the Darcy equation (Q=Kia). The results are given in Table 5-24.

	Q	а	i	К
	Average dewatering rate (m <sup>3</sup> /d)	Compartment area (m²)	Hydraulic gradient	Hydraulic conductivity (m/d)
Bank	7.00E+04	156600000	750	5.96E-07
Oberholzer	5.00E+04	153800000	950	3.42E-07
Venterspost	4.00E+04	54300000	800	9.19E-07

Table 5-24 Determination of average K values for the compartments

When the mines are flooded, some mines will have little gradient between the inflow points, i.e. the karst and the points where water is entering the mines; others may have a gradient depending on the subsurface arrangement of karst and water percolation points. A maximum of 150 m difference was assumed. The potential head differences are shown in an enlarged portion of Figure 5-65 as Figure 5-66.

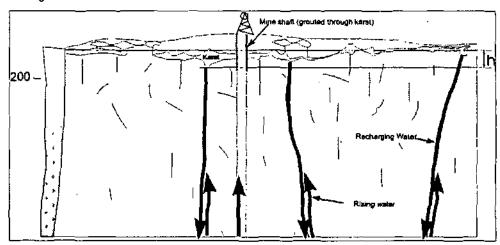


Figure 5-66. Possible head difference (h) to give gradient driving mine discharge.

Using the Darcy equation, it is possible to calculate the maximum rate of upward mine water effusion into the dolomites. The possible water dissipation into the karst thus could be between zero in cases where there is no significant

head difference between the water source and the recovered water level to the maximum values given in Table 5-25.

Table 5-25. Maximum mine water flushing rates.

	а	1	К	Q
	Compartment area (m²)	Hydraulic gradient	Hydraulic conductivity (m/d)	Maximum rate of mine water flushing (m³/d)
Bank	156600000	150	5.96E-07	1.40E+04
Oberholzer	153800000	150	3.42E-07	7.89E+03
Venterspost	54300000	150	9.19E-07	7.50E+03

If acid production and hence water degradation stop after flooding of the mine openings, the polluted water in the mines will be flushed. Due to incomplete mixing, flushing is not an exchange but rather a logarithmic decrease in concentration. The time for the water quality to reach some acceptable concentration is called renewal time. The calculation of renewal time is based on the assumptions that the system will be in a steady state with equal inflow and outflow in the mine voids, and that mixing is possible. The results are given in Table 5-26.

Table 5-26. Renewal times in different compartments.

	Mine void volume (m³)	Maximum rate of mine water flushing (m³/d)	Renewal time (years)
Bank	1134100000	1.40E+04	220
Oberholzer	1134100000	7.89E+03	390
Venterspost	102100000	7.50E+03	37

The graph in Figure 5-67 illustrates the logarithmic decrease in concentration.

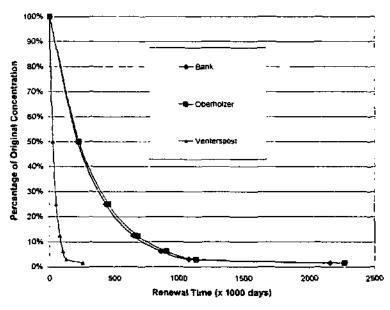


Figure 5-67. Dissipation in concentration due to renewal.

Based on the maximum flow rates and the worst case concentrations, the salt loads added to the system in this worst case scenario were calculated. These results are given in Table 5-27.

The worst case water in Section 7 was used and the sulphate values in the different mines were given a generalised value of 2000 mg/L based on this water. Using the 2000 mg/L sulphate values, the following salt loads will be added to the system.

Table 5-27. Loads associated with water effusion from filled mines (worst case scenario).

	Result of water quality after nth renewal (kg/d)						
	Original discharge	1st	2nd	3rd	4th	5 <sup>th</sup>	6th
Bank	2.80E+04	1.40E+04	7.00E+03	3.50E+03	1.75E+03	8.75E+02	4.38E+02
Oberholzer	1.58E+04	7.89E+03	3.95E+03	1.97E+03	9.87E+02	4.93E+02	2.47E+02
Venterspost	1.50E+04	7.50E+03	3.75E+03	1.88E+03	9.38E+02	4.69E+02	2.34E+02

The long renewal times imply that an ongoing problem might exist. In reality, far less of the contaminated water will be flushed out due to incomplete mixing and dead end mine voids. Table 5-28 shows the influence, calculated by simple mixing model, if between 10 and 30% of the discharging water is made up of mine contaminated water.

Table 5-28. Effect of different mixing proportions on discharge water.

		Mine water con	tribution	
	10%	20%	30%	•
рН	7.34	7.28	7.22	
Alkalinity as CaCO <sub>3</sub>	121	113	105	
Ca	72	117	162	•
Mg	33	49	65	
Na	69	135	201	
SO₄	195	388	581	
CI	85 ·	166	247	

Figures 5-68 to 5-72, derived from a three-dimensional model set up for the area and based on previous models (see Section 9.3.2), show the pollution dissipation due to the water rise, mixing and renewal. The model and thus the figure results are based on a porous continuum, thus the whole volume is depicted as being affected. In reality, only the secondary porosity and mine openings are involved as shown in Figure 5-12.

Post Mining Impacts 5-89

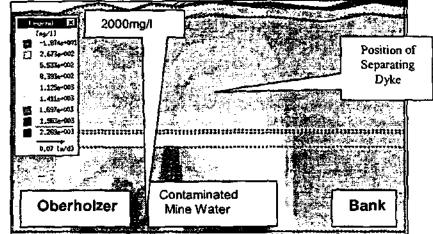


Figure 5-68. Pollution in Mine Void with upward migration after one year of rewatering.

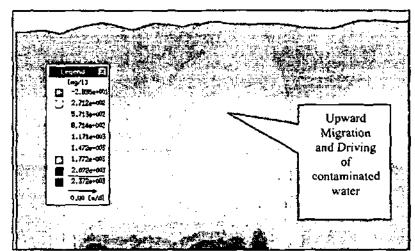


Figure 5-69. Pollution migration from rewatering after two years of rewatering.

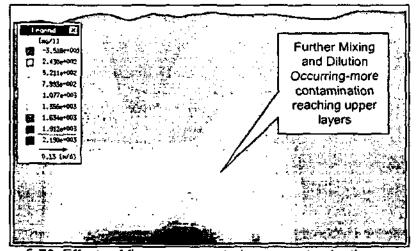


Figure 5-70. Effects of five years rewatering on contamination spread.

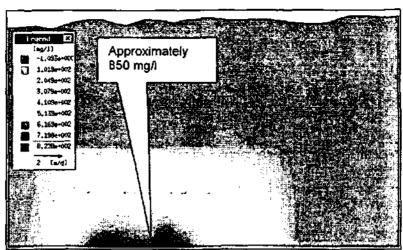


Figure 5-71. Decrease in concentrations of mine water pollution after 25 years of rewatering.

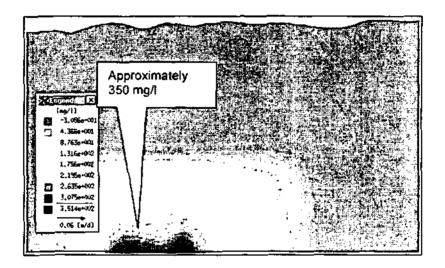


Figure 5-72. Diluted mine water after 45 years of rewatering - complete mixing and flushing - an unlikely best case end member.

# 5.10 Management Options

The management options discussed in this section have been indirectly dealt with already. They have driven some of the aspects of this investigation; some of the data gathering, modelling and descriptions have been working toward being able to discuss the management options. In spite of this, the options are still conceptual, since the scale of the mining and the available time preclude experimentation. The only experimentation possible was numeric modelling.

Thus the management option that is chosen for this area will not have been tested. What this report will attempt to provide is where water will accumulate, what the water quality will be and how much water there will be. The management tools discussed in the following sections must therefore be regarded as conceptual management options based on the information that is available.

In this section the scenarios that are possible will be described and related to conditions that have been found so far in the investigation.

The results will then be presented in a way that will facilitate choices and decisions about management in the area, now and what the future options will be.

## 5.10,1 Options

There are two option groups:

- 1. Full recovery of water levels and natural water passage through the system.
- Control of water recovery and discharge from the system by pumping.

The first option is appealing since it is self-managing and therefore sustainable.

The second option offers an engineered type of control, but has many disadvantages, such as:

- The long-term (endless) pumping costs and responsibility would be impossible for any of the mines to take on.
- Mine-closure approval would be extremely difficult to obtain, since the State would have to be sure that pumping costs would never revert to them.

The continued pumping option could only be accepted if it were self-sustaining and cost-effective. Options to achieve this for the Witwatersrand mines should be investigated as a future management strategy.

The permutations within each of these option groups will be discussed in the next sections:

- 1(a) Synchronous Rewatering No compartmentalisation.
- 1(b) Rewatering Engineered no-flow boundaries.
- 1(c) Rewatering Engineered single decant point.
- 2 Continued Pumping.

## 5.10.1.1 Option 1(a) Synchronous rewatering

This option is described in Section 9.1.2.

Unless further engineering is done, this option is limited as it might not occur naturally. For the option to be considered, the flow through the dykes would have to be assured. This might involve some engineered fracturing.

The Turffontein eye will be a single decant point, which can be controlled. A large volume of water will be available in the order of 150 ML/d, provided all the recharging water emanates here.

This scenario will prevent reactivation of the other eyes, thus water may have to be supplied at preferential rates to agricultural users, who would have benefited from a return to pre-mining conditions with all eyes yielding water.

Recharge water will be derived from a number of sources; its quality may be poor before it recharges the dolomite. This needs to be quantified by further research. If this water is allowed to recharge the dolomites, additional dissolution and increase in salinity are possible. These factors must be investigated before management options can be selected or implemented.

## 5.10.1.2 Option1(b) Rewatering- engineered no-flow boundaries

This option is described in Section 9.1.3.

If the compartmentalising dykes are still relatively intact, as opposed to holed through or weathered, so that they do form compartments. Evidence suggesting that this might be the case, includes the water-level maps given by Fleischer (1976) and SRK (1993). These maps indicate that the compartments react as independent systems with very little influence from one compartment to the next.

If the dykes have only been breached where mining has taken place through them, it should be possible to reverse the process and plug the "holes" to reinstate the integrity of the dykes. If the workings below the level of the dolomites can be sealed to prevent exchange of water between the Malmani dolomites and the lower workings, it may be possible to have the dolomites refilling in a "natural" way. (This option is mentioned in the SWAMP document, discussed below.). This is the only way for the system to return to the premining conditions. It will prevent water mixing and allow water levels to recover to elevations where it is possible for the original eyes to start flowing again.

This option may not be possible financially or from an engineering point of view. Despite this, its viability should be evaluated.

#### 5.10.1.3 Option1(c) Rewatering- engineered single decant point

Mines in the "Carltonville" section of the West Wits Line are located on Pretoria Group sediments. If the outflow could be engineered (e.g. a tunnel) to occur at a low enough elevation, onto the Pretoria group sediments south of the Weswitsrante range of hills, complete recharge of the dolomites would be prevented. This option also prevents discharging water from recharging the dolomites.

The southern part of the section given in Figure 5-10 and shown here as Figure 5-74, highlights this option.

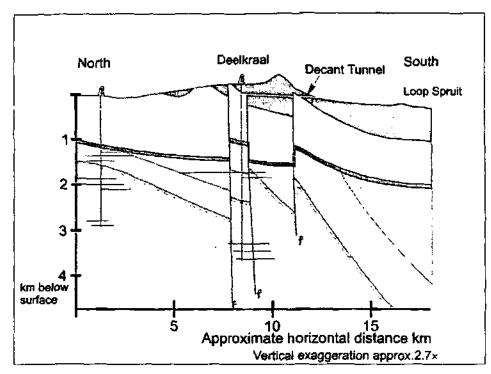


Figure 5-73. Section showing the relationships for engineered flow through Weswitzante Hills.

If the mines were interlinked so that all water discharged through such a tunnel, full recharge of the dolomites by mine water could be avoided. Discharge would then be toward the Potchefstroom Dam via the Loop Spruit. Thus the ultimate receiving water body, i.e. the Vaal River, would not change. Water treatment may be necessary.

This option has a major shortcoming since shaft elevations of the Doornfontein Mine are the lowest in the area. Discharge would thus occur naturally from Doornfontein into the dolomitic area. It would be necessary to transform the underground pathways to channel the water to Deelkraal or Western Deep Levels mines. This option thus involves major underground engineering.

This option, in conjunction with that outlined in Section 5.10.1.4, offers the greatest benefits for preserving the dolomitic aquifers.

The elevations of the shafts in the area, ordered from lowest to highest are shown in Table 5-29.

Table 5-29. Shaft positions and elevations. West Wits Line.

	x	у	Z
Venterspost 6	-68152	2906554	?
Doomfontein 2	-29584	2922819	1523
Driefontein Cons. 7W	-48820	2915063	1548
Driefontein Cons. 8W	-48800	2915232	1550
Western Deep Levels 1	<b>-42722</b>	2925186	1555
Driefontein Cons. 4W	-46916	2916844	1559
Venterspost 2	-63470	2910182	1562
Driefontein Cons. North	-47105	2917183	1565
Blyvooruitzicht 3	-37320	2919600	1567
Venterspost 5	-64110	2906705	1567
Blyvooruitzicht 4	-38255	2919091	1568

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Venterspost 5V	-64301	2907005	1570
Venterspost 2v	-62448.85 <b>6</b>	2911679	1575
Driefontein Cons. 3W	-44252.897	2918469	1578
Blyvooruitzicht 1	-38868.843	2920072	1582
Leeudoom 1V	-57035.036	2925899	1585
Blyvooruitzicht 2	-36812.547	2920837	1588
Doomfontein 3	-34274.012	2924146	1588
Doornfontein Annan	-33790.981	2920846	1588
Leeudoorn 1	-57159.078	2925903	1589
Libanon 1	-60704.288	2914490	1590
Driefontein Cons. 6W	-46687.922	2918601	1595
Driefontein Cons. 2W	-42648.626	2919095	1598
Libanon 1V	-60937.795	2914975	1601
Kloof 4V	-62192.086	2924473	1604
Driefontein Cons. 5W	-43070.728	2920697	1610
Driefontein Cons. 1W	-41948.162	2918770	1612
Kloof 4	-62299.004	2924702	1620
Libanon 4V	-60116.047	2916508	1620
Western Deep Levels 2	-40273.592	2923257	1620
Deelkraal 1	-30854.244	2928302	1621
Deelkraal 2	-30718.53 <del>9</del>	2928381	1621
Doornfontein 1	-32729.443	2921626	1622
Driefontein Cons. 4E	-51797,293	2918959	1622
Driefontein Cons. 2E	-50272.027	2919525	1625
Driefontein Cons. 3E	-50338.779	2919646	1630
Libanon 4	-61716.707	2916086	1630
Driefontein Cons. 1E	-48559.892	2919608	1641
Libanon Harvie Watt	-58853.612	2919165	1642
Elandsrand 1	-35713.768	2927209	1661
Western Deep Levels 3	-42966.709	2922785	1665
Kloof 1	-59707.231	2921288	1679
Kloof 1V	-59648.053	2921261	1681
Kloof 3	-61792.653	2918854	1726
Driefontein Cons. 5E	-50244.572	2922720	1730
Driefontein Cons. 9W	-48214.655	2923128	1735
	<del></del> -		

Figure 5-74 shows all the positions and elevations of the likely decant points and shafts. The most likely decant positions, are Doornfontein Shaft No.2 and Deelkraal surface water outflow.

Post-mining Impacts

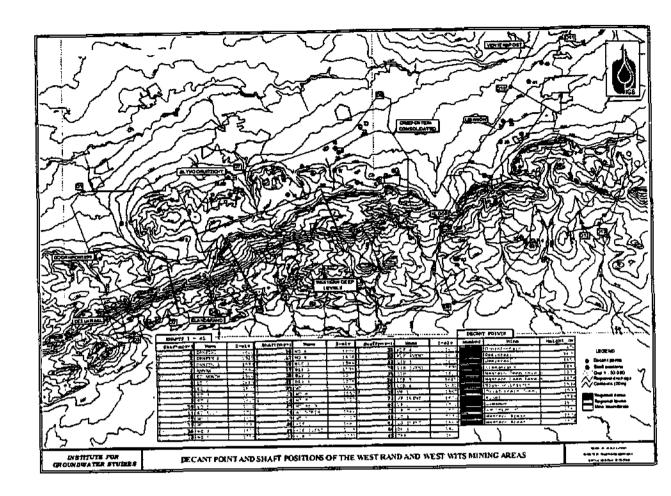


Figure 5-74. Decant positions and elevations of all shafts.

## 5.10.1.4 Option 2: Continued pumping

The pumping scenario has the following advantages:

- It allows greater control over the discharge rate and positions of water.
- Water treatment options can be engineered in such a way to maximise the benefits (or minimise the negative impacts).
- The danger of poor quality water reaching the dolomitic aquifer is greatly reduced.

Long-term pumping and dewatering of the areas can only be regarded as a realistic option if it is self-financing. A plan to achieve such a situation was being investigated at the time that this report was prepared.

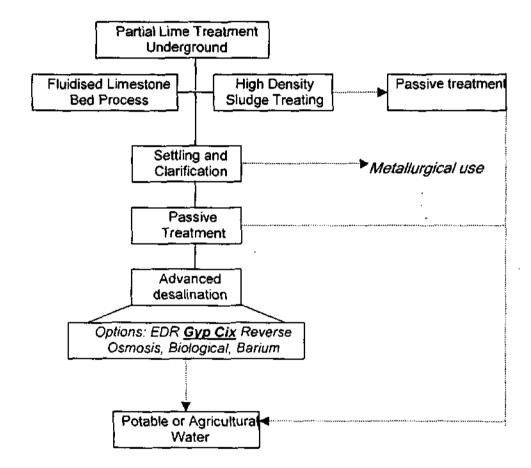
The West Rand mines, in collaboration with the mines on the Central and East Rand had formed a Strategic Water Management Plan for the area (SWAMP, 1998). This plan proposes to treat the water for sale and thus finance long-term pumping. Continued dewatering of mining areas will also benefit the mines and will help them to finance the project.

The mines involved; Randfontein Estates, West Rand Cons, First Westgold, Durban Roodepoort Deep and Grootvlei are sharing the cost of the project.

The water pumped out of the total area will have to be greater than 240 ML/d to prevent water level rise in the West Rand Mines and eventual pollution of the Sterkfontein dolomites to the north (See discussion of the West Rand model in Section 10). An additional pumpage of 107 Ml/d will expose currently flooded ore reserves, which will then be able to be exploited.

The pumped water will be of relatively poor quality; water treatment will produce two saleable by-products - gypsum and potable water. The gypsum industry has expressed interest in buying the gypsum provided the quality meets their requirements. Rand Water has indicated its interest in accepting the water if the quality is acceptable.

Processes are being designed and tested but will generally follow the following process flow chart.



#### 5.10.1.5 Benefits:

- Additional water to meet demand.
- Reliable long-term supply.
- Mining areas remain dry increasing profit, life of the mines and associated socio-economic benefits.
- Gypsum, an imported raw material, will be locally available saving foreign exchange.

 Poor quality inflows to the dolomite aquifer of the West Rand area will be prevented.

Implications regarding incoming water quality to West Wits Line mines were discussed in Section 5.

There are 3 scenarios discussed in the SWAMP (1998) documentation:

- Mines on the West Rand are allowed to recharge and decant.
- 2. Mine water is not discharged into the Wonderfontein stream.
- 3. Mine water treated, used and returned to stream as sewage effluent.

From these scenarios the following volumes, salt loads and salt concentrations are foreseen:

Table 5-30. Salt loads to Lower Wonderfontein from different Upper Catchment strategies.

	Scenario 1	Scenario 2	Scenario 3
	Mine water discharged into stream	Water not discharged into stream	Water treated, used, then discharged into stream
Volume (m³/d)	49 8	16 4	38
Salt load (kg/d)	138 9	10 7	18
Salt concentration (mg/L)	2800	650	490

It is clear, provided the system works as set out in the document, that treatment would be a better option than direct discharge into the stream. An alternative end receiver is also an option that should be investigated, if the project is implemented.

The SWAMP plan is still in development, comment will have to be reserved for the final proposal.

## 5.10.2 Other management options

Some of the other management options that have been proposed are discussed in the following sections and include:

- · Use water before it enters the mines
- Reduce recharge from stream losses

## 5.10.2.1 Consumptive use.

This will entail the planned productive use of water as it enters or before it enters the different compartments. If the SWAMP strategy were adopted in the West Rand, a large volume of water could be diverted through the treatment works. This will decrease the flow in the Wonderfontein Spruit, which in turn, should increase influx into the dolomitic compartments further south. Other options of utilising the water, before it reaches the compartments, should also be explored.

The result of use, whether consumptive or by diverting it to be disposed of in catchments where the dolomites cannot be recharged, will be a decrease in the

volume that will enter the mines. Thus decant or pumpage will be decreased, reducing pumping and water treatment costs.

# 5.10.2.2 Decreasing the amount of recharge.

The mines have done this in various areas to reduce recirculation and hence, pumping of water. Chief amongst these practices is the use of pipelines and concreted canals and improved water holding ponds. The benefits are therefore reduced decant or pumpage volumes, so reducing pumping and water treatment costs.

## 5.10.2.3 Finding uses for the poor quality waters. .

One of Fleisher's (1981) suggestions was that the viability of fish farming be investigated. This is the type of synergistic solution that will be necessary to solve the problem and active involvement should be sought to identify ideas and evaluate options.

In most of the mines, environmental management plans to minimise impacts were planned. Their implementation should be monitored and ensured by the responsible agencies.

# Appendix 1 Mine Plans and Surface Waste Sources

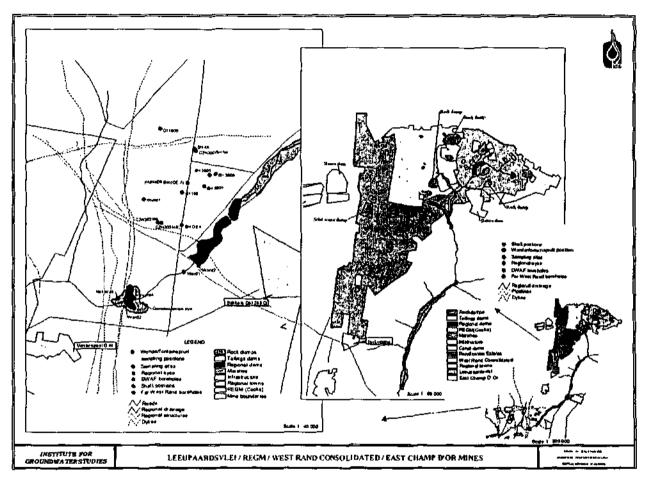


Figure 5-75. : West Rand Area.

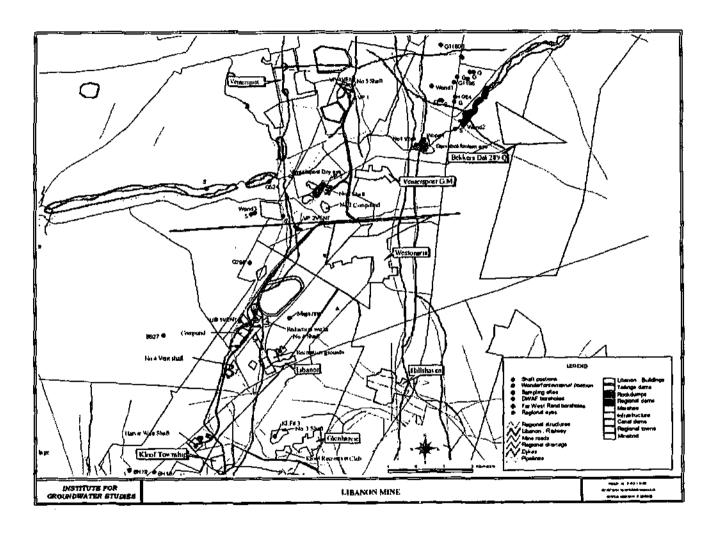


Figure 5-76: Libanon, and Venterpost Mine Areas.

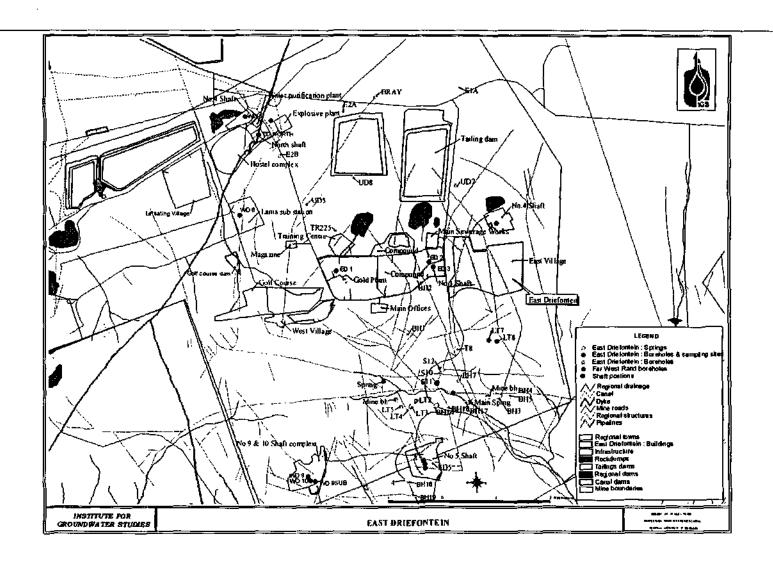


Figure 5-77. East Driefontein Mine.

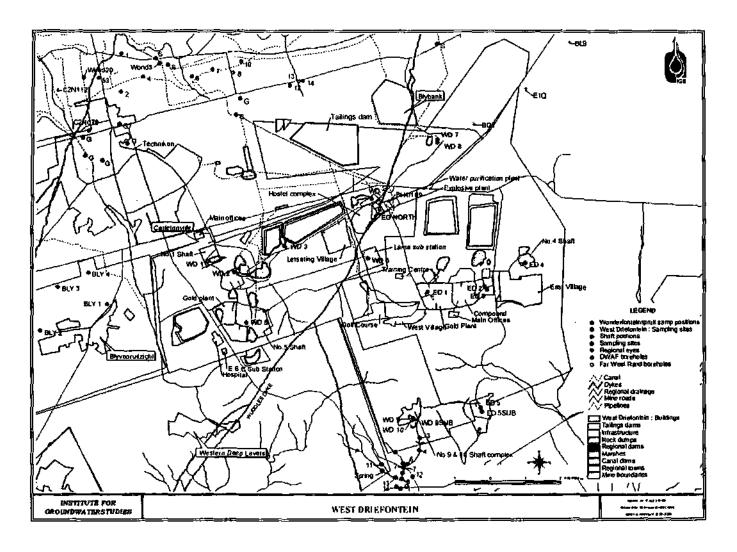


Figure 5-78. West Driefontein Mine.

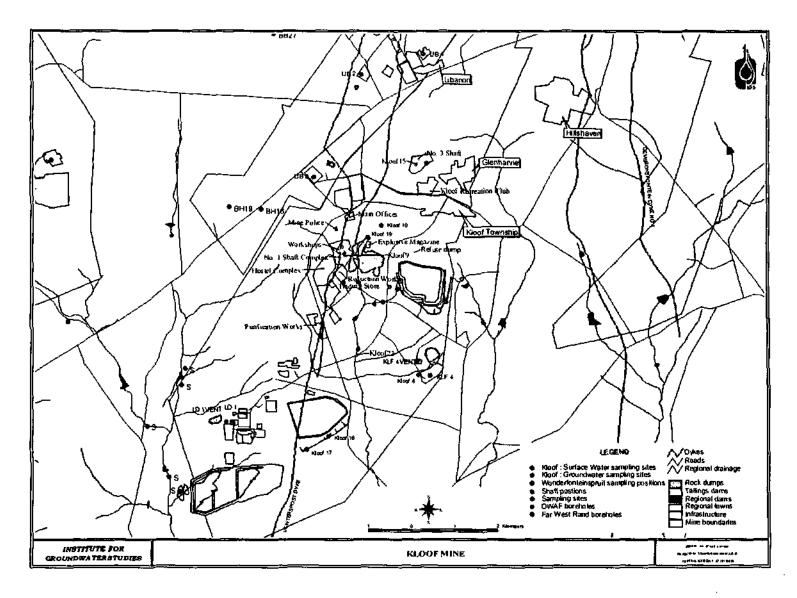


Figure 5-79. Kloof Mine.

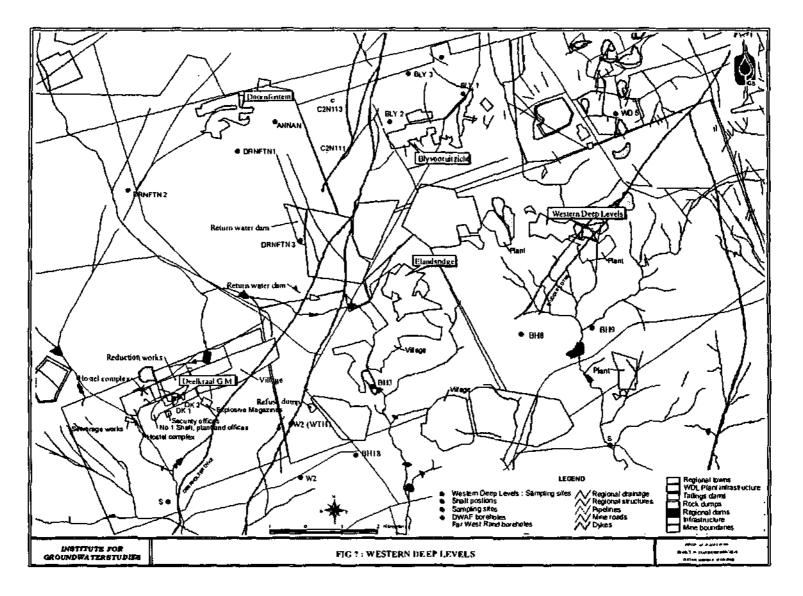


Figure 5-80. Western Deep Levels.

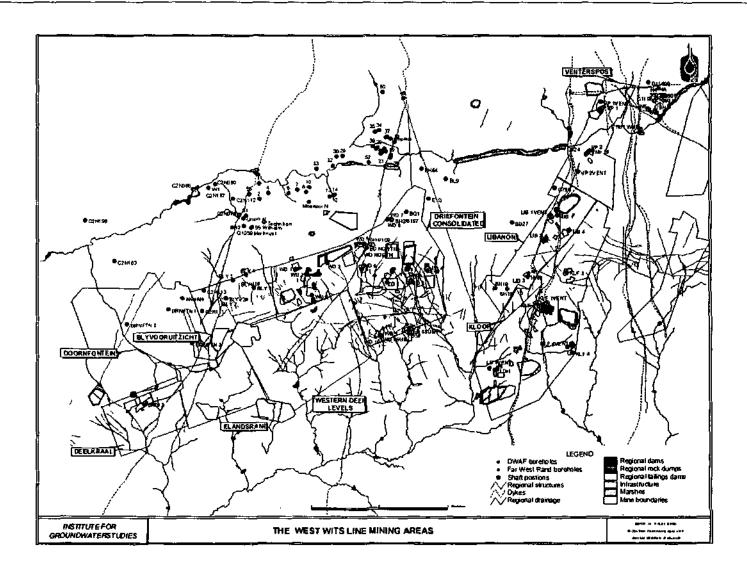


Figure 5-81: West Wits Line mining area.

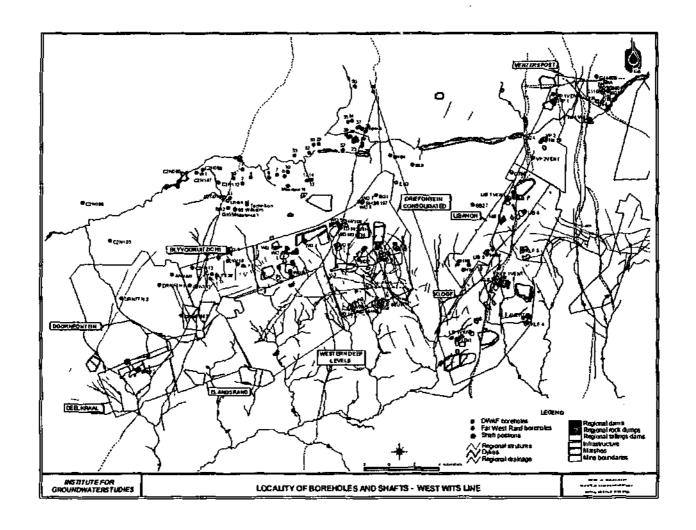


Figure 5-82. West Wits Line monitoring boreholes used by GFSA

# APPENDIX 2 GLOSSARY OF TERMS

1000 mm pipeline. This pipeline conveys water from the Wonderfontein Spruit. It was introduced in 1978 to prevent recharge of the karstic dolomite from the stream. This reduced the amount of water that entered the mines.

Arenaceous, sandy. Sediments consisting of coarse material, usually sand. They usually are nearly monominerallic being made up of quartz. This mineral is non-reactive and water stored in such rocks or sediments usually has good quality.

Argillaceous, clay. Sediments consisting of fine material, often deposited in backswamp or stagnant water conditions. The sediments have high surface areas and may display a variety of surface chemical reactions including ion exchange and adsorption. Water that has moved through these sediments commonly has a high salt content

Chert, amorphous  $SiO_2$ , formed by chemical precipitation, forms bands in dolomite and is resistant to weathering, thus giving some of the dolomite formations a characteristic banded appearance on outcrop. Because of this appearance, these rocks are desirable as garden stones.

Colluvial. Material that has been transported by slight gravity movement e.g. soil creep or hill wash, as opposed to alluvial movement by wind and alluvial movement by rivers. It does not imply long distances nor high-energy transportation and will not form discrete sedimentary layers or textures. It is part of natural pedogenic and weathering processes.

Diffuse pollution source. Diffuse pollution is pollution that cannot be traced to any definable source but emanates from combined sources over a large area and often over a long time. It may be cumulative so that monitoring of sources show that they are all within limits, but collectively pollution is generated. Because the source cannot be identified, diffuse pollution can often not be remediated. At best, if the general source is known, management options can be employed to lower the outputs and thus reduce the diffuse pollution.

Eye (in Afrikaans oog). This is an Afrikaans synonym for source. The term was used to name the source spring of a river, as in: <Rivername> Oog. In the investigation area, a number of very large springs issued from the dolomites and thus a number of sources were named. In this karst area, many of them disappeared underground to reappear as another source downstream. Thus the name Eye is common in the area. Grike. Solution along joints or fractures produces channels called grikes. Two or more joint or fracture orientations producing a network of crossing grikes leave pillars or clints between the channels. When water has gone underground, a soil cover may obscure the topography.

Hazard. This is a term usually used when risks have been evaluated using nonparametric methods. Thus crossing the road constitutes a hazard the variables and the threat may have been identified, but statistical parameters or degrees of the hazard cannot be determined.

Karst. A result of solution weathering in dolomites or other carbonate rocks. Natural fractures in the rocks are widened by solution, rivers go underground and flow in the solution openings, at surface potholes (round solution holes formed by swirling water), swallow holes (holes in which water swirls and then funnels down to solution cavities below) and grikes (channels that develop along joints or fractures). As solution progresses downwards, large caverns may be left dry forming caves and cave systems. Frequently, cave roves collapse as the openings become large giving rise to sinkholes if the surface collapses or dolines if the surface sags. Dry rivers, pot holes, grikes, clints, sinkholes and dolines are all topographic features that are part of a karst topography.

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Leachate. A solution derived by water percolation through material that by its chemical reactivity, the solubility or toxicity of its contents changes the water chemistry. The resulting solution usually contains unacceptable levels of salts, toxicants, pH or combinations of these.

#### Minerals

Carbonate Minerals. A group of minerals with very similar properties, consisting of divalent metals and carbonate  $(CO_3^2)$ .

Calcite, CaCO<sub>3</sub>

Cerusite, lead carbonate PbCO 3.

Dolomite, CaCO<sub>3</sub>.MgCO<sub>3</sub>. Dolomite is also a name given to a rock type consisting predominantly of crystalline carbonate minerals.

Rhodocrosite, magnesium carbonate MnCO 34

Siderite, iron carbonate FeCO<sub>3</sub>.

Smithsonite, zinc carbonate Zn CO<sub>3</sub>.

Ore minerals. Minerals from which metals are recovered. This is not a well-defined term. In the study of rock in thin sections all opaque minerals are commonly referred to as ore minerals, these include many metal oxides. Some valuable minerals are not opaque, such as rutile, sphalerite and cassiterite.

Sulphide minerals. Metal sulphides and arsenides are common constituents of ore deposits. They have usually formed in reducing environments and on oxidation yield metal oxide crusts referred to as gossans. The gossans associated with large sulphide deposits can affect large volumes of rock and deep weathering is commonly associated. This is evidence of the aggressive nature of oxidising sulphide deposits. A few examples referred to in this document include:

Arsenopyrite FeAsS.

Chalcopyrite CuFe S<sub>2</sub>

Galena, lead sulphate and principal ore mineral mined for lead. PbS.

Gersdorffite NiAsS.

Mackinawite (Ni)FeS.

Marcasite, a low temperature polymorph of pyrite FeS<sub>2</sub>.

Pyrite FeS<sub>2</sub>

Pyrrhotite Fe<sub>1-x</sub>S.

Sphalerite, zinc sulphate and principal ore mineral mined for zinc.

ZnS.

Troilite FeS.

#### Oxide minerals

Many metals combine with oxygen to form oxide minerals. Some of these are also mined as a source of those metals.

Haematite, principal ore mineral of iron Fe<sub>2</sub>O<sub>3.</sub>

Magnetite, development of the energy saving direct reduction technique has introduced this mineral as a source iron, Fe<sub>3</sub>O<sub>4</sub>.

Silica, SiO<sub>2</sub>. There are a number of forms of this oxide:

Quartz is a very common rock forming mineral. It is the most common constituent of sand. Tridymite and cristobalite are high temperature and pressure polymorphs.

Chert is an amorphous (non-crystalline) form and formed from a chemical precipitate.

Urannite UO2

Mylonite. A rock produced by movement of rocks against each other during tectonism, e.g. along a fault. Mylonite consists of fine fragments and dust of the original rock types now crystallised into a solid mass.

Phyllosilicates. A group name for minerals that have a platy morphology. Minerals that belong to the group include mica, clay minerals and talc. The minerals are common as weathered products and in tectonic environments where rocks have been

fractured, bent or moved. Many of the minerals in the group occur as microscopic to submicroscopic (<100 mm) grains and when present can impede the passage of water due to characteristics like high surface area and electrochemical water retention.

Point pollution source. Point pollution may be from a single source. It may be an accidental spill and therefore short lived or from some illegal waste disposal. Point sources can be identified and usually removed or more easily regulated.

Porosity. This refers to the pore spaces between solid particles in rocks. This could be filled with air as in dry sand or with water as in saturated sand. Such porosity is referred to as *primary porosity*. As sediments are lithified or weathered, the pore spaces may be filled with other secondary minerals, e.g. clays, thus reducing the pore space. Crystalline rocks have little pore space because they are made up of interlocking crystals. Rocks are brittle so any crustal movement can cause various types of fracturing. These fractures are a form of porosity, which could be air filled or store and convey water in saturated conditions, called *secondary porosity*.

Risk. This is usually a statistical procedure to determine whether an identified user could come to some harm from a product. Risk implies that there is a threat or source of danger, be it failure or contamination and that there is a consumer be it human, or natural that is exposed to the threat. Evaluating the risk then implies that there is some measure or standard against which we can evaluate the degree of danger or threat. Thus if a contaminant level has been determined which will cause death, we can then evaluate the risk that a certain source will produce contamination at that level. Risk will be expressed in statistical terms of probability. For example, there is a 50% probability that x practice will contribute a lethal (to most sensitive user) dose of y contaminant into a stream. The risk being defined, some precautions can be applied after which the risk may be reduced to acceptable standards for example a 5% chance that the practice will contribute the lethal dose. In many activities, it may be impossible to reduce the risk completely. For example, you may have a high risk of being knocked down if you cross a busy road (the risk of a child being knocked down would be even higher); the risk could be reduced but not eliminated by installing a traffic light.

Solubility product. This is a measure of the solubility of a substance, in equilibrium, in pure water. Theoretical values have been determined and published by many authors, e.g. Stumm and Morgan (1991). It is determined by the equilibrium

Solubility product = 
$$\frac{\prod (Pr \ oducts)}{\prod (Re \ ac \ tan \ ts)}$$

concentrations in activity of reactants and products:

For dolomite, the dissociation reaction is  $CaMg(CO_3)_2 = Ca^{2+} + Mg^{2+} + 2CO_3^{2-}$  with solubility product 1.995 $IIO^{-12}$ . Thus showing that the ratio of products to reactants is extremely small, i.e. the substance is virtually insoluble in pure water. Statistical terms

Analytical. Based on exact values that may be evaluated using an equation (exact), or mathematical model (numeric).

Deterministic. An mathematical technique that may be determined by ranking and order of variables as opposed to exact or stochastic values.

Monte Carlo. A technique whereby stochastic variables are applied to an analytical solution to give a stochastic answer.

Stochastic. Based on measurements that follow a normal distribution (range of values). Stochastic solutions may be given as probabilities.

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#### 6 CONCLUSIONS

Conclusions have been drawn in each of the preceding chapters. The conclusions in this chapter are therefore of a general nature. These are as follows:

#### 6.1 Risk assessment

- Mining in South Africa has a greatly variable potential to pollute groundwater resources. This is due to a variety of circumstances, all of which play a role in the potential to generate and transmit polluted mine water. The risk assessment in this study takes 22 factors into account. Of these, the overriding concern is acidification of systems. Upon acidification, mine water converts from a harmful to a toxic status.
- Of the other 21 factors that contribute to the risk assessment, the salinity of
  the water is probably the overriding one. Usually, saline water has to be
  diluted or desalinated before it can be used. Both these options are not
  feasible in the South African context, because of its low annual run-off and
  a problem of disposing the brine after desalination.
- The importance of each of the risk factors may vary from one mining type to the next. Weighting factors can be adjusted to suit individual needs, but this should be done with caution since it will distort regional evaluations.
- This risk assessment is intended to be used on all levels. It should be used by mines to evaluate specific actions. Mining houses should use it to compare the performance between mines. The DWA&F should use it to compare mines on a catchment, province or national basis.

## 6.2 Case study investigations

#### 6.2.1 Underground high extraction of coal

Several significant conclusions have been drawn from this research:

- Much can be done by mining companies alleviating matters during mining.
  The mining sequence should be from deep areas retreating to higher ground. The surface above high extraction areas should be rehabilitated.
  Pillar extraction and shortwall mining are preferred above longwall mining.
  Streams should not be undermined. Through proper planning, most underground high extraction collieries should be able to contain their water by utilising underground space.
- The current practice of desalinating mine water is expensive and only viable
  if a disposal site for the brine from the desalination process can be found.
  This has not been the case to date.
- High extraction collieries will fill up with water after mining has ceased. Mine
  water will then decant onto the surface. Depending on the local
  hydrodynamics, the decanting water will at first be clean, then saline, as the
  mine water is displaced by influx from the top. Decant of water from the
  mine will exhibit a logarithmic decay in salinity. It is likely that salinity will
  drop by 50% in 25 years.

#### 6.2.2 Coal mining in KwaZulu-Natal

Much of the larger, continuous coal reserves in KwaZulu-Natal have already been mined. Conclusions are as follows:

- The coal hydrochemistry has been researched in detail in five collieries of the Vryheid Coal-field. A conceptual model has been suggested, stressing the importance of complete data sets.
- The buffering of sodium, calcium and magnesium carbonate is explained and the mines are classified accordingly.
- The acidification of certain mines against others that have not acidified has been tested against the conceptual model.
- The conclusion is drawn that conceptual models of this kind, based on sound scientific principles and complete data sets are sufficient to describe current and future behaviour of the system. The Vryheid Collieries have already reached equilibrium status in terms of water throughflow and values should be measured rather than modell ed.
- Hydrochemically, values range from sodium-buffering to acidic phases. It is concluded that the high throughflow of water will leach the remainder sodium-buffering from the coal and rock. The calcium/magnesium-buffering potential of the coal is inadequate to neutralise all acid to be produced. In the long term, acidification of all the collieries in the Vryheid Area is expected.

In terms of actions to minimise the impact on the Nkongolana River, very few options are open.

- Water influx into the mine is highly variable and cannot be controlled.
- · All available space in the mines has been filled with water.
- Treatment of the acid water that decants is a foregone conclusion.
- Treatment should be on a catchment basis rather than by the individual collieries.
- To ensure efficiency, a water management company should be established.
- In view of changing legislation and new information on the scale of the problem, the Government should share responsibilities with the mines.

#### 6.2.3 Mining in the West Rand Area

Mining is due to continue for many years in the gold-mines of the West Rand. This study has therefore been appropriate to draw awareness to potential problems that may arise in terms of the long-term groundwater management. Conclusions are:

- Pollution from mine water and slimes disposal currently have the main impact on water quality in the Mooi River.
- The extent of the current dewatering by mines is likely to persist until mining ceases.
- Thereafter, the mines will fill up with water and seepage will commence into the dolomites. This will be in the time frame of 6 - 36 years for different mine groups.
- Seepage is anticipated to be from several localities. The quality of this water
  will be excellent at first, with possible degradation over time. The extent of
  this degradation will depend on flow paths and mixing. The combined effect
  of this seepage on the catchment will be less than the current impact.

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- The slimes dams have been identified as the major current source of groundwater pollution in the area. Much of this pollution drains into the mines. After recovery of the water table, the direct impact from slimes dams will increase significantly.
- Of the two strategies for water management, pumpage versus free discharge, the latter is preferred. If for any reason, free discharge poses a problem, the system can be reverted to abstraction, which would have a cleansing effect on the dolomite aquifer.

# 7 RECOMMENDATIONS FOR FURTHER ACTIONS

The most important issue emanating this study is that insufficient data is often available to evaluate the regional and long-term impact of mines, particularly for the period after closure. The details in the EMPR documents are mostly of a descriptive nature and insufficient for a scientific regional impact assessment. The following recommendations are made for further work:

## Establish regional information systems

Regional information systems that combine relevant information from the mines should be established and maintained. The RISKY software, coupled with GIS, is a first step. The Intermine Flow Project, currently under way, would also serve as a sound basis for the establishment of such a regional information system.

#### Investigate areas of insufficient information

Regional risk factors should be extracted from the regional information system. Investigations should be launched into areas of insufficient information. These should be researched to the extent that they could serve as guide-lines for granting closure. The regional information system should be populated with relevant time series and other data which can be used for extrapolation purposes.

#### Integrate data

Integration of the numerous bits of information should be done. Water is an interrelated discipline. Many studies have been done to date on mine water deterioration. This information should be integrated to identify data deficiencies and allow the definition of solutions.

#### Define solutions

Definition of solutions at a very early stage is essential. The industry and the government should tackle problems from a futuristic point of view. Solutions that would be valid in 50 years from now should be identified, researched and implemented as a combined strategy.

Post-mining Impacts 7-1

