Scoping level assessment of how water quality and quantity will be affected by mining method and mining of the shallow Waterberg coal reserves west of the Daarby fault.

Report to the
Water Research Commission

by

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Executive Summary

Introduction

The Lephalale region of the Waterberg contains the third largest coal reserves in South Africa. This has been identified as giving a unique competitive advantage to the Waterberg District, so that it can become a new powerhouse for coal-fuelled electricity production in the country.

The study area is located west of the town of Lephalale in the Waterberg region of the Limpopo Province of South Africa and stretches from the town of Lephalale in the east, to just west of the town of Steenbokpan in the west and all the way to the border of Botswana in the north. The Limpopo Province is South Africa's northernmost province, lying within the great curve of the Limpopo River. The Limpopo Province is seen as the gateway to the rest of Africa, with its shared borders making it favourably situated for economic cooperation with other parts of southern Africa. The Limpopo Province shares international borders with three countries, namely Botswana, Zimbabwe and Mozambique. The study area lies within the greater Limpopo River catchment, has a low rainfall and is drained by two rivers; the Mokolo, running north-south and the Limpopo, running roughly south/west-north.

The area has generally dry climate, with temperatures reaching 40°C and higher during the summer months. The area receives little rainfall during the year. The rainfall is concentrated between September and March (summer rainfall area). The study area has a mean annual run-off of 150-397 mm and the MAE (evaporation) is 1800-2000 mm/a. Recharge is estimated at <10 mm/a or <1.5% of the annual rainfall (Vegter, 1995). The average rainfall is between 285 mm and 560 mm per year (SA Weather Service, 2008).

The rain is not evenly spread during the rainy season and happens as massive downpours that can last from a few minutes to several hours. October has the highest precipitation when compared to the other months of the year

It is unknown how many additional mines are planned for the study area, but in all likelihood it is doubtful that there will be such a large number of pits that they will change the surface topography to such a dramatic extent that they will change the flow direction of surface runoff. Efforts should be made by all parties to minimise the amount of damage done to the environment. This will be challenging, as all the mines located in the study area will be open-pit mines. This requires the removal of overburden, plants and animals from the pit location. An effort should also be made to safeguard the endangered species that inhabit the area in question.

Scope of the investigation

This is where the importance of this project comes into play. Due to the planned expansion of the mining enterprises in the area and the accompanying developments, it is important to determine the extent of the impacts these developments will have in the study area. This study will look specifically at the impacts these developments will have on the groundwater quality and quantity in the area.

A scoping level study was performed to consolidate the existing information on:

- The different aquifers in the study area and their geohydrological parameters.
- Pre-mining water quantity and quality of water resources associated with the Waterberg coal field.
- The acid generating potential of the geology found in the study area.
- Detect potential problem lithologies with regards to higher acid generation potential.
- Predict what the impact will be of additional mines in the area.
- Determine if the mines would ever reach decant level.
- Provide recommendations on management methods that are applicable to the study area and that have relevance for the study area.

Methods of Investigation

To obtain the necessary information to complete the objectives of the study, many different methods needed to be employed. The project was conducted in several stages to accommodate the different types of information required. Accordingly the initial stages of the project consisted of two hydrocensus, the aim of which was to locate as many boreholes in the study area as possible.

The information recorded during this initial field work included parameters such as water levels, borehole depths, location (X, Y, Z), and preliminary EC and pH measurements. Together with these parameters groundwater samples were collected from boreholes in the study area to be used for quality determinations.

In addition to the hydrocensus, other information sources were approached such as the geologists at the Grootegeluk mine, Sasol mining and Eskom to name but a few, in order to gather additional information on the study area. From the Grootegeluk mine and Sasol, geological samples were obtained to be used for determining the acid potential of the rocks in the study area.

Once sufficient information had been gathered it was compiled into a single database. This database was used for the other determination such as for example the construction of contour maps, the determination of recharge and so forth. Following the initial hydrocensus and information gathering expeditions, numerous tests were conducted in the field to determine the aquifer parameters of the different aquifers present in the study area.

These parameters were necessary for the determination of, for example, yields of the different aquifers and they would additionally be used during numerical groundwater flow modelling. These tests were comprised of pumping test and slug tests. The tests were performed where possible and according to the requirements of the project.

To account for influx of water to the study area, the recharge for the study area was calculated by means of the Chloride Mass Balance method and the E.A.R.T.H. model for calculating recharge. These calculations indicated a low recharge for the study area in accordance with maps constructed by Vegter (1995), which indicated a recharge of between 1.5% and 1.9%.

All of these parameters would later be used during the modelling. For the purpose of determining the acid potential, acid-base accounting (ABA) was performed on the collected samples by using the peroxide static test method. This method is only a screening mechanism to determine if certain rocks would become acidic, it can unfortunately give no indication of the amount of acid that will be generated or the length of time it will take for the acid to be generated.

The ABA tests indicated that most of the samples collected would become acidic upon oxidation. To form a more complete conclusion of the potential impact of mining of the coal field, samples were collected from the beneficiation plants at the Grootegeluk mine. These samples were also analysed for acid potential, the results of which indicated that the samples will become acidic upon oxidation. The sampling for the ABA was done according to the weathering depth of the geology in the study area. Accordingly the study area was divided into three zones according to the level of weathering. The results from the tests indicated that some areas were more prone to acid generation and in certain areas the rocks located at certain depths even more so.

Numerical modelling was used in order to determine the impact the mines would have on the groundwater and the flow directions of the groundwater. Several different scenarios were simulated using the parameters that had been collected during the field work. The scenarios were constructed in such a manner as to simulate the conditions for both dewatering and decant potential of the mine pits. The dewatering models indicated that there was very little water available in the study area with small volumes of water predicted to flow into the mines. The decant models indicated that there was no possibility of the pits ever reaching decant levels with the highest recorded rise being seven meters 50 years after mining had stopped.

Given all the results obtained from the various tests, the relevant literature and people from the mining industry were consulted as to the appropriate water management options for the study area. It was concluded that the most effective way to preserve the water quality and protect the groundwater quality from further deterioration, was to keep all acid generating material dry as it would not be possible to flood this material once the mine closes due to the small volumes of water in the study area.

Geology

Large quantities of coal are available for mining in the Waterberg coalfield. Iscor began the development of the Grootegeluk colliery in the 1970s which is currently the only active mine in the study area. The study area includes most of the Karoo Supergroup, The predominant structures (the three main faults) are the Daarby, the Zoetfontein and the Eenzaamheid faults.

The Waterberg Coalfield trends east / west and is heavily faulted. It is composed of sedimentary rocks of the Karoo Sequence and forms a graben structure bounded in the north by the Zoetfontein fault and in the south by the Eenzaamheid fault. The Daarby fault subdivides the coalfield into the shallow opencastable western part and the deeper north-eastern part of the coalfield (a displacement of approximately 400 m). The Zoetfontein fault resulted from pre-/during Karoo depositional tectonism, whilst the Eenzaamheid and Daarby faults resulted from post-Karoo depositional tectonism.

The coal-bearing sequence is 115 m thick and subdivided into 11 zones. The lower four form part of the Vryheid formation. These zones coincide with the four lower seams of predominantly dull coal, with an average thickness of 1.5-5.5 m. The ash content of these seams increase upwards from 20% to roughly 45%.

Once the mines reach Coal Seam 2, the opencast mining method will cease to be economically viable and underground mining will be required to remove the remaining coal. The barrier between the opencastable underground coals is a thick succession of Ecca sandstone.

It is apparent that the coal seams are located at shallower depths in the west and at much deeper depths in the east and north/east.

The study area was further divided into three main categories according to weathered geology. They are:

- Areas that contain the full succession of geology
- Areas that have been weathered down to the middle Ecca
- Areas that have been weathered down to the lower Ecca
- The coal is of such low quality that it will need to be beneficiated to maintain profitability. The necessity for beneficiation plants gives rise to other potential problems. These beneficiation plants will require large volumes of water to operate, which will increase the strain on groundwater systems if the required water is to be abstracted from boreholes. In an area where there is already a shortage of water (including usable groundwater), this would present a serious problem. Furthermore, the discard from the beneficiating plants contains minerals that are prone to acid generation.

Mining Methods in the Waterberg Coalfield

The entire area west of the Daarby fault will be mined using the opencast method due to the shallow depths of the coal. The mining method currently employed at the Grootegeluk mine is known as bulk mining, a form of opencast mining. Exhausted mines are sometimes converted to landfills for the disposal of solid wastes. However, some form of water control is usually required to prevent the mine pit from becoming a lake, and also to prevent the water from becoming acidic. The problem of the open pit becoming a lake is of less concern in the study area, due to the low levels of annual precipitation, low transmissivities, high evaporation and the deep groundwater levels found in the area (which will be discussed later). The mining method used at the Grootegeluk mine is known as bulk mining, it is a form of open cast mining that involves the removal of all relevant material and then processing all the material. This form of mining is practiced as it has been found that is the most inexpensive and the most efficient way of mining the coal seams in the study area. This is due to the fact that the coal occurs inter-bedded with thin layers of shale and mudstone. Selective mining is thus not seen as a viable option for the study area. However it is recommended that the new mines start with mining the deeper coals west of the Daarby fault. This will initially be expensive as the stripping ratio of overburden will be higher but this will be to the benefit of the mine at a later stage.

The coal seam in the study area is sub-divided into eleven coal seams, one being the deepest and eleven being the shallowest. At Grootegeluk the mining process only mines down to beneath seam three. It has been deemed uneconomical to mine beneath seam three, as the seams below seam three are covered by thick sandstone layers and the additional excavation of these layers will increase the stripping ratio of in the mine. It is recommended that the new mines planned for the area follow the example of the Grootegeluk mine with regard to mining methods, spoil handling, water management and rehabilitation. For the planned sub-surface mining in the future there are three methods used elsewhere in South Africa that can be used to the same level in the study area. The specific conditions for the different mines will however need to be taken into account when planning for sub-surface mining.

Pre water quality

It is expected that the addition of new mines and power stations will impact negatively on the quality of the groundwater in the study area. It is expected that the EC values will increase along with the SO_4^{2-} values in the vicinity of the mines owing to ARD. It is expected that the Cl values may fall depending on the activity and the local conditions near the mines (geology, elevation). The water quality of the study area that has been unaffected by activities such as mining and power generation, can be classified as moderate at best. The area as a whole in general has high electrical conductivity (EC) and Cl values with near neutral pH values. At present there exists a fine line between usable groundwater and unusable groundwater in the study area. It is predicted that the addition of the new mine to the area will have an adverse effect on the groundwater in the immediate vicinity of the mines.

Water levels

The predominant flow directions of groundwater in the study area will be towards the east, the west and to the north, away from the central elevated regions with little if any flow towards the south. From observations made at the Grootegeluk Mine with regards to the influence the mine and the dewatering of the mine have on the surrounding aquifers, it is expected that the addition of new open pits to the area (specifically in the central areas) will change the flow direction of groundwater. The changes that the open pits will create to the topography (the excavation of big holes in the ground) will have an impact on the direction of flow of the groundwater. For example, if all the mines that are planned for the area were to be located near the centre of the study area, the excavation of the pits will lower the topography to such an extent that the flow direction of the groundwater will be influenced.

Aquifer Parameter Testing Results

According to the slug and pumping tests of the western parts of the study area, there are vast differences in the transmissivities of the area and yields of the boreholes. It must however be kept in mind that these test results could have been influenced by the high quantities of rainfall during the time of testing. A total of 51 boreholes have been pump tested in the study area from 1987 to the present.

From the information gathered it is apparent that the aquifers in the study area are low yielding and that the formations have low transmissivities. These findings conform to typical Karoo aquifer parameters. Given the low transmissivities of the formations it is predicted that the new mines planned for the study area will not have problems with regards to large volumes of water flooding the mines. Furthermore, as a result of the low rainfall, the low transmissivities, the water level (averaging around 28 m) and the high evapotranspiration in the study area, it is predicted that the water levels in the mines will not reach decant levels.

This was confirmed by the numerical modelling, which indicated that 50 years after mining had stopped the water levels in the modelled pits rose by between two and three meters. The largest contributor to the rise in water levels in the pits being surface runoff during periods of high rainfall. From these results together with the deep water levels, the low rainfall and the high evapotranspiration, it is predicted that the pits in the study area may have water flowing into them, but they will never decant.

Recharge

The recharge determinations for the study area indicated a value of between 1.5-1.6% for the entire study area. This is in accordance with the maps that Vegter (1995) has drawn up of the study area, placing the recharge at between 1.5% and 1.9%. Both the E.A.R.T.H. and Chloride methods for determining recharge gave values in the same order, indicating that both of these methods can be used with a high degree of certainty in the study area. Furthermore, the low recharge coupled with the low transmissivities found in the study area present both positive and negative situations for the mines and farmers in the study area. For mining it is positive in the sense that there will be little inflow of water into the mines (which has been confirmed by modelling). On the negative side this poses problems, because as boreholes in the vicinity of the mines are dewatered, they will take very long to reach their initial levels, if ever.

For the farmers the situation is only negative. Dewatered boreholes will take long times to reach their initial levels and boreholes in the vicinity of the mines are unlikely to ever recover. Therefore, precautions should be taken to minimize the impact of the mining on the groundwater.

Acid-Base Accounting Results

From the results of the Acid-Base Accounting (ABA) analyses one can conclude that, in most cases, there is sufficient neutralisation potential to account for any acid generated if a constant ratio is maintained (every ton of acid rock should be mixed with a tone of base potential rocks). There are however some exceptions:

The North Western Samples:

- The analyses of the samples taken from the north western sampling location indicated that the rocks in the area contain sufficient pyrite to generate acid.
- The data further indicated that there is sufficient calcite present to serve as a buffer to limit the amount of acid generated, but not enough to completely eliminate the potential for acid generation.

Northern and South Eastern Samples:

- It was found that the samples have the potential to generate acid, although they also contain buffer potential.
- The ABA analyses of the sandstone samples indicated that some acid will be generated for any given mass of the sandstone.
- For the discard it was concluded that these samples had a high acid generation potential, and if oxidised, the samples will produce acid.

Acid-Base Accounting Compared to Weathering

The results of the comparison between the ABA results to the level of weathering are inconclusive.

- In the areas that contain the full succession there is correlation between rocks from the zone 50-80 m below the surface.
- The rocks at this depth have a higher potential for acid generation in both the north western sampling location as well as the south eastern sampling location.
- The lack of additional samples for both the yellow areas and the red areas makes comparison difficult and no concrete conclusions can be drawn.
- It is therefore recommended that additional samples be collected and the same analyses be performed on these samples in order to identify potential correlation.

Modelling

Numerical modelling was done for the study area to determine the quantities of groundwater flow into mines (dewatering model) and to predict whether the mines would reach decant level (decant models). To achieve this, data gathered from the study area was used. This data included; borehole water levels, transmissivities from pump testing and geological data. The data from the currently active mine revealed that the measured inflow from groundwater into the mine was in the order of 19 000 m^3/month during the initial stages of mining. This translates to 633 m^3/d. At present the estimated flow into the mine is approximately 30 000 m^3/month (1000 m^3/d). This is a very small volume of water entering the workings of the mine.

From the different scenarios simulated during modelling several conclusions can be drawn for both decant and dewatering scenarios.

Dewatering

The dewatering simulations indicated that there is very little groundwater in the study area and that the water moves slowly (due to the low transmissivities of the rocks), predominantly along structures such as dykes, fractures and faults. The predominant geological structures in the study area (the three main faults) act as conduits for water movement. This was indicated by the modelling and is also observed in the field, by the fact that boreholes located near the structures have higher yields than boreholes located further away from the structures. Accordingly, it is predicted that should a mine intersect a fault during mining operations, the volume of water expected to flow into the mines will increase. It is therefore recommended that mines try to avoid mining through a fault.

Decant

From the results of both dewatering and decanting models, there is no evidence that the pits will reach decant levels. There are not large enough volumes of water present and due to the low transmissivities and high evaporation in the flat and sandy terrain it is concluded that the pits will not reach decant level.

Management

From the results of the modelling it is clear that the volumes of water that will enter the mines from both groundwater sources and from surface runoff will be small. Due to the small volumes of water expected to enter the workings of the mines, it is recommended that the water be pumped out and used for run of mine operations such as dust suppression or washing of the ore.

Steps should be taken to ensure or minimize the risk of encountering a fault during mining. If the mines encounter large faults and start to dewater the faults, many farmers with boreholes along the length of the fault might see significant decline in the water levels of their boreholes.

There are many possible water quality control measures that can be used to either prevent groundwater contamination or to contain any possible contaminants in the study area. It is recommended that preventative measures be taken rather than containment for the new mines planned for the area. Additionally for the data it is recommended that the rehabilitation methods currently employed by the Grootegeluk mine (as discussed later in the report) be used by the new mines as it has proven to be an effective form of rehabilitation for the local conditions in the study area.

Overall Conclusions

Introduction

From the various aspects of the groundwater systems of the Waterberg coalfields that were investigated during the course of the project certain conclusions can be drawn. A conceptual model (Figure 161) for the Waterberg coalfield was constructed to summarize the findings of the project. The model is not to scale and focuses on the areas to the west of the Daarby fault as this area will be mined by means of opencast methods.

Climate

From the conceptual model one can observe that the study area has a dry climate, with low rainfall and high evapotranspiration. The model displays the primary runoff for the study area and the location of the Limpopo River.

Geology

The conceptual model additionally displays the primary geological structures and the divisions of the coal seams in 11 zones as found in the study area. The location of the three main geological structures (the Daarby, Eenzaamheid and Zoetfontein faults) and the relation the structures has to the location of the coal in the study area can also be seen. The conceptual model also displays the distribution of the primary geological formations found in the study area namely the relation of the Karoo and Waterberg group rocks to the faults. The model further shows the sub division of the study area on the basis of the weathering that had taken place. With the green areas shown the full succession of geology, the yellow areas have been eroded down to the middle Ecca and the red parts have been weathered in parts.

The Mine Workings

In addition to these geological parameters the model displays the location of a single pit modelled on the Grootegeluk pit. The pit displays the method of rehabilitation currently being used at the Grootegeluk mine, in an effort to reduce the amount of acid generated as it was determined by the investigation that a certain amount of acid generation is unavoidable. The current measured parameters such as the influx of water and the drawdown cone of the pit at the Grootegeluk mine are also given, showing an influx of 30 000 m^3/month and a drawdown cone of approximately 3 km 25 years after the mining started.

Measured Parameters and Modelling Results

Measures results such as the average water level of 28 m below surface, recharge (determined by the Cl and E.A.R.T.H. methods) of 1.5% and the expected rise of 2 m in water level once mining has stopped area also displayed in the model. In addition the model also shows the effect the mining infrastructure has on the groundwater in its vicinity, as is manifested by the artificial recharge witnessed at the Grootegeluk mine on the eastern side of the Daarby fault.

Acid-Base Accounting Results

The results of the ABA performed according to the weathering depth of the geology are summarized in the conceptual model. With the green areas showing signs of being likely acid generators with and increased likely hood of acid generation at a depth of 50-80 m beneath the surface. The results for the yellow areas were inconclusive as no determinations could be made with regards to acid potential and weathering depth for these areas. In addition the results indicated that samples taken from the red areas along with discard samples from the beneficiation plants at the Grootegeluk mine will generate acid once exposed to water and oxygen.

Water Quality

A summary of the observed water qualities for the different localities examined during the study, is provided in the model. There can be distinguished between four primary localities namely;

- The areas that are unaffected by activities, showing fair water qualities, with high Cl contents and EC values
- The areas affected by Coal Bed Methane extraction, which display very high EC and Cl values. These values are not the result of pollution but, are a natural phenomenon concerned with the depth of the boreholes and the age of the water.
- The areas that have been affected by mining, these areas display EC and Cl values that area similar to those observed for the unaffected areas. These areas do however have severely elevated SO_4 levels as a result of mining activities.
- Areas affected by power generation, there was concentrated on the results of coal fire power generation, namely the fly ash dump found in the area, which indicated high EC values, lower pH values and elevated Cl and SO_4 values.

This study concludes that the addition of new mines to the area will have a deleterious effect on the quality and quantity of the groundwater in the study area. The small volumes of water that is available in the study area will be reduced by the excavation of new mines. The effects will be more visible in areas located west of the Daarby fault. The impermeable nature of the fault will prevent groundwater movement from the areas east of the fault to area west of the fault. The same can be stated for the areas north of the Eenzaamheid fault, as according to Dreyer (2009) this fault is also impermeable and groundwater on the southern side of the fault will not be affected by abstraction on the northern side of the fault.

Recommendations

It is recommended that the method of mining, beneficiation, remediation and water management currently being employed by the Grootegeluk mine be employed by the new mines. The methods being used at the Grootegeluk mine have been proven to be the best possible solutions for the conditions found in the study area.

Additional Recommendations are:

- A study to determine the percentage of water moving into the groundwater system from the washing plants and the effect thereof on the water quality.
- It is recommended that the size of the material to be placed back into the pits as backfill be varied as this will decrease the porosity of the backfilled pit and slow the movement of contaminants.
- It is recommended that the discard and spoils be slurried, pumped back into the mine and that the entire mine then be sealed by bentonite clay or other absorbent material, that will prevent the movement of the pollutants into the groundwater system.

Future recommended studies:

- The performing of additional ABA testing over a larger area and the expansion of the testing program to include kinetic tests.
- A study to be done on the possibility of using water from the new pipeline to flood the spoils and how this will influence the rehabilitation methods for backfilling the pit.
- A study should be done on what the impact of the water from the new pipeline will be and how much of the water from the pipeline will enter into the groundwater system.

Achieving the goals of the investigation

All goals and objectives of the study have been met. The groundwater parameters were determined, water level contour maps was created and recharge for the area was calculated. The pre-mining water quality was measured and the operational qualities predicted. An ABA study was performed to determine the acid potential of all the different geological layers. A numerical model was set up to determine if the water will eventually decant, and what the impact of the mining will be on the area. Different management options were looked into and recommendations were made. Recommendations on future studies were also made.

Technology transfer

All information generated during the investigation has been transferred electronically to the WRC. Publishing this information through the WRC will make it available to a wide spectrum of individuals and stakeholders. These findings were also presented at the biennial Groundwater Division Conference in 2009, as well as at the Annual International Mine Water Association conference in Pretoria 2009. Two papers will be published in accredited journals.

Participation and upliftment

In 2009 Mr Michael Bester submitted this work as fulfilment towards a Master's degree in Geohydrology to the University of the Free State.

Two BSc. (Hons) students completed tasks on this project in 2008. They were Stephen Fonkem (Cameroon) and MPHO Kejeleng (Botswana). Mr Fonkem has gone on to complete his Masters degree in Geohydrology as well in 2009.

Mrs L-M Cruywagen will use the ABA data as part of her PhD research into "Liberation of groundwater contaminants from different waste types at South African Mines".

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The Reference Group responsible for this project and for peer-reviewing this report prior to publication consisting of the following persons:

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- There are many experts who contributed to the ideas and understanding in this report, especially personnel of the IGS at the University of the Free State.

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List of Abbreviations

ABA	Acid-Base Accounting
ABATE	Acid Base: Accounting, Techniques and Evaluation
AP	Acidification Potential
AMD	Acid Mine Drainage
ARD	Acid Rock Drainage
CSIR	Council for Scientific and Industrial Research
Cl	Chloride
CBM	Coal Bed Methane
DWA	Department of Water Affairs
Eskom	Electricity Supply Commission
E.A.R.T.H. model	Extended model for Aquifer Recharge and soil moisture Transport through the unsaturated Hard rock
FC	Flow Characteristics
FD	Finite Difference
GUI	graphical-user-interface
ICP-MS	Inductively Coupled Plasma Spectrometer
IGS	Institute for Groundwater Studies
K	Hydraulic conductivity
NAG	Net Acid Generation
NAP	Net Acid Production
NCV	Net Carbonate Value
NP	neutralisation potential
NNP	net neutralising potential
T	transmissivity
S	storage coefficient
WISH	Windows Interpretation System for Hydrogeologists
XRD	X-ray diffraction
XRF	X-ray Fluorescence

1 Introduction

From local and international experience, it is known that coal mining has a pronounced impact on surface and groundwater quality and quantity. The influx of water may be as low as 1% of rainfall for deep bord-and-pillar mines with no subsidence, to as much as 20% for some opencast mines (Hodgson *et al.,* 2007). Such differences have significant impacts on the quantity and quality of surface and groundwater resources on the local scale and further afield. The Waterberg represents the only large area with proven coal reserves remaining in South Africa. These resources have been targeted for large-scale mining in the foreseeable future.

The application of lessons from other mining areas is appropriate here. The fact that new extraction options such as *in-situ* coal gasification are considered in addition to more traditional mining options brings additional uncertainties to the fore. Although several factors should be considered when selecting a mining method in addition to the effect on water resources, the long-term effect on water quality calls for a careful consideration of alternatives. It is desirable that both developers and regulators be aware of the long-term liabilities and costs associated with different mining methods. The Waterberg coal reserves are situated in a relatively dry area. In view of the low rainfall and limited surface water resources, the necessary level of safeguard measures to ensure the quantity and quality of existing water resources is unclear. Experience from other areas cannot necessarily be extrapolated directly as the area is unique in its setting and local conditions for a South African coal field.

1.1 Objectives

A scoping level study was performed to consolidate the existing information on the following:

- The different aquifers in the study area and their geohydrological parameters.
- Pre-mining water quantity and quality of water resources associated with the Waterberg coal field.
- The acid generating potential of the geology found in the study area.
- Detect potential problem lithologies with regards to higher acid generation potential.
- Predict what the impact will be of additional mines in the area.
- Determine if the mines would ever reach decant level.
- Provide recommendations on management methods that are applicable to the study area and that have relevance for the study area.

1.2 Methods of Investigation

To obtain the necessary information to complete the objectives of the study, many different methods needed to be employed. The project was conducted in several stages to accommodate the different types of information required. Accordingly the initial stages of the project consisted out of two hydrocensus, the aim of which was to locate as many boreholes in the study area as possible.

The information recorded during this initial field work included parameters such as water levels, borehole depths, location (X, Y, Z), and preliminary electrical conductivity (EC) and pH measurements. Together with these parameters groundwater samples were collected from boreholes in the study area to be used for quality determinations.

The samples were collected by means of through flow bailers, which were cleaned with deionised water prior to sampling. In addition to the hydrocensus other sources were approached such as the geologists at the Grootegeluk mine, Sasol mining and Eskom to name but a few, in order to gather additional information on the study area. From the Grootegeluk mine and Sasol, geological samples were obtained to be used for determining the acid potential of the rocks in the study area.

Once sufficient information had been gathered the information was compiled into a single database. This database was used for the other determination such as for example the construction of contour maps, the determination of recharge and so forth. Following the initial hydrocensus and information gathering expeditions, numerous tests were conducted in the field to determine the aquifer parameters of the different aquifers present in the study area.

These parameters were necessary for the determination of for example yields of the different aquifers and they would additionally be used during numerical groundwater flow modelling. These tests were comprised of pumping test and slug tests. The tests were performed where possible and according to the requirements of the project.

To account for influx of water to the study area, the recharge for the study area was calculated by means of the Chloride mass balance method and the E.A.R.T.H. model for calculating recharge. These calculations indicated a low recharge for the study area in accordance with maps constructed by Vegter (1995), which indicated a recharge of between 1.5% and 1.9%.

All of these parameters would later be used during the modelling. For the purpose of determining the acid potential, acid-base accounting was performed on the collected samples by using the peroxide static test method.

This method is only a screening mechanism to determine if certain rocks would become acidic, it can unfortunately give no indication of the amount of acid that will be generated or the length of time it will take for the acid to be generated.

The ABA test indicated that most of the samples collected would become acidic upon oxidation. To form a more rounded conclusion of the potential impact of mining of the coal field samples were collected from the beneficiation plants at the Grootegeluk mine.

These samples were also analysed for acid potential the results of which indicated that the samples will become acidic upon oxidation. The sampling for the ABA was done according to the weathering depth of the geology in the study area. This information was provided by Dreyer (2009) whom indicated that due to the difference in the level of weathering it might also be possible that different areas in the study area would have different acid potentials based on this weathering pattern.

Accordingly the study area was divided into three zones according to the level of weathering. The results from the tests indicated that some areas where more prone to acid generation and in certain areas the rocks located at certain depths even more so.

In order to determine the impact the mines would have on the groundwater and the flow directions of the groundwater numerical modelling was done using the Visual MODFLOW and PMWIN. Several different scenarios were simulated using the parameters that had been collected during the field work.

The scenarios were constructed in such a manner as to simulate the conditions for both dewatering and decant potential of the mine pits. The dewatering models indicated that there was very little water available in the study area with small volumes of water predicted to flow into the mines. The decant models indicated that there was no possibility of the pits ever reaching decant levels with the highest recorded rise being seven meters 50 years after mining had stopped.

Given all the results obtained from the various test, the relevant literature and people from the mining industry were consulted as to the appropriate water management options for the study area. It was concluded that the most effective way to preserve the water quality and protect the groundwater quality form further deterioration, was to keep all acid generating material dry as it would not be possible to flood this material once the mine closes due to the small volumes of water in the study area.

1.3 Structure of the Report

This report consists of 11 chapters.

- Chapter 1 serves as an introduction, focussing on the reasons for doing the project and the types of investigations performed.
- Chapter 2 is a discussion and background information on the importance of coal and the impacts its mining and use as a fuel, has on the environment.

- In Chapter 3, the most commonly used methods for mining coal are discussed.
- Chapter 4 is a discussion on the study area.
- Chapter 5 is a discussion on the methods used during the testing and analyses of and for the parameters used and discussed in the project.
- Chapter 6 is a brief overview of the geology of the Waterberg coalfields.
- Chapters 7 and 8 are respectively, discussions on acid-base accounting and a discussion of the water quality or the study area,
- Chapter 9, a discussion of analysis and testing of aquifer parameters
- Chapter 10, a discussion on the numerical modelling and the results for the study area with
- Chapter 11, a discussion of possible water management strategies to be employed in the study area.
- This is followed by Chapter 12, a conclusion and recommendations.
- Chapter 13 contains a list of appropriate references.

This is followed by appropriate attached appendices.

2 Coal and its Place in the World

2.1 Introduction

As the primary objective of the project is to determine the impact that coal mining of the Waterberg coal fields will have on the groundwater resources it is prudent to first examine the importance of coal and the role it plays in energy production. This, together with the energy policies of the South African government, plays a vital role in the extent to which the Waterberg coal reserves will be mined and for how long these resources can be exploited. Of additional importance, is the different methods used for the extraction of coal. The reasons for this being that, different extraction methods have different impacts on the environment. It was determined early in the project that, at present only one form of extraction is used in the coal field namely bulk mining and according to Dreyer (2009) it is the only form of surface mining planned for the study area. The surface mining will be conducted to the west of the Daarby fault, as this fault marks the transition from shallow coal to the west and deeper coal to the east of the fault. Sub-surface mining of the coal field west of the Daarby fault is possible but will only be used once all the coal that can be extracted by surface mining methods has been removed. In addition, east of the Daarby fault, in the deeper coal beds, Coal Bed Methane (CBM) extraction is being tested as a potential mining method for the deeper coal fields with the methane being eligible for use in power generation.

According to Snyman (1998), coal is a readily combustible sedimentary rock that contains more than 50% by mass and more than 70% by volume, carbonaceous material (petrified plants) and is formed by the accumulation, compaction and induration of variously altered plant remains in an anoxic environment. Coal is generally classified as a sedimentary rock, but the harder forms, such as anthracite, can be regarded as metamorphic rock, due to their later exposure to elevated temperatures and pressure. Coal is primarily composed of carbon and hydrogen along with small quantities of other elements; notably sulphur.

Coal is extracted from the ground by mining; either by underground or surface methods. Coal is the primary source of fuel used for the generation of electricity and also one of the main contributors to carbon dioxide emissions around the world. According to Vermeulen (2006) 68% of South Africa's produced energy was coal dependent in 1997. Coal is classified according to grade, rank and typed into six different types of coal, which are formed when geological processes apply pressure to dead biotic matter over time. Under suitable conditions, the material is slowly transformed successively into; peat, lignite, sub-bituminous coal, bituminous coal, anthracite and graphite.

2.2 Coal as Fuel

Coal as a mineral has a wide variety of uses, some of which are:

- As a fuel source,
- For coke burning used in metallurgical process,
- Gasification for the production of syngas,
- Liquefaction (coal to liquids) which is presently practised by Sasol.
- A trade commodity and some cultural uses.

However, for this study the focus will be on the use of coal as a fuel source. The primary use of coal is as a solid fuel, used for the production of electricity and heat through combustion. According to the British Petroleum Statistical Review of World Energy, the world coal consumption was around 3303 million tonnes oil equivalent (Mtoe) in 2008. China consumed roughly 1406 Mtoe, while producing 2782 Mt in 2008 (www.bp.com). India consumed roughly 231 Mtoe and produced 512 Mt in 2008 (www.bp.com). Accordingly, the USA consumed 565 Mtoe in 2008 with a country-wide production of 1062 Mt for the same year of which 49% was used for the generation of electricity (www.eia.doe.gov).

When coal is used as fuel for the generation of electricity, it is pulverised and then burned in a furnace with a boiler. The furnace heat converts the boiler water to steam, which is used to spin the turbines attached to the system. These turn generators that create (generate) electricity.

Currently the most advanced steam turbines have reached 35% thermodynamic efficiency for the entire process, which indicates that 65% of the energy is wasted in the form of heat that is released into the surrounding environment (www.worldcoal.org). Older coal power plants are significantly less efficient and produce even higher levels of waste heat. Roughly 40% of the world's electricity is generated with coal as primary fuel source, with approximately 49% of electricity generated in the United States being generated with coal (www.eia.doe.gov).

There is a very high demand worldwide for coal as a cheap and effective fuel for the generation of electricity. These are however limited and non-renewable resources which are dwindling fast. The worlds hunger for a cheap and effective energy source will lead to the consumption of all such resources with the environment being left to pick up the bill. At present South Africa’s primary source of fuel for the production of electricity is coal, with coal accounting for 94% of all electricity generated in South Africa (www.worldcoal.org).

2.3 Environmental Effects of Coal Burning and Mining

Coal mining and coal burning result in a number of adverse environmental effects. These effects are in many cases especially visible in and around power stations and coal mines.

The environmental impacts associated with the burning of coal are numerous. Some of the more common problems are briefly discussed. Burning coal releases carbon dioxide, which is a greenhouse gas that causes climate change and global warming. Additionally, the burning of coal generates hundreds of millions of tons in waste products, including fly ash, bottom ash, flue gas, desulphurisation sludge, which contain mercury, uranium, thorium, arsenic and other heavy metals. The release of SO_2 into the atmosphere can lead to the generation of acid rain. This is however a more localized phenomenon but it is still a cause for concern.

Coal-fired power plants without effective fly ash capture are one of the largest sources of human-caused background radiation exposure. The sheer volume of fly-ash produced by a single power station and the area needed for dumping the ash poses its own problems. The ashes heaps are unsightly and take up a very large area that increases with the age of the power station. There are no known beneficial uses of the fly-ash except for use in management of acid mine drainage, but this also has some drawbacks associated with it. An example of the drawbacks associated with the use of flay-ash for acid neutralization was discussed by Hodgson and Krantz (1995) whom indicated that if all the acid is not initially neutralized, the low pH values present in the effluent can mobilize the heavy metals in the fly-ash. This would lead to more dangerous effluents than that which was initially present. All of the above mentioned environmental impacts can be extremely dangerous if not properly monitored and it should be the power generator or the burner of the coal’s first priority to minimise these impacts to as large a degree as possible.

The excavation of open pits and excavations for sub-surface mining leads to disturbances in the water table. These disturbances are not only felt locally within the mine, but can be felt further a field by groundwater users near the mines. The mining may lead to a decrease in water levels and might alter the groundwater flow direction in severe cases. Coal mining may have impacts on water use and flows of rivers and consequential impact on other land uses. Other impacts that coal mining have are for example acid-mine-drainage.

Acid mine drainage can find its way into the groundwater system or, it can decant from abandoned mine workings into surface water bodies where it decreases the pH of the water and releasing all the pollutants that were held in solution. The transport of the coal in the mine and from the mine to the beneficiation plants and the manner in which an open cast mine is excavated, leads to the generation of vast quantities of dust. In most cases efforts are made to suppress dust, but inevitably dust is generated and does not stay confined to the perimeter of the mine. Besides being a nuisance, the dust can lead to respiratory disease, reduced visibility in severe cases and in extreme cases may even halt the production of the mine. The tunnelling from sub-surface mining can lead to subsidence above the tunnels which can cause damage to infrastructure (Grobbelaar, 2001).

The subsidence can in severe cases lead to a total collapse of the mined out areas which can render a piece of land unsuitable for farming. This will depend on the use of the land and the size of the collapse

(Grobbelaar, 2001). Opencast mining can also alter the land on which it and its dumps are located making it unfit for other uses, due to contamination of the soil, or due to the scarring left by the open pit. Subsurface mines can reduce the integrity of the surrounding rock to such a degree that the rock will not support large structures on the surface. Another big problem associated with open cast mining is noise pollution. The noise from the blasting and the excavation can be very disturbing to both humans and animals. Therefore, the environmental impacts of coal and its attributed mining and burning are far reaching and can be devastating. It is recommended that the impacts of the mining of coal be considered thoroughly by the mining houses involved in the development of the mines, before mining starts.

2.4 World Coal Reserves

It is estimated that by the end of 2006, the recoverable global coal reserves amounted to around 800 or 900 gigatons (International Energy Annual, 2005).It is estimated that approximately half of this is hard coal (International Energy Annual 2005, and www.eia.doe.gov). According to www.eia.doe.gov, “At the current global consumption rate, these resources will last 164 years”. According to British Petroleum (www.bp.com), the total recoverable reserves of coal from around the world were 826 001 Mt at the end of 2008 (Major Coal Producers). Coal is commercially mined in over 50 countries worldwide (www.bp.com). According to the British Petroleum (www.bp.com), 6780 Mt of coal was produced in 2008 (Table 1). From these statistics one can conclude that there is a very large demand for coal. It is likely that this demand will increase as more African and Asian nations develop and expand. The expansion in these countries goes hand in hand with the production of electricity for which coal is still one of the cheapest fuel sources.

Generally most of the coal produced in a country is used in the country of origin mainly for power generation, or in the process of making steel. Some coal is however exported. Table 2 shows that there has been a sharp increase in the production of coal over the past 20 years. This is likely due to large scale development of many African and Asian countries. With Asia showing the biggest increase in the tonnes of coal produced over the past 20 years.

This gives a reserve-to-production ration (the ration of remaining reserves to the amount of reserves being removed) of 122 years for the world as a whole. For South Africa the estimated reserves are placed at 30 408 Mt and 121 years of reserves if the reserve-to-production ratio is taken into account. Only reserves classified as "proven" are included in these estimates as exploration drilling programmes by mining companies, particularly in under-explored areas, are continually uncovering new reserves.

Companies are however often aware of coal deposits that have not been sufficiently drilled to qualify as "proven". Some nations also do not update their information and assume that reserves remain at the same levels even after much of the resources have been removed. According to British Petroleum (www.bp.com), the world coal consumption of coal was 4954.5 Mt (3303 Mtoe) at the end of 2008. At current consumption levels (4954.5 Mt/a for 2008) there are sufficient coal reserves to supply the worlds demand for coal for 166 years. It can concluded from the differing levels of estimated remaining coal reserves, that there is a level of uncertainty with regards to just how much coal is still available for exploitation. Coal has the most widely distributed reserves of the three fossil fuels and is mined in over 100 countries and all continents, except Antarctica. The largest reserves are located in the USA, Russia, Australia, China, India and South Africa (www.bp.com).

2.5 Major Coal Producers

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Table 1: World coal reserves taken from the BP statistical review of world energy (2009).

Coal: Proved Reserves at end 2008					
Million tonnes	Anthracite and bituminus	Sub-bituminous and lignite	Total	Share of Total	R/P ratio
US	108950	129358	**238308**	28.9%	224
Canada	3471	3107	**6578**	0.8%	97
Mexico	860	351	**1211**	0.1%	106
Total North America	**113281**	**132816**	**246097**	**29.8%**	**216**
Brazil	-	7059	**7059**	0.9%	*
Colombia	6434	380	**6814**	0.8%	93
Venezuela	479	-	**479**	0.1%	74
Other S. & Cent. America	51	603	**654**	0.1%	*
Total S. & Cent. America	**6964**	**8042**	**15006**	**1.8%**	**172**
Bulgaria	5	1991	**1996**	0.2%	70
Czech Republic	1673	2828	**4501**	0.5%	75
Germany	152	6556	**6708**	0.8%	35
Greece	-	3900	**3900**	0.5%	58
Hungary	199	3103	**3302**	0.4%	351
Kazakhstan	28170	3130	**31300**	3.8%	273
Poland	6012	1490	**7502**	0.9%	52
Romania	12	410	**422**	0.1%	12
Russian Federation	49088	107922	**157010**	19.0%	481
Spain	200	330	**530**	0.1%	32
Turkey	-	1814	**1814**	0.2%	21
Ukraine	15351	18522	**33873**	4.1%	438
United Kingdom	155	-	**155**		9
Other Europe & Eurasia	1025	18208	**19233**	2.3%	268
Total Europe & Eurasia	**102042**	**170204**	**272246**	**33.0%**	**218**
South Africa	30408	-	**30408**	3.7%	121
Zimbabwe	502	-	**502**	0.1%	287
Other Africa	929	174	**1103**	0.1%	*
Middle East	1386	-	**1386**	0.2%	*
Total Middle East & Africa	**33225**	**174**	**33399**	**4.0%**	**131**
Australia	36800	39400	**76200**	9.2%	190
China	62200	52300	**114500**	13.9%	41
India	54000	4600	**58600**	7.1%	114
Indonesia	1721	2607	**4328**	0.5%	19
Japan	355	-	**355**		289
New Zealand	33	538	**571**	0.1%	111
North Korea	300	300	**600**	0.1%	17
Pakistan	1	2069	**2070**	0.3%	496
South Korea	133	-	**133**		48
Thailand	-	1354	**1354**	0.2%	75
Vietnam	150	-	**150**		4
Other Asia Pacific	115	276	**391**		26
Total Asia Pacific	**155809**	**103444**	**259253**	**31.4%**	**64**
Total World	**411321**	**414680**	**826001**	**100.0%**	**122**
of which: European Union	8427	21143	**29570**	3.6%	51
OECD	159012	193083	**352095**	42.6%	164
Former Soviet Union	93609	132386	**225995**	27.4%	433
Other EMEs	158700	89211	**247911**	30.0%	60

The largest producers of coal are also the countries that have the largest reserve, namely the USA, Russia, Australia, China, India and South Africa. The production figures (2008) are:

- China: 2782 Mt
- USA: 1062 Mt
- India: 512 Mt
- Australia: 401 Mt
- Russia: 326 Mt,
- South Africa: 250 Mt in 2008 (www.bp.com).

Table 2: World coal production from 1988-2008 (courtesy of the BP Statistical Review of World Energy).

Coal: Production *																						Change 2008 over 2007	2008 share of total
Million tonnes	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	**2008**		
US	862.1	889.7	933.6	903.5	905.0	857.7	937.6	937.1	965.1	988.8	1013.8	998.3	974.0	1023.0	992.7	972.3	1008.9	1026.5	1054.8	1040.2	**1062.8**	1.3%	18.0%
Canada	70.7	70.5	68.4	71.1	65.3	69.1	72.8	75.0	75.8	78.7	75.4	72.5	69.2	70.4	66.6	62.1	66.3	67.6	66.0	69.4	**67.7**	-2.6%	1.1%
Mexico	5.6	6.0	6.9	6.5	6.1	6.6	8.9	9.3	10.3	10.4	11.2	10.3	11.3	11.3	11.1	9.6	9.9	10.8	11.5	12.5	**11.5**	-8.6%	0.2%
Total North America	**938.3**	**966.2**	**1008.9**	**981.1**	**976.4**	**933.3**	**1019.3**	**1021.4**	**1051.2**	**1077.8**	**1100.4**	**1081.1**	**1054.5**	**1104.7**	**1070.4**	**1044.0**	**1085.1**	**1104.8**	**1132.3**	**1122.1**	**1142.0**	**1.0%**	**19.2%**
Brazil	7.3	6.7	4.6	5.2	4.7	4.6	5.1	5.2	4.8	5.7	5.5	5.7	6.8	5.7	5.1	4.7	5.4	6.3	5.9	6.0	**6.4**	7.6%	0.1%
Colombia	15.8	19.9	20.5	21.2	23.5	21.7	22.7	25.7	30.1	32.3	33.8	32.8	38.2	43.9	39.5	50.0	53.7	59.1	65.6	69.9	**73.5**	4.9%	1.4%
Venezuela	1.1	2.1	2.2	2.4	2.5	4.0	4.4	4.4	4.2	5.3	6.5	6.6	7.9	7.7	8.1	7.0	8.1	7.2	7.5	8.0	**6.4**	-20.2%	0.1%
Other S. & Cent. America	2.6	2.6	2.5	2.6	1.9	1.6	1.5	1.4	1.3	1.3	1.2	0.8	0.6	0.8	0.5	0.7	0.3	0.5	0.9	0.7	**0.9**	36.3%	
Total S. & Cent. America	**26.8**	**31.3**	**29.8**	**31.3**	**32.6**	**31.9**	**33.8**	**36.7**	**40.4**	**44.6**	**47.0**	**45.8**	**53.6**	**58.0**	**53.3**	**62.4**	**67.5**	**73.0**	**79.9**	**84.6**	**87.3**	**2.5%**	**1.7%**
Bulgaria	34.2	34.3	31.7	28.5	30.3	29.0	28.8	30.8	31.3	29.7	30.1	25.3	26.4	26.6	26.1	27.3	26.6	24.6	25.3	28.2	**28.4**	1.3%	0.1%
Czech Republic	119.8	114.1	102.8	96.2	86.6	85.2	77.0	74.3	73.9	73.5	67.5	59.1	65.2	66.1	63.4	63.9	62.0	62.0	62.4	62.2	**60.3**	-3.0%	0.7%
France	15.2	14.5	13.6	12.9	11.8	11.0	9.5	8.9	8.6	7.3	6.1	5.7	4.1	2.8	2.0	2.2	0.9	0.6	0.5	0.4	**0.2**	-50.1%	
Germany	497.9	482.3	426.7	345.9	307.3	279.7	259.5	245.9	235.1	223.3	207.0	200.8	201.0	202.5	208.2	204.9	207.8	202.8	197.1	201.9	**192.4**	-7.7%	1.4%
Greece	48.3	51.9	51.9	52.7	55.1	54.8	56.7	57.7	59.8	58.8	60.9	62.1	63.9	66.3	70.5	71.0	71.6	70.6	64.8	67.4	**67.8**	0.3%	0.3%
Hungary	20.9	20.0	17.6	17.0	15.8	12.6	13.9	12.2	15.1	15.6	14.5	14.6	14.0	13.9	13.0	13.3	11.5	9.6	10.0	9.8	**9.4**	-4.5%	0.1%
Kazakhstan	143.1	138.4	131.4	130.0	126.5	111.9	104.6	83.4	76.8	72.6	69.8	58.4	74.9	79.1	73.7	84.9	86.9	86.6	96.2	97.8	**114.7**	17.1%	1.8%
Poland	266.5	249.5	215.3	209.8	198.4	198.6	200.7	200.7	201.7	200.9	178.6	172.7	162.8	163.5	161.9	163.8	162.4	159.5	156.1	145.9	**143.9**	-3.3%	1.8%
Romania	58.8	61.3	38.2	32.4	38.4	39.8	40.6	41.1	41.9	33.8	26.2	22.9	29.3	33.3	30.4	33.1	31.8	31.2	34.9	35.8	**34.7**	-3.2%	0.2%
Russian Federation	425.5	409.8	395.3	353.3	337.3	305.9	272.0	262.8	256.5	245.0	231.9	249.5	258.3	269.6	255.8	276.7	281.7	298.3	309.9	314.2	**326.5**	2.8%	4.6%
Spain	31.9	36.5	36.0	33.9	33.3	31.8	29.5	28.5	27.4	26.5	26.1	24.3	23.5	22.7	22.0	20.5	20.5	19.4	19.2	18.2	**16.6**	-9.1%	0.2%
Turkey	39.2	52.2	47.4	46.1	51.4	48.6	54.4	55.1	56.4	59.9	67.4	67.0	66.6	67.7	54.4	49.3	49.9	61.7	64.9	76.6	**86.2**	12.6%	0.5%
Ukraine	191.7	180.2	164.9	135.6	133.6	115.7	94.4	83.8	70.5	76.9	77.2	81.7	81.0	83.9	82.5	80.2	81.3	78.7	80.4	76.8	**77.3**	0.4%	1.2%
United Kingdom	104.1	99.8	92.8	94.2	84.5	68.2	49.0	53.0	50.2	48.5	41.2	37.1	31.2	31.9	30.0	28.3	25.1	20.5	18.5	17.0	**17.9**	5.0%	0.3%
Other Europe & Eurasia	98.0	99.8	101.7	87.9	82.3	75.0	60.4	62.2	59.4	69.5	73.8	58.4	62.9	62.2	65.1	66.6	65.4	64.0	67.0	68.3	**71.7**	2.0%	0.5%
Total Europe & Eurasia	**2095.0**	**2044.5**	**1867.2**	**1676.4**	**1592.6**	**1467.7**	**1350.9**	**1300.5**	**1264.4**	**1242.0**	**1178.2**	**1139.5**	**1165.0**	**1192.2**	**1158.9**	**1186.1**	**1185.3**	**1190.1**	**1207.3**	**1220.3**	**1248.1**	**1.8%**	**13.7%**
Total Middle East	**1.3**	**1.2**	**1.3**	**1.0**	**1.0**	**1.0**	**1.3**	**1.1**	**1.2**	**0.9**	**1.0**	**1.1**	**1.0**	**0.8**	**0.6**	**1.0**	**1.1**	**1.1**	**0.8**	**0.8**	**0.8**	**-0.3%**	
South Africa	181.4	176.3	174.8	178.4	174.4	182.3	195.8	206.2	206.3	219.9	224.8	222.3	224.1	223.7	220.2	237.9	243.4	244.4	244.8	247.7	**250.4**	0.8%	4.2%
Zimbabwe	5.1	5.1	5.5	5.6	5.6	5.3	5.5	5.5	5.2	5.3	5.5	5.0	4.4	4.5	3.9	2.8	3.8	2.9	2.1	2.1	**1.7**	-17.2%	
Other Africa	2.4	2.2	2.3	2.4	2.4	2.2	2.3	2.3	2.1	2.0	2.3	2.2	2.0	2.0	2.1	2.6	2.1	1.9	2.0	1.8	**1.8**	-0.3%	
Total Africa	**188.8**	**183.6**	**182.6**	**186.4**	**182.3**	**189.8**	**203.6**	**214.1**	**213.6**	**227.2**	**232.6**	**229.5**	**230.6**	**230.2**	**226.3**	**243.3**	**249.3**	**249.2**	**248.8**	**251.6**	**254.0**	**0.6%**	**4.3%**
Australia	187.5	201.9	210.4	218.4	229.1	228.7	233.6	245.3	256.1	279.7	288.0	303.0	310.9	333.2	342.0	351.5	366.1	378.8	385.3	399.0	**401.5**	0.3%	6.6%
China	979.9	1054.2	1079.9	1087.4	1116.4	1150.7	1239.9	1360.7	1396.7	1372.8	1250.0	1280.0	1299.2	1381.5	1454.6	1722.0	1992.3	2205.7	2373.0	2526.0	**2782.0**	10.0%	42.5%
India	197.0	215.3	223.3	239.9	253.8	263.2	270.9	289.0	311.0	319.4	320.9	314.4	334.8	341.9	358.1	375.4	407.7	428.4	449.2	478.4	**512.3**	7.0%	5.8%
Indonesia	4.5	8.7	10.7	13.8	22.4	27.6	32.9	41.8	50.4	54.8	62.2	73.7	77.0	91.9	103.4	114.3	132.4	152.7	193.8	217.4	**229.5**	5.3%	4.2%
Japan	11.2	10.2	8.3	8.1	7.6	7.2	6.9	6.3	6.5	4.3	3.7	3.9	3.1	3.2	1.4	1.3	1.3	1.1	1.4	1.4	**1.2**	-14.0%	
New Zealand	2.4	2.7	2.6	2.7	3.0	3.1	3.0	3.5	3.6	3.4	3.3	3.5	3.6	3.9	4.5	5.2	5.2	5.3	5.8	4.8	**5.1**	5.5%	0.1%
Pakistan	2.7	2.7	2.8	2.8	3.0	3.2	3.0	3.2	3.5	3.1	3.3	3.3	3.2	3.3	3.5	3.3	3.3	3.5	3.9	3.6	**4.2**	14.8%	0.1%
South Korea	24.3	20.8	17.2	15.1	12.0	9.4	7.4	5.7	5.0	4.5	4.4	4.2	4.2	3.8	3.3	3.3	3.2	2.8	2.8	2.9	**2.8**	-4.0%	
Thailand	7.3	8.9	12.4	14.7	15.4	15.6	17.1	18.4	21.5	23.4	20.2	18.3	17.7	19.6	19.6	18.8	20.1	20.9	19.0	18.2	**18.1**	-1.3%	0.2%
Vietnam	6.1	5.1	5.1	5.2	5.2	6.5	6.0	6.9	8.8	11.3	11.4	8.8	11.6	13.4	16.4	19.3	26.3	32.6	38.9	41.2	**42.2**	2.1%	0.7%
Other Asia Pacific	61.2	60.0	56.2	54.4	47.4	43.7	40.5	38.0	34.2	33.5	30.9	34.3	36.7	37.6	36.8	38.2	41.9	46.2	47.0	48.8	**50.2**	1.6%	0.8%
Total Asia Pacific	**1484.1**	**1590.4**	**1628.9**	**1662.5**	**1715.2**	**1758.8**	**1861.3**	**2018.8**	**2097.1**	**2110.2**	**1998.2**	**2047.4**	**2102.0**	**2233.4**	**2343.5**	**2652.6**	**2999.7**	**3278.1**	**3520.1**	**3741.8**	**4049.1**	**8.0%**	**61.1%**
Total World	**4734.2**	**4817.2**	**4718.6**	**4538.7**	**4500.1**	**4382.4**	**4470.1**	**4592.6**	**4667.9**	**4702.8**	**4557.5**	**4544.4**	**4606.6**	**4819.3**	**4852.9**	**5189.4**	**5587.8**	**5896.2**	**6189.1**	**6421.2**	**6781.2**	**5.3%**	**100.0%**
of which: European Union #	1209.0	1174.7	1036.0	936.7	873.6	821.7	773.3	761.9	753.3	728.1	668.1	633.9	630.9	638.6	637.2	638.0	628.4	608.0	595.5	593.4	**578.7**	-3.9%	5.2%
OECD	2319.3	2333.3	2261.2	2142.4	2079.1	1978.5	2024.1	2022.5	2054.3	2089.6	2074.3	2044.3	2014.1	2093.0	2054.1	2030.4	2078.8	2103.5	2125.7	2135.8	**2153.2**	0.1%	31.4%
Former Soviet Uni	771.9	740.3	703.8	629.6	604.8	539.5	476.0	433.6	407.1	398.1	382.2	393.0	417.1	435.8	415.2	444.2	453.2	467.3	489.8	492.2	**522.0**	5.4%	7.6%
Other EMEs	1642.9	1743.6	1753.6	1766.7	1816.1	1864.5	1970.0	2136.5	2206.5	2215.1	2100.9	2107.2	2175.3	2290.5	2383.6	2714.8	3055.8	3325.3	3573.6	3793.2	**4106.0**	8.1%	61.0%

This places South Africa as the sixth biggest producer of coal in the world, with China being the biggest. These production trends are likely to continue in the future as countries continue to expand and the need for cheap and efficient fuels are ever present. A map of the coalfields in South Africa is shown in Figure 1.

Figure 1Figure 1: The South African Coalfields, after Erasmus et al. (1981).

2.6 Coal in South Africa

The Karoo Supergroup hosts all the coal reserves in South Africa. Coal seams are found to be virtually horizontal throughout the main Karoo basin. The only significant disturbances to this trend is produced by sills, dykes and / or faulting, which does not merely displace the seams, but which also leads to devolatilisation of the coal. According to Cadle *et al. (*1993) the primary control on the distribution, lateral extent, maceral content and thickness of the coal seams, have been basin tectonics and differential subsidence. Pre-Karoo and Dwyka glacial topographic features along with sedimentological factors (depositional environment, palaeoclimates, timing of marine transgressions and fluvial clastic influences) also played a role in coal distribution. The wide range of depositional settings within which peats can accumulate, combined with variations in climate and plant communities, as well as Jurassic dolerite intrusions, impart to the coals of South Africa, significant differences in grade and type of the coal found in the Karoo basin. For example the peats of the Vryheid Formation accumulated in swamps in a cool temperate climate regime.

The lower and upper delta-plains, back-barriers and fluvial environments, are generally associated with peat formation, with thick, laterally extensive coal seams preferentially accumulating in fluvial environments. The coals from the Karoo basin are generally, inertinite-rich with high ash content. However, it has been found by Johnson *et al. (*2006) that there is an increase in vitrinite content and a decrease in ash content within seams moving from west to east across the coalfields of South Africa. The Molteno coal seams, dating from the Triassic, accumulated within restricted swamps in fluvial environments under a warm temperate climactic regime (Snyman, 1998). Work done by Johnson *et al. (*2006) indicted that rapid subsidence coinciding with high sedimentation rates, resulted in coals that are “thin, laterally impresistent, vitrinite rich and shaly”. According to studies done by Snyman (1998) a generally accepted setting for the formation of peat in the Ellisras (Lephalale) area is a floodplain setting with meandering rivers. The repeated flooding together with the creation of crevasse splays contributed to the rapid alteration of mudstone and coal in the Grootegeluk formation. The Grootegeluk formation being present in the study area and being the predominant formation from which coal is mined.

Similar depositional environments may be postulated for the Tuli and Springbok Flats sub-basins. According to the results of a study done by Bredell (1987) the total recoverable coal reserves of the Karoo Supergroup is estimated to be 55333 Mt (in situ resources of 121218 Mt), with 37625 Mt present in the Main Karoo basin. According to Snyman (1998) the total beneficiated reserves located within the Karoo basin are in the order of 29000 Mt, a large component (77%) of which is low-grade (<25.5 Mj/kg) bituminous coal. Johnson *et al. (*2006) further indicates that high-grade (non-coking) bituminous reserves (12%) contribute the bulk of the 59.7 Mt of coal exported in 1995.

From information collected by Johnson *et al.* (2006) it is estimated that of the approximately 206 Mt coal produced during 1995, 94% was non-coking bituminous coal constituted, with coking coal and anthracite accounting for approximately 4% and 1.5% of saleable (beneficiated) reserves respectively. According to Source Watch, it was estimated that in 2005, coal-fired power stations accounted for approximately 93% of South Africa's electricity production, with Eskom being the dominant domestic coal consumer. Approximately one-third of coal domestically consumed is used by Sasol as the source for synthetic fuel and chemical production. South Africa has become a major player in the global coal trade, exporting an estimated 69 million tonnes of coal in 2006, the bulk of which is exported to Germany, Spain and Japan. According to Eskom, 53% of domestic consumption is used for electricity generation, with a further "12% for metallurgical industries and 2% for domestic heating and cooking".

According to Source Watch, Eskom confines its considerations to major centralised power station options of gas, hydro and nuclear power. The energy provider argues “that domestic gas and hydro resources are limited; importing hydro power from the Zaire River basin could be unreliable due to political instability”. The as yet unproven pebble-bed nuclear reactors are projected in a somewhat more positive light in terms of their future potential as a power source, but are still far from being implemented. From information provided by Source Watch, Eskom is considering no other options for power generation and places its faith in "clean coal" technologies. According to its spokespersons: "There are many existing and emerging clean coal technologies that will enable the production, processing, conveyance and utilisation of coal in a more environmentally compatible manner".

2.7 South African Government coal related strategy

After years of substantial overcapacity, the recent rapid economic growth of South Africa and power generation constraints, led to the proposal by the South African government of a massive expansion of the country’s electricity generation system. According to Source Watch instead of relying solely on the publicly owned electricity utility (Eskom) the government directed that 30% of the new capacity should be provided by independent power producers. In 2004 this led to the approval of a five-year R93 billion expansion plan being approved by the South African Cabinet, of which Eskom would be funding R84 billion. In response to this, Eskom increased its projected electricity demand forecast from 2.3% per annum, to 4% in 2004 and is now set to spend R150 billion in the five-year period to be concluded in the financial year 2011-2012. To meet these deadlines Eskom has taken the following steps: “As of November 2007, there are currently 11 941 megawatts of plants in the ‘project execution phase”. Of this, Eskom reported that 1577 megawatts have already been commissioned. Other ‘in execution’ generation projects comprise the construction of six new coal-fired 6-900 megawatt units (for between 3600 megawatts and 5400 megawatts capacity); the re-commissioning of previously decommissioned power stations providing 3600 megawatts; the construction of the Ingula Pumped Storage Scheme hydro scheme, with four 333 megawatt turbines (for 1332 megawatts of installed capacity) to provide increased peaking capacity; the construction of fourteen 150 megawatt open cycle gas units for a total of 2100 megawatts installed capacity; a 100 megawatt wind farm” (www.sourcewatch.org). This ambitious expansion project can be witnessed firsthand in the study area in the form of the Medupi Power Station Construction Project. The re-commissioning and up-keep of older and decommissioned power stations has led to widespread blackouts, termed "load shedding" by the Department of Minerals and Energy (www.sourcewatch.org). According to Source Watch this “load shedding” emphasised the need for urgent measures to increase the ability of the electricity system in South Africa to cater for peak demand and to allow sufficient time for necessary maintenance. To help fund the cost of the massive construction programme, Eskom was initially granted permission by the South African Government to increase its electricity tariff by 27.5% in the 2008 / 2009 financial year. Recently however, the government has granted Eskom permission to increase its tariff by 31%, but this is still in the negotiation phase.

2.8 The Waterberg Coalfields

The importance of the Waterberg Coalfields resides in the fact that the coalfields have, to a large extent, not been exploited with only one colliery currently active in the study area (Figure 2). Therefore, with the projected expansion of energy resources and the accompanying increase in the demand for coal, the future expansion of these coalfields are necessary in order to contend with the ever-growing need for coal in South Africa.

These coal reserves are currently being actively prospected and will be mined extensively in the near future (Dreyer, 2009). The opening of several new mines, power stations and petro-chemical plants in the area will have far-reaching and lasting impact on the area and the region. According to Dreyer (2009) the Waterberg coal fields account for nearly 50% of the remaining coal reserves of South Africa.

2.8.1 Existing Coal-Fired Power Stations

The follow was taken from Source Watch (www.sourcewatch.org) to demonstrate the current lack of capacity and the attempts to alleviate the problem:

- Arnot Power Station: 2140 MW installed capacity comprising 4 × 350 MW units and 2 × 370 MW units. The power station is located in Middelburg, Mpumalanga; Eskom plans to commission 60 megawatts upgrades in 2008, a further 60 megawatts in each of 2009 and a further 30 megawatts in 2010.
- Duvha Power Station: 3600 MW installed capacity comprising 6 × 600 MW units. The power station is located in Witbank, Mpumalanga.
- Hendrina Power Station: 2000 MW installed capacity comprising 10 × 200 MW units. The power station is located in Hendrina, Mpumalanga.
- Kendal Power Station: 4116 MW installed capacity comprising 6 × 686 MW units. The power station is located in Witbank, Mpumalanga.
- Kriel Power Station: 3000 MW installed capacity comprising 6 × 500 MW units. The power station is located in Kriel, Mpumalanga.
- Lethabo Power Station: 3708 MW installed capacity comprising 6 × 618 MW units. The power station is located in Sasolburg, Free State.
- Majuba Power Station: 4110 MW installed capacity comprising 3 × 657 MW units and 3 × 713 MW units. The power station is located in Volksrust, Mpumalanga.
- Matimba Power Station: 3990 MW installed capacity comprising 6 × 665 MW units. The power station is located in Lephalale, Limpopo Province.
- Matla Power Station: 3600 MW installed capacity comprising 6 × 600 MW units. The power station is located in Kriel, Mpumalanga.
- Tutuka Power Station: 3654 MW installed capacity comprising 6 × 609 MW units. The power station is located in Standerton, Mpumalanga.

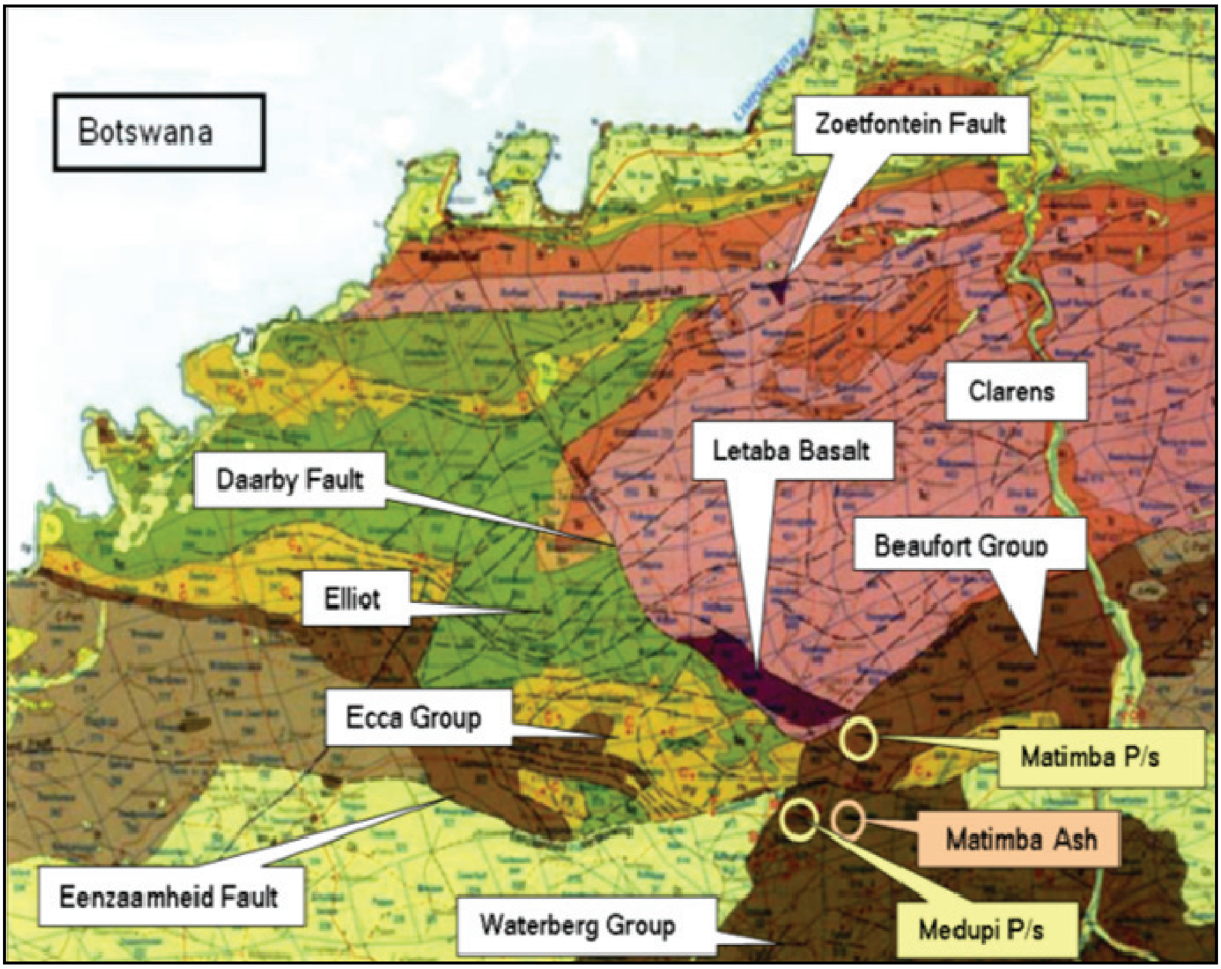


Figure 2: Geological map of the Waterberg coal fields- map number 2327DA (after Roux, 2003).

2.8.2 Currently Mothballed Coal-fired Stations Being Re-Commissioned

The following coal-fired power stations were mothballed in 1990, but are currently in the process of being re-commissioned having started in 2005:

- Camden Power Station: 1580 MW installed capacity comprising 6 × 200 MW units and 2 × 190 MW units. The power station is located in Ermelo, Mpumalanga. In 2007 Eskom re-commissioned 390 megawatts. Plans are to re-commission a further 390 megawatts in 2008.
- Grootvlei Power Station: 1200 MW installed capacity comprising 6 × 200 MW units. The power station is located in Balfour, Mpumalanga. Eskom plans to re-commission 585 megawatts in 2008 and 2009 respectively.
- Komati Power Station: 1000 MW installed capacity comprising 5 × 100 MW units and 4 × 125 MW units. The power station is located in Middelburg, Mpumalanga. Eskom plans to re-commission 120 megawatts in 2008, 240 megawatts in 2009, 320 megawatts in 2010 and 285 megawatts in 2011.

2.8.3 New Coal-Fired Power Stations

As part of its "new build" expansion plan, Eskom is building two new coal-fired power stations (www.sourcewatch.org). They are:

- The 4788 MW Medupi Power Station at Lephalale, proposed to be progressively commissioned from 2013 (803 MW in 2012, 1,596 MW in 2013, 798 MW in 2014, and a further 1596 in 2015.
- The 3212 MW Kusile Power Station at Witbank, proposed to be progressively commissioned from 2012 (798 MW in 2013, 1606 MW in 2014, and a further 803 MW in 2015.

This ambitious expansion project has attracted new investors to South Africa. A number of mining and petroleum companies have prospecting rights in the area. Some of these are Exxaro, Sasol, Anglo Coal, BHP Biliton, Kongoni, Ledjadja Coal, Lukale, Sekoko and Nozala.

3 Mining Methods

3.1 Introduction

As stated in the previous chapter, coal mining has a significant impact on the environment, which is often not just confined to the immediate area of the mine. The effects are often far reaching and lasting, such as for example if the tunnels of a sub-surface mine collapses, the land can be rendered unfit for agriculture or development through construction.

Accordingly it was felt that for this study that some of the different coal mining methods be examined and the potential impacts that the different methods have on the environment. Coal mining is the economical extraction or removal of coal from the earth by means of different mining methods. Coal that is used for fuel in power generation is referred to as steaming or thermal coal (Figure 3).

Figure 3: Dragline mining in an opencast pit.

3.2 History of Coal Mining in South Africa

The discovery of coal in the Kwazulu-Natal, Mpumalanga and Eastern Cape provinces was first documented between 1838 and 1859. The first commercial exploitation of coal on a reasonable scale took place in 1870 in the now dormant Molteno coal field of the Eastern Cape. This coal was transported to the newly opened diamond fields of Kimberly in the Northern Cape. The East Rand coal fields (Springs, Boksburg, Steenkoolspruit) were brought into production shortly after the discovery of the Witwatersrand gold fields in 1886. According to Snyman (1998) the commercial exploitation of the Free State, Mpumalanga and KwaZulu-Natal coalfields commenced between 1881 and 1895.

The accelerated industrialisation of South Africa after World War II as reflected by the development of the Far West-Rand, Free State, Evander and Klerksdorp gold fields, the establishment of steel plants at Vanderbijlpark and Newcastle, and the establishment of Sasol I, II and III etc. created an increased demand for electricity, this lead to the erection of many coal-fired power stations by Eskom. These power stations were in the main supplied by dedicated collieries. In the 1980s however the demand for electricity fell below the expected levels and as a result some of the older coal-fired power stations were moth-balled which resulted in the temporary closure of the relevant dedicated collieries. Since this time it has become Eskom's policy to interlink power stations and possible coal suppliers to ensure a greater mobility of coal and to alleviate the dependence on a single colliery for coal provision to the power stations.

The 1973 world oil crisis stimulated overseas interests in South African coal and enabled South Africa to penetrate the world coal market with coal exports, which at present play a big part in the economy of South Africa (Snyman, 1998). Thus there has been a great demand for South African coal both locally and abroad and this is not likely to change soon. The extraction of coal in South Africa will be taking place for a long time and it is important to know the methods by which coal extraction takes place at present.

3.3 Methods of Coal Extraction

The most economic method for the extraction of coal depends on the depth and quality of the seams, and factors such as the geology and environmental factors of the area being mined. Coal mining processes are differentiated by whether the mine is located beneath the surface or on the surface. This distinction is important as the methods that are employed to remove the coal vary according to the spatial location of the mine (on or below the surface). Coal is only mined where technically feasible and economically justifiable or in cases where the necessity for the coal outweighs the economical implications.

Evaluation of the technical and economic feasibility of a potential coal mine requires the consideration of many factors. Some of these are:

- The regional geologic conditions, such as faulting, folding, intrusions and the successions in which the coal is located, are important as these will affect the placement and size of the mine.
- The overburden (e.g. rock and soil removed during mining) characteristics such as thickness, type, location and strength (for sub-surface mines) are important. Another factor to be taken into account with the overburden is its potential to generate acid. Many coal mines have a problem with acid generation and if the potential of the overburden to produce acid can be determined beforehand much money can be saved in the long run.
- The coal seam continuity, thickness, structure, quality, depth, thickness of partings between the seams, variations in the elevation of the seam floor, in-seam partings and coal washouts.
- The strength of materials above and below the seam for roof and floor conditions which can influence the location of supports or the ease of mining which are important for sub-surface mining.
- The topography can have a serious effect on the type of mining that will take place at a specific location (for example the presence of mountains will impact the decision on what type of mining will be used, surface or sub-surface).
- The climate, in an open pit environment to much precipitation can slow or stop production and for example extraction of coal in very cold climates can also reduce the efficiency of the mining process.
- The surface drainage patterns in a potential mining area are important as the presence of rivers and streams will have an impact on the placement of the mining infrastructure and will also influence the decision making with regards to water quality monitoring programs (surface and / or groundwater).
- The groundwater conditions in the immediate mining area as well as the surrounding area are generally heavily impacted by the mining activity, the level of impact depending on the type of mining operation taking place and the size of the mine. It is very important that this aspect be taken into account when planning a mine.
- The availability of labour, materials and infrastructure.
- With any type of mining a large capital investment is required to get the mining operation of the ground.

The choice of which mining method will be used depends on the depth and thickness of the coal seam the location of the planned mine and the above mentioned factors.

3.3.1 Modern Surface Mining

Coal seams located near enough to the surface, are usually extracted by opencast (also referred to as open-cut or open-pit) mining methods. In most cases involving near surface coal, some form of strip mining is typically used (Figure 4).

Figure 4: Open-pit mining (www.numahammers.com)

Strip mining works by exposing the coal through the advancement of an open-pit or strip by removal of the overburden. A strip of overburden next to the previously mined strip is usually drilled and filled with explosives for blasting. The overburden loosened by the blasting, is removed using large earthmoving equipment such as draglines, shovel and trucks, excavator and trucks, or bucket-wheels and conveyors. The overburden is then transferred to the previously mined (and now empty) strip, where it is used for rehabilitation and backfill.

When all the overburden has been removed, the underlying coal seam is exposed as a strip. Depending on the hardness of the coal it may be drilled and blasted (if the coal is hard) or (if the coal is soft) loaded onto trucks or conveyors for transport to the coal beneficiation plant. This process is repeated until all the coal that can be extracted in this fashion has been removed. Surface coal mining recovers a greater proportion of the coal deposit than sub-surface methods, as more of the coal seams in the strata may be exploited and nothing needs to be left behind as is the case with sub-surface mines where pillars of coal are left as roof supports. Surface coal mines can vary in size greatly, from only a few hectares to many square kilometres.

3.3.1.1 Area Mining

During area mining, overburden is removed in long cuts to expose the coal beneath it. The removed spoil from the first cut is deposited in an area outside the planned mining area and is later used as backfill in the previous cut (Figure 5). A large number of separate operations are involved in this type of surface mining, and a wide range of equipment is used to remove the coal and overburden, such as draglines, truck and shovel, front-end loader, and bucket wheel excavators. The suitability of the equipment used is generally governed by geological conditions.

3.3.1.2 Contour Mining

Contour mining consists of removing the overburden from the seam in a manner following the contours along a ridge or around a hillside. This method is most commonly practised in areas with a rolling to steep topography.

Figure 5: Area mining (courtesy of Vermeulen).

Figure 6: Mountaintop removal mining (www.coal-is-dirty.com).

3.3.1.3 Mountaintop Removal

Mountaintop removal coal mining is a surface mining method that involves the removal of mountaintops to expose coal seams, and disposing of associated mining overburden in adjacent valleys (Figure 6).

These valley fills occur in steep areas that have limited disposal alternatives. Mountaintop removal is a combination of both contour mining and area mining. In areas with a rolling or steep topography, with the coal seams being present near the top of a ridge or hill, the entire top is removed in a series of parallel cuts. The overburden is deposited in nearby valleys and hollows. This method usually leaves ridges and hill tops as flattened plateaus. Spoil is placed at the head of a narrow, steep-sided valley or hollow usually located very near the mine.

In preparation for filling of this area, the vegetation and soil are removed and a rock drain constructed down the middle of the area to be filled, where a natural drainage course previously existed. When the fill is completed, this under-drain will form a continuous water run-off system from the upper end of the valley to the lower end of the fill. This poses its own problems as there might be pollution generated by the fill that then leaks into these run off systems. Typically head-of-hollow fills are graded and terraced to create permanently stable slopes.

3.3.2 Sub-Surface Mining Methods

What follows is a brief description of the most common underground mining methods used in South African coal fields.

3.3.2.1 Bord-and-Pillar Extraction

The bord-and-pillar method of extraction has been the primary method of mining throughout the Mpumalanga Coalfields (Grobbelaar, 2001). Bord-and-pillar mining consists of coal deposits that are mined by cutting a network of “bords” into the coal seam (Figure 7). “Pillars” of coal are left behind as roof supports. The pillars can make up to much of 40% of the total coal in the seam. These pillars are mainly mined out at a later stage. This mining method has several advantages:

- It requires comparatively little capital to get started.
- It allows access to the coal in a structured and organised way.
- It can be manoeuvred around geological or coal quality constraints.
- The extraction rate is reasonably high, ranging from 70% in the shallow mines to 50% in deeper areas (Grobbelaar, 2001).

3.3.2.2 Stoping

Stoping is a method for subsurface mining that has been used for at least 30 years in the Mpumalanga Coalfields (Grobbelaar, 2001). The Usutu Colliery was one of the first mines where this method was used on a significant scale (Figure 8). Stooping works by removing the wanted ore from an underground mine and leaving behind an open space known as a stoop. Stoping is used when the overburden is sufficiently strong not to cave into the stope, but artificial support is usually provided.

Bord-and-pillar methods and stoping are often used in conjunction. The pillars left behind from bord-and-pillar mining may be halved, quartered or completely removed as time goes on and the mine progresses (Grobbelaar, 2001). The dominating factor regulating the extraction patterns of the pillars area safety constraints rather than economic considerations. According to Grobbelaar, (2001) the extraction rate per area is highly variable, being dependent on factors, such as mining depth, percentage extraction and rock competency. Due to the removal of the pillars, the overlying strata may collapse and these collapses may extend as fur as the surface which in the case of the Waterberg coal fields might potentially present a problem. Underground mining in the study area will only be used once all the coal capable of being removed by surface methods has been mined out. The sub-surface mines will be located either beneath the surface mines or in close proximity.

Accordingly the thickness of the rocks overlaying the coal to be mined by underground methods will not be of a substantial thickness. If the overburden should crack or fracture as is the case in the Mpumalanga coal fields surface runoff might enter into the underground workings of the mine. During the course of the modelling the surface runoff into a pit with an area of 800 ha was calculated by means of the rational equation for the estimation of runoff ($Q=CiA$, where Q is the run-off, C is a constant, i is rainfall intensity and

A is the expected run-off area (in this instance C was selected as 0.07)). The results indicated an expected run off in the order of 43200 m^3/d (Q was calculated to be 0.5 m^3/d).

This is a large volume of water that can flow into the pits and eventually might find its way into the underground mines. Care should be taken when selecting the type of subsurface mining to be employed to minimise the potential for forming vertical fractures.

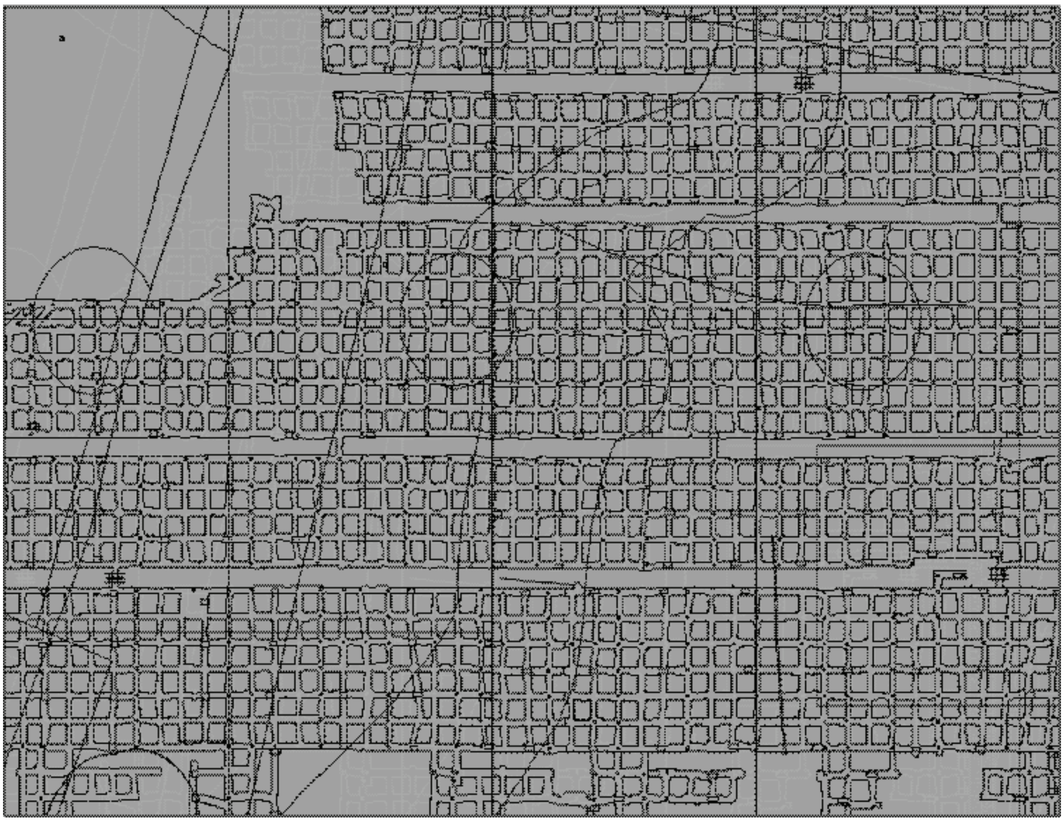


Figure 7: Example of bord-and-pillar mining in a modern underground colliery (Grobbelaar, 2001).

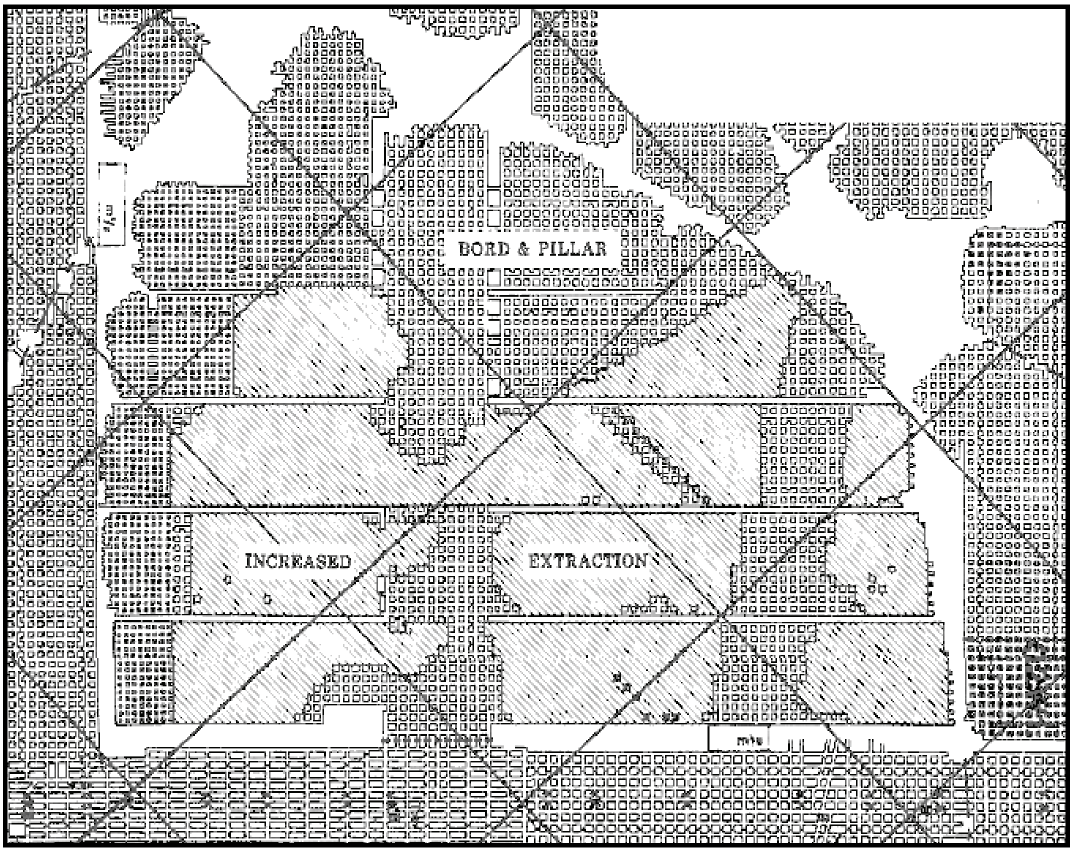


Figure 8: Example of stooped areas at Usutu Colliery (Grobbelaar, 2001).

3.3.2.3 Longwall Mining

Longwall mining (Figure 9) has been used since 1979 (Grobbelaar, 2001) and was first introduced in the Mpumalanga Coalfields at Matla and Secunda Collieries. Longwall mining is usually practised in areas that contain few or little structural disruptions. The method works by mining in panels that are usually 200 m wide, but according to Grobbelaar (2001), the width can vary depending on local considerations. The panels are mined by means of a cutting machine that is tipped with tungsten carbide teeth, that cuts away the coal as it moves along the length of the panel. The mining height for this method is seam dependent, but according to Grobbelaar (2001), 3 m is usually the maximum height at which this method can be used. A positive factor when considering longwall mining as a mining method is that it is not constrained by depth (Grobbelaar, 2001). For example Grobbelaar (2001) remarks that at the Matla Colliery, “the shallowest longwall mining panel is less that 50 m below surface with the deepest planned longwall mining at the New Denmark Colliery, where a depth of 270 m will be reached”.

Figure 9: A longwall mining operation (Grobbelaar, 2001).

3.4 Coal Production

As stated in paragraph 2.5, coal is commercially mined in over 50 countries worldwide. According to British Petroleum (www.bp.com), some 6780 million tonnes of coal were produced in 2008 (Table). From these statistics one can see that there is a very large demand for coal. It is likely that this demand will increase as more African and Asian nations develop and expand. The expansion in these countries goes hand in hand with the production of electricity for which coal is still one of the cheapest and most widely used fuel sources. Generally most of the coal produced in a country is used in the country of origin mainly for power generation or in the process of making steel. Some coal is however exported. Table (page 9) shows that there has been a sharp increase in the production of coal over the past 20 years, with Asia showing the largest increase in the tonnes of coal produced over the past 20 years.

The never ending advancement of technology has dramatically increased the production and efficiency of coal mining today. In order to keep up with the advancements in technology, and to extract coal as efficiently as possible, modern miners are required to be highly skilled and well trained in the use of complex and state-of-the-art instruments and equipment. This is likely to become even more necessary due to high cost associated with mining in this day and age and mines must be as efficient and as profitable as possible.

The advancement in technology and training of miners has led to increases in the amounts of coal extracted from current mines. Additionally the advancements in other field such as chemistry (processing of the coal and the manufacture of steel) and geology (better delineation of ore bodies) have greatly increased the efficiency of coal mines.

3.5 Environmental impacts of Coal Mining

According to the U.S. Department of the Interior (1979) coal mining has many damaging effects on the environment. Some of these include:

- Surface mining of coal completely destroys existing vegetation,
- destroys the soil profile,
- displaces or destroys wildlife and habitat,
- degrades air quality,
- alters current land uses,

- permanently changes the general topography of the area being mined,
- creates noise pollution from blasting and machinery
- causes groundwater pollution
- causes surface water pollution
- catchment reduction

Mining in general often results in a scarred landscape with no scenic value which is of great concern for the Waterberg areas as the area is generally seen as a tourist attraction. Although, if practised correctly, rehabilitation can mitigate some of these concerns it can never completely repair the damage (U.S. Department of the Interior, 1979). Mine tailing dumps can produce acid mine drainage which is a primary concern within the study area, which can seep into waterways and aquifers, with consequences for both the environment and human health. Great care needs to be taken to minimise the impact of mining.

3.6 Mining Methods in the Waterberg Coalfield

According to Dreyer (2009), the entire area west of the Daarby fault will be mined using the opencast mining method due to the shallow depths of the coal. Opencast mining refers to a method of extracting rock or minerals from the earth by their removal from an open pit (Figure 10 and Figure 11). The term is used to differentiate this mining from extractive methods that require tunnelling into the earth. The mining method currently employed at the Grootegeluk mine is known as bulk mining, a form of opencast mining. Opencast mines are used when deposits of commercially useful minerals or rock are found near the surface; that is, where the overburden is relatively thin or the material of interest is structurally unsuitable for tunnelling, as is the case in the Waterberg coal fields, due to the high degree of faulting in the area. Opencast mines are typically enlarged until either the mineral resource is exhausted, or an increasing ratio of overburden to ore (stripping ratio) makes further mining uneconomic.

Mined out mines are sometimes converted to landfills for the disposal of solid wastes. However, some form of water control is usually required to prevent the mine pit from becoming a lake, and also to prevent the water from becoming acidic. The problem of the open pit becoming a lake is of less concern in the study area, due to the low levels of annual precipitation, low transmissivities, high evaporation and the deep groundwater levels found in the area (which will be discussed later). The mining method used at the Grootegeluk mine is known as bulk mining, it is a form of open cast mining that involves the removal of all relevant material and then processing all the material. This form of mining is practiced as it has been found that is the most inexpensive and the most efficient way of mining the coal seams in the study area. This is due to the fact that the coal occurs inter-bedded with thin layers of shale and mudstone. Selective mining is thus not seen as a viable option for the study area. The best possible surface mining method to use for the study area is the bulk mining method that is currently being employed at the Grootegeluk mine. The method is efficient and cost effective. However it is recommended that the new mines start with the mining the deeper coals west of the Daarby fault. This will initially be expensive as the stripping ratio will be higher but this will be to the benefit of the mine at a later stage.

This method does however present a problem with the handling of the spoil, as all the spoil is removed and dumped on big heaps outside the mine. Due to the way mining is conducted, selective spoil handling cannot be used to identify or separate rocks with high acid generation potential from those with lower acid potentials.

Figure 10: Opencast mine in the study area (courtesy of the Grootegeluk mine).

Figure 11: The opencast at the Grootegeluk mine (courtesy of the Grootegeluk mine).

It is therefore recommended that these high acid generation potential rocks be mixed with high base potential rocks to counter act any acid that will be generated. Detailed ABA analysis will be needed to identify the acid generation potential for the different rocks. Due to the high evaporation in the study area, the use of evaporation ponds is recommended for the disposal of waste water. However, the use of such ponds increases the salt content as the ponds are evaporated. If these concentrated salts enter the groundwater or surface water system, they will be difficult to remove and increase the costs of rehabilitation after mining stops. It would be in the mines best interest to isolate these ponds in areas that are “safe”, and poses a low risk for groundwater contamination. These will be any areas that have very low transmissivities and vertical conductivities. Areas that should be avoided for the placement of such ponds area areas near faults.

3.7 Proposed Mining Plans and Methods

The entire study area west of the Daarby fault is currently being prospected by different companies interested in the coalfield. It has been proposed by Dreyer (personal communication 2009) that the entire area west of the Daarby fault can be mined by opencast mining methods. According to Dreyer (2009), all the mines in the area will initially be opencast, but might be converted into sub-surface mines at a later stage once the opencastable coal has been removed. The coal seams in the study area is sub-divided into eleven coal seams, one being the deepest and eleven being the shallowest of the coal seams. At Grootegeluk the mining process only mines down to beneath coal zone two. It has been deemed uneconomical to mine beneath seam three, as the seams below seam three are covered by thick sandstone layers and the additional excavation of these layers will increase the stripping ratio in the mine.

3.8 Conclusions

There are many methods for the extraction of coal for both surface and sub-surface mining. Some of these methods will not be economically viable in the study area and it is recommended that the new mines use the same methods as the Grootegeluk mine. For the planned subsurface mining in the future there are three methods used elsewhere in South Africa that can be used to the same level in the study area. The specific conditions for the different mines will however need to be taken into account when planning for subsurface mining.

4 Study Area Location

4.1 Introduction

The study area is located in the Waterberg region of the Limpopo Province of South Africa. The Limpopo Province is South Africa's northernmost province, lying within the great curve of the Limpopo River (Figure 12). It is a region of contrasts, from true bushveld country, to majestic mountains, primeval indigenous forests, unspoilt wilderness and patchworks of farmland.

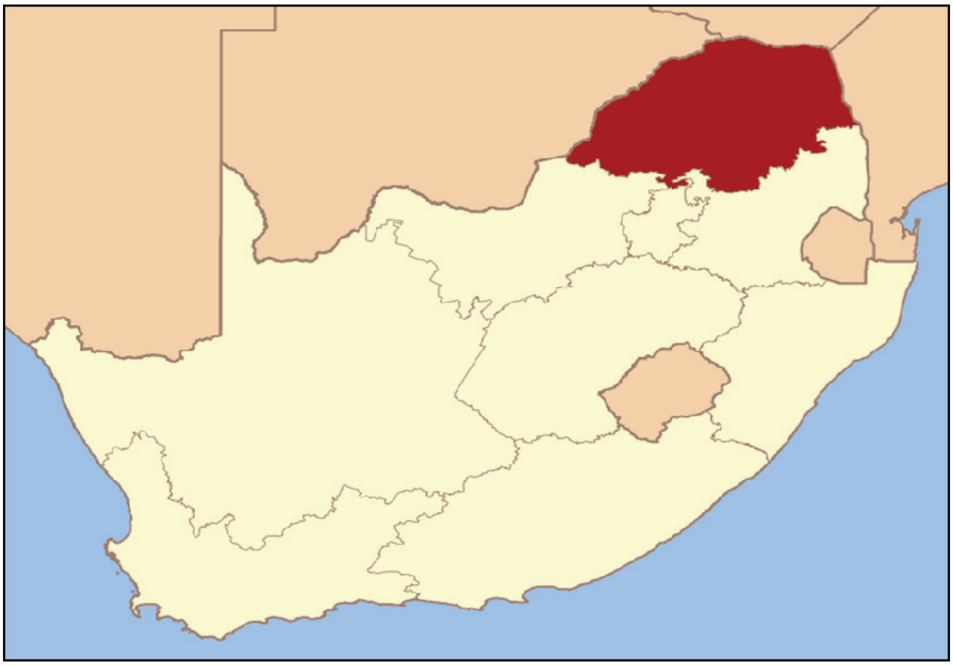


Figure 12: Location of the Limpopo province

The Limpopo Province is seen as the gateway to the rest of Africa, with its shared borders making it favourably situated for economic cooperation with other parts of southern Africa (www.southafrica.info). The Limpopo Province shares international borders with three countries namely; Botswana, Zimbabwe and Mozambique. The province also serves as a link between South Africa and these countries and other countries further a field in sub-Saharan Africa. On the southern tip of the province it shares borders with the provinces of Mpumalanga, Gauteng, and the North West province. From the province's links with Gauteng (including the Johannesburg-Pretoria axis, the most industrious metropole on the continent) and its links with Maputo development corridor, the province is ideally located for rapid development and expansion of economic opportunities (www.southafrica.info).

Limpopo is a province that has been blessed with massive mineral riches. Some of these riches include; mineral deposits of platinum group metals, iron ore, chromium high- and middle-grade coking coal, diamonds, antimony, phosphate and copper, as well as mineral reserves like gold, emeralds, scheelite, magnetite, vermiculite, silicon and mica (www.southafrica.info). Base commodities such as norite (known commercially as black granite), corundum and feldspar are also commercially exploited in the province. This leads to mining contributing to over a fifth of the provincial economy.

The province is generally classified as a developing area, exporting primary products and importing manufactured goods and services. It has a high potential for development with many investment opportunities in the mining and tourism sectors. According to South Africa Info (www.southafrica.info) the Lephalale region of the Waterberg has the third largest coal reserves in South Africa. The local municipality has identified this and sees this as giving a unique competitive advantage to the Waterberg District, so that it can become a new powerhouse in the country for coal-fuelled electricity production.

This is where the importance of this project becomes evident. Due to the planned expansion of the mining enterprises in the area and the accompanying developments, it is important to determine the extent of the impacts these developments will have in the study area. This study will look specifically at the impacts these developments will have on the groundwater quality and quantity in the area.

The Waterberg region of Limpopo is vast and incredibly beautiful. The region is mainly comprised of vast tracts of bushveld savannah, punctuated with clusters of trees and tall savannah shrubs. The Waterberg as we know it today is more than three million years old with archaeological finds and San paintings providing glimpses of the regions past. Presently, mining is an extremely important part of the economic structure of the Waterberg region, which is one of the richest areas of mineral deposits in the world and forms part of the Bushveld Igneous Complex.

4.2 The Study Area

The study area is located west of the town of Lephalale and near the Botswana border (Figure 13).The study area stretches from the town of Lephalale in the east, to just west of the town of Steenbokpan in the west and all the way to the border of Botswana in the north.

The study area is approximately 2300 km^2 in size and is mainly composed of farms. The Grootegeluk Coal Mine, Matimba Power Station and the Medupi Power Station Construction Project (Figure 14) are located within the study area.

According to Eskom, this power station (Medupi) is expected to commence its operations in 2015. The study area has a flat to gently undulating topography, surrounded by mountains to the east and the south. The main agricultural activities in the study area are farming with game and livestock (mainly cattle).

The area has generally dry climate, with temperatures reaching 40°C and higher during the summer months. The area has little rainfall during the year. The rainfall is concentrated between September and March (summer rainfall area). The study area has a mean annual run-off of 150-397 mm and the MAE (evaporation) is 1800-2000 mm/a (SA Weather Service, 2008). Recharge is estimated at <10 mm/a or <1.5% of the annual rainfall (Vegter, 1995). As illustrated in Figure 15, the average rainfall is between 285 mm and 560 mm per year (SA Weather Service, 2008).

The rain is not evenly spread during the rainy season and happens as massive downpours that can last from a few minutes to several hours. During these times of intense precipitation, the soil becomes saturated very quickly and water pools on the surface in low-lying areas (Figure 16*)*. Due to the small degree of vertical variation in the topography of the study area, the run-off is limited and in many situations more local. (Local implies that the run-off does not move very far, only towards local depressions in the topography). The areas with elevated topography located near the rivers, show run-off towards the rivers.

According to rainfall data (Figure 17) received from the Grootegeluk mine, October has the highest precipitation when compared to the other months of the year. Additionally, the data indicates a particularly problematic time for mines in terms of surface water influx into the pits and surface run-off from discard dumps and coal stockpiles.

The heavy rains are usually not sufficient to terminate mining operations, but in severe circumstances, the influx of water does pose a serious threat to the safety of miners (roads can become rivers of mud) (Dreyer 2008/2009). During these heavy precipitation events, mines need to pump out the excess water flowing into the pits. As the study area is a water scarce zone, water preservation should be a top priority. Of the large downpours, roughly 1.5-1.9% (according to Vegter, 1995) is recharged to the groundwater system. The recharge in the area will be discussed in a later chapter.

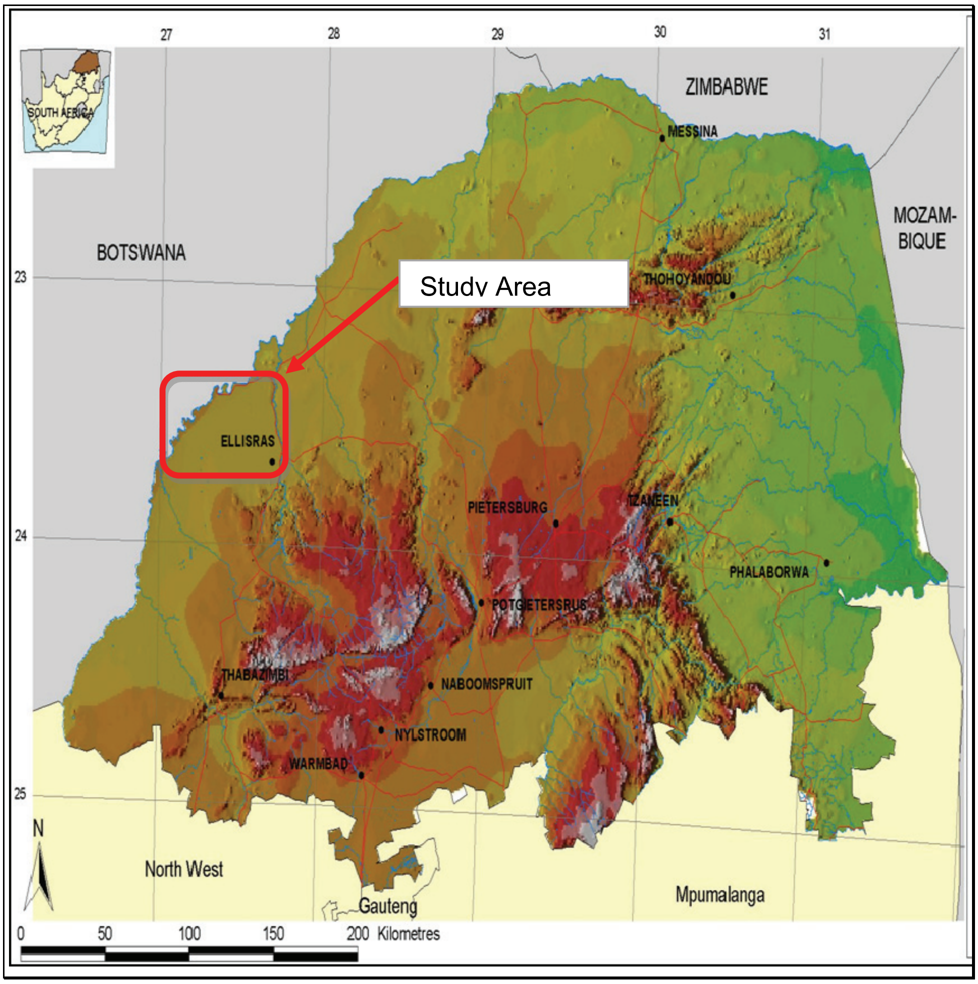


Figure 13: Location of the study area (regional), (http://www.deat.gov.za/Maps).

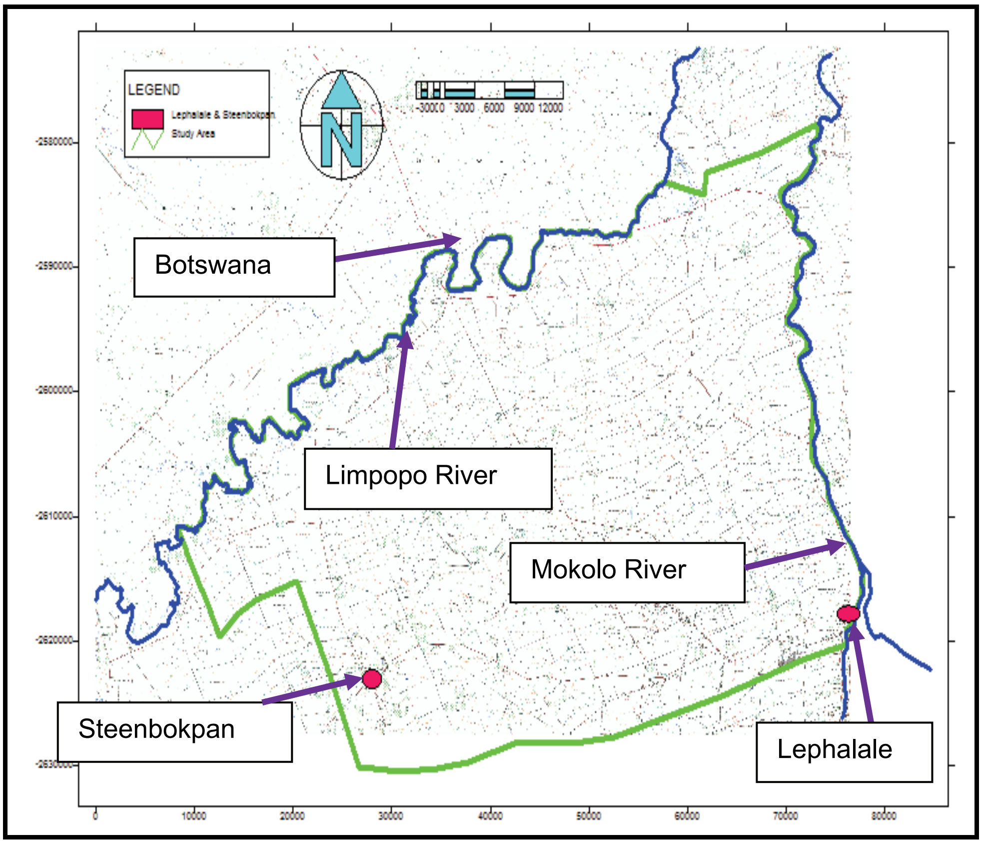


Figure 14: Location of the study area.

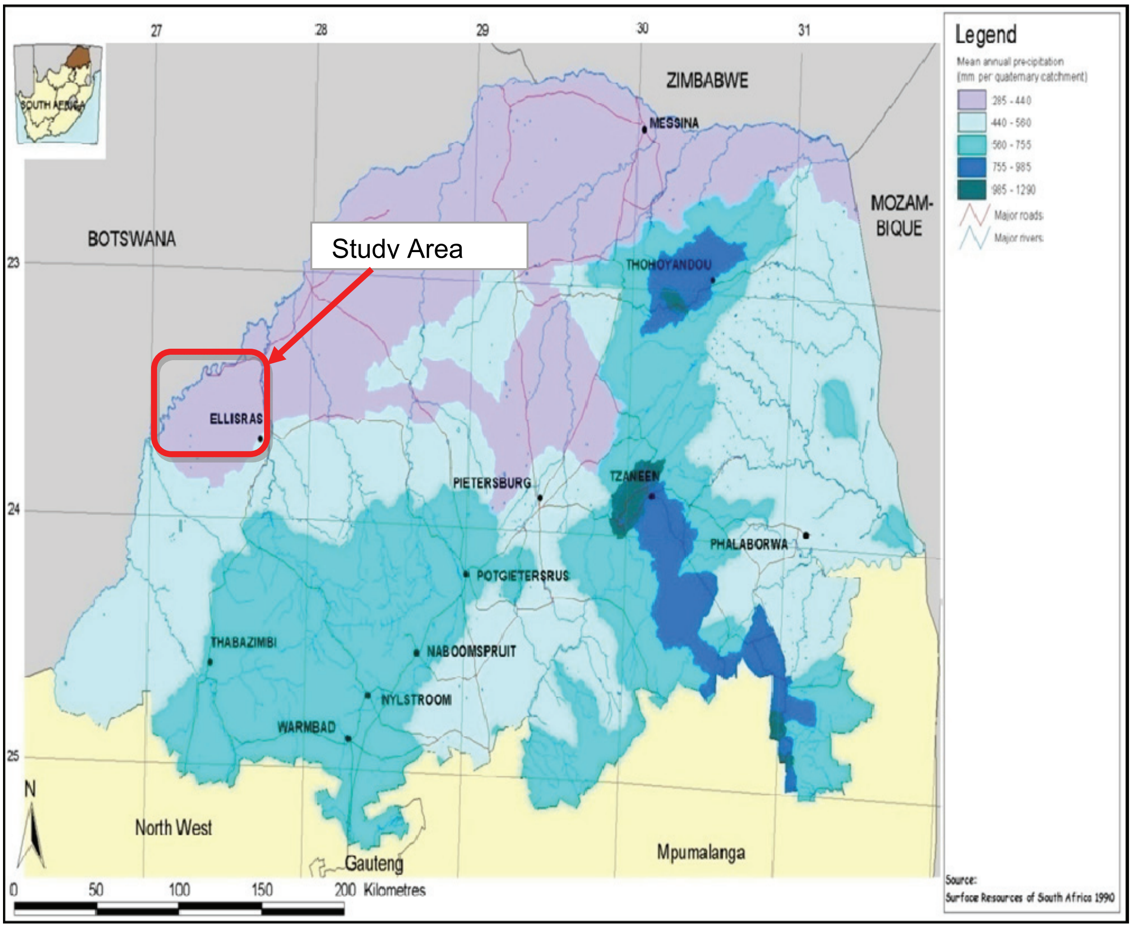


Figure 15: Rainfall in the study area (regional) (http://www.deat.gov.za/Maps).

Figure 16: Saturated soil with water pooling in the surface during the rainy season.

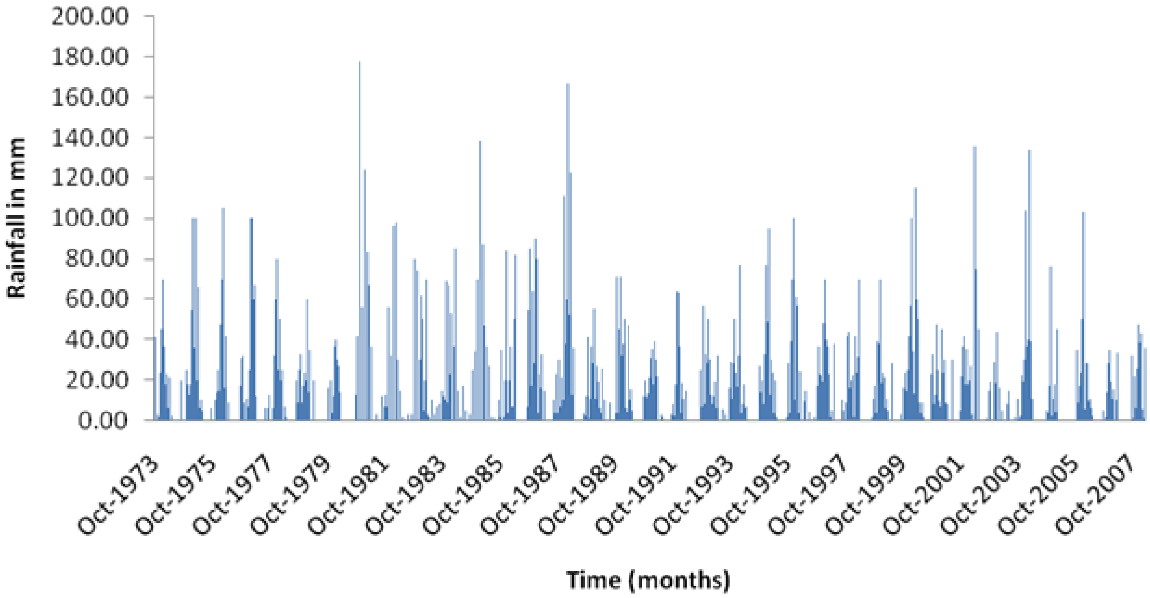


Figure 17: Rainfall figures for the study area (1973-2007).

4.3 Surface Hydrology & Topography

The study area lies within the greater Limpopo River catchment (Figure 18), has a low rainfall and is drained by two rivers; the Mokolo running north-south and the Limpopo running roughly south/west-north. The Limpopo River can be classified as a perennial river. The Mokolo river is a non-perennial. The study area is located within quaternary catchments A41E and A42J (Figure 19). It was believed that the runoff from the area would flow towards the river and other low lying areas (for location of rivers, refer to Figure 14).

In order to confirm that the runoff would move towards the rivers, it was necessary to construct contour maps of the topography of the study area. The elevation information was obtained by means of the Global Mapper Version 10 software program. The information was contoured with the Windows Interpretative Software for

Hydrogeologists (WISH). Figure 20 indicates a flat to gently undulating topography, with the exception of an area near the centre of the study area that indicated an elevated topography (Figure 20).

From this it can be concluded that the central area of the study area acts as the driving force for water flow, with water flowing from areas with a high elevation, to areas with a low elevation. In order to confirm this flow vectors were added to the topographic contour using the WISH software (the results are displayed in Figure 21).

From Figure 21 it can be concluded that surface run-off will drain towards the low-lying areas from the elevated areas, these predominantly being the two rivers in the study area. It is possible that the excavation of additional open pits in the area may alter the surface topography to such an extent, that the flow direction may change. If the size of the mines is sufficient, the flow maybe redirected towards the mines instead of the rivers. According to Dreyer (2008/2009) only the area west of the Daarby fault will initially be mined (Figure 21).

Figure 21 indicates that the impact of the mines will only be felt down-gradient towards the town of Steenbokpan and only on the western side of the Daarby fault. The areas east of the fault will be unaffected by the mines with regards to surface runoff. Due to the location of the pits in the elevated areas, this would mean an increased influx of water into the pits during periods of high precipitation. In an exaggerated three-dimensional (3D) view of the contour map, some changes in elevation can be seen, although none of these are extreme (Figure 22).

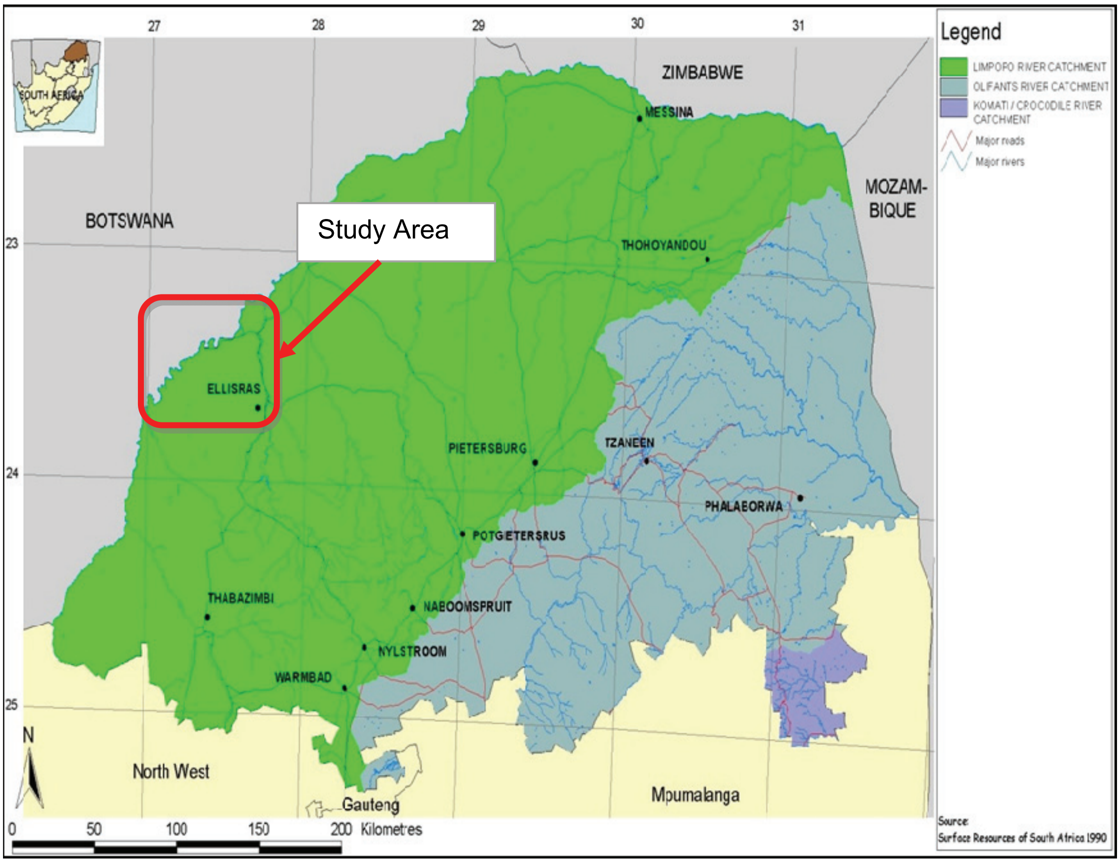


Figure 18: Location of the study area in the Limpopo catchment (http://www.deat.gov.za/Maps).

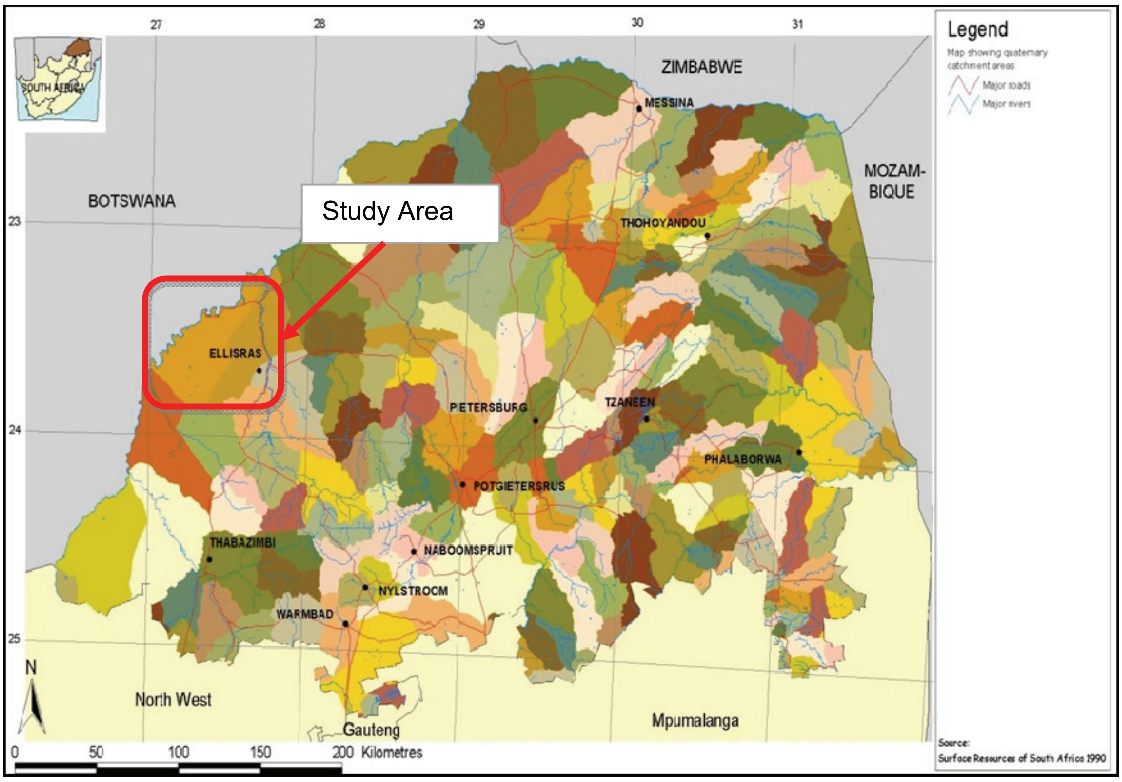


Figure 19: Location of the study area in the quaternary catchments A41E and A42J (http://www.deat.gov.za/Maps)

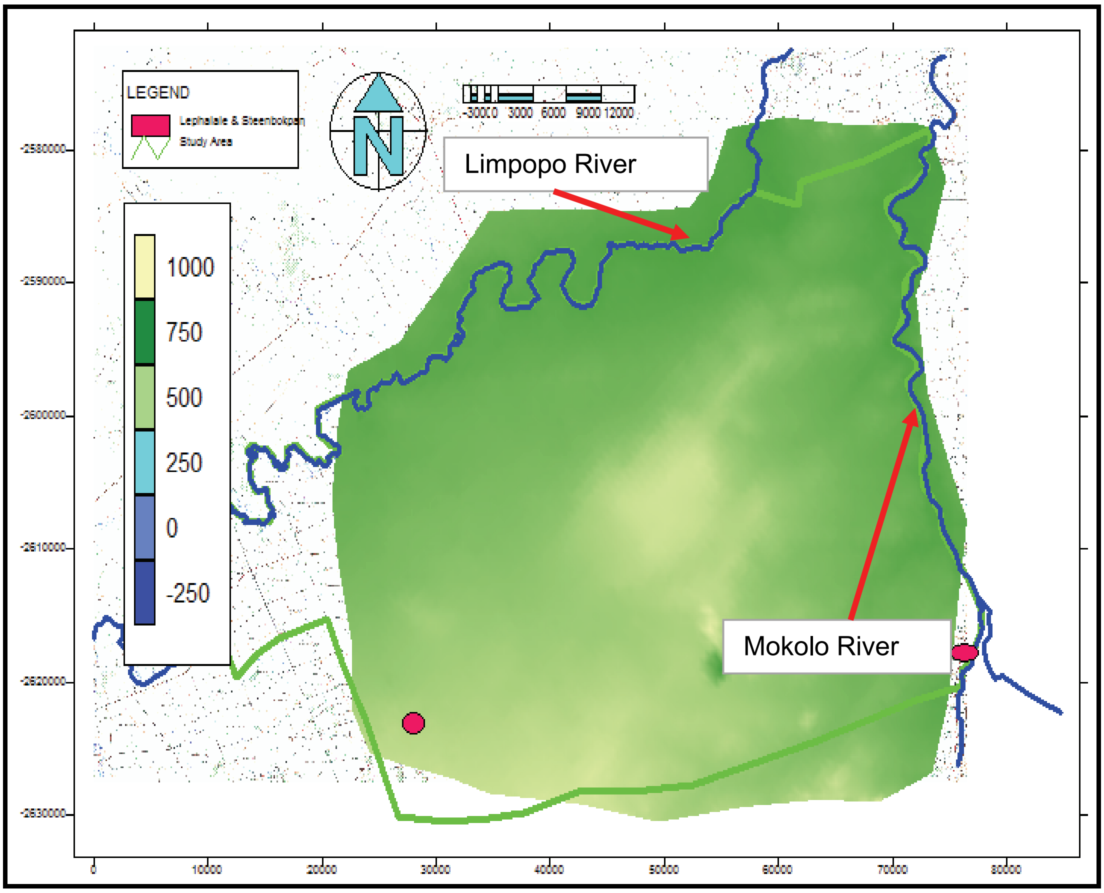


Figure 20: Topographic contour map (mamsl) generated for the study area.

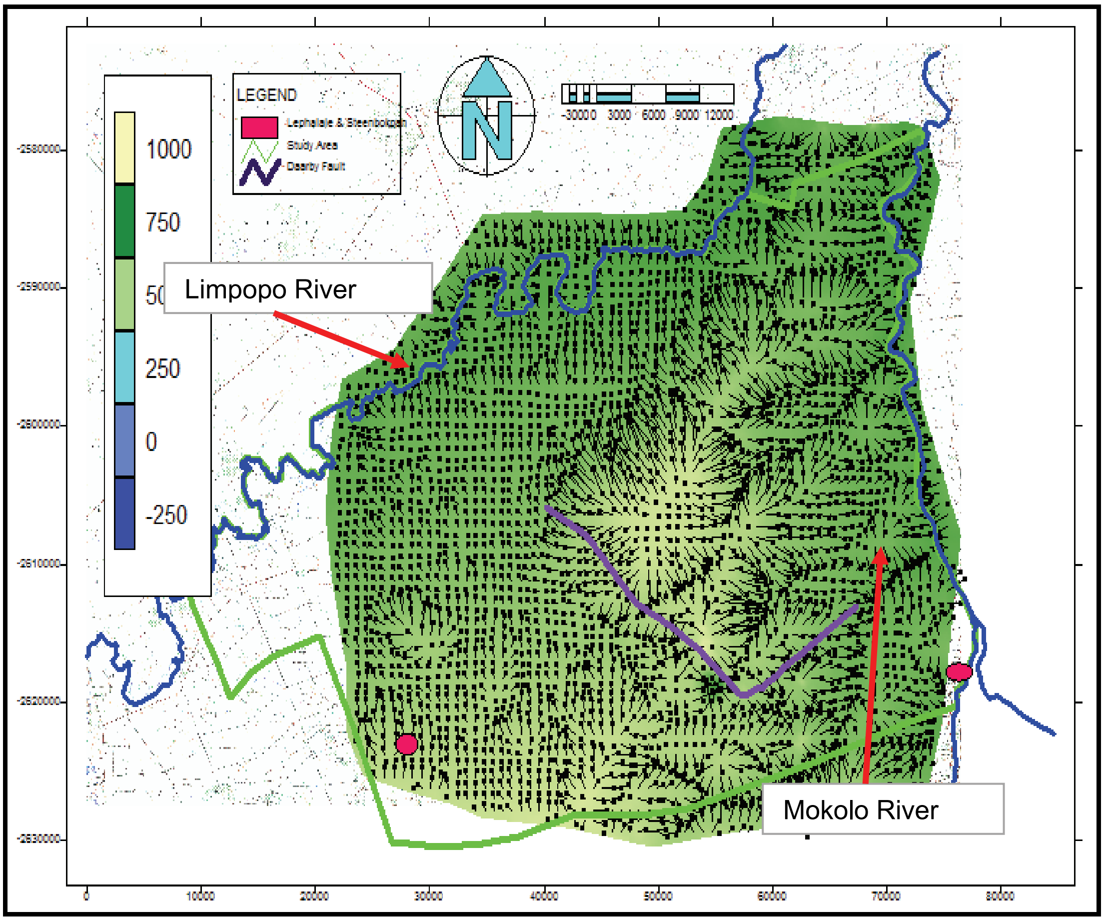


Figure 21: Topographic contour map of the study area showing flow vectors and the Daarby fault.

Towards the south lies a very deep area compared to the rest of the study area. This area indicates the open pit at the Grootegeluk Mine. As indicated in Figure 22, the open pit has an impact on the surface of the study area and the addition of more open pits in the area will increase the impact. Additionally Figure 22 indicates that the area of the pit is small when compared to the size of the study area as a whole. This will mean that in order for the pits to have a large enough impact on the topography to change the flow directions of surface runoff, there would need to be many pits of great size present in close proximity to one another.

The number of additional mines planned for the study area is unknown, but in all likelihood it is doubtful that there will be a large enough number of pits to change the surface topography to such a dramatic extent that they will change the flow direction of surface runoff. In general, it is believed that the groundwater flow of an area mirrors the topography of that area.

Accordingly from the data in Figure 22 it would be a safe assumption that the groundwater in the study area will be moving away from the central parts of the study area towards the lower-lying areas. The areas of higher elevation will therefore serve as the recharge zone for the lower lying areas of the study area. It can be expected that the excavation of large open pits in the study area will have an influence on the flow of ground water in the area west of the Daarby fault. In Figure 23 the area outlined in red indicates the location of the Grootegeluk Mine. Bearing in mind that the image is exaggerated, it can be expected that groundwater will flow in the direction of the pit.

Figure 23 indicates that the water would move towards the Grootegeluk pit from the north-west and away from the Grootegeluk pit in the south-east. Due to the movement of water away from this area, it would therefore also be a safe assumption that mines near the centre of the study area will have less influx of surface water and groundwater. In conclusion, due to the flat topography and the low rainfall, there will be little inflow of runoff into the pits.

4.4 Soil Depths, Soil Types and Land Cover

According to soil maps of the area (Figure 24), the soil depth of the study area is around 750 mm and deeper. Some of the soil's presence can be explained as being the result of strong winds and vast amounts of sand blown in from the Kalahari Desert. Much of the sand present in the study area have been formed *in-situ* as a result of weathering. Accordingly, the entire study area has deep top soils. The study area has a flat topography which contributes to the movement of sand. The area is highly overgrown, which in turn slows the migration of sand. The thick layers of sand could be used as land cover once the mines reach a point of rehabilitation. The vast amounts of soil also present a problem in terms of dust, the suppression of which will require vast quantities of water. The soil in the study area varies among three main types; red – yellow and greenish soils with high base status, soils with negligible to weak profile development (these types of soils usually occur on recent flood plains) and red massive or weak structured soils with a high base status (Figure 25).

The primary land cover in the study area is thicket and bushland, followed by woodlands and degraded land cover. Vegetation is mostly mixed bushveld forming part of the savannah biome. This bushveld represents a great variety of plant communities, with many variations and transitions. The vegetation varies from dense short bushveld, to open tree savannah. Protected tree species occur abundantly in the study area and includes the Baobab tree, Camel thorn, Shepherds tree and Lead wood, Marula and Tamboti trees.

Efforts should be made by all parties to minimise the amount of damage done to the environment (Figure 26). This will be challenging, as all the mines located in the study area will be open-pit mines. This requires the removal of overburden, plants and animals from the pit location. An effort should also be made to safeguard the endangered species that inhabit the area in question. For example, in terms of the Medupi Power Station Construction Project, Baobab trees were identified in the construction area and successfully moved to a safe location.

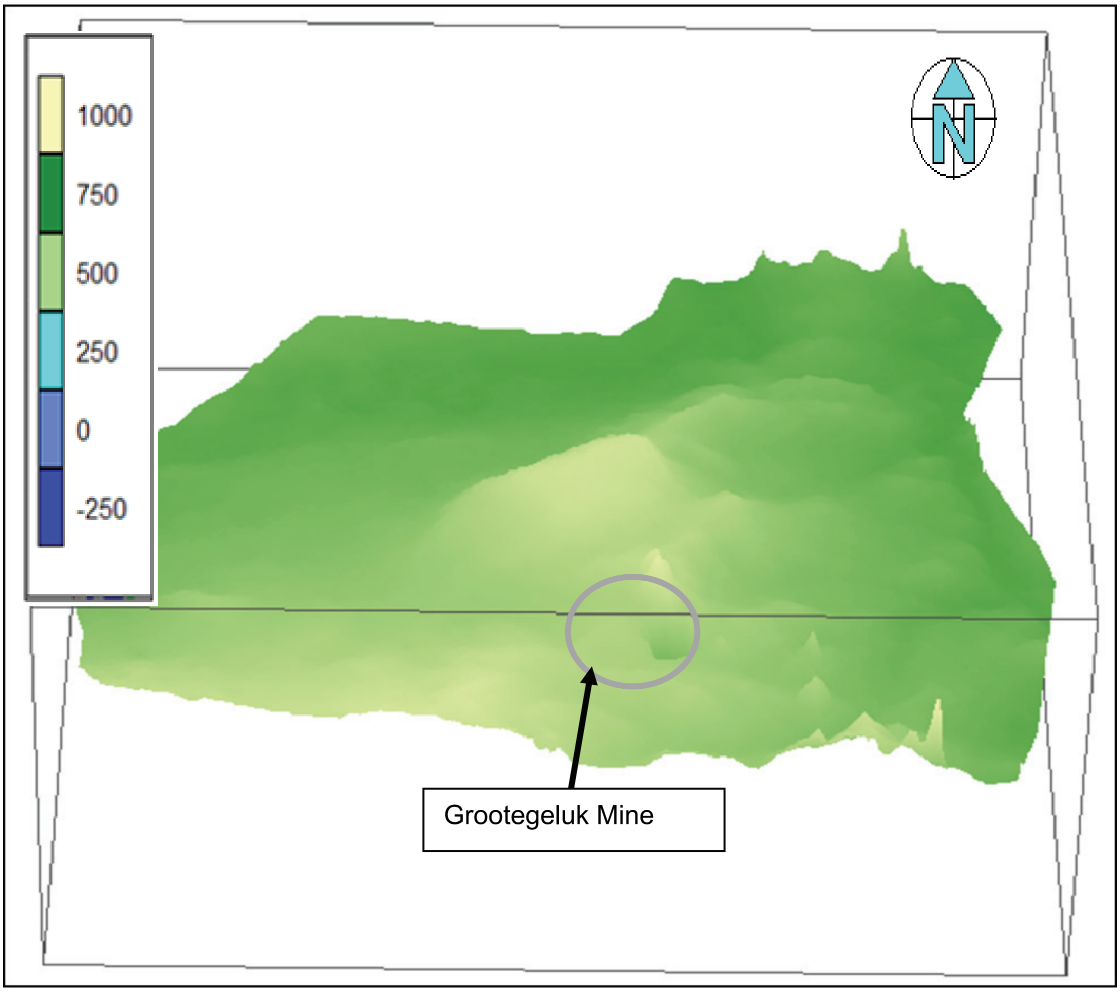


Figure 22: Exaggerated 3D view of the study area topography (created from the topographic contour map in Figure 20).

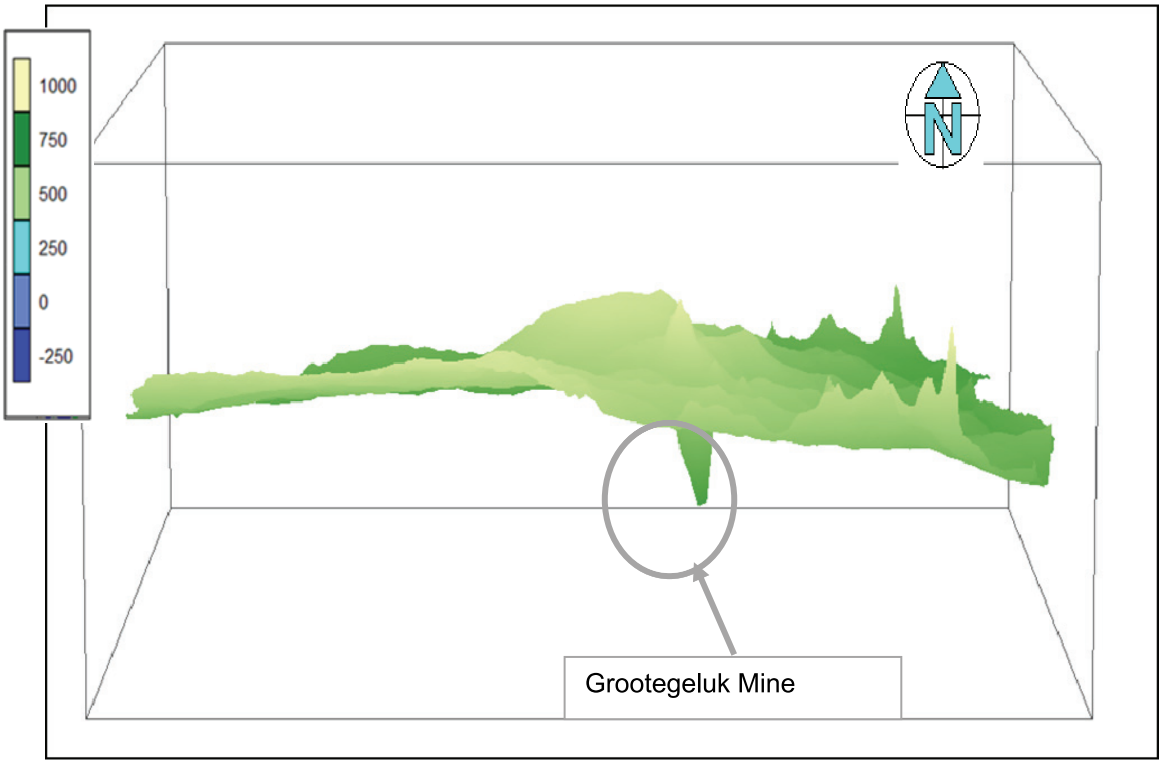


Figure 23: Exaggerated 3D view of the study area topography (Side view, created from the topographic contour map in Figure 20).

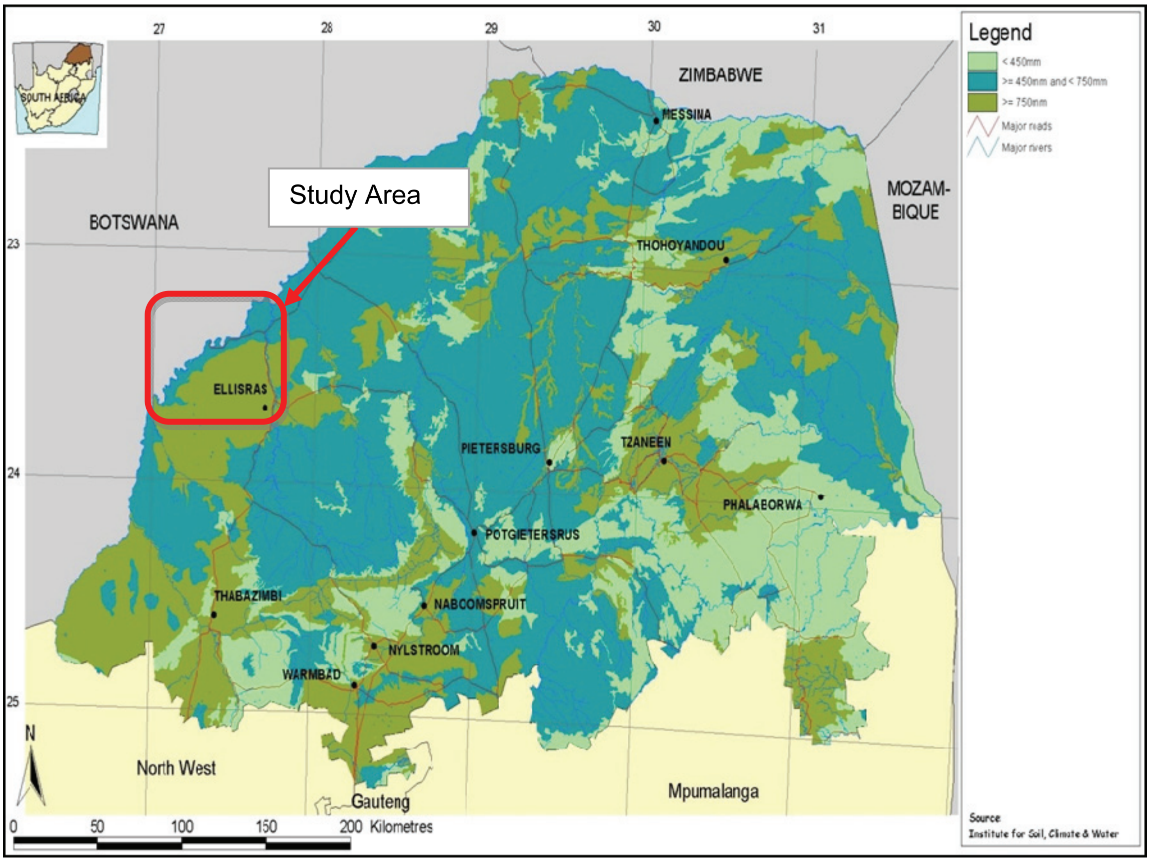


Figure 24: Soil depths in the study area (regional) (http://www.deat.gov.za /Maps/)

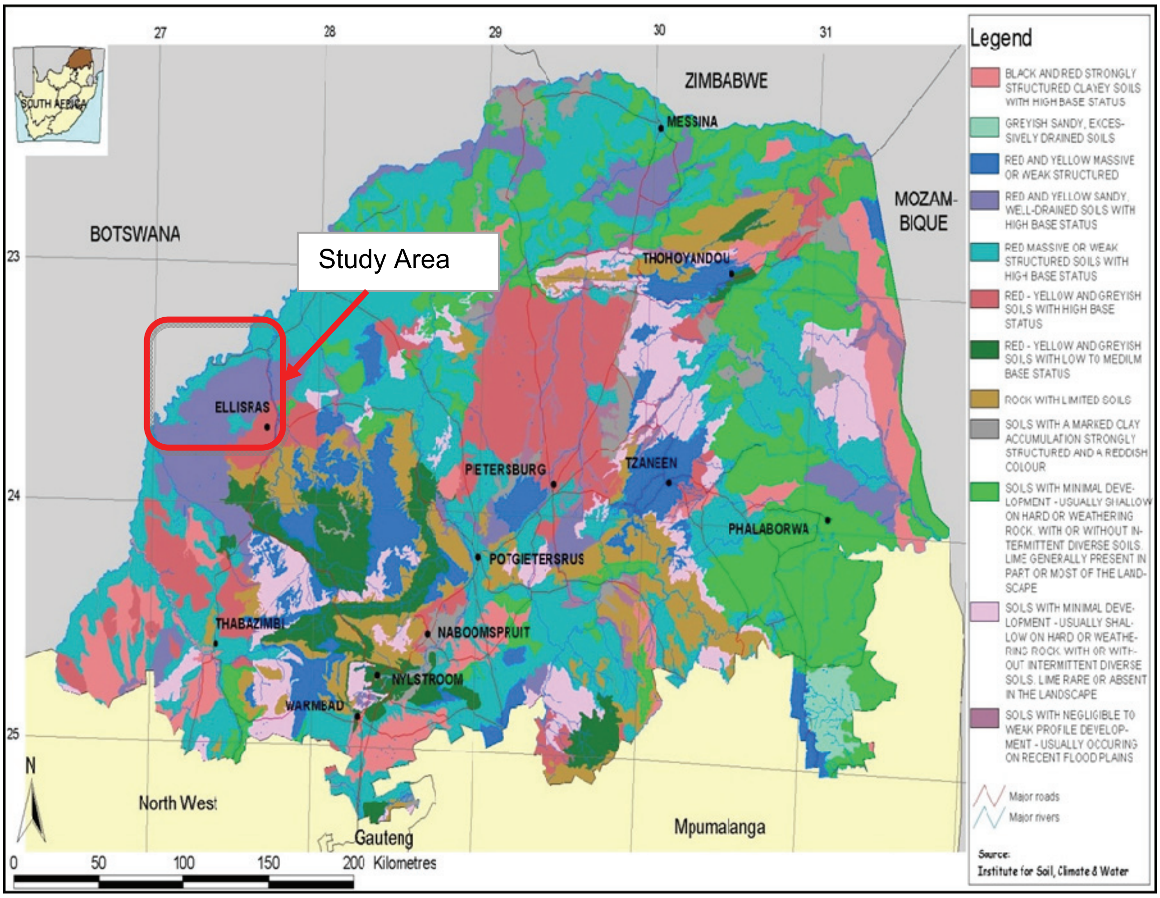


Figure 25: Soil types in the study area (regional) (http://www.deat.gov.za/ Maps).

Figure 26: Photo of the land cover of the study area.

5 Methodology

5.1 Introduction

This chapter will be a discussion of the different methods analysed and sample collection used during the project. From a sampling point of view, the focus will be on groundwater sample collection and geological sample collection. For the analytical methods used, the focus will be on acid-base accounting analyses and the analyses of pump test and slug test results.

Additionally, the steps used in conducting a pump test and a slug test will be discussed. Analytical methods used for the project that will not be discussed are the use of the Inductively Coupled Plasma spectrometer for the analyses of the groundwater samples and the use of X-ray Diffraction analyses to determine the mineral composition of the geological samples.

The methods used for the determination of recharge for the study area, namely the chloride mass balance method and the E.A.R.T.H. model, will also be discussed.

5.2 Sampling

In order to conduct qualitative analysis of the groundwater found in the study area and on the potential of the geology of the area to generate acid mine drainage, two types of samples were collected namely:

- Groundwater samples, samples were collected to determine the present status of the groundwater resources in the study area and to determine if, at present, there are any areas that have been affected by activities such as mining.
- Geological samples, samples collected for the use of acid-base accounting analyses, in order to determine if the rocks found in the study area will generate acid mine drainage if the samples are oxidized. Additionally the analyses were conducted to determine if sufficient base potential exists in the rocks to counter the acid generation.

The samples were collected from a wide range of location from within the study area. The collection of samples, or the quantity of samples collected, were often limited by a lack of access to sampling location (farms with locked gates), or due to confidentiality concerns (core samples containing coal)

5.2.1 Groundwater Samples

The water samples were obtained from boreholes by means of through flow bailers (Figure 27). These bailers were cleaned with de-ionised water before each sample was taken. The samples were stored in 500 ml plastic bottles and transported to the IGS laboratory for analysis. The samples were taken 5 m below the water level, or at fracture levels that had been determined by means of profiling. As an addition to the sampling, the water levels and the pH and EC were measured in the field.

5.2.2 Geological Samples

A total of 84 samples (after separation) were collected from various localities throughout the study area. The samples varied from core samples to chip samples (Figure 28 and Figure 29). Also included in the samples were two samples of processing plant waste from the Grootegeluk Mine and one sample of the sandstone layer located below the coal succession.

The samples were collected in plastic sample bags and transported to the Institute for Groundwater Studies. Here the samples were crushed and used in acid-base accounting analysis and X-Ray diffraction analysis.

X-ray diffraction (XRD) was performed on the samples to determine the exact mineralogical composition of the samples. The reasoning behind the testing for mineral composition, as well as the acid-base accounting, is the identification of layers in the geology of the Waterberg Coal Fields that are prone to acid generation or have high base potentials.

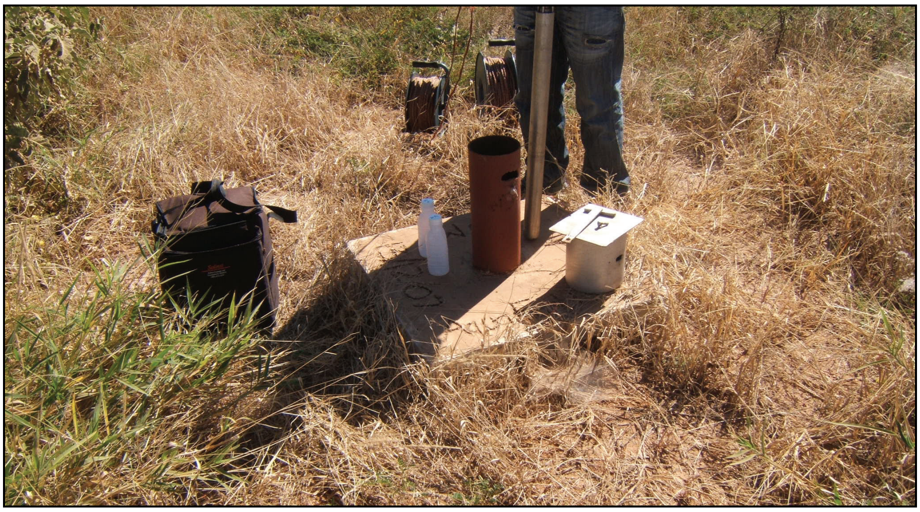


Figure 27: Groundwater sampling in the study area.

Figure 28: Core sample from exploration borehole near the Grootegeluk mine.

Figure 29: To the left Core samples, to the right Chip samples.

5.3 Water Quality

Listed in Table 3 are the determinants that were tested for during the water quality analysis of the water samples.

Table 3: Determinants included in the chemical analyses.

pH	EC	PAlk	MAlk	Ca	Mg	Na	K	F	Cl
$NO_3(N)$	SO_4	Cr6	Al	Fe	Mn	Cu	Co	Cr	COD

The elements listed in Table 3 cover a wide range and are good indicators of potential pollution in the groundwater due to coal mining. The measurements of the pH and EC will indicate the acidity or alkalinity of the water samples (pH), as well as the overall salt loads of the water respectively. The EC only provides an indication of salt quantities, without an indication of the type. The water quality determinations were done by the use of an Inductively Coupled Plasma Spectrometer (ICP).

5.4 Acid-Base Accounting

Acid-base accounting (ABA) analysis is a first-order classification procedure only, during which the acid-neutralising and acid-generating potential of rock samples are determined and the difference, also known as the net neutralising potential (NNP), can be calculated (Usher *et al.,* 2002). The NNP and / or ratio of neutralising potential to acid-generating potential is compared with a predetermined value, or a set of values. This is done in order to divide samples into categories that do, or do not require further ABA testing (Usher *et al.,* 2002). It was decided not to focus on the generation of poor quality leachate from the mines as it is expected that a certain level of acid generation at the mines is inevitable and that this should be covered in an additional study, as this was only a scoping level assessment. Different methods of conducting ABA test work will lead to different sets of sample data for evaluation. Rules and guidelines for testing have been developed by mine regulatory and permitting agencies (Usher *et al.,* 2002). Acid-base accounting only indicates the overall balance of acidification potential (AP) and neutralisation potential (NP) and is in its most basic form, merely a screening process. Accordingly, it provides no information on the speed (kinetic rate) at which acid generation or neutralisation will take place and due to limitations, ABA procedures are known as Static Procedures (Usher *et al.,* 2002). A given rock's potential to generate or neutralise acid is determined by its mineralogical composition (Usher *et al.,* 2002). It is not only the quantitative mineralogical composition, but also includes individual mineral grain size, shape, texture, and spatial relationship with other grains in the rock (Usher *et al.,* 2002).

Acid-base accounting can only yield a "worst case scenario" value for potential acid production and a "worst case", "most likely case", or "best case" value for potential neutralisation (Usher *et al.,* 2002). According to Usher *et al. (*2002) the neutralisation potential is a measurement of the sum of the total carbonates, alkaline earth's and bases available to neutralise acidity and therefore represents the most favourable condition.

The calculations of the maximum potential acidity and neutralisation potential are structured in such a fashion that they equate the two measurements to a common basis for comparison.

The values resulting from these calculations, expressed as calcium carbonate equivalent, are compared in order to compute a net acid-producing or neutralising potential. According to Usher *et al. (*2002), "material exhibiting a net acid production potential of 5 tons/1000 tons of overburden material or more as calcium carbonate equivalent, is classed as toxic or potentially toxic". Studies have shown that "the application of the acid-base accounting methods to overburden handling and placement throughout the USA and Canada has generally been effective in eliminating or reducing adverse water quality impacts".

5.4.1 The Primary Advantages of ABA

- Short turn-around time for sample processing,
- Low cost,
- Relatively simple analytical procedures,
- Relatively simple interpretation of results (Usher *et al.,* 2002),

5.4.2 The Primary Disadvantages of ABA

- The method only predicts a maximum potential acidity and a maximum neutralisation capability, assuming a 1:1 acid to base reaction. According to Usher *et al. (*2002), the actual acid production and neutralisation release rates cannot be predicted in this manner, nor can the completeness of the reaction be assessed.
- Acid-base accounting assumes that all the acid production from a rock can be attributable to iron disulphide minerals (predominantly pyrite), with none being produced by sulphate or organic sulphur forms (Usher *et al.,* 2002).
- The measurement of NP utilises a hot acid extract to measure carbonates and bases.
- Acid-base accounting becomes a very powerful tool when used in conjunction with other data such as hydrologic data, mining and reclamation plans and mineralogy.

5.4.3 Prediction Methods

It is believed that an accurate form of prediction offers the most cost-effective means of reducing the potential impact of AMD. These impacts that are being measured on the environment and in the mining sector as the costs associated with AMD can be prevented by allowing advanced planning for prevention and control (Usher *et al.,* 2002).

According to Usher *et al.* (2002), the objective of a prediction programme is to reduce uncertainty to a level at which potential risk and liability can be identified and effective extraction, waste handling and where necessary, mitigation and monitoring strategies, can be selected.

The scope of a prediction programme will depend on site-specific conditions and factors. Some programmes may comprise a few simple tests, in a relatively short period of time and with a modest budget. Others can involve extensive testing and analyses lasting several months to more than two years, with much higher costs.

The approach can include some or all of the following:

- Initial assessment and site reconnaissance.
- Sampling.
- Chemical, mineralogical and physical analyses.

- Short-term leaching tests.
- Geochemical static tests (ABA).
- Geochemical kinetic tests.
- Mathematical models.

With sufficient data the potentially higher accuracy of models and predictions can minimise the impact of acid generation in the mines. The IGS most commonly, uses the static peroxide method for ABA.

5.4.4 Static Methods (Acid-Base Accounting)

Static methods are some of the more common tests generally used for ABA calculations. These are screening methods to determine the difference between the acid-generating capability and the acid-neutralising potential of a particular sample or set of samples. Table 4*Table* lists the most common procedures used in static ABA testing.

Table 4: Most commonly used static ABA methods after Usher et al. (2002).

Paste pH	Static Net Acid Generation (NAG) procedure.
Peroxide methods.	BC Research Initial test
Sulphur content.	BC Research Confirmation Test.
Calculated NP.	Sobek Neutralisation Potential method.
Carbonate NP determination.	Modified acid-base accounting procedures for neutralising potential.
Lapakko neutralisation potential test procedure.	COASTECH modified biological oxidation test.
Net Carbonate Value (NCV) for acid-base accounting.	

5.4.5 Peroxide Methods

Several tests using hydrogen peroxide as an oxidant for sulphide minerals exist for use in ABA calculations. The one that will be used for this study is the Net Acid Production (NAP), or Net Acid Generation (NAG) test. The NAP, or NAG test, was developed to provide an alternative to acid-base accounting in order to predict acid rock drainage. The NAP test was used as it possesses the advantage of not requiring sulphur analysis and therefore has potential to be a quick method usable in the field if necessary. The NAP test can also provide an accurate quantitative assessment of acid-generating potential under controlled laboratory conditions.

Current work indicates that NAP test results correlate well with ABA, particularly when the NNP values are relatively low and negative, which is the range in which greater certainty is required (Usher *et al.,* 2002). When the NNP values are negative, the NAP values tend to underestimate the acid-generating potential. This should however not seriously affect waste management decisions. The test relies on the ability of hydrogen peroxide to oxidise sulphides, such as pyrite, in a sample of mining waste to produce sulphuric acid.

The acid produced is simultaneously neutralised by carbonates and/or other acid-consuming minerals in the sample. At the end of the reaction, the final pH of slurry provides a qualitative indication of acid-generating potential. Titration of the slurry to determine its acid content, allows the calculation of the net acid produced by the peroxide digestion and a quantitative assessment of the acid-generating potential.

The pH recorded at the end of the H_2O_2 digestion step prior to titration, can provide a qualitative indication of the acid-generating potential (Table 5).

Table 5: Interpretation of final NAG test pH (Usher et al., 2002)

Final pH in NAG Test:	Acid-Generating Potential:
> 5.5	Non-acid-generating
3.5 to 5.5	Low risk acid-generating
<3.5	High risk acid-generating

Precaution should be exercised when interpreting NAP data in this way, since the pH values are dependent on the specific site lithology and mineralogy. Calibration with other tests and analyses is therefore recommended if the test is to be used in this way. Caution should also be exercised when interpreting NAG test results for coal reject samples and other materials that may contain high levels of organic material (such as potentially acid sulphate soils, dredge sediments, and other lake or marine sediments).

All organic material must be completely oxidised, otherwise acid NAG results could be unrelated to sulphides. Several aliquots of H_2O_2 reagent may be added to the sample to break down organic acidity. Samples with a positive NAP value and high sulphur content must be evaluated carefully (Usher *et al.,* 2002).

5.5 Aquifer Parameters

In order to obtain aquifer parameters for the study area, several slug tests and pumping test were conducted and analysed to determine and identify any trend or divergence from the expected norms for aquifers in Karoo type rocks. These parameters were to be used for the construction of numerical flow models for the study area. The purpose of the models was to:

- Determine the volumes of water that would flow into the mines.
- Determine if the mines would decant.
- Determine the impact the mines would have on the surrounding area.

The parameters that were analysed were to determine water levels and transmissivities, which were obtained from pump testing and slug testing. The pump testing and slug testing were done primarily to obtain values for transmissivities and to determine the sustainable yields for the boreholes.

5.5.1 Slug Tests

A slug test is an efficient method which predicts the yield of the borehole by measuring the recovery rate of the water level after a sudden change. This test is performed by suddenly raising or lowering the static water level in the borehole with the aid of a closed cylinder or known volume of water. The volume of water in the borehole is displaced, therefore increasing the pressure in the borehole. The equilibrium in the water level is changed and will recover or stabilise to its initial value. By measuring the rate of recovery or recession (time to recover) of the water level, the borehole's transmissivity or hydraulic conductivity can be measured. The recession time of the water level to recover to at least 90% of its initial value is used in a formula to determine the yield of the borehole. The formula indicates the possible yield of the borehole in L/h y = 117155 x -0.824 (where x = recession time in seconds). The graph below was created from results obtained by testing 32 boreholes (Van Tonder *et al.,* 2002). On the graph a straight line is obtained with the log-log scale. If the recession time for the borehole is entered on the x-axis, the possible yield can be read from the y-axis. If a slug test indicates the potential yield of a borehole at less than 0.3 l/s, additional tests should be considered. If the potential yield is more than 0.3 l/s, it is recommended that further tests such as step drawdown, multi-rate and constant rate pumping tests be conducted on the borehole. The data gathered from the slug test was loaded into a software program developed by the Institute for Groundwater Studies, which works on a similar principal as the FC software program that is used to determine sustainable yields from pump testing data.

The results are then interpreted and used as a quick estimate of the yield of a borehole. The data obtained from the slug tests were used as indicator parameters for the yields at which boreholes, that had been identified as candidates for pump testing, could be pumped.

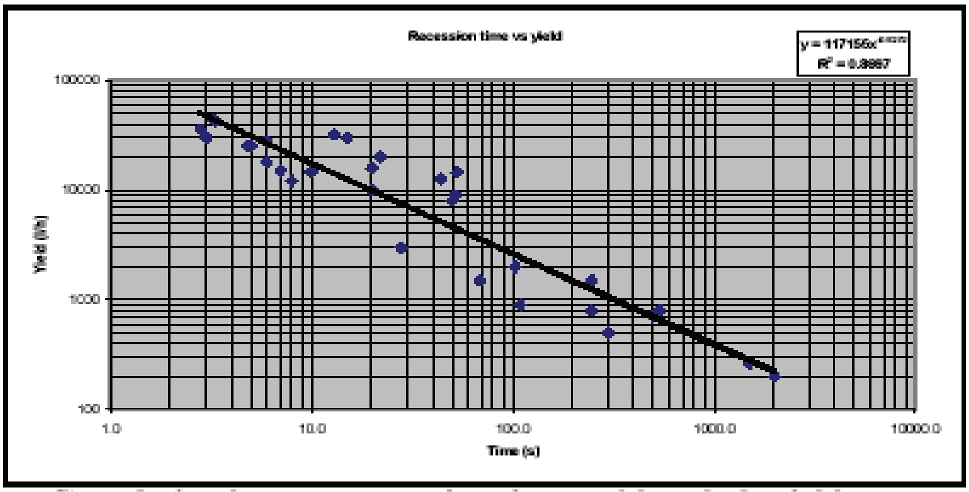


Figure 30: Slug test yield determinations.

5.5.2 Pumping Tests

In an effort to obtain information on aquifer parameters for the study area, pump testing was conducted on several boreholes in the study area. The pump test can be divided into three parts; installing equipment and preparing the test, conducting the tests and measurements, and removing the equipment and checking the field data. Submersible pumps were used, as they handle easily in the field. The pumps were fitted with lay flat pipes of approximately 50 m length. The pumps were powered by generators and the time intervals for the test are measured with stop watches. The maximum yield of the pump was chosen so that sufficient drawdown is reached in time. During test measurements, the water levels and discharge rate are measured at fixed time intervals. The duration of the test, discharge rate and conditions of the measurement (manually, electronically) depend on the type and goal of the test (Van Tonder *et al.,* 2002).

Due to differences in transmissivities, depths and the available drawdown in the different borehole, the tests conducted by the researchers varied a great deal in their length. The time intervals were measured manually and the pumping rates were set to obtain the maximum possible drawdown. It is recommended that every measurement and observation on site should be recorded. Changes in the condition of the test, such as the discharge rate, heavy rainfall or interruptions of the test due to technical problems, must be recorded to ensure that the test is analysed correctly. After completion of the tests, the equipment was removed from the boreholes, cleaned or decontaminated (where necessary) and the site was left in the same condition as before the test. The field data and all information were checked directly after the test and again before beginning the analysis. As the objective of the pumping tests was to determine parameter values for the aquifer, the test were performed as follows:

- Firstly, a slug test was performed to obtain a first estimate of the possible maximum yield for the borehole (not done for every borehole)
- Secondly, a constant rate pumping test was conducted. It is recommended that the pumping rate should allow for sufficient drawdown during the constant rate test, without allowing the water level to reach the position of the main water strike. If the position of the main water strike or fracture is not known, a revised minimum one-hour step drawdown test should be performed.

According to Van Tonder *et al.* (2002) no equal time steps are required, and the pumping rates can be increased at any time during the test. A flattening water level usually indicates the positions of the fractures.

- Thirdly, if the position of the fractures is known, a constant rate pumping test can be performed. The abstraction rate should not allow the water level to reach the position of the main water strike.

- The minimum proposed duration of pumping should be approximately 8 hours according to Van Tonder *et al.* (2002), although this is a guideline value that can be adjusted as needed. For estimating the impact of inner boundaries (extent of fracture, matrix) or outer boundaries (no-flow or recharge boundaries), the duration of the constant rate pumping test should be several days. This is however not always practical and should be adjusted as needed (Van Tonder *et al.,* 2002). A pumping time of four hours was generally used for the pumping test, but longer tests were also conducted.
- Finally, the recovery inside the abstraction borehole was measured until the *water* level recovered to 95% of the original static water level. A recovery test has no external interferences.

The pump test data were analysed using the FC software program that has been developed at the Institute for Groundwater Studies in Bloemfontein. The software was used to determine sustainable yields for the boreholes that were tested. From the diagnostic plots generated by the FC program (log-log plots) it was concluded that the transmissivities of the boreholes were very low.

5.6 Recharge

The recharge for the study areas was required as an input parameter for the modelling phase of the project in order to simulate the real world scenario as closely as possible. Two methods were used for recharge determinations of the study area. The selection of methods was based on the accuracy of the methods for the prediction of recharge and the availability of data. The methods selected were the Chloride Mass Balance Method and the E.A.R.T.H. model for determining recharge.

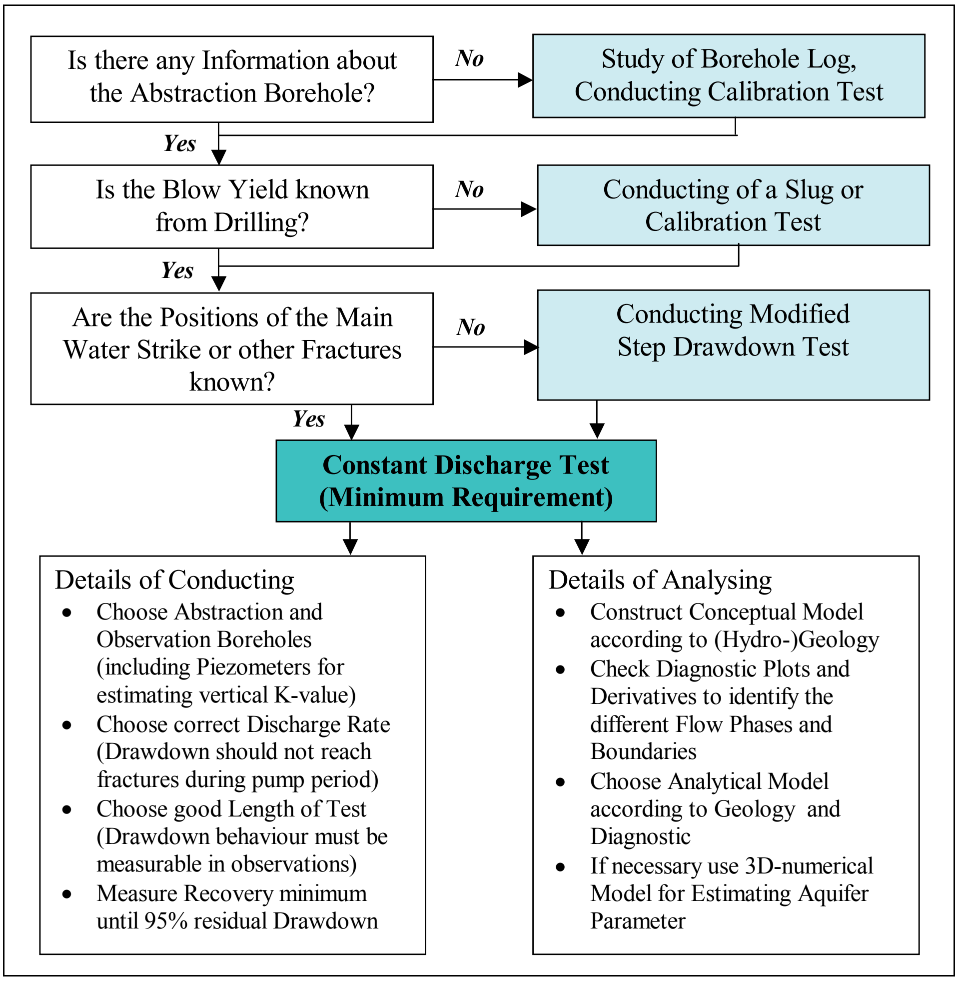


Figure 31: Processes involved in pumping tests (after Van Tonder et al., 2002).

5.6.1 The Chloride Mass Balance Method

The chloride method for determining recharge (also known as the chloride mass balance method) is one of the techniques which are often used to estimate groundwater recharge (Van Tonder and Xu, 2001). The chloride mass balance method has been used to evaluate recharge processes in a wide range of semi-arid environments, as these environments are more suited to this type of recharge estimation. Due to its conservative nature and the relative abundance thereof in precipitation, chloride is used for recharge estimation. (Van Tonder and Xu, 2001). According to Van Tonder and Xu (2001) "The application is based on comparison of the chloride deposition rate at the soil surface with the concentration in the soil water or groundwater. The Cl concentration increases relative to the concentration of rainwater as a result of interception, soil evaporation and/or root water uptake by the vegetation. The total (wet and dry) chloride deposition and the total precipitation depth determine the chloride concentration of the rainwater at the surface."

The chloride method used in this study is as follows:

*[% Recharge = 100*Cl (rain)/Cl (groundwater)]* [1]

The above mentioned recharge calculations were used on information from 222 boreholes. From the analysed values, the data suggests that there is a large range for the Cl values found in the study area. The calculations indicated a recharge of 1.59% of the annual rainfall (see Appendix C).

5.6.2 The E.A.R.T.H. Model

In an effort to confirm the recharge values obtained from the Chloride method, the E.A.R.T.H. method for recharge estimation was used. What follows is a brief description of the method: According to Van Tonder and Xu (2001), the variability of the surface, soil and plant characteristics, often leads to a complex, three dimensional, water and solute movement taking place in the upper part of the unsaturated zones.

They continue by stating that: "Soils which are formed by *in-situ* weathering often form a cover with a highly variable thickness adding to the complexity of determining accurate figures on the downward percolation (recharge) of soil water to the water table". Van Tonder and Xu (2001) stated that Van der Lee and Gehrels (1990; 1997) developed a lumped parametric model which they named the E.A.R.T.H. model (Extended model for Aquifer Recharge and soil moisture Transport through the unsaturated Hard rock). This model was to be used for the estimation of groundwater recharge. The modelled space is schematically represented by a number of modules, or reservoirs, as illustrated by Figure 32. Each reservoir has an acronym, which roughly describes the main function or processes where:

MAXIL = maximum interception loss
SOMOS = soil moisture storage
SUST = surface storage
LINRES = linear reservoir
SATFLOW = saturated flow

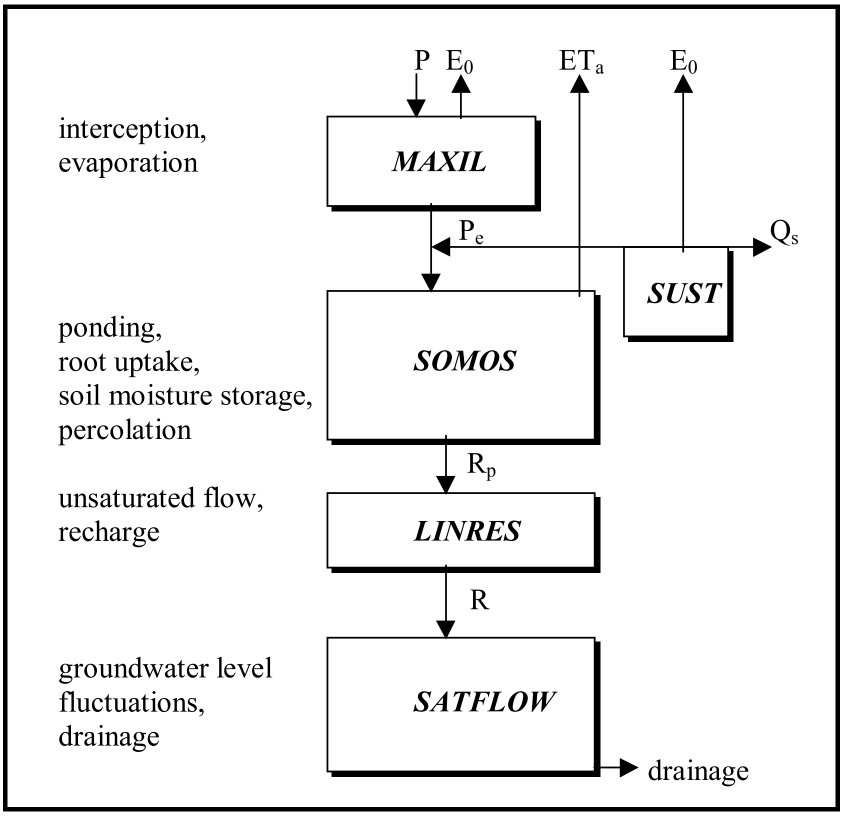


Figure 32: Illustration of the E.A.R.T.H model.

Using the E.A.R.T.H. model, eight boreholes were used for the recharge determination. These boreholes were selected due to their availability of data dating back through time. Some of the boreholes have information stretching back as far as 1973. Some of the other boreholes unfortunately only have data for five or eight years. The above mention model was applied to the gathered information and a recharge of 1.51% was calculated for the study area (see Appendix D).

5.7 Numerical Groundwater Models

As the main goal of the study is to determine the impact the mines and other activities planned for the study area, it was determined that models should be used to determine this impact. Given that models can sometimes be one sided often differing from researcher to researcher, it was decided to construct numerical flow models and in addition a conceptual model to serve as a conclusion for the project.

What follows is a brief discussion on numerical modelling. The relatively recent development of the simulation of groundwater flow and transport by means of numerical modelling (dating from the 1970s according to Vermeulen and Dennis 2007), has evolved to the point where the study of complex groundwater problems is dominated by numerical modelling. Due to the large advances in recent years in the domain of computer technology, has ensured that the standard procedure for the solution of groundwater flow and mass transport is the use of numerical models.

According to Vermeulen and Dennis (2007) numerical modelling can be used to solve complex and simple problems. One of the major advantages of numerical modelling being, that various scenarios can be investigated without much effort. The large scale application of numerical modelling to groundwater problems as led to the synonymous use of modelling when speaking about numerical modelling. What follows is a brief discussion on the steps involved in the construction of a numerical model.

5.7.1 Collection and Interpretation of Field Data

Field data play an integral part in understanding the natural system and to specify the groundwater problem that needs to be investigated. A numerical model can be developed into a site-specific groundwater model if the appropriate field parameters are assigned to the model (Vermeulen and Dennis 2007). The quality of the generated model generally depends on the quality of the input data used and the level of calibration achieved.

5.7.2 Conceptualizing the Natural System

It is recommended that in each model study, a conceptual model be constructed. This model is then to represent the natural systems present in the area to be studied. The purpose of a conceptual model is to design and construct the equivalent (but simplified) conditions of the real world problem to be modelled. The next step is to transfer the real world situation into a model equivalent. This transferral, being a crucial step in the domain of groundwater modelling.

The following parameters are generally included in a model (Vermeulen and Dennis 2007):

- The geological and geohydrological features and characteristics of the area being studied.
- The static water levels/piezometric heads measured for the study area.
- Interactions taking place between the geology and geohydrology on the boundaries of the study area.
- Processes and interactions taking place within the study area that potentially have influences on the movement of groundwater
- Simplifying assumptions necessary for the development of a numerical model such as for example a flat topography or homogeneous geology, and
- The selection of a numerical code suitable for the needs of the model.

5.7.3 Calibration and Validation

The importance of model calibration and validation are found in the necessity to overcome the lack of input data. Additionally this is done to accommodate the simplification of the natural system in the model. During model calibration, simulated values of for example water levels or water level elevation are compared with the values measured in the field. The input data are then altered and modified within ranges, until the data simulated by the model and values observed in the field, are fitted on a graph, within an acceptable tolerance (Vermeulen and Dennis 2007). The input data and the comparison of simulated and measured values can either be altered manually or automatically although manual modification of the values is normally preferential.

Model validation is required in order to demonstrate the applicability of the model for use in making predictions. A practice commonly used for the validation of models is the comparison of the model with a set of data that was not used during model calibration. Calibration and validation are however some of the more difficult aspects of numerical groundwater modelling. Often it is not possible to validate a model as there are no alternate data sets available for validation.

In the case of the models constructed for the study area, calibration was done according to the amount of inflow currently being measured at the Grootegeluk mine. The model was not fully calibrated however as there was a general lack of input parameters with which to calibrate.

5.7.4 Modelling Scenarios

It is possible to assess alternative scenarios for a given area with relative ease by means of numerical modelling. When the application of numerical models is considered in a predictive sense, there are limitations on the application of the model. According to Vermeulen and Dennis (2007) models used for predictions should be applied to prediction of a relative nature rather than those of an absolute nature. Five dewatering and accompanying decant models were constructed for the study area to illustrate different scenarios that may occur during the course of mining in the study area.

Scenario 1

- Three dewatering models were constructed using all the parameters collected for the study area (see Chapter 10) and only one pit (the northern pit).
- In the models, the faults found in the study area were not activated.

- The models were systematically dewatered, first to the second layer, then to the third layer and finally to the fourth layer to simulate progression of the mine over time.
- All the models were constructed for all three transmissivities used for the models in general (0.4 m^2/d, 0.28 m^2/d and 0.12 m^2/d) and run for 10 years for each layer being dewatered.
- For the decant purposes the pits were filled and dewatered for 50 years.

Scenario 2

- The fourth dewatering model possessed the same parameters as scenario 1 (see Chapter 10) and in addition, contained one activated fault that ran through the pit. This was done to simulate a scenario where a zone of higher transmissivity might be encountered during the course of mining. Only a transmissivity of 0.4 m^2/d for the model in general was used with higher transmissivities being applied to the faults.
- The decant model was run for 50 years simulating a time when the mining had stopped.

Scenario 3

- The final model constructed had all three pits on the model and all the faults found in the study area activated. All the pits were dewatered to 110 m below surface.
- Once the models were dewatered they were run for 50 years. The models contained the parameters as stated in Chapter 10 used for the decant models.

5.7.5 Assumptions and Limitations of Numerical Modelling

In order to develop a model of an aquifer system, certain assumptions have to be made. The following assumptions were made to develop the model:

- The aquifer system is represented by a two-dimensional system consisting of four layers with dominating horizontal flow. The horizontal flow is due to the large lateral extent of the area modelled (tens of kilometres) if compared to the depth of the aquifers.
- The geology was assumed to be homogeneous with the exception of the models during which the faults were activated as high transmissivity zones. However even during these scenarios the geology was assumed to be homogeneous.
- The system was taken as being in steady state, even though the natural conditions have been disturbed.
- The available information on field tests and predominant geological structures was assumed to be correct.
- No abstraction boreholes were included in the model.
- Many of the aquifer parameters could not been determined in the field and were accordingly estimated.
- It was assumed that the entire study area had an average water level of 28 m below the surface.

It must be noted that a numerical model simulating groundwater flow is merely a representation of the real system. Accordingly it can be viewed at most as an approximation, with the accuracy depending on quality of the available data. This implying that errors are always associated with numerical groundwater models. This is largely due to uncertainties in the data and the inability of numerical methods to accurately describe natural physical processes (Vermeulen and Dennis, 2007).

5.7.6 Generation of a Finite Difference Network

5.7.6.1 General

According to Vermeulen and Dennis (2007) "in order to investigate the behaviour of aquifer systems in time and space, it is necessary to employ a mathematical model". The software program MODFLOW developed by Harbaugh and McDonald (1996) was used for this investigation. The programme is an internationally accepted modelling package, capable of calculating the solution of the groundwater flow equation by means of the finite difference approach.

A professional graphical-user-interface (GUI), PMWIN, developed by Chaing and Kinzelbach (1999), was used for the creation of the model. It was additionally used to analyse and display the modelling results. The finite difference (FD) method was the first method to be used for the systematic numerical solution of partial differential equations.

For the construction of FD models the user creates a regular grid covering the entire study area. The model area is then subdivided into rectangular sub domains commonly referred to as cells. The cell values are assigned individually and can contain such parameters as, water level, transmissivity and recharge are. Each cell can hold a value for each parameter, but cannot have different values for the same parameters.

5.7.6.2 Boundary Conditions

One of the first and most demanding tasks in groundwater modelling is that of identifying the model area and its boundaries. Consequently, a model boundary is the interface between the model area and the surrounding environment. Conditions on the boundaries, however, have to be specified. Boundaries occur at the edges of the model area and at locations in the model area where external influences are represented, such as rivers, wells and leaky impoundments. Criteria for selecting hydraulic boundary conditions are primarily topography, hydrology and geology. The topography, geology, or both, may yield boundaries such as impermeable strata or potentiometric surface controlled by surface water, or recharge/discharge areas such as inflow boundaries along mountain ranges. The flow system allows the specification of boundaries in situations where natural boundaries are a great distance away. Boundary conditions must be specified for the entire boundary and may vary with time. At a given boundary section just one type of boundary condition can be assigned. As a simple example, it is not possible to specify groundwater flux and groundwater head at an identical boundary section. Boundaries in groundwater models can be specified as:

- Dirichlet (also known as constant head or constant concentration) boundary conditions
- Neuman (or specified flux) boundary conditions
- Cauchy (or a combination of Dirichlet and Neuman) boundary conditions

A box model was used in which the northern, eastern, southern and western borders of the model were set to constant head boundaries. This was done to simplify the model. For the dewatering models, constant head boundaries were placed on the lowest levels of the layer that was to be dewatered. For the decant models, these boundaries were removed.

5.7.6.3 Initial Conditions

Initial conditions are vital for modelling flow problems. Initial conditions must be specified for the entire area. Generally, the initial water level/head distribution acts as the starting distribution for the numerical calculation. The initial water level was set to surface level (for the model zero (0) as the modelling program can only simulate saturated flow.

5.7.6.4 Sources and Sinks

Sources and sinks can be defined as recharge and abstraction sources in the aquifer, respectively. Sources can be precipitation and inflow from surface water and recharging boreholes. Sinks can be abstraction boreholes, springs, evapotranspiration, mines and outflow to surface water.

The groundwater recharge (R) for the area was calculated using the chloride method and the E.A.R.T.H. method. Accordingly the recharge for the study area was calculated to be 1.5% of the annual rainfall. The recharge entering into the model in general was determined at 0.023 mm/y, and at 20% of the annual rainfall in the open pits (Hodgson *et al.,* 2007), amounting to 0.31 mm/y.

5.7.6.5 Aquifer Parameters

Two main parameters are used to describe the physical properties of the aquifer, namely transmissivity (T) and storage coefficient (S). Transmissivity is a measure of the ease with which groundwater flows in the subsurface. Transmissivity is related to hydraulic conductivity (K): $T = Kd$ where d is the saturated thickness of the aquifer. Storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. For a confined aquifer, the storage coefficient is equal to the product of the specific storage and aquifer thickness of the saturated porous medium. For an unconfined aquifer, the storage is the ratio of the volume of water that drains by gravity to that of the total volume and is known as specific yield.

- The calculated harmonic mean of the transmissivities was 1.6 m^2/d, as calculated from pumping test data.
- This was taken as the total transmissivity for the system and divided among the layers for an even distribution of 0.4 m^2/d for each layer.
- Two additional transmissivities were taken to test the model (different scenarios).
- It was decided to take transmissivities of roughly 1/3 (0.12 m^2/d) and 2/3 (0.28 m^2/d) respectively.
- The reason for taking these transmissivities was to simulate different scenarios as it was felt that the transmissivity of 0.4 m^2/d was too high and did not correspond to the volumes of water entering into the pit.
- An additional reason was that the model could not be calibrated due to lack of data.
- These transmissivities were used for the area as a whole, with the transmissivities in the pits set at 100 m^2/d for the dewatering models, and 500 m^2/d for the decant models respectively.
- The transmissivities selected for the faults were 500 m^2/d.

A general storage coefficient of 0.003 was selected for the model in general, and storage coefficients of 1 and 0.25 for the dewatering and decant models in the pits themselves. These values were selected as they conform well to expected norms for Karoo aquifers. Vertical hydraulic conductivity was set to $1E^{-5}$ for the model as a whole, and at 10 in the pits to simulate worst case scenario situations.

5.7.6.6 Time

For the dewatering models, a time frame of 10 years was determined for the purpose of simulating the dewatering of each layer as mining progresses ever deeper into the geology. The 10 years were divided into lengths of 360 days (to remove leap years from the modelling calculations), with the time steps set to 12 (12 months). For the decant models, a time frame of 50 years divided into lengths of 360 days and 12 time steps was selected.

5.7.6.7 Pits

Initially only one pit was simulated with the three different transmissivity values. This was finally expanded to three pits; one to the north, one towards the south-east and one between the other pits. The sizes of the pits varied, with the northern pit being 1750 ha, the central pit being 2793 ha, and the south-eastern pit being 2070 ha. The large sizes for the pits were chosen to simulate the absolute worst case scenario situations.

6 Geology of the Waterberg Coalfields

6.1 Introduction

In 1920, coal was discovered while drilling for water on the farm Grootegeluk. Since then a large number of exploration boreholes has been drilled in the study area. There are also large numbers of boreholes being drilled as part of ongoing prospecting programmes within the study area. Iscor began the development of the Grootegeluk colliery in the 1970s which is currently the only active mine in the study area. Figure 33 indicates the regional geology of the study area. As indicated in Figure 33, the study area includes most of the Karoo Supergroup, The predominant structures (the three main faults) namely the Daarby, the Zoetfontein and the Eenzaamheid faults, are indicated on the map.

The Waterberg Coalfield trends east / west and is heavily faulted (Figure 33 and Figure 34). It is composed of sedimentary rocks of the Karoo Sequence and forms a graben structure bounded in the north by the Zoetfontein fault and in the south by the Eenzaamheid fault. The Daarby fault subdivides the coalfield into the shallow opencastable western part and the deeper north-eastern part of the coalfield (a displacement of approximately 400 m).

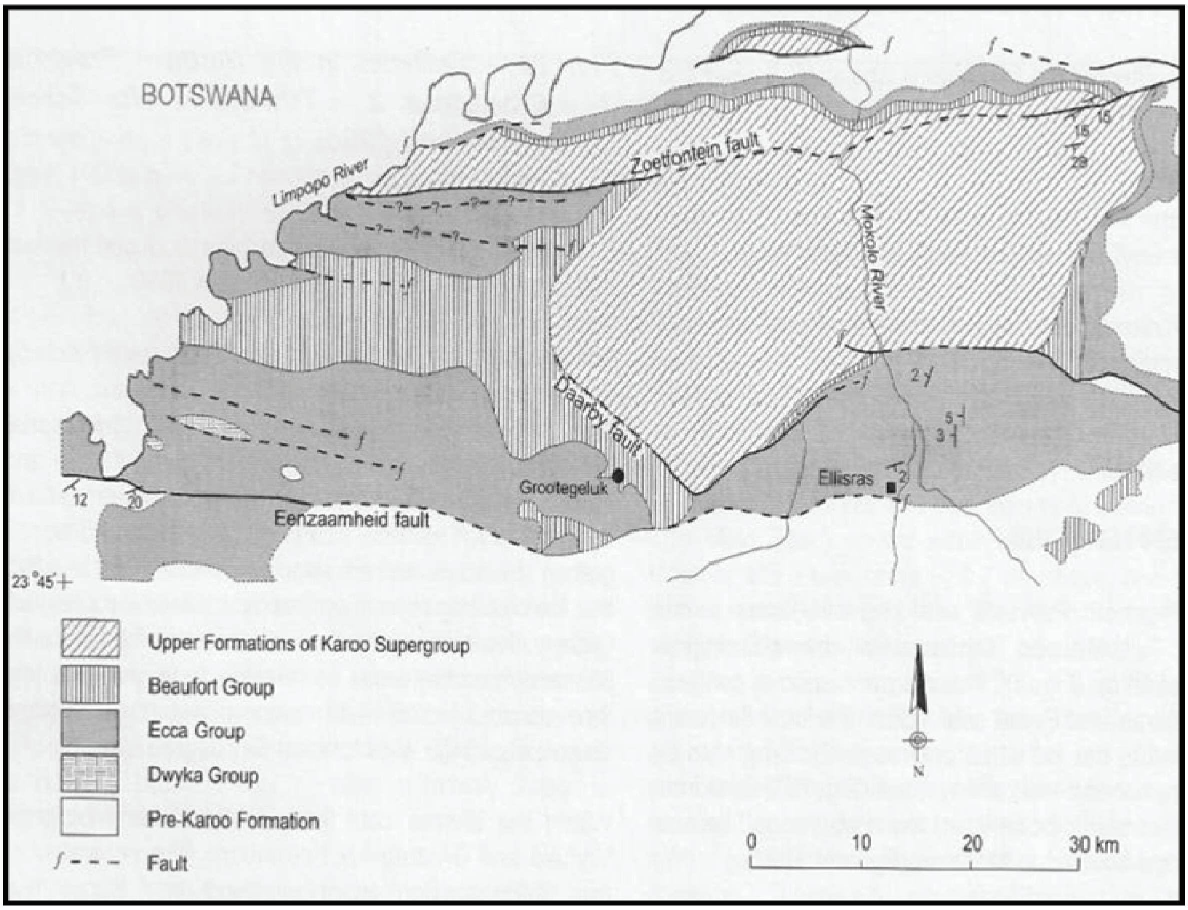


Figure 33: Simplified geological map of the Waterberg coalfield (Snyman, 1998).

The Zoetfontein fault resulted from pre-/during Karoo depositional tectonism, whilst the Eenzaamheid and Daarby faults resulted from post-Karoo depositional tectonism. Figure 34 displays a phase magnetics map of the study area (courtesy of the CSIR), indicating all the dominant structures found in the study area with the three main faults indicated on the map. The map indicates faults as well as igneous intrusions with pre-Karoo topography also playing a role.

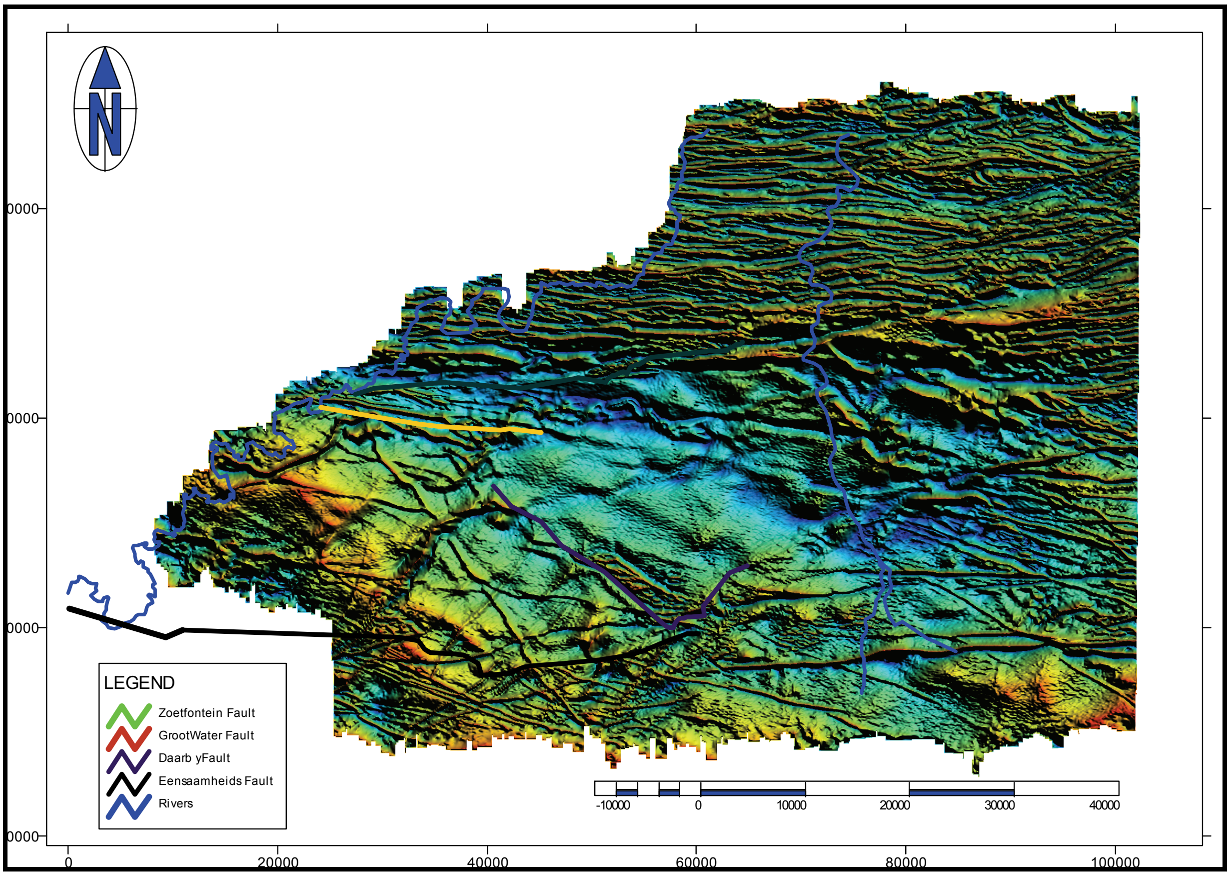


Figure 34: Phase magnetics map of the study area indicating the dominant structures (courtesy of the CSIR).

All the units of the Karoo Sequence are present in the coalfield and the subdivision of this Sequence is mainly based on lithological boundaries, consisting from top to bottom of the Stormberg Group (Letaba Formation), followed by the Beaufort Group, the Ecca Group and the Dwyka Group. Within the Waterberg Coalfield, coal occurs in both the Vryheid and Grootegeluk formation, which are equivalent to the Volksrust formation of the Karoo Supergroup. In addition to the Karoo Supergroup rocks, there are also rocks present in the study area from the Mokolian Supergroup.

6.2 Coal-Bearing Successions in the Coalfield

The coal-bearing sequence is 115 m thick (Figure 28 and Figure 35) and subdivided into 11 zones (Snyman, 1998). The lower four form part of the Vryheid formation. These zones coincide with the four lower seams of predominantly dull coal, with average thicknesses of 1.5-5.5 m. The ash content of these seams increases from 20% to roughly 45%.

Once the mines reach Coal Zone 2, the opencast mining method will cease to be economically viable and underground mining will be required to remove the remaining coal. The barrier between the opencastable underground coals is a thick succession of Ecca sandstone (Dreyer, 2008).

According to Dreyer (2009) it should be noted that due to the thickness of the last coal seam (1.5 m) it would be possible to remove the coal by means of underground mining methods. This will only be done in future and is not currently an economically viable option.

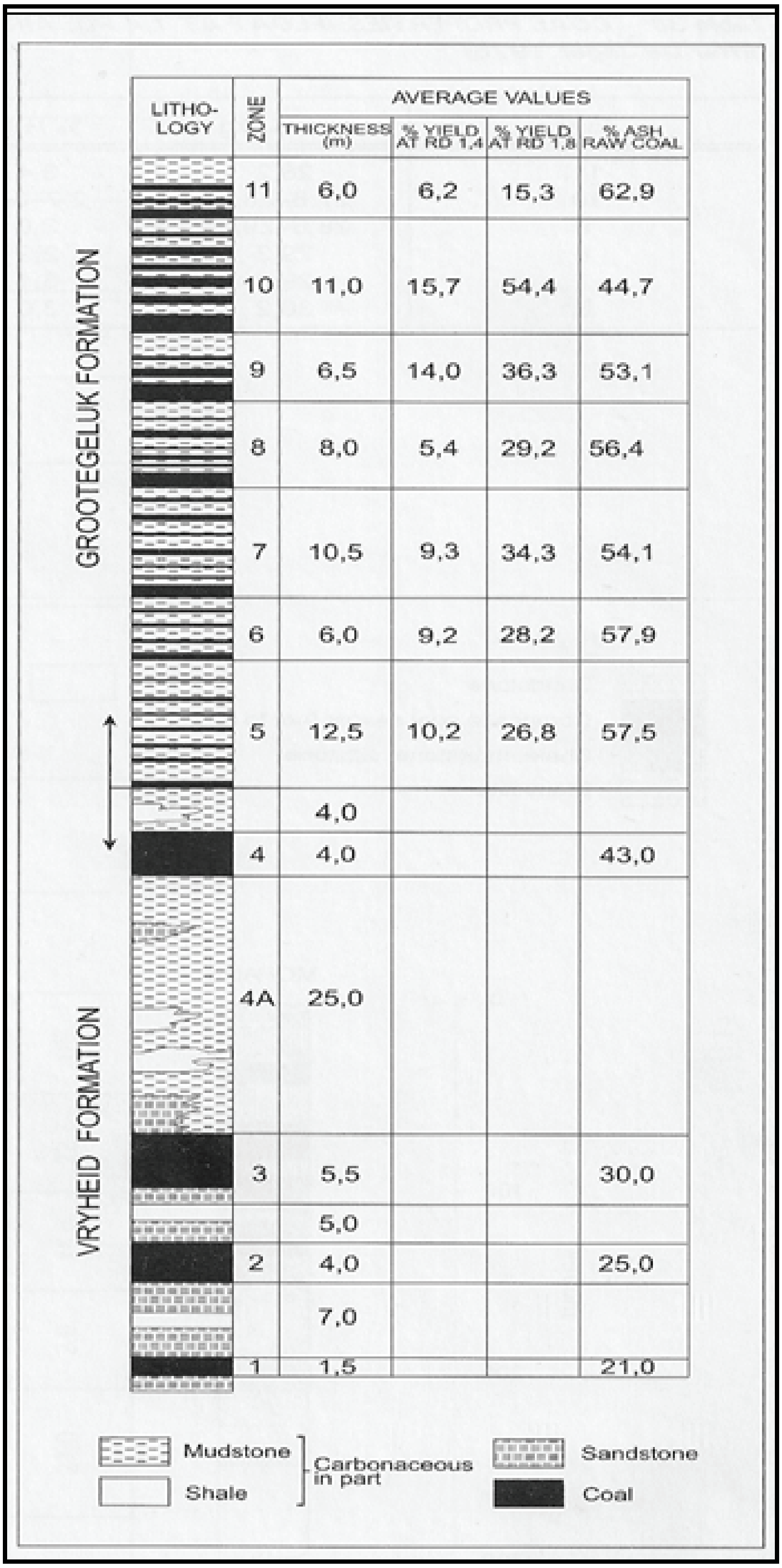


Figure 35: Generalized stratigraphic column of the coal-bearing interval in the Waterberg coalfield.

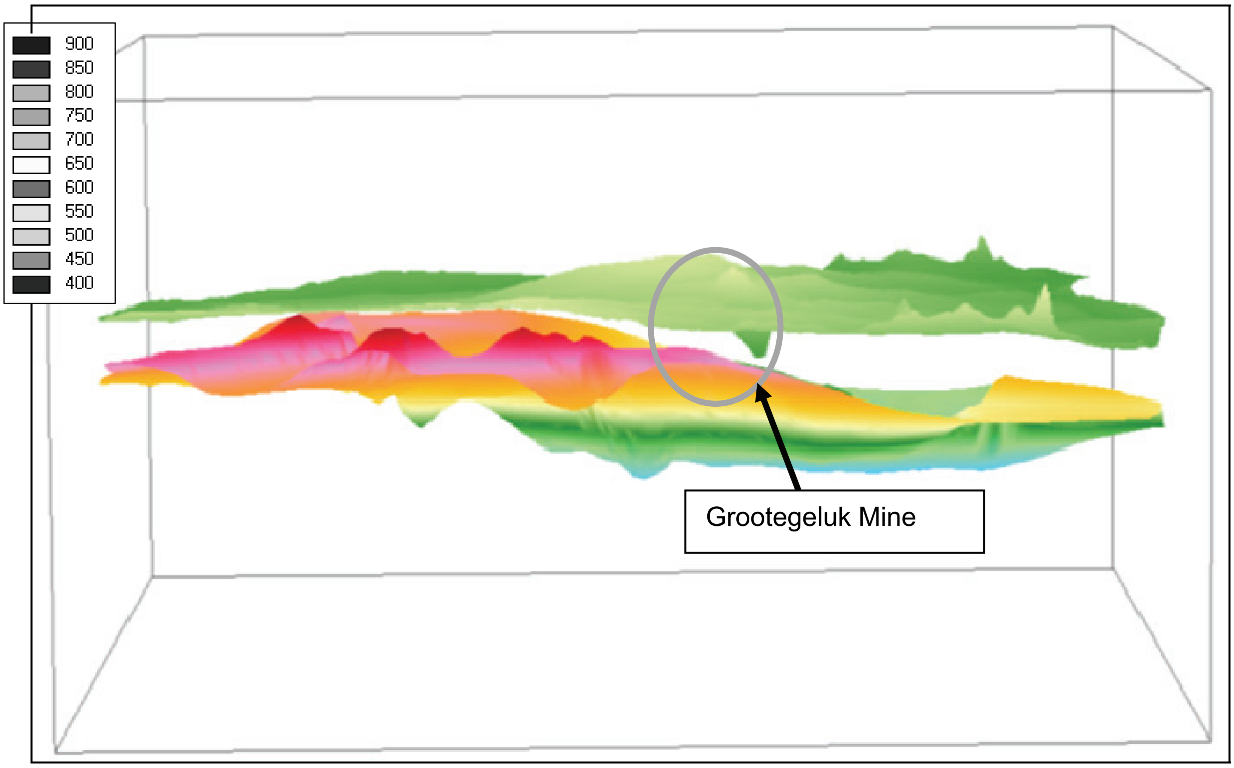


Figure 36: Exaggerated 3D side view of the topography and Coal Zone 2.

From Figure 37, it is apparent that the coal seams are located at shallower depths in the west and at much deeper depths in the east and north/east. The cut-off between the deeper and shallower coal (the Daarby fault) can also be seen.

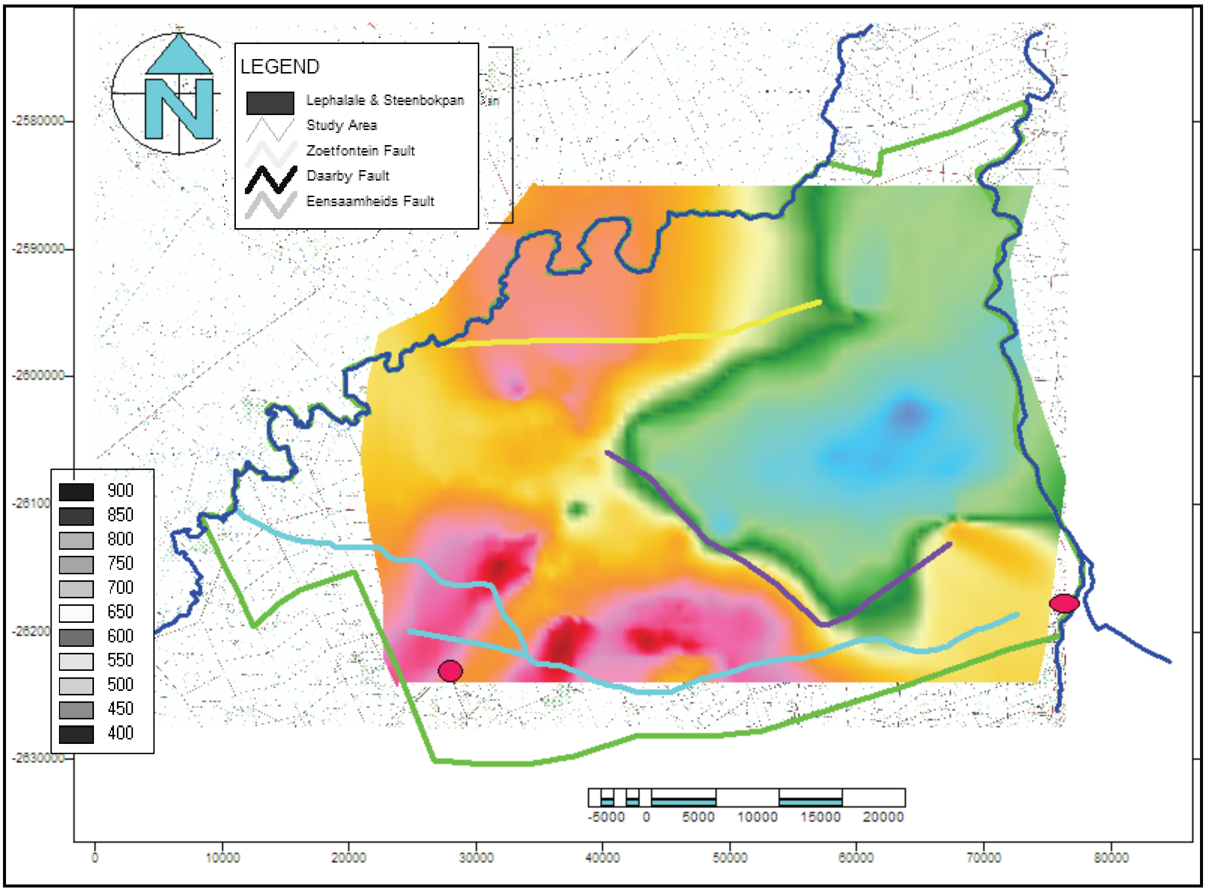


Figure 37: Plan view of Coal Zone 2.

Figure 38 indicates cross-sections through the study area. The north/south cross-section was made through the Grootegeluk pit and the figure clearly shows that the water levels follow the topography of the area. The pit at Grootegeluk has a significant impact on the movement of groundwater in the area. In both sections deeper and shallower coal-bearing strata can be seen. The zones are separated by the Daarby fault that divides the coal-bearing strata into deeper eastern area and shallower western area.

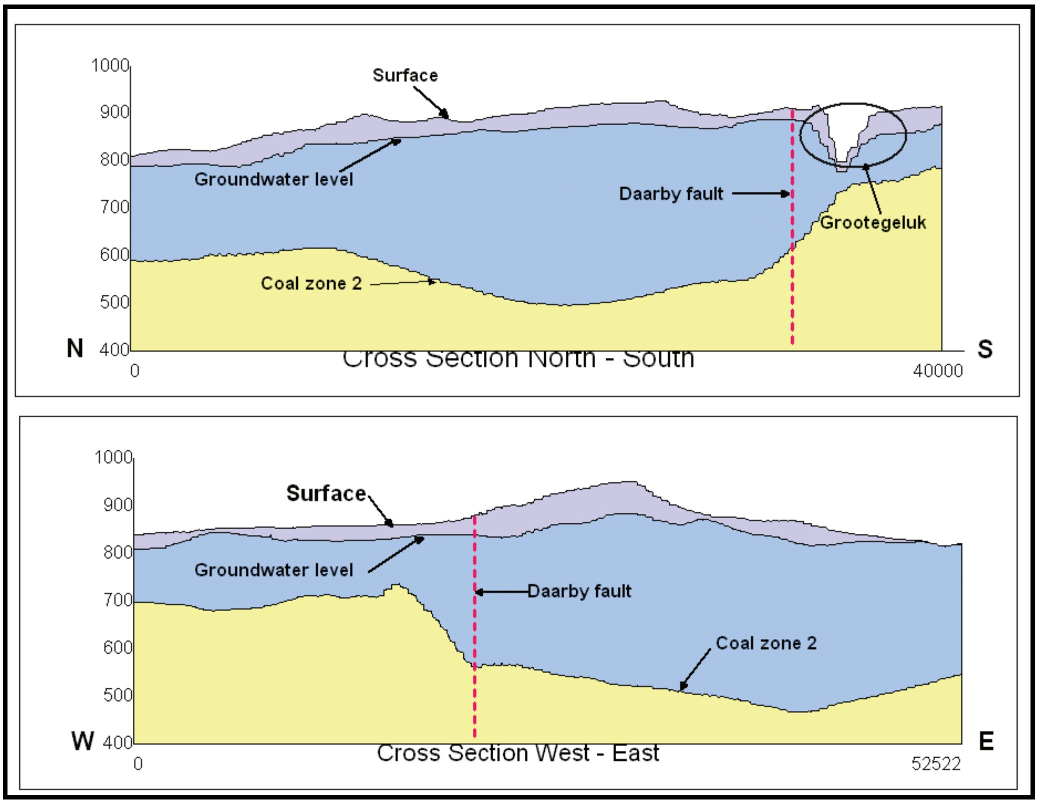


Figure 38: North-south and west-east cross-sections of the study area.

The study area was further divided into three main categories according to weathered geology. They are:

- Areas that contain the full coal-bearing succession (Figure 39)
- Areas that have been weathered down to the Vryheid Formation of the middle Ecca (Figure 39)
- Areas that have been weathered down to the Pietermaritzburg Formation of the lower Ecca (Figure 39).

Figure 39 shows that there is significant variation in the level to which the geology has been eroded and thus also the depth of the coal which varies greatly in the study area. From the information gathered, it is clear that there are large volumes of coal that can be economically extracted from the Waterberg Coalfield. However, the coal is of such low quality that it will need to be beneficiated to maintain profitability (Dreyer, 2009). The necessity for beneficiation plants gives rise to other potential problems. These beneficiation plants will require large volumes of water to operate, which will increase the strain on groundwater systems if the required water is to be abstracted from boreholes. In an area where there is already a shortage of water (including usable groundwater), this would present a serious problem. Furthermore, the discard from the beneficiating plants contains minerals that are prone to acid generation.

Large volumes of this discard will be produced during the life of the mines. It is recommended that the discard be placed in such a manner that they minimize the possibility for pollution of groundwater resources. The main rock types in the area are blue/green mudstone, shales and white Ecca formation sandstones. These formations are divided into different layers, and the coal is intermixed with the mudstones and shale. The overburden (and in some cases interburden like Ecca sandstones) will be used to backfill the pits once mining has stopped. It is therefore important to know the characteristics and potential for acid generation, or neutralisation, of the interburden.

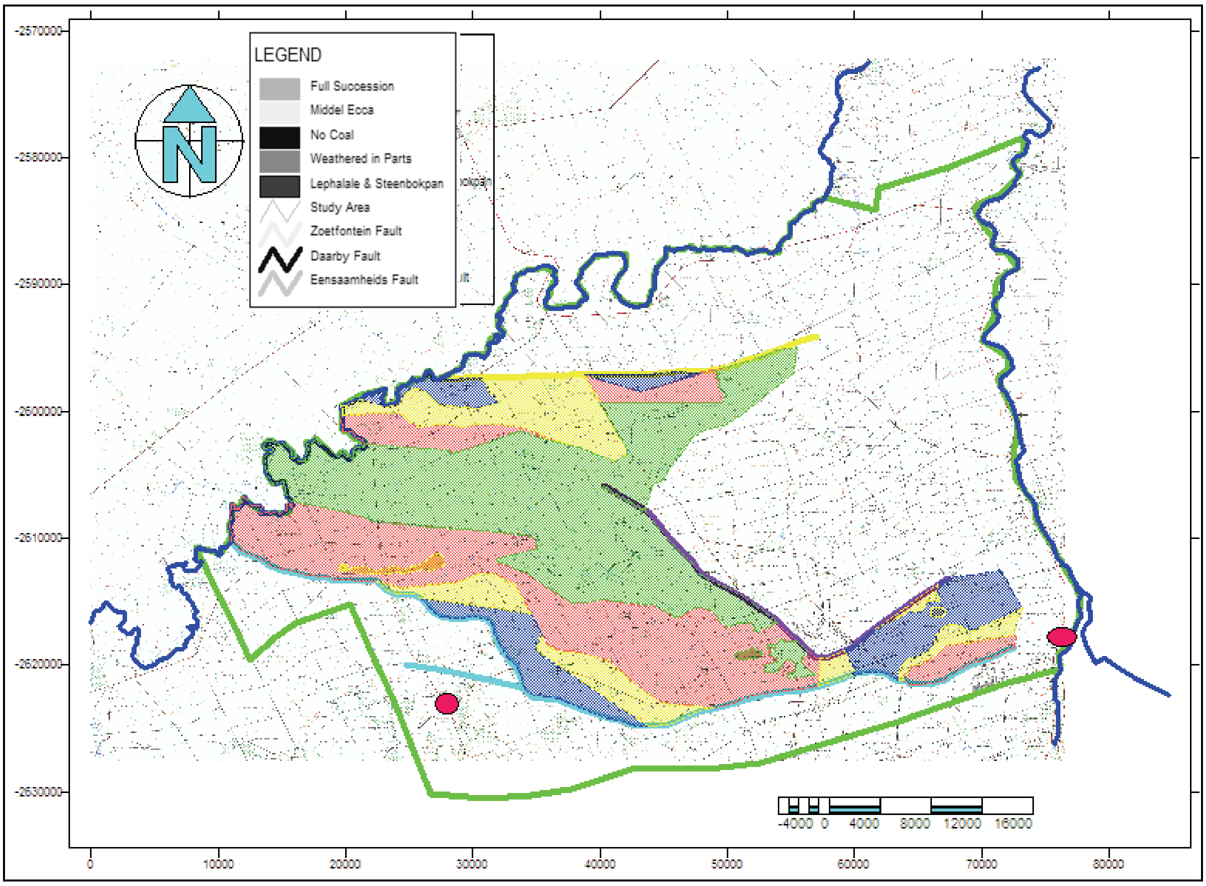


Figure 39: The weathered zones and major faults in the study area.

6.3 Conclusions

From the data, large quantities of coal are available for mining in the Waterberg coalfield. The coalfield is contained between boundaries formed by the three main faults of which the Daarby divides the coalfield into a deeper eastern half and a shallower western half. Only the western area will be mined initially. The coal is subdivided into 11 zones and the deepest level to which surface methods of extraction can economically be used is coal layer two (Dreyer, 2009). The coal will be mined using only one method and due to the low quality of the coal it will need to be beneficiated. The discard produced from the beneficiation plants will be used as back fill along with other material removed from the pit.

7 Acid-Base Accounting

7.1 Introduction

Acid-base-accounting analyses were conducted on geological samples gathered from the study area. The goals of these analyses were three fold:

- Firstly to determine if the rocks (geological units) in the study area that will be removed during mining will become acidic upon oxidation or if the rocks contain a high enough base potential to prevent this from happening.
- Secondly; to determine if a correlation exists between the depth of weathering in the different parts of the study area and the acid potential of the rocks of these areas.
- Thirdly to determine if there are any “problem” layers that have a higher acid potential than the other rocks found in the study area.

In order to achieve these goals geological samples were collected from various localities throughout the study area. These samples consisted of various core and chip samples. Additionally the samples included two processing plant discard samples (one from each plant) obtained from the two plants at the Grootegeluk mine. These samples were taken to the lab at the Institute for Groundwater Studies for static acid-base accounting tests. To assess the geochemical nature of the most likely reacting components, several laboratory tests were undertaken. Detail on the objectives, methodology and interpretation of each type of test is provided in the sections to follow. Analytical tests to determine the acid-generating potential of rock samples are either static or kinetic in nature. A static test determines both the total acid-generating and total acid-neutralising potential (NP) of a sample. The capacity of the sample to generate acidic drainage is calculated as either the difference of the values or a ratio of the values, as will be discussed in the following section.

These tests are intended to predict the potential to produce acid, and not the generation rate of acid. Static tests can be conducted quickly and are inexpensive compared to kinetic tests. Acid-base accounting is a screening procedure whereby the acid-neutralising potential and acid-generating potential of rock samples are determined and the difference (NNP) is calculated. The NNP and/or the ratio of neutralising potential to acid-generation potential are compared with a predetermined value, or set of values, to divide samples into categories that either do or do not require further determinative acid potential test work. Rules and guidelines were developed (e.g. Price and Errington, 1995; Steffen *et al*., 1989; Brady *et al.,* 1994 for ABA procedures by mine regulatory and permitting agencies and presented by Usher *et al.,* 2002). In its most basic form, ABA is a screening process. It provides no information on the speed (or kinetic rate) with which acid generation or neutralisation will proceed, and because of this limitation, the test work procedures used in ABA are referred to as Static Procedures (Ziemkiewicz, 1994). The potential for a given rock to generate and neutralise acid is determined by its mineralogical composition and other mineralogical properties. This includes the quantitative mineralogical composition and individual mineral grain size, shape, texture and spatial relationship with other mineral grains. The term "potential" indicates that even the most detailed mineralogical analysis, when combined with ABA, can give only a "worst-case" value for potential acid production and, depending upon the NP procedure, a "worst-case", "most likely case" or "best-case" value for potential neutralisation capability (Usher *et al.,* 2002). The NP measures the total carbonates, alkaline earths and bases available to neutralise acidity, and represents the most favourable condition. Calculations of maximum potential acidity and NP are structured to equate the two measurements to a common basis for comparison. The resulting values, expressed as calcium carbonate equivalent, are compared to compute a net acid-producing or acid-neutralising potential. Material exhibiting a net acid-production potential of 5 tons/1000 tons of material or more as calcium carbonate equivalent are classed as toxic or potentially toxic (Hunter, 1997a and Sobek *et al.,* 1978).

7.1.1 The Primary Advantages of the ABA Methods:

a. Short turn-around time for sample processing.

b. Low cost.
c. Relatively simple analytical procedures.
d. Relatively simple interpretation of results (Hunter, 1997a).

7.1.2 The Principal Disadvantages of Acid-Base Accounting:

a. The method predicts maximum potential acidity and maximum neutralisation capability, thus implying a 1:1 acid to base reaction. Actual acid production and neutralisation release rates (Usher *et al.,* 2002) cannot be predicted with this technique, nor can the completeness of the reaction be assessed.

b. Acid-Base Accounting assumes that all acid production is attributable to iron disulphide minerals (chiefly pyrite) and that no acid is produced by sulphate or organic sulphur forms.

c. It only provides a possibility of occurrence.

d. Reaction rates are ignored (ABA generally tests the fast-reacting species; slow-reacting neutralising species will usually not prevent acidification.

e. Instant availability of reactive species is assumed. However, nearly all rock samples lacking carbonates (which are fast-reacting and thus instantly available) or not of dunite composition (predominantly olivine + serpentine) have insufficient NP to be classifiable as "not potentially acid generating" if the minimum limit for this category were to be set at, for example, 20 kg $CaCO_3$ equivalent/tons of material.

f. Size effects are ignored (Limestone particles of greater than 6.4 mm are coated with precipitates and are only 20% utilised when acid conditions are in evidence (Scharer *et al.,* 2000).

g. Extrapolation to the field is uncertain when volumetric calculations cannot be made.

The widespread use of static tests in ARD prediction has been justified on the basis of historical and generally successful applications to North American coalfields. Overall, the static test can be regarded as a first screening level for mine drainage prediction, which provides a very good indication of acid-generating potential. Most non-carbonate minerals can participate in the attenuation of acidity, but only to a modest degree, and only in the longer term, after an ARD scenario has already been developed (Usher *et al.*, 2002).

Since static tests involve only single analyses and the procedures are simple, they are rapid and relatively inexpensive. Thus, although the amount of information provided by kinetic tests exceeds that of static tests, the latter are much more widely used in terms of number. Usher *et al.* (2002) cite several researchers who indicate the value of ABA as a legitimate tool for mine drainage quality prediction across the world, including South Africa. It becomes a very powerful tool when used in conjunction with other data such as hydrologic data, mining and reclamation plans, and mineralogy data, as proposed in the ABATE strategy, and in the study specifically focused on ABA (Usher *et al.,* 2002).

7.1.3 Static Tests Used in this Study

The following methods were used for this study:
- Determination of reactive %S using hydrogen peroxide oxidation
- Neutralising potential using a sulphuric acid adaptation of the Sobek method (Sobek *et al*., 1978)
- Calculation of acid-base accounting
- Determination of liberated elements during oxidation.
- Mineralogy of each sample using X-ray Diffraction (XRD) and X-ray Florescence (XRF) determination.

7.2 Overview of ABA Data Types Obtained

In the procedure followed, the pH of the pulverised samples is measured in water (start or initial pH) and after complete oxidation (final pH) (Table 6). This is the first indicator of the overall behaviour of the sample.

High-risk acid generators are those samples turning acidic upon oxidation. These results are indicated in tables, as follows.

Table 6: Initial and Final pH and Interpretation

Site Name	Initial pH	Final pH	Interpretation
Sample 1	8.4	6.7	Lower Acid Risk
Sample 2	8.66	6.28	Lower Acid Risk

If the initial and final pH values (the pH of the sample after complete oxidation using hydrogen peroxide) are alkaline, then the sample will not be acid producing, but will have a potential to buffer acid. When the final pH turns acidic, the acid-generating processes consume all the available neutralisation in the sample upon oxidation. Under these conditions, the sample is net acid producing. With an initial pH that is already acidic, this means that the sample has already undergone oxidation in the field, resulting in acid mine drainage. The initial and final pH values are plotted together with the overall difference between the acid potential and neutralisation potential in kg/tonne (NNP). By convention, $CaCO_3$ rather than H_2SO_4 is used to express acid or neutralisation potential. If the NNP value is negative, there is no neutralisation potential and acid generation will take place, and *vice versa*. The determined pH values, together with the NNP (whether open or closed) indicated a similar scenario, as shown in Figure 40.

To the far left on the graph, the samples are already oxidised in the field and have a high acid potential. Closer to values of -50 NNP on the graph, samples have an alkaline initial pH, which will become acidic upon oxidation, but will not produce as much acid as the first. On the positive side, the final pH did not become acidic upon oxidation. These samples contain a neutralisation potential with a lower likelihood of producing ARD.

It is important to differentiate between so-called “open” and “closed” systems. The carbonate system is predominant in controlling the buffering intensity and neutralising capacity of natural waters, and represents a complex system that involves the transfer of carbon among three phases: solid, liquid and gas. When $CO_{2(g)}$ comes into contact with water, it will dissolve to form carbonic acid (H_2CO_3) until equilibrium is reached. Depending on the pH of the solution, the carbonic acid will dissociate to hydrogen, bicarbonate (HCO_3) and carbonate (CO_3^{2-}) ions.

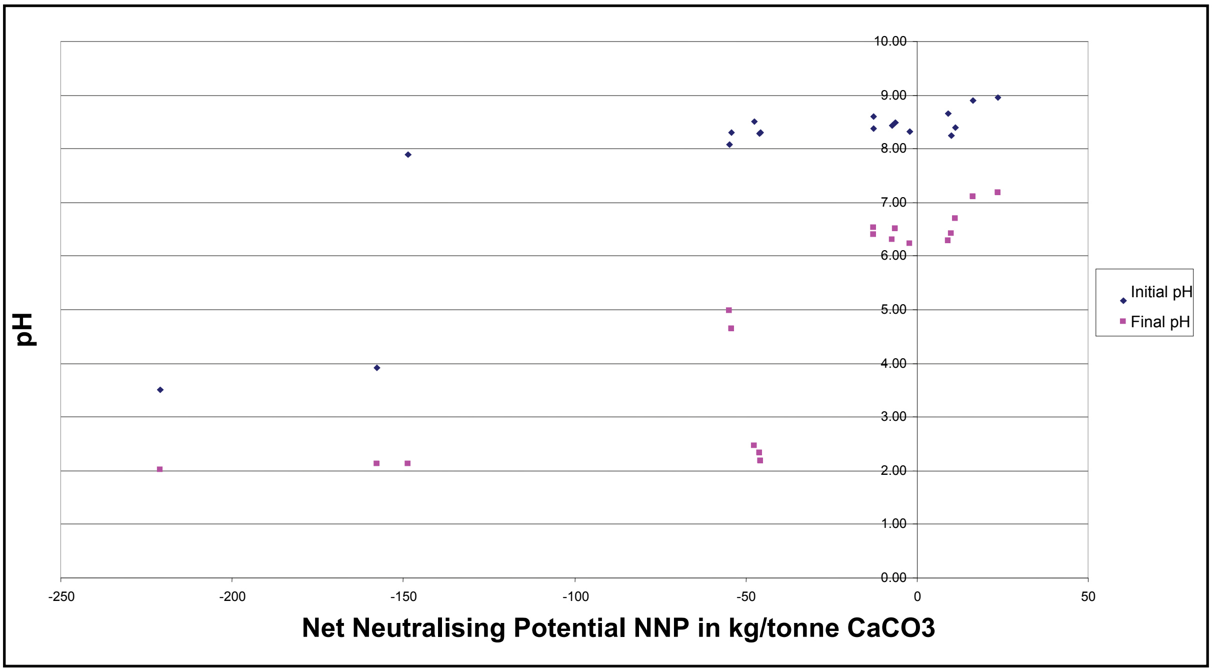


Figure 40: NNP vs. pH (initial and final) (closed system).

7.2.1 In an Open System

$$FeS_2 + 2CaCO_3 + 3,75O_2 + 1.5H_2O \Leftrightarrow Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2 \quad [2]$$

(carbon dioxide exsolves into the atmosphere).

Acidity produced from 1 mole of FeS_2 (64 g sulphur) is neutralised by 2 moles of $CaCO_3$ (200 g) or 1 g sulphur: 3.125 g $CaCO_3$ (Brady *et al.,* 1994).

7.2.2 In a Closed System

$$FeS_2 + 2CaCO_3 + 3,75O_2 + 3,5H_2O \Leftrightarrow Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2H_2CO_3 \quad [3]$$

(carbon dioxide dissolves in water)

H_2CO_3 reacts with carbonate in the following reaction:

$$H_2CO_3 + CaCO_3 \Leftrightarrow Ca^{2+} + 2HCO_3^- \quad [4]$$

A second reaction depicting the maximum calcium carbonate requirements for acid neutralisation in a closed system may therefore be written as (Usher *et al.,* 2001):

$$FeS_2 + 4CaCO_3 + 3,75O_2 + 3,5H_2O \Leftrightarrow Fe(OH)_3 + 2SO_4^{2-} + 4Ca^{2+} + 4HCO_3 \quad [5]$$

In this reaction, 1 mole of FeS_2 is neutralised by 4 moles of $CaCO_3$, which results in a mass ratio of 1 g pyrite: 6.25 g calcite. It is therefore very important that the correct conceptual model be applied when interpreting the results

7.3 Calculated Parameters from ABA

Based on the above tests, the following parameters can be calculated:

Net Neutralising Potential (NNP) = Neutralising Potential (kg/t $CaCO_3$) – Acid-Generating Potential (kg/t $CaCO_3$), and Neutralising Potential Ratio (NPR) = NP/AP.

The results for these determinations are given in Table .

Table 7: Calculated parameters from ABA

Sample number	Net NP (Open system)	Net NP (closed system)	NP ratio (NPR) NP/AP for open system	NP ratio (NPR) NP/AP for closed system
Sample 1	21.185	11.259	3.13	1.57
Sample 2	21.978	9.245	2.73	1.36

The table indicates that a differentiation exists between open and closed systems. The open system is indicative of the waste rock piles, while the tailings will have areas that vary between open and closed conditions. Negative values indicate insufficient neutralisation potential and a potential for acid production, and vice versa.

7.4 Interpretation of Results

7.4.1 Screening Criteria

Details of the screening criteria for each type of test are given in publications such as Price and Errington (1995) and summarised in Usher *et al. (*2001).

The most important criteria are as follows:

For NNP

- If NNP =NP-AP <0 The sample has the potential to generate acid, and

- If NNP =NP-AP >0 The sample has the potential to neutralise produced acid.
- More specifically, any sample with NNP<20 is potentially acid generating, and any sample with NNP >-20 might not generate acid.

There is a strongly defined “grey area” between -20 and = 20 kg/t $CaCO_3$, since the nature of static testing and the field variability makes it risky to assign potentially acid or non-acid generating properties to such samples.

For NPR, the following guidelines are used for the classification of samples (Table).

Table 8: Guidelines for ABA screening criteria (from Price et al., 1997b)

ARD POTENTIAL	NPR SCREENING CRITERIA	COMMENTS
Likely	<1:1	Likely ARD generating
Possibly	1:1-2:1	Possibly ARD generating if NP is insufficiently reactive or depleted at a faster rate than sulphides
Low	2:1-4:1	Not potentially ARD generating unless significant preferential exposure of sulphides along fracture planes, or extremely reactive sulphides in combination with insufficiently reactive NP
None	>4:1	No further ARD testing required unless materials are to be used as a source of alkalinity

7.4.1.1 Interpretation of Individual Samples

Tables 9 and 10 provide an interpretation of selected samples, based purely on screening criteria.

Table 9: Interpretation of each sample according to NNP criteria.

Site Name	NNP (Open)	NNP (Closed)	Interpretation
Sample 1	21.18	11.26	Verify with other tests
Sample 2	21.98	9.25	Verify with other tests

Table 10: Interpretation of each sample according to NPR criteria.

Site Name	NP Ratio(NP/AP) for Open System	NP Ratio(NP/AP) for Closed System	Interpretation Open System	Interpretation Closed System
Sample 1	3.13	1.57	Acid under certain conditions	Acid under certain conditions
Sample 2	2.73	1.36	Acid under certain conditions	Acid under certain conditions

7.4.1.2 Interpretive Diagrams

As an initial step in the interpretation of these data, interpretive diagrams will be used. There is an internationally recognised zone of uncertainty, where values should be interpreted with circumspection of NNP values between –20 to 20 kg/t $CaCO_3$.

Figure 41 shows the subdivision according to the ratio between AP and NP (NPR). This diagram for all the Waterberg samples indicates that, for the bulk of the samples, there is the potential for acid production for those plotting above the red and blue lines. An alternative way to indicate the results are shown in Figure 42.

Most of the samples have sufficient sulphide to yield long-term acidity (most samples contain more than 0.3 % S) (red area on the graph). This implies that, although some neutralisation potential is possible according to international findings, acid mine drainage will be produced. It is therefore clear that the majority of samples can be regarded as acid producers, and that the ABA results should be interpreted in conjunction with the on-site conditions, leaching rate and long-term conceptual models.

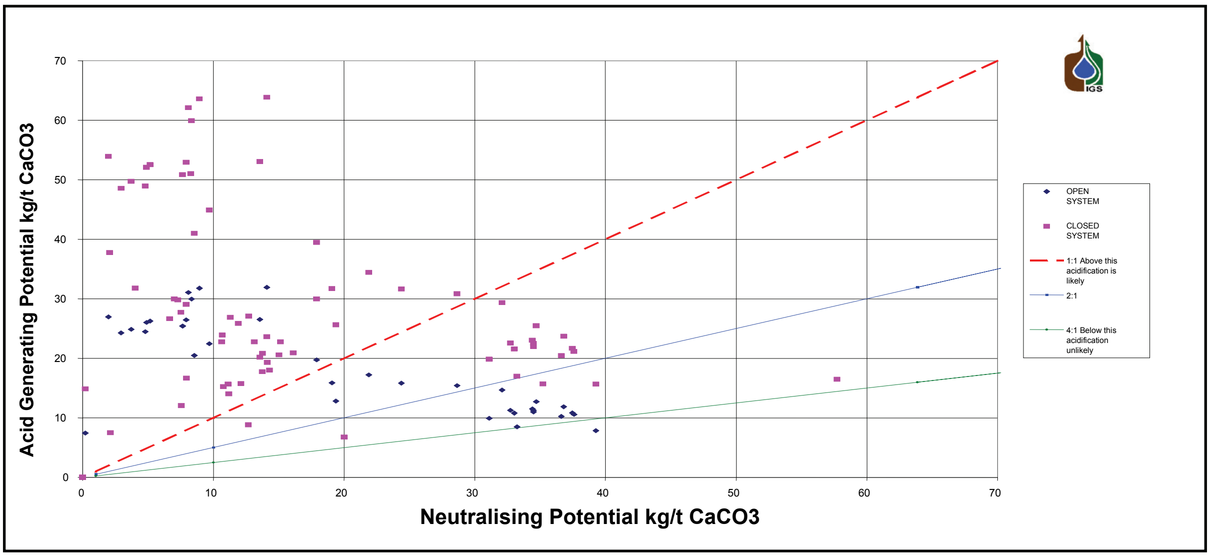


Figure 41: NP vs. AP graph, indicating areas of likely and unlikely acid generation.

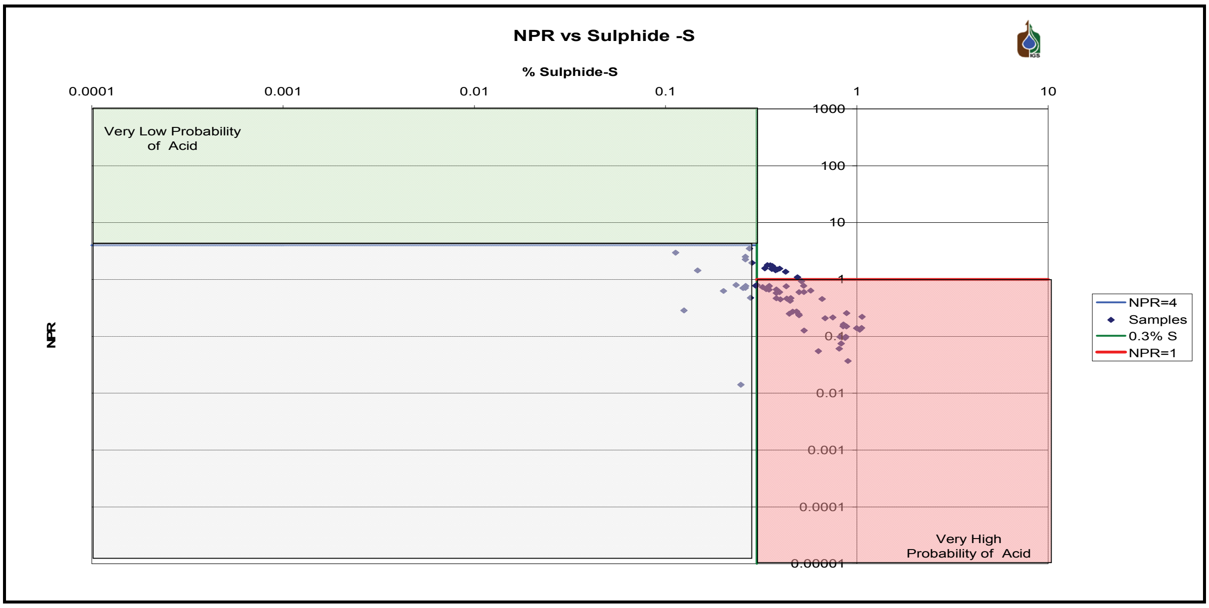


Figure 42: %S vs. NPR.

7.5 Results for the Waterberg Samples

Chip and core samples were obtained from the existing colliery and core samples were obtained from a second company at present prospecting in the study area. The samples were subjected to static ABA testing to determine acid or base generating potential and analysed by means of x-ray diffraction to obtain their mineral composition.

7.5.1 Acid-Base Accounting

A summary of the static acid base results is displayed in the following graphs. The graphs indicate that both base potential and acid mine drainage potential exist for samples from the Waterberg area.

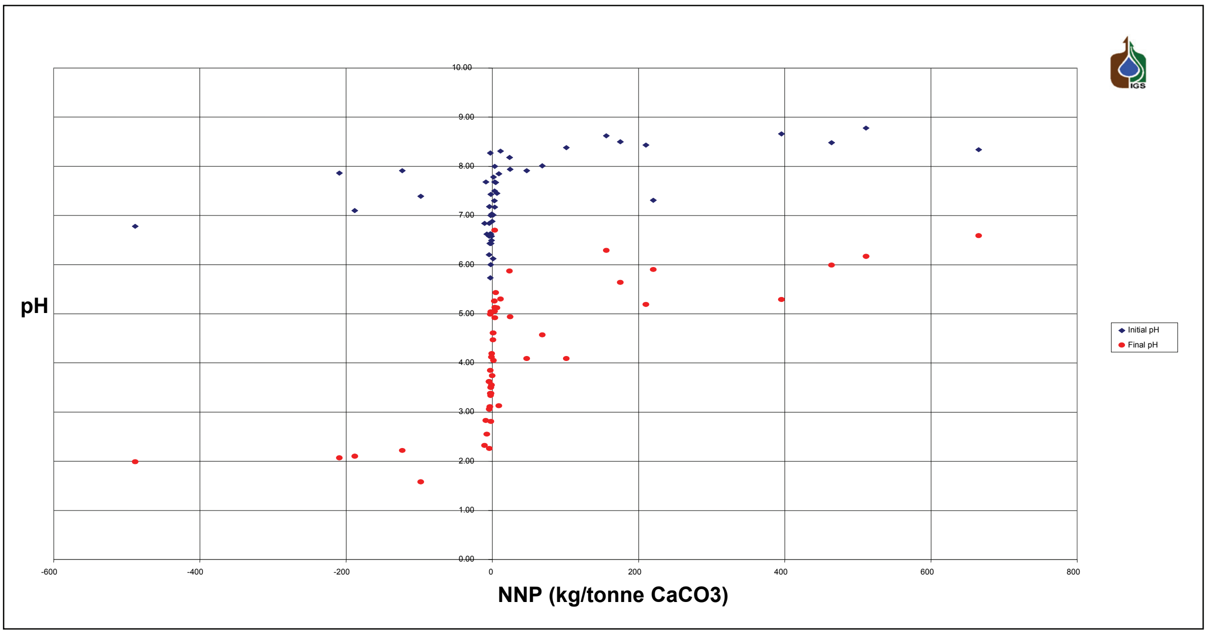


Figure 43: NNP vs. pH for all samples tested.

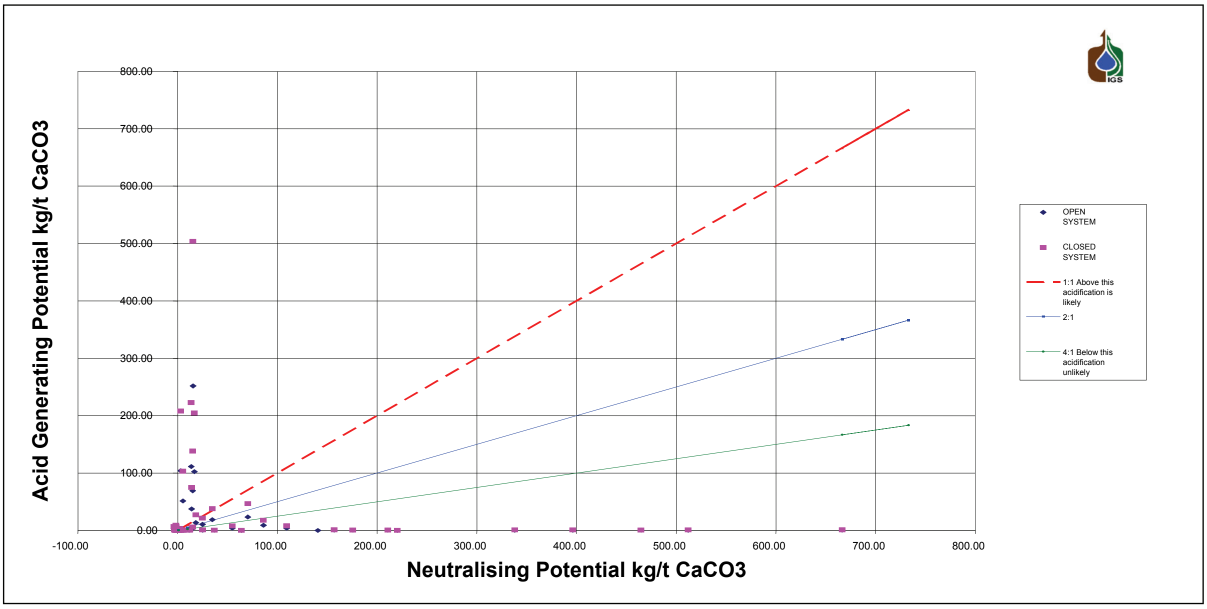


Figure 44: AP vs. NP for all samples tested.

7.5.2 Mineralogy

The XRD results indicate that Quartz and Ferroan Chlinochlore are the major components of the core and chip samples. Other minerals that are present include calcite, siderite, ankerite, goethite/hematite, illite and pyrite. The northern chip samples contain dominant calcite.

Occurrence classification of the minerals is indicated as follows:

Table 11: XRD classification table.

Dominant	XX	>40%
Major	X	15-40%
Minor	xx	5-15%
Accessory	x	2-5%
Rare	<x	<2%

7.5.3 Weathering Zones

The study area was divided into three distinct zones with regards to sampling and weathering. The study area contains areas that:

- Have the full coal-bearing succession present (green areas)
- Areas that have been weathered down to the middle Ecca and (yellow areas)
- Areas that have only been weathered in parts (red areas).

This division governed the selection of sampling locations in an effort to identify trends with regards to weathering level and the degree of acid/base potential. The study area was further divided into sampling locations in the northwest, the north and to the south east. The ABA results for each of these areas will be discussed separately and then compared.

7.6 Full Succession Areas (Green Areas)

7.6.1 North western samples

Core samples were collected from one borehole located in the north western sampling location as indicated in Figure 45. The core was divided according to the lithology into 20 samples over a depth of 200 m. Initial and final pH values are summarised in the following table. Some of these samples indicate a high risk of acid generation, with the final pH values becoming acidic upon complete oxidation, while others indicate a lower risk. The net neutralising potential for both closed and open systems is summarised in **Error! Reference source not found.** and Table of Appendix A. The negative values indicate acid mine production while the positive values indicate neutralising potential.

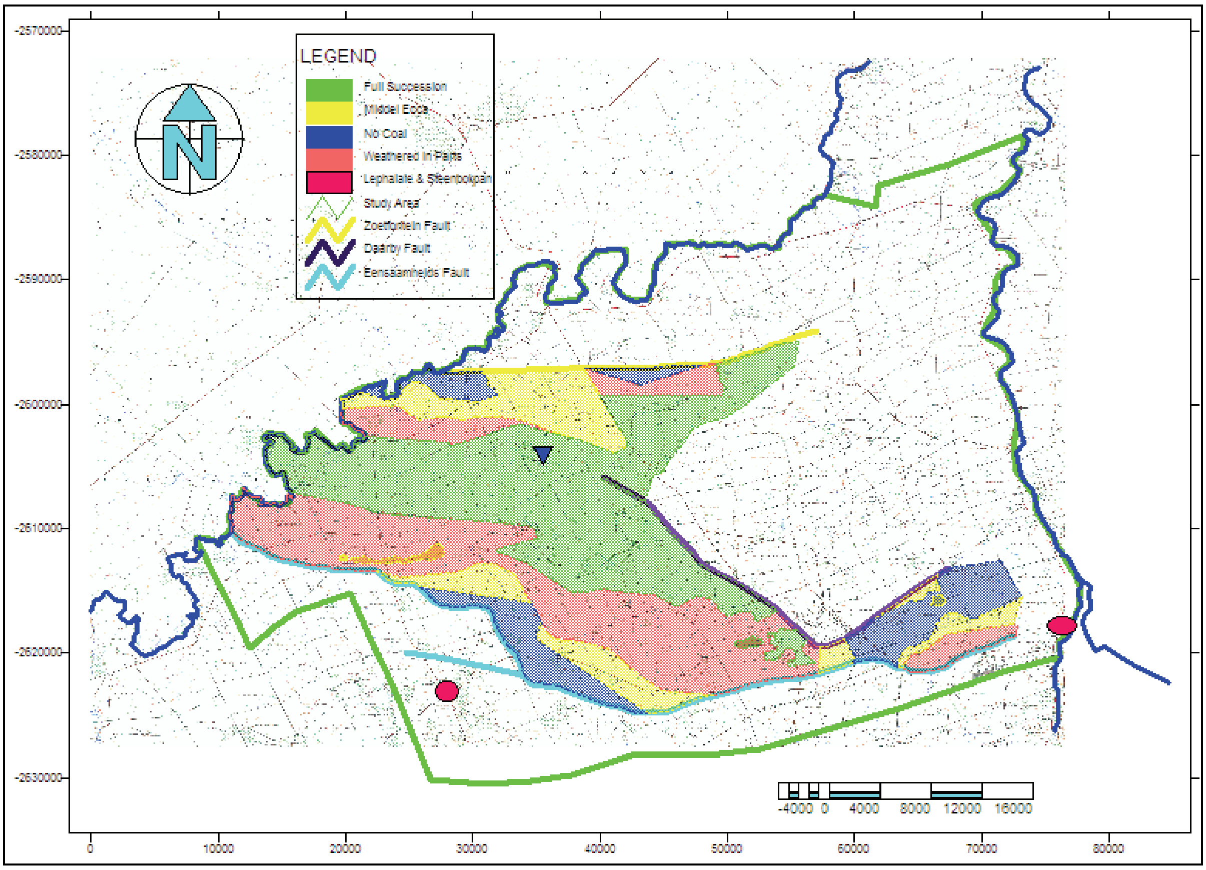


Figure 45: Borehole position of the north western sample.

The NNP (for a closed system) and pH values from the above mentioned tables are plotted in Figure 46 and Figure 47, indicating a mixture of acid producers, as well as some with neutralising capabilities.

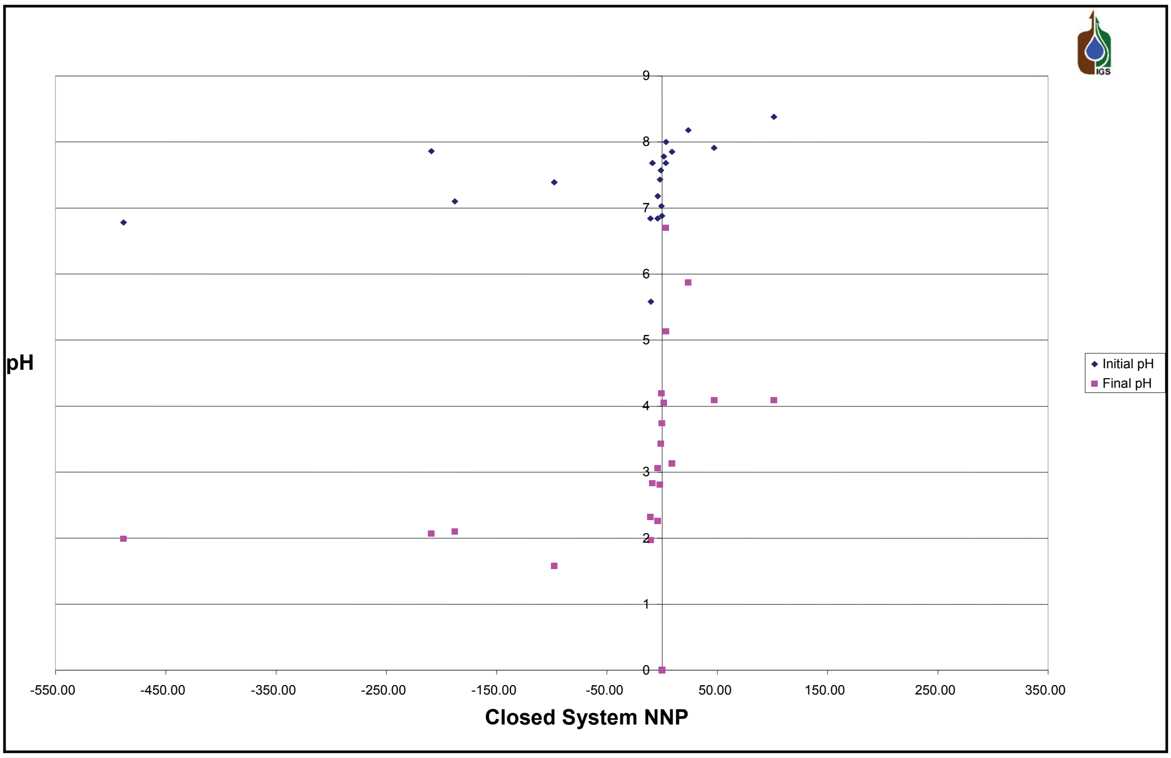


Figure 46: Net neutralizing potential (closed) vs. pH for north/western core.

The percentage sulphur in the samples plotted against the NPR also indicates a high risk of acid production, with some of the samples plotting in the red area. Other samples plot in the neutralising capacity region (green). The neutralising potential ratio for the North western samples can be seen in Table (Appendix A). Those samples with values close to zero indicate no neutralising potential, while those with values greater than four indicates no acid potential. This is also indicated in Figure 48.

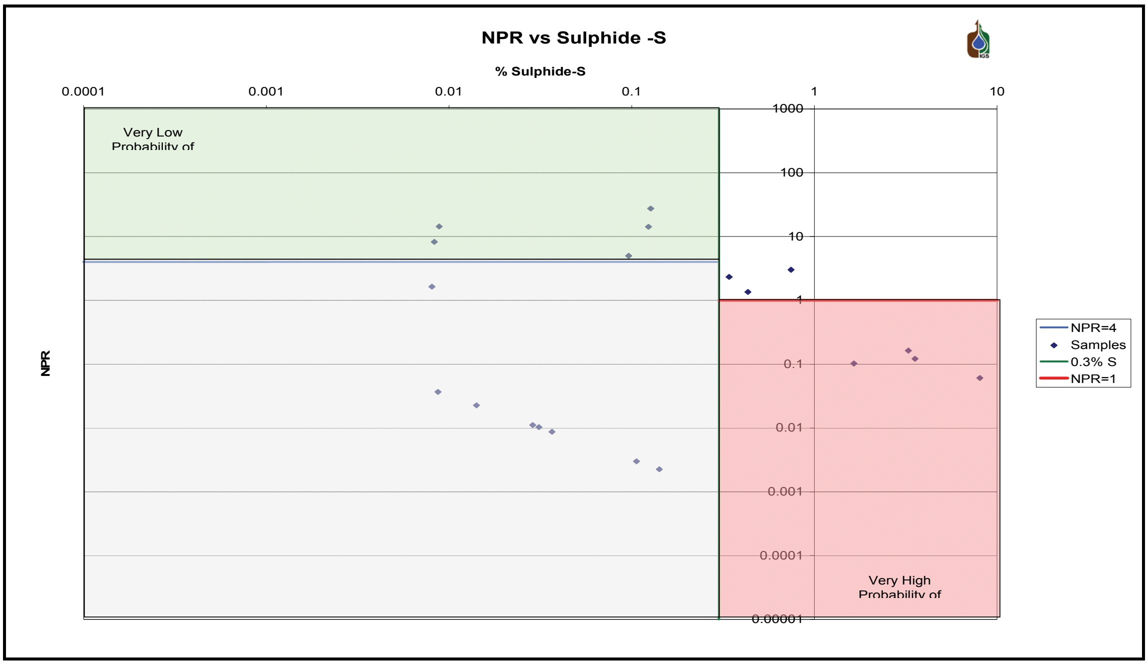


Figure 47: %S vs. NPR for the north/western core.

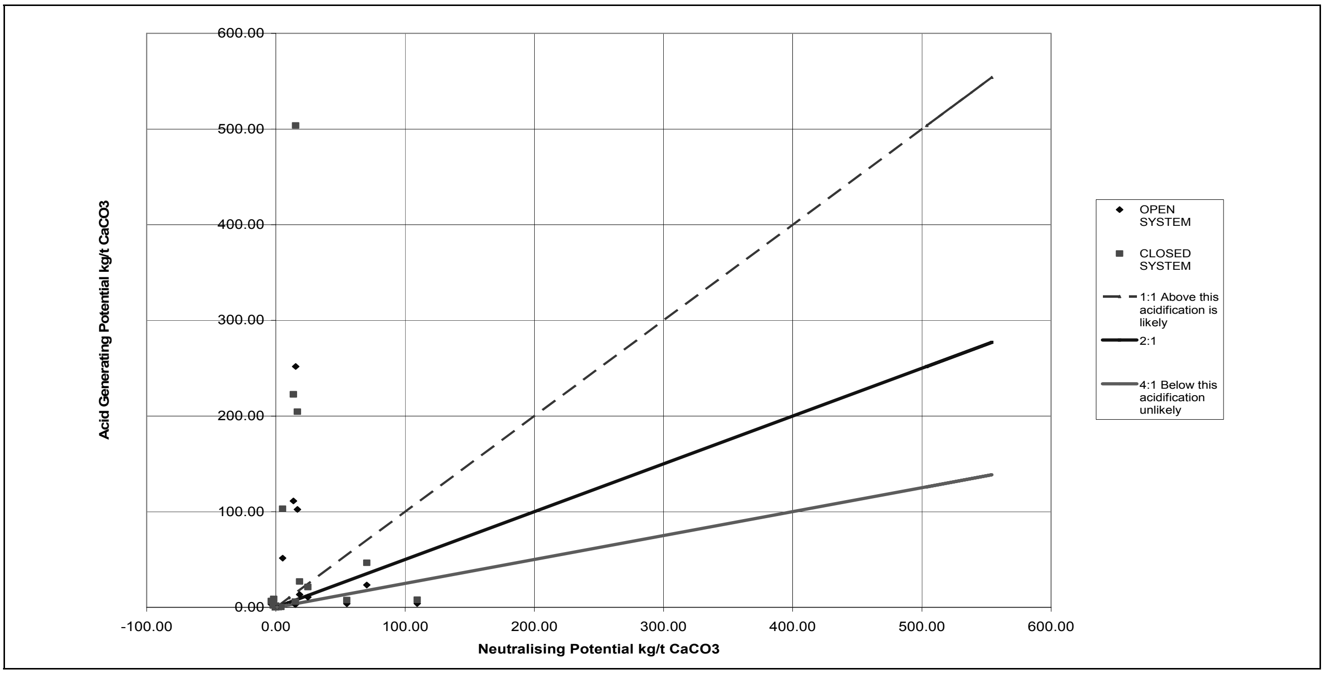


Figure 48: NP vs. NA (NPR) for the north/western samples.

The XRD analyses indicate the dominant mineral as quartz and Ferroan Chlinochlore (Table 12). The samples containing 2-10% calcite vary in terms of base potential. The three samples (SS7, 11 and 15, marked in red) with 1-2 % pyrite have a high acid generating potential.

Table 12: XRD results for the north western samples.

Sample	Quartz	Ferroan Clinochlore	Calcite	Siderite	Ankerite	Goethite/Hematite	Illite	Pyrite
SS1	XX						x	
SS2	XX						x	
SS3	XX	xx				xx	xx	
SS4	XX	X				x	xx	
SS5	XX	xx	xx	x	x		xx	
SS6	XX	xx	xx	x			xx	
SS7	XX	xx		xx	xx	X	x	x
SS8	XX	xx	xx	x	x		x	
SS9	XX	X					xx	
SS10	X	xx		XX	xx		xx	
SS11	XX	X		xx	x	xx	x	x
SS12	X	X		X			x	
SS14	X	XX	xx	X	xx		xx	
SS15	X	XX	xx	X	x	xx	x	x
SS17	X	XX		x			xx	
SS18a	XX	xx		X	xx	xx	x	
SS18b	XX	xx					x	
SS19	XX	X					x	

Where:

XX	Dominant	(>40% per volume)
X	Major	(10-40% per volume)
xx	Minor	(2-10% per volume)
x	Accessory	(1-2% per volume)

From the static tests conducted on the core samples from the north/western site in the Waterberg area, it is clear that acid mine drainage will be produced upon oxidation in some of the samples, although there is some buffering potential in some of the samples. The volume of production will depend on the thickness of the geological successions in the area.

7.6.2 South Eastern Samples

Samples were collected from boreholes as indicated on the map (Figure 49). Four core samples were collected from one borehole over a depth of 160 m (green area/full succession). One chip sample was collected from one other prospecting borehole (green area / full succession) and four additional samples from an area falling into the area that has been eroded in parts (red areas/weathered in parts). These different samples will be discussed as a whole as they were collected and analysed at the same time. Their differences will be discussed later in the report. Initial and final pH values are summarised in Table (Appendix A). Some of these samples indicated a high risk of acid generation, with the final pH becoming acidic upon complete oxidation, while others indicated a lower risk. The NNP for both closed and open systems is summarised in Table (Appendix A). The negative values indicate acid mine production, while the positive values indicate neutralising potential.

The NNP (for a closed system) and pH values from the above tables are plotted in Figure 50, indicating one major of acid producer (GGS2) and one with neutralising capabilities (GGS4).

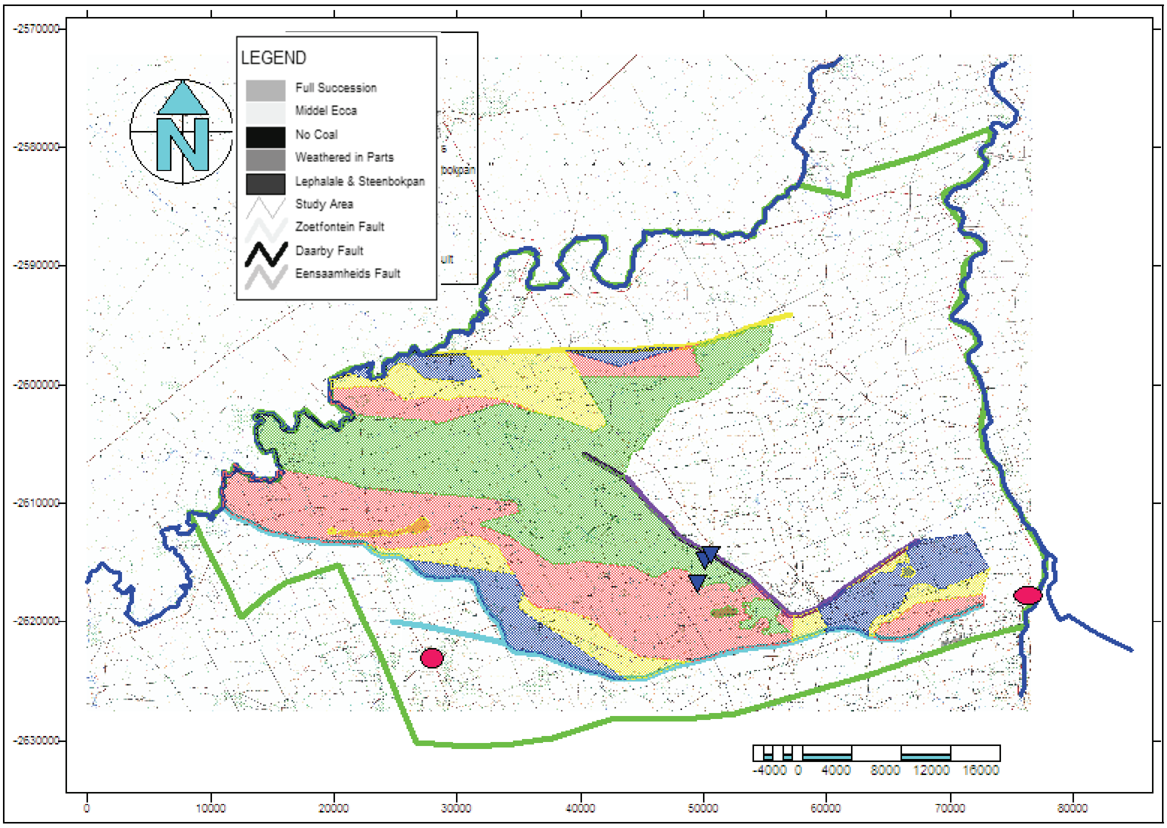


Figure 49: Borehole positions of the south eastern boreholes.

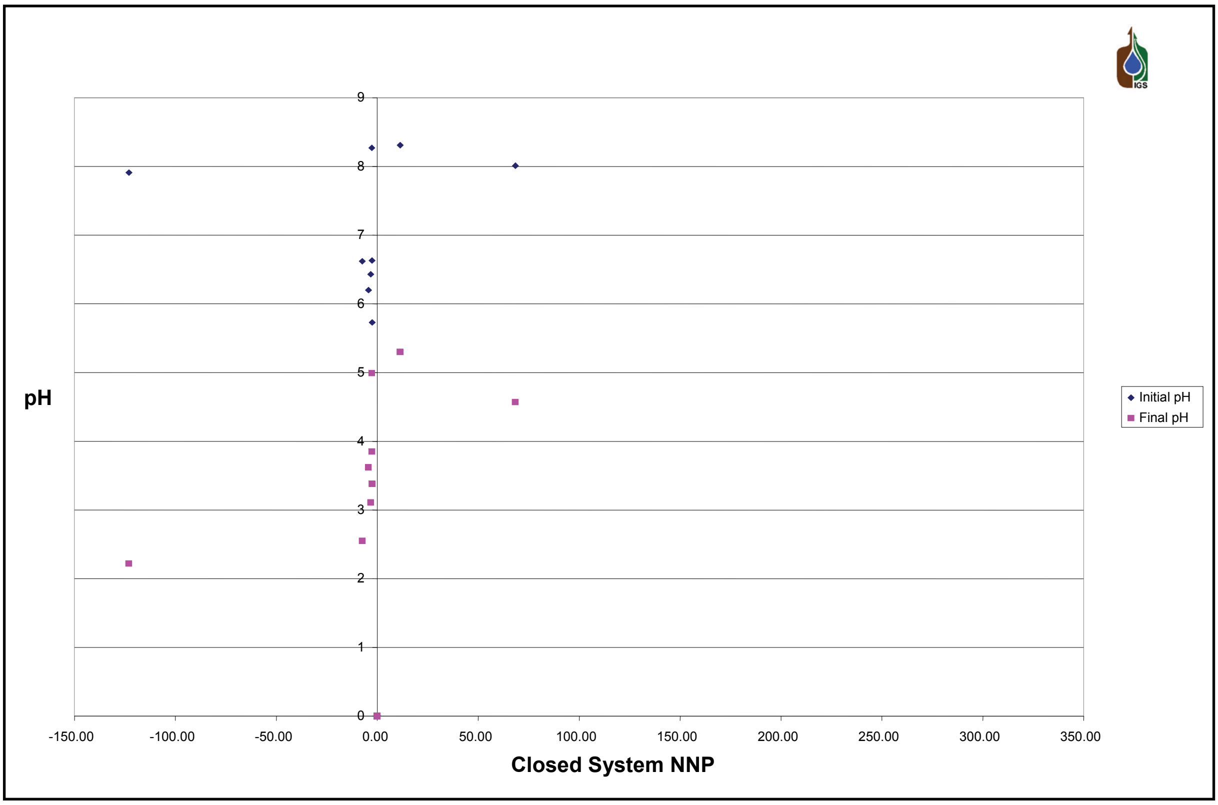


Figure 50: NNP (closed) vs. pH for south/eastern core.

The percentage sulphur in the samples plotted against the NPR also indicates a high risk of acid production, with the GGS2 sample plotting in the red area and GGS4 plotting in the neutralising capacity region (green) (Figure 51).

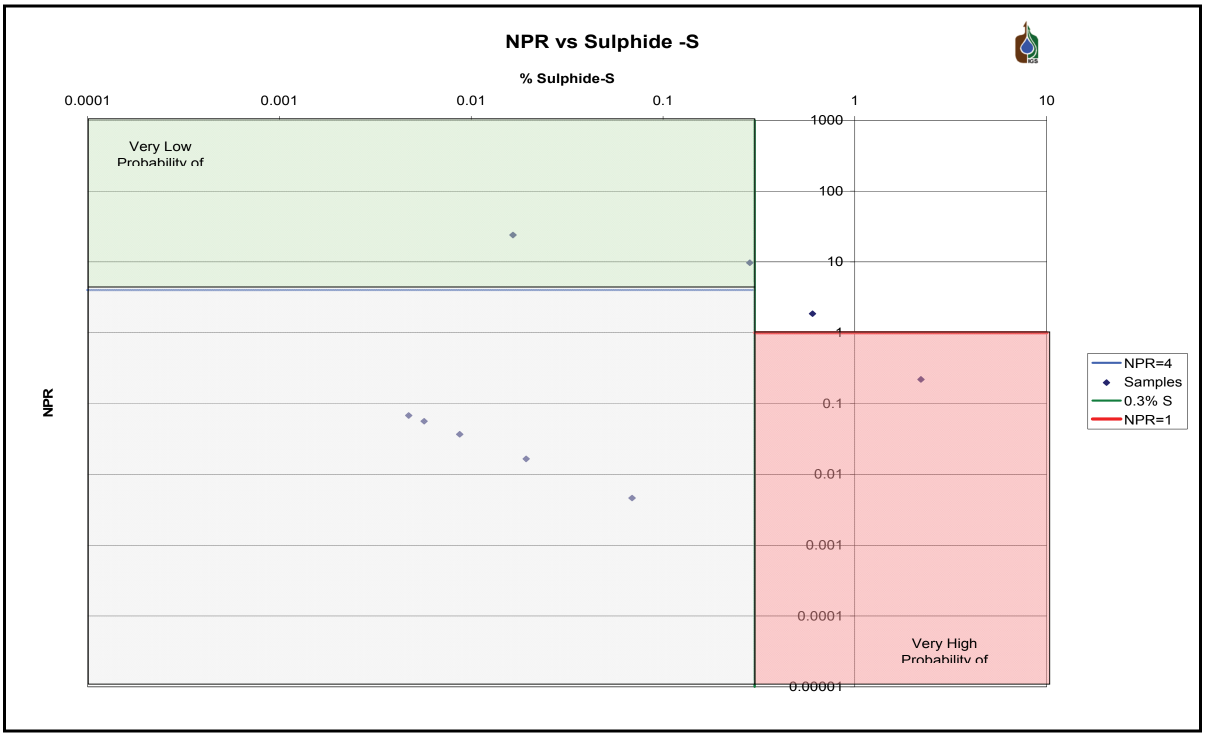


Figure 51: % S vs. NPR for the south/eastern core samples.

The NPR for the south eastern samples can be seen in Table . Those samples with values close to zero indicate no NP, while those with values greater than four indicates no acid potential. This is also indicated in Figure 52.

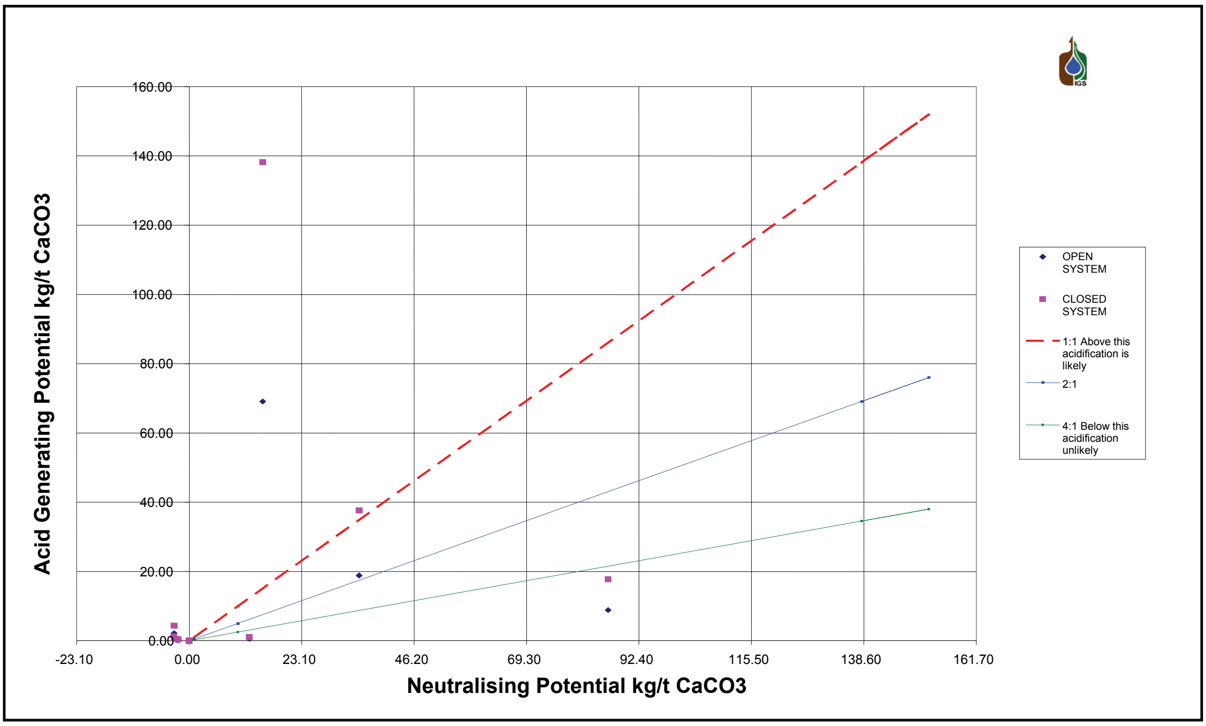


Figure 52: NP vs. NA (NPR) for the south/eastern samples.

The XRD analysis indicates the dominant mineral as quartz and Ferroan Chlinochlore (Table). The sample containing 2-10% calcite (GGS4) is the only one with a base potential. No pyrite could be identified in any of these samples.

Table 13: XRD results for the south/eastern core samples.

Sample	Quartz	Ferroan Clinochlore	Calcite	Siderite	Ankerite	Goethite/Hematite	Illite
GGS1	XX	X		x	x	x	x
GGS2	XX	X		x	x	xx	xx
GGS3	XX	xx					xx
GGS4	XX	X	xx	x		x	x
GGS1A	XX	xx					x
GGSVZ1	XX	X				x	xx
GGSVZ2	XX	xx					x
GGXVZ3	XX	xx					x
GGSVZ4	XX	xx					xx

From the static tests conducted on the samples from the south eastern site surrounding the Grootegeluk mine, it is clear that acid mine drainage will be produced upon oxidation in some of the samples, although there is also some buffering potential in other samples. The volume of production will depend on the thickness of the geology over the area. As these samples were taken from the area surrounding the currently active mine and falls into the same weathering grouping as the mine, it is concluded that the rocks to be used as backfill for the mine will generate acidity, the volumes generated will accordingly depend on the thickness of the rocks placed back into the pit.

7.7 Middle Ecca Weathering (Yellow Areas)

Chip samples were collected from boreholes in the northern site, as indicated on the map (Figure 53). The samples were collected from five different prospecting boreholes on the farm Goedgedacht. The depths of the samples range from 1-14 m below the surface. This area contains geology that has been eroded down to the middle Ecca. Initial and final pH values are summarised in Table 36 (Appendix A). Some of these samples indicate a high risk of acid generation, with the final pH of these samples becoming acidic upon complete oxidation; some indicate a lower risk. The net neutralising potential for both closed and open systems is summarised in Table 38 (Appendix A). The negative values indicate acid rock production, while the positive values indicate neutralising potential. Most of the samples indicate a base potential. The table indicates that each site appears to have similar properties. The NNP (for a closed system) and pH values from the above mentioned tables are plotted in Figure 54, indicating a neutralising capacity in most of the samples with a some just acidifying, although this is not a major concern for acid production.

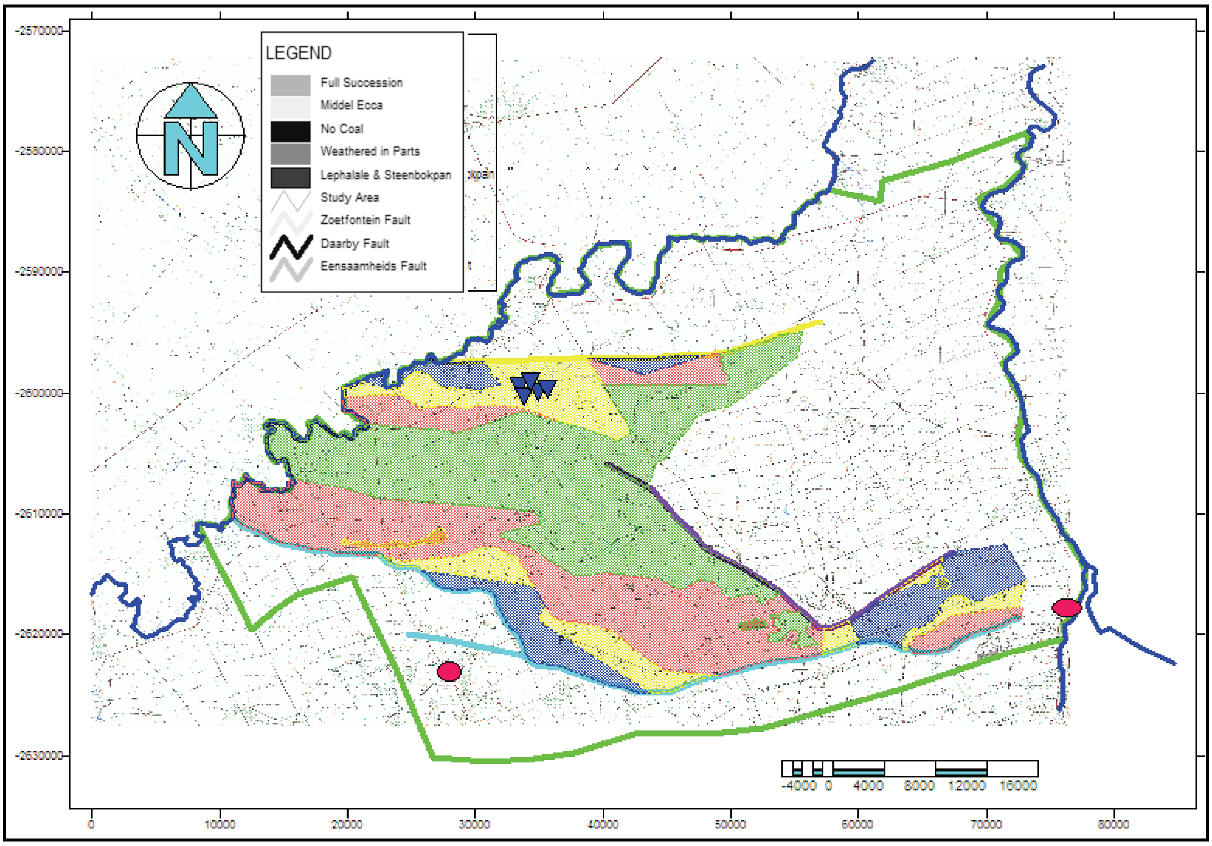


Figure 53: Positions of the chip sampling points.

The percentage sulphur in the samples plotted against the NPR also indicates a low risk of acid production, with no sample plotting in the red area and a batch plotting in the neutralising capacity region (green) (Figure 55).

The neutralising potential ratio for the northern samples can be seen in Table of Appendix A. Those samples with values close to zero indicate no neutralising potential, while those with values higher than four indicate no acid potential. This is also indicated in Table (Appendix A), where it can be seen that most samples shows an acid neutralising capacity.

The XRD mineralogy indicates the dominant mineral of the GT2 range as calcite (Table). This mineral contributes to the neutralising potential of the sample.

Table 14: XRD results for the northern samples.

Sample	Quartz	Ferroan Clinochlore	Calcite
GT2S2	X	x	XX
GT2S3	X	xx	XX

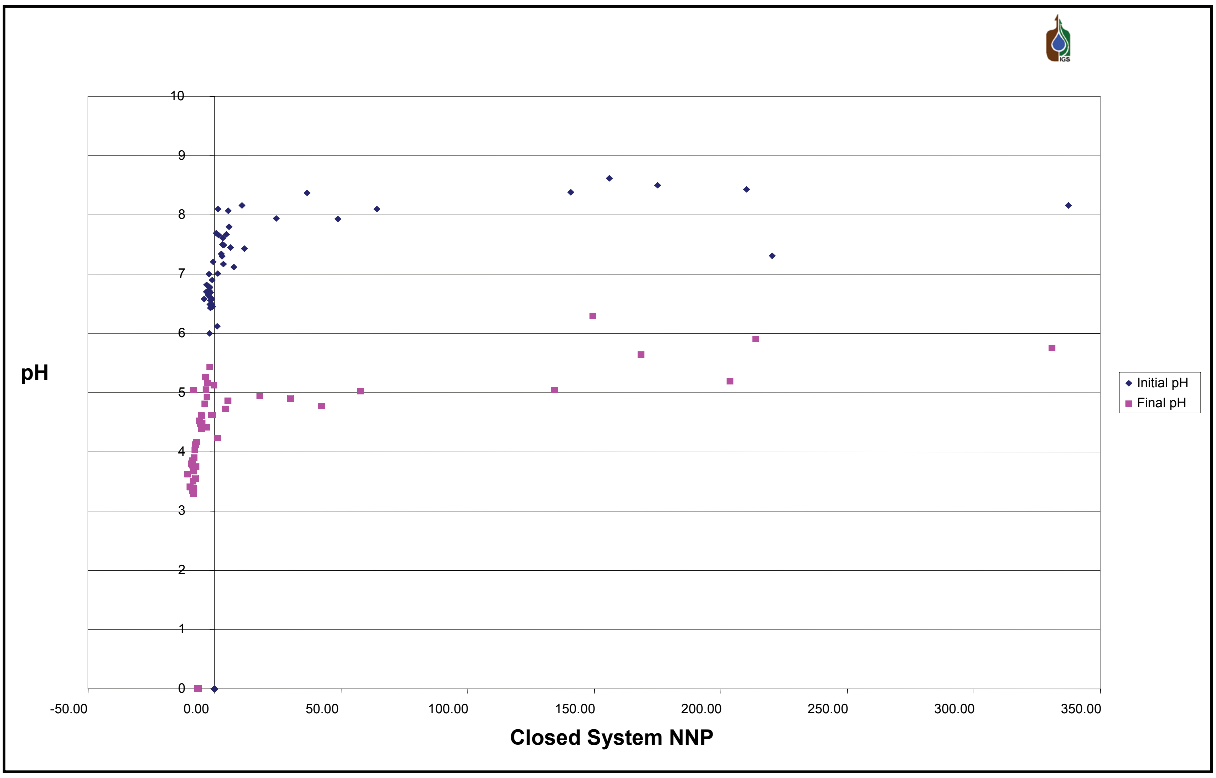


Figure 54: NNP (closed) vs. pH for northern chips samples.

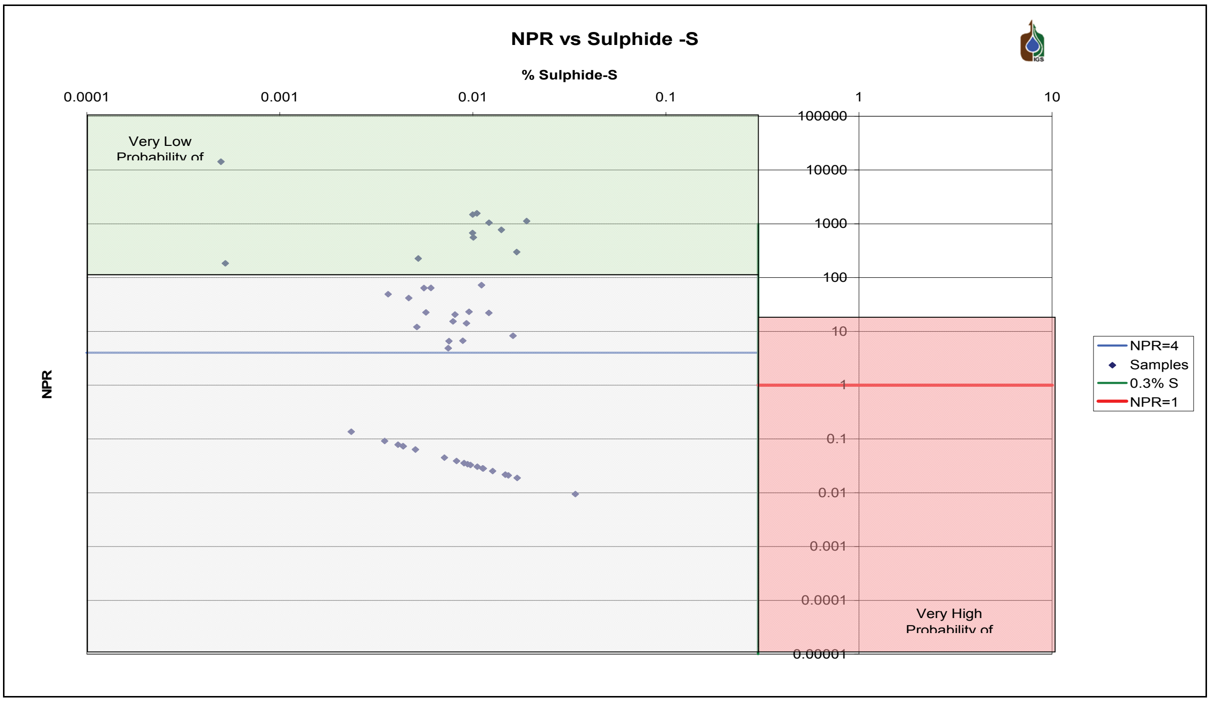


Figure 55: %S vs. NPR for the northern chip samples.

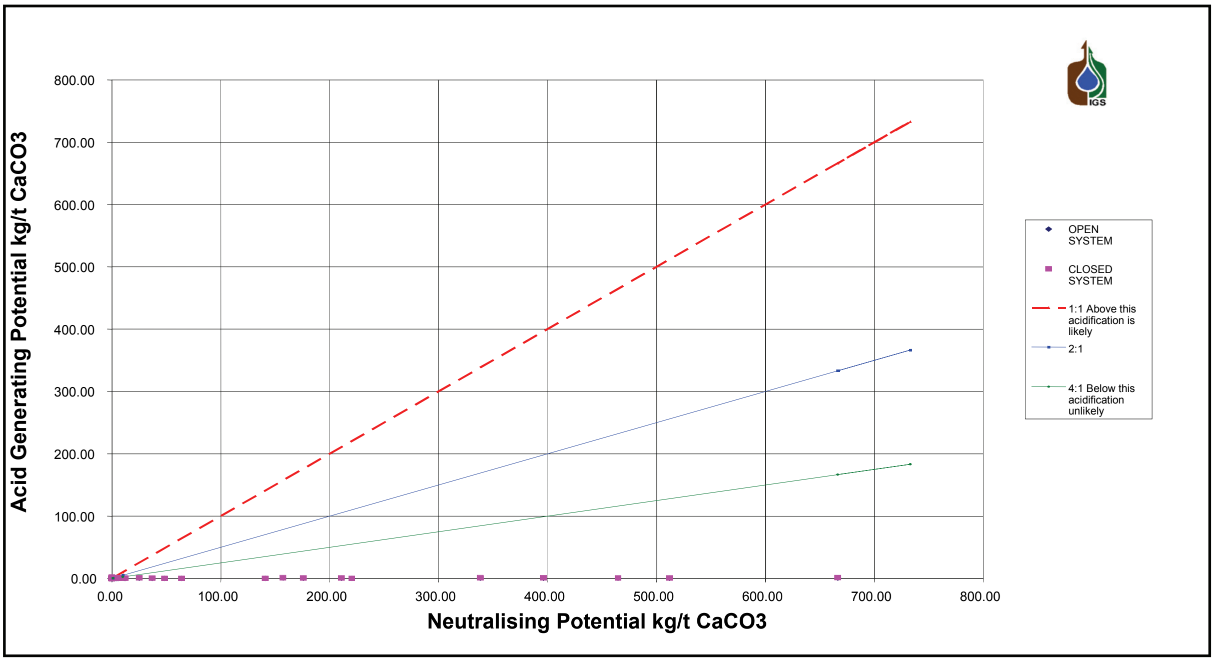


Figure 56: NP vs. NA (NPR) for the northern samples.

7.8 Sandstone Samples

A sample of sandstone located beneath Coal Zone 2 (the base of current mining operations) was collected for ABA analyses. The sample represents sandstone with a thickness of 60 m. The initial and final pH values are summarised in Appendix A. The sandstone sample indicates a risk of acid production after oxidation. The NNP for both closed and open systems is summarised in Table (Appendix A). These values are around zero NNP, which will need to be confirmed with kinetic tests. This however does not fall within the scope of this project. The NNP (for a closed system) and pH values from the above mentioned tables are plotted in Figure 57, indicating that there is no major acid or neutralising capacity.

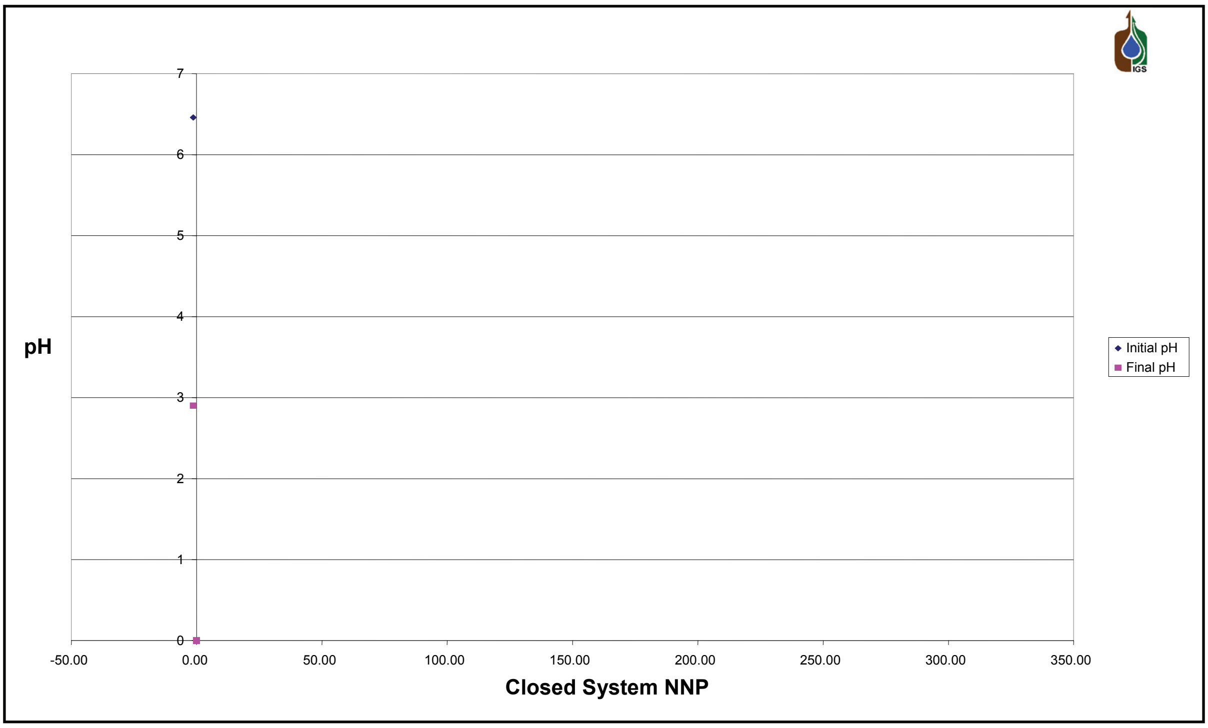


Figure 57: NNP (closed) vs. pH for Sandstone.

The percentage sulphur in the samples plotted against the NPR indicates a very low risk of acid production (Figure 58). The NPR for the samples can be seen in Table (Appendix A).

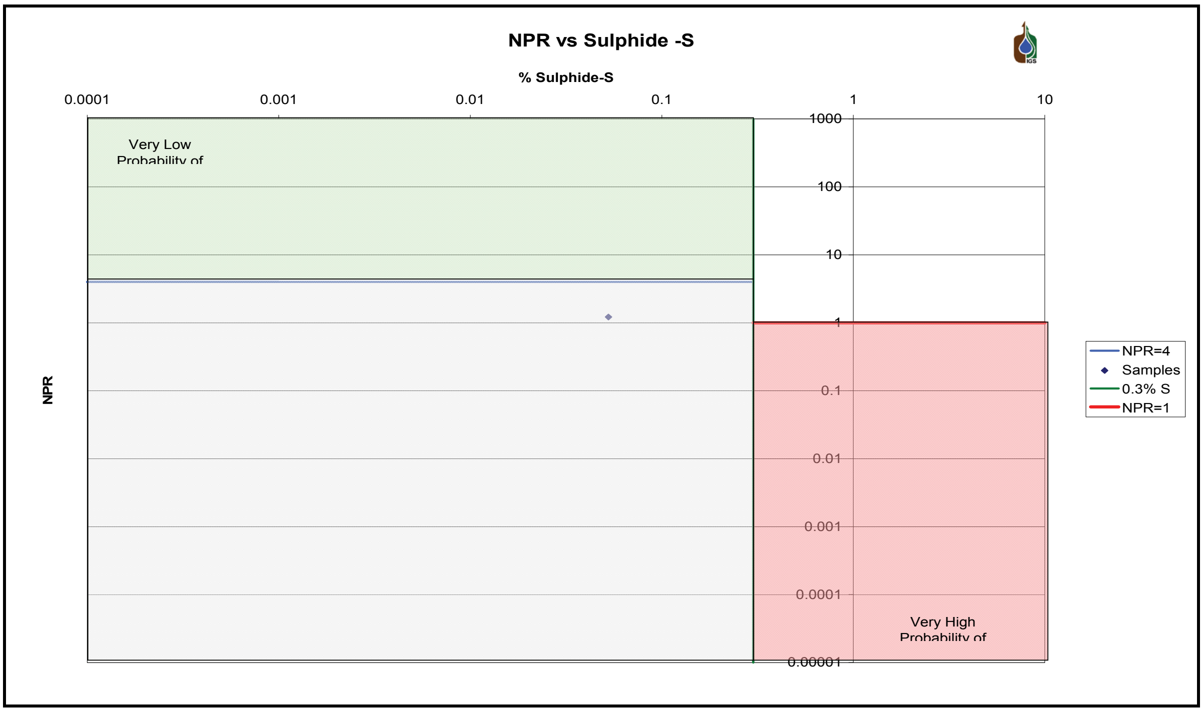


Figure 58: %S vs. NPR for the sandstone samples.

Those samples with values close to zero indicate no neutralising potential, while those with values >4 indicate no acid potential. This is also indicated in the NPR (NP/AP) graph (Figure 59).

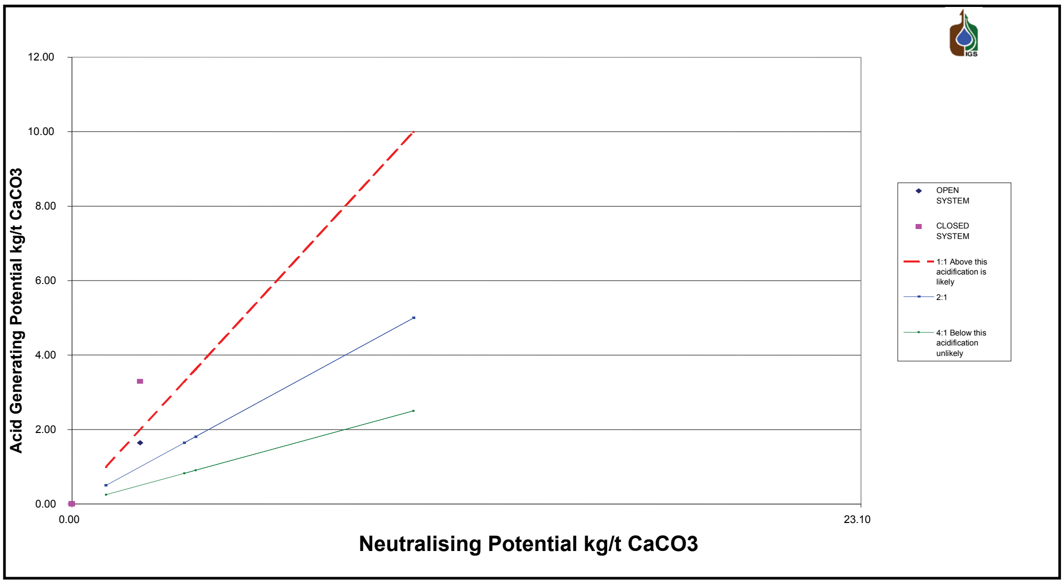


Figure 59: NP vs. NA (NPR) for the sandstone samples

The mineralogy of the sandstone sample is not known, as no XRD analyses were conducted. From the static tests on the sandstone samples in the Waterberg area, it is clear that a small quantity of AMD will be produced per mass of the specimen.

7.9 Discard Samples

Two composite samples over time of discard material from the two beneficiation plants at the Grootegeluk mine were collected for ABA analyses. No XRD analyses were conducted on the samples. The initial and final pH values are summarised in Table (Appendix A). This discard samples indicate a high risk of acid production after oxidation. The NNP for both closed and open systems is summarized in Table (Appendix A). These values are negative, indicating a potential for acid generation. The NNP (for a closed system) and pH values from the above mentioned tables are plotted in Figure 60, indicating that there is a high acid producing potential.

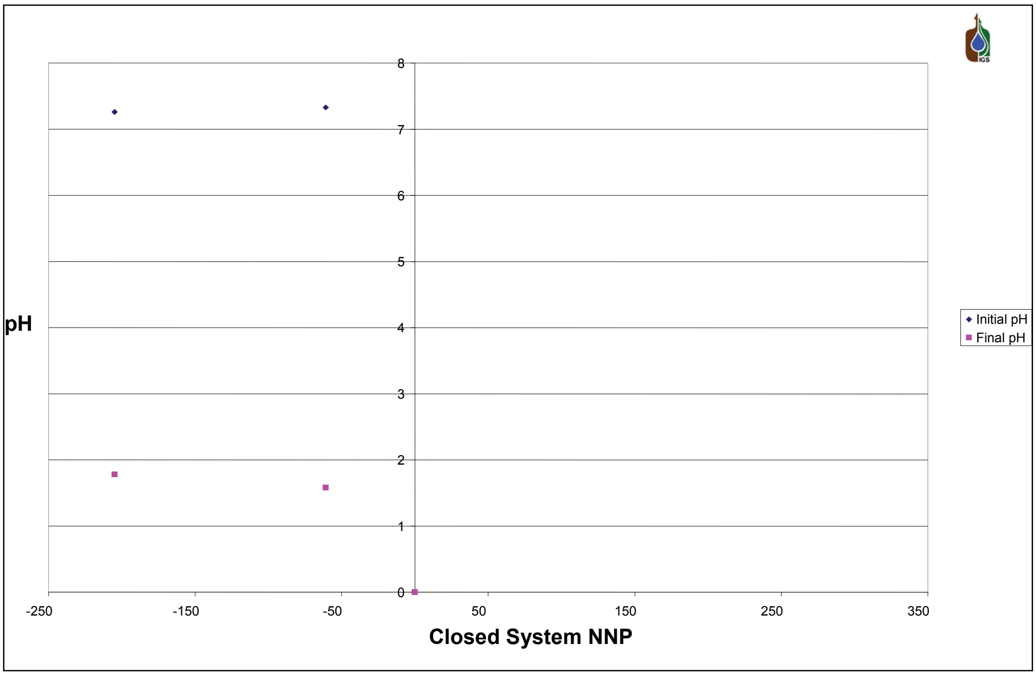


Figure 60: Net neutralizing potential (closed) vs. pH values for discard samples.

The percentage sulphur in the samples plotted against the NPR also indicates a high risk of acid production (plotting in the red area), with sulphur percentages of over 1% (Figure 61). The NPR for the discard samples can be seen in Table (Appendix A). All the samples have an NP: AP ratio of less than one, indicating potential acid production (Figure 62).

From the static tests conducted on the discards from the Waterberg area, it is clear that acid will be produced upon oxidation of the samples. This has been observed in the field by Dreyer (2009), who indicated that there is acidic effluent flowing out from the discard dumps at the Grootegeluk mine. Dreyer (2009) stated that the volume of effluent was small and that many of the primary polluting components have been removed via burning of the discard dumps due to spontaneous combustion.

7.10 Discussion

From the results of the ABA analyses one can conclude that, in most cases, there is sufficient neutralisation potential to account for any acid generated if a constant ratio is maintained (every ton of acid rock should be mixed with a ton of base potential rocks). There are however some exceptions:

7.10.1 The North Western Samples

The analyses of the samples taken from the north western sampling location indicate that there is sufficient pyrite to generate acid. The data further indicate that there is calcite to serve as a buffer to limit the amount of acid generated, depending on the thickness of the successions that contains the pyrite (in general, the pyrite is found as disseminated deposits in the sandstones and in the coal). It is recommended that care be taken when handling the spoil. The current method used at the Grootegeluk mine, whereby the rocks (geology) is placed back into the pit in the same successions as it was removed, should be practised.

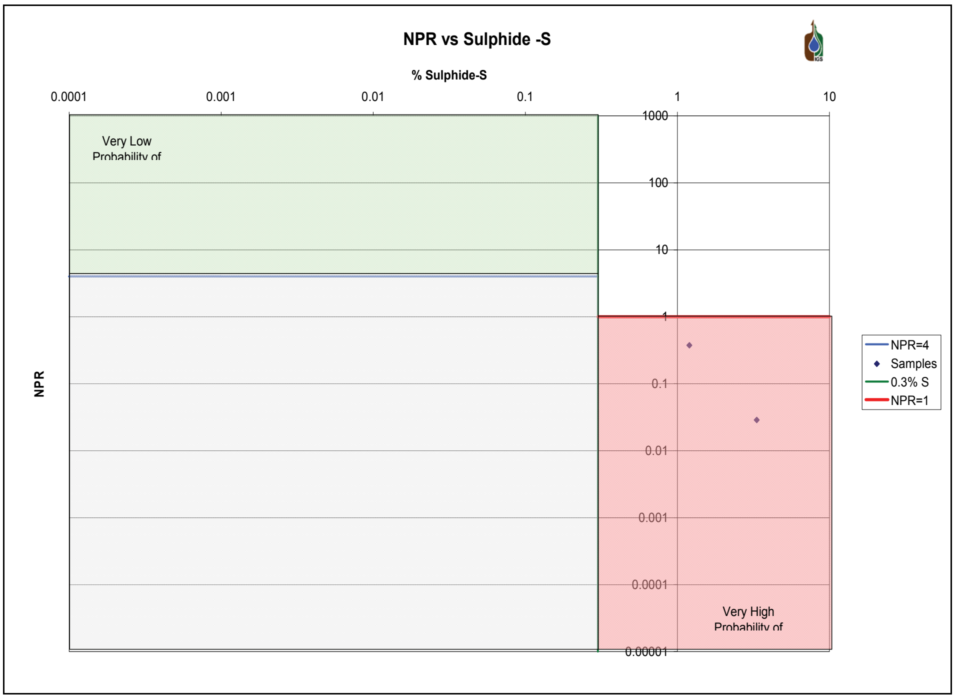


Figure 61: %S vs. NPR for the discard samples.

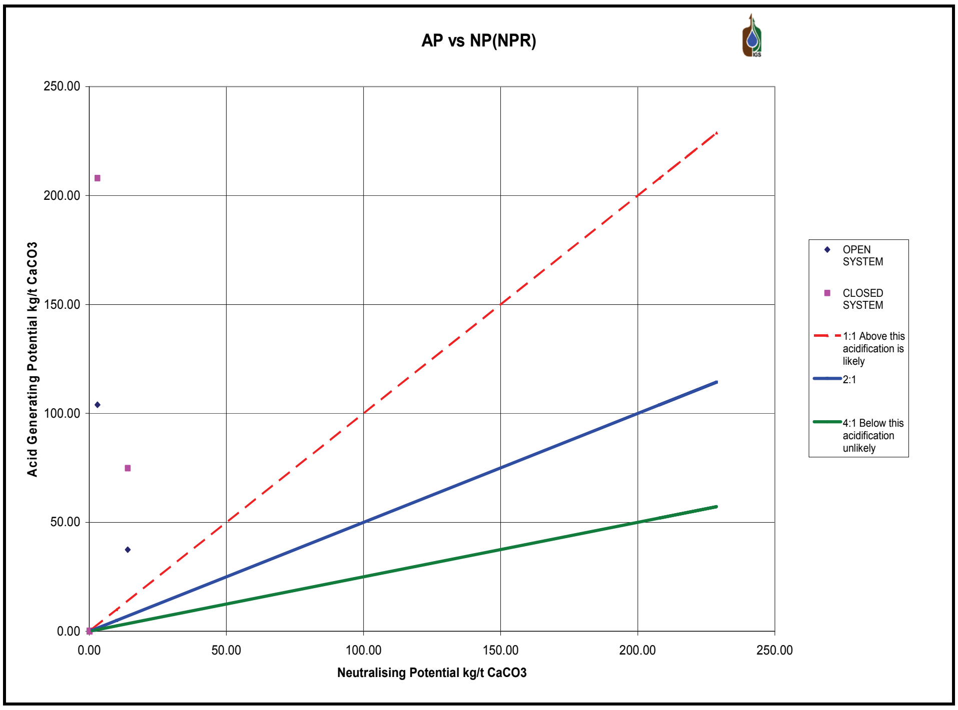


Figure 62: NP vs. NA (NPR) for the discard samples.

7.10.2 The Northern and South Eastern Samples

Four sets of samples were collected from and ABA analyses were conducted. It was found that the samples have the potential to generate acid, although they also contain buffer potential. Care should be exercised when re-depositing the spoil in the pit in these locations. Three other sets of samples were collected and analysed. The data for the samples from the farm Goedgedacht indicate that there is sufficient buffer potential in most cases to limit the level of acid production. The samples collected from the farm only represent the top 14 m of the geological succession in the study area, and were collected from the weathered zone, in which a certain level of leaching has likely occurred. It is therefore recommended that more detailed work be done and that ABA be conducted on core samples at greater depth. The third set of samples collected and analysed includes a sandstone sample from beneath the second coal seam. This sandstone indicates the lowest level to which opencast mining in the study area will take place. The ABA analyses of these samples indicate that some acid will be generated for any given mass of the sandstone. The sandstone will not be removed in the near future, accordingly it is recommended that sandstones be placed near the bottom of the pits to reduce or limit the potential for acid generation.

The best practice is to place the sandstone beneath the water table and attempting to flood the sandstone as soon as possible to substantially reduce the potential for acid generation. This will however not be possible in the study area due to the low volumes of water available in the study area, both from groundwater and surface water sources.

Under the circumstances it is recommended that the sandstone be placed at a higher level in order to minimize moisture content and thus decrease the potential for acid generation. The final set of samples collected for analyses includes two samples of discard generated by the processing plants at the Grootegeluk mine. These samples were analysed by static ABA methods. It was found that the samples had a high acid generation potential, and if oxidised, the samples will produce acid. It is recommended that the same steps be taken as with the sandstone. The discard should be placed above the water table in order to keep the discard “dry” and thus minimise the generation of acid. It is furthermore recommended that the discard not be mixed with other rocks, unless these have a high base potential.

7.11 Comparison of ABA Results to Weathering Depth

It was decided that a comparison between the depth of weathering and the results from the ABA analyses be conducted in an effort to identify any patterns of potential problem layers that are prone to acid generation. Accordingly the study area was divided into three areas with regards to weathering (Figure 63). From the map, the areas indicated in green contain the full succession of geology and all the coal seams. The area in yellow indicates areas that have been eroded down to the middle Ecca geology with some of the coal containing strata missing. The area in red includes areas that have been badly eroded, with much of the coal succession removed.

7.11.1 The Green Areas (NW and SE Sampling Locations)

The samples from the green areas on the map (Figure 63) indicate that there is a general increase in the potential to generate acid up to a depth of roughly 80 m below surface. From this point, the acid potential begins to diminish as the neutralisation potential increases, with the deepest samples having very little potential for the generation of acid. Both core samples collected from the green area show a predisposition to generate acid at depths of between 50 m and 80 m below the surface.

It must also be made clear that these increases in the acid generation potential of the rocks coincide with the increased presence of pyrite in the rocks. In fact, the increase in the potential to generate acid by the rocks in most cases coincides with the presence of pyrite (Figure 66), while the potential for base generation or neutralisation potential increases with the increase of calcite content in the rocks.

The rocks between a depth 50 m to 80 m, (Figure 64 and Figure 65) beneath the surface contains alternating layers of mudstone and shale inter-bedded with coal.

The data indicated that the highest potential for acid generation is found in the areas of the succession that have the highest concentrations of pyrite. According to the data this area is concentrated in the areas that contain the full succession, between 50 m and 80 m below the surface. At present, management options at the only active colliery in the study area, with regard to minimizing acid mine drainage is to replace the rocks back into the pit in the same order as its removal. It is recommended that the geology from this area be carefully noted for future reference once the new mines open in order to follow the same procedure for backfilling of the pit. It is further recommended that these rocks be mixed with rocks that have a high base potential to further minimise the acid potential of the pyrite containing rocks. This should be done in an effort to minimise the potential for acid generation should the acid generating layers oxidise.

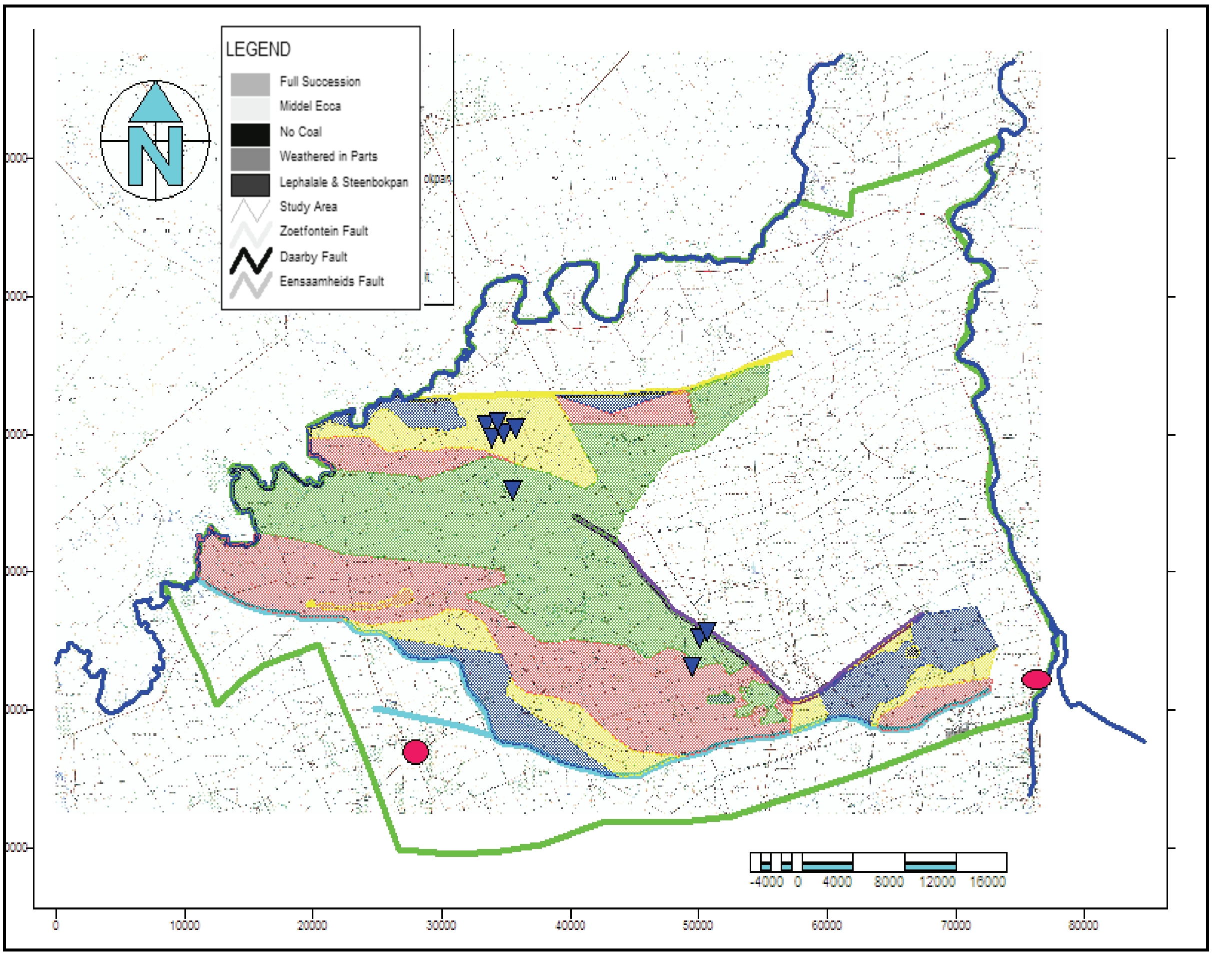


Figure 63: Location of the sample localities with regards to weathering.

Figure 64: Sample GGS 2 Taken 52 m below the surface in the south eastern area.

Figure 65: Samples SS5 and SS6 Taken 54 m and 66 m respectively below the surface in the north western area.

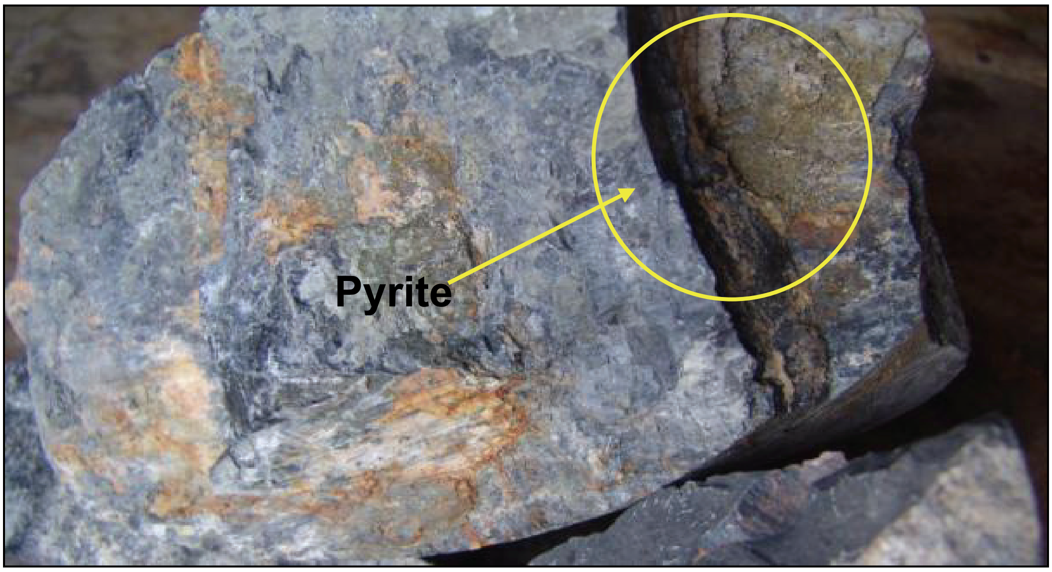


Figure 66: Sample SS6 showing the presence of pyrite.

7.11.2 The Yellow Areas (Northern Sampling Locations)

The geological samples collected from the yellow area were comprised of chip samples only, as no core samples were available at the time of sampling. There is no identifiable pattern to the acid potential from these samples. Samples, GT1 (Figure 67 and Figure 68) and GT4 show a trend to start generating acid from roughly 5m below the surface. From this depth, the acid potential steadily increases with depth. With the exception of the first sample, the samples from Borehole GT7 (Figure 67 and Figure 68) shows a similar pattern.

Acid generation potential starts at a depth of roughly 11 m below surface. Unfortunately, the boreholes from which these samples were collected were shallow and the acid potential with depth can only be guessed.

Samples from Borehole GT2 (Figure 69) show a very high base potential and no acid generation potential. Sample GT3 (Figure 70) fluctuates greatly. Some samples from the very top of the succession indicate acid generation potential, together with all of those near the centre and near the bottom of the succession. This is interspersed with samples that have high base potential.

Figure 67: Samples GT1.1 and GT7.5, respectively, with no acid potential.

Figure 68: Samples GT1.9 and GT7.1, respectively, with acid potential.

Figure 69: Sample GT2.12 with no acid potential.

Figure 70: Sample GT3.2 (on the left) with acid potential and sample GT3.3 (on the right) with no acid potential

According to the data from the boreholes located in the yellow areas, there is too great a variation in the acid and base potential of the samples to be indicative of a specific layer with higher than expected acid generation potential. It is recommended that further ABA studies be conducted in this region, and that core samples be used in an effort to ascertain the location of any layers with the potential for acid generation at greater depth.

7.11.3 The Red Areas (South Eastern Sampling Location)

Only one set of samples was collected from the red areas. The samples collected were chip samples and were collected down to a depth of 4m (Figure 71 and Figure 72). According to the results of the ABA testing, there is a high degree of certainty that the samples from the red areas will generate acid in both open and closed system conditions. The samples also contain no potential for buffering the acid once it is generated. It is however recommended that core samples are taken from this area and that further ABA analyses be conducted in an effort to identify any potential problem layers located deeper in the succession.

Figure 71: Sample GGVZ1, collected 1 m below the surface with acid potential.

Figure 72: Sample GGSVZ1.4 4 m below the surface with acid potential.

7.12 Conclusions

7.12.1 The North Western Samples

- The analyses of the samples taken from the north western sampling location indicate that the rocks in the area contain sufficient pyrite to generate acid.
- The data further indicate that there is sufficient calcite present to serve as a buffer to limit the amount of acid generated, but not enough to completely eliminate the potential for acid generation.

7.12.2 Northern and South Eastern Samples:

- It was found that the samples have the potential to generate acid, although they also contain buffer potential.
- The ABA analyses of the sandstone samples indicate that some acid will be generated for any given mass of the sandstone.
- For the discard it was concluded that these samples had a high acid generation potential, and if oxidised, the samples will produce acid.

7.12.3 ABA Compared to Weathering

The results of the comparison between the ABA results to the level of weathering are inconclusive.

- In the areas that contain the full succession there is correlation between rocks from the zone 50-80 m below the surface. The rocks at this depth have a greater potential for acid generation in both the north western and south eastern sampling locations.
- The lack of additional samples for both the yellow areas and the red areas makes comparison difficult and no concrete conclusions can be drawn.
- It is therefore recommended that additional samples be collected and the same analyses be done on these samples in order to identify potential correlation.

8 Pre-Mining Water Quality of the Waterberg Coalfields

8.1 Introduction

The primary goal of this project was to determine the pre-mining groundwater quality for the study area and how it would be affected by mining. In order to achieve this, chemical data on the current quality of the groundwater in the study area was necessary. Chemistry data for the study area was obtained from various sources. Much of the data obtained were collected from existing data bases, compiled by the companies that have been active in the study area in the past, or that are currently active in the study area. Companies such as Exxaro, Eskom, Sasol and Anglo Coal were the major contributors to the data base. There was however gaps in the data that needed to be filled in. These gaps were rectified by sampling of boreholes for which no data were available. These samples were transported to and accordingly analysed at the laboratory of the Institute for Groundwater Studies at the University of the Free State.

8.2 Sampling

8.2.1 Water Samples

The water samples were obtained from boreholes by means of flow-through bailers. The bailers were cleaned with deionised water before each sample was taken. The samples were stored in 500 ml plastic bottles and transported to the IGS laboratory for analysis. The samples were taken 5 m below the water level, or at fractures as identified by multi-parameter profiling where possible.

8.3 Water Quality Determination

The determinants are listed in Table . The analyses were performed using an Inductively Coupled Plasma Spectrometer (ICP-MS). The elements listed above cover a wide range and are good indicators of potential inorganic pollution in groundwater as a result of coal mining. The EC and pH measurements were taken both in the field and in the laboratory. The pH gives indications of the acidity or alkalinity of the water where as the EC gives an indication of the salt content of the water.

The EC can however only give the total dissolved salts and can give no indication of the types of salts. In total chemical data for 509 boreholes scattered throughout the study area was gathered. The data from the boreholes included information on the parameters listed in Table . However, not all the boreholes had information on all of the parameters listed, but were analysed according to the information from the available databases.

To determine the impact mining and power generation has on the quality of groundwater in the study area the rest of the chapter will be discussed as a comparison between areas that have been affected by the aforementioned activities and areas that have not been affected by these activities.

8.4 Discussion of Results

8.4.1 pH

Figure 73 indicates that, with the exception of a few boreholes, the observed pH values of the sampled boreholes, is well within safe limits (averaging 7.27) and does not vary to a great degree. Within these exceptions one does however find a large degree of variation, being 2.40 at the lowest point and 9.80 at the highest. The low pH is likely the result of a spill or some other point source pollution, for when one compares the other pH values for the same borehole over time one finds that the pH gradually increases to a value of 6. This large degree in variation is only found in a small number of boreholes (Figure 73).

There is no discernable pattern with regards to the locations of the high or low pH values. The lower pH values are all associated with specific areas of active mining or power generation. This cannot be given as a reason for the low pH values in general, as only a few of the boreholes show acidic pH levels and the boreholes located within close proximity to the acidic ones do not show any signs of acidification. There is no correlation between the pH values and the depth of the borehole, or the geology in which the boreholes are situated (almost all the boreholes have been drilled through sandstone and shale and only a few have acidic pH values).

It is therefore concluded that the acidic pH values are either the results of spills or of unknown geological conditions local to the boreholes displaying acidic pH values. From the data collected a contour map of the pH values for the study area was constructed *(*Figure 74*)*. There are no discernable patterns noticeable in the distribution of the pH values, with the exception of the boreholes with low pH values being located near areas of active mining or power generation.

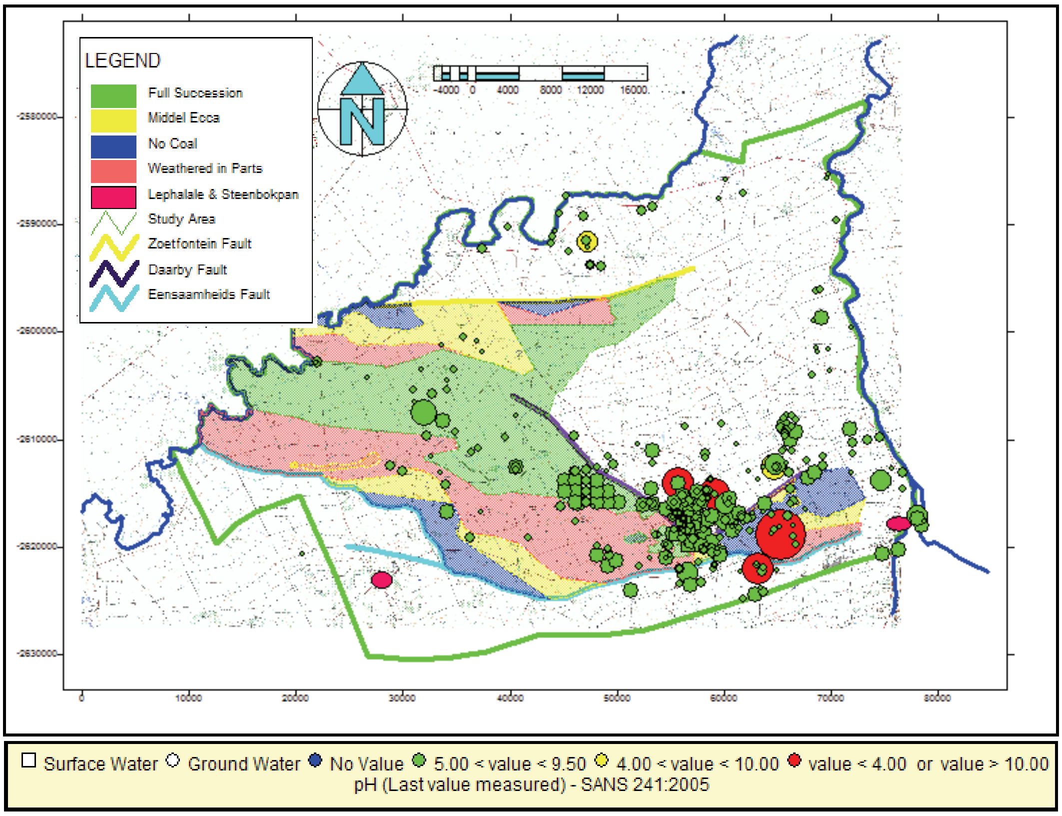


Figure 73: Proportional distribution of pH levels in the study area.

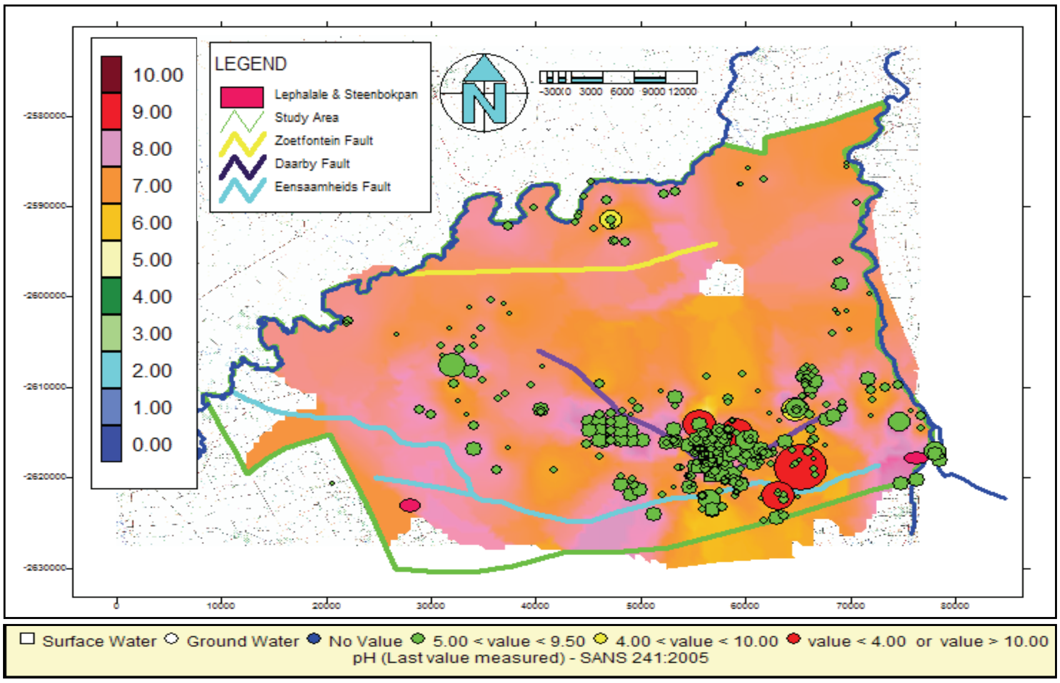


Figure 74: pH contour map of the study area.

From Figure 73 and Figure 74 it can be concluded that there is no definitive impact on the groundwater pH from the activities taking place in the study area. There is no visible difference between the values observed for areas where there are activities presently and areas where there are none. The exceptions found in the areas currently displaying activities such as mining or power generation are likely the result of spills or of local unknown geological phenomenon and can't be taken as an indication the impact of the activities on the groundwater.

8.4.2 Electrical Conductivity (EC)

The electrical conductivity (EC) of the groundwater in the study area varies greatly, with the highest levels located on the farms towards the east of the Daarby fault, predominantly located on the farm Zonderwater The largest concentration of mid-range EC values are located in the vicinity of the Grootegeluk mine and the Matimba power station near the central south east of the study area, indicating the impact of these activities on the groundwater. There is no discernable pattern to the distribution of EC values in the area.

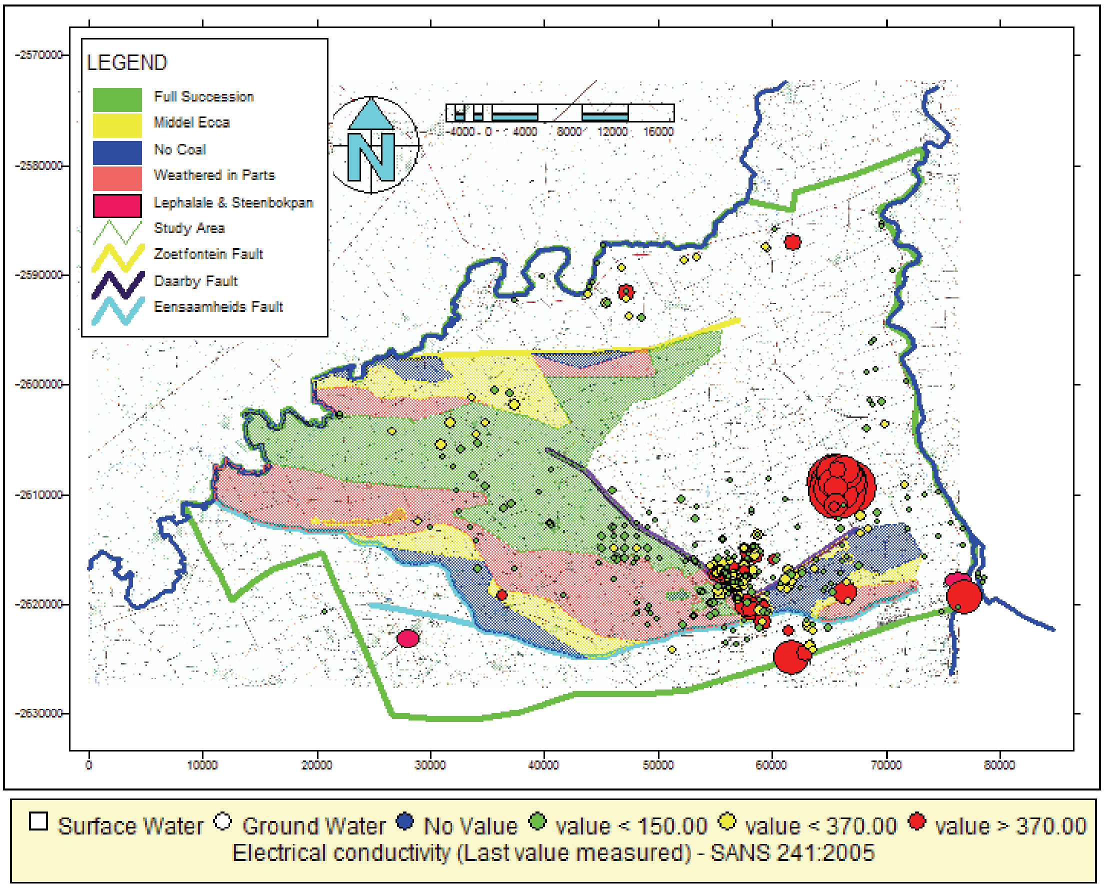


Figure 75: Distribution of elevated EC values found in the study area.

8.4.2.1 Groundwater in the Waterberg Group Rocks (Areas with Current Activities)

The data indicated that the EC values for the boreholes located on the farm Zwartwater are much higher than the EC values in the surrounding area. This farm marks the location of the fly-ash dump for the Matimba power station. The data indicates that the boreholes on this farm have high EC values. The reasons for this are twofold. Firstly:

- The boreholes were drilled south of the Eenzaamheid fault.
- The Eenzaamheid fault marks the transition from Karoo rocks north of the fault into Waterberg Group rocks south of the fault.
- The Waterberg Group rocks have a generally higher salt content than the rocks from the Karoo groups. This has been observed at other boreholes close to the town of Lephalale that have been drilled into the Waterberg Group rocks.
- Accordingly it is possible that the salts from the rocks have leached into the groundwater resulting in the higher EC values.

Secondly:

- The farm is the location of the fly-ash dump for the Matimba power station and it is very likely that the salts have leached from the dump and has ended up in the boreholes.
- These boreholes are drilled in the Waterberg Group rocks and are located in the shallow aquifer.
- These salts would have entered into the upper weathered aquifer during periods of high recharge (large precipitation events) and would move through the un-weathered aquifer.

Figure 76 shows the data for boreholes drilled at the site of the new Medupi power station. The boreholes were drilled in pairs, one deep borehole and one shallow borehole per site. This was done to determine if there was a difference in water quality between the shallow and deeper aquifers.

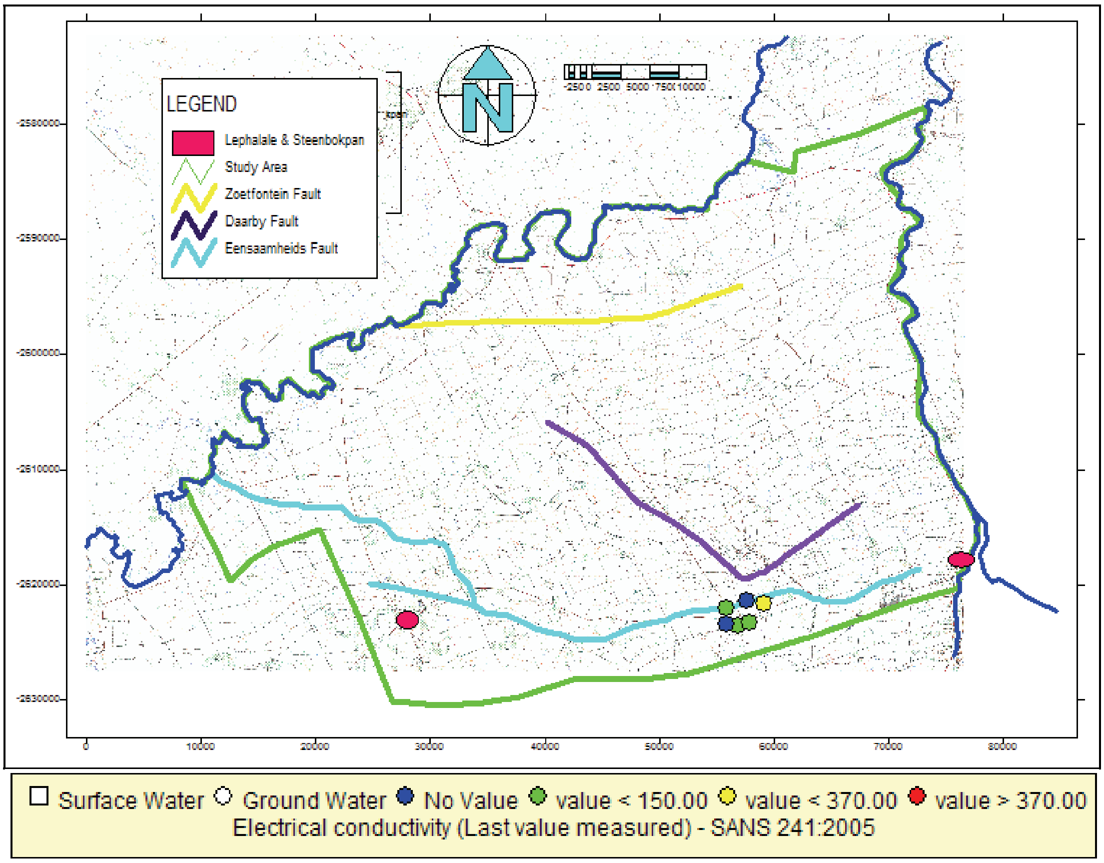


Figure 76: Location of the 6 borehole pairs at the Medupi power station.

Figure 77 illustrates that with the exception of boreholes MBH4D, MBH2S and MBH6D there are no significant differences in the measured EC values for the boreholes. For the most part the shallow boreholes and the deeper boreholes display EC values that are very similar. This indicates that there is movement between the shallow and deeper aquifers.

When discounting borehole pairs 1 and 5, due to lack of data for the shallow boreholes (dry boreholes) and only taking the four remaining pairs, one finds that boreholes MBH2S and MBH6S, boreholes drilled in the shallow aquifers have higher EC values than those drilled in the deeper aquifers. Additionally boreholes MBH3D and MBH4D, drilled into the deeper aquifers, indicated higher EC values than the ones drilled into the shallow aquifers. Borehole pairs MBH4 and MBH6 were drilled into the Karoo group rocks and pairs MBH2 and MBH3 were drilled into the Waterberg group rocks.

The data showed that for the boreholes drilled in the vicinity of the Medupi power station, there is movement between the deeper and shallower aquifers. It was initially expected that the shallow boreholes (drilled in the weathered zone) would display lower values than the deeper boreholes (Hodgson *et al.,* 2007).

This was found to be true with the exception of two of the boreholes, namely MBH6S and MBH2S. With both boreholes indicating elevated EC values in the shallow aquifers. It is expected that due to the difference in transmissivities, the time it takes for the water to move in the different rocks will differ greatly. With water movement in the Karoo group rocks expected to be faster than in the Waterberg Group rocks.

It is suspected that boreholes MBH4D and MBH2S were drilled on an unknown geological anomaly (probably a dyke) that was responsible for the elevated EC values. Accordingly it was concluded that the elevated EC values found in the borehole near the Matimba ash dump were the result of downward movement of effluent draining from the dump. Vermeulen and Dennis (2007) also noted these elevated EC levels in the vicinity of the ash dump during a survey conducted for the Matimba power station.

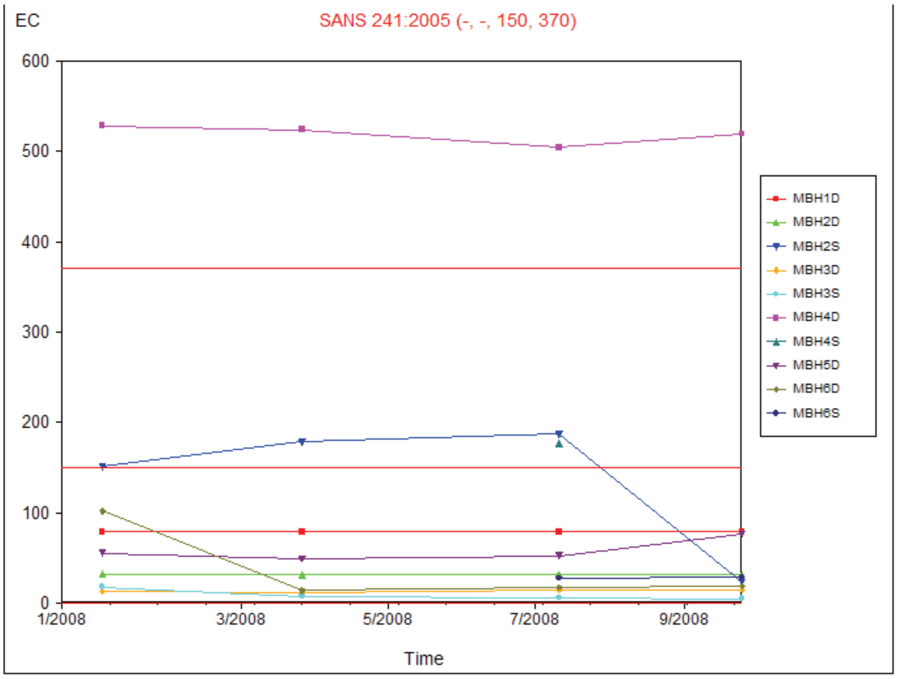


Figure 77: Graph of the EC for the deep (D) and shallow (S) boreholes drilled at the Medupi power station.

Vermeulen and Dennis (2007) additionally noted that "according to the point size distribution of electrical conductivity values around the ash dump, the dump has a definite impact on the groundwater quality of the monitoring boreholes near the structure. The boreholes further away, show no elevation and are currently unaffected", illustrated in Figure 78.

Figure 78 indicates a general increase of the EC values in the boreholes located near the ash dump over a period of eight years. The ash dump is situated on Waterberg Group rocks and according to Dreyer (2009) all of the newly planned infrastructure for the new mines and the new power station are to be located on the Waterberg Group rocks, west of the Eenzaamheid fault. The data suggests that the same forms of contamination can be expected at the location of the new power stations (slow seepage from the ash dumps and coal stock yards into the groundwater).

It is recommended that monitoring boreholes drilled at the sites of the new power stations and their planned infrastructure. Additionally it is recommended that the boreholes be monitored regularly and that measures (such as lining of the dump areas with bentonite) be taken to prevent the leached salts from entering into the upper aquifers.

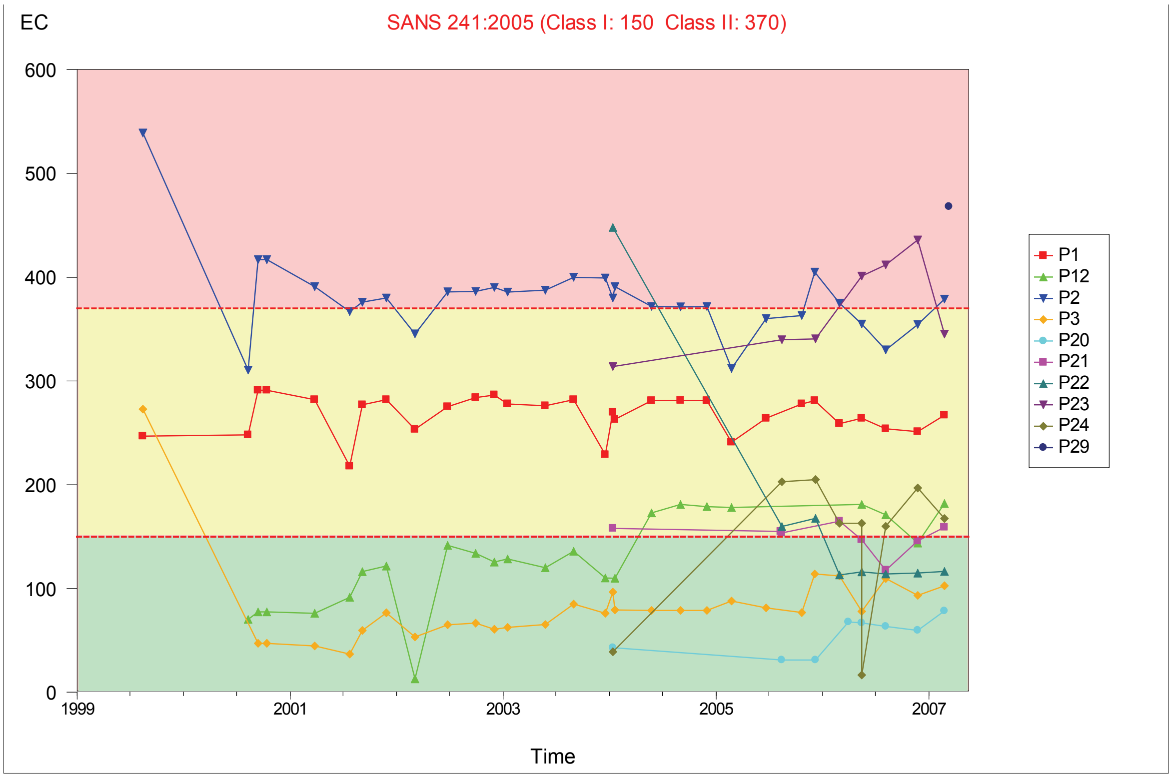


Figure 78: Graph of electrical conductivity at the ash dump boreholes (Vermeulen and Dennis 2007).

8.4.2.2 Groundwater in the Karoo Aquifers (Areas with Current Activities)

The data in Figure 79 (outlined in red) indicate areas found in the Karoo group rocks that have elevated EC values. Figure 79 displays the contour map of the EC values for the study area. The area outlined in black indicates an area for which no data could be gathered. Additionally, the data from Figure 79 indicates that, with the exception of the boreholes towards the east and the central south east, the area displays generally low EC values. These areas towards the east and south east are cause for concern and show the influence of activities on the groundwater.

The area to the east indicates the area in which Anglo Coal is presently testing the viability of hydro fracturing to remove methane from the subterranean coal deposits. The area to the south east, marks the location of the Grootegeluk mine and the Matimba power station. There is also the area to the south near the Matimba fly-ash dump located between the Daarby and Eenzaamheid faults. This is area is not directly linked to the Matimba ash dump and is spatially far removed from the dump. The area is located too far away from the mine infrastructure at Grootegeluk to have been contaminated by for example a spoils dump. Furthermore the boreholes are located south of the Daarby fault, which according to Dreyer (2009) is impermeable. It is therefore likely that these boreholes are very deep boreholes and are naturally saline, with the high EC values not being the result of pollution.

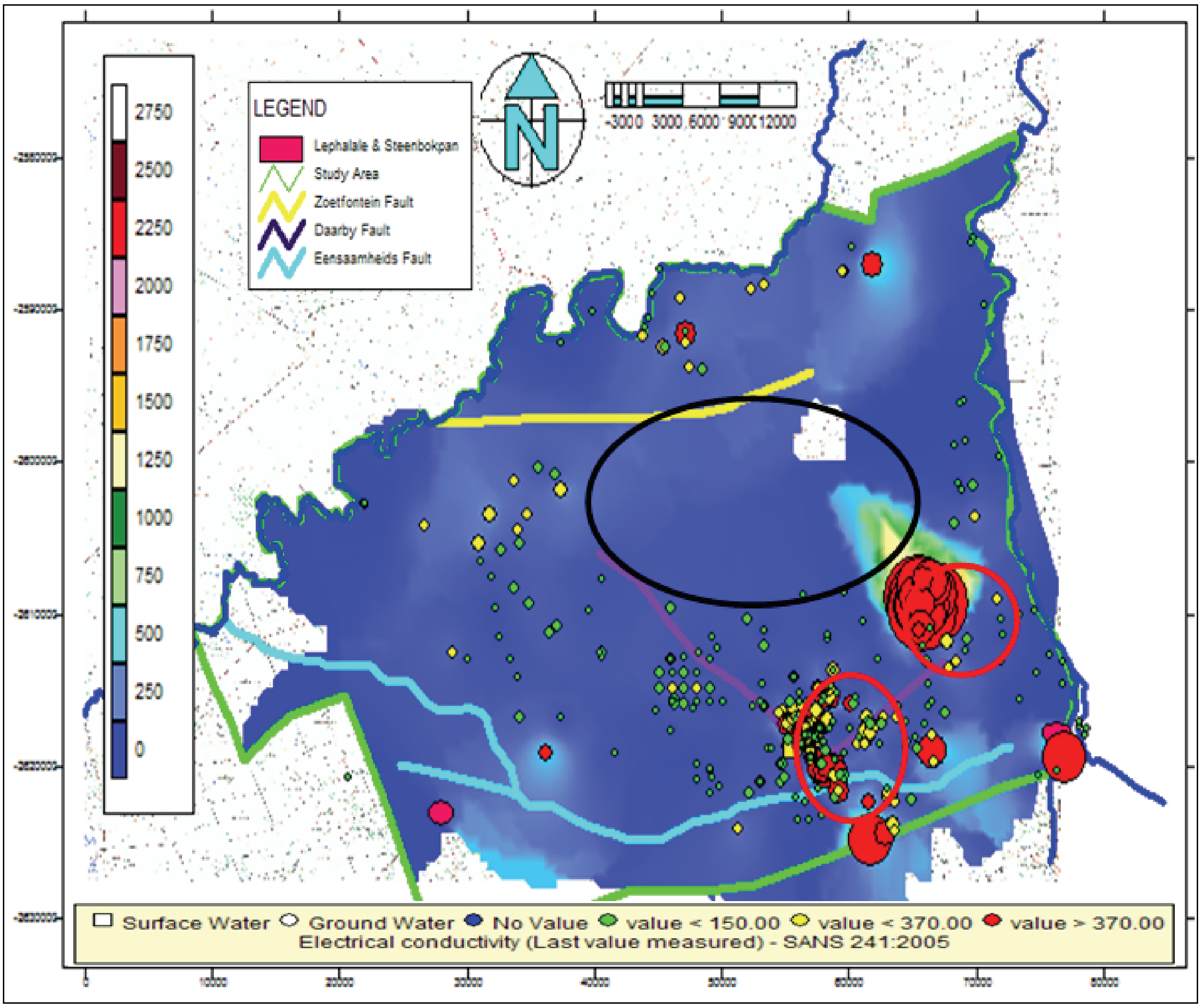


Figure 79: Contour map of the EC values encountered in the study area, with the proportional distribution of the EC values on top of the contours.

8.4.2.3 Far Eastern Boreholes

The boreholes drilled in the far east of the study area, display the highest EC values in the study area (Figure 80). According to a study done by Usher *et al.* (2005), the anomalously high EC values found in the groundwater for these boreholes are naturally saline.

According to Usher *et al.* (2005) the high EC values are the direct result of the depth of the boreholes (some reaching depths of 420 m) and not the result of pollution. The data from Figure 81 indicate that the EC values are much higher than the values for the boreholes drilled into the Waterberg Group rocks. There are however not sufficient data on the surrounding farms to determine the extent of the elevated EC values.

These values appear to remain constant according to Figure 81 with the exception of three boreholes in which the values fluctuated. These boreholes fell outside the primary focus area of the project, but the effect that the activities in the area are having on the water quality should be noted.

The areas towards the south east around the Grootegeluk mine exhibited elevated EC levels (Figure 82) and in some of the boreholes elevated sulphate values. These elevated values are associated with the activities at the mine (coal washing, stockpiling, and evaporation ponds). Accordingly it can be expected that the similar effects will be present at the new mines planned for the study area.

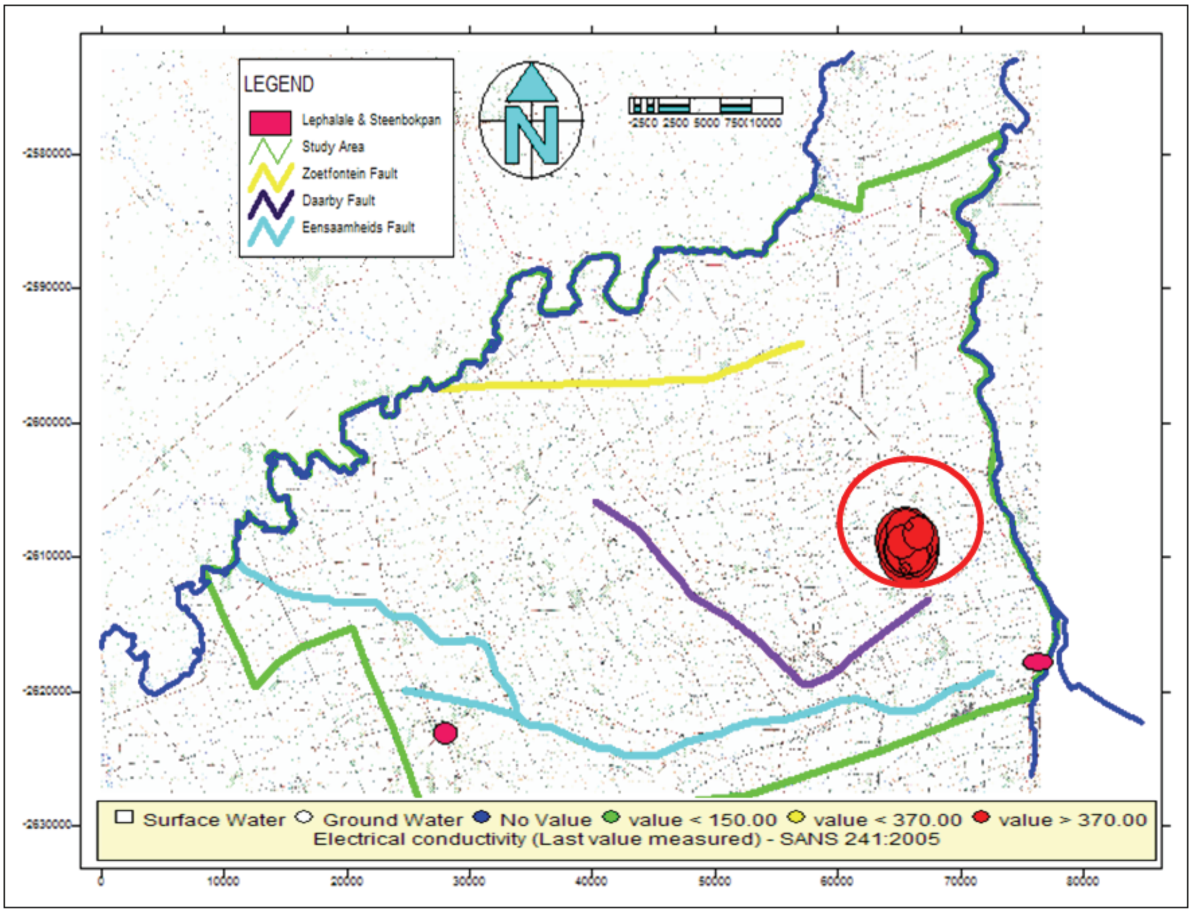


Figure 80: Proportional distribution of the high EC values of the eastern boreholes.

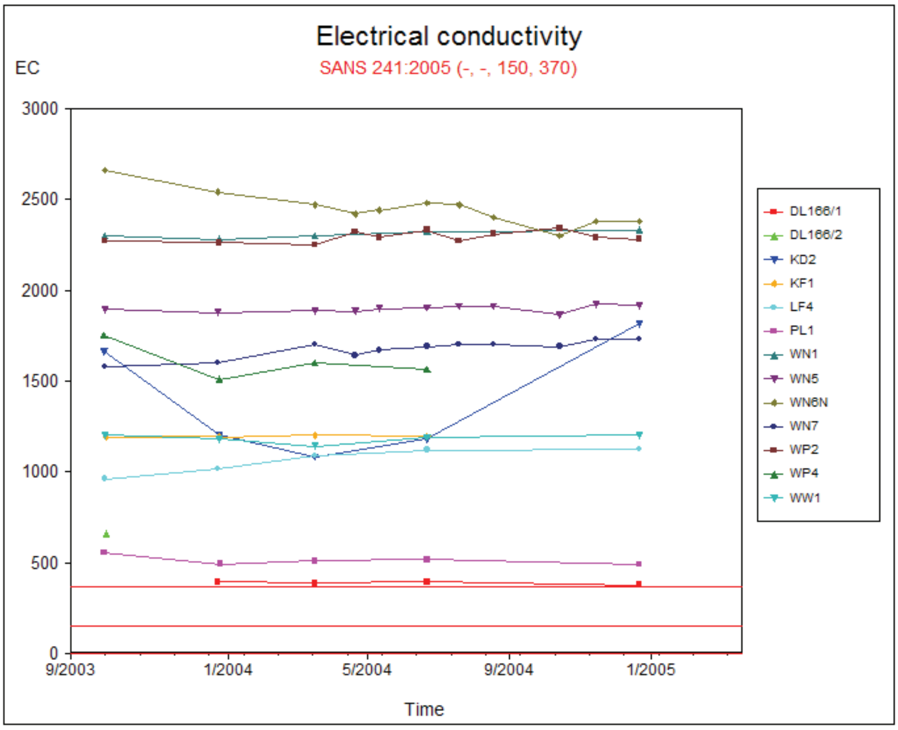


Figure 81: Time series data for the eastern boreholes.

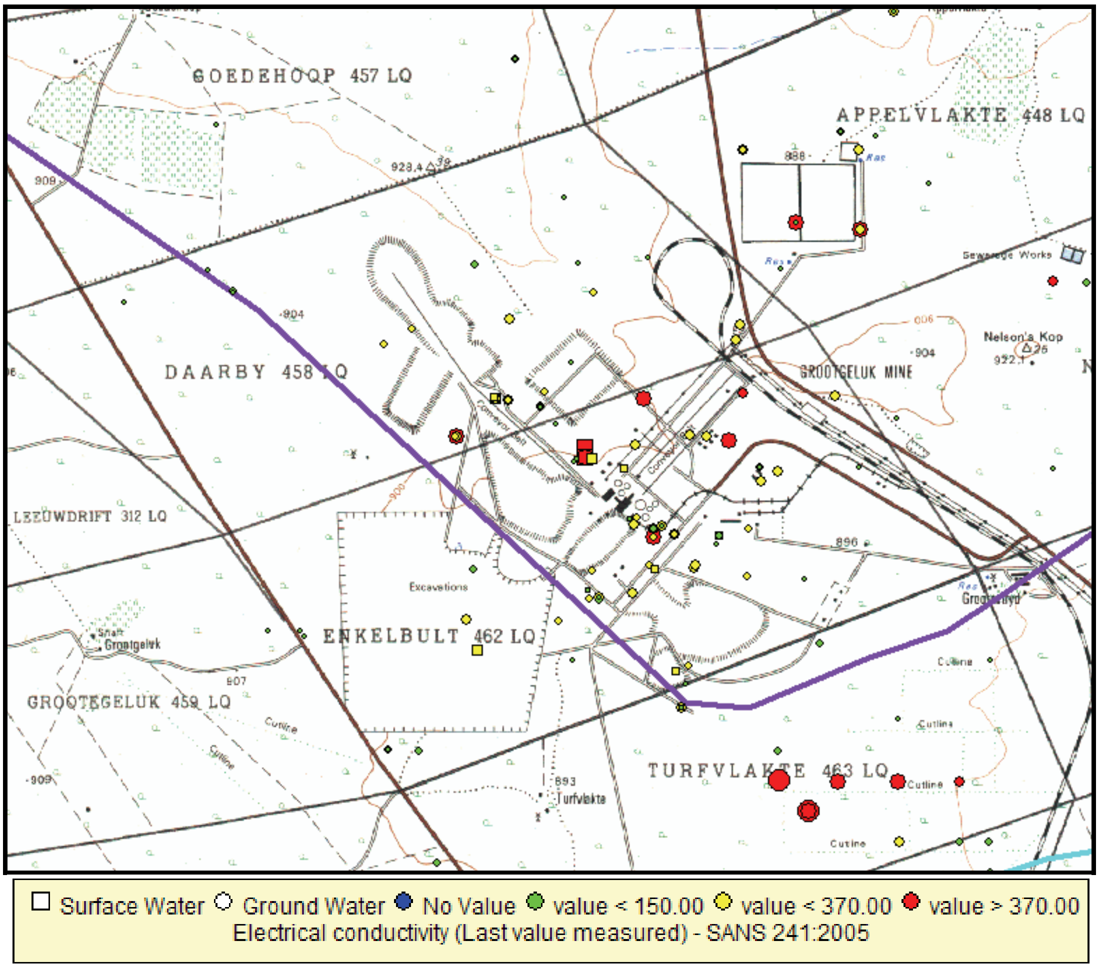


Figure 82: Size distribution for EC values of boreholes (circles) and evaporation ponds (squares) at the Grootegeluk mine.

Figure 83 indicates the EC values recorded for the boreholes drilled on the site of the Grootegeluk mine. The values fluctuate between high and low values and all the values show a large decline to nearly zero between 2004 and 2005. This reduction in values coincides with a period of high rainfall. It can therefore be concluded that the water in the boreholes was diluted during this time of elevated precipitation.

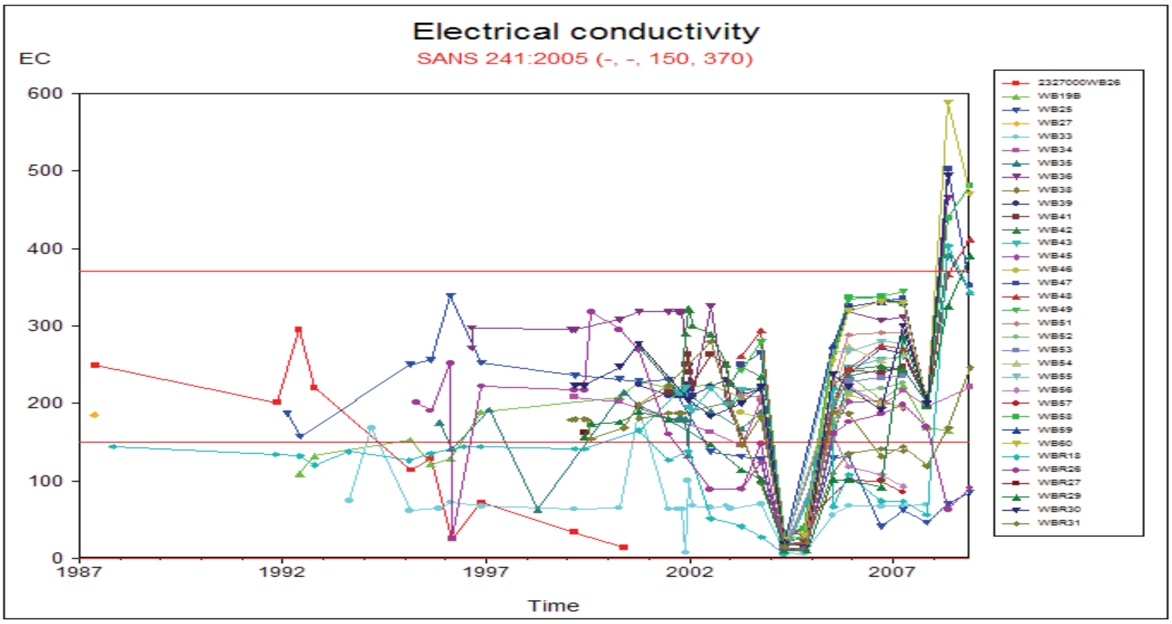


Figure 83: EC values for the boreholes drilled on the Grootegeluk mine site.

The decline of the EC values was accompanied by an increase of the sulphate values over the same period (Figure 84), implicating that runoff from discard dumps and coal stockpiles infiltrated into the aquifers during this period of high rainfall. Normally the EC and sulphate graphs follow the same pattern; this implicates that due to the high concentration of sulphate, other constituents which dissolved more readily than sulphate, moved into solution. This is a phenomenon that should be carefully monitored at new mines in the area.

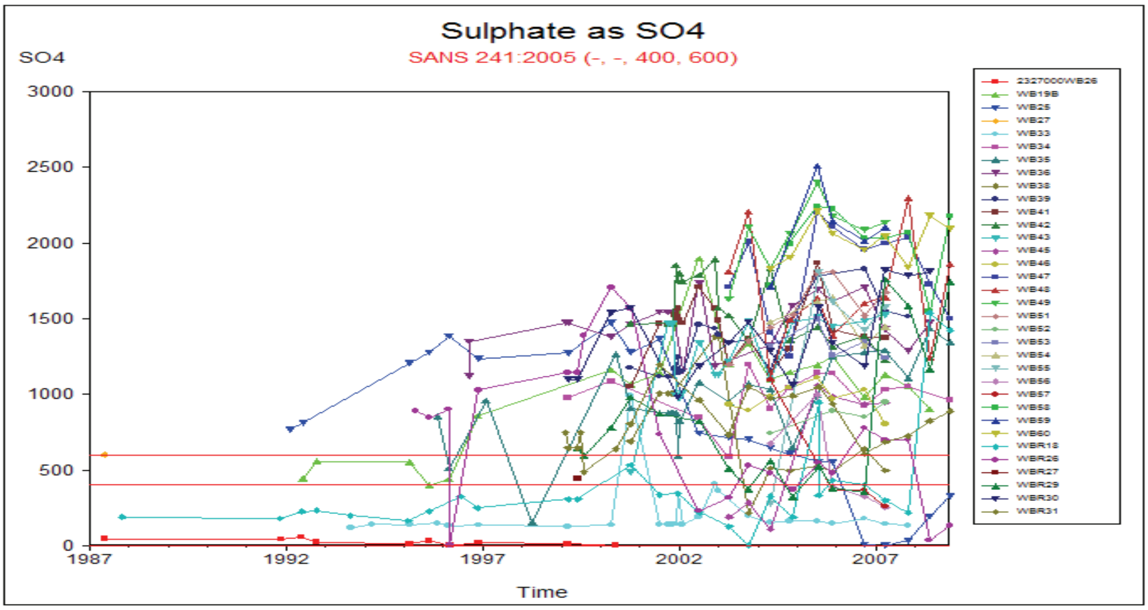


Figure 84: SO_4 values for boreholes drilled on the Grootegeluk mine.

The data from the previous figures indicate that in the Karoo aquifers there is sufficient movement to allow for the infiltration of dissolved inorganic pollutants. The data in Figure 84 indicate a dramatic rise in the SO_4^{2-} levels since 1992. It is expected that these values will continue to rise as the operations at the mines continue, and should be carefully monitored. This poses problems for groundwater resources located outside of the faults that delineate the coal field. The reason for this is that all of the infrastructure for the mines and the power stations will be constructed south of the Eenzaamheid fault and thus outside the coal field. The groundwater resources located in the vicinity of the mining infrastructure is likely to be affected by the vertical movement of these pollutants but the low transmissivities of the rocks along with the low recharge, will effectively retard the horizontal movement of the these pollutants.

8.4.2.4 The Areas West of the Daarby Fault (Unaffected Areas)

For the areas that have not been affected on by activities such as mining or power generation the general groundwater quality ranges from fair to good (Figure 85). Figure 85 indicates that, in general, the EC values for the area that has not been influenced by activities ranges between values that can be classified as low and medium. With the medium values likely the result of abstraction. Figure 86 indicates that there is no visible trend in the EC values, with the values remaining stable over time. There are exceptions to this, with the predominant rise and falling in the values coinciding with precipitation events.

The Cl values displayed in Figure 87 are generally above medium for the groundwater in the study area. There are areas that have lower Cl values but the values are related to the geology and it is unclear to which degree the Cl levels in the groundwater will be affected by activities such as mining or power generation. An interesting observation is that in the vicinity of the Grootegeluk mine the Cl values are very low.

This is according to Dreyer (2009) the result of artificial recharge being generated by the workings at the Grootegeluk mine. It is anticipated the same situation might happen at the new collieries with infrastructure located on the eastern side of the Daarby fault. This will require further investigation as the conditions at the new collieries may differ from those found at the Grootegeluk mine as a result of local geological conditions.

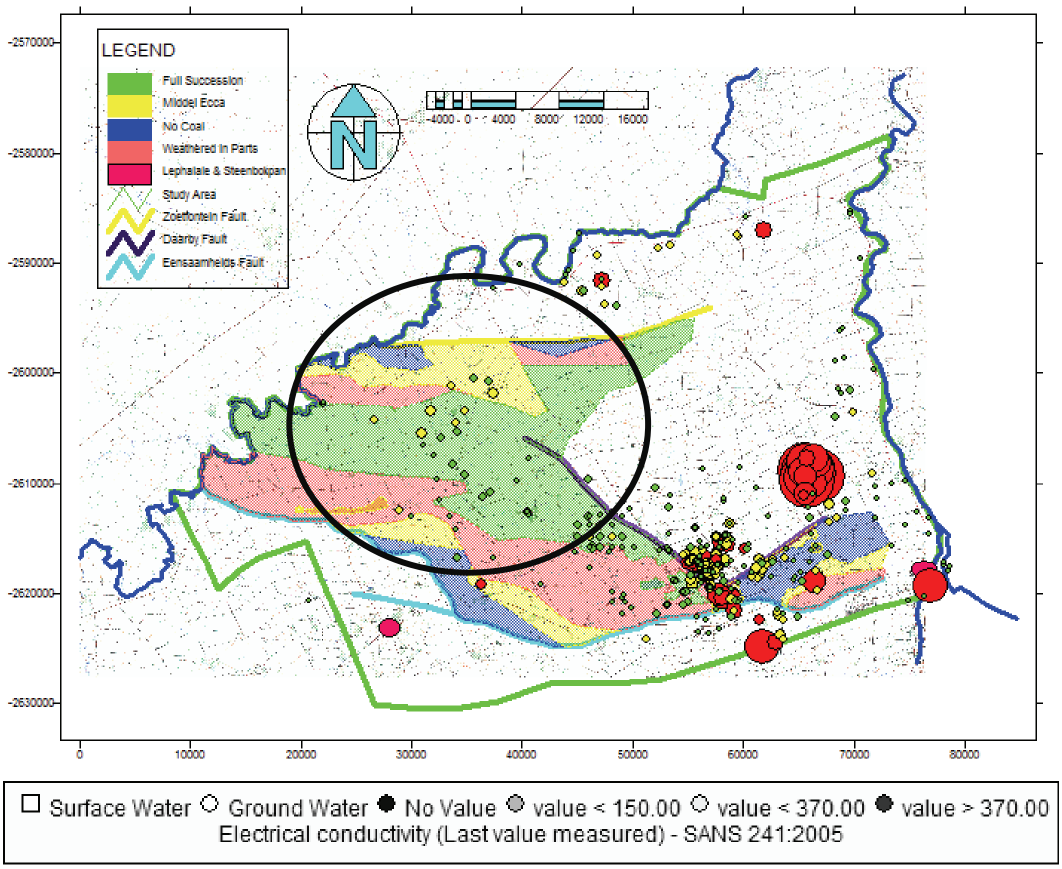


Figure 85: EC map of the study area showing the areas that have not been affected by activities such as mining or power generation (outline in black).

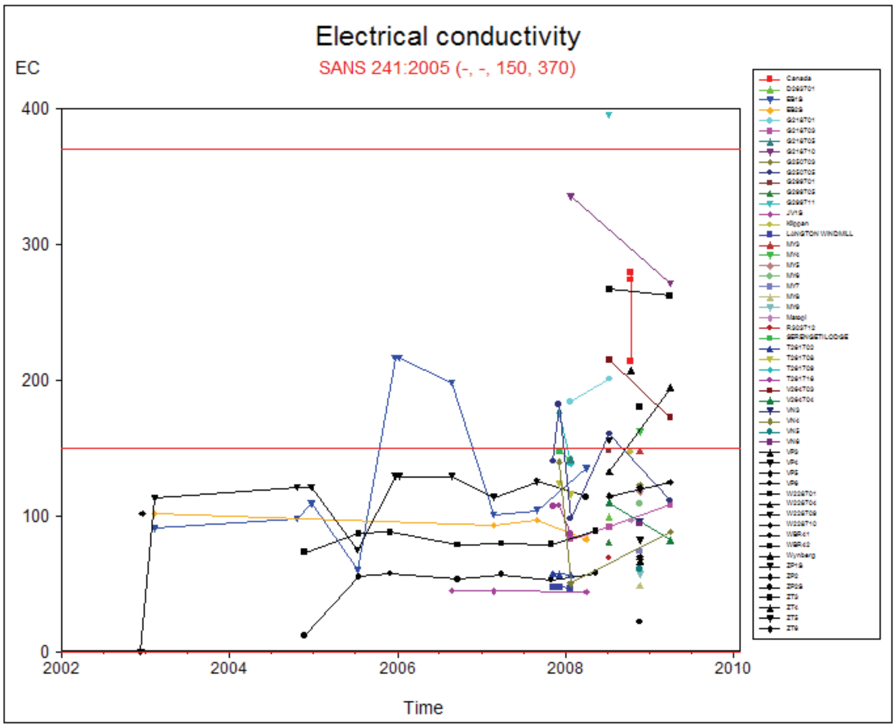


Figure 86: Time graph for EC values in areas that have not been affected by activities.

The same observations made for the EC values in unaffected areas, can be made for the sulphate values in the same areas (Figure 88). The values are generally low with the exception of a few boreholes. The large values such as those found in the vicinity of the Grootegeluk mine are not present with the exception of areas where boreholes have been drilled into the coal seams. It is expected that the sulphate values for the groundwater will increase with the addition of new mines.

The higher sulphate concentrations were probably not the result of direct groundwater pollution, but more likely to have been caused by runoff from the dumps into the groundwater system or into the boreholes where the measurements were taken.

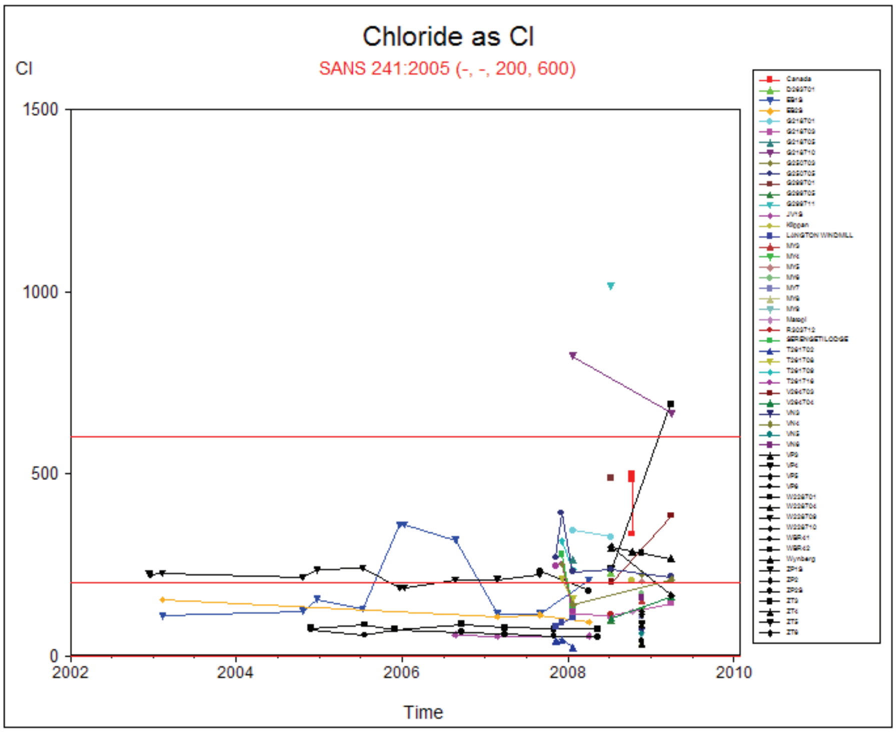


Figure 87: Time graph for Cl values of groundwater unaffected by activities.

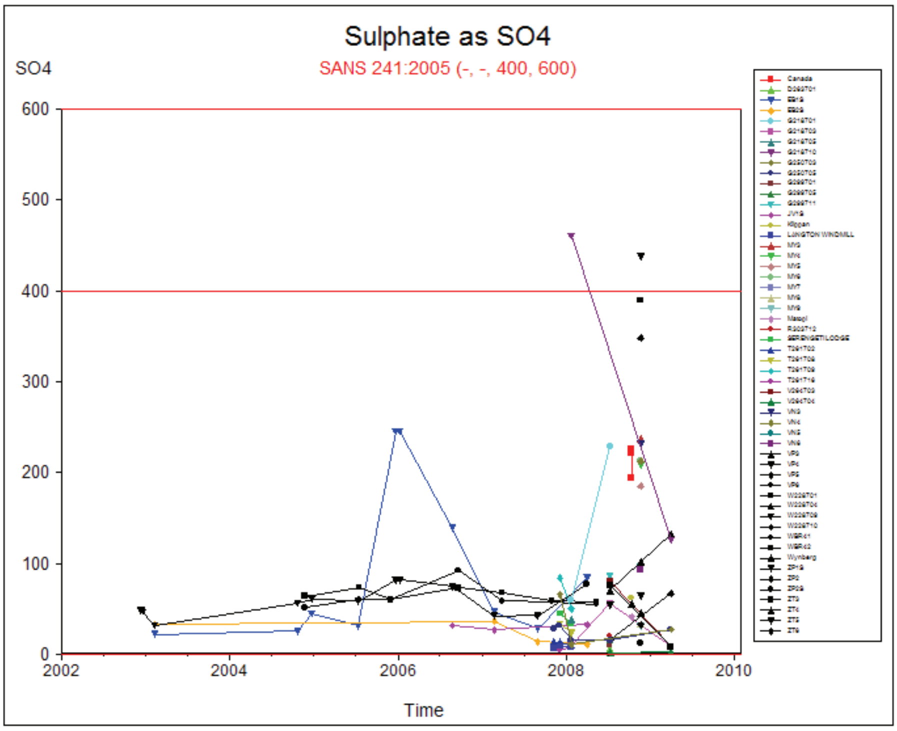


Figure 88: Time graph of SO_4 values for areas that have not been affected by activities.

8.5 Conclusions

In conclusion, it is expected that the addition of new mines and power stations will diminish the quality of the groundwater in the study area. It is expected that the EC values will rise along with the SO_4^{2-} values in the vicinity of the mines. It is expected that the Cl values may fall depending on the activity and the local conditions near the mines (geology, elevation). The water quality of the study area that has been unaffected by activities such as mining and power generation, can be classified as moderate at best. The area as a whole in general has high EC and Cl values with near neutral pH values. At present there exists a fine line between usable groundwater and unusable groundwater in the study area. It is predicted that the addition of the new mine to the area will have an adverse effect on the groundwater in the immediate vicinity of the mines.

8.5.1 Power Generation and its Impact on Groundwater Quality

Possible sources of groundwater pollution at power stations are mainly fly ash disposal, coal stockpiling and dirty water dams. The Matimba power station is well equipped with monitoring boreholes. Such monitoring boreholes will also need to be drilled for future power stations. These boreholes should be monitored frequently (once every 6 months) to monitor potential pollution from occurring or spreading beyond the perimeters of the power stations (Hodgson and Krantz (1995). In this regard, the geology of the study area plays a significant role.

The proposed power stations to the south of Steenbokspan and the Medupi power station currently under construction are located on the much denser Waterberg Group quartzites south and west of the Eenzaamheid fault. These formations have very low transmissivities and effective porosities, making the movement of groundwater in these quartzites very slow.

According to Hodgson and Krantz (1995), the following impacts on the groundwater can be expected from power stations and its supporting bodies (stockpiles and ash dumps):

- The ash water chemistry is unstable in the presence of open air.
- Accordingly it readjusts by a decrease in pH (from >12 to around 8) and the precipitation of calcium carbonate.
- This precipitation of calcium carbonate and the near neutral pH have been cited as parameters that would qualify fly-ash as possible remediation for AMD.
- The heavy metal leachability from ash at neutral pH levels is so low as to be insignificant.
- The base potential of fly ash is usually 2-5 times higher than that of all waste rock material in opencast mines.
- The introduction of fly ash into mining environments can therefore add additional base potential.
- A prerequisite for fly ash disposal within mining environments is that the system as a whole will remain alkaline.
- Under acidic conditions, the heavy metal leachability from fly ash is very high.
- Heavy metal availability occurs at pH levels below 3.0.
- It is concluded that great care should be exercised in instances where fly ash is introduced into coal mines.
- Alkaline systems should be maintained.
- A well-managed dry ash dump does not pose any threat to groundwater pollution.
- Although no pollution is generally found at the modern coal stockyards at some power stations, this does not imply that pollution does not occur.

8.5.2 Coal Mining and its Effect on Groundwater Quality

According to (Hodgson and Krantz (1995), the main problems identified at collieries around South Africa (mainly in the Witbank area) are:

- Heavy metals found in the mines may become available for leaching under certain chemical conditions (low or high pH values depending on the metals involved).
- These metals that pose a potential for leaching may include iron, aluminium, manganese, copper, zinc and, in rare instances, nickel, cobalt and cadmium. Lead, arsenic, selenium, molybdenum and chromium which are normally only present in trace amounts according to (Hodgson and Krantz (1995).
- The rate of sulphate generation in backfilled opencast areas has been calculated at around 5-10 kg/ha/d in the Witbank area (Hodgson and Krantz (1995). These generation rates need to be taken into consideration, as the geology in the Witbank coalfields are similar to that of the Waterberg coalfields (both being located in the Karoo Super Group Rocks).

- On the basis of the present scale of opencast mining in the Witbank Catchment, this amounts to 70 t/d of sulphate. It must be mentioned that the Witbank area has many more rivers and much higher levels of rainfall that contribute to the distribution of the sulphates than the Waterberg study area.
- According to (Hodgson and Krantz (1995) pits that have been mined out in the Witbank coal fields, fill up with water to their decant level within 5-10 years after mining has stopped. According to modelling of possible decant scenarios in the study area, the pits in the Waterberg coal field will not reach decant level.
- When the pits reach decant level, the polluted water flows out onto the surface, contaminating surface water sources.
- Recharge averages 20% of the rainfall, of which 12% is run-off into the mine and 8% infiltration through the spoil (in the pits).
- In the Witbank area, saturation levels for salts have not been reached in any of the opencast mines, due to the significant dilution of the pit water by rainfall. Sulphate levels are typically between 2000-3000 mg/L in backfilled opencast areas.
- This will however not occur in the study area due to the low levels of rainfall. Saturation might take place at a much higher rate and take much longer than in the case of the Witbank coalfields (Hodgson and Krantz (1995).
- According to (Hodgson and Krantz (1995) the mineral most likely to precipitate upon saturation is gypsum.
- Once gypsum precipitation occurs, a cycle of chemical instability is initiated, precipitating most of the calcium, while magnesium and sulphate concentrations could rise in excess of 2 000 mg/l and 10 000 mg/l respectively in these open pits.
- This would be a problem in the study area, as the groundwater already contains high levels of magnesium and calcium.
- This situation can be avoided by dilution from rainwater, which is a problem in the study area, due to low levels of rain (average rainfall between 285 mm and 560 mm per year).
- Mixing cell modelling of open pits in the Witbank area has indicated that the inclusion of coal discards into the unsaturated zone in opencast pits creates local acid conditions that will lead to acidification above and below the water level.
- This method of isolating the discard from the water level is proposed as water quality management measure for the study area as there will be (according to modelling done by the researcher) very little and slow influx of water into the mines.
- The primary inflow of water into the pit will be from surface runoff.
- This together with the results from acid-base-accounting that indicated that the discard will become acidic over time show that there will be substantial acid generated from the discard stored in the unsaturated zone in the Waterberg coal fields.

Potentially alkaline pits will, under these conditions, become acid. It is concluded that coal discard disposal constitutes one of the main problems because of the vast volumes of material.

9 Geohydrology

9.1 Introduction

In order to make accurate determinations as to the characteristics of the aquifers in the study area, several boreholes throughout the study area were tested. The tests were limited to pumping tests and slug tests as these can be accurately interpreted and give good quality results if conducted properly. The southern boundary of the study area is formed by the Eenzaamheid fault. This fault divides the study area into two areas of distinct geology; the Karoo Supergroup geology to the north of the fault, and the Mokolian Supergroup to the south of the fault, being represented in the study area by the Waterberg Group quartzites.

The Eenzaamheid fault acts as a watershed for groundwater flow in the study area, dividing the study area into two distinct groundwater compartments with very little (if any) flow across the fault boundary. It was observed from water chemistry data collected in the study area, specifically the chloride values for the water of boreholes located between the Daarby fault and the Eenzaamheid fault, that the water found in these boreholes have very high chloride values which can be indicative of low recharge and little flow.

This cannot be taken as an indication of no flow across the fault boundary however, as there are many boreholes present in the same vicinity that do not display the same elevated Cl values. It is concluded that the most plausible explanation is the presence of high Cl values of the geology into which the boreholes have been drilled.

From observations in the study area, the faults serve as preferred pathways for the flow of water, having much higher transmissivities than the surrounding rock, with boreholes (in most cases) drilled near the faults showing higher yields than boreholes drilled further away from the faults.

The Eenzaamheid fault and the Daarby fault are impermeable as evident by the difference in water levels displayed by boreholes drilled along the Daarby fault, boreholes on the western side of the fault have deeper water levels than boreholes drilled on the eastern side of the fault. The assumption can therefore be made that the three main faults in the study area (the Eenzaamheid, Daarby and Zoetfontein faults) serve as no flow boundaries, although the faults themselves act as zones of higher transmissivities.

Consequently the study area can be divided into four distinct groundwater compartments (Figure 89) by the faults. The compartments are:

- South of the Eenzaamheid-fault
- The area between the Eenzaamheid-fault, the Daarby-fault and the Zoetfontein-fault
- The area north of the Zoetfontein-fault
- The area to the east of the Daarby-fault

According to Dreyer (2009) all the surface mining planned for the area will be carried out in the area north and west of the Daarby fault, the area delineated by the three major faults found in the study area. Taking the impermeability of the faults into consideration it can be concluded that abstraction taking place in the area confined between the Daarby fault in the east, the Eenzaamheid fault in the south, the Zoetfontein fault in the north and the Limpopo River to the west, will not influence the water levels outside the boundary formed by the faults and the river.

9.2 Aquifers

There are two distinct and superimposed groundwater systems in the geological formations of the coalfields in South Africa. These are the upper weathered aquifer and the system in the fractured rock below.

9.2.1 The Weathered Groundwater System

The top 5-15 m normally consists of soil and weathered rock (Figure 90). The upper aquifer is associated with the weathered horizon. In boreholes, water may often be found at this horizon. These aquifers are recharged by rainfall.

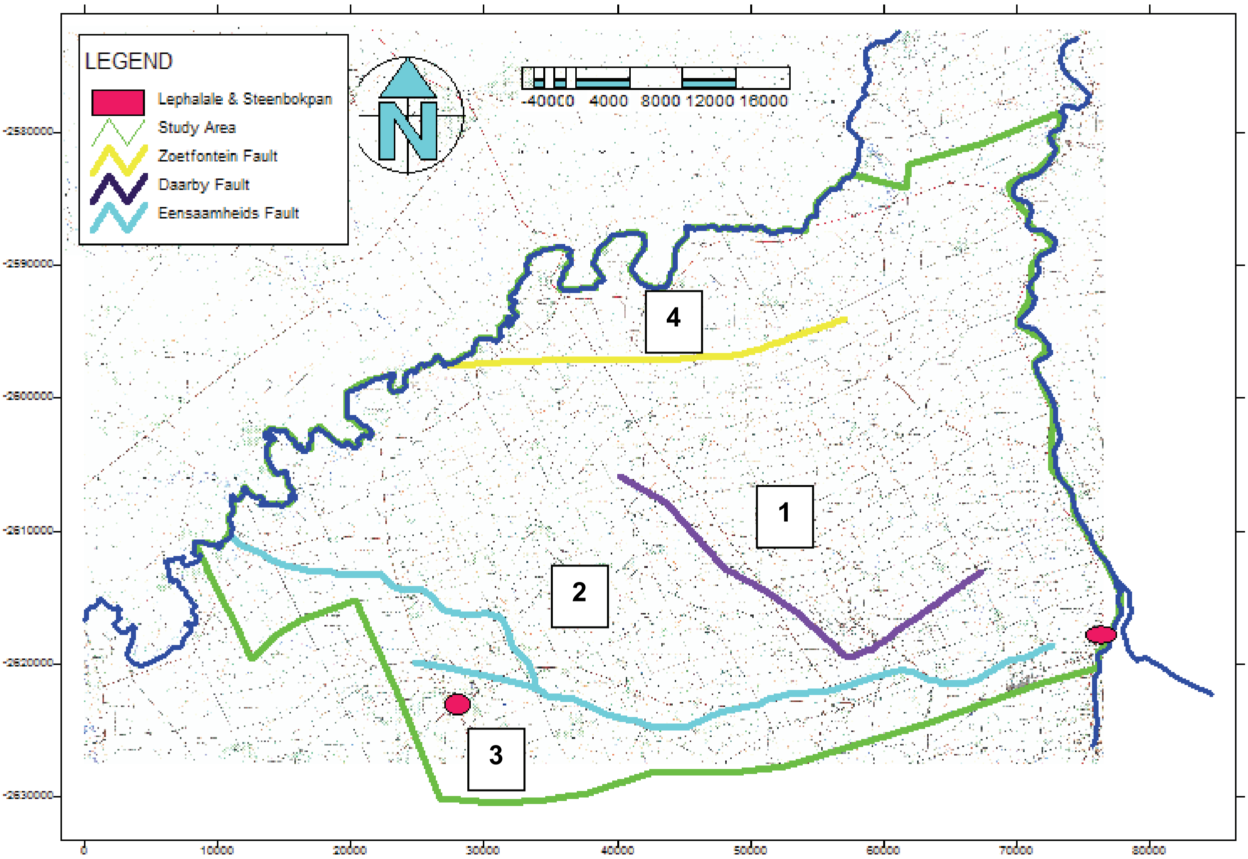


Figure 89: The groundwater compartments numbered 1-4, formed by the faults in the study area.

Figure 90: Rocks from the weathered aquifer zones of the study area.

Rainfall that infiltrates into the weathered rock reaches impermeable layers of solid rock underneath the weathered zone. Movement of groundwater on top of the solid rock is lateral and mirrors the topography. This water reappears on the surface at fountains, where the flow paths are obstructed by barriers such as dolerite dykes, paleo-topographic highs in the bedrock, or where the surface topography cuts into the groundwater level at streams. The Waterberg Coalfields have a more arid climate when compared to other coal fields in South Africa, receiving only between 280 mm and 560 mm of rain annually.

The effect is less significant, although still visible during high rainfall. This effect can most clearly be seen during periods of high rain in boreholes, drilled into the Waterberg Group geology. The rain water infiltrates through the weathered zones until it reaches an impermeable layer. Once the water reaches an impermeable layer, it will continue to flow along the layer to immerge later as a spring where the surface topography cuts into the groundwater level. It has also been observed in the study area that during times of high precipitation the recharge of these shallow aquifers is so high that boreholes that have been drilled into the aquifers are transformed into "artesian" boreholes. The weathered zone is generally low-yielding, because of its insignificant thickness.

The quality of the water is normally excellent and can be attributed to many years of dynamic groundwater flow through the weathered sediments. Leachable salts in this zone have been washed from the system a long time ago. It is recommended that aquifer testing not be done in the study area during the rainy season, as the above mentioned phenomenon can impair the accuracy of the tests.

9.2.2 The Fractured Groundwater System

The grains in the fresh rock below the weathered zone are well cemented and do not allow significant water flow. All groundwater movement therefore occurs along secondary structures such as fractures, cracks, joints or intrusions in the rock (Figure 91). These structures are best developed in sandstone and quartzite, hence the better water-yielding properties of the latter rock types. Dolerite sills and dykes are generally impermeable to water movement, except in the weathered state. In terms of water quality, the fractured aquifer always contains higher salt loads than the upper weathered aquifer. The higher salt concentrations are attributed to longer contact times between the water and rock.

Figure 91: Rocks from the fractured aquifer zone, showing a bedding plane fracture (circled).

9.3 Water Levels

Water level data are available for 1067 boreholes that have been surveyed in the study area (Figure 92). Significant difference in the water levels have been observed in the study area with the extremes ranging from artesian boreholes, to boreholes that have water levels as deep as 154 m below surface (Figure 93). The average water level of the study area however is approximately 28 m below the surface.

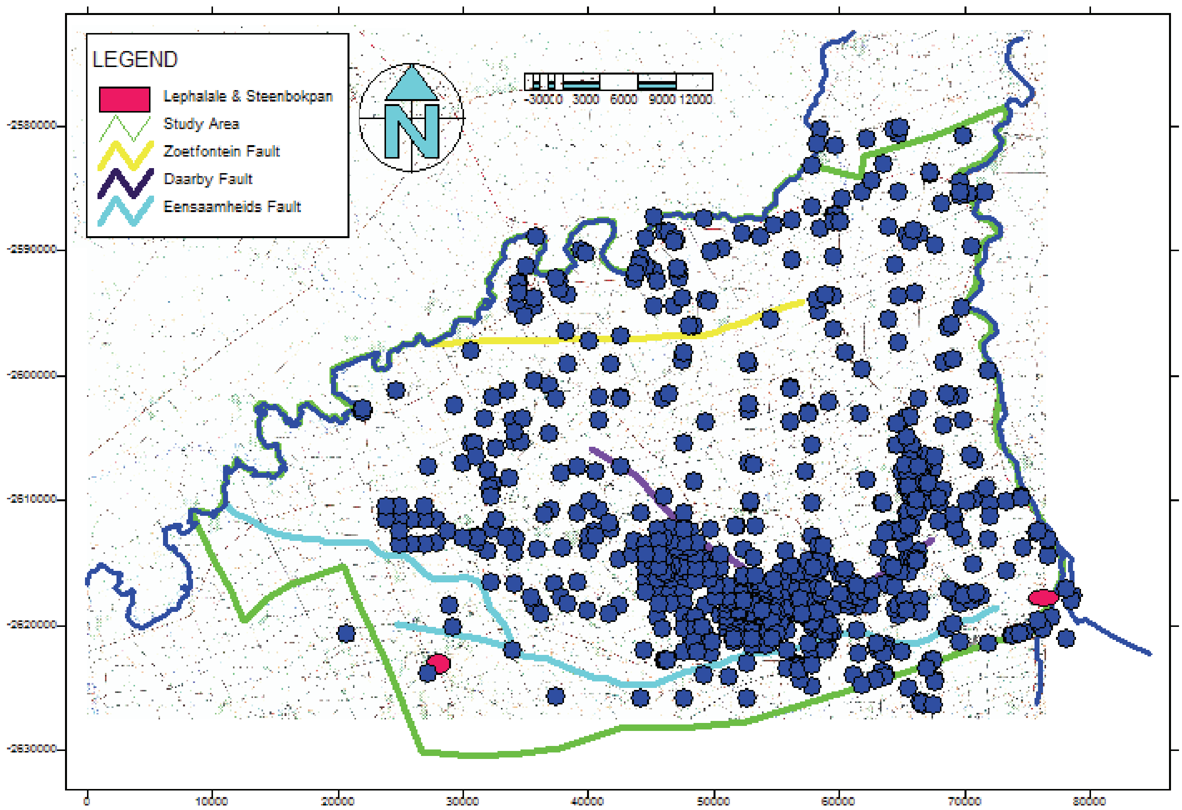


Figure 92: Boreholes in the study area for which water level data is available.

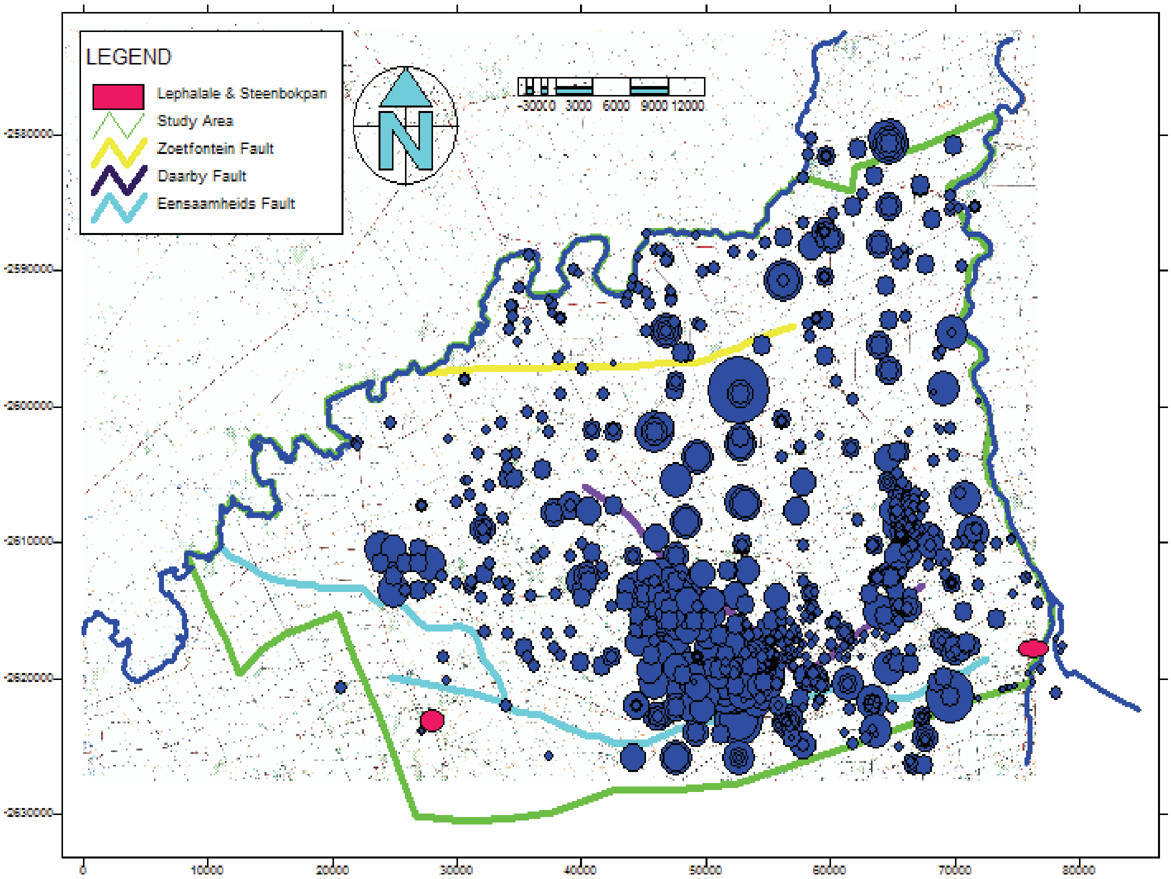


Figure 93: Map showing boreholes with proportional distribution of water level data.

The major contributors to increased water level depth are three fold:

- Firstly, the areas located near the centre of the study area have an elevated topography which leads to an increase in water level depth.
- Large scale abstraction taking place from boreholes in certain areas of the study area. The water abstracted from these boreholes is used for the watering of livestock, game and in some cases for domestic use.
- Due to the mine dewatering taking place at the Grootegeluk Mine, currently the only operational colliery in the study area.

In order to achieve a higher level of accuracy with regards to the groundwater levels and to determine if the water levels truly mirror the topography, the water level data was interpolated by means of Bayesian interpolation methods. These values along with the originally gathered data was contoured and potted together with contour maps of the surface topography. From these maps the level of correlation could be better determined and deviation from the expected norms for Karoo type aquifers could be better observed. The results are as follows.

9.3.1 Water Level Contouring

A contour map of the water level depth was constructed from the data that had been gathered (Figure 94). Figure 94 shows the contour map of the water level distribution found in the study area. The map displays water levels in meters below the surface. From Figure 94 one can observe that there are areas with deeper water levels and areas with shallower water levels.

The central areas show deeper water levels than the surrounding areas and the elevated nature of the central area are the likely cause of this. Additionally Figure 94 indicated that the average water levels for the study area are between 20 m and 40 m below the surface (numerically determined to be 28 m).

To this contour map, a map of the surface topography was added the results of which are displayed in Figure 95. Figure 95 indicates that the water levels do mirror the topography and the elevated regions of the study area near the centre, along with the increased water levels can also be seen. It is interesting to note that the elevation near the centre of the study area has a north/south trend and the water levels reflect this trend.

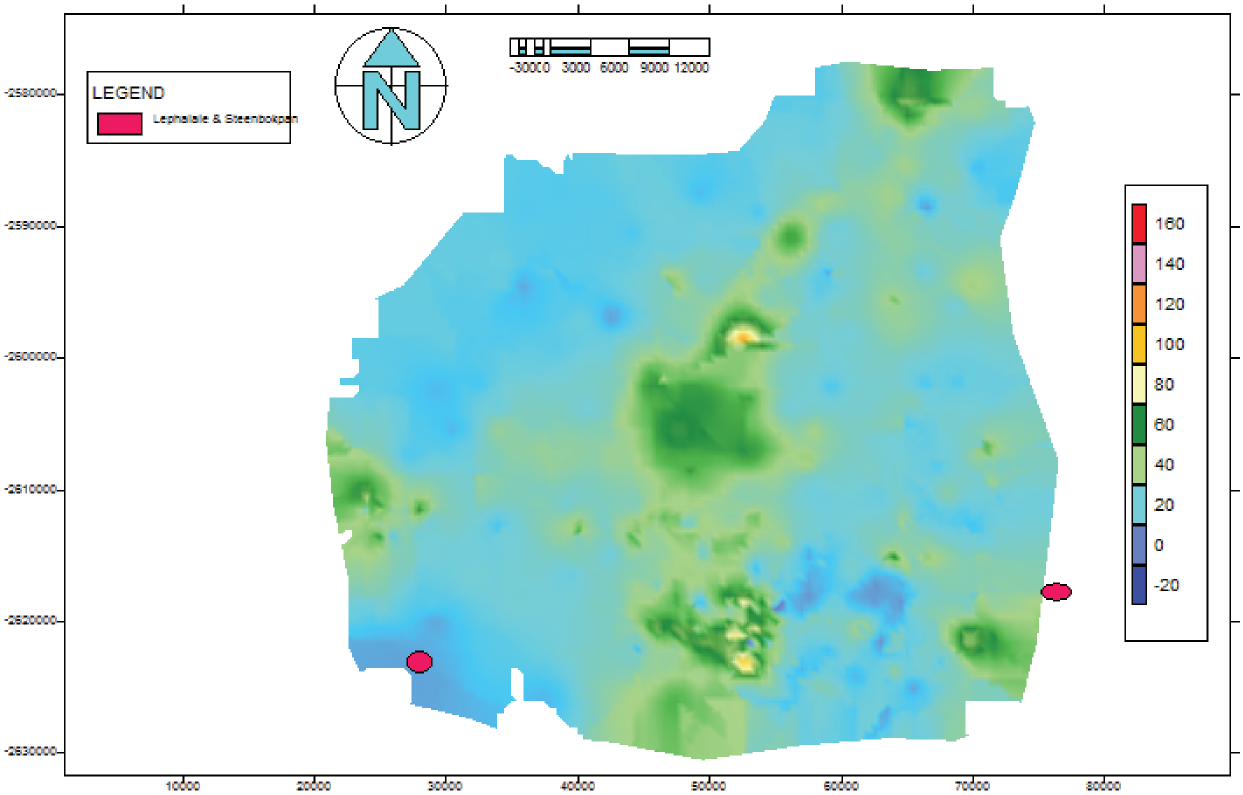


Figure 94: Contour map of the depth of water levels found in the study area (mbgl)

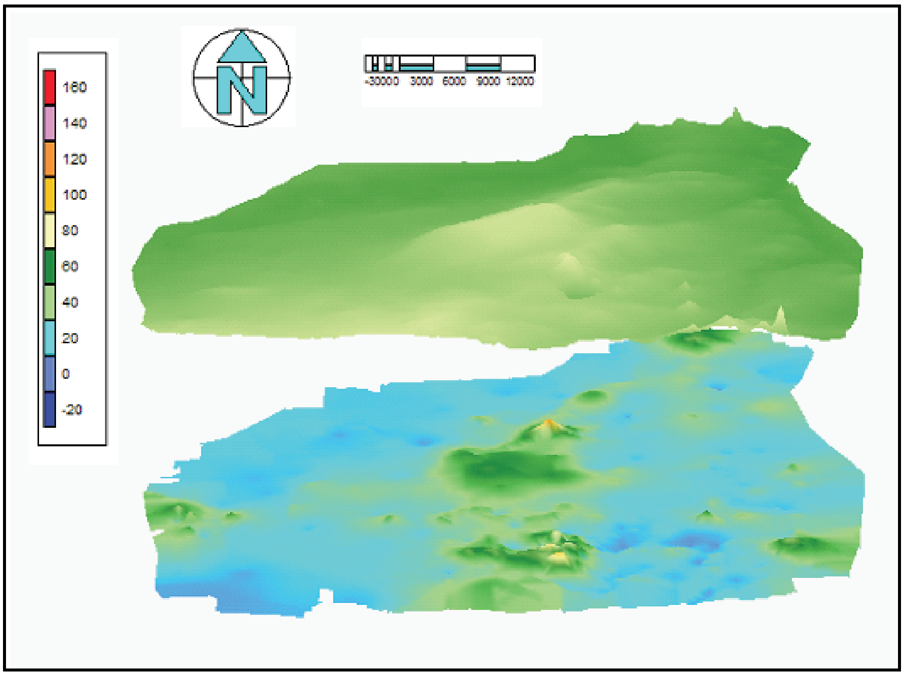


Figure 95: Topography and water level contour maps on top of each other.

9.3.2 Water Level Elevation Contouring

Once it had been established that the water levels follow the topography contour maps of the water level elevations for the study area were constructed (Figure 96).

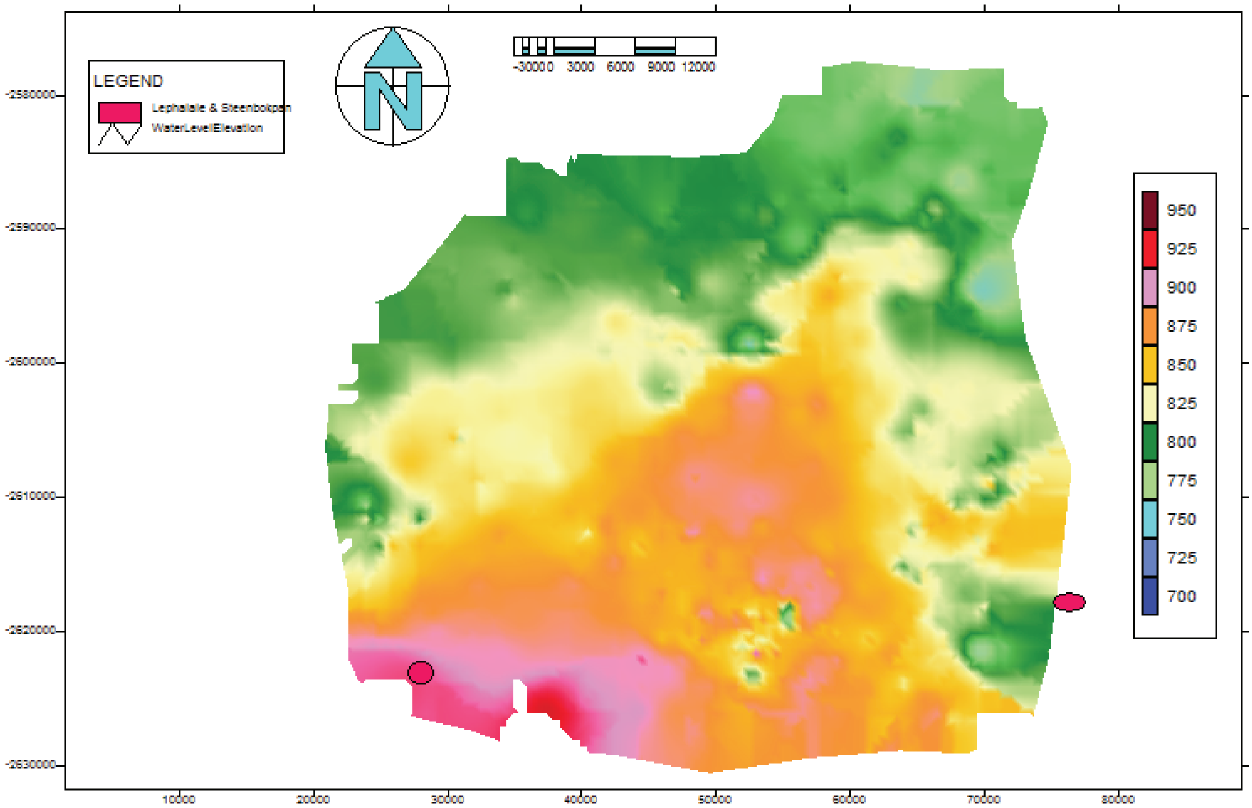


Figure 96: Water level elevation contour map for the study area (mamsl).

Figure 96 displays much the same characteristics as Figure 94, with the centrally elevated areas displaying deeper water levels as the lower areas of the study area. Again when Figure 96 is added to a contour map of the topography one observes that the water levels mirror the topography, the same as in Figure 95.

9.3.3 Bayesian Interpolated Water Level Contouring

The final set of water level data that was contoured, was that which had been interpolated by means of Bayesian interpolation. This was done to achieve more accurate water level data for the study area. The results were plotted as a contour map and displayed in Figure 98. The correlation between the groundwater level data used during the Bayesian interpolation and the topography is displayed in Figure 97.

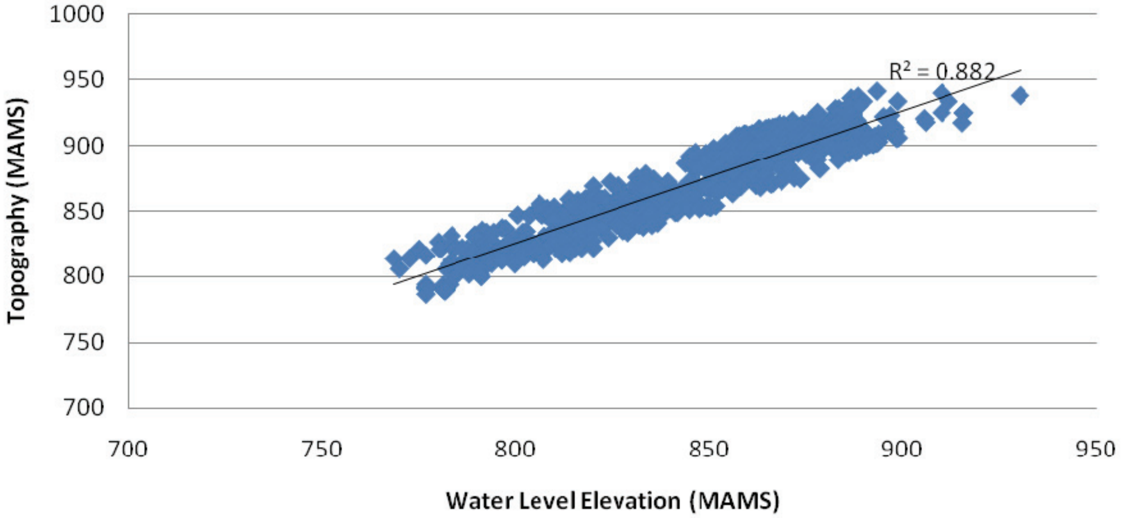


Figure 97: Correlation between Topography and water level data used for Bayesian interpolation.

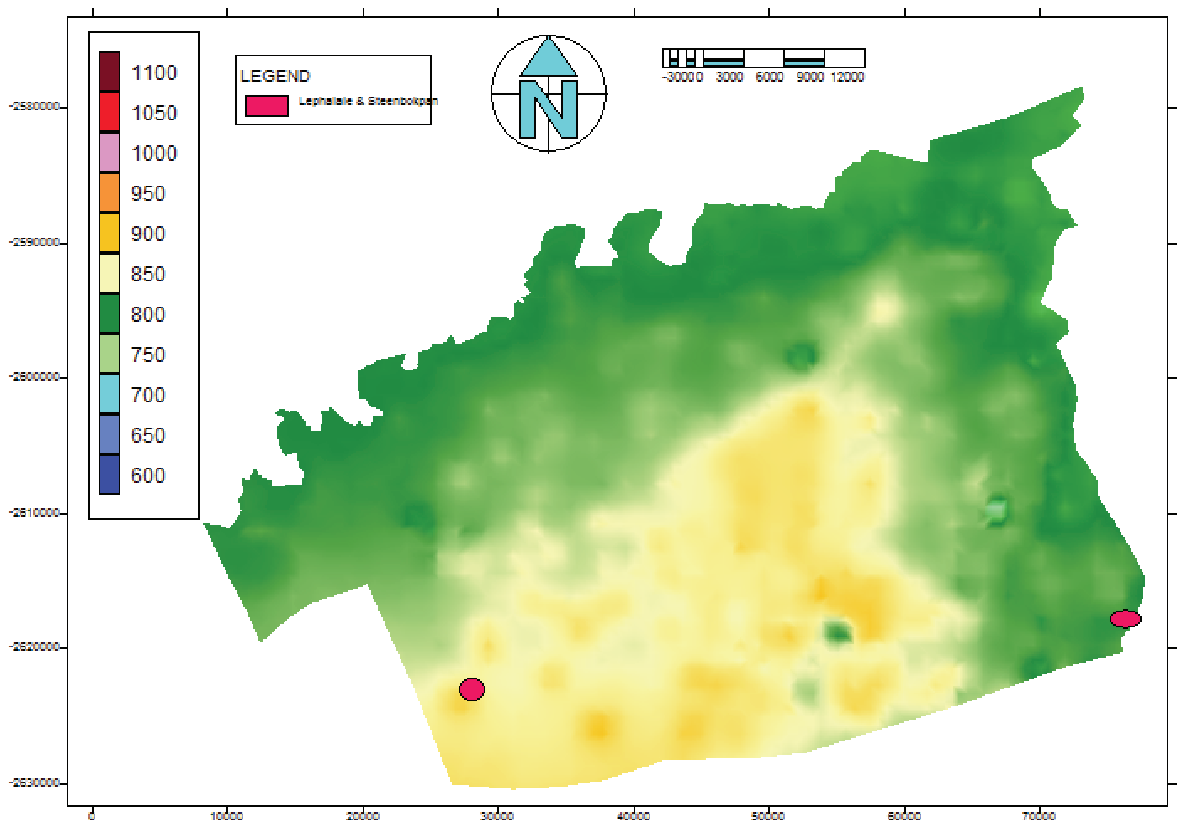


Figure 98: Bayesian interpolated water levels for the study area.

From the contour maps of the topography, the groundwater levels, the groundwater elevations and the Bayesian interpolated water levels of the study area, it is clear that the water levels in the area follow the topography. Furthermore all three different water level contour maps show the same trends namely, that there is an elevated ridge of water levels (and topography) near the central part of the study area that runs roughly north/east south/west.

Using the water level elevation data and Bayesian data, flow vectors were added to the contour maps to determine the predominant flow directions for ground water in the study area (Figure 99). According to these flow vectors the central areas of the study area are the driving force for groundwater flow in the area. From the data shown in Figure 94 to Figure 99, there can be no doubt that the groundwater flow in the study area follows the topography and would therefore flow away from the central part of the study area towards the low laying areas near the boundaries of the study area, namely the two rivers.

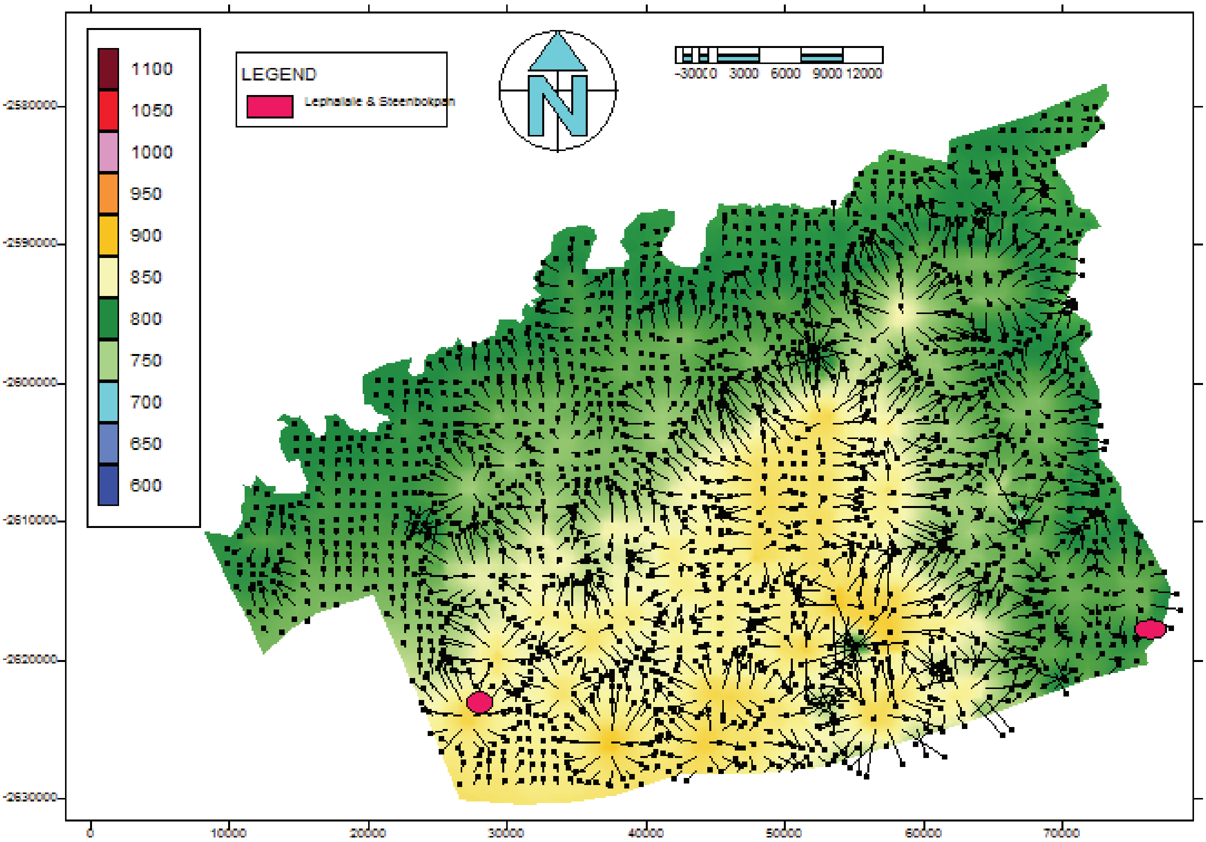


Figure 99: Bayesian interpolated water level contour map with flow vectors, indicting flow away from the central parts of the study area.

According to the flow vectors in Figure 99 the predominant flow directions of groundwater in the study area will be towards the east, the west and to the north, away from the central elevated regions with little if any flow towards the south. From observations made at the Grootegeluk Mine with regards to the influence the mine and the dewatering of the mine has on the surrounding aquifers, it is expected that the addition of new open pits to the area (specifically in the central areas) will change the flow direction of groundwater (Figure 100) (discussed in more detail in Chapter 10). The changes that the open pits will create to the topography (the excavation of big holes in the ground) will have an impact on the direction of flow of the groundwater. For example, if all the mines that are planned for the area were to be located near the centre of the study area, the excavation of the pits will lower the topography to such an extent that the flow direction of the groundwater will be influenced.

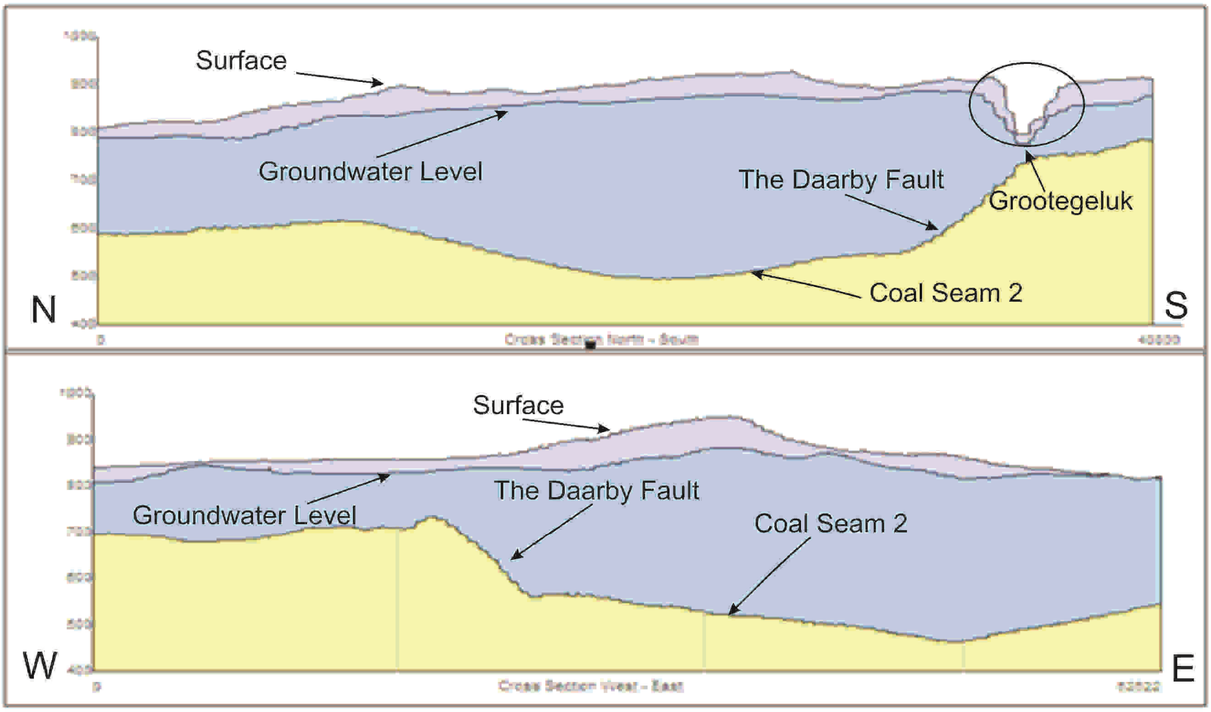


Figure 100: Sections through the study area, with the top section running through the Grootegeluk mine.

It is suspected that given the data displayed in Figure 100 the lower topography that will artificially be created by the excavations of the mines will reverse the flow of groundwater. To put it differently, the groundwater will not be flowing away from the central areas, but towards them, more specifically towards the mines. The degree to which this will impact the rest of the study area is unknown and will be determined by factors such as the depth, size and locations of the open pits. This will be discussed in more detail in Chapter 10.

9.4 Aquifer Parameters

In order to obtain aquifer parameters for the study area, several slug tests and pumping test were conducted and analysed to determine and identify any trend or divergence from the expected norms for Karoo type aquifers. These parameters were additionally needed to serve as input parameters for the numerical modelling of the groundwater flow in the study area that were used to predict dewatering cones and decant times.

9.4.1 Slug Testing

As slug testing can only give an indication of the parameters of a certain aquifer, only four such tests results will be discussed. The four boreholes that were slug tested are located on the farms Vlakfontein, Tambotievley and Groenfontein (Figure 101).

These farms are located in the north/western part of the study area. Three of these boreholes were subsequently pump tested as well. The slug test results indicated that the transmissivity of the boreholes vary greatly, keeping in mind that slug test data are inconclusive for the transmissivity of the whole area. These tests were conducted during a period of very high precipitation and it is expected that the results are only indicative of the transmissivities of the weathered aquifer zone. Accordingly the results may differ if the same boreholes are tested during the dry season. Table 15 provides a summary of results of the slug tests for the four boreholes.

As can be seen from the table the transmissivities and yields of the boreholes vary greatly. However, the trend can be observed that the boreholes with high yields have high transmissivities. Following is a brief discussion of the findings of each individually slug tested borehole.

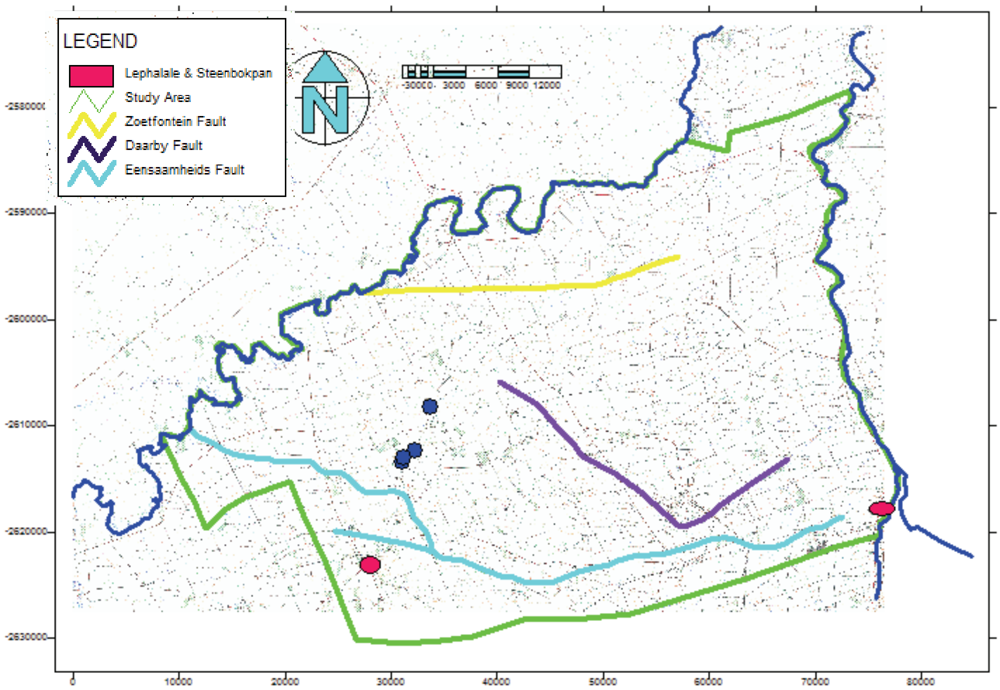


Figure 101: Location of the slug tested boreholes.

Table 15: Summary of slug test results for the study area.

Borehole name	Yield (l/s)	Transmissivity (m^2/d)	Transmissivity (m^2/d) of Formation – Average
Slpmt1	26.22	131.08	65.54
Slpmt2	2.09	10.45	5.22
Slpmt3	1.97	9.87	4.93
Slpmt4	4.88	24.4	12.2

9.4.1.1 Borehole Slpmt 1

The borehole Slpmt 1 was slug tested and recovered to its initial water level in 1.3 seconds, accordingly the estimated yield for the borehole was calculated to be 26.22 l/s. A transmissivity of 131.08 m^2/d was calculated for the formation in the vicinity of the borehole. A transmissivity of 65.5 m^2/d was calculated for the formation in the vicinity of the borehole on average (Table).

Table 16: Slug test results for Slpmt1.

SLUG TEST - YIELD ESTIMATE

Note: All the estimates are qualified guesses and could be wrong

BH Name =	**BH1 (Sasolpmt1)**
Recession time (s) for 70% recovery	1.3
Yield of BH (L/s) =	**26.22**
T (m^2/d) of formation in vicinity of BH =	**131.08**
T (m^2/d) of formation - Average =	**65.54**

RECOMMENDATION

Conduct a Pumptest on BH

First estimate of sustainable yield (L/s)

5.24

K-value of fracture (m/d) =	**50243.70**
T-value of fracture (m^2/d) =	**10048.74**

9.4.1.2 Borehole Slpmt 2

The slug test for the borehole displayed a yield of 2.09 l/s with a transmissivity of 10.45 m^2/d for the formation in the vicinity of the borehole, and a transmissivity of 5.22 m^2/d for the formation in the vicinity of the borehole on average (Appendix B). The borehole recovered to its initial level after 2.09 seconds.

9.4.1.3 Borehole Slpmt 3

From the slug test of Slpmt3, the yield of the borehole was 1.97 l/s with a transmissivity of 9.87 m^2/d for the formation in the vicinity of the borehole and a transmissivity of 4.93 m^2/d for the formation in the vicinity of the borehole on average (Appendix B). The borehole recovered to its initial water level of 1.97 s. This borehole is spatially located the furthest away from the other boreholes that were slug tested. The borehole also has a low yield and a correspondingly low transmissivity.

9.4.1.4 Borehole Slpmt 4

From the slug test of Slpmt4, the yield of the borehole was 4.88 l/s with a transmissivity of 24.40 m^2/d for the formation in the vicinity of the borehole and a transmissivity of 12.20 m^2/d for the formation in the vicinity of the borehole on average (Appendix B).

The borehole recovered to its initial water level of 4.88 seconds. Borehole Slpmt 4 is specially located between boreholes Slpmt 1 and Slpmt 2. The borehole has a higher yield and transmissivity than borehole Slpmt2 but nowhere near the values observed for borehole Sasolpmt1. It is likely that this borehole is located on, or near the same fracture system as Slpmt1 even though a distance of approximately 100 m separates the two boreholes.

From the slug tests, the transmissivity in the formations vary greatly, although two of the transmissivity values do fall within the same range. There is no clear indication of the transmissivity from the slug test results, taking into account that a slug test is at best only a guess of the parameter values.

9.4.2 Pumping Tests

A total of 51 boreholes located throughout the study area have been pump tested and analysed (Figure 102) in order to obtain parameters for the aquifers of the study area. As it is impractical to discuss all of the analysed boreholes, the methods used will be shown by means of using the data and analyses of the three boreholes Slpmt1, 2, 3 and 4. A summary of the results of the analyses for the boreholes is given in Table 17. Three of the four boreholes that were slug tested were subsequently pump tested and the results of these tests were analysed by means of the FC software program that has been developed at the Institute for Groundwater Studies at the University of the Free State.

9.4.2.1 Borehole 1 (Slpmt1)

The borehole is located on the farm Vlakfontein. The depth of the borehole is 45 m and the static water level was at 21.07 m below surface after the pump had been lowered into the borehole. During the slug test, the water level recovered almost instantly, indicating a yield of approximately 20 l/s. A pumping rate of 2 l/s was chosen due to constraints on pump size. The borehole was pump tested for three hours and then left to recover. The water level recovered to within 90% of its original level within 15 minutes. The pumping test data was analysed with the FC software programme developed by the Institute for Groundwater Studies. The results indicate a yield of 6.35 l/s and the recovery tests indicated a high transmissivity of 600 m^2/d (Table).

When analysing a logarithmic plot of the analysed pumping test data, the graph displays three areas where the data levels off (underlined in red). These areas indicate possible fractures. Accordingly, Figure 103 indicates three fractures located below the water level located approximately 27 cm, 32 cm and 35 cm below the water level respectively (fracture zone). These fracture zones contain large quantities of water as is evident from the low level of drawdown that was achieved during the test. The fracture zone is located very close to the water level surface and will be in danger of running dry during either a drought, or from over abstraction. It is unknown if there are more fractures present further down the borehole, as very little drawdown was achieved during the test.

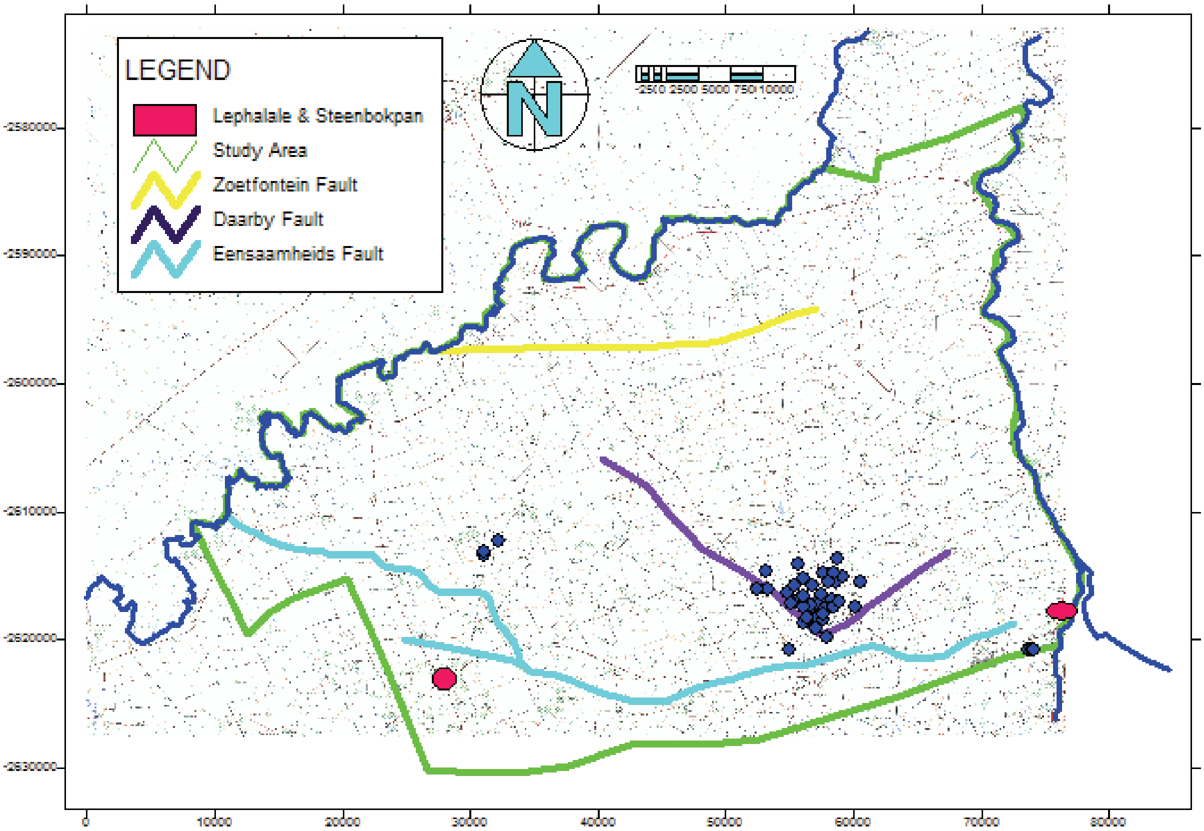


Figure 102: Location of the pump tested boreholes.

Table 17: Summary of pumping test results for the boreholes in the study area.

Site name	T (D)m^2/d	Yield (l/d)	Site name	T (D)m^2/d	Yield (l/d)	Site name	T (D)m^2/d	Yield (l/d)
OBS2	4.4	5 000	WB56	6.5	72 576	WBR15	19.64	7 200
WB19B	15.5	11 356	WB57	20.6	70 848	WBR16	8.95	2 880
WB24	0.35	3 785	WB59	60.2	209 088	WBR17	507.85	12 000
WB27	124.06	44 400	WB61	46.8	192 672	WBR18	1.53	1 200
WB33	26.64	168 000	WB62	12.6	157 248	WBR19	0.31	960
WB35	8.78	160 000	WBR1	93.52	10 800	WBR20	0.93	2 400
WB36	35	62 068	WBR2	10.02	7 200	WBR21	0.36	1 200
WB45	3.7	92 448	WBR3	10.62	8 400	WBR22	1.19	2 040
WB46	201.5	107 136	WBR4	9.16	4 200	WBR24	0.5	4 320
WB47	1.33	864 000	WBR5	5.53	3 600	WBR25	11.3	201 312
WB48	2.4	61 344	WBR6	30.07	7 200	WBR28	0.18	19 047
WB49	82.2	152 064	WBR7	1.12	960	Sasolpmt1	600	22 860
WB50	38.1	76 032	WBR8	0.57	1 200	Sasolpmt2	3	684
WB51	54.3	104 544	WBR9	5.45	1 000	Sasolpmt3	15	2 592
WB53	108	162 432	WBR10	1.3	4 800	H21-0637	206.3	47 844
WB54	224	220 320	WBR13	0.19	1 200	H21-0638	14302	56 412
WB55	30.7	240 192	WBR14	10.75	36 000	H21-0663	141.5	72 720

Table 18: Sustainable yield for Slpmt1.

Method	Sustainable yield (l/s)	Late T (m^2/d)
Basic FC	5.10	632.4
Cooper-Jacob	7.59	497.5
Barker	0.54	
Average Q_sust (l/s)	6.35	

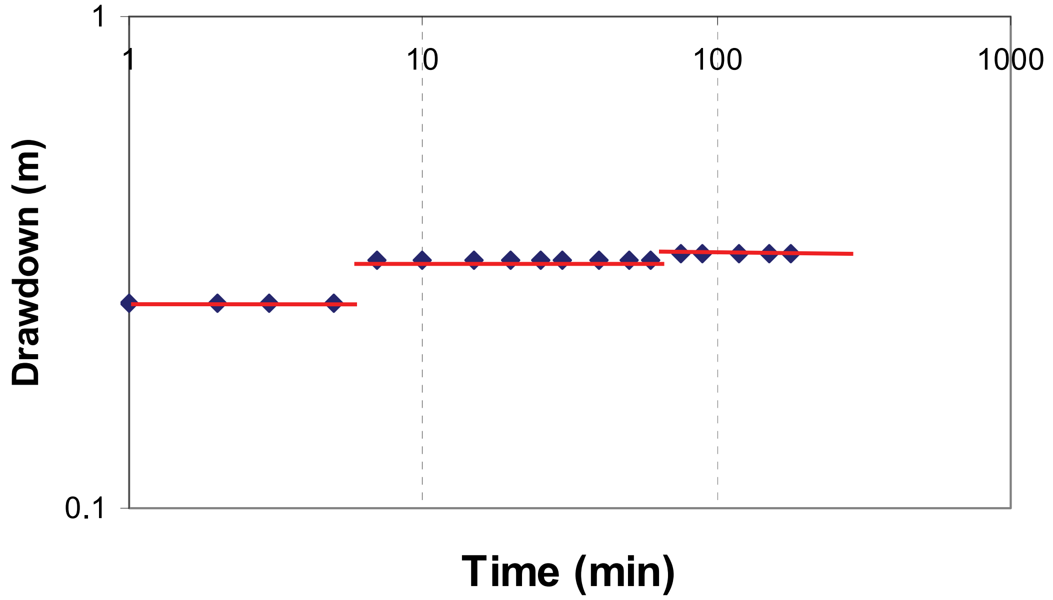


Figure 103: Log vs. Log plot of the analysed pump test data.

To obtain the recommended sustainable yield by means of the Cooper-Jacob method for yield estimation, the drawdown data obtained from the pumping test of the borehole was entered into the FC software programme. The data was fitted accordingly. The fitted graph is displayed in Figure 104 and the results of the analyses are displayed in Table 9.

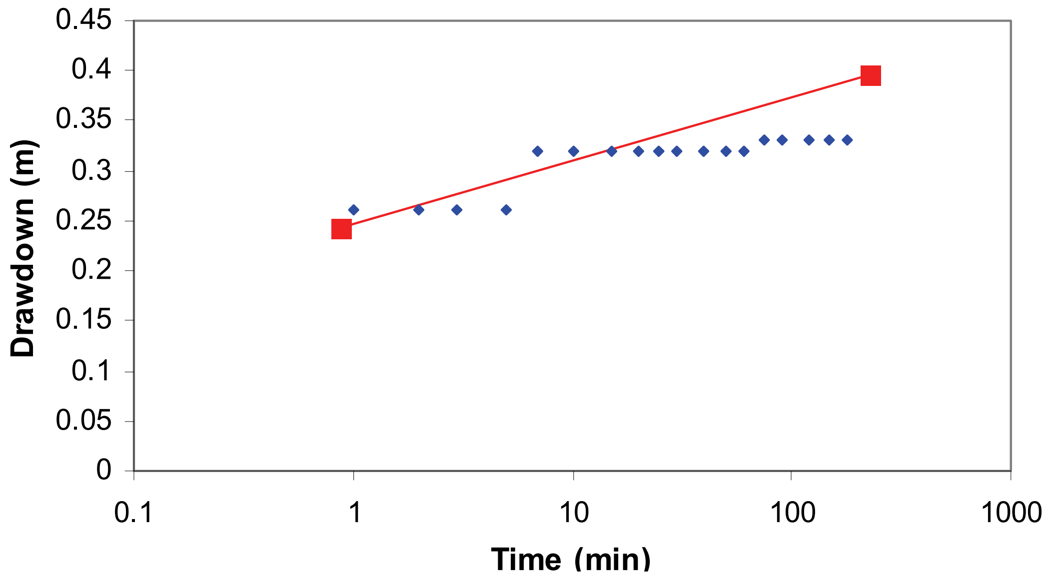


Figure 104: A Cooper-Jacob graph of the drawdown at Borehole 1 (Slpmt1).

The water level and the cluster of fractures, is located at a depth between 21 m and 22 m below the surface. From the pumping test it could not be determined if this area forms part of the weathered zone, in which case the yield obtained is not a true reflection of a safe yield for the borehole and it is recommended that the borehole be retested during the dry season.

Table 19: Pumping test result summary for Slpmt1.

Recommended abstraction rate (L/s)		7.00	for 24 hours per day		
Hours per day of pumping	8	12.13	L/s for	8	H/d
Amount of water allowed to be abstracted per month		18144	m^3		
Borehole could satisfy the basic human need of		24192	persons		

Due to the precipitation during the summer months, more water will assemble in the weathered zone than during the dry season. If this is the case, the borehole yield may drop, or even run dry during winter months. However, if the water level is below the weathered zone, the yield obtained will be a true reflection of the yield of the borehole. The pump used for this test did not have the capacity to stress the borehole to its limits, to determine the additional fractures, or to determine the location of the weathered zone. No boundaries could be identified. The findings for this borehole are inconclusive, but do give an indication of conditions of the aquifers found in the study area. The test further indicates that there are boreholes present in the study area that have very large yields and high transmissivities.

9.4.2.2 Borehole 2 (Slpmt2)

This borehole is located near the entrance of the farm Tambotievley. The depth of this borehole could not be determined. The borehole had a static water level of 26.39 m. The borehole was slug tested indicated a yield of 2.5 l/s. The pumping test was performed at a pumping rate of 1.5 l/s after the slug yield had been determined at 2.5 l/s, with the pumping test lasting 90 minutes. Once the pumping had stopped the borehole was recovered for 60 minutes. The results of the test indicated a yield of 0.19 l/s, (Table 20) with the recovery tests indicating a transmissivity of 3 m^2/d.

Table 20: Sustainable yield for Slpmt2.

Method	Sustainable yield (l/s)	Late T (m^2/d)
Basic FC	0.19	2.2
Cooper-Jacob	0.17	2.2
Barker		
Average Q_sust (l/s)	0.18	

The test results indicate a low yielding borehole with a low transmissivity. The log vs. log graph of this borehole, indicate two areas of possible fractures, the first is located 8 m below the water level (a small fracture) and the second 16 m below the water level (Figure 105). The borehole could however not be stressed enough to dewater the second fracture due to pump limitations. There may be additional fractures deeper down the borehole, which could not be determined.

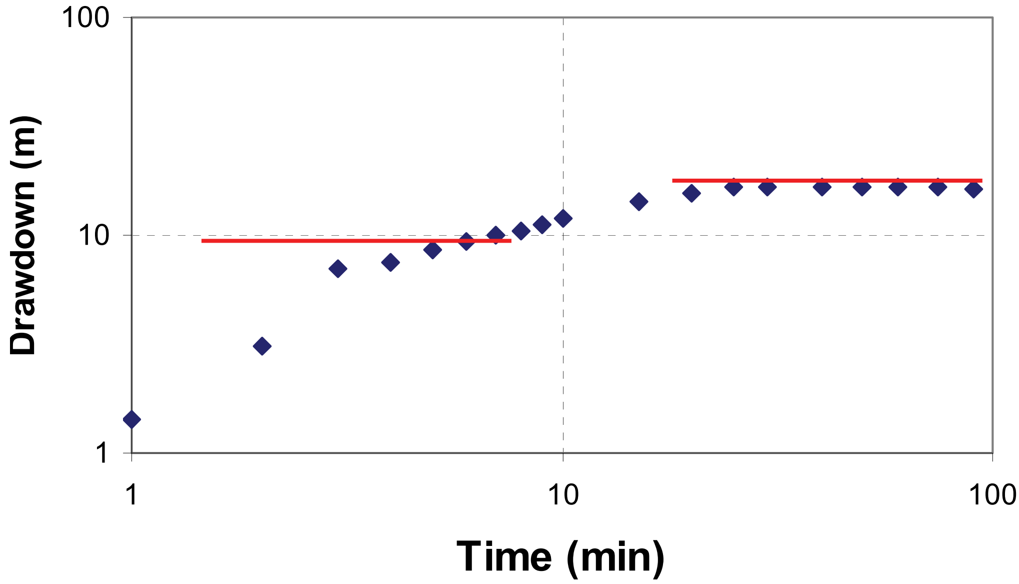


Figure 105: Log vs. log plot of borehole Slpmt 2.

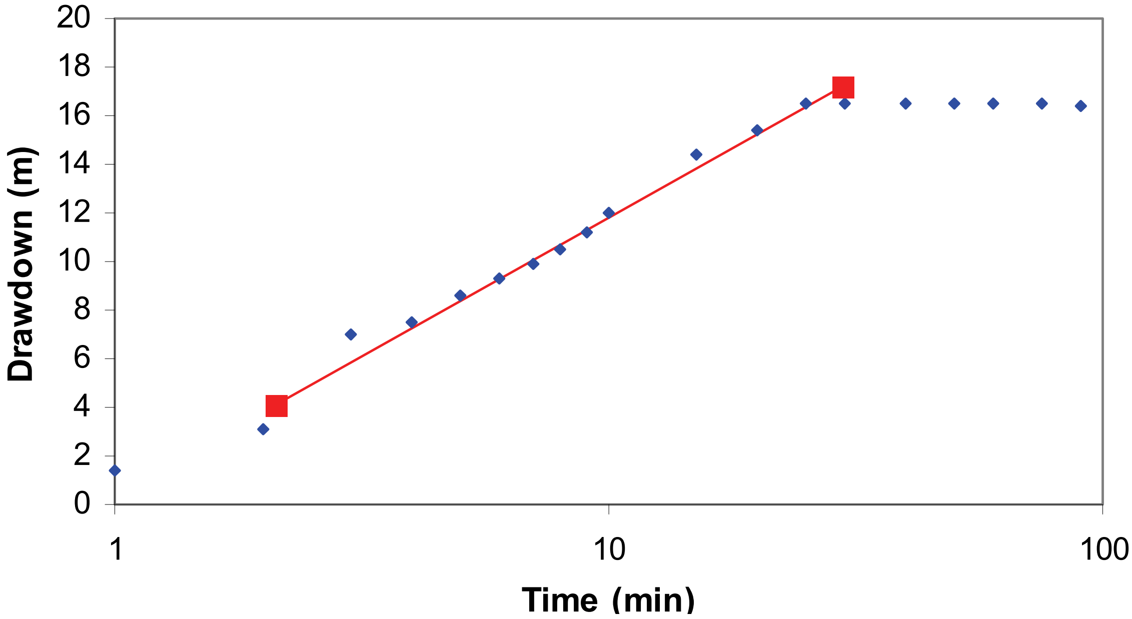


Figure 106: A Cooper-Jacob graph of the drawdown for Borehole 2 (Slpmt2).

The results from the testing indicated a low yielding borehole and that the initial slug test yields were incorrect. Once again due to the shallow water depth there is uncertainty to the depth of the weathered zone for this borehole. It is likely that the initial high yields observed from the slug test was the result of the water level being in the weathered zone and not the result of high yielding fractures.

Two fractures were observed in the borehole, but the latter of these could not be stressed to the extent that an accurate yield could be calculated for the borehole. It is recommended that the borehole be tested during the dry season and that the results be compared to the results obtained during this study in order to determine a more accurate yield for the borehole. No boundaries could be identified during the course of the test.

Table 21: Pumping test result summary for borehole Slpmt2.

Recommended abstraction rate (L/s)		0.50	for 24 hours per day		
Hours per day of pumping	8	0.87	L/s for	8	hours per day
Amount of water allowed to be abstracted per month		1296	m^3		
Borehole could satisfy the basic human need of		1728	persons		

9.4.2.3 Borehole 3 (Slpmt4)

This borehole is located on the farm Vlakfontein. The static water level for this borehole was located at 19.57 m, with a depth of approximately 40 m. The slug test indicated a yield of 4.5 l/s. From the slug test a pumping rate of 2 l/s was determined and the pumping test lasted for 3 hours after which the borehole was allowed to recover for 3 minutes, Thereafter the water level recovered to 90% of its original level. A summary of the test indicates a yield of 0.72 l/s, with the recovery tests indicating a transmissivity of 15 m^2/d (Table).

Table 22: Sustainable yield for Slpmt4.

Method	Sustainable yield (l/s)	Late T (m^2/d)
Basic FC	0.74	22
Cooper-Jacob	0.7	25
Barker		
Average Q_sust (l/s)	0.72	

The yield and transmissivity of this borehole is considerably higher than that of borehole 2 (Slpmt 2) and might be an indication that the borehole is located near the same fracture network as borehole 1 (Slpmt 1). However, once again the borehole could not be stressed to a large enough degree due to pump constrictions.

The log vs. log graph for this particular borehole indicates two potential fractures which could also potentially be interpreted as one large fracture. In all likelihood these are not two different fractures but a zone of fractures located 2 m below the water level.

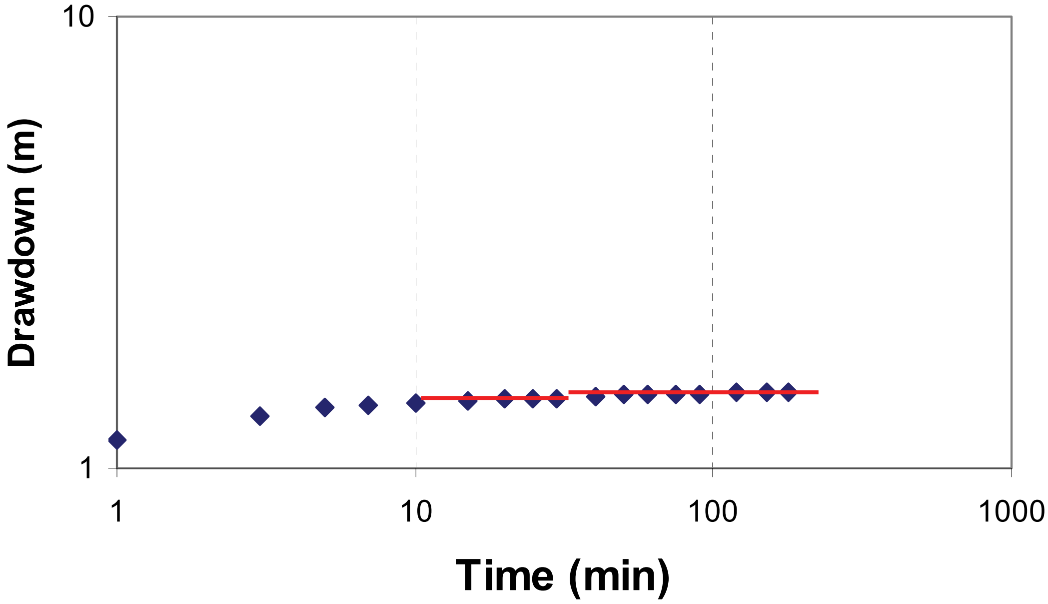


Figure 107: A Log-Log graph of the drawdown observed at Slpmt3, the red line indicating a possible fracture.

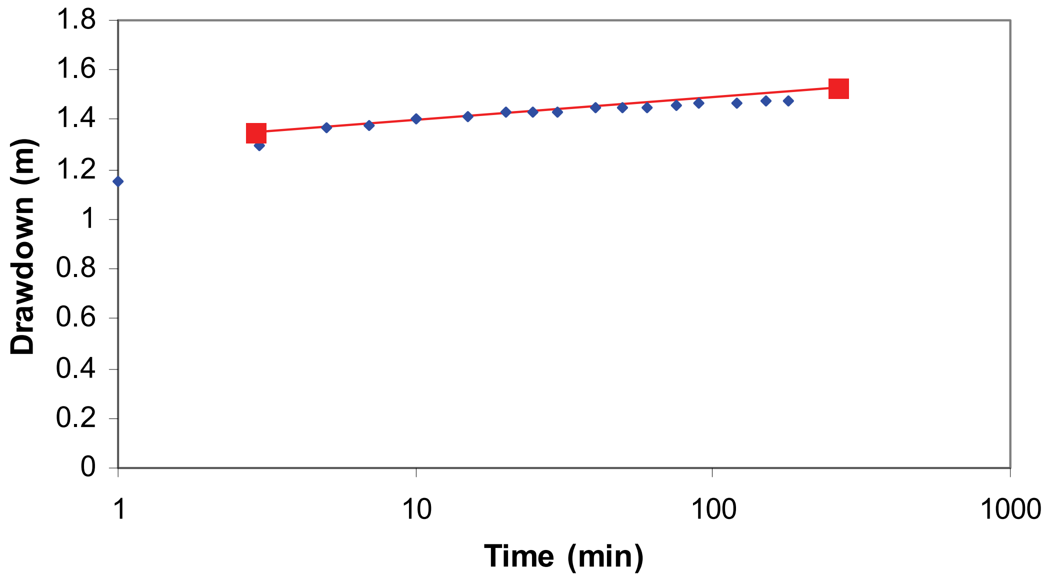


Figure 108: A Cooper-Jacob graph of the drawdown at Slpmt3.

The results for borehole Slpmt 4 were inconclusive (Table 23). From observations in the field it was determined that the water level of the borehole is well within the suspected weathered zone for the study area (top 30 m). This fact combined with the high precipitation that took place during the time of testing has likely influenced the outcome of the tests. The high yield of the borehole, combined with the inadequate strength of the pump, resulted in insufficient draw down for the borehole to make any accurate conclusions about the yield or the location of potential boundaries.

Table 23: Pumping test result summary for Slpmt4.

Recommended abstraction rate (L/s)		1.00	for 24 hours per day			
Hours per day of pumping	8	1.73	L/s for	8	hours per day	
Amount of water allowed to be abstracted per month		2592	m^3			
Borehole could satisfy the basic human need of		3456	persons			

9.4.3 Discussion of Aquifer Parameter Testing Results

According to the slug and pumping tests of the western parts of the study area, there are vast differences in the transmissivities of the area and yields of the boreholes. It must however be kept in mind that these test results could have been influenced by the high quantities of rainfall during the time of testing. A total of 51 boreholes have been pump tested in the study area from 1987 to the present.

A greater quantity of boreholes has been tested around the Grootegeluk Mine than in any other location in the study area. Some tests have been conducted to the west (Slpmt1-4) and some to the east (H21-0637, H21-0638 and H21-0663). Those to the east were drilled by the Department for Water Affairs and Forestry and are located in the Waterberg Group. The north-eastern parts of the study area have not been tested, as this area will not be mined (Dreyer 2009).

The pumping test results indicated that the transmissivities and yields of the boreholes in the study area vary greatly, with transmissivities as low as 0.31 m^2/d to as high as 600 m^2/d. The harmonic mean for the transmissivity values for all the tested boreholes was calculated to be 0.4m^2/d. This low transmissivity is a result of the geology of the study area (mostly alternating layers of shale and mudstone interspersed with sandstone and coal) and the fact that these geological formations are very dense, allowed for very little flow through them.

From the findings it is predicted that regardless of the location of the mines in the study area, with the exception of a mine being located on a fault, there will be very little influx of water into the mines. The low trends in transmissivity result in the slow movement of water and will result in the slow influx of groundwater to the mines (30 000 l per month at the Grootegeluk Mine), with the exception of the mines located in the areas that have much higher transmissivities such as fault zones. Additionally the data indicates that there are only a few areas displaying large transmissivities most commonly found in the vicinity of faults. Accordingly it is expected, that in at least some of the cases, where mines are located near faults, they stand to have a much greater influx of groundwater into their workings.

For example, the boreholes drilled in the vicinity of the Grootegeluk Mine that had the highest yields and transmissivities are drilled either on, or in close proximity to the Daarby and Eenzaamheid faults. Some of the other boreholes that have large yields and high transmissivities are the ones that have been drilled into the Waterberg Group of Rocks. As indicated, these boreholes have much higher yields and transmissivities than other boreholes found in the study area. It must be noted that even these boreholes are located near faults. The data for the three boreholes drilled in the Waterberg Group showed higher transmissivity than the boreholes drilled into Karoo rocks in the rest of the study area (Table). This happens regardless of the fact that the Waterberg Group rocks are much denser than the Karoo rocks and should accordingly have lower transmissivities. These higher transmissivities are likely due to a larger degree of fracturing in the Waterberg Group compared to the Karoo rocks.

These fractures provide flow conduits for groundwater moving through the formations at much faster velocities than the water in the Karoo formations. It could however also be caused by higher levels of piezometric pressure in the Waterberg rocks than in the Karoo rocks.

From these results together with the deep water levels, the low rainfall and the high evapotranspiration, it is predicted that the pits in the study area will display similar characteristics as the Big Hole in Kimberly (Figure 109). Meaning, that the pits in the study area may have water flowing into them, but they will never decant.

Figure 109: The Big Hole located in the city of Kimberley in the Northern Cape province of South Africa.

9.5 Recharge

In order to determine the impacts of the current activities, and to predict he potential impacts of the planned new activities in the study area, it was necessary to determine the recharge of the aquifers in the study area. In order to calculate the recharge for the study area, two methods for determining recharge were used. The first to be used was the chloride mass balance method. This method was used due to the availability of data and the effectiveness of this type of recharge calculation. The second method used was the E.A.R.T.H. model. Once again, the availability of data and the reliability of the calculations were the deciding factor in selecting this method.

9.5.1 Chloride in the Study Area

Before a discussion of the recharge itself, the Cl values in the study area will firstly be briefly discussed.

The data for the recharge determinations was gathered from various sources; these included data received from the Grootegeluk Mine, other companies currently operating in the study area and from groundwater samples taken from the study area which were analysed at the IGS laboratory. The distribution of the samples is displayed in Figure 110.

Due to the lack of access of some parts, samples covering the entire study area could unfortunately not be obtained. A total of 222 samples were analysed for their chloride content, the results of which are given in Appendix C. From the analysed values, the data suggests that there is a large range for the Cl values found in the study area. With the lowest value being as low as 6 mg/L and the highest value going as high as 2573 mg/l (Figure 111).

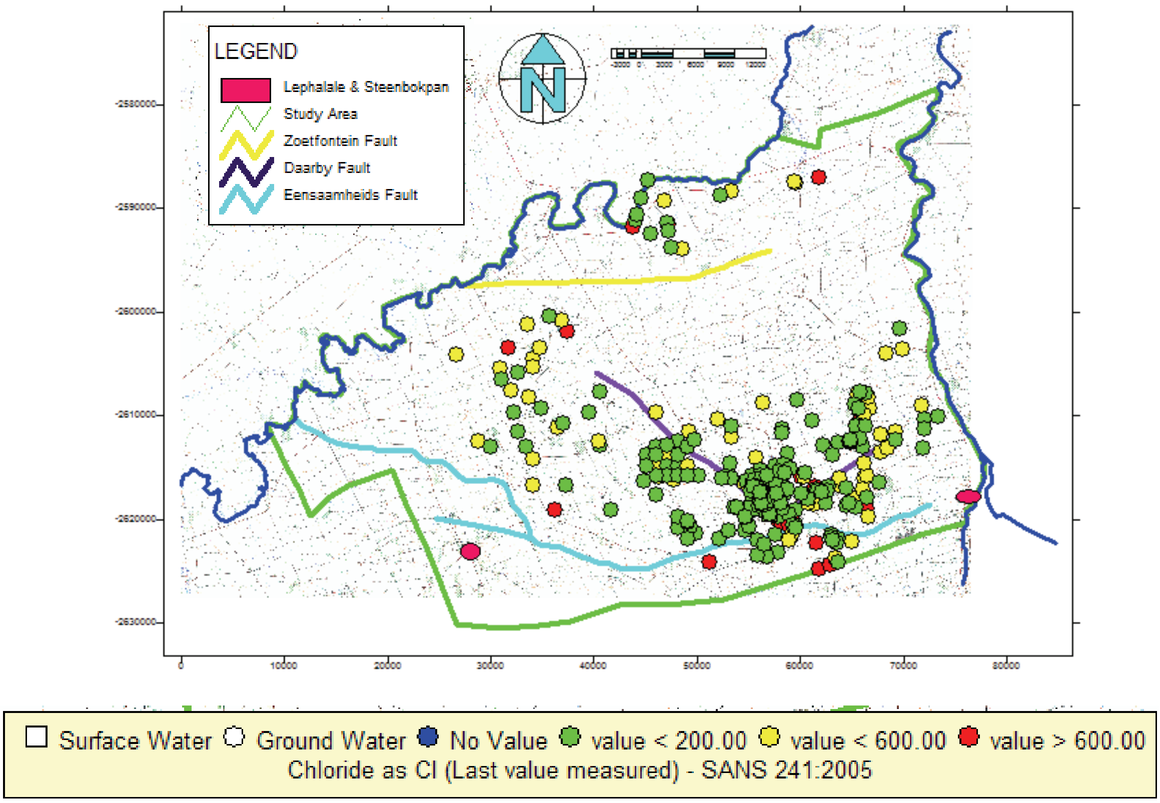


Figure 110: Distribution of the samples boreholes in the study area.

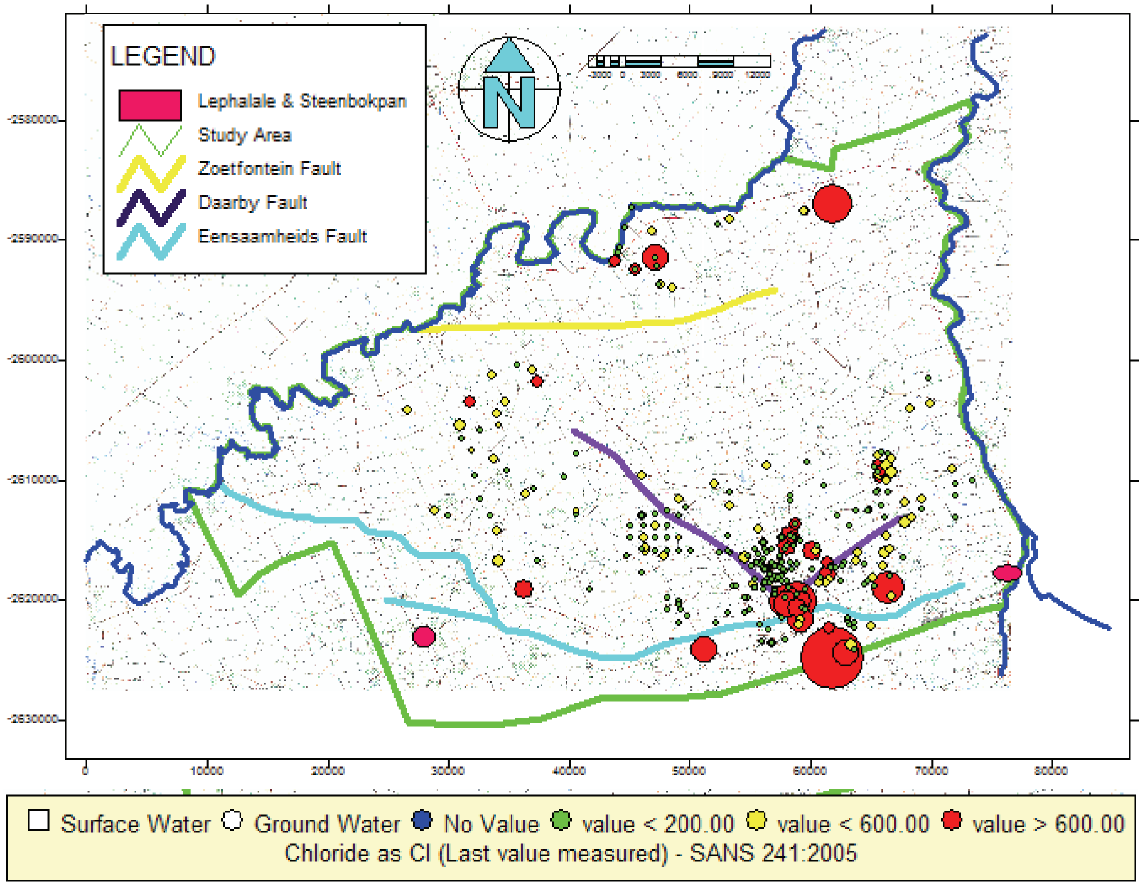


Figure 111: Value distribution for the measured Cl in the study area.

The causes for these variations are unknown.

Some of the theories that account for the high Cl values are:

- The high Cl values found are related to geology (the rocks have salt contents).
- Due to large levels of abstraction the Cl in the water has become concentrated resulting in these high values.
- The high values are possibly related to power station activities.
- The waters are naturally saline with the boreholes being of great depth (Usher *et al.,* 2005).

In an effort to better gauge the overall Cl levels for the study area a contour map of the Cl values for the study area was constructed (Figure 112).

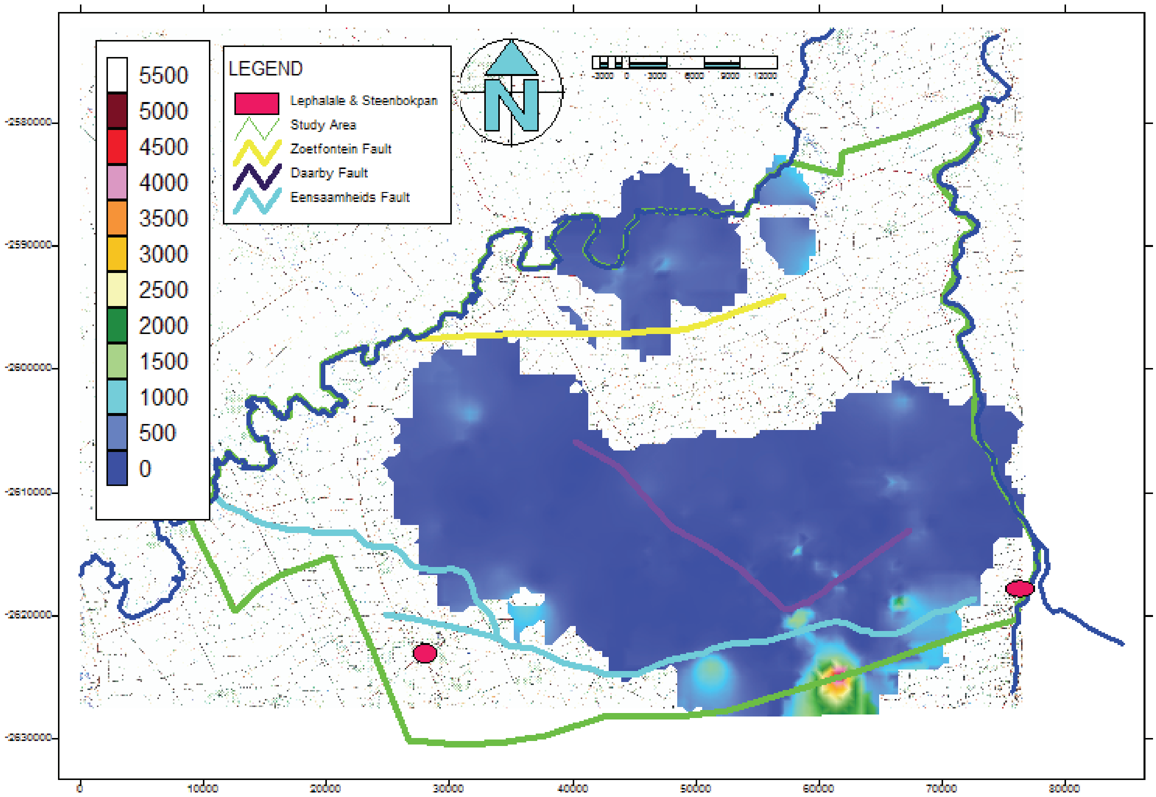


Figure 112: Contour map for Cl values in the study area.

Figure 112 shows that with the exception of the extreme values, the Cl levels in the study area are generally high. This has been observed in the field by the salty taste of the water samples from the boreholes. When the data was analysed it indicted six boreholes that have been drilled between the Eenzaamheid fault and the Daarby fault with high Cl values (Figure 113 and Figure 114).This was initially suspected as being indicative of no flow taking place between these two faults as it was indicated by Dreyer (2009) that the faults are impermeable.

This hypothesis was however discarded upon closer inspection of the data, which indicated that there were boreholes in the vicinity of the boreholes with the high Cl values that displayed low Cl values. It is suspected that the six boreholes located between the faults displaying the elevated EC values, are located in geology that is responsible for the elevated EC values.

There is an extension of the Daarby fault the runs along the same area the boreholes displaying the elevated EC are located in. It is possible the inorganic pollutants may have moved along this extension and contaminated the boreholes. Dreyer (2009) additionally indicated that this extension connects the Daarby and Eenzaamheid faults in this vicinity. It is therefore plausible that the elevated Cl values are the result of groundwater flowing from the contact zone between the Karoo and Waterberg group rocks.

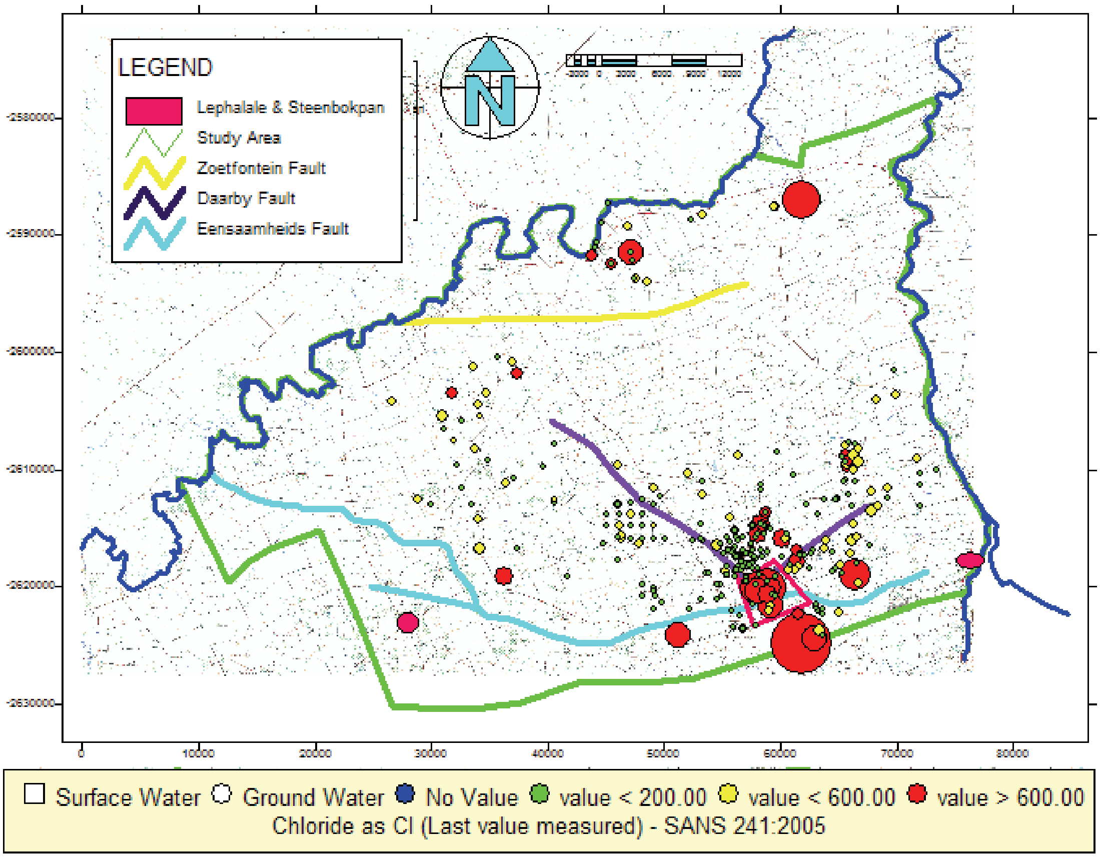


Figure 113: Boreholes located between the faults.

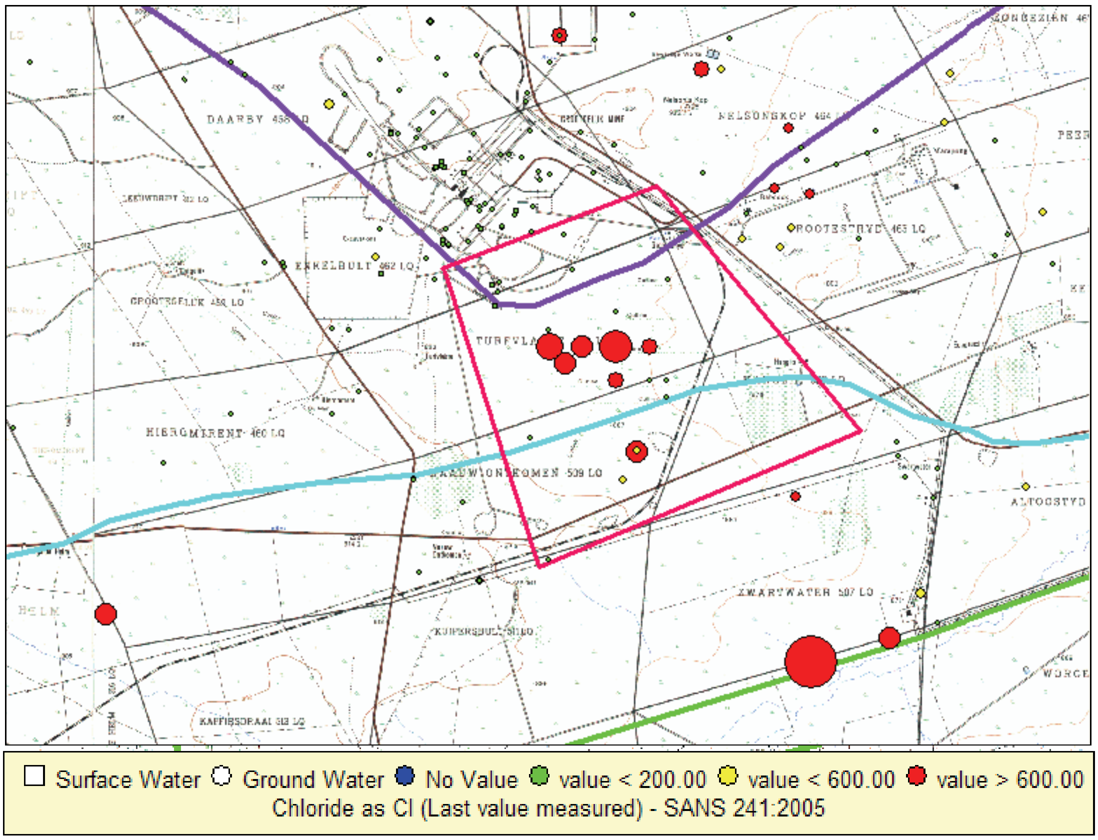


Figure 114: Close-up look at the boreholes located between the faults.

9.6 Recharge Determinations

9.6.1 The Chloride Mass Balance Method for Determining Recharge

As previously mentioned information on 222 boreholes was collected for information that could be used for recharge determination with the Cl method. From the analysed values the data suggests that there is a large range for the Cl values found in the study area, with the lowest value being as low as 6 mg/l and the highest value going as high as 2573 mg/l. For the recharge determinations of the study area the harmonic mean was calculated and used. This came to a value 62.76 mg/l Cl. From the calculations using this harmonic mean values a total recharge of 1.59% for the study area was calculated. The great degree of variation in the Cl values lead to a great variation for the recharge calculations, if the recharge was calculated for the individual boreholes. The results ranged from recharge as high as 18% (6 mg/L Cl), to as low as 0.4% (2573 mg/l Cl) depending on the location of the boreholes and the Cl content of their waters.

The results obtained from the recharge calculations for each individual borehole was plotted against the boreholes (Figure 115) and the same was done for the Cl values (Figure 116). This was to obtain a better comprehension of the distribution of the recharge percentages and the Cl values. These two graphs were then combined to produce Figure 117, which indicated that an inverse correlation between the recharge and the Cl values exists (as one would expect). The data therefore indicates a good correlation between the present recharge and the Cl values (Figure 117).

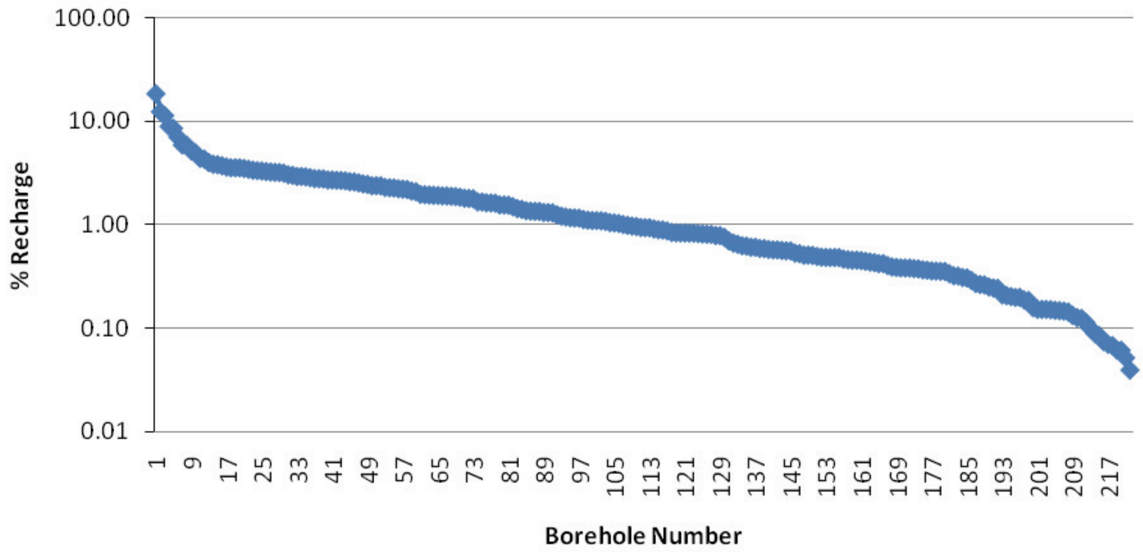


Figure 115: % Recharge for individual boreholes.

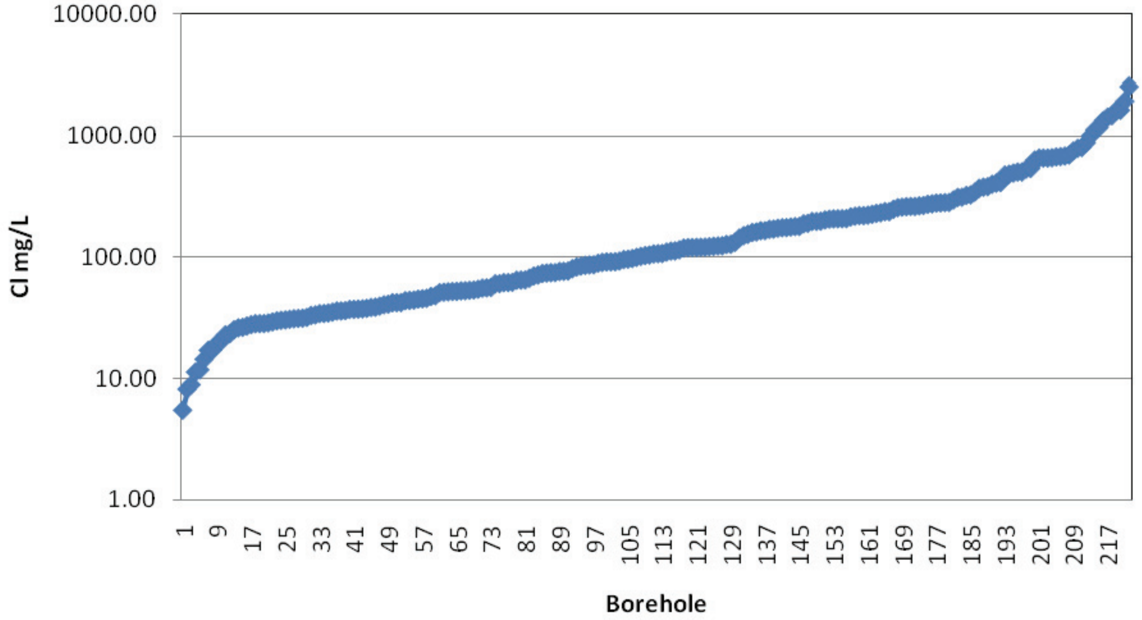


Figure 116: Cl values for each individual borehole.

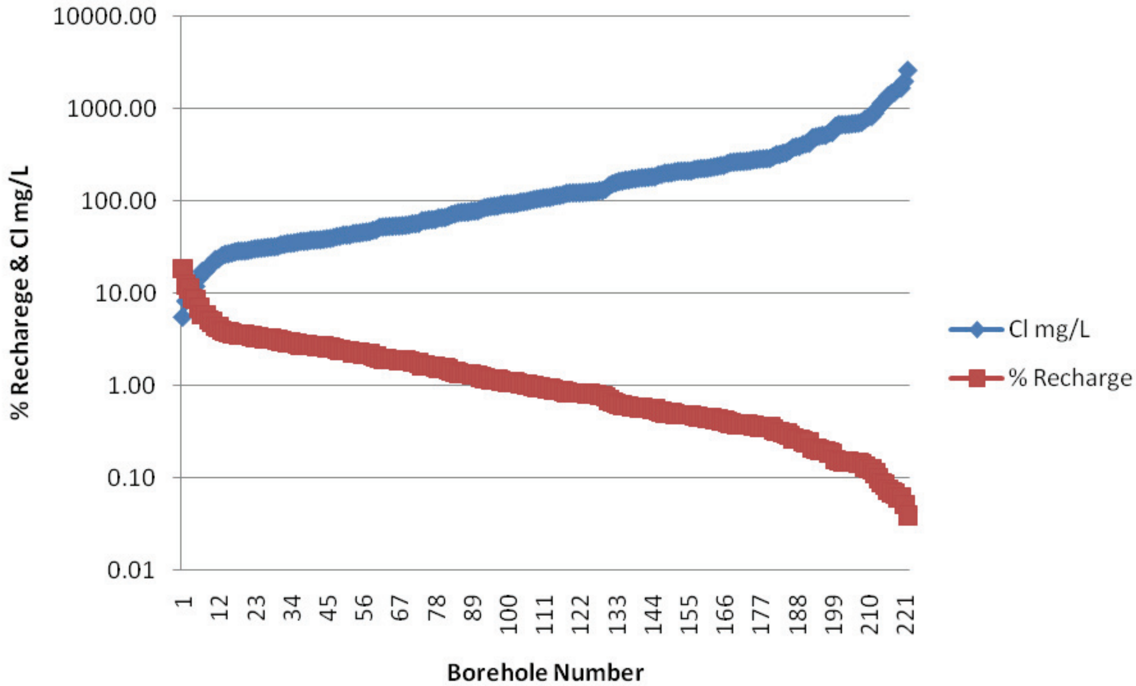


Figure 117: % Recharge v Cl in mg/l.

When the water level elevation, the percentage recharge and the Cl values are plotted against one another, the data indicates that there is no correlation between the elevation of the water level and the other two components (Figure 118).

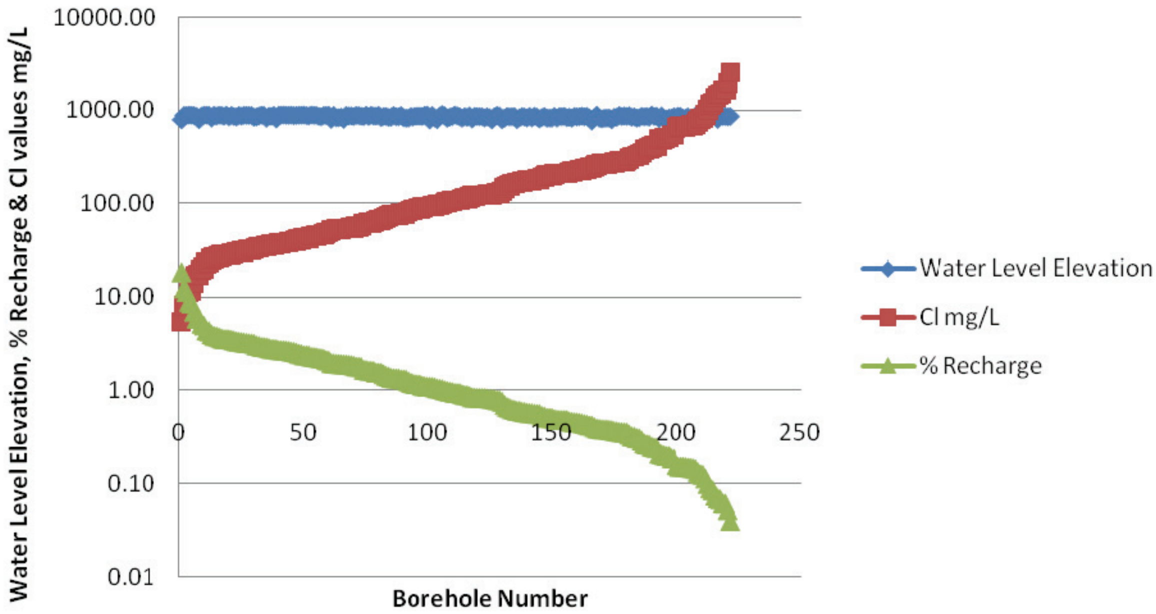


Figure 118: Water Level elevation, % Recharge and Cl plotted against one another.

The calculations from the Cl method indicated that the recharge of the study area is 1.59%. This was found to be in accordance with typical Karoo aquifers and with maps produced by Vegter (1995) for the study area, which indicated a recharge of between 1.5-1.9%.

From the recharge values calculated for each individual borehole by means of the Cl method, a contour map for the recharge in the study area was constructed (Figure 119). This was done in order to identify areas with high and low recharge and to determine if there was any correlation between the faults and recharge. Figure 119 indicates that recharge in the study area ranges from almost zero to as high 11% (according to the contour map). These areas of high recharge will need to be investigated as it is unlikely that recharge as high as 11% occurs within the study area.

Additionally the data indicated that the area near the centre of the study area (that shows an increase in elevation), in general also displays a higher recharge percentage than the surrounding areas. This is most clearly seen in the areas between the Daarby and Eenzaamheid faults in the south. This area towards the south displaying a higher recharge, are possibly the result of the influence of the faults in the area, with the areas between the faults displaying a generally higher recharge than that of the areas outside the faults. The areas south of the Eenzaamheid fault indicate high levels of recharge. This is probably due to these boreholes being drilled in the Waterberg Group rocks that recharge along fractures and cracks and that these boreholes were recently "flushed" at the time of sampling.

Additional samples and a more detailed study, is necessary to determine the cause of these high recharge values. Additionally, there are areas towards the north that indicate areas of high recharge (Figure 120). The area outlined in red on the contour map indicates an area that has an average recharge of 4.1 %. This is much higher than the surrounding areas and the area adjacent to this area, outlined in white, also indicates higher recharge than the surrounding area (Figure 120).

In all possibility the Zoetfontein fault passing through this area is serving as a conduit for recharge. This, together with the proximity of this area to the river, is likely the reason for the high recharge values. The data indicated that the areas of high recharge are located near the major faults in the study area. Therefore it can be inferred that the faults do not just act as watersheds, but also as recharge conduits for the rocks through which they run.

This was verified during dewatering and decants modelling for the new mines planned for the study area (see Chapter 10). The models showed that 50 years after mining had stopped; the flow towards the mines will be heavily influenced by the faults near the mines (Figure 157). Care should be taken when interpreting recharge for the area as the area itself is a complex system of which firsthand knowledge is necessary to form any preconceptions.

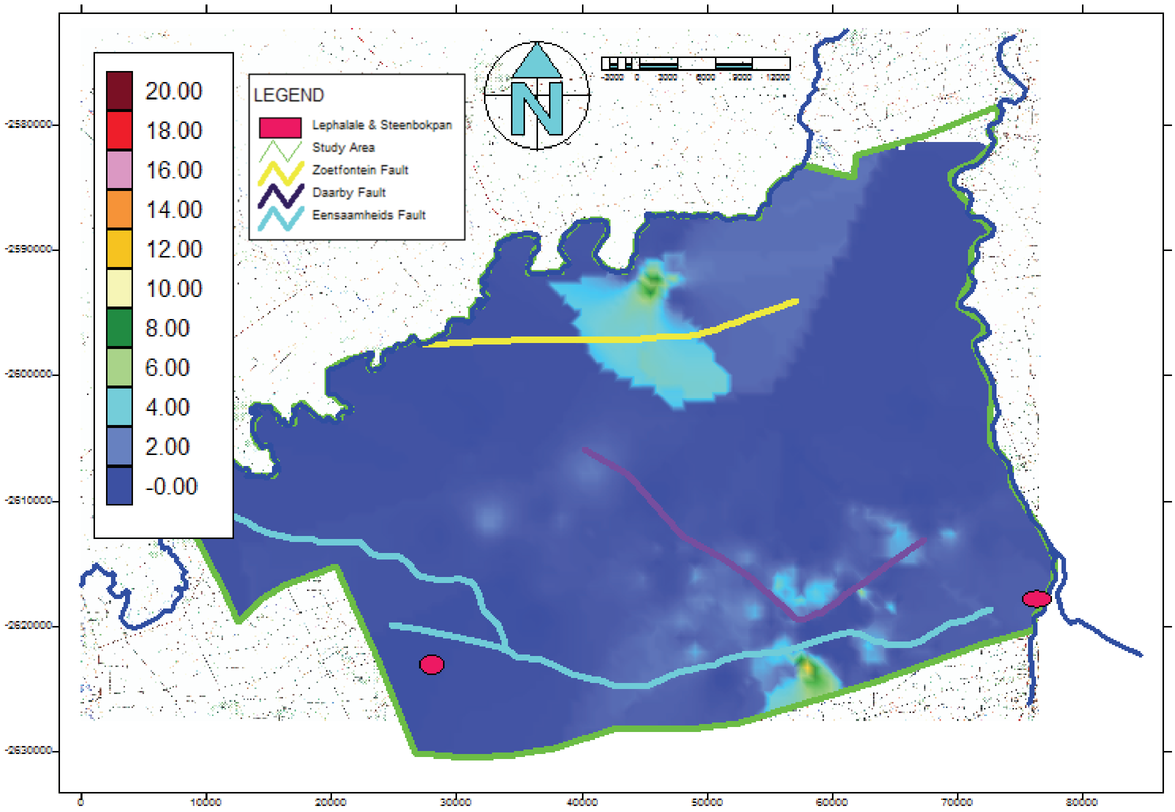


Figure 119: Recharge contour map of the study area.

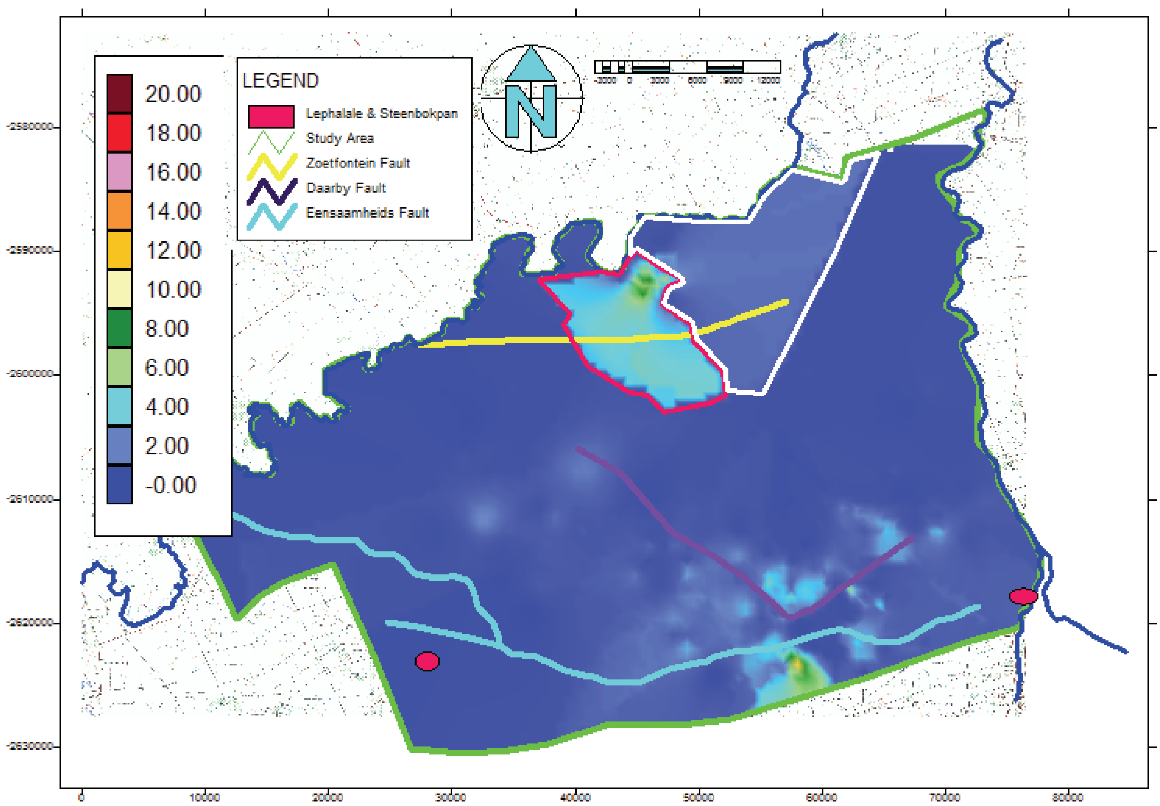


Figure 120: Recharge contour map of the study area outlining northern high recharge zones.

9.6.1.1 Discussion of the Chloride Method

From the analysed data it is clear that the central part of the study area is not only the driving force behind the movement of groundwater in the study area, but is also a driving force with regards to the recharge of the area. From other contour maps that have been generated of the study area, it has been observed that the primary flow directions of groundwater, is in directions away from this central area. It is therefore plausible that these areas are recharged faster than the low laying areas and that these chlorides then migrate down to the lower laying areas. Given the low transmissivity found in the aquifers of the study area, this takes a very long time. The recharge for the study area can be considered as being low, but does vary from one location to the next. For this reason a second method for determining recharge was used.

9.6.2 The E.A.R.T.H. Method for Determining Recharge

In an effort to confirm the recharge values obtained from the Chloride method, the E.A.R.T.H. method for recharge estimation was used. Eight boreholes were used for the recharge determination and were selected due to their availability of data stretching back in time. Some of the boreholes have information stretching back as far as 1973 but some of the other boreholes unfortunately only have data for five or eight years.

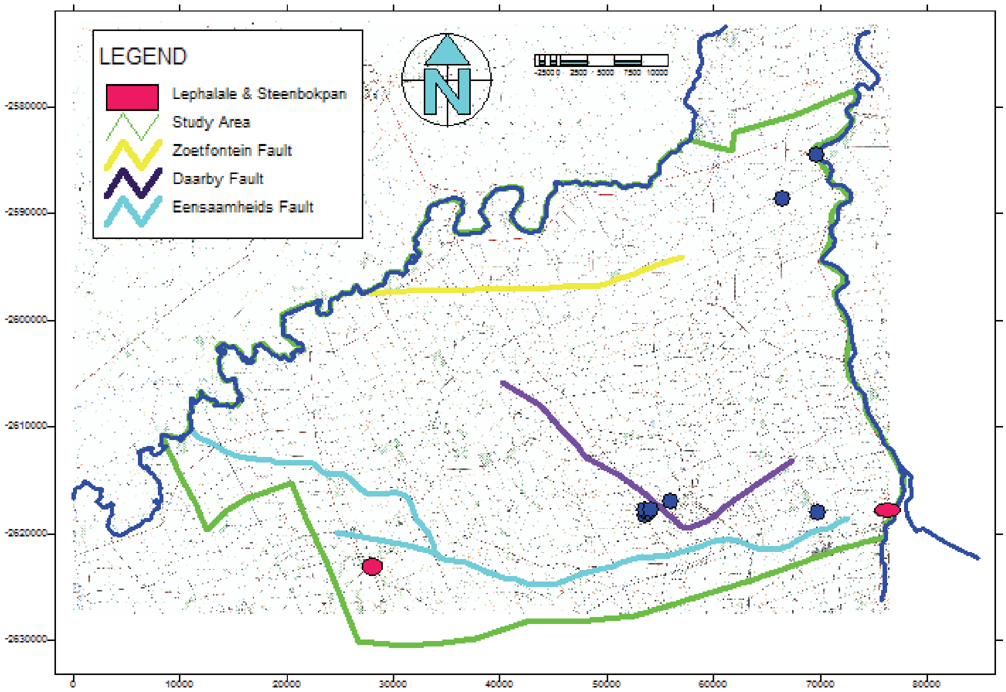


Figure 121: Distribution of the boreholes used for the E.A.R.T.H. model.

The distribution of selected boreholes unfortunately does not cover the entire study area, because additional boreholes with sufficient information could not be located. The boreholes that were analysed will be discussed below.

9.6.2.1 Borehole 1

This borehole is located in the far north/east of the study area on the farm Windhoek. Information for this borehole spans from June 1989 to December 1991. The water levels where plotted against the rainfall for each month that data was available for and the results can be seen in Table 24 and Figure 122.

Table 24: Results for borehole 1.

Borehole no	Resistance	%R	S
1	1411	1.7	0.0005

The model indicated a recharge of 1.7%. This is within the initial estimation according to Vegter's maps for recharge. This is a non unique fit; to obtain a unique fit, the value of S must be known.

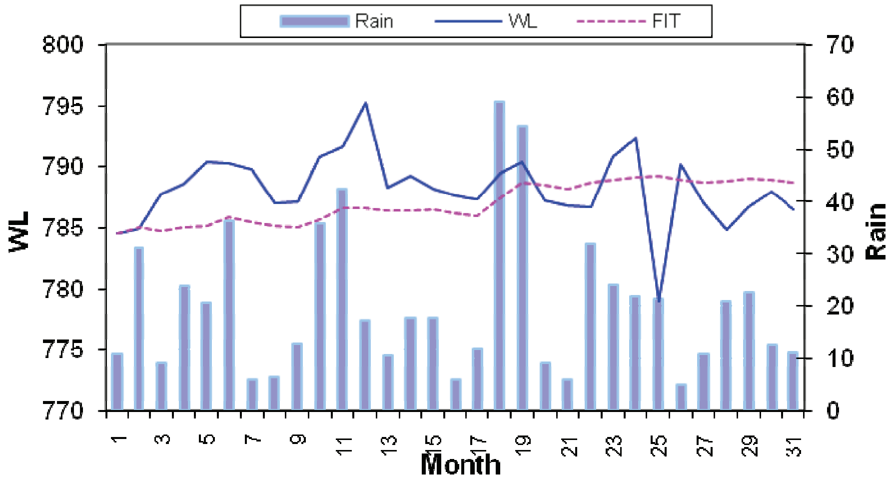


Figure 122: The E.A.R.T.H model for borehole 1.

9.6.2.2 Borehole 2

This borehole is located near the first borehole in the north/eastern part of the study area on the farm Windhoek. The same steps with regards to water levels and rainfall were followed as for the first borehole and will be followed for all the successive boreholes. For this borehole the information spans from June 1989 to May 1991. The results can be seen in Appendix D. The model indicated a recharge of 1.5% There was however much more resistance and a lag of 3 months.

9.6.2.3 Borehole 3

Borehole 3 is located near the Grootegeluk Mine, east of the Daarby fault on the farm Daarby. The borehole has data spanning from June 1989 to June 1994. The results are displayed in Appendix D. The model indicated a recharge of 1.7% with a resistance of 2631 and no lag.

9.6.2.4 Boreholes 4, 5, 6 and 7

These four boreholes are all located within close proximity to one another and will be discussed together. They are located just west of the Daarby fault on the farms Daarby and Enkelbult. The results for the boreholes are displayed in Table 50 and the fitted graphs are displayed in Appendix D.

For borehole 4 the data span from June 1989 to April 1991. The model indicated a recharge of 0.9%. The same recharge was given for borehole 5. Borehole 5 however had a 3 month lag. The data for borehole 5 stretched from June 1989 to March 1994. Borehole 6 indicated a recharge of 1% with no lag, with data from June 1989 to July 1992. The final borehole in the same area was borehole 7. The model gave a recharge of 1.4% for this borehole.

9.6.2.5 Borehole 8

The final borehole-analysis was borehole 8. This borehole is located to the south/east, east of the Daarby fault and just north of the Eenzaamheid fault. The data for this borehole span from June 1989 to September 1999. The results for this borehole are displayed in Appendix D. The model indicated a recharge of 3%. This is much higher than any of the other boreholes analysed so far. The reason for this high recharge is unknown.

When the average of all the boreholes is calculated, a recharge of 1.51% for the area is the result. This is very similar to the results obtained from the Chloride method, which indicated that both methods for determining recharge can effectively be used in the study area.

9.6.2.6 Discussion of the Results for the E.A.R.T.H. Model

From the results of the E.A.R.T.H model the following conclusions can be drawn:

- There is a great degree of variation in the recharge values in the study area.
- The recharge varies between 0.9% and 3% for the E.A.R.T.H. model calculations
- The average of the measured borehole is 1.51%, which is similar to the value obtained from the Chloride method.

9.7 Conclusion

9.7.1 Aquifer Parameters

From the information gathered it is apparent that the aquifers in the study area are low yielding and that the formations have low transmissivities. These findings conform to typical Karoo aquifer parameters. Given the low transmissivities of the formations it is predicted that the new mines planned for the study area will not have problems with regards to large volumes of water flooding the mines. Furthermore, as a result of the low rainfall, the low transmissivities, the water level (averaging around 28 m) and the high evotranspiration in the study area, it is predicted that the water levels in the mines will not reach decant levels.

This was confirmed by the numerical modelling (discussed in more detail in Chapter 10), which indicated that 50 years after mining had stopped the water levels in the modelled pits rose by between two and three meters. The largest contributor to the rise in water levels in the pits being surface runoff during periods of high rainfall. The Big Hole in Kimberley can be used as an example as the area has low transmissivities, deep water levels and high levels of evapotranspiration. According to these parameters it has been predicted that the Big hole will never decant (Figure 109).

9.7.2 Recharge

The recharge determinations for the study area indicated a value of between1.5-1.6% for the entire study area. This is in accordance with the maps that Vegter (1995) has drawn up of the study area, placing the recharge at between 1.5% and 1.9%. Both the E.A.R.T.H. and Chloride methods for determining recharge gave values in the same order, indicating that both of these methods can be used with a high degree of certainty in the study area. Furthermore, the low recharge coupled with the low transmissivities found in the study area present both positive and negative situations for the mines and farmers in the study area. For mining it is positive in the sense that there will be little inflow of water into the mines (which has been confirmed by modelling). On the negative side this poses problems, because as boreholes in the vicinity of the mines are dewatered, they will, if ever, take very long to reach their initial levels.

For the farmers the situation is only negative. Dewatered boreholes will take long to reach their initial levels and boreholes in the vicinity of the mines are unlikely to ever recover. Therefore, precaution should be taken to minimize the impact of the mining on the groundwater.

10 Modelling

10.1 Introduction

The study area was modelled numerically to determine the quantities of groundwater flow into mines (dewatering model) and to predict whether the mines would reach decant level (decant models). To achieve this, data gathered from the study area was used. This data included; borehole water levels, transmissivities from pump testing and geological data. The data from the currently active mine (Dreyer, 2009) revealed that the measured inflow from groundwater into the mine was in the order of 19 000 m^3/month during the initial stages of mining. This translates to 633 m^3/d. At present the estimated flow into the mine is in the order of 30 000 m^3/month (1000 m^3/d). This is a very small volume of water entering the workings of the mine.

Additional information from the mine included:

- The mine removes roughly 60 m of coal from the pit as mining progresses.
- The pit extends to roughly 110 m at its deepest point.
- This means that the additional 40% can be used as backfill once mining operations. stop, meaning that 60% of the rock removed from the pit will not be replaced.
- The pit will therefore not be rehabilitated to surface level, but will be backfilled in a stepped manner, the highest step being at the eastern end of the mine and the lowest step towards the western parts of the mine.
- There will be open voids in the mines that will not be backfilled.
- Additional information that played a role in modelling was the average water levels of roughly 28 m below surface, and the low transmissivities measured in the study area by means of pumping tests.
- The very high evaporation of between 1800-2000 mm/y (5.6 mm per day) and low rainfall were taken into account (SA Weather Service, 2008), as surface run-off into the mine is the primary contributing factor to water in the pit.

10.2 Numerical Modelling

The Processing ModFlow for Windows (PMWin) modelling software program was used for the modelling. It was decided not to model the entire study area, as this would decrease the accuracy of the model and increase model run times. Instead, there was focused on the areas west of the Daarby fault, as this is the primary area in which coal will be mined by means of surface mining methods.

10.2.1 Parameters for the Model

10.2.1.1 Regional Finite Difference Network

A grid of 40 km long by 30 km wide was chosen. This grid was divided into 200 columns and 150 rows respectively, each 200 m $\times$ 200 m in size.

Grid co-ordinates: X1 25507, Y1 -2627437

X2 65837, Y2 -2597484

A four layer model was selected in an effort to better simulate the conditions in the study area. A thickness of 28 m per layer was taken as the average water depth in the study area is at 28 m below the surface and Modflow can only simulate saturated flow. The topmost layer were assigned a value of zero, with the deepest receiving a value of -110 m. Because Modflow cannot simulate unsaturated flow, water levels in the study area were valued at the zero level, and the depth of the pits at110 m to be taken into account for future mining activities (Vermeulen and Dennis, 2007). In addition, the layers were all classified as confined, given the geology of the study area (predominantly alternating layers of shale and mudstone with some sandstone and coal). Once the network was set up, all initial and boundary conditions, sources, sinks, and aquifer parameters were entered. Under normal circumstances a steady state calibration is then conducted to ensure the flow model has the same behaviour as the actual system under investigation, this was however not done due to a lack of data.

10.2.1.2 Boundary Conditions

One of the first and most demanding tasks in groundwater modelling is that of identifying the model area and its boundaries. Consequently, a model boundary is the interface between the model area and the surrounding environment. Conditions on the boundaries, however, have to be specified. Boundaries occur at the edges of the model area and at locations in the model area where external influences are represented, such as rivers, wells and leaky impoundments (Vermeulen and Dennis, 2007). Criteria for selecting hydraulic boundary conditions are primarily topography, hydrology and geology. The topography, geology, or both, may yield boundaries such as impermeable strata or potentiometric surface controlled by surface water, or recharge/discharge areas such as inflow boundaries along mountain ranges. The flow system allows the specification of boundaries in situations where natural boundaries are a great distance away. Boundary conditions must be specified for the entire boundary and may vary with time. At a given boundary section just one type of boundary condition can be assigned. As a simple example, it is not possible to specify groundwater flux and groundwater head at an identical boundary section (Vermeulen and Dennis, 2007).

Boundaries in groundwater models can be specified as:

- Dirichlet (also known as constant head or constant concentration) boundary conditions
- Neuman (or specified flux) boundary conditions
- Cauchy (or a combination of Dirichlet and Neuman) boundary conditions

A box model was used, in which the northern, eastern, southern and western borders of the model were set to constant head boundaries. This was done to simplify the model. For the dewatering models, constant head boundaries were placed on the lowest levels of the layer that was to be dewatered. For the decant models, these boundaries were removed.

10.2.1.3 Initial Conditions

Initial conditions are vital for modelling flow problems. Initial conditions must be specified for the entire area. Generally, the initial water level/head distribution acts as the starting distribution for the numerical calculation (Vermeulen and Dennis, 2007). The initial water level was set to zero as the modelling program can only simulate saturated flow.

10.2.1.4 Sources and Sinks

Sources and sinks can be defined as recharge and abstraction sources in the aquifer, respectively. Sources can be precipitation and inflow from surface water and recharging boreholes. Sinks can be abstraction boreholes, springs, evapotranspiration, mines and outflow to surface water (Vermeulen and Dennis, 2007). The groundwater recharge (R) for the area was calculated using the chloride method and is expressed as a percentage of the Mean Annual Precipitation (MAP). Accordingly the recharge for the study area was calculated to be 1.5% of the annual rainfall. The recharge entering into the model in general was determined at 0.023 mm/y, and at 20% of the annual rainfall in the open pits (Hodgson *et al.,* 2007), amounting to 0.31 mm/y.

10.2.1.5 Aquifer Parameters

Two main parameters are used to describe the physical properties of the aquifer, namely transmissivity (T) and storage coefficient (S). Transmissivity is a measure of the ease with which groundwater flows in the subsurface. Transmissivity is related to hydraulic conductivity (K): $T = Kd$ where d is the saturated thickness of the aquifer. Storage coefficient is the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Vermeulen and Dennis, 2007).

For a confined aquifer, the storage coefficient is equal to the product of the specific storage and aquifer thickness of the saturated porous medium. For an unconfined aquifer, the storage is the ratio of the volume of water that drains by gravity to that of the total volume and is known as specific yield.

- The calculated harmonic mean of the transmissivities was 1.6 m^2/d.

- This was taken as the total transmissivity for the system and divided among the layers for an even distribution of 0.4 m^2/d for each layer.
- Two additional transmissivities were taken to test the model (different scenarios).
- It was decided to take transmissivities of roughly 1/3 (0.12 m^2/d) and 2/3 (0.28 m^2/d)
- The reason for taking these transmissivities was to simulate different scenarios as it was suspected that the transmissivity of 0.4 m^2/d was too high and did not correspond to the volumes of water entering into the pit in reality.
- An additional reason was that the model could not be calibrated due to lack of data.
- These transmissivities were used for the area as a whole, with the transmissivities in the pits set at 100 m^2/d for the dewatering models, and 500 m^2/d for the decant models respectively.
- The transmissivities selected for the faults was 500 m^2/d.

A general storage coefficient of 0.003 was selected for the model with storage coefficients of 1 and 0.25 for the dewatering and decant models in the pits themselves. Vertical hydraulic conductivity was set to $1E^{-5}$ for the model as a whole, and at 10 in the pits to simulate worst case scenario situations.

10.2.1.6 Time

For the dewatering models, a time frame of 10 years was determined for the purpose of simulating the dewatering of each layer as mining progresses ever deeper into the geology. The 10 years were divided into lengths of 360 days (to remove leap years from the modelling calculations), with the time steps set to 12 (12 months). For the decant models, a time frame of 50 years divided into lengths of 360 days and 12 time steps was selected.

10.2.1.7 Pits

Initially only one pit was simulated with the three different transmissivity values. This was expanded to three pits for the final model; one to the north, one towards the south-east and one between the other pits. The sizes of the pits vary, with the northern pit being 1750 ha, the central pit being 2793 ha, and the south-eastern pit being 2070 ha. The large sizes for the pits were chosen to simulate the absolute worst case scenario situations.

10.2.2 Model Scenarios

Five dewatering and accompanying decant models were constructed to illustrate different scenarios that may occur during the course of mining in the study area.

10.2.2.1 Scenario 1

- Three dewatering models were constructed using all the parameters and only one pit (the northern pit).
- In the models, the faults found in the study area were not activated.
- The models were systematically dewatered, First to the second layer, then to the third layer and finally to the fourth layer to simulate progression of the mine.
- All the models were constructed for all three transmissivities (0.4 m^2/d, 0.28 m^2/d and 0.12 m^2/d) and run for 10 years for each layer being dewatered.

10.2.2.2 Scenario 2

- The fourth dewatering model contained one activated fault that ran through the pit. This was done to simulate a scenario where a zone of higher transmissivity might be encountered during the course of mining. Only a transmissivity of 0.4 m^2/d was used.

10.2.2.3 Scenario 3

- The final model constructed had all three pits on the model and all the faults found in the study area were activated. All the pits were dewatered to 110 m below surface.

The results of the modelling will be discussed according the transmissivities used.

10.2.3 Dewatering for Scenario 1

10.2.3.1 Transmissivity 0.4 m^2/d

For the dewatering of layer 2, the constant head boundaries were placed at the bottom of the layer (56 m below surface). The model yielded a drawdown cone of 2.6 km (Figure 123) around the pit, with an inflow of 388 m^3/d into the mine. For layer 3 at a transmissivity of 0.4 m^2/d, the model generated a drawdown cone of 2.6 km for layer 2 (Figure 124) around the mine, with an inflow of 604 m^3/d. For layer *3 (*Figure 125*),* the drawdown cone was given as 2.4 km and the predicted inflow was 897 m^3/d. For the dewatering of layer 4 at the same transmissivity (0.4 m^2/d), the model depicted a drawdown cone of 2.8 km for layer 2 (Figure 126), 2.8 km for layer 3 (Figure 127), and 2.6 km for layer 4 (Figure 128) respectively.

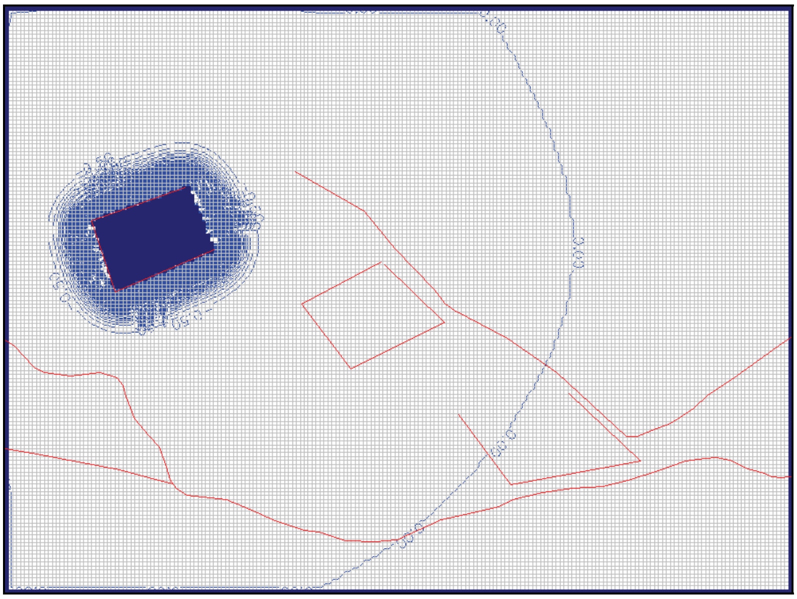


Figure 123: Dewatering of Layer 2 with a transmissivity of 0.4 m^2/d showing the drawdown cone.

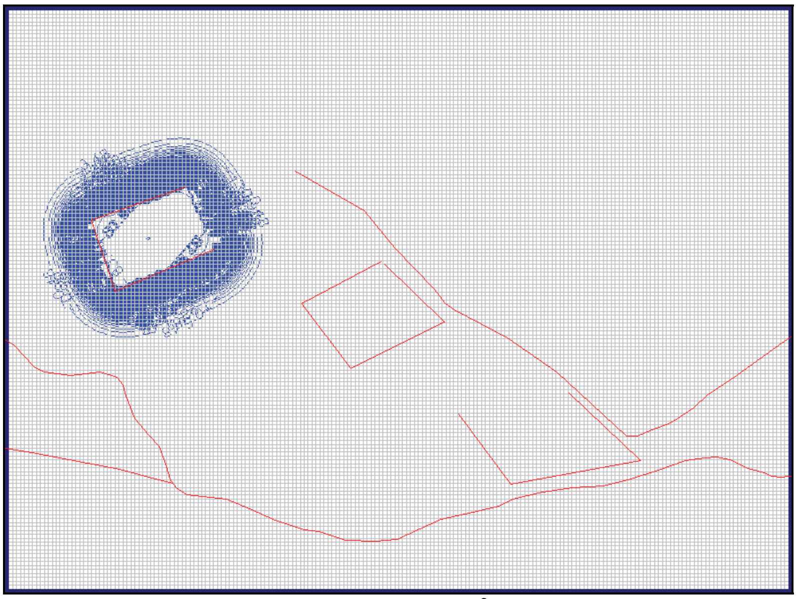


Figure 124: Layer 2 at a transmissivity of 0.4 m^2/d with Layer 3 being dewatered.

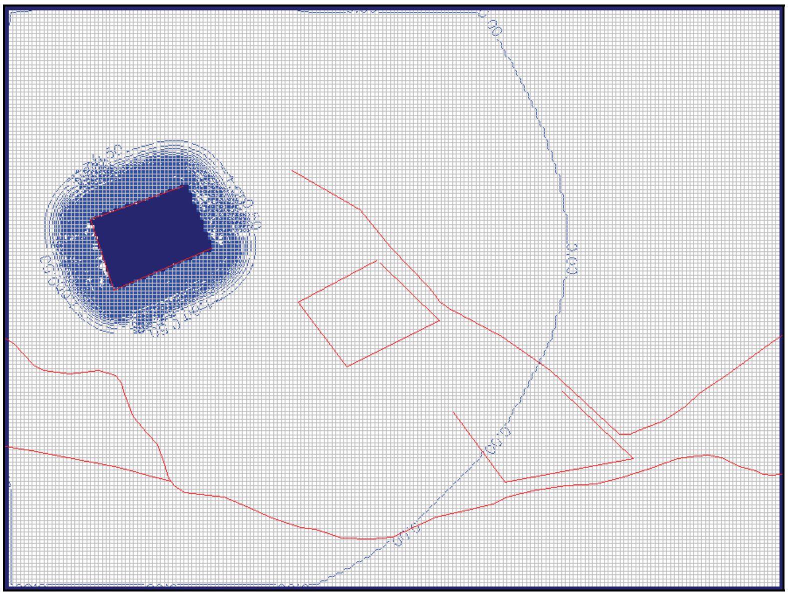


Figure 125: Layer 3 at a transmissivity of 0.4 m2/d with Layer 3 being dewatered.

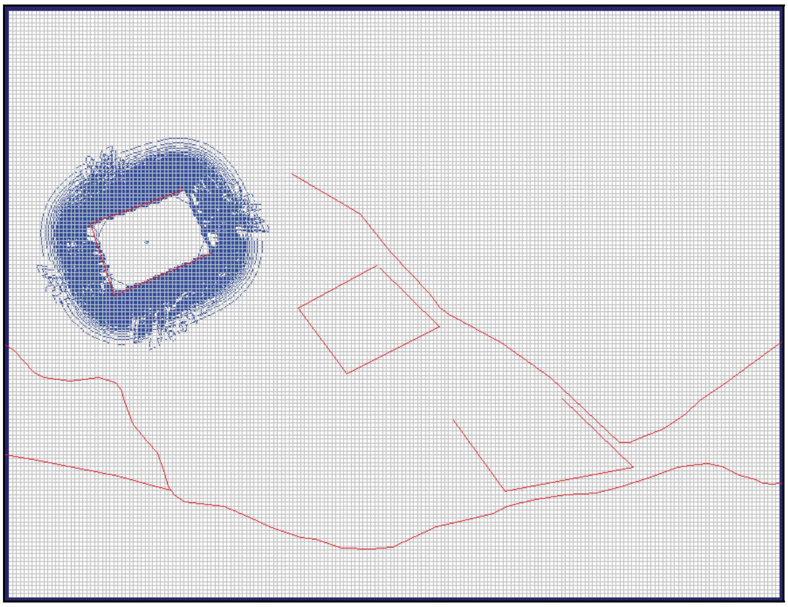


Figure 126: Dewatering of Layer 4 showing the drawdown cone for layer 2.

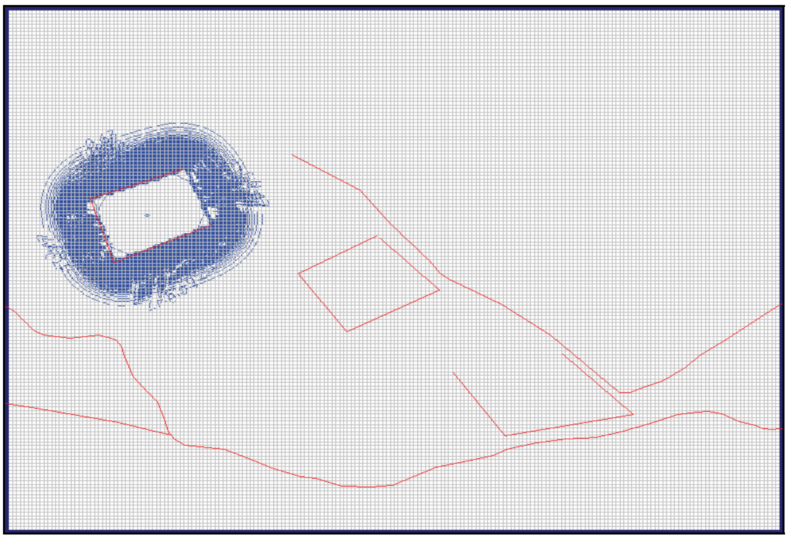


Figure 127: Dewatering of layer 4, showing layer 3's drawdown cone.

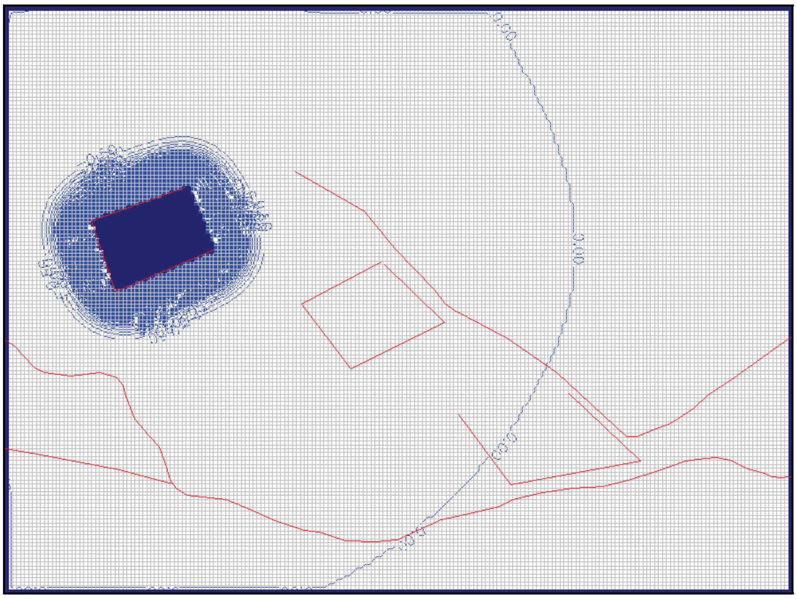


Figure 128: Showing the drawdown cone for layer 4 with layer 4 being dewatered.

The models indicated inflows of 749 m^3/d, 749 m^3/d, 748 m^3/d and 755 m^3/d for layers 1, 2, 3 and 4 respectively. As can be seen, there is very little difference in inflow between the layers, with the largest amount of water influx occurring on the layer that is being dewatered. There is also a small change in the size of the drawdown cones from the different layers, with the exception of layer 3.

10.2.3.2 Transmissivity 0.28 m^2/d

The same models constructed for the 0.4 m^2/d transmissivity, were done for a transmissivity of 0.28 m^2/d, the results are as follows. For the dewatering of layer 2 the model generated a drawdown cone of 2 km (Figure 129) and an estimated inflow of 319 m^3/d. For the dewatering of layer 3, the model estimated a drawdown cone of 2.2 km for layer 2 (Figure 130) and 2 km for layer 3 (Figure 131). The estimated influx of groundwater was 496 m^3/d and 701 m^3/d for layers 2 and 3 respectively.

From these values, it is clear that there is a large difference in the inflow of groundwater between layers 2 and 3. This difference is however less significant than the difference in influx between layers 2 and 3 for a transmissivity of 0.4 m^2/d. The dewatering model constructed for layer 4 showed drawdown cones of 2.2 km, 2.2 km, and 2.2 km for layers 2 (Figure 132), 3 (Figure 133) and 4 (Figure 134) respectively. The predicted inflow for the model was 614 m^3/d, 613 m^3/d, 618 m^3/d for layers 2, 3 and 4 respectively.

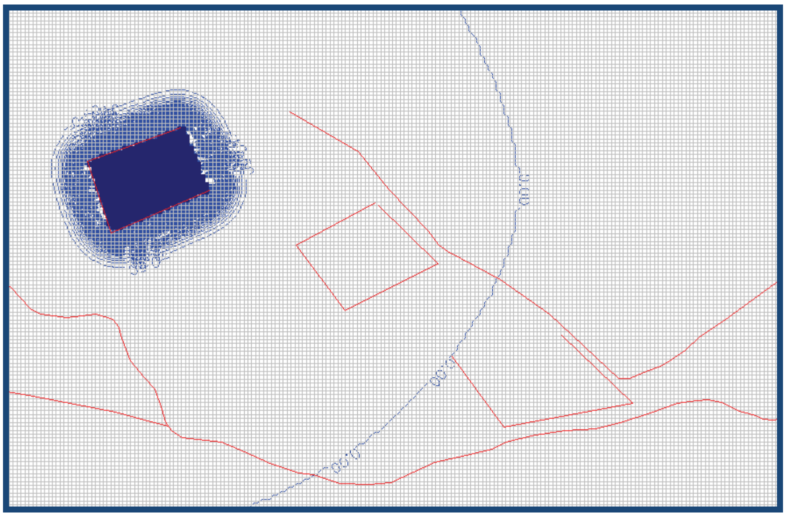


Figure 129: Showing the drawdown cone for layer 2 with layer 2 being dewatered at a transmissivity of 0.28 m^2/d.

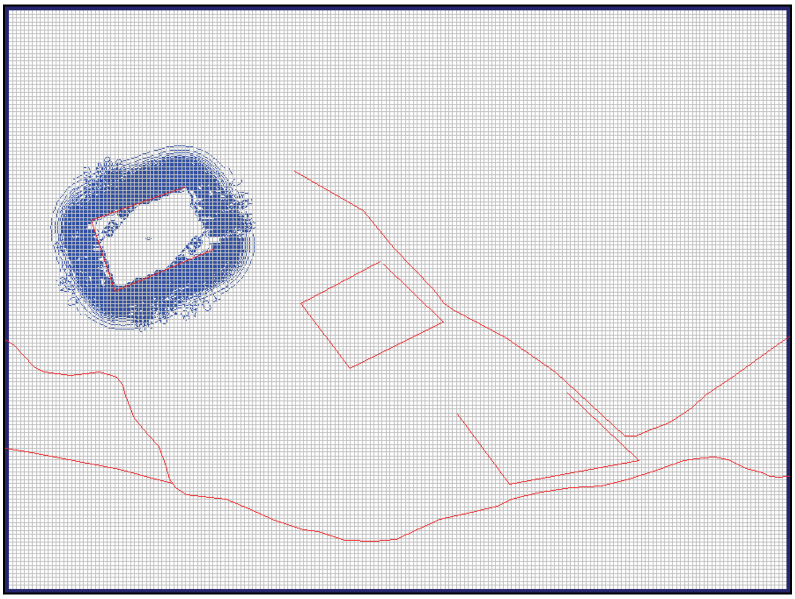


Figure 130: Drawdown cone for layer 2 with layer 3 being dewatered.

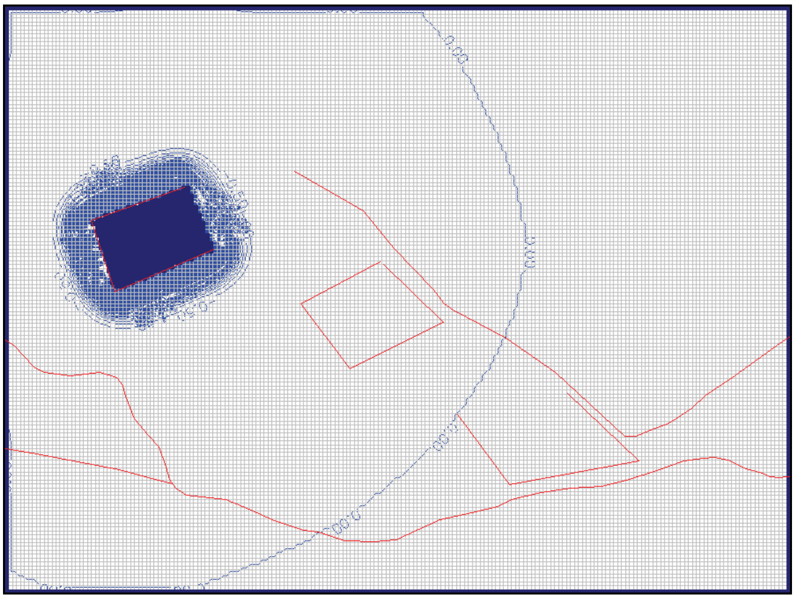


Figure 131: Drawdown cone for layer 3 with layer 3 being dewatered.

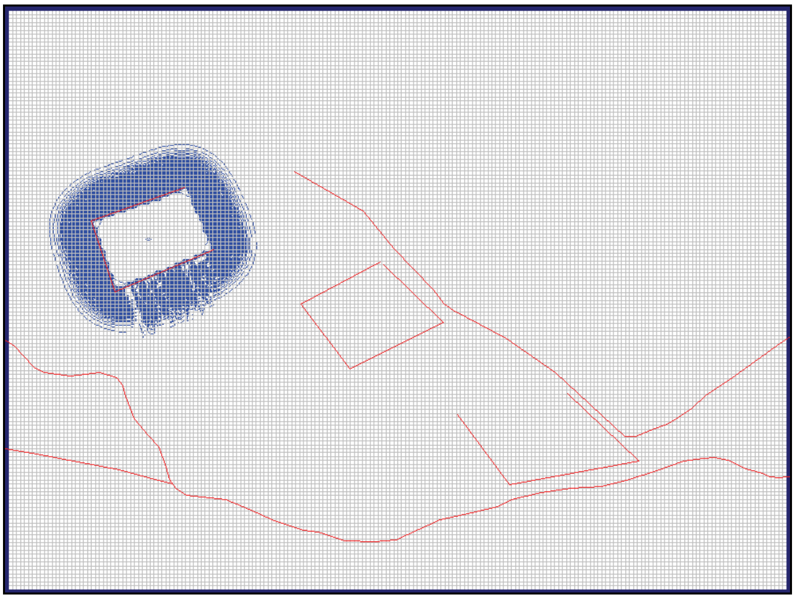


Figure 132: Drawdown cone for layer 2 with layer 4 being dewatered.

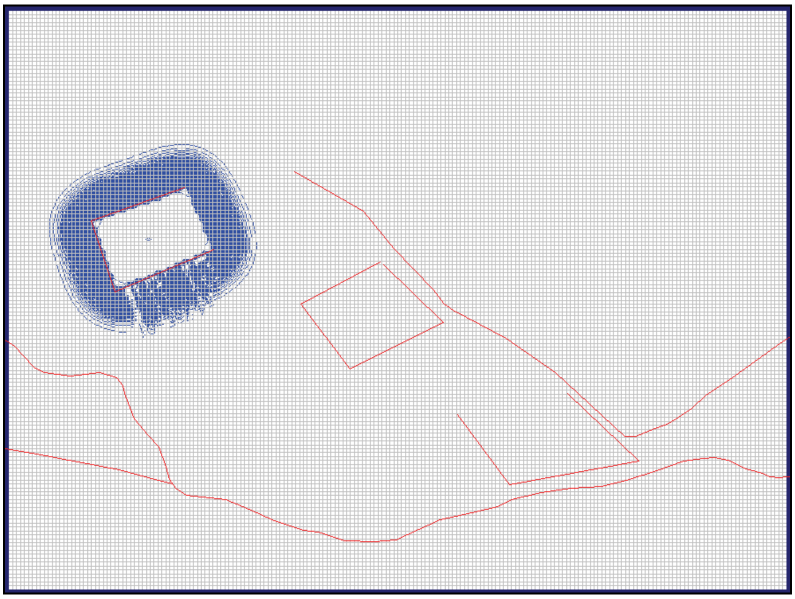


Figure 133: The drawdown cone for layer 3 with layer 4 being dewatered.

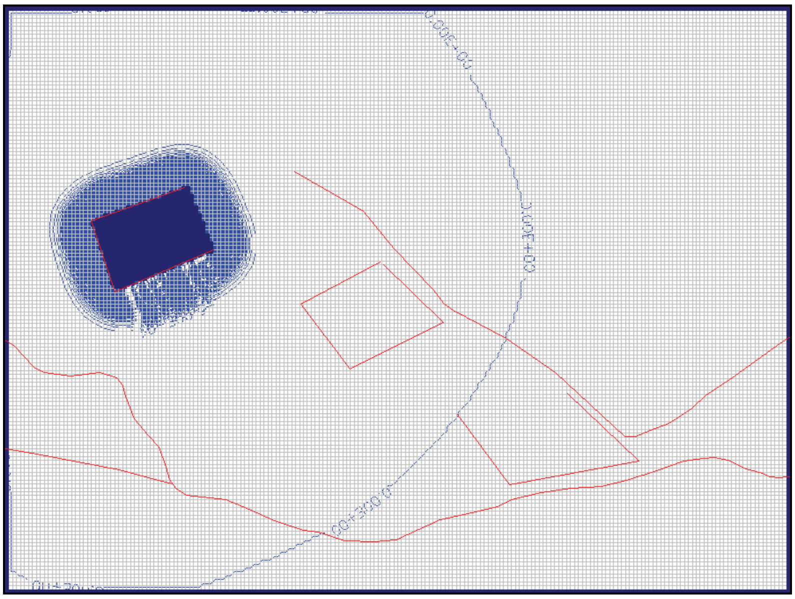


Figure 134: The dewatering of layer 4 showing the drawdown cone for layer 4.

10.2.3.3 Transmissivity 0.12 m^2/d

The final set of dewatering models for this scenario was constructed using a transmissivity of 0.12 m^2/d. The same parameters were used as for the previous models. For the dewatering of layer 2, a drawdown cone of 1.4 km (Figure 135) and an estimated inflow of 203 m^3/d were determined. For layers 2 and 3, the model generated a drawdown cone of 1.4km (Figure 136 and Figure 137 respectively) for both layers and an inflow of 315 m^3/d and 403 m^3/d for layers 2 and 3 respectively. For the dewatering of layer 4, drawdown cones of 1.6 km (Figure 138, Figure 139 and Figure 140) for all three layers (2, 3 and 4) were estimated, along with inflows of 390 m^3/d, 389 m^3/d and 391 m^3/d for layers 2, 3 and 4 respectively.

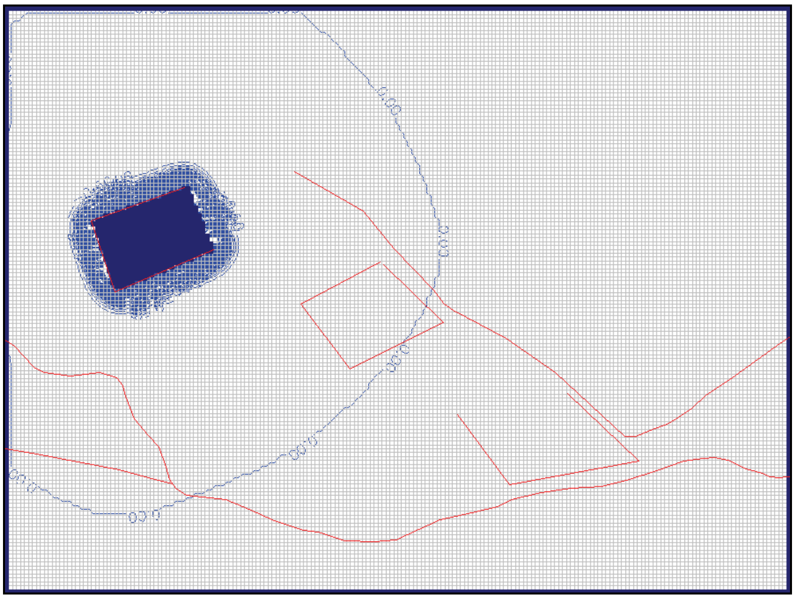


Figure 135: Dewatering of layer 2, showing drawdown cone of layer 2.

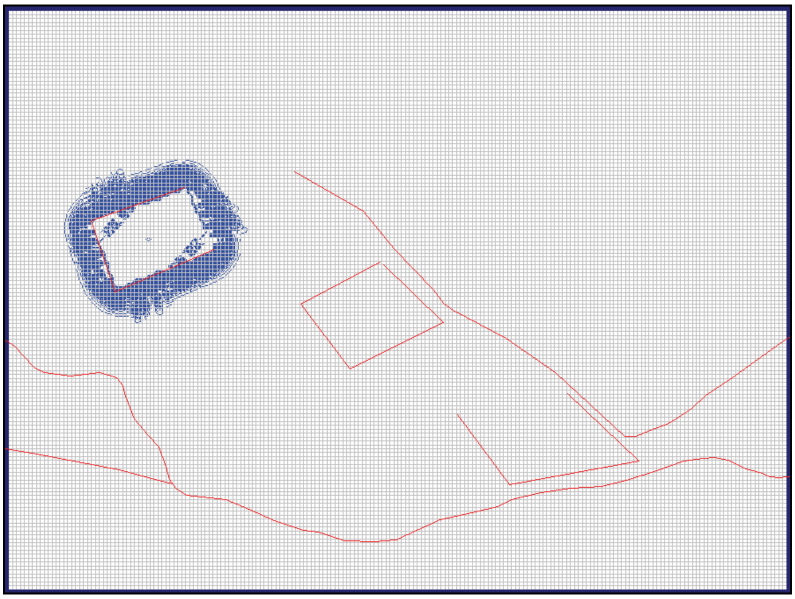


Figure 136: Drawdown cone for layer 2 with layer 3 being dewatered.

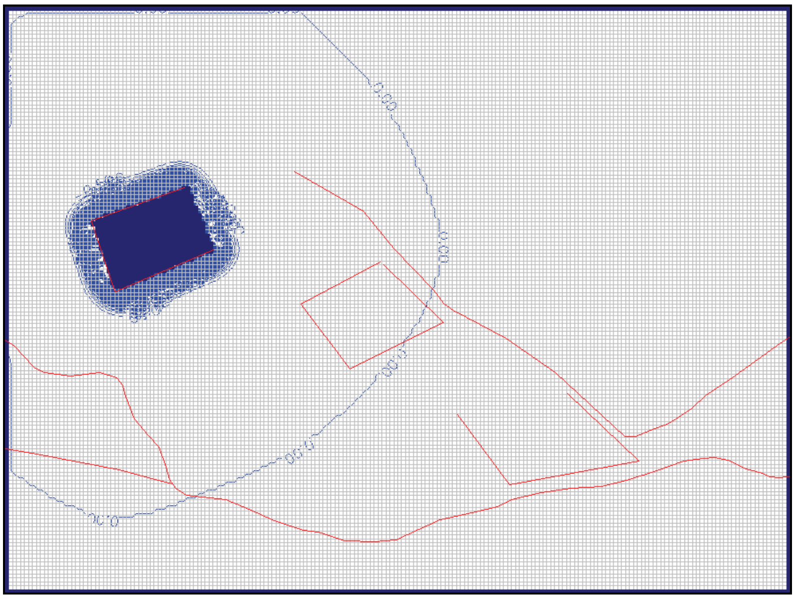


Figure 137: Drawdown cone for layer 3 with layer 3 being dewatered.

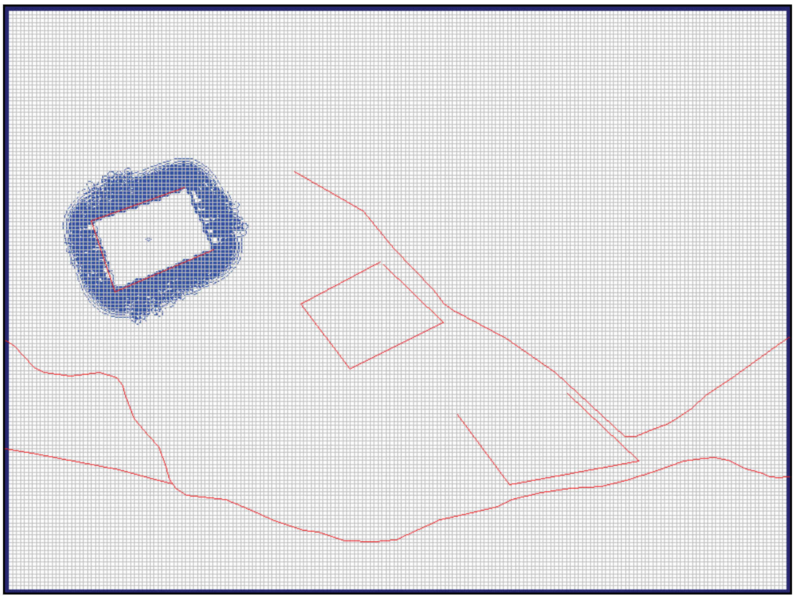


Figure 138: Showing drawdown cone for layer 2with layer 4 being dewatered.

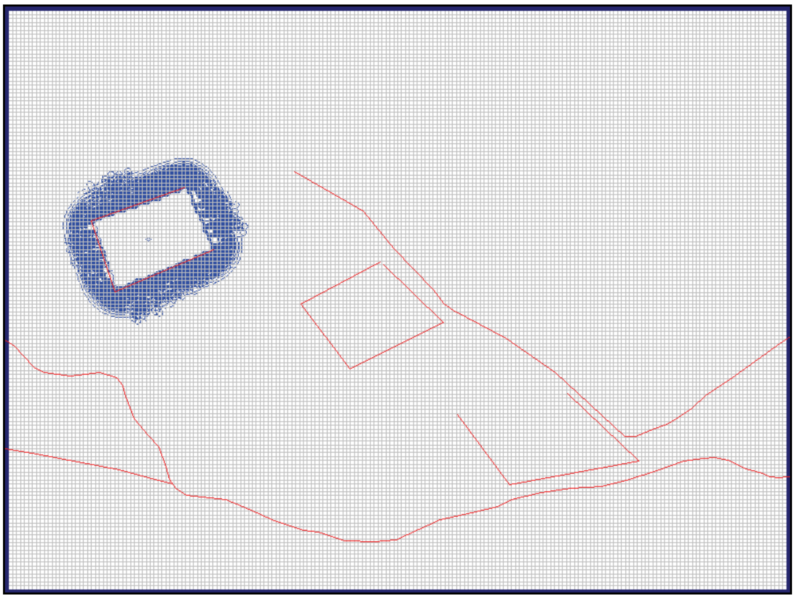


Figure 139: Drawdown cone for layer 3 with layer 4 being dewatered.

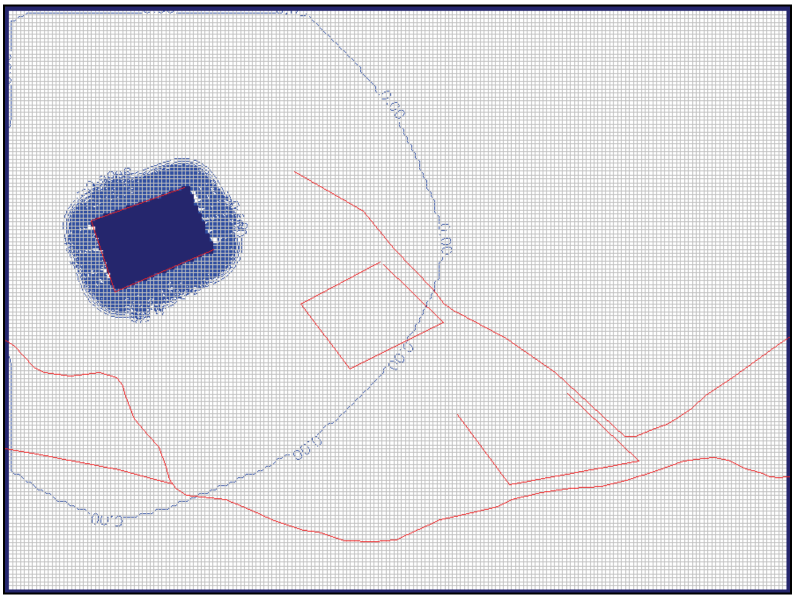


Figure 140: Showing the drawdown cone for layer 4 with layer 4 being dewatered.

10.2.3.4 Discussion of Dewatering Models for Scenario 1

From the models used to simulate dewatering for the different layers, it is clear that the different transmissivities for scenario 1 lead to different drawdown cones and different quantities of water flowing into the mine (Table 35).

Table 25: A summary of the predicted water influxes and drawdown cones for the three different transmissivities.

Initial Dewatering Models					
Layer	**Transmissivity (m^2/d)**	**Inflow (m^3/d)**	**Time (years)**	**Drawdown cone (km)**	**Location of constant head**
1	0.40	388.29	10	2.8	*Layer 2*
2	0.40	500.71	10	2.6	
1	0.28	318.65	10	2.2	*Layer 2*
2	0.28	409.72	10	2.0	
1	0.12	202.69	10	1.4	*Layer 2*
2	0.12	259.20	10	1.4	
1	0.40	574.20	10	2.6	*Layer 3*
2	0.40	604.68	10	2.6	
3	0.40	897.08	10	2.4	
1	0.28	470.80	10	2.2	*Layer 3*
2	0.28	496.27	10	2.2	
3	0.28	701.58	10	2.0	
1	0.12	298.81	10	1.4	*Layer 3*
2	0.12	315.14	10	1.4	
3	0.12	402.57	10	1.4	
1	0.40	748.83	10	2.8	*Layer 4*
2	0.40	748.77	10	2.8	
3	0.40	747.78	10	2.8	
4	0.40	754.73	10	2.6	
1	0.28	613.90	10	2.2	*Layer 4*
2	0.28	613.87	10	2.2	
3	0.28	613.19	10	2.2	
4	0.28	617.86	10	2.2	
1	0.12	389.52	10	1.6	*Layer 4*
2	0.12	389.50	10	1.6	
3	0.12	389.24	10	1.6	
4	0.12	391.09	10	1.6	

The models indicate that, during the initial stages of mining, there will be “large” influxes of water into the mine, the quantity of which depends on the transmissivity of the rocks and rock formations that will be determined by the location of the mine. The largest differences in water levels with regards to pre-and post mining water levels, will be observed in the immediate vicinity of the mines and this will diminish with increased distance from the mine, reaching a maximum of 2.8 km from the mine after 10 years. According to Dreyer (2009), the recorded drawdown cone generated by the Grootegeluk mine after nearly 30 years of operation is approximately 3 km. Therefore the transmissivity of 0.4 m^3/d can be taken as a worst case scenario for the study area, with the transmissivity of 0.12 m^3/d being closer to the actual situation, though it is likely to vary from one location in the study area to the next.

10.2.4 Decant Model for Scenario 1

As the primary objective of this project is to determine what the effects of mining will be one the groundwater resources, it is prudent to determine if the mines would ever reach a level at which the mines would decant onto surface. Accordingly a decant model for the same scenarios as the dewatering models was constructed. A situation was simulated where the pit had been filled to surface level and a recharge of 20% of the annual rainfall was assigned to the pit itself. A transmissivity of 0.4 m^2/d was assigned to the model to simulate worst case conditions and the transmissivity in the pit was set to 500 m^2/d. The model was run for 50 years. According to the model, there was a total rise in water level of 2 m in the pit after 50 years (Figures

141 and 142). Given this insignificant rise in the water level after 50 years and the high level of evaporation in the study area, it was determined, that the pits in the study area are not likely to decant.

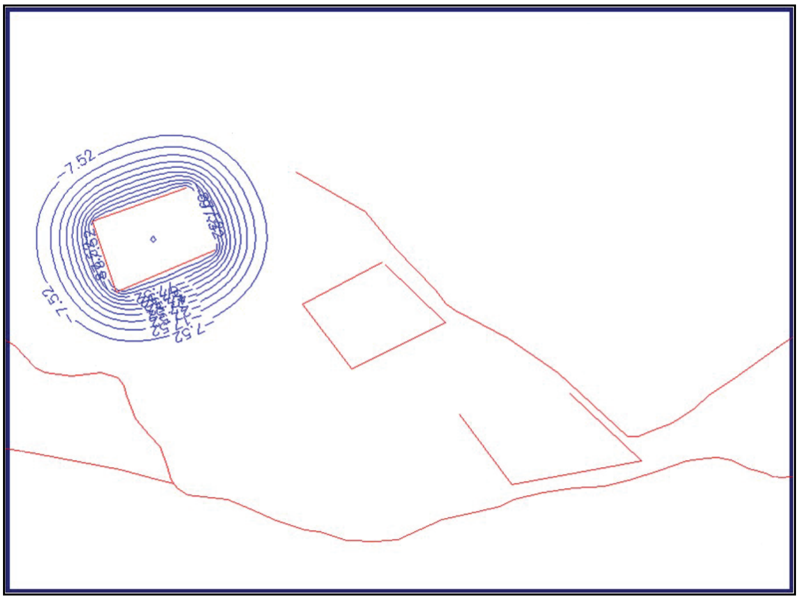


Figure 141: Showing the drawdown cone for layer 4, 50 years after mining has stopped.

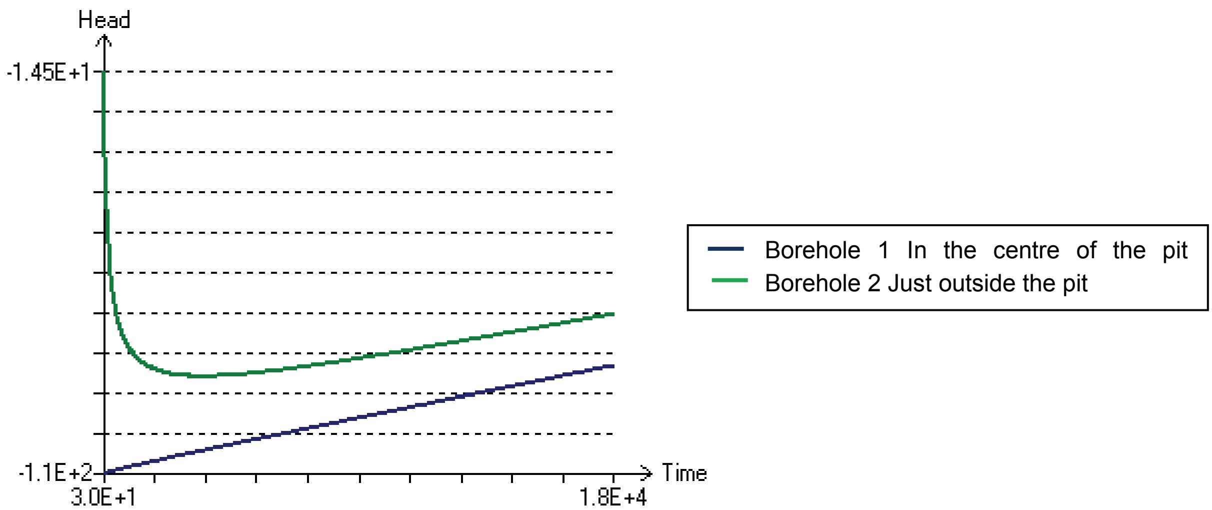


Figure 142: Head-Time graph of the first decant scenario, showing the initial fall in water level and the later rise of the water in the pit.

Two additional scenarios were modelled to improve the simulation of the situation in the study area. The first of these was to determine the conditions in the mine should the mine intersect an unknown fault running through the study area. The scenario was simulated for both dewatering and decanting. For the second scenario, all the faults in the study area were activated as zones of high transmissivity, and three pits were modelled for both dewatering and decanting scenarios.

10.2.5 Dewatering for Scenario 2: Mine Intersecting a Fault

The model was run with all the same parameters as for the models in the first scenario, with the additional parameter of one activated fault that ran through the mine from north to south. The fault was assigned a transmissivity of 500 m^2/d, and the pit a transmissivity of 100 m^2/d, while a transmissivity of 0.4 m^2/d was assigned to the model in general to simulate worst case conditions. The model ran for 50 years and influx into the mine was calculated at 10 year intervals. The following figures show the differences in the drawdown cones displayed by the different layers after dewatering layer 4 for 10 and 50 years respectively.

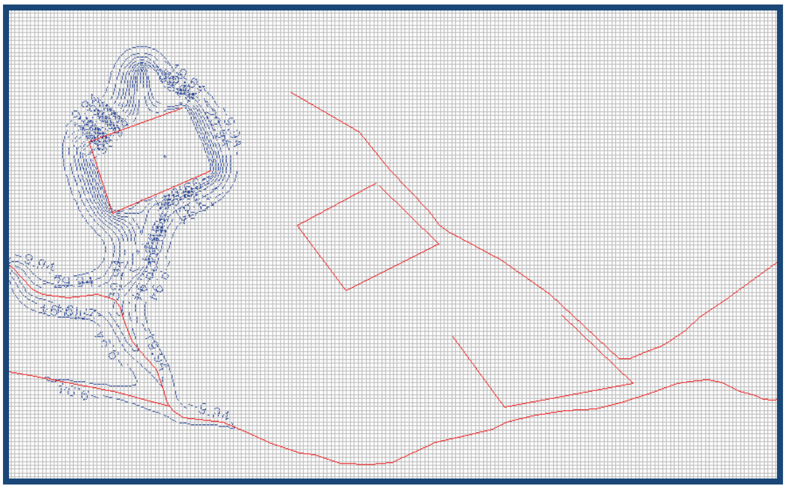


Figure 143: Draw down cone for Layer 2, dewatering of layer 4, after 10 years.

Figure 144: Drawdown cone for layer 2, dewatering layer 4, after 50 years.

Figure 145: Drawdown cone for layer 3 after 10 years.

Figure 146: Drawdown cone for layer 3 after 50 years.

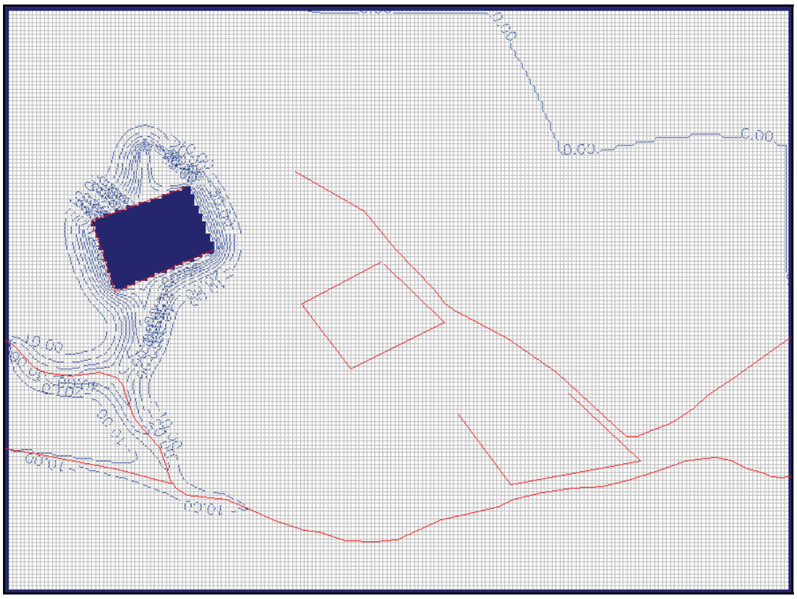


Figure 147: Drawdown cone for layer 4 after 10 years.

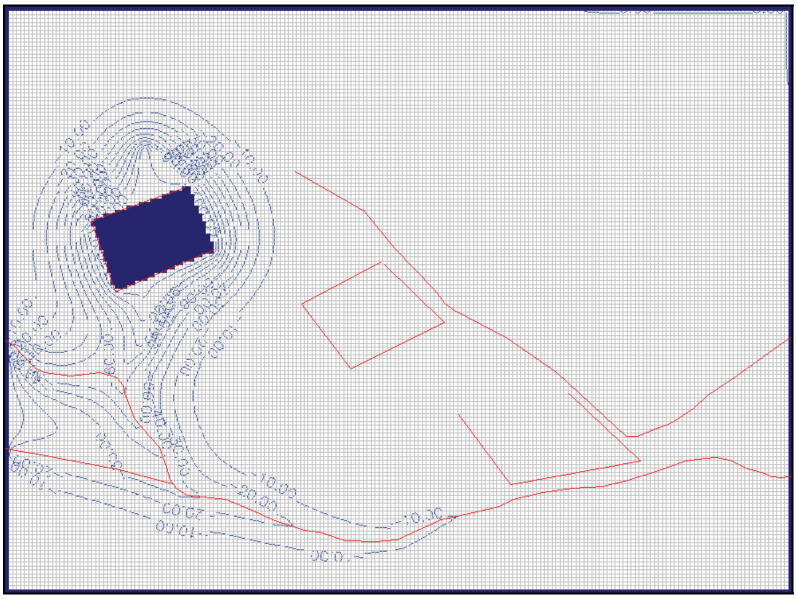


Figure 148: Drawdown cone for layer 4 after 50 years.

10.2.5.1 Discussion of Dewatering Models for Scenario 2

According to Table 4 there is a great difference in the volume of water predicted to flow into the mine should a major fault be encountered. As expected, the amount of water entering the mine decreases with time as a result of the fault being dewatered. The size of the drawdown cones increase as one move's from layer 1 down to layer 4. With layer 1 displaying a drawdown cone of 1.4 km and layer 4 a drawdown cone of 3.2 km after 50 years of dewatering. When comparing these findings to the findings for the first scenario, using the same transmissivity there is a marked difference. The drawdown cone for layer 4 in the first scenario, after 10 years, was 2.6 km. In this scenario the drawdown cone for the same layer at the same transmissivity is far smaller (1.4 km).

Table 26: A summary of the inflow and drawdown cones for the dewatering of scenario 2.

Mine intersecting a fault scenario:					
Layer	**Transmissivity (m^2/d)**	**Inflow (m^3/d)**	**Time (years)**	**Drawdown cone (km)**	**Location of constant head**
1	0.4	1751.52	10	1.4	*Layer 4*
2	0.4	1750.47	10	1.4	
3	0.4	1738.45	10	1.4	
4	0.4	1870.53	10	1.4	
1	0.4	1381.22	20	2.0	*Layer 4*
2	0.4	1378.77	20	2.0	
3	0.4	1364.28	20	2.0	
4	0.4	1486.50	20	2.0	
1	0.4	1034.37	50	3.2	*Layer 4*
2	0.4	1028.77	50	3.2	
3	0.4	1012.45	50	3.2	
4	0.4	1133.02	50	3.2	

However where in the first scenario the drawdown cone of 2.6 km was observed around the entire perimeter of the pit, the 1.4 km drawdown cone in the second scenario is only observed at the northern, eastern and western areas of the pit. Towards the south the drawdown cone follows the length of the fault, extending nearly 20 km towards the southeast, indicating that the fault acts as a preferred pathway. Therefore if the mine should intersect a fault, depending on the size, location and orientation of the fault, the impact on the water levels along the length of the fault may be severe.

It is therefore recommended that thorough surveys be conducted prior to mining in order to avoid sighting or expanding the mine through a fault. With time, the size of the drawdown cone around the pit increases as more and more of the surrounding aquifers are dewatered.

10.2.6 Decant Model for Scenario 2

A model was constructed to simulate the possibility for decanting should a fault be encountered. The model ran for 50 years with the results given in Figure 149. The model indicated a water level rise of 6-7 m after 50 years (Figure 150).

It is therefore concluded that, even if a fault is encountered during the course of mining, the mine will still not reach decant level. Even with a significant increase in the water level, the high degree of evaporation and the natural water level (being around 28 m below the surface) will prevent the mine from reaching decant level. It is recommended that the mining houses, conduct thorough surveys of the areas where the mines are to be located, to avoid or minimise the potential for encountering faults during the course of mining operations.

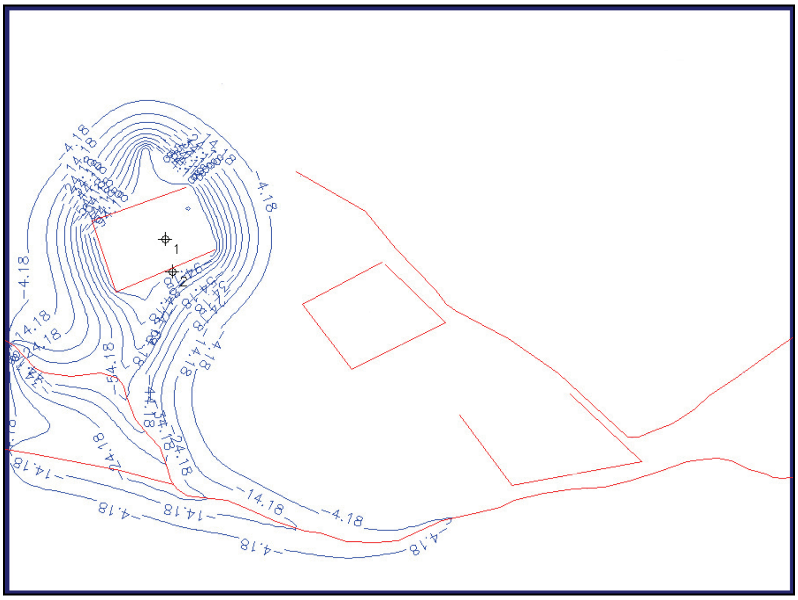


Figure 149: Decant model for Scenario 2.

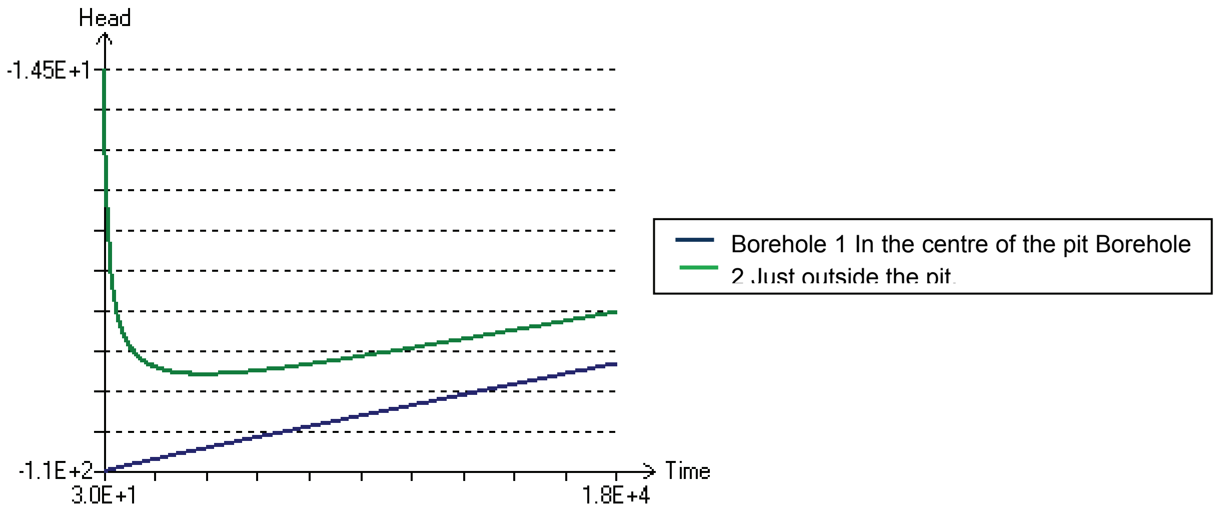


Figure 150: The Head-Time graph for the second scenario.

10.2.7 Dewatering Models for Scenario 3: Three Pits and Active Faults

The final set of models constructed was to demonstrate a scenario in which three pits are operational and have been mined down to a level of 110 m below surface. For this model, all the faults were activated and assigned transmissivities of 500 m^2/d. The model was run for 50 years and inflow into the mine calculated for every 10 years. A transmissivity of 0.4 m^2/d was used for the model.

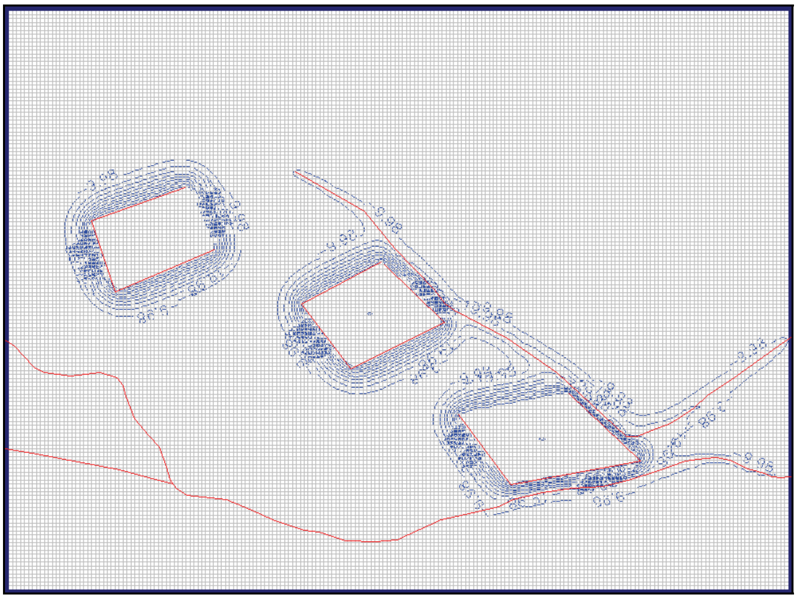


Figure 151: Drawdown cone for layer 2, 10 years after dewatering.

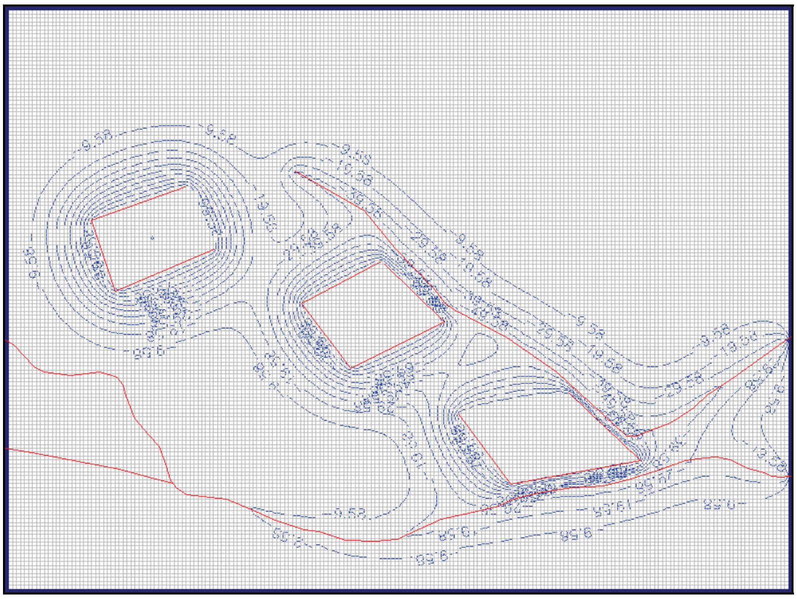


Figure 152: Drawdown cone for layer 2, 50 years after dewatering.

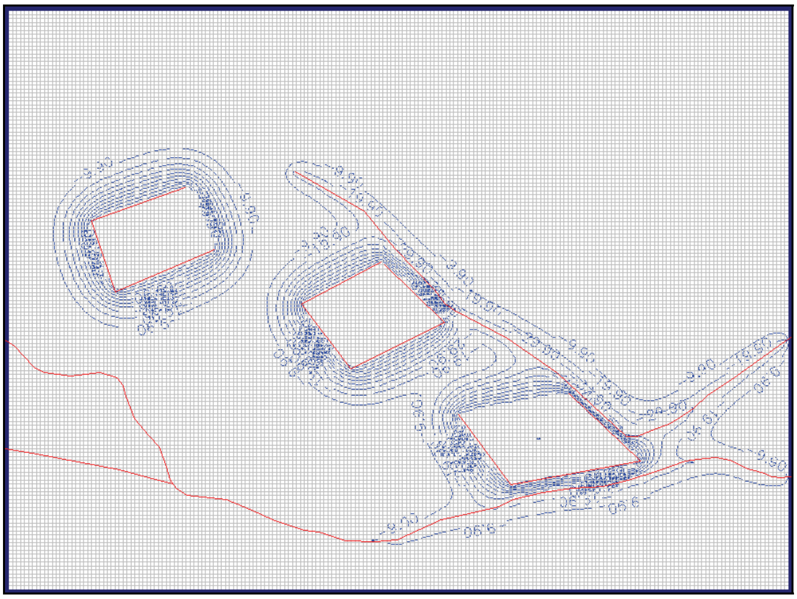


Figure 153: Drawdown cone for layer 3 after 10 years of dewatering.

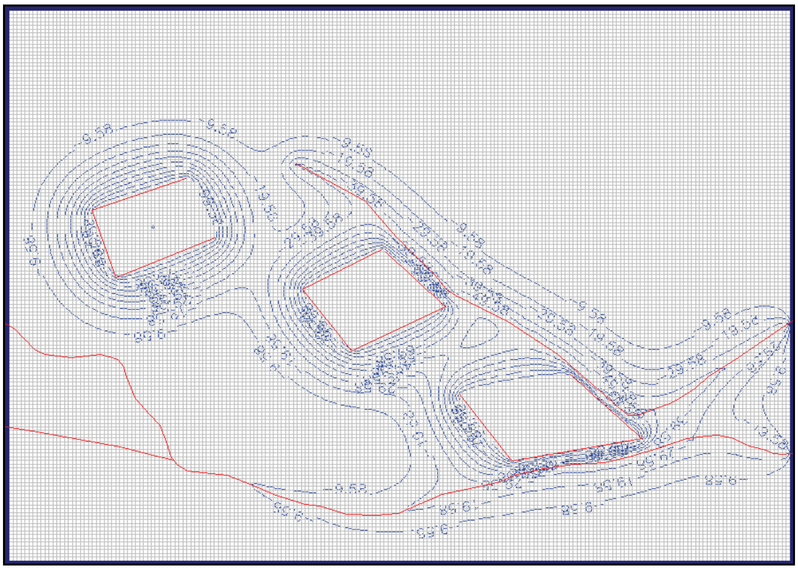


Figure 154: Drawdown cones for layer 3 after 50 years of dewatering.

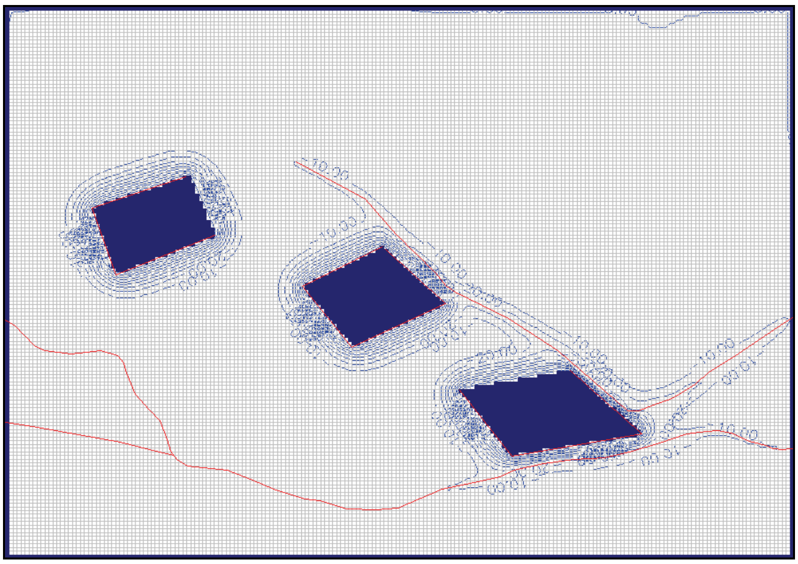


Figure 155: Drawdown cones for layer 4, 10 years after dewatering.

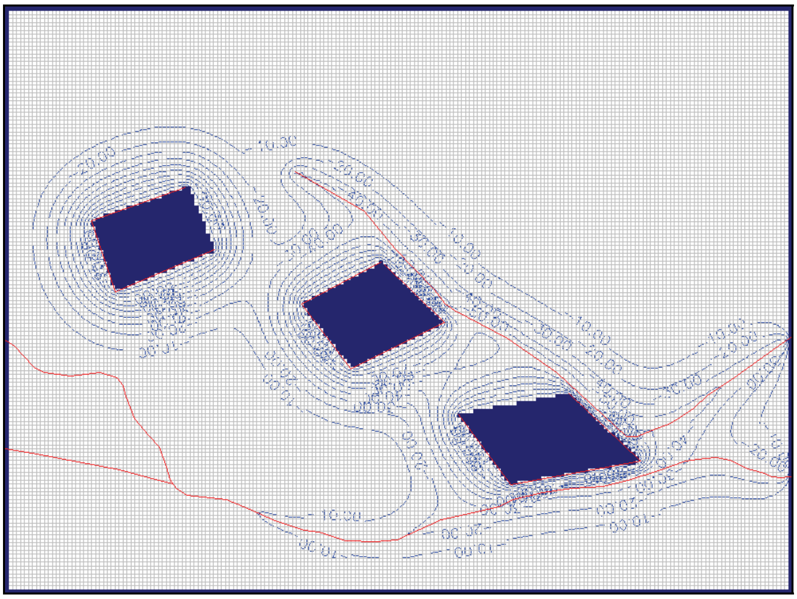


Figure 156: Drawdown cones for layer 4 after 50 years of dewatering.

10.2.7.1 Discussion of Dewatering Models for Scenario 3

The model indicates that, if the mines are located in close proximity to one another (5 km, chosen to simulate worst case situations), dewatering from one mine will have an impact on adjacent mines. Furthermore, the faults will have an impact on both the drawdown cones of the mines and the volumes of water flowing into the mines located in the vicinity of the faults. For the northern pit, the model indicates that the amount of water entering the mine decreases with time, with an increase in the extent of the drawdown cone (Table 27).

For the central pit, a similar scenario is observed, although it is notable that the volumes of water increase due to the proximity of the pit to a fault (Table 2). Furthermore, the initial size of the drawdown cone is smaller than that for the northern pit, although it is much larger after 50 years. The volumes of water entering into the central pit decreases with time, as was the case in the northern pit, however the volumes entering into the mine workings is higher with the addition of the much large drawdown cones.

The initial drawdown cones for the central pit and the northern pit are very much similar with them varying by 0.2 km after 10 years of dewatering (larger as in the case with the northern pit or smaller for the central pit). There is however, a much larger difference (1.4 km) in the final drawdown cones after 50 years of dewatering. At this stage the influence of the proximity of the mines to the faults and the proximity of the mines to one another can be seen.

Again as in the case with the second scenario, the extent of the drawdown cone is amplified by the presence of the faults, with the drawdown cones “following” the faults. It is recommended that the selection of mine locations be forgone by extensive exploration to determine the location of faults. For the south eastern pit, very much the same situations as was observed in the other two pits (Table 2). The initial drawdown cones are similar to those in the other pits, and the final cone observed after 50 years is very large. The volumes of water flowing into the pit, it is significantly more than in the case of the other two pits.

This is due to the location of the south-eastern pit between two faults. Thus the pit is influenced by both faults and is “drawing” water from both the faults. From the data in Tables 27, 28 and 29 there is a clear decrease in the volume of water flowing into the pit with the progression of time.

It must be stated that in reality the likelihood (if only initially) of the pits being in such close proximity is fairly small. It is likely that, as the models predicted, the pit proximity will play a role in determining the volumes of water flowing into the mines. This will increase with the sizes of the pits and with growing proximity of the pits to one another.

Table 27: A Summary of the drawdown cones and expected inflow in the northern pit for scenario 3.

Three pits active and all faults active scenario (North pit)					
Layer	**Transmissivity (m^2/d)**	**Inflow (m^3/d)**	**Time (years)**	**Drawdown cone (km)**	**Location of constant head**
1	0.4	748.83	10	1.4	*Layer 4*
2	0.4	748.77	10	1.4	
3	0.4	747.78	10	1.4	
4	0.4	754.73	10	1.4	
1	0.4	558.13	20	2	*Layer 4*
2	0.4	558.01	20	2	
3	0.4	556.65	20	2	
4	0.4	564.00	20	2	
1	0.4	474.04	30		*Layer 4*
2	0.4	473.86	30		
3	0.4	472.26	30		
4	0.4	480.14	30		
1	0.4	423.52	40		*Layer 4*
2	0.4	423.30	40		
3	0.4	421.51	40		
4	0.4	429.95	40		
1	0.4	388.41	50	3.2	*Layer 4*
2	0.4	388.15	50	3.2	
3	0.4	386.20	50	3.2	
4	0.4	395.18	50	3.2	

Table 28: A summary of the expected inflow and drawdown cones for the central pit.

Three pits active and all faults active scenario (Middle pit)					
Layer	**Transmissivity m^2/d**	**Inflow m^3/d**	**Time (years)**	**Drawdown cone (km)**	**Location of constant head**
1	0.4	804.82	10	1.2	*Layer 4*
2	0.4	804.77	10	1.2	
3	0.4	803.77	10	1.2	
4	0.4	811.35	10	1.2	
1	0.4	624.84	20	1.8	*Layer 4*
2	0.4	624.72	20	1.8	
3	0.4	623.32	20	1.8	
4	0.4	631.60	20	1.8	
1	0.4	537.63	30		*Layer 4*
2	0.4	537.45	30		
3	0.4	535.77	30		
4	0.4	544.73	30		
1	0.4	480.36	40		*Layer 4*
2	0.4	480.13	40		
3	0.4	478.22	40		
4	0.4	487.80	40		
1	0.4	437.68	50	4.6	*Layer 4*
2	0.4	437.41	50	4.6	
3	0.4	435.31	50	4.6	
4	0.4	445.48	50	4.6	

Table 29: A Summary of the drawdown cones and the expected inflow for the south eastern pit.

Three pits active and all faults active scenario (South Eastern pit)					
Layer	**Transmissivity m^2/d**	**Inflow m^3/d**	**Time (years)**	**Drawdown cone (km)**	**Location of constant head**
1	0.4	1271.40	10	1.4	*Layer 4*
2	0.4	1271.34	10	1.4	
3	0.4	1270.13	10	1.4	
4	0.4	1282.59	10	1.4	
1	0.4	1069.80	20	2.2	*Layer 4*
2	0.4	1069.66	20	2.2	
3	0.4	1067.84	20	2.2	
4	0.4	1082.77	20	2.2	
1	0.4	964.59	30		*Layer 4*
2	0.4	964.36	30		
3	0.4	962.08	30		
4	0.4	979.12	30		
1	0.4	893.41	40		*Layer 4*
2	0.4	893.09	40		
3	0.4	890.43	40		
4	0.4	909.37	40		
1	0.4	840.09	50	5.2	*Layer 4*
2	0.4	839.71	50	5.2	
3	0.4	836.71	50	5.2	
4	0.4	857.39	50	5.0	

10.2.8 Decant Model for Scenario 3

The decant model for scenario 3 indicated rises in water levels of between 2.5 m and 2.6 m for the northern pit, 2.7 m in the central pit, and between 3.4 m and 3.5 m in the south-eastern pit after 50 years (Figure 157). This is in accordance with the initial models that indicated a rise of 2 m in the northern pit. Accordingly the proximity of the adjacent pits help to reduce the volumes of water that will flow back into the pit once mining has stopped.

According to information received from the Grootegeluk mine, the main influx of water into the pit at the mine occurs during times of intense rainfall (rainfall events measuring 25 mm or more). To account for this, the rational formula for predicting run-off ($Q = CiA$, where Q is the run-off, C is a constant, i is rainfall intensity and A is the expected run-off area (in this instance C was selected as 0.07)) was used to calculate the expected run-off into a pit with an area of 800 ha. This leads to an expected rise in water level of 0.026 m and a volume of 43200 m^3/d (Q calculated to be 0.5 m^3/d). This will have almost no effect on the potential for the mines to reach decant levels. The modelling results indicate that the volumes of water moving into the mines are small, this coupled with the low rainfall, deep water levels and high evapotranspiration will result in the mines not reaching levels at which the mines will be able to decant.

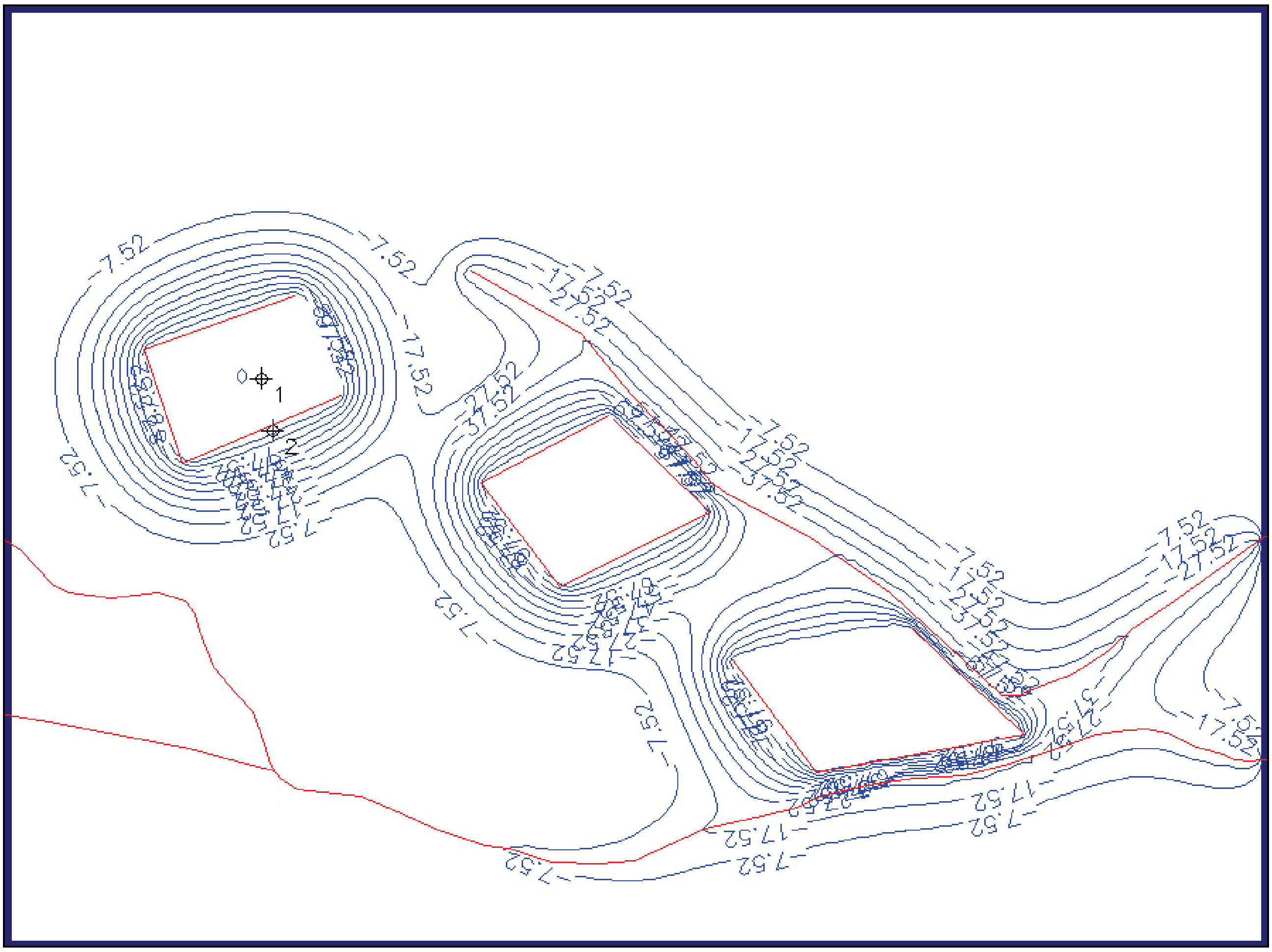


Figure 157: Decant model for the third scenario.

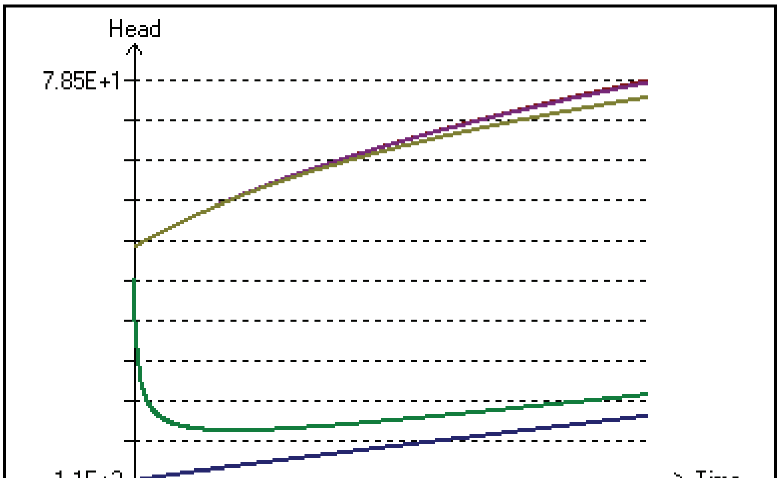


Figure 158: A graph for the decant model of the third scenario.

10.3 Discussion of Model Results

10.3.1 Inflow of Water

For all the scenarios there is very little inflow into the pits. When taking only the worst case transmissivities of 0.4 m^2/d the inflow is:

- **Scenario 1:** The inflow varies between 749 m^3/d and 755 m^3/d for layers 1 and 4 respectively. These are very small volumes, translating to 22465 m^3/month and 22642 m^3/month.
- This is in accordance with what has been observed at the presently active mine.
- **Scenario 2:** For this scenario the inflow for the same layers over the same time period is much higher due to the influence of the fault running through the pit. The inflow is predicted to be in the order of between 1752 m^3/d and 1871 m^3/d for layers 1 and 4 respectively.
- This is a substantial increase in the water influx and care should be taken by the mining houses to avoid mining through a fault as this will lead to a much larger radius of influence from the mining activities.
- **Scenario 3:** According to the data for this scenario, the closer the pits are located to the faults and to one another, the larger the impact of the faults and the adjacent mines will be. With increasing proximity to the faults the volumes of water expected to move into the mines increases.
- For example for layer 4 of the northern pit located the furthest away for a fault the expected influx is 755 m^3/d while the expected influx into the south eastern pit is calculated to be 1283 m^3/ in the same layer over 10 years.
- It is therefore recommended that the mines not be located to near the faults and further that the sizes of the mines be monitored to prevent the pits from becoming excessively large (larger than 1000 ha).

10.3.2 Drawdown Cones

- **Scenario 1**: When taking the worst case there is little variation in the drawdown cones produced in the different layers after 10 years. With all the layers displaying a drawdown cone of 2.8 km with the exception of layer 4 displaying a drawdown cone of 2.6 km.
- **Scenario 2**: Due to the fault running through the pit the drawdown cone of the pit is dramatically increased, following the fault.
- The drawdown cone, in the immediate vicinity of the pit, is not as large as in the first scenario (1.4 km for all 4 layers) but the influence of the mine dewatering can be observed for nearly the entire length of the fault.
- **Scenario 3**: In this scenario the influence of the close proximity of the pits to the faults and to one another can be clearly identified by the very large drawdown cones.
- The cones for the different pits do vary with the northern and the south eastern pits displaying a drawdown cone of 1.4 km for all the layers.
- The central pit displays a drawdown cone of 1.2 km around the pit after 10 years.
- The size of the cones increasing as time progresses showing the same trend as with the second scenario in that the faults amplify the impact of the dewatering caused by the mining.

10.4 Conclusions

From the different scenarios simulated during modelling several conclusions can be drawn for both decant and dewatering scenarios.

10.4.1 Dewatering

The dewatering simulations indicated that there is very little groundwater in the study area and that the water moves slowly (due to the low transmissivities of the rocks), predominantly along structures such as dykes, fractures and faults. The predominant geological structures in the study area (the three main faults) act as conduits for water movement. This was indicated by the modelling and is also observed in the field, by the fact that boreholes located near the structures have higher yields than boreholes located further away from the structures. Accordingly, it is predicted that should a mine intersect a fault during mining operations, the volume of water expected to flow into the mines will increase. It is therefore recommended that mines try to avoid mining through a fault.

10.4.2 Decant

From the modelling results both dewatering and decanting models, there is no evidence that the pits will reach decant levels. There are not large enough volumes of water present and due to the low transmissivities and high evaporation it is concluded that the pits will not reach decant level.

11 Groundwater Management in the Waterberg Coalfields

11.1 Introduction

From the results of the modelling it is clear that the volumes of water that will enter the mines from both groundwater sources and from surface runoff will be small. Due to the small volumes of water expected to enter the workings of the mines, it is recommended that the water be pumped out and used for run of mine operations such as dust suppression or washing of the ore. Figure 159 and Figure 160 show sumps at the Grootegeluk mine where all the water that flows into the mine is concentrated and pumped out to be used for run of the mine operations.

Figure 159: Surface runoff and groundwater inflow concentrated in a single location in the mine workings (courtesy of the Grootegeluk mine).

Figure 160: An obsolete sump being backfilled (courtesy of the Grootegeluk mine).

Steps should be taken to ensure or minimize the risk of encountering a fault during mining. If the mines encounter large faults and start to dewater the faults, many farmers with boreholes along the length of the fault might see significant decline in the water levels of their boreholes.

11.2 Water Quality Management

At present the main form of rehabilitating the pit at the Grootegeluk mine, is done by placing the rocks back into the pit in the same order as it was removed. However, due to the large quantity of coal removed from the pit (nearly 60 m), the pit will never be rehabilitated to surface level. Accordingly the pit will be backfilled as a series of benches each lined and sealed, until all the backfill material has been used. This will lead to the generation of a moving void as the pit is continuously mined and areas that have been mined out are backfilled. Additionally to account for the volume of coal removed during mining the spoils/discard from the beneficiation process will be placed into the pit and covered with the rock removed during mining. In an effort to minimize the exposure of these rocks (and the discard from the beneficiation plants) to oxygen and water it was decided early on in the study that it would be best to store the rocks with the highest acid potential near the bottom of the pit. It was hoped to flood the more dangerous acid generators located near the bottom of the pit and thus diminish the capacity for acid generation.

However, due to the low levels of rainfall in the study area, the small transmissivities, low recharge and the high evaporation, flooding of the spoils by means of natural processes will not be possible. It was proposed by Fourie (2009) that water from a pipeline that is currently under construction (for the transport of water to the study area) be used to flood the spoils. This is a possibility but it is predicted that this will be too expensive in both monitory and water volume terms to be sustainable. Given the small volumes of water expected to flow into the mines and the porous nature of the backfilled pit it is predicted that placing the spoil on the lowest level of the pit will inevitably lead to acid generation. It is therefore proposed that the spoil, along with other rock units that have the potential to produce acid, be placed at a higher level to keep the spoil "dry." The spoil should only be exposed to the minimal influx of groundwater into the pit and the occasional heavy surface runoff. This will minimize the level of acid generation that will take place from the spoils. By doing so, the runoff that reaches the spoil will, unfortunately become acidic. This effluent will collect in the area of the pit that is not to be rehabilitated with waste rock. To reduce the level of acidity that will be generated it is recommended that the rocks with high base potential be mixed with the rocks with a high acid potential, as this will further minimize the amount of acidity that will be generated.

The effluent that will be generated from this mixture of high acid potential and high base potential rocks is expected to have high salt contents and will likely turn acidic with time as the buffer potential is diminished. This effluent will become very concentrated as time passes.

The reasons for this are twofold:

- The effluent will gather in a single area in the pit.
- The effluent will be exposed to the open air and thus the high evaporation in the study area.

The generation of the acidity is unavoidable, but the collection of this effluent in one location and the low volume expected to enter into the pit, does have certain advantages. The localization of the effluent can localize the treatment of said effluent, thus for example if the addition of carbonates is selected for treatment of the acidity, it will only need to be applied to one area.

Van Tonder (2009) proposed that the size of the material being used for backfill be varied. If this is done it will alter the porosity of the backfilled mine. This will lead to a very slow migration of any acid generated in the backfilled mine. This will serve to delay the movement of the generated acidic effluent. This will not prevent the generation of acid but will serve to provide time for the mining houses to implement the necessary management protocols.

In addition to varying the size of the material used as backfill Van Tonder (2009) recommended that the pits be lined with a layer of Bentonite clay. This would prevent the movement of acidic or other wisely contaminated pit water from moving into the groundwater systems. This is a very solid proposal with the major drawback being however that it would be very expensive to line a pit of 700 ha or more with Bentonite.

If the mining company operating the mine has sufficient funds then this will be a very sound method for the prevention of aquifer contamination. A method of acid generation prevention that has been proposed by Dreyer (2009) is to slurry all the spoils, the discard and the effluent from slimes dams and evaporation ponds. This slurry is then to be pumped back into the pit and the entire pit sealed. This method will be ideal for the solution of the acid generation problem and the potential movement of the contaminants into the groundwater system.

The slurry proposal along with the flooding proposal will both serve to eliminate the acid generation problem. The problem with the methods however are that they can only be employed once all the mining in the pit has stopped. Even if the method currently being used at Grootegeluk of rehabilitating in benches and sealing each bench individually is used the large volumes of contaminated water that will be present in the pit will provide an unacceptable risk to the miners. It is therefore proposed that the method currently employed at the Grootegeluk mine be used for all the new mines planned for the area. In addition it is recommended that spoils/discard be placed at levels that will minimize the exposure of these rocks to the influx of groundwater.

11.3 Potential Rehabilitation Methods for AMD

Many options for the management of water quality within opencast coal mines have been considered in the past. Unfortunately very few practical solutions have generally been available. Some of these measures will be discussed and their viability and applicability to the study area will also be discussed.

The actions in the treatment of AMD are twofold and they can be either:

11.3.1 Preventative measures

- Attempt to control the rate of acid generation
- Attempt to limit the migration of the acid generation products

11.3.2 Containment measures

- To flood as much of the spoils as possible, thus eliminating oxidation of sulphides, and/or
- To contain and evaporate the spoil water

From the above, the most viable form of treatment for AMD will be containment, as the effluent that will be generated will gather in a single location. Although the philosophy behind containment is sound, there are several practical limitations; the final water level in any pit is regulated by its decant level. The decant level is the lowest topographic level where water from the pit will eventually overflow onto surface, but/ and this level will never be reached in the pits in the study area.

The second reason for considering the containment of spoil water is, when evaporation is a potential management strategy. (Hodgson *et al.,* 1995). The evaporation in the study area is 2000 mm/y, a very large amount and will decrease the water stored in the pit considerably. With the evaporation area being contained within the boundaries of the pit itself, this will cut down on costs and exposure of other areas to potential pollution. Containment whether within the spoil or in evaporation areas, will however lead to further salination of the water.

According to the chemical data of the water analysis, it becomes apparent that the groundwater found in some areas in the study area are already saline. Any further deterioration of the groundwater quality will have a detrimental effect on the people who are dependent on groundwater. However, if this low quality water can be contained in the pit itself and not re-enter the groundwater system, it will have no effect on people dependant on the groundwater resource. Containment is a possible option for the management of spoil water. However, containment appears to be more applicable to new opencast mining where total containment can be planned. Containment is therefore a viable option for the newly planned collieries in the study area, but should be monitored closely.

11.3.3 Additional Options for the Treatment of Acidic Waters

11.3.3.1 Introduction of Buffering Agents

The addition of acid-consuming components increases the salt load in the environment. However, saline alkaline leachates are generally more favoured in the environment than acidic waters. Buffering agents introduced into spoils are varied (Hodgson *et al.,* 1995). The introduction of buffering agents in an effort to prevent / manage acid generation, might hold problems for the study area.

From the chemical data of the groundwater analysis of the study area it has become evident that there are already areas that have high salt levels. The introduction of more salt to the system will deteriorate the conditions further. This will cause the already scarce groundwater resources to become even more so.

11.3.3.2 Introduction of Lime

Where lime is added to the spoil surface, the base potential is transported into the spoil via the dissolution of the material by percolating rain water. However, there is a limit to the solubility of mineral phases within rain water. The resultant weakly buffered alkaline water may be insufficient to neutralise all the acidity of the spoil, depending on the rate of acid production (Hodgson *et al.,* 1995). Due to the low levels of rainfall and the concentration of rainfall in the summer months, it is doubtful that this rehabilitation method will have success in the study area. Lime addition is most effective where the neutralising components are thoroughly mixed within the spoil. This places the acid-consuming materials in close proximity to the acid-generating sites, thereby inhibiting the development of acidic environments. This counteracts bacterial oxidation of the pyrite.

11.3.3.3 Introduction of Power Station Fly Ash

Power station fly ash is considered as a commodity by the power-generating industry of South Africa. The capacity of the fly ash to neutralise acid mine drainage is only about 5-16% of that of lime. A further disadvantage of fly ash addition is that the material contains significant concentrations of heavy metals (Hodgson *et al.,* 1995).

If the fly ash dosage is insufficient for complete neutralisation of the system, the resultant acidity will be accompanied by the additional release of heavy metals. An excess dosage of fly ash will therefore be required to compensate for the higher risk associated with the use of this ameliorant. It may be concluded that the use of power station fly ash is only suitable for mines that are slightly acidic or alkaline in nature. It is not recommended that this material be used in very acidic mines, due to the high heavy metal content of the ash. According to Dreyer (2009) there is little to no acid generation at present taking place at the Grootegeluk mine. Due to the close proximity of the Matimba power station and the additional power station planned for the area, there will be no shortage of fly ash. If indeed the mines do not become very acidic and the acid that is generated can be neutralized in a few applications of the method, this method could be utilized with some success in the study area.

11.4 Conclusions

There are many possible water quality control measures that can be used to either prevent groundwater contamination or to contain any possible contaminants in the study area. It is recommended that preventative measures be taken rather than containment for the new mines planned for the area. Additionally for the data it is recommended that the rehabilitation methods currently employed by the Grootegeluk mine be used by the new mines as it has proven to be an effective form of rehabilitation for the local conditions in the study area.

12 Overall Conclusions and Recommendations

12.1 Conclusions

From the various aspects of the groundwater systems of the Waterberg coalfields that were investigated during the course of the project certain conclusions can be drawn. A conceptual model (Figure 161) for the Waterberg coalfield was constructed to summarize the findings of the project. The model is not to scale and focuses on the areas to the west of the Daarby fault as this area will be mined by means of opencast methods.

12.1.1 Climate

From Figure 161 one can observe that the study area has a dry climate, with low rainfall and high evapotranspiration. The model displays the primary runoff for the study area and the location of the Limpopo River

12.1.2 Geology

Figure 161 additionally displays the primary geological structures and the divisions of the coal seams in 11 zones as found in the study area. The location of the three main geological structures (the Daarby-, Eenzaamheid- and Zoetfontein faults) and the relation the structures has to the location of the coal in the study area can also be seen. Figure 161 also displays the distribution of the primary geological formations found in the study area namely the relation of the Karoo and Waterberg group rocks to the faults. The model further shows the sub division of the study area on the basis of the weathering that had taken place. With the green areas shown the full succession of geology, the yellow areas have been eroded down to the middle Ecca and the red parts have been weathered in parts.

12.1.3 The Mine Workings

In addition to these geological parameters the model displays the location of a single pit modeled on the Grootegeluk pit. The pit displays the method of rehabilitation currently being used at the Grootegeluk mine, in an effort to reduce the amount of acid generated as it was determined by the investigation that a certain amount of acid generation is unavoidable. The current measured parameters such as the influx of water and the drawdown cone of the pit at the Grootegeluk mine are also given, showing an influx of 30 000 m^3/month and a drawdown cone of approximately 3 km 25 years after the mining started.

12.1.4 Measured Parameters and Modelling Results

Measures results such as the average water level of 28 m below surface, recharge (determined by the Cl and E.A.R.T.H. methods) of 1.5% and the expected rise of 2 m in water level once mining has stopped area also displayed in the model. In addition the model also shows the effect the mining infrastructure has on the groundwater in its vicinity, as is manifested by the artificial recharge witnessed at the Grootegeluk mine on the eastern side of the Daarby fault.

12.1.5 Acid-Base Results

The results of the ABA as done according to the weathering depth of the geology is summarized in Figure 161. With the green areas showing signs of being likely acid generators with and increased likely hood of acid generation at a depth of 50-80 m beneath the surface. The results for the yellow areas were inconclusive as no determinations could be made with h regards to acid potential and weathering depth for these areas. In addition the results indicated that samples taken from the red areas along with discard samples from the beneficiation plants at the Grootegeluk mine will generate acid once exposed to water and oxygen.

12.1.6 Water Quality

A summary of the observed water qualities for the different localities examined during the study, is provided in the model. There can be distinguished between four primary localities namely;

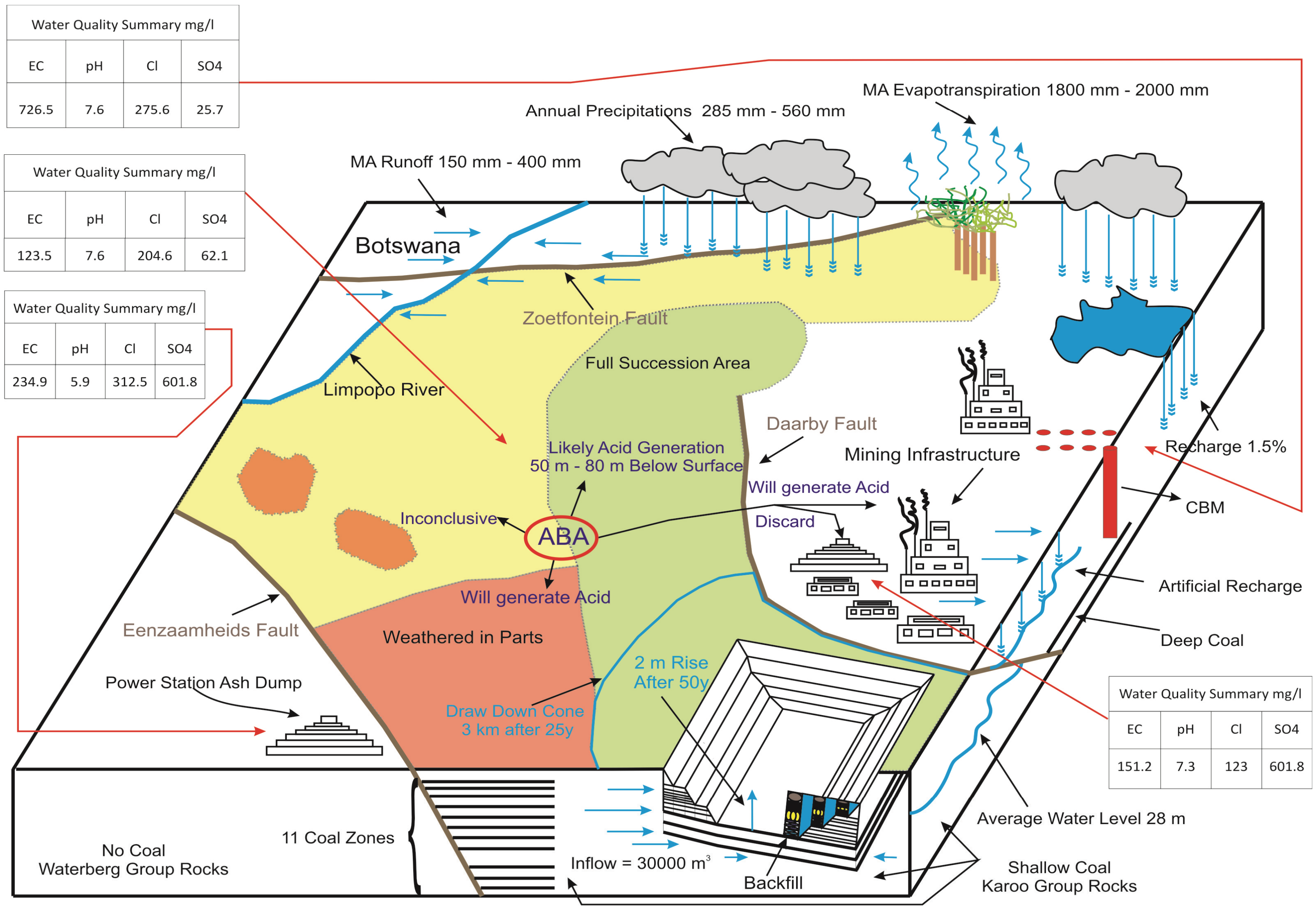
- The areas that are unaffected by activities, showing fair water qualities, with high Cl contents and EC values
- The areas affected by Coal Bed Methane extraction, which display very high EC and Cl values. These values are not the result of pollution but, is a natural phenomenon concerned with the depth of the boreholes and the age of the water.
- The areas that have been affected by mining, these areas display EC and Cl values that area similar to those observed for the unaffected areas. These areas do however have severely elevated SO4 levels as a result of mining activities.
- Areas affected by power generation, there was concentrated on the results of coal fire power generation, namely the fly ash dump found in the area, which indicated high EC values, lower pH values and elevated Cl and SO4 values.

It is the conclusion of this study that the addition of new mines to the area will have a deteriorating effect on the quality and quantity of the groundwater in the study area. The small volumes of water that is available in the study area will be reduced by the excavation of new mines. The effects will be more visible in areas located west of the Daarby fault. The impermeable nature of the fault will prevent groundwater movement from the areas east of the fault to area west of the fault. The same can be stated for the areas north of the Eenzaamheid fault, as according to Dreyer (2009) this fault is also impermeable and groundwater on the southern side of the fault will not be affected by abstraction on the northern side of the fault.

12.2 Recommendations

It is recommended that the method of mining, beneficiation, remediation and water management currently being employed by the Grootegeluk mine, be employed by the new mines. The methods being used at the Grootegeluk mine have been proven to be the best possible solutions for the conditions found in the study area. Additional recommendations are:

- A study to determine the percentage of water moving into the groundwater system from the washing plants and the effect thereof on the water quality.
- It is recommended that the size of the material to be placed back into the pits as backfill be varied as this will decrease the porosity of the backfilled pit and slow the movement of contaminants.
- It is recommended that the discard and spoils be slurried, pumped back into the mine and that the entire mine then be sealed by clay or other absorbent material, that will prevent the movement of the pollutants into the groundwater system.
- Future recommended studies:
- The performing of additional ABA testing over a larger area and the expansion of the testing program to include kinetic tests.
- A study to be done on the possibility of using water from the new pipeline to flood the spoils and how this will influence the rehabilitation methods for backfilling the pit.
- A study should be done on what the impact of the water from the new pipeline will be and how much of the water from the pipeline will enter into the groundwater system.



Water Quality Summary mg/l			
EC	pH	Cl	SO4
726.5	7.6	275.6	25.7

Water Quality Summary mg/l			
EC	pH	Cl	SO4
123.5	7.6	204.6	62.1

Water Quality Summary mg/l			
EC	pH	Cl	SO4
234.9	5.9	312.5	601.8

Water Quality Summary mg/l			
EC	pH	Cl	SO4
151.2	7.3	123	601.8

Figure 161: Conceptual model for the Waterberg coalfield, showing a single pit backfilled in the manner as is being done at the Grootegeluk mine. Additionally the model provides a summary of the water quality for the various localities of the study area along with aquifer parameters such as recharge. This model is not to scale.

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Appendix A – Results for the Acid-Base Accounting Analyses

Table 30: Interpretation of ABA pH results.

[redacted]

Table 31: Interpretation of ABA Net Neutralizing Potential results.

Site Name	Depth	Net Neutralising Potential (Open)	Net Neutralising Potential (Closed)	Interpretation
SS 1	5m	0.16	-0.09	Verify with other tests
SS 2	17m	1.88	1.62	Verify with other tests
SS 3	25m	3.69	3.41	Verify with other tests
SS 4	43m	-0.27	-0.55	Verify with other tests
SS 5	54m	47.02	23.68	Probably Excess Neutralising Minerals
SS 6	66m	14.16	3.49	Verify with other tests
SS 7	68m	-236.52	-488.39	Potential Acid Generator
SS 8	72m	4.80	-8.72	Verify with other tests
SS 9	75m	-6.05	-10.47	Verify with other tests
SS 10	77m	105.41	101.43	Probably Excess Neutralising Minerals
SS 11	83m	-46.23	-97.73	Potential Acid Generator
SS 12	94m	12.02	9.01	Verify with other tests
SS13	96m	-0.58	-1.02	Verify with other tests
SS 14	104m	51.02	47.16	Probably Excess Neutralising Minerals
SS 15	118m	-97.78	-209.12	Potential Acid Generator
SS16	173m	-6.84	-10.17	Verify with other tests
SS 17	187m	-2.80	-3.95	Verify with other tests
SS 18A	188m	-85.60	-187.93	Potential Acid Generator
SS 18B	188m	-0.93	-1.83	Verify with other tests
SS 19	190m	-3.04	-4.01	Verify with other tests

Table 32: Interpretation and NP/AP ratios for the north/western core samples.

Site Name	Depth	Neutralising Potential Ratio(NP/AP) for Open System	Interpretation Open System	Interpretation Closed System
SS 1	5m	1.640	Acid under certain conditions	Likely Acid Generator
SS 2	17m	8.235	No Acid Potential	No Acid Potential
SS 3	25m	14.365	No Acid Potential	No Acid Potential
SS 4	43m	0.037	Likely Acid Generator	Likely Acid Generator
SS 5	54m	3.015	Acid under certain conditions	Acid under certain conditions
SS 6	66m	2.327	Acid under certain conditions	Acid under certain conditions
SS 7	68m	0.061	Likely Acid Generator	Likely Acid Generator
SS 8	72m	1.355	Acid under certain conditions	Likely Acid Generator
SS 9	75m	0.000	Likely Acid Generator	Likely Acid Generator
SS 10	77m	27.499	No Acid Potential	No Acid Potential
SS 11	83m	0.102	Likely Acid Generator	Likely Acid Generator
SS 12	94m	4.990	No Acid Potential	Acid under certain conditions
SS13	96m	0.023	Likely Acid Generator	Likely Acid Generator
SS 14	104m	14.213	No Acid Potential	No Acid Potential
SS 15	118m	0.122	Likely Acid Generator	Likely Acid Generator
SS16	173m	0.000	Likely Acid Generator	Likely Acid Generator
SS 17	187m	0.009	Likely Acid Generator	Likely Acid Generator
SS 18A	188m	0.163	Likely Acid Generator	Likely Acid Generator
SS 18B	188m	0.011	Likely Acid Generator	Likely Acid Generator
SS 19	190m	0.010	Likely Acid Generator	Likely Acid Generator

Table 33: Initial and final pH values for south eastern samples.

Site Name	Depth	Initial pH	Final pH	Interpretation
GGS 1	33m	8.27	4.99	Medium Risk Acid Generation
GGS 2	52m	7.91	2.22	Higher Risk Acid Generation
GGS 3	150m	6.62	2.55	Higher Risk Acid Generation
GGS 4	156m	8.01	4.57	Medium Risk Acid Generation
GGS 1A	-	8.31	5.30	Medium Risk Acid Generation
GGSVZ 1	1m	5.73	3.38	Higher Risk Acid Generation
GGSVZ 2	2m	6.43	3.11	Higher Risk Acid Generation
GGSVZ 3	3m	6.63	3.85	Medium Risk Acid Generation
GGSVZ 4	4m	6.2	3.62	Medium Risk Acid Generation

Table 34: Interpretation of ABA Net Neutralizing Potential results.

Site Name	Depth	Net NP (Open)	Net NP (Closed)	Interpretation
GGS 1	33m	16.12	-2.70	Verify with other tests
GGS 2	52m	-53.97	-123.05	Potential Acid Generator
GGS 3	150m	-5.26	-7.42	Verify with other tests
GGS 4	156m	77.25	68.40	Probably Excess Neutralising Minerals
GGS 1A	-	11.87	11.35	Verify with other tests
GGSVZ 1	1m	-2.39	-2.56	Verify with other tests
GGSVZ 2	2m	-2.93	-3.20	Verify with other tests
GGSVZ 3	3m	-2.49	-2.64	Verify with other tests
GGSVZ 4	4m	-3.74	-4.35	Verify with other tests

Table 35: Interpretation and NP/AP ratios for Exxaro core samples.

Site Name	Depth	NP Ratio(NP/AP) for Open System	Interpretation Open System	Interpretation Closed System
GGS 1	33m	1.857	Acid under certain conditions	Likely Acid Generator
GGS 2	52m	0.219	Likely Acid Generator	Likely Acid Generator
GGS 3	150m	0.005	Likely Acid Generator	Likely Acid Generator
GGS 4	156m	9.728	No Acid Potential	No Acid Potential
GGS 1A	-	24.010	No Acid Potential	No Acid Potential
GGSVZ 1	1m	0.056	Likely Acid Generator	Likely Acid Generator
GGSVZ 2	2m	0.037	Likely Acid Generator	Likely Acid Generator
GGSVZ 3	3m	0.068	Likely Acid Generator	Likely Acid Generator
GGSVZ 4	4m	0.017	Likely Acid Generator	Likely Acid Generator

Table 36: Interpretation of ABA pH results.

Site Name	Depth	Initial pH	Final pH	Interpretation
GT1 S1	1m	6.12	4.47	Medium Risk Acid Generation
GT1 S2	2m	7.45	5.12	Medium Risk Acid Generation
GT1 S3	3m	7.17	4.92	Medium Risk Acid Generation
GT1 S4	4m	7.01	4.61	Medium Risk Acid Generation
GT1 S5	5m	6.49	4.12	Medium Risk Acid Generation
GT1 S6	6m	6.58	3.55	Medium Risk Acid Generation
GT1 S7	7m	6.43	3.38	Higher Risk Acid Generation
GT1 S8	8m	7.00	3.34	Higher Risk Acid Generation
GT1 S9	9m	6.58	3.62	Medium Risk Acid Generation
GT2 S1	1m	8.62	6.29	Lower Acid Risk
GT2 S2	2m	8.34	6.59	Lower Acid Risk
GT2 S3	3m	8.78	6.17	Lower Acid Risk
GT2 S4	4m	8.66	5.29	Medium Risk Acid Generation
GT2 S5	5m	8.48	5.99	Lower Acid Risk
GT2 S6	6m	7.31	5.90	Lower Acid Risk
GT2 S7	7m	8.50	5.64	Lower Acid Risk
GT2 S8	8m	8.43	5.19	Medium Risk Acid Generation
GT2 S9	9m	7.94	4.94	Medium Risk Acid Generation
GT3 S1	1m	6.00	3.50	Lower Acid Risk
GT3 S2	2m	6.62	5.04	Medium Risk Acid Generation
GT3 S3	3m	7.67	5.43	Medium Risk Acid Generation
GT3 S4	4m	7.30	5.26	Medium Risk Acid Generation
GT3 S5	5m	7.50	5.05	Medium Risk Acid Generation
GT3 S6	6m	7.34	4.81	Medium Risk Acid Generation
GT3 S7	7m	6.90	3.74	Medium Risk Acid Generation
GT3 S8	8m	6.82	3.40	Higher Risk Acid Generation
GT3 S9	9m	6.70	3.41	Higher Risk Acid Generation
GT3 S10	10m	6.65	3.80	Medium Risk Acid Generation
GT4 S1	1m	8.38	5.04	Medium Risk Acid Generation
GT4 S2	2m	8.10	5.02	Medium Risk Acid Generation
GT4 S3	3m	8.37	4.90	Medium Risk Acid Generation
GT4 S4	4m	8.16	4.72	Medium Risk Acid Generation
GT4 S5	5m	7.80	4.62	Medium Risk Acid Generation
GT4 S6	6m	8.07	4.62	Medium Risk Acid Generation
GT4 S7	7m	7.21	4.16	Medium Risk Acid Generation
GT4 S8	8m	6.79	3.85	Medium Risk Acid Generation
GT4 S9	9m	6.72	3.77	Medium Risk Acid Generation
GT4 S10	10m	6.77	3.73	Medium Risk Acid Generation
GT7 S1	1m	6.56	3.90	Medium Risk Acid Generation
GT7 S2	2m	7.69	4.52	Medium Risk Acid Generation
GT7 S3	3m	7.49	5.16	Medium Risk Acid Generation
GT7 S4	4m	8.10	4.39	Medium Risk Acid Generation
GT7 S5	5m	7.66	4.48	Medium Risk Acid Generation
GT7 S6	6m	7.61	4.41	Medium Risk Acid Generation
GT7 S7	7m	7.93	4.77	Medium Risk Acid Generation
GT7 S8	8m	8.16	5.75	Lower Acid Risk
GT7 S9	9m	7.43	4.86	Medium Risk Acid Generation
GT7 S10	10m	7.12	4.23	Medium Risk Acid Generation
GT7 S11	11m	6.45	3.75	Medium Risk Acid Generation
GT7 S12	12m	6.49	3.29	Higher Risk Acid Generation
GT7 S13	13m	6.46	4.03	Medium Risk Acid Generation
GT7 S14	14m	6.69	3.67	Medium Risk Acid Generation

Table 37: Interpretation of ABA Net Neutralizing Potential results.

Site Name	Depth	Net NP (Open)	Net NP (Closed)	Interpretation
GT1 S1	1m	1.317	1.082	Verify with other tests
GT1 S2	2m	6.601	6.303	Verify with other tests
GT1 S3	3m	3.781	3.492	Verify with other tests
GT1 S4	4m	1.585	1.307	Verify with other tests
GT1 S5	5m	-0.665	-1.019	Verify with other tests
GT1 S6	6m	-0.956	-1.029	Verify with other tests
GT1 S7	7m	-1.525	-1.634	Verify with other tests
GT1 S8	8m	-1.653	-2.183	Verify with other tests
GT1 S9	9m	-2.994	-4.054	Verify with other tests
GT2 S1	1m	156.529	156.001	Probably Excess Neutralising Minerals
GT2 S2	2m	665.853	665.260	Probably Excess Neutralising Minerals
GT2 S3	3m	511.680	511.352	Probably Excess Neutralising Minerals
GT2 S4	4m	395.971	395.593	Probably Excess Neutralising Minerals
GT2 S5	5m	464.427	464.115	Probably Excess Neutralising Minerals
GT2 S6	6m	220.295	220.279	Probably Excess Neutralising Minerals
GT2 S7	7m	175.360	175.046	Probably Excess Neutralising Minerals
GT2 S8	8m	210.480	210.169	Probably Excess Neutralising Minerals
GT2 S9	9m	24.734	24.388	Probably Excess Neutralising Minerals
GT3 S1	1m	-1.685	-1.988	Verify with other tests
GT3 S2	2m	-1.538	-1.867	Verify with other tests
GT3 S3	3m	4.922	4.670	Verify with other tests
GT3 S4	4m	2.984	2.968	Verify with other tests
GT3 S5	5m	3.670	3.166	Verify with other tests
GT3 S6	6m	2.661	2.701	Verify with other tests
GT3 S7	7m	-1.094	-0.875	Verify with other tests
GT3 S8	8m	-2.953	-3.110	Verify with other tests
GT3 S9	9m	-2.951	-3.244	Verify with other tests
GT3 S10	10m	-2.379	-2.515	Verify with other tests
GT4 S1	1m	140.723	140.790	Probably Excess Neutralising Minerals
GT4 S2	2m	64.082	64.127	Probably Excess Neutralising Minerals
GT4 S3	3m	36.717	36.554	Probably Excess Neutralising Minerals
GT4 S4	4m	11.003	10.828	Verify with other tests
GT4 S5	5m	5.891	5.746	Verify with other tests
GT4 S6	6m	5.474	5.361	Verify with other tests
GT4 S7	7m	-0.379	-0.515	Verify with other tests
GT4 S8	8m	-1.845	-2.102	Verify with other tests
GT4 S9	9m	-1.800	-2.081	Verify with other tests
GT4 S10	10m	-1.673	-1.895	Verify with other tests
GT7 S1	1m	-1.405	-1.533	Verify with other tests
GT7 S2	2m	0.905	0.672	Verify with other tests
GT7 S3	3m	3.822	3.644	Verify with other tests
GT7 S4	4m	1.161	1.392	Verify with other tests
GT7 S5	5m	1.771	1.610	Verify with other tests
GT7 S6	6m	3.547	3.301	Verify with other tests
GT7 S7	7m	48.483	48.651	Probably Excess Neutralising Minerals
GT7 S8	8m	337.764	337.325	Probably Excess Neutralising Minerals
GT7 S9	9m	11.988	11.799	Verify with other tests
GT7 S10	10m	7.970	7.592	Verify with other tests
GT7 S11	11m	-0.421	-0.771	Verify with other tests
GT7 S12	12m	-1.397	-1.793	Verify with other tests
GT7 S13	13m	-0.788	-1.265	Verify with other tests
GT7 S14	14m	-1.220	-1.680	Verify with other tests

Table 38: Interpretation and NP/AP ratios for northern samples.

Site Name	Depth	NP Ratio(NP/AP) for Open System	Interpretation Open System	Interpretation Closed System
GT1 S1	1m	6.608	No Acid Potential	Acid under certain conditions
GT1 S2	2m	23.148	No Acid Potential	No Acid Potential
GT1 S3	3m	14.082	No Acid Potential	No Acid Potential
GT1 S4	4m	6.715	No Acid Potential	Acid under certain conditions
GT1 S5	5m	0.028	Likely Acid Generator	Likely Acid Generator
GT1 S6	6m	0.137	Likely Acid Generator	Likely Acid Generator
GT1 S7	7m	0.092	Likely Acid Generator	Likely Acid Generator
GT1 S8	8m	0.019	Likely Acid Generator	Likely Acid Generator
GT1 S9	9m	0.009	Likely Acid Generator	Likely Acid Generator
GT2 S1	1m	297.754	No Acid Potential	No Acid Potential
GT2 S2	2m	1123.348	No Acid Potential	No Acid Potential
GT2 S3	3m	1562.742	No Acid Potential	No Acid Potential
GT2 S4	4m	1047.468	No Acid Potential	No Acid Potential
GT2 S5	5m	1489.050	No Acid Potential	No Acid Potential
GT2 S6	6m	14219.899	No Acid Potential	No Acid Potential
GT2 S7	7m	559.614	No Acid Potential	No Acid Potential
GT2 S8	8m	676.923	No Acid Potential	No Acid Potential
GT2 S9	9m	72.473	No Acid Potential	No Acid Potential
GT3 S1	1m	0.033	Likely Acid Generator	Likely Acid Generator
GT3 S2	2m	0.030	Likely Acid Generator	Likely Acid Generator
GT3 S3	3m	20.520	No Acid Potential	No Acid Potential
GT3 S4	4m	183.825	No Acid Potential	No Acid Potential
GT3 S5	5m	8.288	No Acid Potential	No Acid Potential
GT3 S6	6m	26.210	No Acid Potential	No Acid Potential
GT3 S7	7m	6.009	No Acid Potential	No Acid Potential
GT3 S8	8m	0.064	Likely Acid Generator	Likely Acid Generator
GT3 S9	9m	0.034	Likely Acid Generator	Likely Acid Generator
GT3 S10	10m	0.074	Likely Acid Generator	Likely Acid Generator
GT4 S1	1m	14.000	No Acid Potential	No Acid Potential
GT4 S2	2m	64.000	No Acid Potential	No Acid Potential
GT4 S3	3m	226.389	No Acid Potential	No Acid Potential
GT4 S4	4m	64.128	No Acid Potential	No Acid Potential
GT4 S5	5m	41.547	No Acid Potential	No Acid Potential
GT4 S6	6m	49.159	No Acid Potential	No Acid Potential
GT4 S7	7m	0.073	Likely Acid Generator	Likely Acid Generator
GT4 S8	8m	0.039	Likely Acid Generator	Likely Acid Generator
GT4 S9	9m	0.036	Likely Acid Generator	Likely Acid Generator
GT4 S10	10m	0.045	Likely Acid Generator	Likely Acid Generator
GT7 S1	1m	0.078	Likely Acid Generator	Likely Acid Generator
GT7 S2	2m	4.884	No Acid Potential	Acid under certain conditions
GT7 S3	3m	22.410	No Acid Potential	No Acid Potential
GT7 S4	4m	9.300	No Acid Potential	No Acid Potential
GT7 S5	5m	12.044	No Acid Potential	No Acid Potential
GT7 S6	6m	15.385	No Acid Potential	No Acid Potential
GT7 S7	7m	48.000	No Acid Potential	No Acid Potential
GT7 S8	8m	770.600	No Acid Potential	No Acid Potential
GT7 S9	9m	64.306	No Acid Potential	No Acid Potential
GT7 S10	10m	22.095	No Acid Potential	No Acid Potential
GT7 S11	11m	0.029	Likely Acid Generator	Likely Acid Generator
GT7 S12	12m	0.025	Likely Acid Generator	Likely Acid Generator
GT7 S13	13m	0.021	Likely Acid Generator	Likely Acid Generator
GT7 S14	14m	0.022	Likely Acid Generator	Likely Acid Generator

Table 39: Interpretation of ABA pH results.

Site Name	Initial pH	Final pH	Interpretation
GGC55	6.46	2.90	Higher Risk Acid Generation

Table 40: Interpretation of ABA Net Neutralizing Potential results.

Site Name	Net NP (Open)	Net NP (Closed)	Interpretation
GGC55	0.354	-1.291	Verify with other tests

Table 41: Interpretation and NP/AP ratios for the sandstone samples.

Site Name	NP Ratio(NP/AP) for Open System	Interpretation Open System	Interpretation Closed System
GGC55	1.215	Acid under certain conditions.	Likely Acid Generator.

Table 42: Interpretation of ABA pH results.

Site Name	Initial pH	Final pH	Interpretation
Discard GG1	7.33	1.58	Higher Risk Acid Generation
Discard GG2	7.26	1.78	Higher Risk Acid Generation

Table 43: Interpretation of ABA Net Neutralizing Potential results.

Site Name	Net NP (Open)	Net NP (Closed)	Interpretation
Discard GG1	-23.442	-60.890	Potential Acid Generator
Discard GG2	-100.973	-204.946	Potential Acid Generator

Table 44: Interpretation and NP/AP ratios for Exxaro core samples.

Site Name	NP Ratio(NP/AP) for Open System	Interpretation Open System	Interpretation Closed System
Discard GG1	0.374	Likely Acid Generator	Likely Acid Generator
Discard GG2	0.029	Likely Acid Generator	Likely Acid Generator

Appendix B – Slug Test Results

Table 45: Slug test results for Slpmt2

SLUG TEST - YIELD ESTIMATE	
Note: All the estimates are qualified guesses and could be wrong	
BH Name =	BH2 (Sasolpmt2)
Recession time (s) for 70% recovery	28
Yield of BH (L/s) =	2.09
T (m^2/d) of formation in vicinity of BH =	10.45
T (m^2/d) of formation - Average =	5.22
RECOMMENDATION	Conduct a Pumptest on BH
First estimate of sustainable yield (L/s)	0.42
K-value of fracture (m/d) =	431.12
T-value of fracture (m^2/d) =	86.22

Table 46: Slug test results for Slpmt3.

SLUG TEST - YIELD ESTIMATE	
Note: All the estimates are qualified guesses and could be wrong	
BH Name =	BH3 (Sasolpmt3)
Recession time (s) for 70% recovery	30
Yield of BH (L/s) =	1.97
T (m^2/d) of formation in vicinity of BH =	9.87
T (m^2/d) of formation - Average =	4.93
RECOMMENDATION	Conduct a Pumptest on BH
First estimate of sustainable yield (L/s)	0.39
K-value of fracture (m/d) =	387.40
T-value of fracture (m^2/d) =	77.48

Table 47: Slug test results for Slpmt4

SLUG TEST - YIELD ESTIMATE	
Note: All the estimates are qualified guesses and could be wrong	
BH Name =	BH4 (Sasolpmt4)
Recession time (s) for 70% recovery	10
Yield of BH (L/s) =	4.88
T (m^2/d) of formation in vicinity of BH =	24.40
T (m^2/d) of formation - Average =	12.20
RECOMMENDATION	Conduct a Pumptest on BH
First estimate of sustainable yield (L/s)	0.98
K-value of fracture (m/d) =	2126.64
T-value of fracture (m^2/d) =	425.33

Appendix C – Cl Values and Recharge

[redacted]

Appendix D – Recharge Determination Results for the E.A.R.T.H. Model.

Table 48: Results for borehole 2.

Borehole	Resistance	%R	S
2	2631	1.5	0.0005

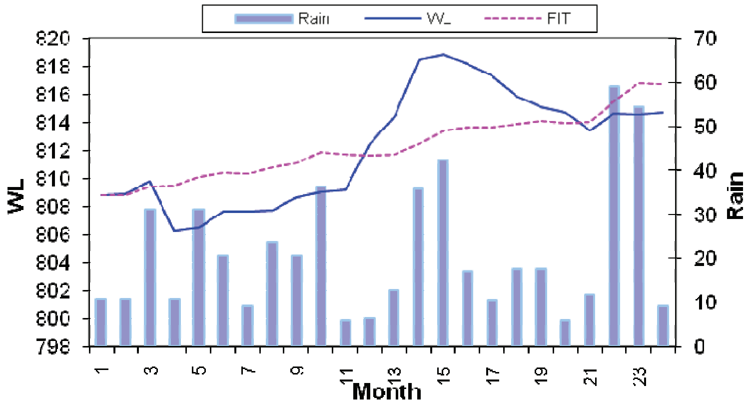

Figure 162: The fitted curve for borehole 2.

Table 49: Results for borehole 3.

Borehole	Resistance	%R	S
3	2631	1.7	0.0005

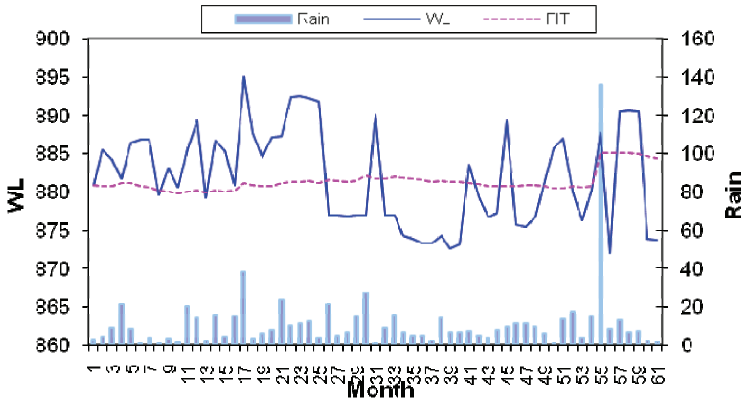

Figure 163: E.A.R.T.H model results for borehole 3.

Table 50: Results for borehole 4.

Borehole	Resistance	%R	S
4	2641	0.9	0.0005

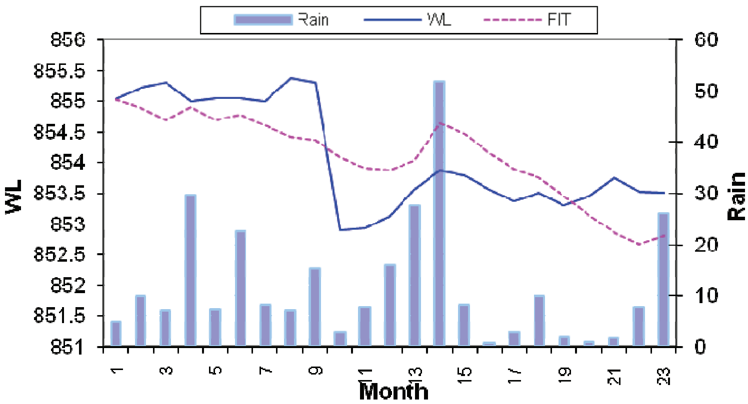

Figure 164: E.A.R.T.H model results for borehole 4.

Table 51: Results for borehole 5.

Borehole	Resistance	%R	S
5	2811	1	0.0005

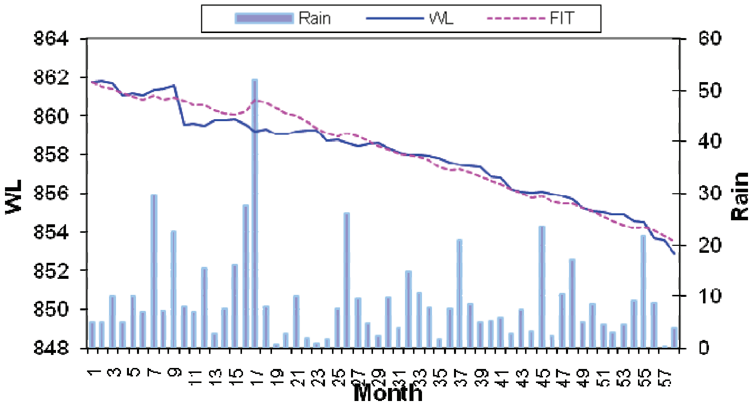

Figure 165: E.A.R.T.H model results for borehole 5.

Table 52: Results for borehole 6.

Borehole	Resistance	%R	S
6	2811	1	0.0005

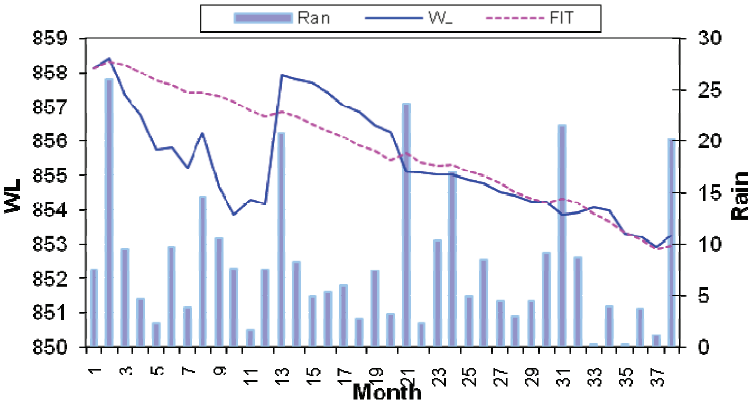

Figure 166: E.A.R.T.H model results for borehole 6.

Table 53: Results for borehole 7.

Borehole	Resistance	%R	S
7	2691	1.4	0.0005

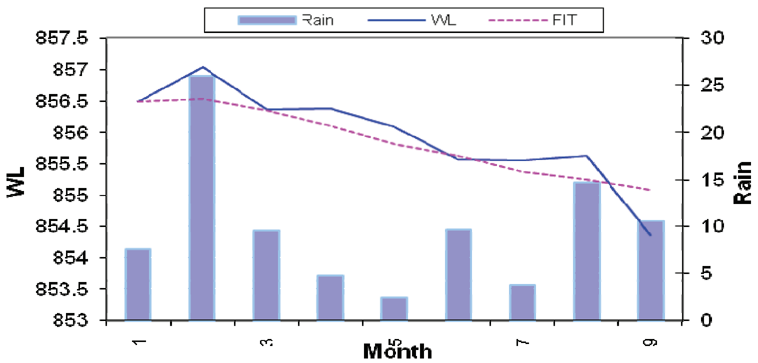

Figure 167: E.A.R.T.H model results for borehole 7.

Table 54: Results for borehole 8.

Borehole	Resistance	%R	S
8	2681	3	0.0001

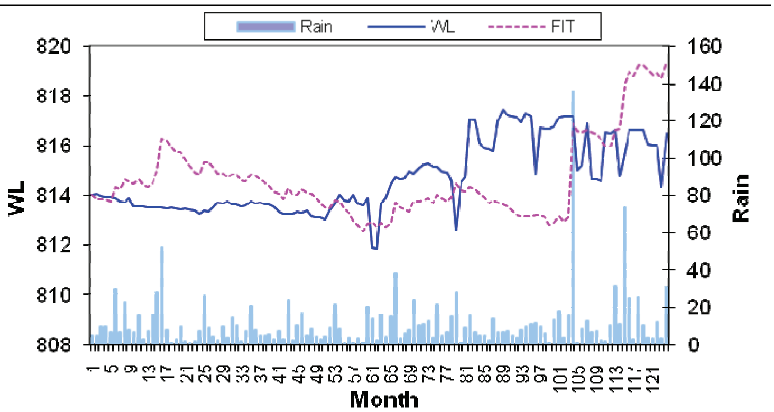

Figure 168: E.A.R.T.H model results for borehole 8.