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Sulphate generation in South African underground and opencast collieries

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Abstract Deterioration in the water quality results from coal mining, and the significant impact on the environment in South Africa has been reported (Funke in SA Water, Sci Technol 15:115–144; 1983). Pyrite in with South African coal can be oxidised to yield acidic and high salinity water. This study deals with the rate at which sulphate could be produced for collieries under different conditions. Four collieries in the Witbank coalfield were selected for this investigation. The boreholes were investigated with an in-situ multi-parameter probe, and then sampled at different times with a specific depth sampler to determine the chemical composition of the water in the collieries. Water level measure-

ments and volumetric calculations were done to determine influx rates. Daily sulphate generation rate for underground mining was found to be in the range of 0.4–2.7 kg/ha, depending on the availability of oxygen and the residence time of the water (the time available for neutralising agents present to react) in the mining void. The exclusion of oxygen due to flooding and the presence of calcareous carbonates influences the observed sulphate generation.

Keywords Coalmines · Underground · Opencast · Sulphate generation · Flooding · South Africa

Introduction

South Africa is a country blessed with an abundance of minerals. Coal, which is the main source of energy in South Africa, is one of these abundant minerals. In 1997, 68% of the energy consumption of Southern Africa was coalbased (Energy Information Administration 2000).

In South Africa coal resources occur in 19 coalfields (Erasmus et al. 1981). The most important coalfields in the Mpumalanga Province are the Springs-Witbank coalfield and the Highveld coalfield. A map of these coalfields is shown in Fig. 1.

Coal mining has been ongoing in the Mpumalanga Area since 1870 (Barker 1999). Initially, all the mines around Witbank were shallow. Bord-and-pillar mining was used throughout. (First bords (streets) are driven, leaving supporting coal between. This is followed by

cross drives, connecting the bords. Supporting coal is left behind as rectangular pillars to support the weight of the strata overlying the coal seams).

During the 1970s, wide-scale expansion leads to the development of mega-mine structures south of the existing coalfields (Vermeulen PD Investigation of water decant from underground collieries in Mpumalanga. Unpublished MSc, Thesis (2003), UFS, Bloemfontein, South Africa). Almost all of these developments were associated with power generation or the utilisation of the coal by the chemical industry.

Water in South African Collieries

As far as mine water is concerned, complexities that arise from mining are:

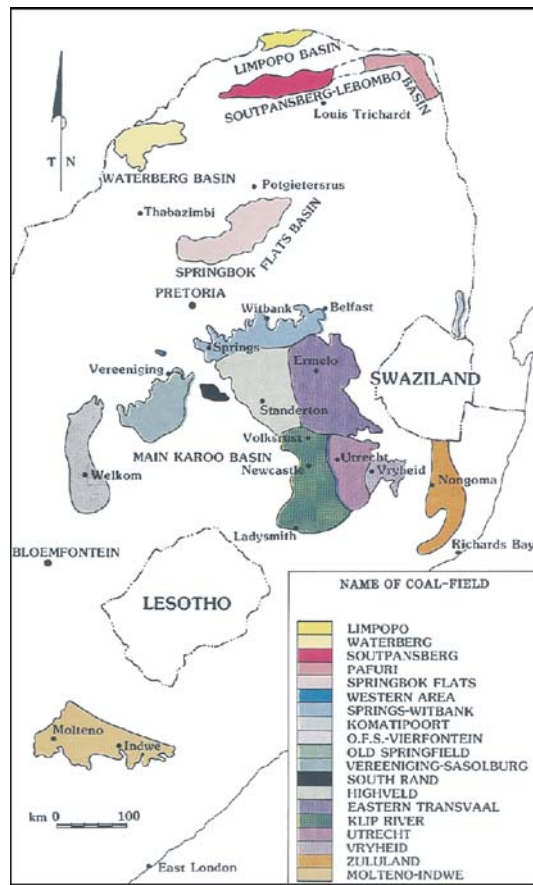


Fig. 1 The South African Coalfields, after Erasmus et al. (1981)

- Mining is often so shallow that it enters into the weathered zone. Pillars are unstable and collapse. Cracks develop in the overlying strata, and rock that is generally impermeable to water flow becomes conduits for groundwater from overlying aquifers and surface water to enter into the mine workings (Hodgson and Krantz 1998).
- Groundwater flow is possible in the weathered zone, regardless if pillars have collapsed.
- Areas of collapse aggravate the influx of water and oxygen to the mine workings, resulting in an increase in oxidation rates, sometimes leading to spontaneous combustion of coal left in the mines.
- As a guideline, it has generally been accepted that between 1 and 4% of the rainfall above bord-and-pillar mining infiltrate into deeper mines (> 80 m), and 5–10% in the shallower mines (< 80 m). In areas where extensive collapse of the pillars has occurred, recharge is enhanced (Vermeulen 2003).
- Associated with coal mining in South Africa, the phenomenon of acid mine drainage (AMD) occurs. AMD occurs when sulphide minerals in rocks are oxidised, usually as a result of exposure to moisture

and oxygen. This results in the generation of sulphates, metals and acidity that can have manifold environmental consequences. Pyrite (FeS_2) is the most important sulphide found in South African coalmines. When exposed to water and oxygen, it can react to form sulphuric acid (H_2SO_4).

- In the South African coalfields there are co-existing carbonates such as calcite and dolomite, which help neutralise the acidity generated. The results of this are that many of the mine waters are not necessarily acidic, but often high in dissolved salts. (Usher 2003)
- After nearly 20 years of operation, all of these mines are still in the early stages of this chemical evolutionary process.

In the 1970s, large-scale opencast mining became widespread in the Mpumalanga Coalfields. Many mines have opened where up to four of the five coal seams are extracted by dragline methods. Coal produced per operating opencast mine is in the range of 4–12 Mt/a (Hodgson and Krantz 1998). For each ton of coal extracted, eight tons of overburden or interburden rock, on average, is removed and replaced as spoil. In consequence, this:

- Increases the hydraulic conductivity of the medium.
- Enhances recharge and about 15–20% of the rainfall ends up in the opencast pits.
- Causes oxygen ingress due to thermal gradients that develop in the spoil.
- Results in water quality deterioration of the pit water at an average sulphate production rate of 5–10 kg/ha of spoil per day at sulphate concentrations of between 1,000 and 2,000 mg/l (Hodgson and Krantz 1998).

Influences of mine water in South African collieries

Once the economically mineable coal has been removed, mines close down and are left to fill up with water. Some of them, depending on the local geology, depth of mining and geohydrological flow paths (natural or man-made) will eventually decant and/or seep into the adjacent strata and environment, thus polluting aquifers and rivers. Projections for future volumes of water to decant from the mines have been made by Grobbelaar et al. (2000). According to this work, a total of approximately 360,000 m³/day of excess mining-related water will be available from the Mpumalanga province's collieries after closure.

Deterioration in the mine water quality results from coal mining. Sulphuric acid is formed as a result of oxidation reactions in the mines. There are four commonly accepted chemical reactions that represent the chemistry of pyrite weathering to form AMD, and which are described in many literature studies e.g. Seif (2002) and Appelo and Postma (1993):

- The first reaction in the weathering of pyrite includes the oxidation of pyrite by oxygen.
- The second reaction involves the conversion of ferrous iron to ferric iron.
- The third reaction, which may occur is the hydrolysis of iron. Hydrolysis is a reaction that splits the water molecule.
- The fourth reaction is the oxidation of additional pyrite by ferric iron. For sulphate to be generated, the process needs sulphide (in the form of pyrite) and oxygen. Secondary sulphate minerals may also occur from the acid neutralisation reactions. One of the minerals that are relevant to this study is the formation of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$).

This study examines the rate at which sulphate will be produced once mining has ceased and how to overcome this problem by allowing flooding of the void and thereby excluding oxygen from the system. Four collieries were selected for this investigation as depicted in Fig. 2. A summary of the characteristics is given in Table 1.

Methodology of the investigation

The investigation was conducted over a period of nearly 5 years and time series data of water levels and water qualities was gathered at regular intervals.

Recharge into the collieries was calculated by measuring water levels in the mine. The water-holding capacities for the mining voids were obtained using the WISH software, an interpretation system for hydrogeologists (Lukas 2002) to calculate stage curves (Fig. 5). Stage curves present the water volume versus elevation for the mining area by making use of the floor contours and expected storage based on the extraction ratio and mining method. A volume at each elevation is then plotted on the stage curves.

The assumption was made that the difference between lateral inflow and outflow was negligible in the mines and that the volumes gained in the collieries were equal to the recharge:

$$I - O + \text{Re} = \Delta S,$$

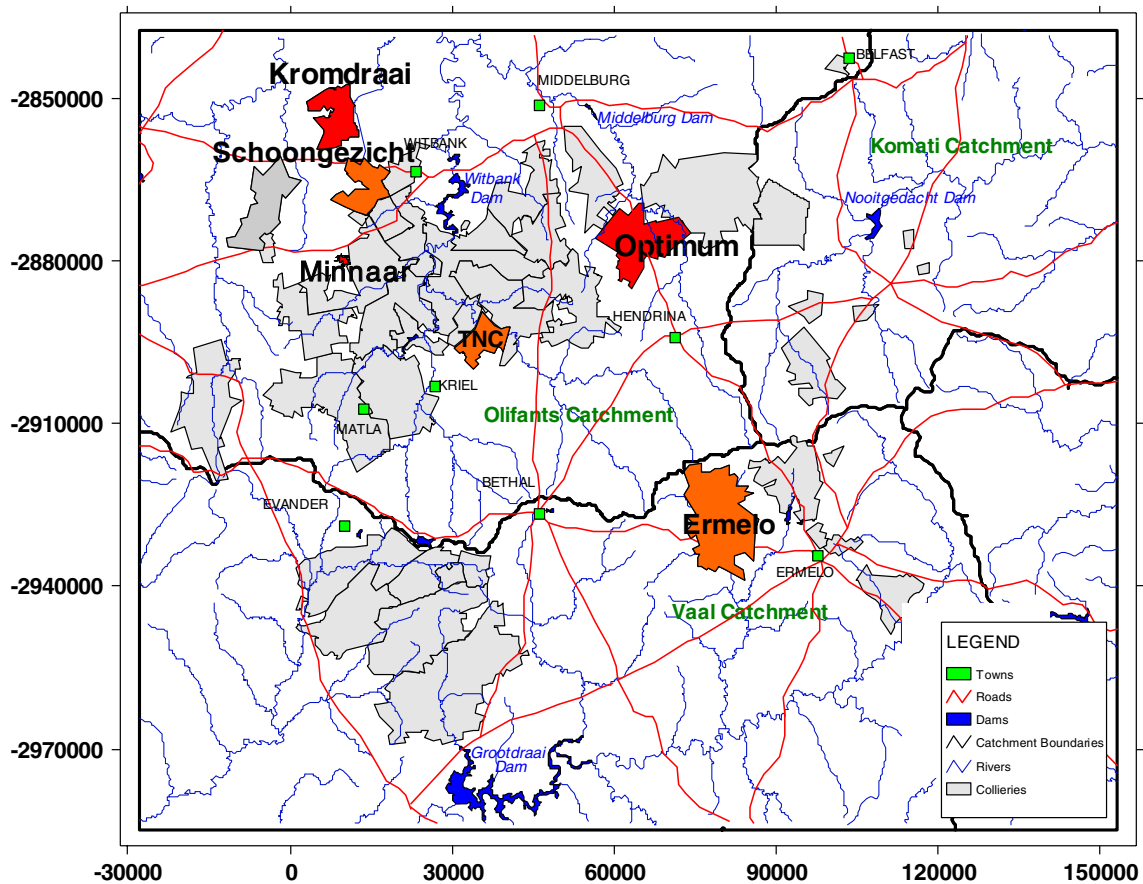


Fig. 2 Mine lease areas for collieries in Mpumalanga

Table 1 Summary of the characteristics of the selected collieries

Colliery	Characteristics	Mining method
Minnaar	Small underground mine; compartments; artificial recharge; mine water irrigation	Bord-and-pillar
Ermelo	Large underground mine, partially stooped; in the process of filling up with water; flushing option considered	Bord-and-pillar Stooeping
Schoongezicht	Underground mine; currently decanting; water and salt balance studies	Bord-and-pillar Opencast
Optimum	Opencast mine; currently decanting	Opencast

where

I	inflow into mining cavity
O	outflow from mining cavity
Re	recharge into mine
ΔS	change of volume water in mining cavity

To investigate the chemical composition of the water in the collieries, the boreholes were first investigated with an in-situ multi-parameter probe. Use was made of the YSI multi-parameter sonde for this purpose. This instrument measures the water temperature, conductivity, pH, redox state and dissolved oxygen with depth in the water (Fig. 3). From these results, the stratigraphic nature of the water column and the exact position of the mining cavities could be determined.

A Solinst specific-depth sampler was then used to sample at the determined positions in the mining cavity. These samples were analysed for inorganic parameters at the laboratory at the Institute for Groundwater Studies at the University of the Free State.

The total sulphate increase over time was compared against the volume water increase in the underground voids. A production rate was calculated for sulphate generation. Where voids are still in the process of filling, production rates were calculated for different stages of filling. This also provides a means to extrapolate sulphate production and concentrations in the collieries over time. The method has been utilised by Hough J Evaluation of management options for intermine flow and associated impacts in the Central Witbank Coalfield. Unpublished

Fig. 3 Example of a multi-parameter log at different periods

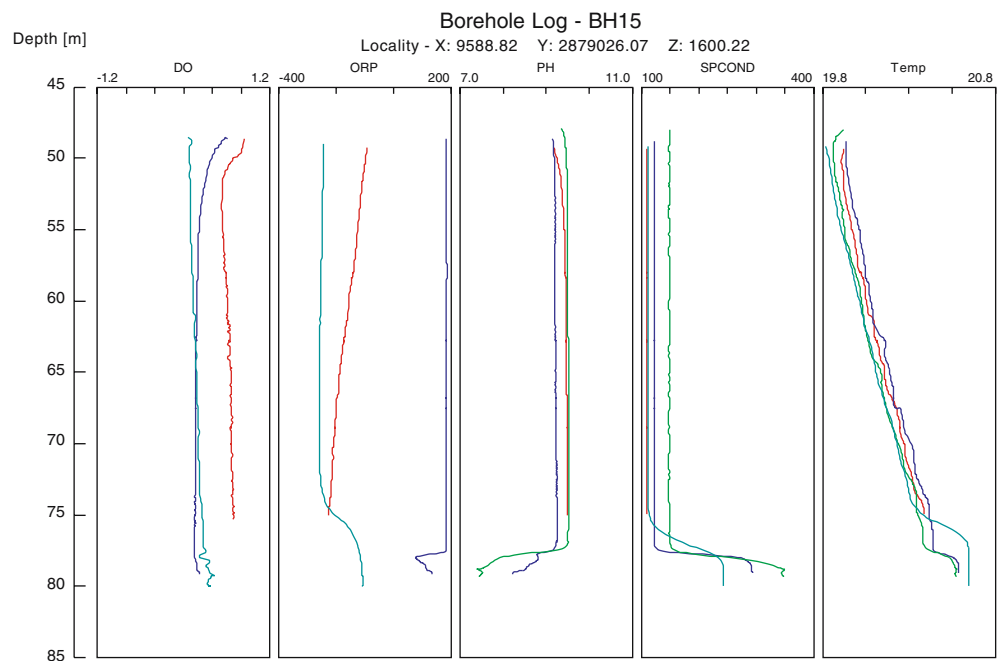
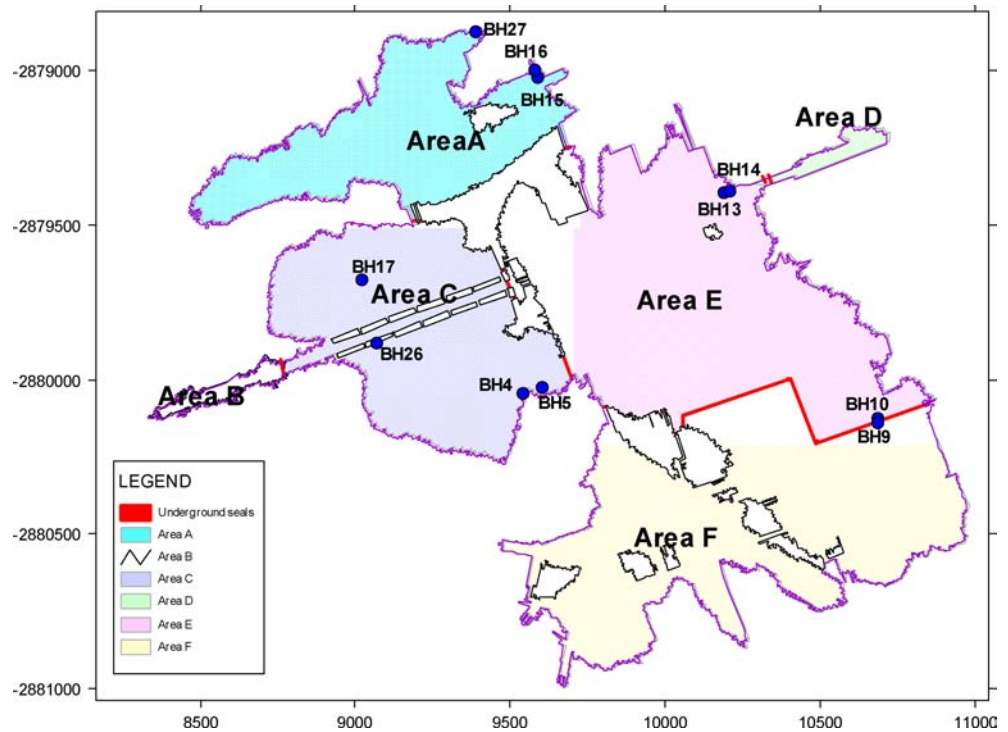


Fig. 4 Map indicating the underground areas at Minnaar Colliery, including monitoring boreholes



MSc. Thesis (2002), UFS, Bloemfontein; Usher B H, Havenga A, and Hough JJH Quantification of water quantities and qualities in the Witbank Coalfield: Base Case Modelling. Unpublished report to Coaltech 2020 (2003). COALTECH 2020 Task 6.8.3, 254p, Johannesburg, South African; Vermeulen 2003.

Case studies

Minnaar Colliery

The area mined constitutes of 235 ha and conventional bord-and-pillar mining was done. The mine consists of four separate main areas (A, C, E and F) and two small areas (B and D), as illustrated in Fig. 4. These are linked by narrow development in which seals have been installed. Table 2 depicts the compartment sizes and mining depth. Minnaar Colliery is in a unique situation

Table 2 Statistics on Minnaar Colliery are as follows

Description	Value
Total area mined (ha)	235
Area A (ha)	35
Area B (ha)	2
Area C (ha)	47
Area D (ha)	2
Area E (ha)	74
Area F (ha)	75
Mining depth below surface (m)	12–77

in that the different compartments are recharged and exploited separately. This impacts differently on the water chemistry in the different areas. The main areas will therefore be discussed separately.

Minnaar area A

Block A is an isolated sealed-off area, situated on a topographic high and is still in the process of filling up. This compartment is recharged mainly from the surface with little lateral influx. This suggests that the influx into area A is dominantly due to vertical influx, translating into a vertical K -value of $1.02E-4$. There is no abnormally high recharge through subsided areas.

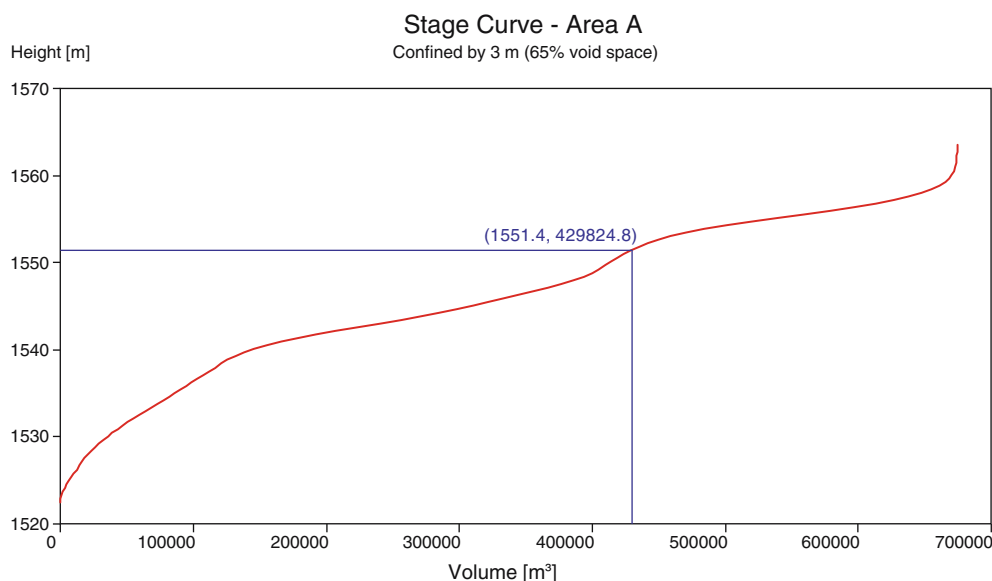
Water balance The water levels used for calculations in this area over the period 28 October 1999 to 4 November 2002, and the volumes determined from stage curves (of which Fig. 5 is an example at 28 October 1999) are shown in Table 3.

The water balance calculations are summarised in Table 4. Water from BH27 is utilised for irrigation of

Table 3 Water levels and volumes for area A

Area A	Area size (ha)	WL (28/10/1999)	WL (4/11/2002)
	34.7	1551.43	1552.63
Water volume (m^3)		429,825	449,515

Fig. 5 Stage curve for area A at 28/10/1999



the garden (6,400 m³ over the period of 1,102 days).
Sulphate generation Figure 6 illustrates a time graph of the electrical conductivity and sulphate concentration in the mining cavity.

Table 5 shows the SO₄-generating calculations for two different periods, one from mine closure when the mining cavity was empty, and one since October 1999 when the cavity was already filled with water. The average SO₄ per day since the mine closed down some 30 years ago is 1.24 kg/ha (at an average measured SO₄ concentration of 1,050 mg/l). This was calculated as follows:

$$(1,050 \text{ mg/L} \times 1,000)449,515 \text{ m}^3 / (30 \times 365 \text{ days})/34.7 \text{ ha} = 1.24 \text{ kg/ha/day}$$

as the mine filled up, and oxygen availability diminished, the sulphate generation rate decreased. For the period from 28 October 1999 the SO₄ generated daily is only 0.49 kg/ha (at an average SO₄ concentration of 953 mg/l). A graph to simulate the SO₄ dilution over time, based on recharge into this compartment, is shown in Fig. 7. This graph suggests that concentrations could drop by another 50% in the next 50 years.

Table 4 Water balance calculations area A

Days	1,102
Rainfall (m)	2.655
Outflux distance (m)	785
Lateral outflux (m ³)	12,976
Extraction (m ³)	6,400
Total influx (m ³)	39,069
Water volume gain (m ³)	19,690
Recharge (%)	4.24
Vertical K-value	1.02E-4

Minnaar area C

A statistical analysis of water qualities in area C is provided in Fig. 8. Table 6 shows the SO₄-generating calculations for this area. The average SO₄ per day since the mine closed down approximately 30 years ago is 2.03 kg, based on an average SO₄ concentration of 1,150 mg/l.

These results show that area C with high recharge (Vermeulen 2003) has a higher sulphate production than area A, which appears to be contradictory as the compartment is already filled with water and less oxygen is available than in compartment A (Vermeulen 2003). The reason for this is the over saturation of the waters in compartment C with gypsum.

Standard thermodynamic approaches to determine the saturation state of particular minerals in the mine water were used (Stumm and Morgan 1970)

The saturation index is defined as:

$$SI = \log \frac{IAP}{K_{sp}}$$

Table 5 Sulphate generating calculations for different periods in area A

Area (ha)	34.7
1.Total period (years)	30
Total influx (m ³)	449,500
SO ₄ (mg/l)	1,050
Total SO ₄ (kg)	471,900
Daily SO ₄ (kg/ha)	1.24
2.Period 28/10/1999–4/11/2002 (days)	1,100
Total influx (m ³)	19,690
SO ₄ (mg/l)	953
Total SO ₄ (kg)	18,760
Daily SO ₄ (kg/ha)	0.49

Fig. 6 Chemistry of water in area A (mg/l)

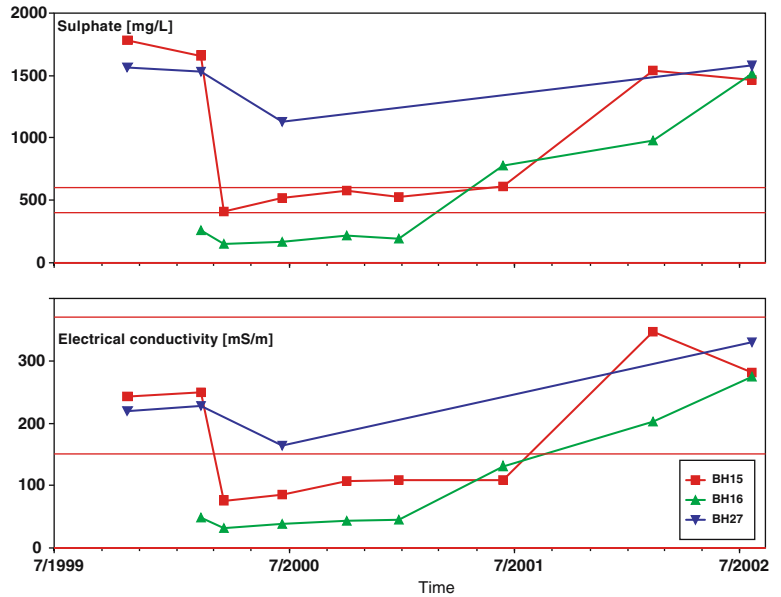
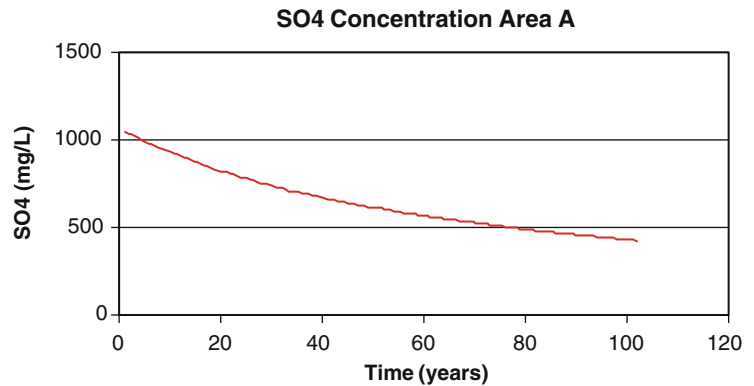


Fig.7 Simulated SO₄ concentration for area A, based on recharge and dilution



where

IAP ion activity product calculated from measured concentrations

K_{sp} the solubility product of the solid species.

When the $SI > 0$, the water is supersaturated with the solid components and precipitation should occur. Using the hydrochemical modelling program PHREEQC (Parkhurst and Appelo 1999), together with the Minteq

database, where the $K_{sp} = 10^{-4.848}$, the saturation index of gypsum for BH 27 in area A, and BH 5 in area C, was calculated. The model indicates that the water is over-saturated in gypsum and the sulphate can only reach a value of 1,500–1,600 mg/l before precipitation occurs. The results are illustrated in Table 7.

Calcite and/or dolomite from the surrounding rock reacting to neutralise the acidity generated by pyrite oxidation and from the pillars provide the calcium. From PHREEQC it is determined that the calcium and

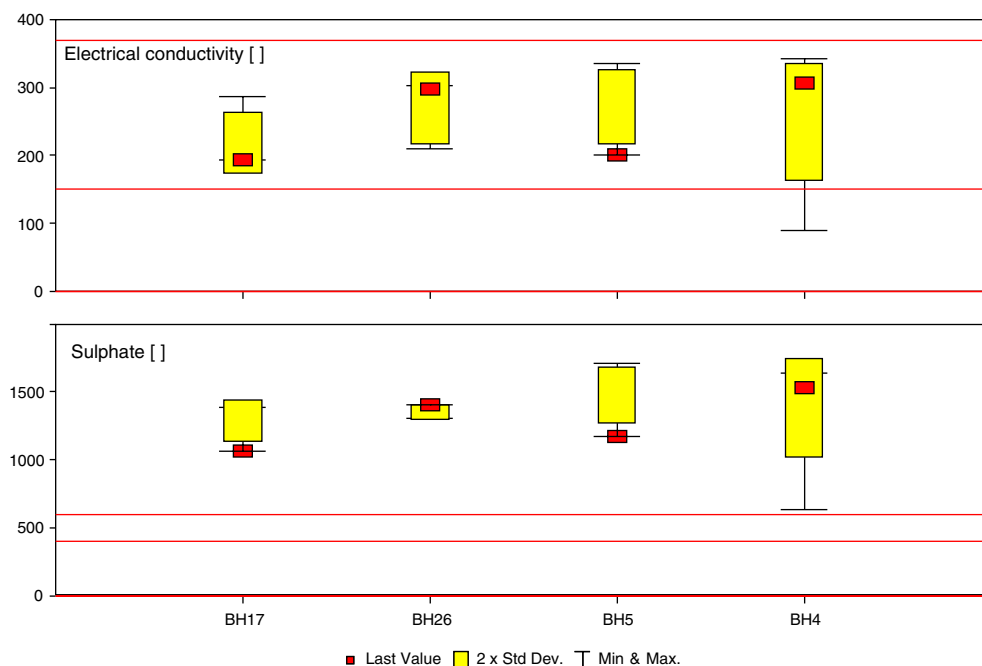
Table 6 Sulphate generating calculations for area C

Area (ha)	46.85
Total years	30
Total water influx (m ³)	903,590
SO ₄ (mg/l)	1,150
Total SO ₄ generated (kg)	1,039,100
Daily SO ₄ (kg/ha)	2.03

Table 7 Saturation index values for areas A and C

BH number	Date	Saturation index for gypsum
BH27	23/02/2000	0.16
BH5	26/02/2002	0.22

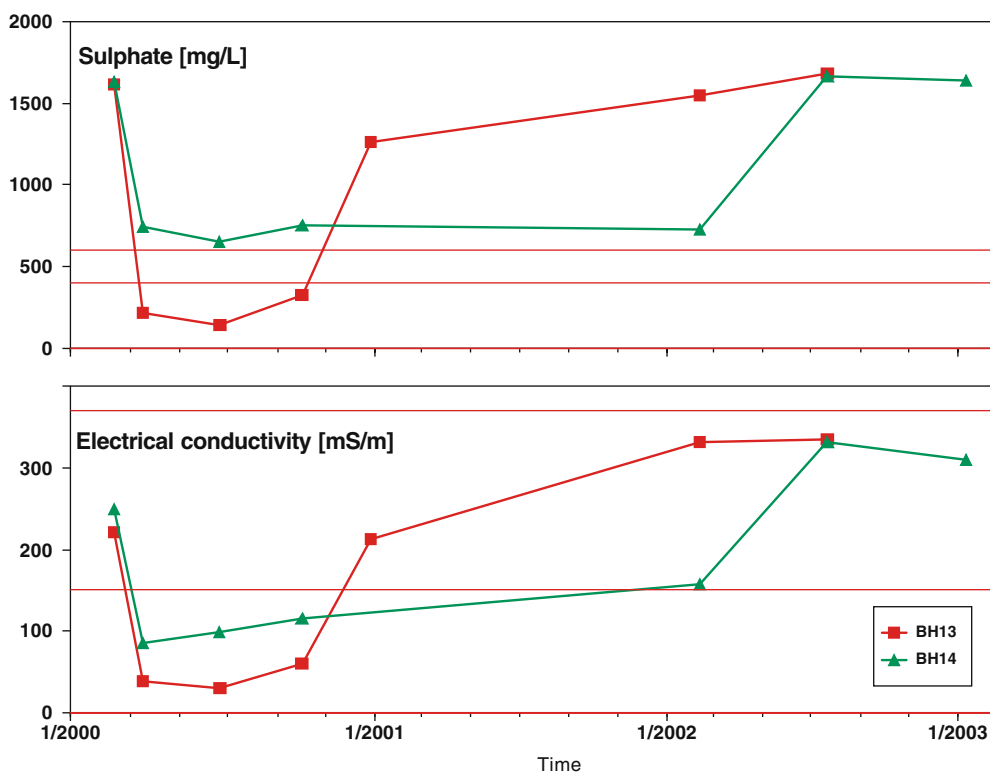
Fig. 8 Box and whisker plot of the water quality in area C (mg/l)



dolomite are slightly above the equilibrium, indicating that these species are still in abundance and able to maintain neutral pH. The lower magnesium concentrations measured indicates that calcite is more likely to react from the surrounding rock.

The reason why the high recharge area C has a high daily SO_4 generation of 2.03 kg/ha/day, in contrast with a much lower value of apparent sulphate generation rates 1.24 kg/ha/day and lately 0.49 kg/ha/day, is because gypsum saturation is not reached in

Fig. 9 Chemistry of the water in area E (mg/l)



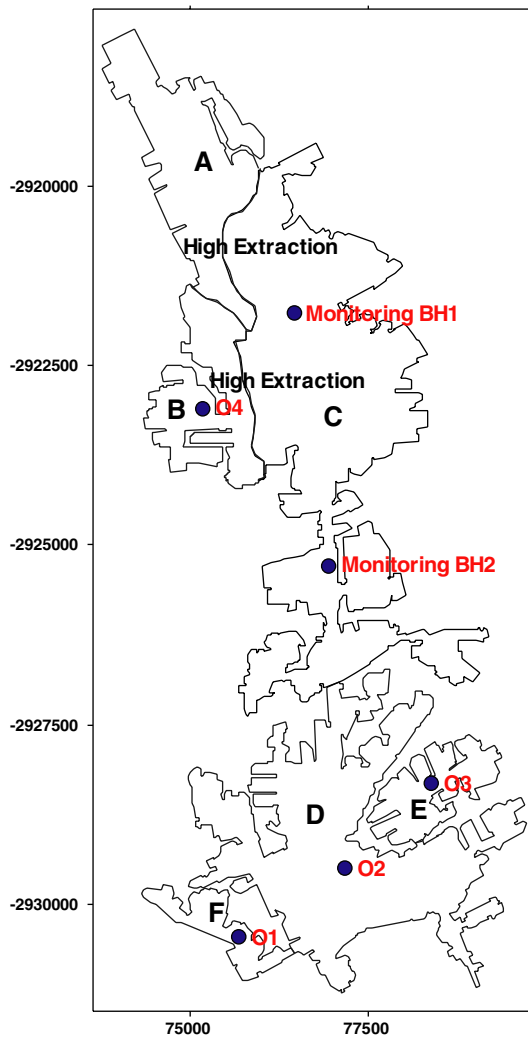


Fig. 10 Ermelo Colliery mining area and localities of monitoring boreholes

area C. This indicates that the mass balance method of calculating SO_4 generation in oversaturated waters can be erroneous. More sulphate than 0.49 kg/ha is probably generated in area A, but is undetectable using this method because of precipitation of the gypsum.

Table 8 Sulphate generating calculations for area E

Area (ha)	73.4
SO_4 mg/l	1,042
Total years	30
Total influx (m^3)	1,427,417
Total SO_4 (kg)	1,487,369
SO_4 rate (kg/day)	1.85

Minnaar area E

This compartment is recharged by natural influx, with leakage through ventilation walls into area F. The water quality in this compartment is graphed in Fig. 9.

Table 8 shows the SO_4 -generating calculations for this area. The daily sulphate generation in this area is calculated at 1.85 kg/ha/day over a period of 30 years.

Ermelo Colliery

Ermelo Colliery is an underground colliery in the Mpumalanga Province (Fig. 10) between the towns of Ermelo and Bethal. Production ceased in April 1997.

Two mining methods have been employed at Ermelo Colliery. Primary development was done by the bord-and-pillar method. This was followed by secondary extraction, mainly in the north, resulting in subsidence. Approximately 790 ha of the pillars have been stooped which relates to 29% of the total mined area of 2,680 and 514 ha (19%), have been partially stooped (Latilla and Olivier 1998). The coal floor is undulating but has a general dip to the south).

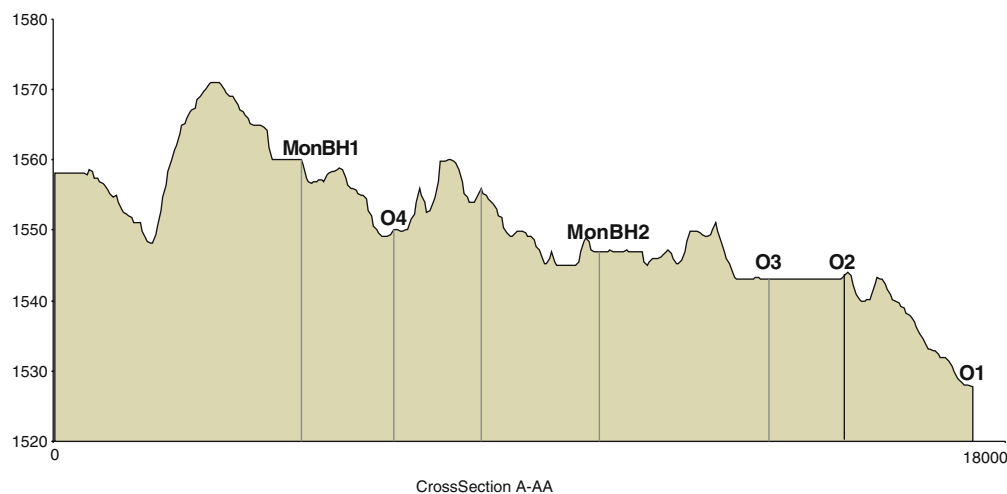
The floor elevations range 1,520–1,580 mamsl (Fig. 11). The deepest areas are in the southwest (F) and in an isolated area in the east (E), where the coal floor has been displaced through the intrusion of a dolerite sill. The latter areas are interconnected with the northern portion of the mine through a large, rather flat area (D). It was anticipated that significant amounts of water would have been retained within the undulations before allowing the flow of water to the south. Further north, the coal floor dips steeply from the southeast to the northwest. In this area, local smaller depressions are also present. It is anticipated that depression storage amounts to about 15% of the mine volume (Vermeulen 2003).

Water balance: Recharge was initially mainly in the northern compartments (A–C). The exceptionally high rainfall since December 1999 resulted in the sharp rise in water levels of borehole O₄ (Fig. 12). The streams above the stooped areas would have been in flood, enhancing recharge. During this period there was no rise in the water levels of boreholes in the southern parts of the mine. The rise in water levels of boreholes in the southern areas since 2000 resulted from water spilling over undulations of the coal floor in the northern areas A and B, causing the water levels of the northern areas to stabilise. Influx was calculated at 2,500 m^3 /day. Since

Table 9 Sulphate generating calculations for Schoongezicht

Area (ha) 1,2 and 4 seam	1,012
Daily water influx (m^3)	944
SO_4 (mg/l)	2,500
Daily SO_4 (kg/ha)	2.33

Fig. 11 North-south cross section of the coal floor, also showing the boreholes



2002 the water levels of areas C, D and F have equalised. The water levels of these areas now rise at the same rate. The daily calculated influx of 1,300 m³ since 2002 is attributed to the lower than normal rainfall.

Sulphate generation: Sulphate generation is dependent on pyrite oxidation. Oxidation does occur in flooded areas, as long as that the mine water remains alkaline and thereby limits ferric iron as oxidant due to its insolubility. The geochemical log in Fig. 13 indicates that O₂ has been excluded since the mining cavity has filled up.

Figure 14 shows the ranges of sulphate and pH values for each of the boreholes. Dilution from groundwater influx through the boreholes could contribute to the significant spread of values.

In Fig. 15 the sulphate concentrations, in relation to the water levels in the different compartments in the mine, are illustrated as a line graph. Just after mine closure, salinity was high due to small amounts of water

reacting with freshly exposed pyrite. Ideal oxidising conditions prevailed, generating sulphate concentrations in excess of 2,000 mg/l. The drop in concentrations occurred during the high 1999 summer rainfall when dilution occurred because of high influx of water.

The increase in the sulphate generation since February 2002 is ascribed to the lower recharge during this period; with the water levels staying relatively constant, the sulphate generation rate is maintained but dilution is decreased. This means that the daily calculated influx of 1,300 m³ is too slow for effective dilution, compared to 2,500 m³ during the previous year. Currently the mine generates 0.39 kg/ha SO₄ per day based on an average sulphate value of 398 mg/l (calculated from an average for the different boreholes). Both the exclusion of oxygen as well as the rate of influx of water into the mining cavity has an effect on the observed sulphate concentration and rate of sulphate production.

Fig. 12 Time graph of the water levels at Ermelo Colliery

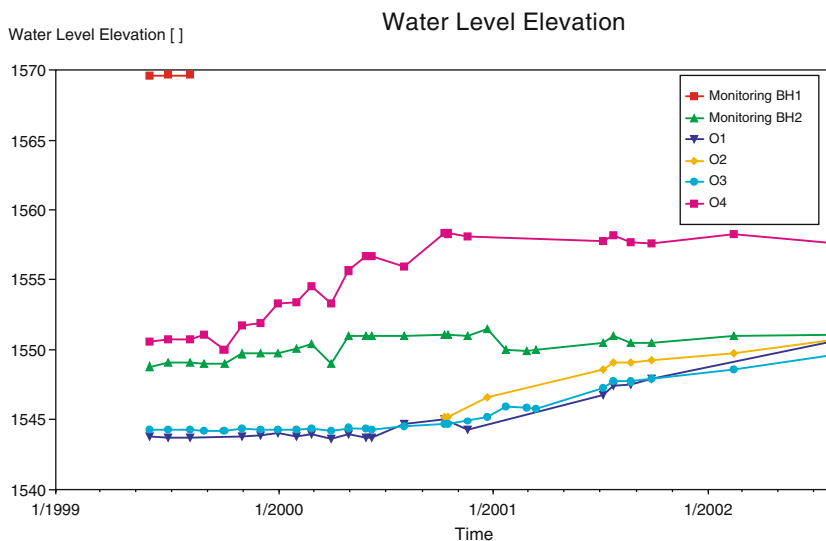
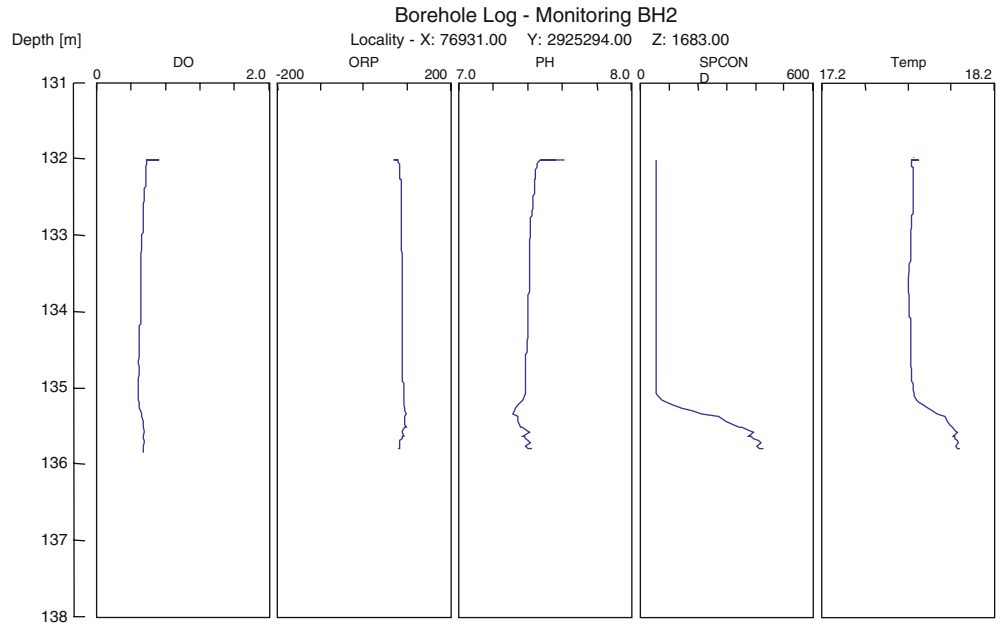


Fig. 13 Geochemical log of Monitoring BH2 during April 2002



Schoongezicht

Schoongezicht Colliery was a very shallow mine which ceased production 25 years ago. The depth of mining varies between 7 and 54 m. Mining was by the bord-and-pillar method, with the No. 1-Seam being the most dominant seam (540 ha). The No. 2-Seam (420 ha), and the No. 4 Seam to a lesser degree (52 ha), were mined (Fig. 16).

There is no hydraulic connection between the Schoongezicht workings (BH101 and BH 201) and mining to the south (BH202). This is confirmed through monitoring and the water level graphs (Fig. 17).

Water decants from the 1-seam into Dam1 at an average rate per day of 940 m³. The water quality of the 1-seam, 2-seam and the decant water is the same, as indicated in the profiling graphs in Fig. 18. This strengthens the belief that the seams, which are only a few meters apart, should be interconnected.

The water character is generally acidic (Fig. 19), especially when decanting into Dam1. This is ascribed to mining under shallow conditions, in the zone where most of the neutralising potential has been leached through circulating water, prior to mining.

Additional characteristics of the water are high calcium and magnesium. This suggests that some neu-

Fig. 14 pH and sulphate statistics for Ermelo Colliery (mg/l)

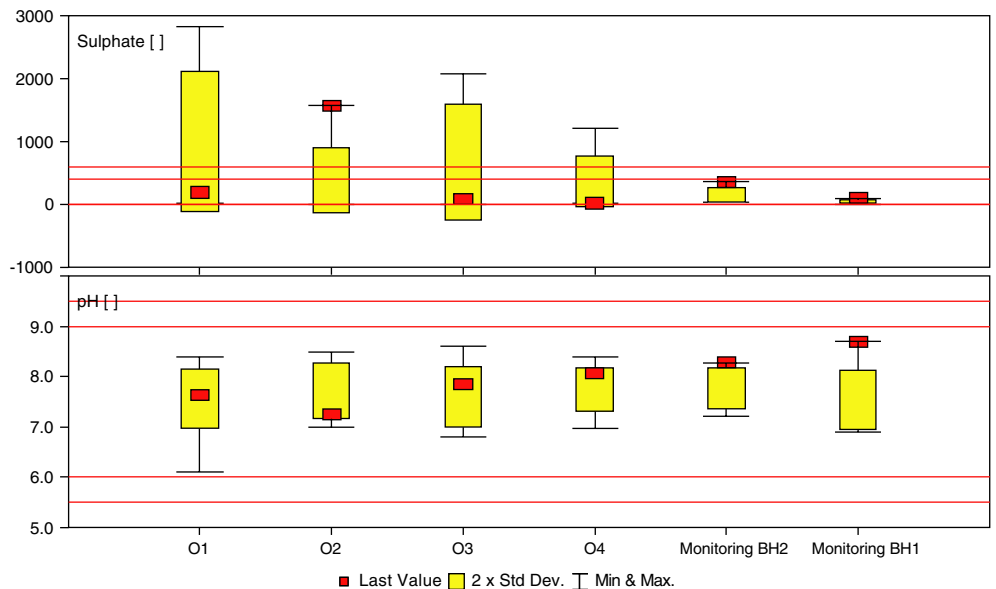
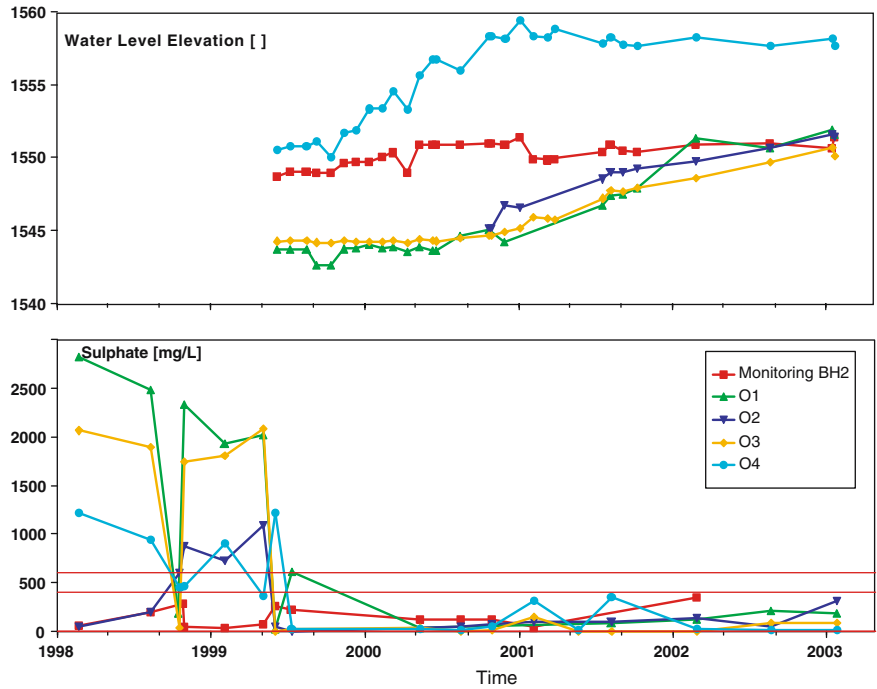


Fig. 15 Line graph of sulphate and water levels



tralisation potential is still present in the form of calcite with a lesser amount of dolomite in the sediments. The amount of carbonate minerals is too low to neutralise the acid water at sufficiently high rates to prevent acidic

conditions. In these waters, the acidic conditions and excess pyrite oxidation compared to carbonate neutralisation have led to very high sulphates, which are not always constrained by secondary mineral saturation.

Fig. 16 Localities of monitoring boreholes

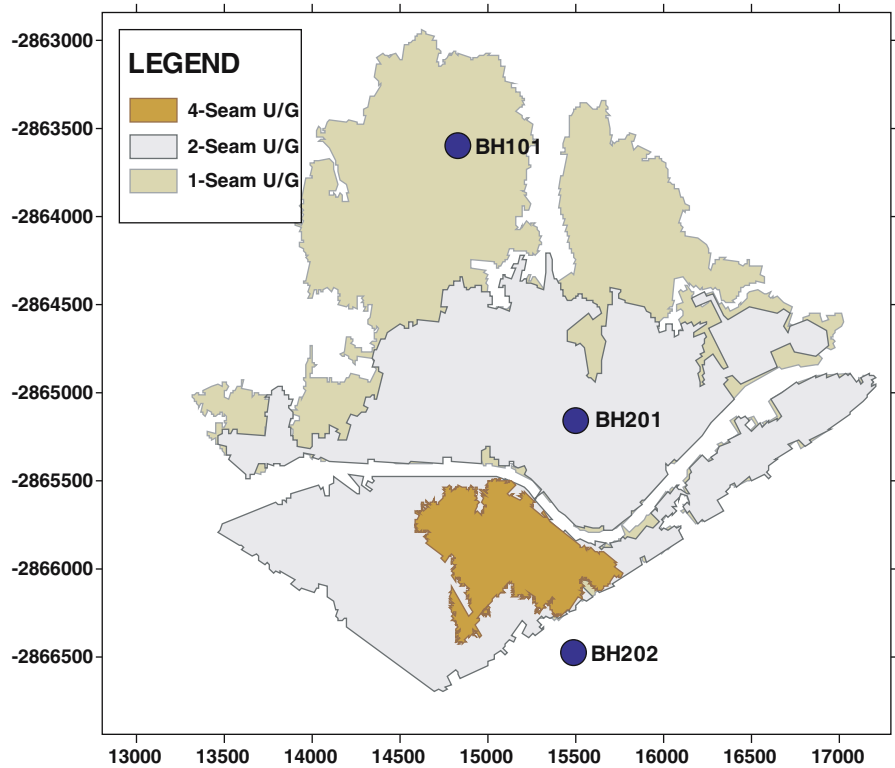
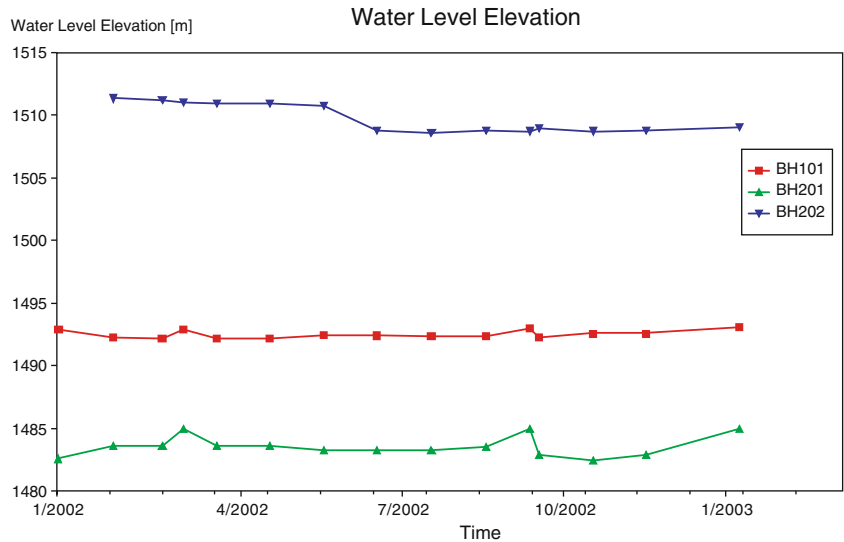


Fig. 17 Localities of monitoring boreholes and water levels



This has been confirmed by using PHREEQC to determine saturation indices of the water.

The colliery is less than 50% flooded. The acid character of Schoongezicht Colliery is directly linked to the lack of flooding of the underground workings. The high decant rate also results in a very short residence time of the water in the colliery.

The sulphate production rate at Schoongezicht is 2.36 t/day for the entire mine, or 2.3 kg/ha/day (Table 9).

Sulphate generation as a function of the degree of inundation

An important consideration in the underground voids is the amount of salt that can be generated. Using data from a multitude of voids, researchers such as Hough (2002) and Vermeulen (2003) have determined the generalised sulphate generation rate for different mines.

The reaction rate points were plotted on a graph and a trend line fitted to the data points by means of a second-order polynomial function of the form (Usher BH 2003 The Development and Evaluation of Hydrogeochemical Prediction tools for South African Coalmines. Unpublished PhD thesis (2003), University of the Free State, Bloemfontein, South Africa):

$$y = -A(x)^2 - B(X) + C,$$

where X = the percentage of the void which is full.

This is in line with values reported by Vermeulen (2003), who obtained an initial sulphate generation rate of 1.4 kg/ha/day in a bord-and-pillar compartment, which rapidly fell as the level of flooding increased. Vermeulen (2003) obtains rates in the order of 2 kg/ha/day for relatively unflooded mines, which decrease to values of around 0.4–0.5 kg SO₄/ha/day when the mines reach the stage of 90–95% full.

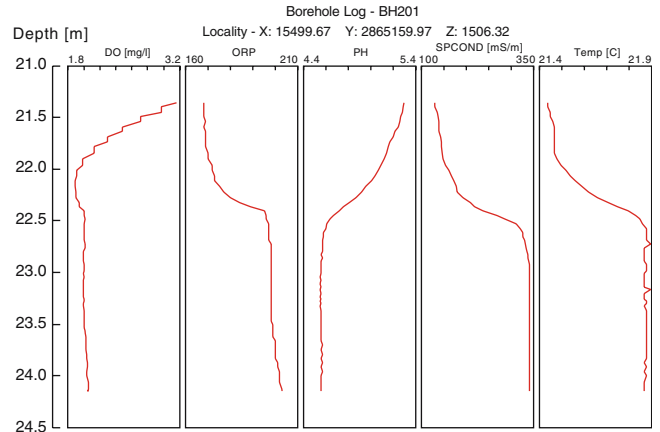
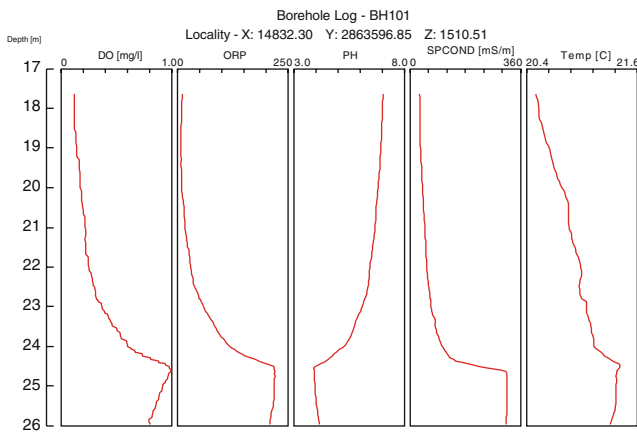
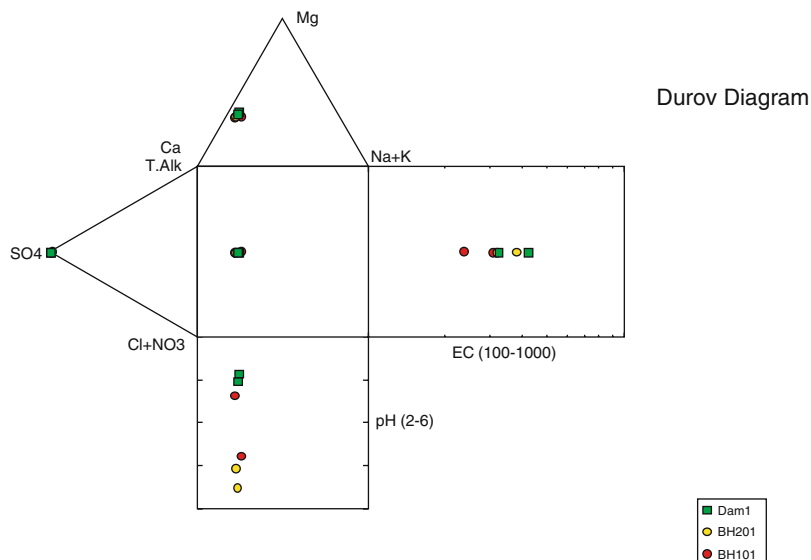


Fig. 18 Multi-parameter profiling of the Schoongezicht boreholes

Fig. 19 Durov diagram for the boreholes and decanting dam



Overall, based on observations at five different collieries (Fig. 20), the following function provides a good estimate of sulphate production (in kg/SO₄/ha/day):

$$y = -8E - 05x^2 - 0.012x + 2.15.$$

From the calculations above, the reaction rate decreases as the underground void fills up with groundwater. As the void fills up with groundwater, the oxygen is cut off from the reaction surface. Oxygen is a necessary oxidant and if it is limited, the AMD process will be inhibited. The first increment of water-

level rise is very important because the mining floor and rubble around the pillars will be inundated first, depriving a large part of the reaction surface for oxygen (Evangelou 1995). Oxygen diffusion to pyritic material is greatly reduced upon inundation because the diffusion coefficient of O₂ through the covering water is only 1×10⁻⁴ of that through the atmosphere. Hence, the rate of O₂-consuming reactions becomes low and ratelimiting, and bacterial oxidation of pyrite becomes slow or nil (Evangelou 1995). Castro and Moore (2000) have also indicated how inundation

Fig. 20 Graph of the calculated reaction rate points, trend line and function

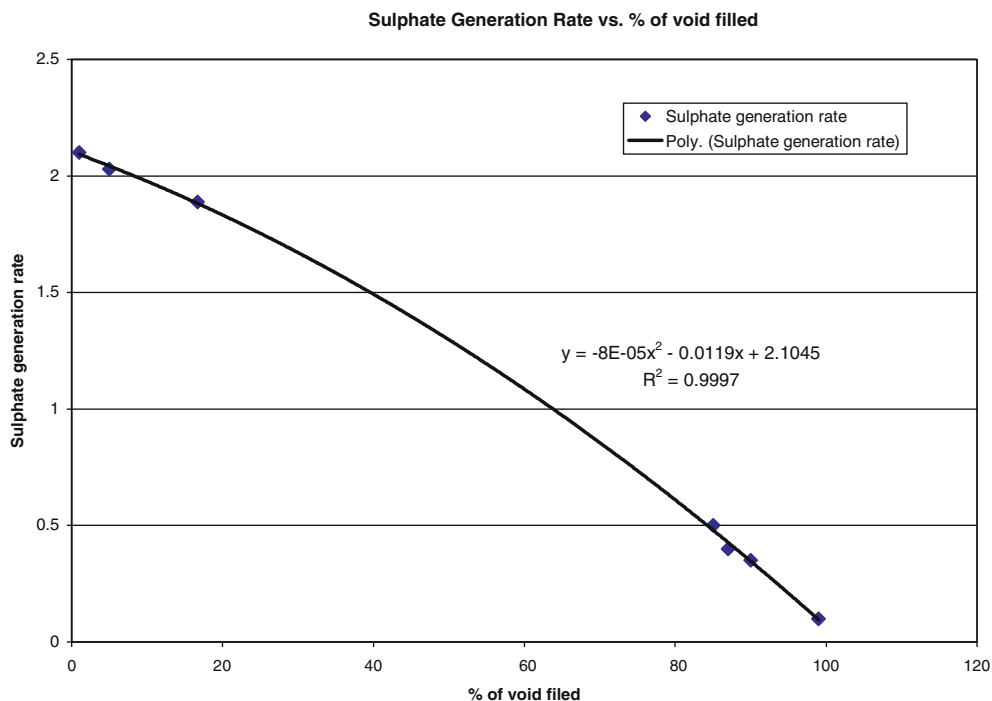
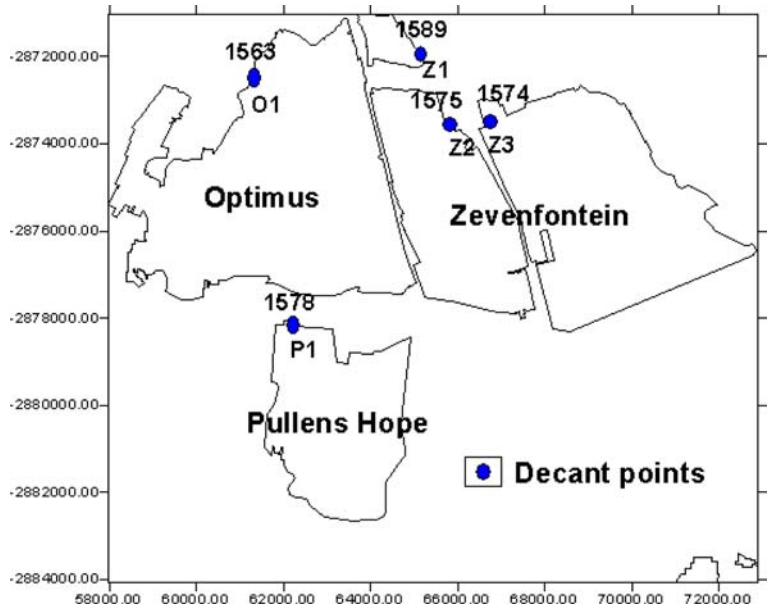


Fig. 21 Location of the different open cast pits at Optimum Colliery



reduces the pyrite oxidation and sulphate generation in a pit lake.

Opencast mining

A number of rehabilitated opencast coalmines in SA are already decanting. A rehabilitated opencast mine (the porosity after back filling is in the order of 0.25) usually has a higher sulphate generation potential compared to that of an underground mine.

At Optimum Colliery (Fig. 21) the following information is available: monthly decant rates and rainfall; sulphate concentrations of the decanting water; water level measurements inside the mine prior to decanting; ABA analyses; information about the rehabilitation (drainage slope, vegetation, soil used). The Optimum Colliery can be subdivided into four units: Optimus,

Zevenfontein and Pullenshope. The study was conducted in the Optimus Pit (Van Tonder and Krantz 1997).

The Optimus Pit (area = 19 km²) was rehabilitated during the late 1980s. Decanting started in September 1992 and flow values and SO₄-concentrations were available up to 1998. Due to the topographic nature of the area, this pit does not fill up with water and residence time is very short. On average the flow was 6,000 m³/day from the pit with an average SO₄-concentration of 2,100 mg/l.

The finite difference model PMWIN (Chiang and Kinzelbach 1999) was selected for the 2D groundwater flow modelling. The only available data that could be used for the calibration were the measured flow at the decant position of the Optimus Pit for 6 years (from September 1992 to April 1998) together with the rainfall data.

Fig. 22 Measured and modelled predicted decant for the Optimus Pit

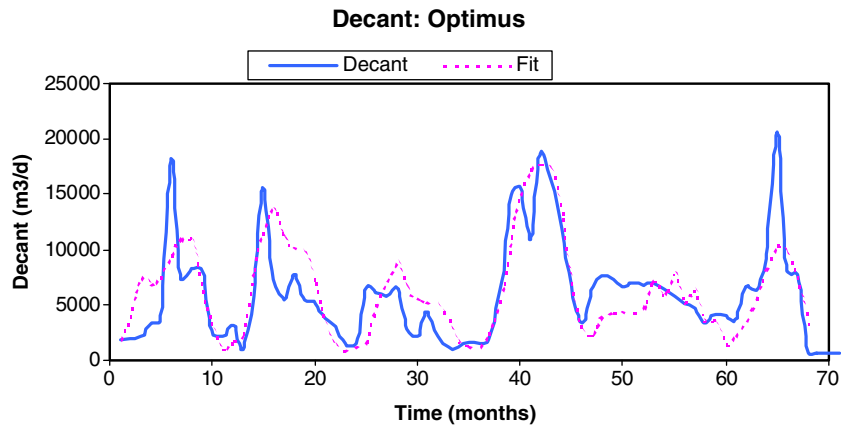
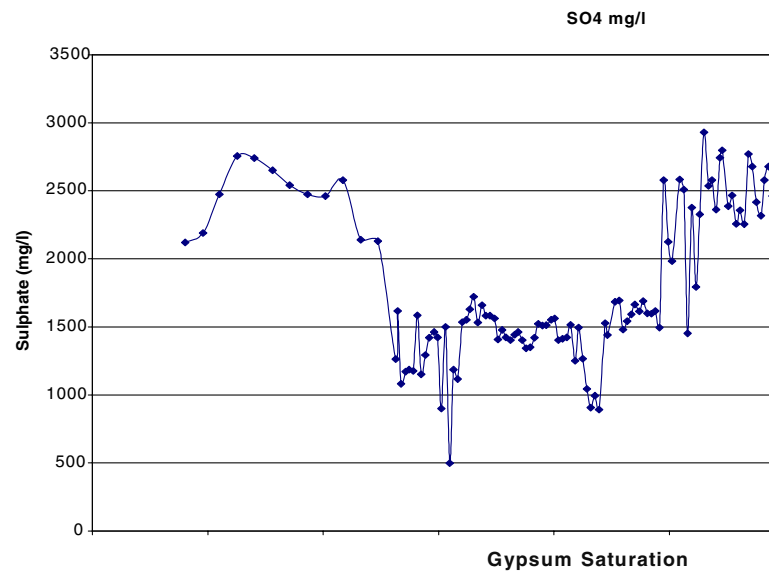


Fig. 23 Sulphate concentration and gypsum saturation for decant water from Optimum Colliery



The closest fit of the measured and modelled decant values was established with an effective recharge of 17% of the rainfall for the rehabilitated pit, which is in line with the recharge normally encountered in opencasts (Hodgson and Krantz 1998). A graph of the measured and model predicted decant volumes with time is presented in Fig. 22. To match the observed SO_4 -concentration of approximately 2,100 mg/l, it was calculated that the sulphate generation rate was approximately 7 kg/ha/day.

This value of 7 kg/ha/day has been found to be a close approximation for many of the decanting opencast collieries in Mpumalanga. However, the gypsum solubility could be significant for the generalised assessments often made e.g. that rehabilitated opencast pits yield between 5 and 10 kg/ha/day sulphate (Hodgson and Krantz 1998). This rate appears to be fairly constant despite differences in degree of spoils saturation, age of spoils or regional impacts. The observed rates, as derived from flow and concentration calibration, may reflect a maximum sulphate concentration with a consistent recharge. The maximum sulphate concentration is determined by the gypsum solubility. Hodgson in subsequent reports has suggested that gypsum precipitation will play a role under low flow conditions.

Values from water at Optimum Colliery clearly indicate this observation. In Fig. 23 the sulphate concentration over time for the decant water where previous determinations regarding the sulphate generation rate were based is shown together with the relative saturation of gypsum.

The SI values indicate that the sulphate values are limited by gypsum precipitation, with values close to saturation as soon as concentrations rise. This could

imply that the true sulphate generation rates are greater than those derived from flow and concentration measurements. (Van Tonder et al. 2003).

Studies at other rehabilitated open cast coalmines also estimated the SO_4 -generating potential to be in the order of 7 kg/day/ha (e.g. at the Middelburg Colliery). This value may even be higher if the upper limit for the SO_4 concentration is bounded by the Ca value of the decanting water due to the saturation of gypsum, as has happened at block C at TNC Colliery.

Conclusions

The water quality of mine drainage is controlled by the chemical content and availability of the rocks that are left exposed in the abandoned mines, and by the composition of overburden rock and soil through which infiltrating water passes. Long-term water quality is also controlled by the availability of oxygen in the mine water system and is influenced by flow factors such as recharge into, and residence time of water in the mines. Watzlaf (1992) states that inundation of abandoned mine voids brings about improvements because generation of AMD is inhibited when the oxygen supply for pyrite oxidation is exhausted.

- The indication is that the deeper Ermelo Colliery does not have a problem with water quality where subsidence contributed to high recharge. After an initial period of poor water quality, it improved drastically as the mine started filling.
- At Minnaar, where the compartments filled over long periods, the sulphate generation is higher than in mines that fill quickly, e.g. Ermelo Colliery.

- At Schoongezicht, where the water decants without the mine being filled up, the quality is a lot worse than the other mines under investigation. Decant is also high, with recharged water flowing at a fast rate through the underground. This decreases the residence time, prohibiting the acid neutralisation by the carbonates from the coal and the strata.
- In unflooded pits, e.g. Optimum, there is a high sulphate production.

The findings above are supported by studies in several areas of western Pennsylvania by Lambert and Dzombak (2002), and by Lambert DC 2000 Development of Steady State and Time-Varying Hydraulic Models of Flow through Flooded and Unflooded Abandoned Underground Coal Mines for the Evaluation of Long-Term Water Quality Improvements. MS Thesis (2002), Carnegie Mellon University, Pittsburgh, PA.

It revealed the following:

- Deep mine discharges that were reliably described as highly acidic in the 1960s and 1970s have shown natural amelioration of acidity and decreases in Fe, Al, Mn, and SO₄ concentrations over time.
- Significant water quality improvements have been observed in discharges from abandoned coalmines in Western Pennsylvania, both from mines that have naturally flooded because of geometry and where flooding was induced via mine sealing.
- Differences in the rate of change between flooded mines may be accounted for by their relative residence times. There is direct interaction in flooded mines, not only with the rocks in and around the coal seam, but potentially all the rocks in the overburden that are hydraulically connected with the mine water. The amount of time water spends in contact with rocks in the system is extremely important in evaluating long-term mine water quality evolution. From previous work (Hodgson and Krantz 1998), the accepted daily rate of sulphate generation in opencast mining is 5–10 kg/ha.

This investigation has found the daily sulphate generation rate for opencasts to be in the region of 7 kg/ha for partially flooded pits, and underground mining to be in the range of 0.4–2.7 kg/ha. When the sulphate generation rate for opencast pits (5–10 kg/ha/day) of

Hodgson and Krantz (1998) is compared to the determined generation rate (0.1–1.5 kg/ha/day) for underground areas, it is clear that the sulphate generation rate for the underground workings is an order smaller. This is due to the much smaller reaction surface in the underground workings when compared to that of an opencast pit. It must also be noted that although the sulphate generation rate might be lower than that of the opencast, the sulphate concentration in underground areas could be higher, due to less dilution as a result of lower water ingress. The gypsum solubility must, however, be considered.

The exclusion of oxygen due to flooding retards sulphate generation. When flooding collieries after mining has been completed, the remaining neutralising potential in the coal is usually sufficient to neutralise the acidity in the mine. Exceptions occur in mines that are only partially flooded. Unflooded areas serve as active areas from where acid water emanates, and a method has been given to determine the expected sulphate generation rate for varying degrees of inundation at South African Collieries.

The recommendation from these results is to flood the mines as quickly as possible. This can be achieved by the selection of mining method, the mining sequence and flooding.

Much can be done to improve mine-water planning in all collieries. It is essential that as much mine water as possible be kept underground during and after mining. To accomplish this, mining should be from low-lying areas to high ground. Compartments should be created that could fill up with water while mining continues in other sections of the mine. This should ensure minimisation of water treatment. Much more can be done in terms of mine planning to flood redundant mine workings.

The mass balance approximation is a method that needs further research to refine the sulphate generation rates. It is felt that this method has great potential to predict future salt loadings from collieries in the Mpumalanga coalfields.

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