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Technical Article

Predicting Rebound in a Deep Colliery in South Africa

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Abstract: The main challenge facing many of the coal mines in South Africa is the management of mine water following the closure of mining operations. The Sigma Colliery is situated in the Free State Province, adjacent to the town of Sasolburg and bordering the Vaal River, one of the country's largest rivers. The mining includes both opencast and underground operations; however, this paper will only discuss the main underground operations. There are several aquifer systems overlying the deeper mining, which was done by bord and pillar and high extraction mining. Detailed conceptual models of the interactions between several aquifer systems and the rebounding mine voids were constructed using mining and monitoring data. From this, numerical flow models were used to model the complex flow system where rebound of water levels is expected. The results have led to an accurate understanding of the complex flow system and the important controls on the final water levels in the area.

Key Words: Coal mines; numerical flow models; rebound; South Africa

Introduction

The main challenge with regard to the Sigma Colliery (Sigma Underground Mine, Wonderwater Strip Mine and Mohlolo Underground Mine) is the management of mine water following the closure of its mining operations. The mining includes both opencast and underground operations; however, this paper will only discuss the main underground operations. This paper will discuss appropriate methods to calculate the current mine water balance, based on existing information, and the use of appropriate modeling tools to determine whether Sigma Underground Mine will discharge on the surface (decant) after rebound is complete and, if so, determine the likely decant positions and volumes.

The Sigma Colliery is situated in the Free State Province, adjacent to the town of Sasolburg in South Africa. The mean annual rainfall for the area is 620 mm (Weather SA). Four rivers/streams drain the area. The main system is the Vaal River to the north. The Leeuspruit and the Rietspruit overlie the Colliery, and have an influence on the mine, especially in areas of subsidence (see Figure 1). Should the water levels rebound to such a degree that mine water decants on the surface, this could have several negative environmental and economic implications. North of the colliery, several wetlands have been identified that have protected status under South African legislation, while the newly introduced Waste Discharge Cost System of the South African Department of Water

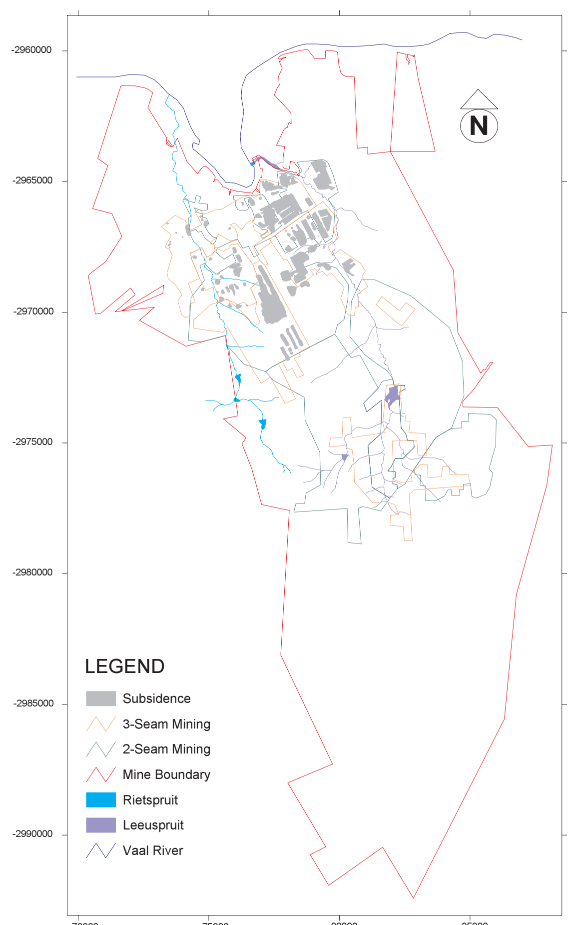

Figure 1. Rivers draining the Sigma mine area with coordinates shown (WGS 84, Transverse Mercator 27)

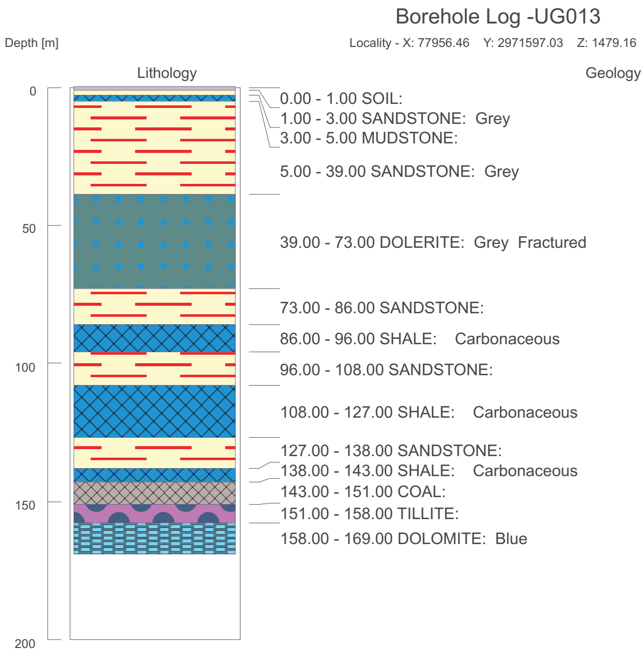

Figure 2. Site-specific stratigraphy of borehole UG013

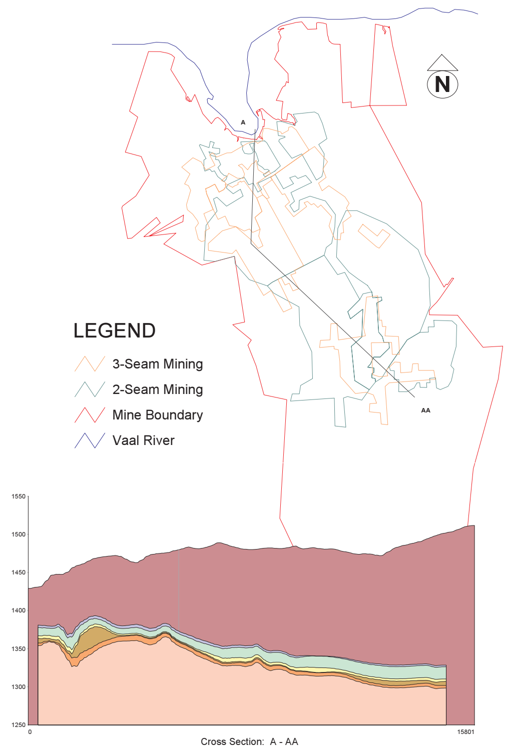

Figure 3. N-S cross section to illustrate the position of the coal seams relative to the surface (units of elevation are in metres above mean sea level on the y-axis, on the x-axis distance in metres is given)

Affairs and Forestry hold potential economic consequences for mining companies discharging poor quality water to the environment. Sigma Colliery lies in the Sasolburg-Vereeniging Coalfield.

Geology

The statigraphy of the coalfield is typical of the coal-bearing margins of the Karoo Sequence. The succession consists of pre-Karoo rocks (dolomites of the Chuniespoort Group of the Transvaal Sequence) overlain by the Dwyka Formation (2-15 m thick), followed by the Ecca Group sediments, of which the Vryheid Formation is the coal-bearing horizon. In some places the lava of the Ventersdorp Supergroup underlies the coal (Cairncross 2001). The Karoo Formation is present over the whole area and consists mainly of sandstone, shale and coal of varying thickness. Alluvium is present in the vicinity of the Vaal River. The Vryheid Formation contains four major coal seams. These seams are named from 1 at the base, 2A and 2B in the centre, and 3 being the topmost seam (Smith and Whittaker, 1986). The seams mined at Sigma Colliery are the No 3-seam, and the No 2 A and B seams, which for the purpose of this discussion, will be treated as a single seam due to the mining methods. A typical borehole log for the area is illustrated in Figure 2.

Dolerite intrusions in the form of dykes and sills are present over the entire coalfield and are responsible for structural complications. The coal seam dips from north to south (Figure 3). The depth of the coal seam ranges from 150 m in the south to 55 m towards the Vaal River.

Geohydrology

Five ground water systems are present in the Sigma area. They are contained in the shallow Quaternary and recent sediments, the intermediate unweathered/fractured Karoo, the subsided and backfilled material above the coal horizon, the coal seams (mining area), and the deep Pre-Karoo system (containing the Dwyka tillite and the dolomites below the tillite) (Hodgson and Krantz 1998).

The upper aquifer is associated with the top 5 - 15 m in the area, which consists of soil and weathered rock. In places, a thick dolerite sill is present close to surface. In boreholes, water may often be found at this horizon. This aquifer is recharged by rainfall, which infiltrates into the weathered rock until it reaches impermeable layers of solid rock beneath the weathered zone. Movement of ground water on top of the solid rock is lateral and in the direction of the surface slope. This water reappears on the surface at locations 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 ground water level at streams. The weathered zone is generally low in yield (range = 100 - 500 L/h) because of its insignificant thickness.

The grains in the fresh rock below the weathered zone are well cemented, which limits significant flow of water. All ground water movement in these intermediate strata is therefore along secondary structures, such as fractures, cracks and joints in the rock. These structures are best developed in the sandstone. Dolerite sills and dykes are generally impermeable to water movement, except where they are weathered.

The coal seam system is mined out, resulting in a far higher transmissivity value than the layers above and below it. The Dwyka Tillite, which lies below the coal seams, is very dense with a very low transmissivity. The next permeable layer is the top section of the dolomite, which is a chert-rich paleo-channel, and serves as a conduit for water. The high piezometric pressure of this system, where it is not overlaid by tillite, forces water upwards, into and above the coal seam.

Mining

Different mining methods have been employed at the Sigma Colliery. Primary development was by bord-and-pillar. This was followed by stoping, which was completed in an irregular pattern. Longwall mining was also conducted in areas of Sigma Underground. The No 2-Seam and the No 3-Seam were mined, as indicated in Figure 4. Due to the nature of the high extraction methods applied at Sigma, several areas of surface subsidence have occurred (Hobbs 1998).

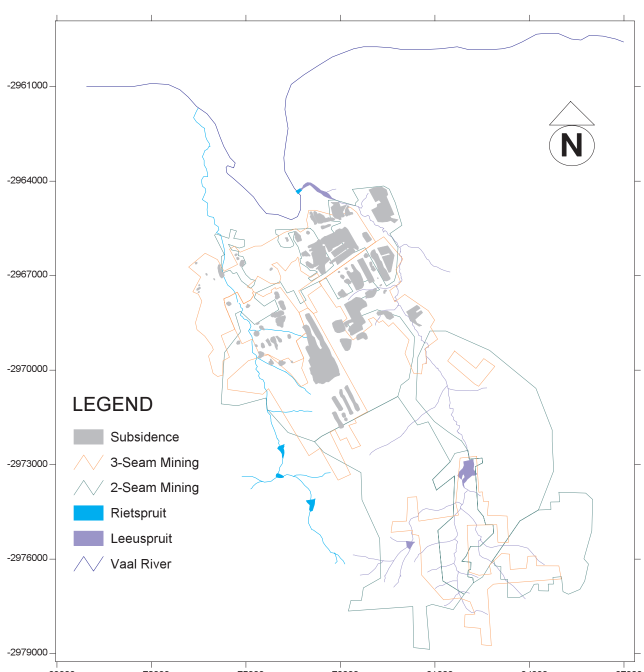

Figure 4. Map to illustrate the different mining and subsidence areas.

Statistics relating to the colliery are shown in Table 1. The water-holding capacities (potential storage volumes for each mining seam and area) for the workings were obtained by calculating the stage curves. Stage curves present the water volume versus elevation for the mining area by making use of the floor contours and expected storage based on extraction ratio, mining height and mining method. Areas of subsidence where high extraction mining has been done is also included in these calculations. A volume at each elevation is plotted on the stage curves. The stage curve for the smallest underground portion is depicted in Figure 5.

Methodology

Feasible conceptual models were constructed, based on the available data and numerical models, using a simplified one-dimensional finite difference model and more detailed three-dimensional modelling, using MODFLOW. This was done during the period of January to November 2003.

A large amount of data on the water regime was available from Sigma's extensive monitoring system, which includes more than 40 boreholes drilled into different stratigraphic layers and into the different mining compartments. This monitoring record had data on water levels and water quality for a period of more than 10 years (VSA Geo-consultants 1997, 1999, 2002, 2003), and this was used to test and verify different potential mechanisms of rebound. From this, feasible conceptual models could be constructed and then translated into the equivalent numerical models from which the predicted rate and manner of water level rise, and the impacts thereof, could be assessed. In mid to late 2006, a post-project audit was undertaken to assess the system's response and compare the results to the predictions from these models.

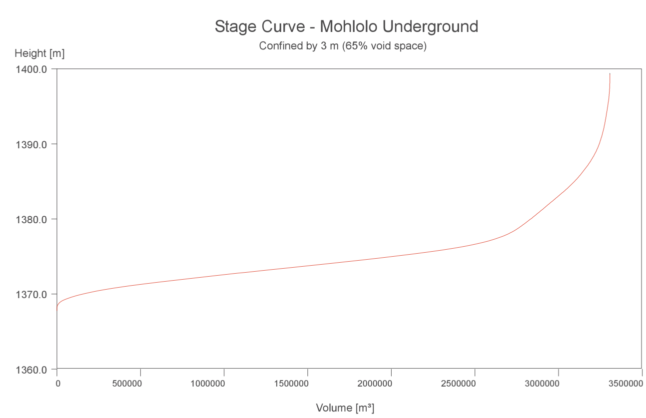

Figure 5. Stage curve for Mohlolo Underground

Table 1. Mining statistics

Mining Unit	Area (Ha)	Mining Height (m)	Void Space	Storage Volume (Mm^3)
2 Seam	7017	152	0.62	152
3 Seam	3865	80	0.62	80
Mohlolo	171	3.5	0.65	3.5

Conceptual Model

General

In every model, the system under investigation is represented by a conceptual model. A conceptual model includes designing and constructing equivalent but simplified conditions for a real world problem that are acceptable in terms of the objectives of the modelling and the associated management problems. Transferring the real world situation into an equivalent model system, which can then be solved using existing software, is a crucial step in ground water modelling. The following information is needed for a conceptual model:

- The known geological and geohydrological features and characteristics of the area.
- The static water levels/piezometric heads of the study area.
- The effects of the geology and geohydrology on the boundary of the study area.
- A description of the processes and interactions taking place within the study area that will influence the movement of ground water and,
- Any simplifying assumptions necessary for the development of a numerical model and the selection of a suitable numerical code.

Sigma underground conceptual model

Figure 6 shows a typical situation at the Sigma Underground Mine. For illustration purposes, only one

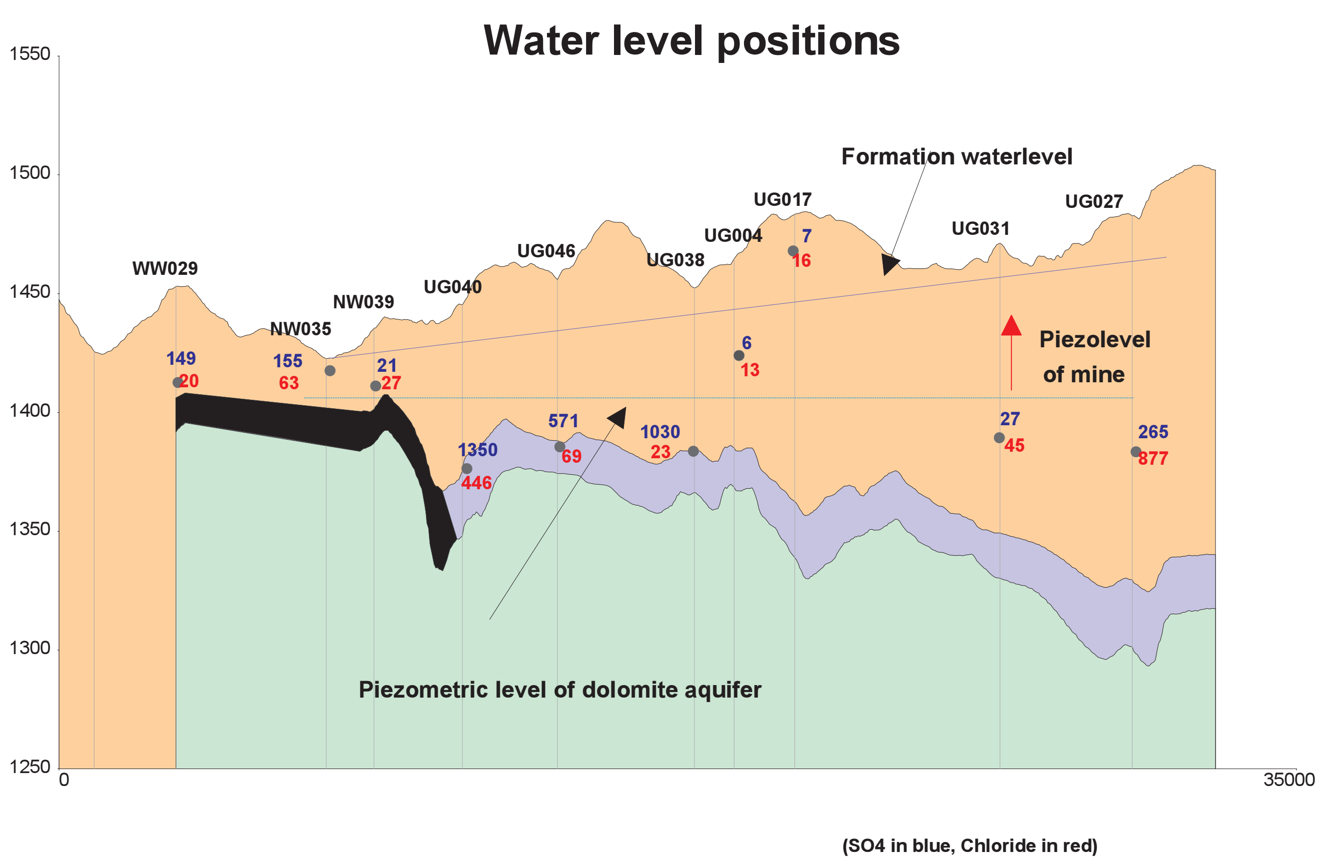

Figure 6. Conceptual model for the Sigma Underground Mine

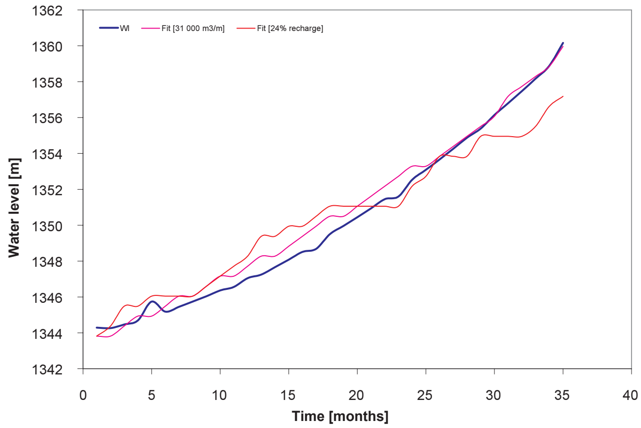

Figure 7. Measured and fitted water level in UG027 and water level fitted with a recharge of 24% (see the erratic behaviour of the model fit line)

seam is taken into account.

The transmissivity (T)-value of the mined coal seam is very high (on the order of 10^3 m²/d) and the storage or specific yield (*S*) is also very high (62% in the mined out section, as opposed to approximately 0.1% in typical Karoo aquifers). Although high extraction mining has been done in places, the majority of the mining was by bord-and-pillar methods, and the collapse which has occurred still results in far more transmissive properties than in the country rock. Once the mine has filled up with water, a horizontal piezometric level will occur (this piezometric level is also horizontal during the rebound due to the high transmissivity in the void). If the piezometric level intersects the surface, decant could take place at the point of intersection if there is a link between this position and the mine (e.g. a borehole).

The rate at which the piezometric level rises is dependent on:

(a) the amount of influx from the layers above the mining void (or along subsidence areas) - denoted by the symbol It,

(b) the flux to the layers below the mining voids and the mine due to differences in piezometric head between the voids and these deeper layers (denoted by Ibout) and

(c) the amount of lateral ground water outflow (denoted by Qo) downstream from the mined out area.

If the inflow from surface exceeds the outflow (It > Ibout+Qo), the mine will decant. However, if It< Qo +Ibout, the mine will not decant and the worst that could occur is that the mine water will flow towards the deeper layers. In situations where other influxes occur, the eventual decant is determined by the relative piezometric level and transmissivity of each contributing system.

This mine is partially underlain by dolomite, which has a far higher transmissivity than the Karoo units lying above the mine. About 10% of the dolomitic aquifer is in direct contact with the coal seams. The dolomite has a piezometric level of 1403 mamsl (Hobbs and Fourie, 2000), which is lower than the water level of the top aquifer, but higher than the piezometric level of the mined out coal seams. It is thus expected that a large volume of water is currently flowing from the dolomite aquifer towards the mine (during mining, water was flowing from the floor of the mine).

Once the mine has filled up with water, the piezometric level of the mine will rise with the storage coefficient value of the mine (and not the specific yield) as conditions change from unconfined to confined. The flux from the overlying aquifers into the mine aquifer will decrease as the two water levels approach each other and the head difference decreases. The flux from the deeper dolomite aquifer (currently at a higher peizometric level than the mine), will also decrease as the mine's piezometric level increases. Once the level of the mine aquifer is higher than that of the dolomite aquifer, water from the mine will flow towards the dolomite aquifer.

Under these circumstances, decant can only occur where the mine water level rises above the level of the top weathered aquifer. The likelihood of the mine water level increasing above the water level of the top aquifer is very low because the dolomite has a much higher transmissivity value than the top aquifer. Water will therefore flow from the mine towards the lower dolomite aquifer.

It is expected that most of the recharge will occur in subsided areas, which will act as preferred pathways. The amount of recharge in the area was calculated using the chloride method (Sharma and Hughes, 1985). In this method the % recharge = 100 × Cl_{rain}/ $Cl_{ground\ water}$. As no information was available on the amount of Cl in rainfall, it was assumed that it was equivalent to the average Cl value of rainfall in Johannesburg, 1 mg/L. The chloride method indicates that there is 4.2% rainfall recharge to the aquifers above the mine (i.e. 100 × 1/24, where 24 mg/L = the harmonic mean of Cl in the boreholes). The harmonic mean was used in the chloride calculation to provide more weighting for the chloride samples depicting natural groundwater chloride concentrations and not those that are contaminated. The average rainfall in the area is 620 mm/a, which yields an average recharge to ground water on the order of 26 mm/a.

Table 2. Summary of results from the numerical 1D- model

Mine	Area (ha)	Rate of refilling in mine (ML/d)	Time before mine is filled up (years)	Decant rate (ML/d)
Sigma Underground No 2- Seam	7760	30	1.1	Highly unlikely to decant*
Sigma Underground No 3-Seam	4466	10	3.3	Highly unlikely to decant*

*Mine could only decant if the influx along subsidence areas are higher than the flow towards the dolomite aquifer.

Numerical Modeling

Assessment with one-dimensional numerical models

In order to investigate the behaviour of aquifer systems in time and space, it is necessary to employ a mathematical model. The ground water mass balance equation was solved using a numerical approach. The 1-D numerical model was based on several observations and simplifications, including the fact that the observed water levels in BHs UG027, UG043 and UG046 showed similar behaviour, which implied that all compartments in the No 2- and 3-Seams were hydraulically linked. The water level has risen by approximately 0.7 m/month (Figure 7).

The values entered into the model for this scenario were: the total area modelled (7700 ha) and the porosity of the mined out area, represented by the extraction ratio of coal except in areas of collapse (average value = 62% void space, based on the extraction ratio and the degree of collapse observed in the selected areas where high extraction mining methods where employed). The model ran in time-step increments of 1 month.

The model was run a number of times with various combinations of parameters until the observed water level correlated with the simulated water level (Figure 7). This shows the best fit obtained if only the recharge from rainfall was used as fitted parameter. The erratic model behaviour clearly shows that rainfall recharge is not the major driver on the water volumes and that the water is derived from the adjacent aquifer systems. The parameters obtained from the best fit are: total inflow into the No 2-Seam = 30,000 m^3/d; total inflow into the No 3-Seam = 10,000 m^3/d.

It is expected that all the water from the lower coal seam (No 2-Seam) comes from the lower dolomite layer, which implies that at least 66% of the water is coming from the dolomite. Boreholes UG027 and UG042 measure the piezometric levels of the mined out seams and the rise in water level, together with the stage curves was used to determine inflow volumes.

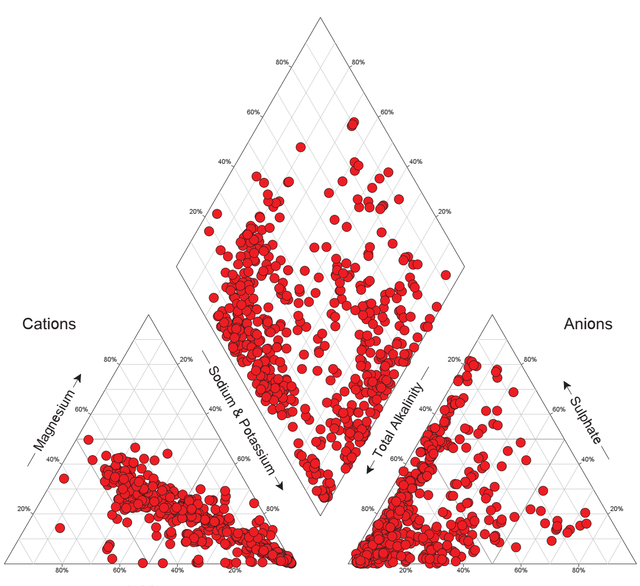

Figure 8. Modified Piper diagram for mine waters showing strong dolomitic evolution in the cations

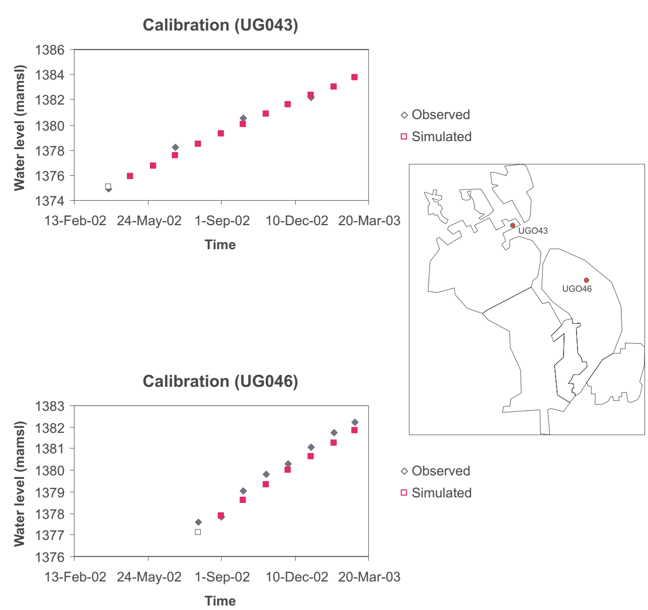

Figure 9. Comparison of modelled and measured values in boreholes UG043 and UG046

Table 3. Results of model calibration

Layer	Description	Type	Transmissivity (m^2/d)	Vertical hydraulic conductivity (m/d)	Storativity
1	Alluvium	Unconfined	50	2	0.15
1, 2, 3	Karoo	Unconfined/confined	5	1×10^{-5}	0.0025
3	Coal seam	Unconfined/confined	5000	0.1	0.62
4	Tillite/dolomite	Confined	3000	15	0.01

Based on the measurements and calculated storage, it was determined that the mine was filling up at an average rate of about 40ML/d. The origin of this water is important and several options were postulated. If the water originated from the aquifers above the 7,700 ha mined out area, it would imply that the vertical hydraulic conductivity (K_v) value of the Karoo aquifer must be on the order of 2×10^{-4} m/d, which is a realistic value. Based on the observation boreholes in the mine, the No 2-seam was filling up at a higher rate than the 3-Seam mine, which implies that a large amount of water was coming from the dolomite below the No 2-Seam. Alternatively, if the inflow was from recharge, it would mean that the recharge occurs along preferred pathways, such as the subsidence areas and that there would be less increase in water levels during dry periods (e.g. the winter). This seems to be unlikely as the water level increase is consistent.

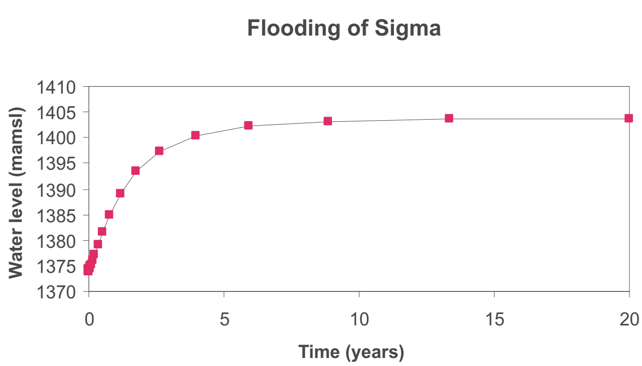

Figure 10. Increase in water level in the Sigma underground mine

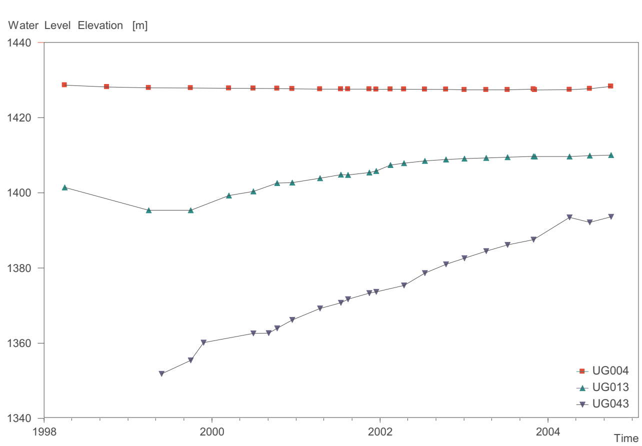

Figure 11. Water levels in boreholes, which measure the pressure in the formation, the subsided areas and the mine, respectively

To support this, the water quality changes in the different boreholes can be considered. The water in the mine itself is characterised by a strong sodium chloride nature which, as acid mining drainage processes occur, becomes enriched in sulphate. It is clear from inspecting the water quality from the mine that there is a strong evolution of water from sodium dominated to more calcium and magnesium enriched water. As shown on the Piper diagram (Figure 8), this evolution occurs predominantly along a line where the Mg:Ca ratio approaches 1, supporting the fact that dolomitic water is entering the mine void.

Assessment with a Three Dimensional Numerical Model

Despite the inherent limitations in using numerical groundwater models such as MODFLOW for rebound, such a modelling approach was used to support the simpler models outlined in the preceding section. The system was modelled using a three-dimensional finite difference numerical model, MODFLOW (Harbaugh and McDonald 1996), to determine the expected rates of water level rise and the factors controlling this rise. A professional graphical interface, PMWIN, developed by Chiang and Kinzelbach (1999) was used to create the model, and to analyse and display the modelling results.

The model network was divided into 4 layers, representing the alluvium and weathered Karoo Formation, the unweathered Karoo Formation, the coal seams, and the tillite/dolomite layer. The Vaal River was simulated using the Dirichlet boundary condition (also know as a constant head or fixed head) at an elevation of 1421 m above mean sea level (mamsl). Initial

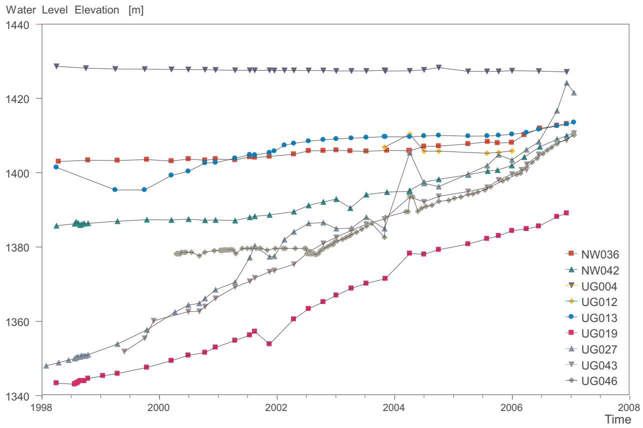

Figure 12. Water levels since 1998 (formation water level given by UG004, NW boreholes provide the dolomite aquifer water levels; UG013 is in a subsided area, and the other UG boreholes reflect the mine's water level)

head values in the model were derived from the monitoring record of boreholes in each of these systems.

Superimposed are the surface water features and outline of the No 2- and No 3-Seams. The mesh constructed for the model consisted of 137 × 120 cells in the *x* and *y* directions, respectively. Each of the elements was 175 × 175 m. The coordinates for the modelled area are 68000, -290000 (lower left corner) to 91975, -2959000 (upper right corner).

The results of the calibration are shown in Figure 9. The parameters considered during calibration were hydraulic conductivity, vertical hydraulic conductivity and storativity. The calibrated parameters obtained are summarised in Table 3. The tillite/dolomite layer is treated as one, as dolomites account for approximately 10% of the floor area of Sigma.

Once the calibration was completed, a scenario was run to determine whether decant would occur and what the impacts of the rebound would be. The results indicated that the Sigma underground mine would not decant (Figure 10). The water level was predicted to increase until it reached the level of the dolomitic layer, after which this level would be the controlling factor in the water level rise. Currently, the total influx towards the mine is between 36 – 39 ML/d (the influx from the dolomitic layer is approximately 27 ML/d).

The mine can only decant if the piezometric level of the underground mine intersects the surface. This can only happen at places where a U-tube structure exists (e.g. shafts, boreholes or subsidence areas (most likely)). Borehole UG013 is drilled into one such subsidence area and Figure 11 shows the water level of this borehole and borehole UG043, which measures the piezometric level in the mine. Another observation borehole measuring the water level in the undisturbed strata adjacent to the mine (UG004) is also plotted on this figure. The water level of UG013 lies between that of UG004 and UG043. This implies that the vertical K value of the subsidence is higher than that of the formation (which equals approximately 2×10^{-4} m/d), but is lower than that of the mine. A maximum vertical K-value of 1×10^{-3} m/d is required so that the water level in the subsidence does not drop to that of the mine water level. The U-tube scenario thus did not exist at this position. Assuming 100% recharge on the subsidence areas with a total area of 100 ha, then the influx is 1700 m^3/d (1.7 ML/d).

The possibility that the mine water could decant is extremely small, since once the mine's piezometric level is higher than the dolomite piezometric level, the mine water will flow towards the dolomitic aquifer. It is only in the case that influx from direct recharge is greater than the flux from the mine towards the dolomite aquifer, that surface decant is possible.

Likelihood of surface decant

The main conclusion of the 2003 assessment report was that it is very unlikely that the mine will decant and that the rate of water level increase would initially be as predicted in Figure 10. The field data and numerical model both point to the importance of the relative piezometric levels of the mine and the underlying deep dolomitic formations.

Post-modelling comparison

In 2006, the mine requested a comparison between the predictions and the actual field values. Concern arose since several of the monitoring boreholes identified as being connected to the mine system showed increases, and it was suspected that an additional source of influx may have been playing a role.

Inspection of the water level elevations shows that there has been an increase in the mine-related water levels since 2003 (Figure 12). This could have led to the conclusion that the voids were full and that decant may be imminent, but it was determined that the formation water levels and the piezometric level of the dolomite aquifer provide the answer to this increase. The water level in the dolomite has risen from 1402 mamsl to about 1412 m amsl due to a very high rainfall in 2006 in the area of the dolomites recharge. As a result of the abnormally high rainfall, recharge to the dolomite and the sediments above the mine has increased non-linearly, meaning that a higher proportion of the increased rainfall has recharged the aquifers (so–called episodic recharge (Bean 2004)), and so the mine water level is also increasing. The water level elevation in borehole NW036 (dolomitic water level) is currently at 1412.74 mamsl, which is still higher than any of the measured water level elevations of the boreholes measuring the mine water level.

As expected, the formation water level elevation as measured in UG004 is still higher than that of the mine water and dolomitic levels. The water level in borehole UG013, which is drilled into the longwall subsidence area, is similar to the dolomite levels.

The data from 2006 still indicates that the possibility that the mine water could decant is extremely low. None of the formation water levels or the mine water levels exceed that of the dolomitic water levels. Once the mine piezometric level is higher than the dolomite piezometric level, the mine water will flow towards the dolomitic aquifer.

This case study represents the first documented example of the control of the final water levels by a deeper lying transmissive aquifer in the South African coalfields.

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