The use and applicability of flow models to quantify intermine flow in the Western Witbank coalfields

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Transaction Paper

Synopsis

After the closure of collieries, they naturally start to fill up with water. As a result, hydraulic gradients develop between them and different hydraulic pressures are exerted onto peripheral areas or compartments within mines. This results in water flow between mines, or onto the surface. This flow is referred to as intermine flow.

The collieries in the Witbank Coalfield have geometries such that there are several areas where this intermine flow is possible. Since the Department of Water Affairs and Forestry has declared intermine flow as one of its greatest concerns for granting closure to South African mines, much research into this phenomenon is required.

The challenges in determining intermine flow are numerous, and attention has focused on identification of areas where these flows can take place. The quantification of these flows is problematic due to the uncertainties in exact geometric configurations and the variation in site-specific hydraulic properties of the coal and overlying lithilogical layers.

During this study, use has been made of numerical flow modelling and several analytic solutions to test the applicability of the flow models as well as to predict groundwater flow directions, filling times of voids and flow volumes. The numerical modelling methodology entailed a downscaling approach starting with a broad regional model covering the entire area, followed by modelling the interactions between interconnected mines, and finally looking in detail at the major areas of interaction.

Introduction to intermine flow

Coalmining in the Witbank Coalfield of South Africa has existed for more than a century. Due to the scale of these operations in areal extent and the time period of operation, these activities have altered the geohydrological environment in the area. These impacts are not only limited to the operational life of mines, but are also expected to continue for many years after mining has ceased.

One of the key areas of concern is the phenomenon of intermine flow. Previous researchers, for example Grobbelaar[3] and Grobbelaar *et al.*[2], have investigated intermine flow. After the closure of mines, water in the mined-out areas will flow along the coal-seam floor and accumulate in the lower-lying areas. These man-made voids will fill up with water and hydraulic gradients will be exerted onto peripheral areas (barriers) or compartments within mines. This results in water flow between mines, or onto the surface. This flow is referred to as intermine flow[2]. Due to the potential long-term impact of intermine flow in terms of water quantities and qualities, the Department of Water Affairs and Forestry regards intermine flow as one the most important challenges in the mining industry[6].

This paper aims to:

- Outline approaches and results of simulation of regional and intermine flows through the study area using numerical methods
- Provide filling times for the opencast and underground areas as well as flow volumes in the intermine flow areas.

Approach to the research

During previous studies in this area, areas were identified where intermine flow is taking place between mining areas[1,2]. During this study, areas were identified where intermine can take place in the future. The study area of this paper consists of seven mines in the Western Witbank Coalfield of South Africa. The study area was divided into three hydraulic units. Grouping of the units was done in terms of current flow directions, by making use of the floor contours of the area. The floor contours give an indication of areas where intermine flow can take place. Figure 1 indicates the locations of the three hydraulic units.

The hydraulic units are the following:

- Unit 1 consists of mine T and mine K
- Unit 2 consists of mine T and mine R
- Unit 3 consists of mine G, mine KK, Mine TF and mine W.

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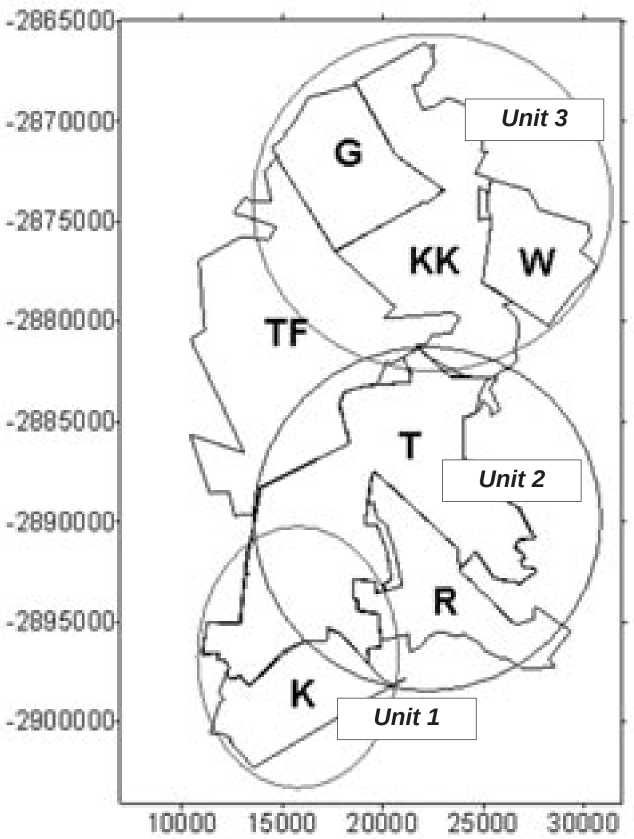

Figure 1—Study area and the grouping of the three hydraulic units

Only the results from the first two units will be discussed in this paper.

The software, Processing Modflow for Windows[1], was used to model the hydraulic interactions in the area. Three models were constructed to predict intermine flow in hydraulic units 1 and 2 described above.

Volumes and potential flows were evaluated using volumetric determination techniques and extensive review of available information. The models enabled prediction of the filling times of the mining pits and workings according to in- and outflows, and the amount of flow through the coal barriers.

Conceptual model

A conceptual model includes designing and constructing equivalent but simplified conditions for the real world problem that are acceptable for the objectives of the modelling and the associated management problems.

A conceptual model gives an interpretation of the characteristics and dynamics of an aquifer system, which is based on an examination of all available hydrogeological data for a modelled area. This includes the external configuration of the system, location and rates of recharge and discharge, location and hydraulic characteristics of natural boundaries, and the directions of groundwater flow throughout the aquifer system. For these models the geometry, storage characteristics and floor and topographical parameters of each mine void in relation to the other hydrogeological factors form an integral part of the conceptual model

Hydraulic Unit 1—Flow model

Future intermine flow is suspected in the area between an opencast area and the Number 4 Seam underground. A flow model was designed to calculate the amount of flow through the unmined boundary between these collieries and the time for the two opencast pits to reach decant level.

In the southwestern part, the Number 4 Seam is currently being mined. Information received from the mine indicated that mining of the opencast pits is planned to start in 2004.

The mining sequence in both pits is such that most of the pits will have to be dewatered during mining because the coal floor dips towards the coalface.

Decanting elevations for each of the pits, i.e. 1566 mamsl for Pit 5 and 1561.5 mamsl for Pit 6 have been taken from the report by the civil engineering department of Anglo American. The positions of the decant points of the opencast pits are shown in Figure 2.

It was estimated that when Pit 6 is at decant level, the pit could hold approximately 29.3 Mm^3 of water. The holding capacity of Pit 5 is approximately 33.6 Mm^3.

A flow model was prepared and a post-mining simulation was done on the area.

Flow model results

After mining, the pits will start to fill up with water. To predict the filling times of the two opencast pits, a sensitivity analysis was done.

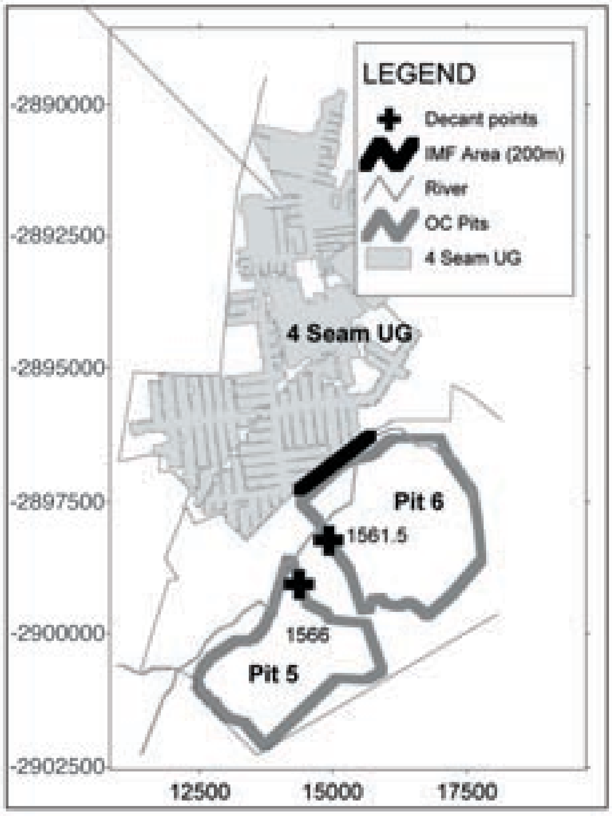

Figure 2—Extent of Hydraulic Unit 1 and the position of intermine flow—flow model

Two parameters, namely hydraulic conductivity (K) and recharge, were used to test the model sensitivity. Recharge is the net addition of water to the zone of saturation. A hydraulic conductivity of 0.000864 m/d was taken from Hodgson and Grobbelaar (1998) to simulate the permeability of the coal layer. Hydraulic conductivities of 0.000864, 0.00864 and 0.8 m/d were simulated against the expected range of recharge of 14 and 20%.

Table I represents details on the sensitivity analyses. Figure 3 represents the filling times using 20% recharge for the 4 seam underground area and the two opencast pits.

The assumption is that with a larger K-value the pits will fill up more quickly, but the model calculated the opposite. By increasing the K-value, the influx from the strata increases. This accelerates the inflow of water but it also accelerates the rate of outflow. In this case, the groundwater is leaving the pit faster than it can flow in. It can thus be predicted that Pit 5 will take between approximately 44 and 70 years and Pit 6, 27 to 62 years to fill to their respective decant elevations for the different K-values (Table I). The importance of site-specific parameters is therefore very clear.

As Pit 6 starts to fill up, small amounts of water start to leak through the coal barrier from Pit 6 to the Number 4 Seam underground area. The coal barrier between the two collieries is approximately 200 m wide (Figure 2). A water budget was calculated during the course of the modelling simulation.

For the calculations of the water budget, the model area was subdivided into sub-regions.(See Table II) The sub-regions are as follows:

Pit 6

The unmined coal barrier between Pit 6 and the underground area

Influx from the strata into Pit 5.

An average flow through the coal barrier was calculated as 5.8 m^3/d. From the model it can be seen that the impact of intermine flow is minimal through the unmined coal barrier. This can be attributed to width of the barrier as well as to the low permeability of the strata. The small amounts of water leaking through the coal barrier to the underground area are not considered to be problematic.

Hydraulic Unit 2—Flow model

Intermine flow can take place in several areas on the boundary between Colliery R and its underground area (Colliery R Underground), as well as between Colliery R and Colliery T.

Two cross-sections were prepared to provide an indication of the expected interaction. The two sections are labelled X and Z respectively (Figure 4).

Table I

Sensitivity analyses for Hydraulic Unit 1—Flow model

Pit	Hydraulic conductivity (m/d)	Recharge %	Time to decant (years)
Pit 5 Pit 6	0.000864 0.000864	20% 20%	44 27
Pit 5 Pit 6	0.000864 0.000864	14% 14%	63 39
Pit 5 Pit 6	0.00864 0.00864	20% 20%	46 31
Pit 5 Pit 6	0.00864 0.00864	14% 14%	67 55
Pit 5 Pit 6	0.864 0.864	20% 20%	47 34
Pit 5 Pit 6	0.864 0.864	14% 14%	70 62

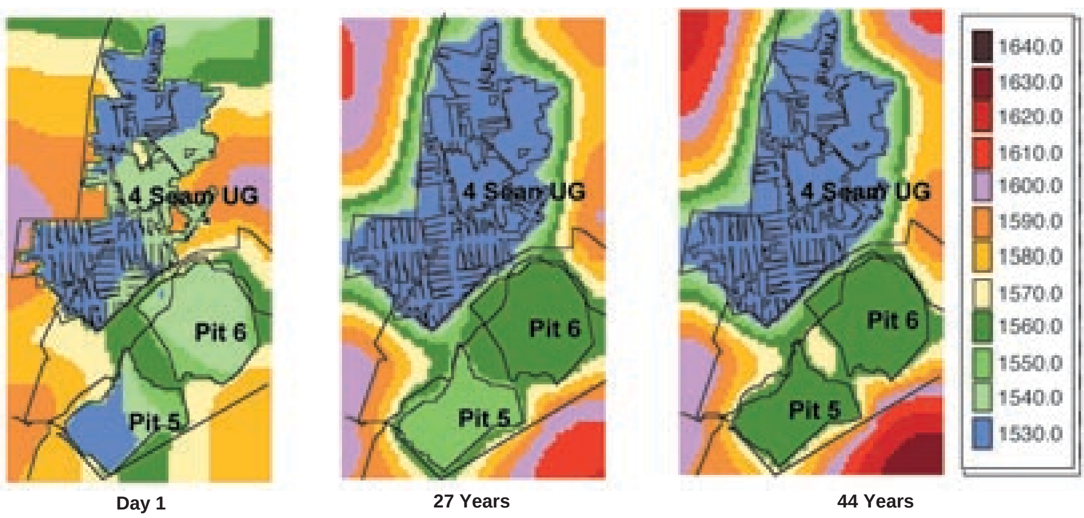

Figure 3—Sensitivity analyses on Hydraulic Unit 1 filling times using 20% recharge

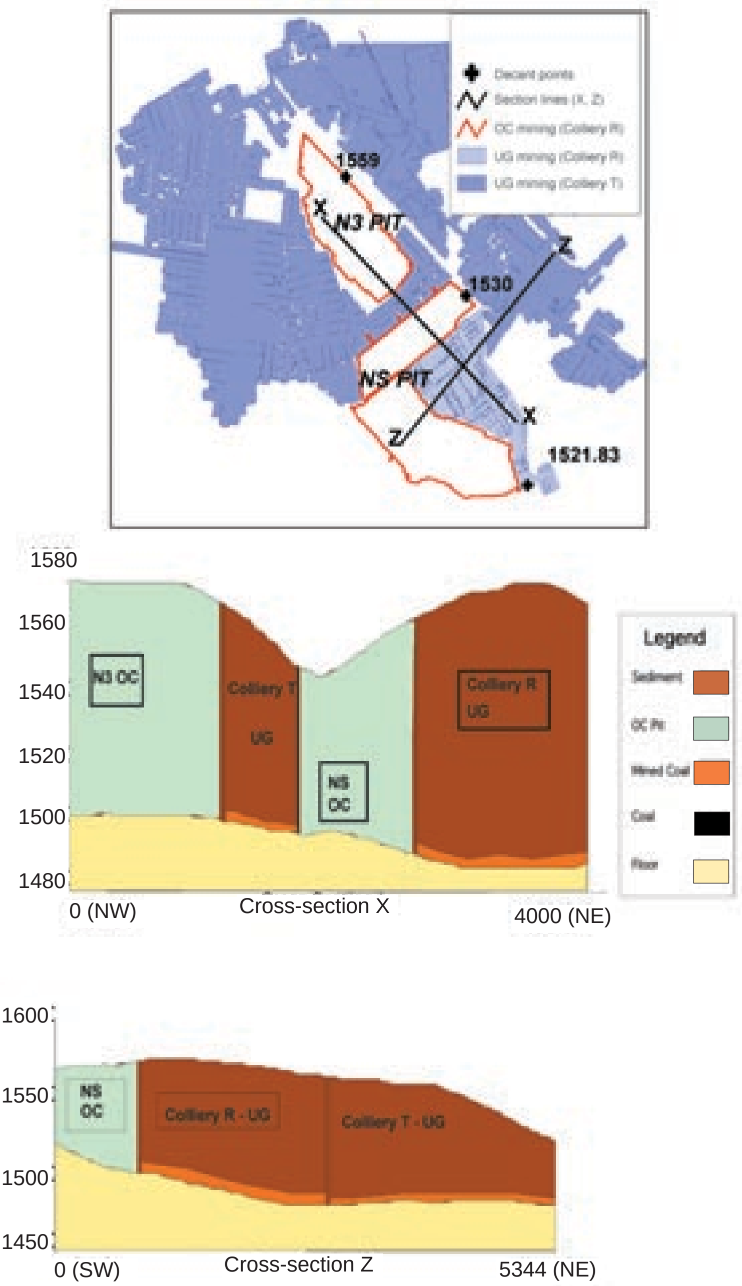

Figure 4—Locations of the cross-section areas. Cross-section X is a Northwest—Southeast cross-section through the N3 pit, Colliery T—2 Seam underground, the North-South Pit and the underground area of Colliery R. Cross section Z is a Southwest-Northeast cross-section through the North-South Pit, Colliery R—underground area, and Colliery T underground area

Water will initially migrate along the floor of the coal-seams, and since the No. 2 coal seam is the dominant seam mined at Colliery R and Colliery T, water migration will at first be along this seam.

On a local scale, water will first accumulate in the opencast pits at Colliery R. From there, it will migrate through the coal barriers to Colliery T and Colliery R underground workings.

The two opencast pits as well as the underground area at Colliery R will decant with rising water levels. The North-South Pit will decant at a level of 1530 mamsl, and hold approximately 44.5 Mm^3. The decant level of the N3 Pit is towards the north, at the much higher level of 1559 mamsl. The capacity of the pit at decant elevation is approximately 47.3 Mm^3. Colliery R's underground area will decant at a level of 1521.

Analytical model

An analytical model was used to predict the alternative filling times of the areas. A hydraulic conductivity for the undisturbed coal has been measured at 0.1 m/d, and for the rest of the model area a hydraulic conductivity of 0.0015 m/d was assigned[5].

From the calculations of the analytical model, the following filling times were predicted for the North-South opencast pit as well as for Colliery R underground area.

For the first 60 years water will flow from the North-South Pit to the underground area. It will take approximately 66 years for the underground area to fill up. After the underground area has been filled, the flow will rapidly decrease. The North-South Pit will take approximately 68.4 years to reach its decant elevation of 1530.

Flow model results

To establish intermine flow paths, particle tracking was done by making use of Modflow's tracking package PMPATH. PMPATH enables the placement of a particle at any position within the model, and then the flow of that specific particle is shown over time. From the particle tracking it is evident that the North-South Pit is constantly losing water (Figure 5).

For the calculations of the water budget, the model area was subdivided into five sub-regions (Figure 6). Figure 6 is an illustration of the area where intermine flow is taking place. Intermine flow will normally take place in the area where the coal barrier is thin and also in areas where the greatest hydraulic gradient exists.

Water budgets were calculated for each of the coal barriers. Because of the uncertainty about true refilling times predicted by the model, only the water budget results for the first 40 years were used to give an indication of the amount of flow through the coal barriers. Flow in the first layer (from the top to the first coal-seam) is much less than the flow in the second layer (coal-seam), because of the permeability of the coal layer. A permeability of 0.1 m/d was assigned to the coal layer[5].

The North-South Pit loses approximately 1100 m^3 of water per day through the four coal barriers because of intermine flow for the first 70 years.

Figure 5—Identification of groundwater flow paths by making us of particle tracking

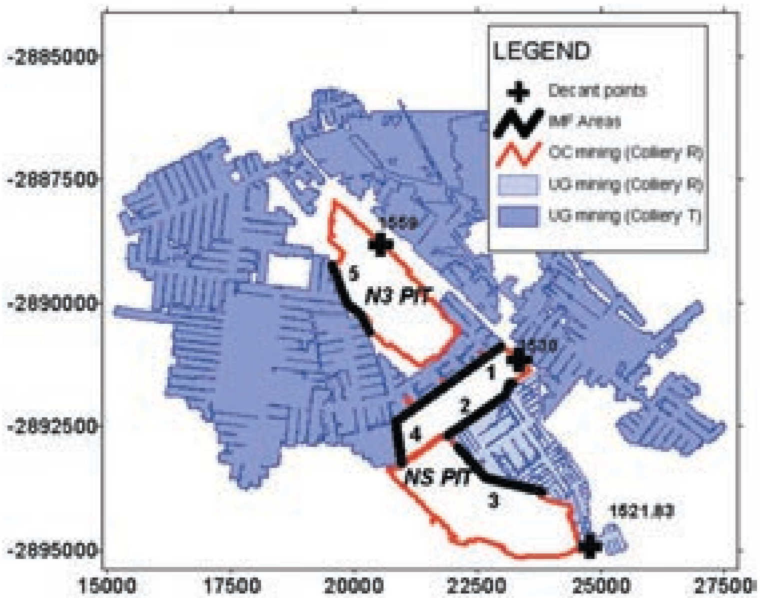

Figure 6—Positions of the intermine flow areas

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From the flow volumes of layer 1 and 2 it can be concluded that Colliery R is losing a huge amount of water through intermine flow to the adjacent underground areas.

The flow model also calculated filling times. The predicted filling times calculated by Modflow appear to be unrealistically long, when compared with more simple volumetric refilling methods. The reasons for this lie in leakage from the pits and an overestimation of flows by the models. Although opencast pits lose a huge amount of water through intermine flow, the filling times are deemed to be unrealistically long.

Issues of concern in the model

During the simulation of the model, all the answers from Modflow were checked by analytical methods. All calculations were in the same order, except for the filling times of the model. Although much of the water from the opencast pits was lost through intermine flow, the opencasts pits still took longer than expected to fill to their decant level. It was decided to investigate the situation to determine a reason for this discrepancy.

Investigation into discrepancy of refilling times

In Hydraulic Unit 2, we are dealing with direct opencast-underground interaction because of intermine flow. The North-South opencast pit and Colliery R underground workings are taken as an example to illustrate the difficulty of simulating an opencast and underground area next to each other.

The Modflow simulation was done with the intention of calculating the flow volumes and specifically the filling times of the specific areas. The filling times were then checked for potential sources of error using independent methods.

Simulation of opencast and underground areas

Two models were built to predict the filling times of opencast and underground areas. For the opencast and underground areas, the following models were used for the simulation:

Opencast area—Modflow simulation and comparison to analytical results

Underground area—Modflow simulation and a box model simulation.

Simulation of an opencast area

A scenario was created by making use of the North-South opencast pit. Filling times were calculated for just the opencast pit and thus no influence of the underground mine adjacent to the pit was taken into account. A two-layer model was prepared to simulate the conditions and to predict the filling times of the opencast area. See Table III for parameters used in the flow simulation.

Figure 7 gives an illustration of the manner in which Modflow does the calculations. The diagram illustrates a two-layer model of the North-South opencast pit.

Results from the flow model indicate that the pit will take approximately 24 years to fill to its decant elevation of 1530 mamsl.

An analytic model was used to check the accuracy of the Modflow predictions. An analytical model is a mathematical model that employs a simplified single set of equations to solve a problem, usually in one step. In groundwater problems, these models generally assume homogeneous aquifer properties, uniform flow direction and hydraulic gradient, uniform aquifer thickness with simple upper and lower boundaries, and lateral boundaries placed at an infinite distance.

From the analytic method, a filling time of 24.8 years was calculated. Filling times were previously predicted by

Table II

Results from the water budget report for the opencast and underground areas at Hydraulic Unit 1—Flow model

Years Volumes	5 (m^3/d)	10 (m^3/d)	20 (m^3/d)	30 (m^3/d)	40 (m^3/d)	50 (m^3/d)
Pit 6	7.7	3.4	1.1	0.8	1.1	1.4
IMF	4.6	4.6	5.7	6.9	6.8	6.7
Pit 5	20.5	12.0	5.4	2.2	0.6	1.0

Table III

Parameters used in the flow simulations

North-South Opencast Pit	
Layers	2
K(horizontal)	0.1 m/d
Rainfall	750 mm/a
Recharge%	20%
Storativity (S)	25%

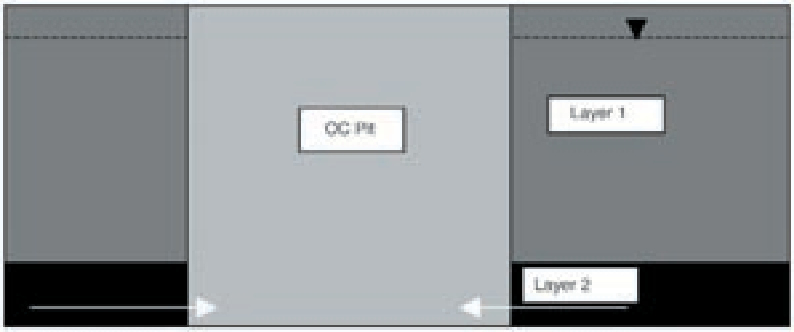

Figure 7—Representation of the Modflow opencast simulation

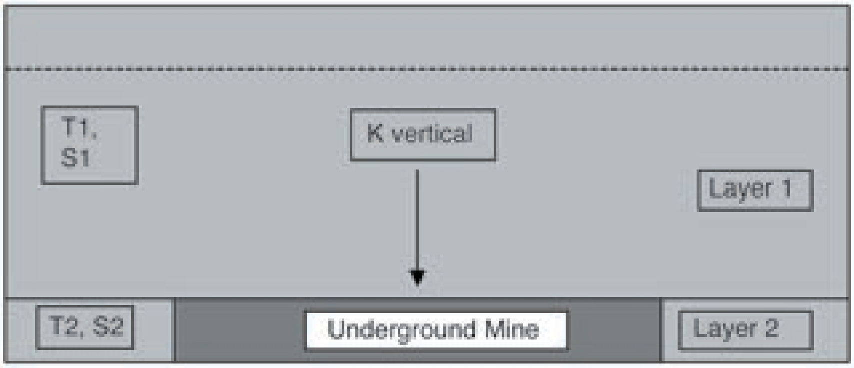

Figure 8—Underground flow model

Hodgson[4] and Van Tonder[7] for the North-South Pit. A filling time of between 25 and 32 years was predicted, depending on the extent of the rehabilitation[7].

The results are thus in the same order and Modflow is considered to simulate the situation correctly.

Simulation of an underground area

The North-South Pit and its neighbouring underground area were chosen to investigate the discrepancy in filling times. Figure 4, Cross section Z was used to get a better idea of the surface, coal-seam floor and water flow directions in the area.

Two approaches were used to predict the filling time of the underground area:

A numerical flow model using Modflow and
an analytical model.

The models assume a homogeneous underground area, representative of the underground void at Colliery R. The void is assumed to be 600 ha, and is 50 m below the water level. A mining height of 3 m was used. The following parameters were used during the simulation of the flow model and the box model:

A K-value of 0.1 m/d was used for the coal and a K of 50 m/d for the mined-out underground area. S-values of 0.001 were used for the coal and 0.7 for the underground area. (S-value (storativity) 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). The vertical hydraulic conductivity (Kv) used for the simulation was 0.01 m/d. Figure 8 illustrates the underground flow models.

It was assumed that the underground mine contains no water at time = 0, i.e. unsaturated conditions exist in the mine. For this situation the following is true:

Vertical influx (m^3/d) = Area*$K_{(v)}$, because the gradient = 1

Horizontal influx (m^3/d) = unsaturated horizontal though flow area*$K_{(horizontal)}$ because the gradient = 1. At time = 0, the unsaturated through flow area is equal to 3 m.

As the unsaturated thickness of the underground mine decreases with time (mine is filling up with water), the saturated horizontal inflow thickness increases. A moving boundary condition thus exists. This implies that, in Modflow, the simulated area of inflow is too big, which causes rapid inflow of water into the underground area. As the underground area fills, the saturated area increases, with an associated decrease in gradient. Thus, as the void fills, Modflow's calculations will become more accurate. It is important to note that Modflow cannot accurately simulate a situation like this.

Two scenarios were run during the simulation to test the sensitivity as well as the accuracy of the two models. See Table IV for results from the two scenarios.

From this it is apparent that Modflow's calculation can be erroneous during the filling time predictions of underground voids, which are overlain by saturated sediments. Modflow is thus overestimating the flow to the underground in these situations.

Figure 9 was plotted to show the real filling time versus Modflow's filling time. It is concluded that Modflow can make a significant error during the calculation of the filling times of the underground area. Modflow will fill the underground area more rapidly, since inflows from the saturated rock overlying it can be overestimated.

Table IV

Results from the two scenarios

Kv	Modflow Q (m^3/d)	Real Q (m^3/d) model	Time to fill the mine (Modflow)—(d)	Real time(d) analytical model
0.01	97000	60000	110	210
0.001	9700	6000	1100	2100

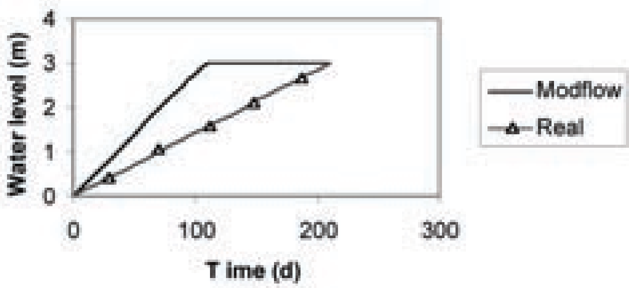

Figure 9—Graph showing the results from the real filling versus Modflow filling times

In the case of the Hydraulic Unit 2 flow model, the very slow filling times of the opencast pits calculated by Modflow can thus be attributed to the fact that Modflow causes the opencast pit to lose more water to the underground areas than occurs in reality. This causes the underground areas to fill more rapidly and, consequently, the opencast continues to lose more water and fills over a longer period. The reason for this is that Modflow is a saturated model and cannot accurately simulate unsaturated conditions.

Conclusion and recommendations

The following conclusions can be drawn from the research in this investigation:

- Numerical models such as Modflow can be fruitfully used to understand the hydrologic interactions that occur in typical intermine flow areas.
- Comparison between numerical models and analytical or empiric approaches often provide the same broad answers. Numerical models allow the evaluation of conditions over time and can resolve complex situations, which other methods are often incapable of handling.
- Modflow is a very good model package to use and is very accurate in predicting flow direction, flow volumes and filling times of opencast areas. Modflow should be used with caution for predictions of filling times of underground areas. Refilling times for underground models using saturated flow models should be checked for consistency using volumetric/inflow calculations
- Although these models are often the best tools to accommodate all the possible influences, in certain instances the values must be used with circumspection.
- It was found that numerical models used in groundwater would not be able to simulate the situation correctly, due to the unsaturated/saturated moving boundary encountered in reality
- For the prediction of the filling times of an underground area, unsaturated conditions may exist between the void and the overlying aquifer or hydraulic units. In these situations a moving boundary condition exists. Modflow cannot simulate a situation like this and may overestimate the flow to the underground.

The following conclusions can be drawn about the quantification of intermine flow in the Western Witbank Coalfield:

- *Hydraulic Unit 1*—As Pit 6 starts to fill up, small amounts of water start to leak through the unmined coal barrier between Pit 6 and the Number 4 Seam underground. An average volume of 5.8 m^3/d is expected to flow through the unmined coal barrier.
- Thus the influence of intermine flow from the opencast area to the No. 4 Seam underground is minimal. The small amounts of water leaking through the unmined coal barrier to the underground area are not considered problematic.
- When Pit 6 reaches decant, an average decant volume of between 2800–2900 m^3/d can be expected, based on the 20% recharge used for the opencast pits. Pit 5 and 6 will take approximately 44 and 27 years, respectively to fill to their decant levels.
- *Hydraulic Unit 2*—From the water budget report of Hydraulic Unit 2 flow model it is evident that the North-South Pit loses approximately 2000 m^3 of water per day through intermine flow. The latter pit loses water to Colliery R as well as from Colliery T underground areas.
- Despite this loss of water, refilling times determined by numerical modelling were different to values obtained previously with other methods.

Numerical models and analytical box models were compared. Results from the flow model for the North-South Pit indicate that the pit will take approximately 24 years to fill. The box model predicted a filling time of 24.8 years. Modflow is a saturated 3D model and thus can simulate the correct filling time of opencast pits.

Recommendations

As was seen from the sensitivity analyses done in the flow models, K-values of the coal and coal barriers play a very big role in the simulation of flow models. K-values of coal and coal barriers are very scarce, and site-specific values at the intermine flow areas are strongly recommended. Site-specific recharge values are also of great value in achieving accurate estimates.

As shown in this paper, it is very important that appropriate models be used to simulate the diverse conditions, which arise with adjacent and overlying mining areas in the Witbank Coalfield.

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