Assessing groundwater quality trends after mine closure - The South African Situation

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ABSTRACT

All South African mines have, in terms of the Minerals Act, No 50 of 1991, the responsibility to manage the effects of mining on the environment. In order to enforce this responsibility, the submission and approval of an environmental management programme (EMPR) is required. The impact of mining on groundwater quality often plays a major role in the development of a mine's EMPR and future financial provision. Prediction of long term groundwater quality trends after closure, is crucial to obtain a closure certificate. It is important that decision makers ensure that the correct data is obtained from the start. Accurate long term predictions ensure correct mine design, applicable mitigation factors and adequate financial provision for remediation. Hydrochemical and solute transport models are indispensable tools in assessing changes in groundwater quality after mine closure. The transport of contaminants can be subdivide in two broad mechanisms: physical mass transport (e.g. advection, dispersion and diffusion) and chemical/biological transport processes (eg. sorption, dissolution/precipitation, acid/base reactions and redox reactions). A realistic analysis of the predicted contamination plume requires that both transport mechanisms are evaluated simultaneously, especially if complex chemical reactions occur, such as acid mine drainage. The impact of acid mine drainage on groundwater quality is dependent on actual groundwater flow mechanisms as well as the geochemical environment. Results of acid/base accounting represent worst-case contamination loads and may severely over-estimate the impacts of mining during and on closure, if considered in isolation. More realistic results can be obtained by assessing the geochemical environment, the composition of rocks and soils and the actual future groundwater flow conditions. The models constructed with the information can further be used to optimize monitoring systems as well as to draft environmental management or remediation plans.

1. INTRODUCTION

At present in South Africa, the proof of purchase of the mineral rights for an area gives the owner mining authorization subject to the submission and approval of an Environmental Management Programme Report (EMPR) under the Minerals Act, No 50 of 1991. Under ideal conditions, this document must be submitted and approved before mining is undertaken, but in many situations, especially with old gold and coal mines in South Africa, the document is compiled while mining is already underway for some time or when the owner seeks mine closure. The EMPR is designed to assist mine management to identify potential environmental impacts due to mining activities as well as manage these impacts in a cost effective manner. The impact of mining on groundwater quality often plays an important role in the development of a mine's EMPR and subsequently on the future financial provision for remediation. The prediction of long term groundwater quality trends after closure, is crucial to obtain a closure certificate. In order to obtain realistic predictions of the long term groundwater quality in the mining environment, the correct data must be obtained from as early as possible.

If an EMPR is submitted before mining is started, the mine design, handling of potentially toxic material and pollution control structures can be designed and managed optimally to ensure a minimum risk on the long run. If the EMPR is compiled during mining or just before mine closure, the management of potentially contaminated groundwater is more difficult and thus costly.

Hydrochemical and solute transport models are indispensable tools in assessing changes in groundwater quality after mining stops. These models require certain information for calibration and verification. A good groundwater quality monitoring system can be put in place to ensure that historical trends are available to calibrate and verify geochemical, groundwater flow and contaminant models.

The objective of this paper is to discuss the methods available for assessing the future groundwater quality trends in the mining environment as well as highlight the data required to construct and verify the models used to assess the trends.

2 LONG TERM PREDICTION OF GROUNDWATER QUALITY

2.1 Hydrogeological environment during and after mining

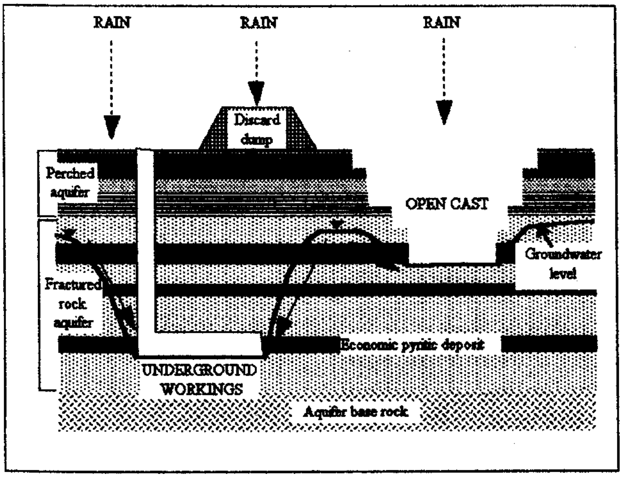

Figure 1 Groundwater flow regime during mining

Long term groundwater quality depends to a large extent on the accurate prediction of future groundwater flow patterns in the aquifer underlying the mining area. The majority of aquifers in South Africa are of a secondary fractured nature. The success of a geohydrological investigation for groundwater quality prediction, depends to a large extent on identifying the preferential flow paths (fractures, joints, intrusions or bedding planes) which occur in the fractured rock aquifer as well as on characterizing their flow characteristics. Preferential flow paths can be identified using geophysical methods and through drilling of exploration and monitoring boreholes. The information obtained from the boreholes form the basis of the groundwater flow model which is to be constructed for the mining environment. The flow model can be used to simulate the complex movement of groundwater during and after mining.

Typical groundwater flow patterns as monitored during mining, are illustrated in Figure 1. While the mine is operational, groundwater flow patterns are locally reversed due to the impact of mine dewatering. This means that groundwater flow will be towards the mining area, thus preventing the spreading of contaminants down gradient into the aquifer.

In many parts of the South Africa, a perched aquifer is formed within the upper 5 metres of the lithological cross section. The perched aquifer has a seasonal character, but plays an important role in the infiltration of rainwater to the deeper seated fractured rock aquifer. Figure 1 shows that, contaminated water may infiltrated through discard dumps or slimes dams into the perched aquifer from where it can either infiltrate vertically into the fractured rock aquifer or seep laterally along the perched aquifer and decant into underground workings or into an open cast pit. As groundwater moves through the discard dump / slimes dam and perched aquifer, it is exposed to a changing geochemical environment which will influence the concentrations of contaminants in the water.

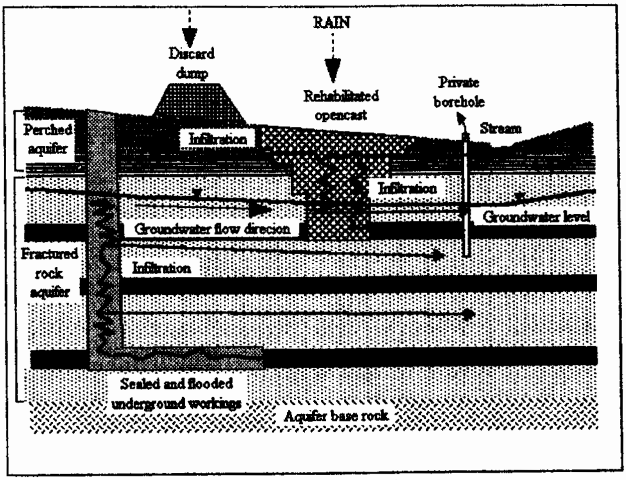

Figure 2 Groundwater flow regime after mine closure

When mining stops, groundwater levels will recover slowly to pre-mining levels, as illustrated in Figure 2. As the groundwater levels recover, the geochemical environment changes while underground workings and rehabilitated opencast voids are flooded. When groundwater levels reach their pre-mining gradients, the contaminants originating from the mining area, can start to move down gradient into the aquifer(s). As the plume spreads down gradient, the risk of contamination of private groundwater users or streams increases. The impact of mining on groundwater quality down gradient of the mine as well as on the receiving water bodies (streams) must be assessed accurately in order to determine the finance provision for rehabilitation (or if the so-called "No Project Option" must be followed if the impact on groundwater quality is identified as a fatal flaw).

Contaminant transport models can be used to assess the shape and movement of plumes during and after mining. The groundwater flow model constructed for the mining area forms the basis of the contaminant transport model . In most cases, commercially available contaminant transport software does not consider a changing geochemical environment during simulations. It is therefor important to run geochemical and contaminant transport models in conjunction to obtain realistic results. Geochemical modelling is discussed in Section 2.2.

Data required for the construction and calibration of contaminant transport models can be obtained from rock analysis of potential sources of contamination (i.e. discard material) and from water analysis. Rock analysis should include leach tests to determine the potential concentrations of elements that could contaminate groundwater. These tests are discussed below.

2.2 Characteristics of long term sources of contamination

The largest risk for long term contamination of groundwater quality in South Africa, and in many other parts of the world, is acid mine drainage (AMD). The EMPR document concentrates specifically on the potential for AMD and the long term impact of AMD on groundwater quality.

Acid mine drainage forms when sulfide minerals in rocks are exposed to oxidizing conditions, i.e are weathered through exposure to oxygen and water. AMD is characterised by a low pH and high iron , sulphate and metal concentrations. In South Africa, acid mine drainage is of most concern in the gold and coal mining environments. Metal sulfides associated with copper, lead, nickel and zinc may cause AMD, but iron sulfides, mainly pyrite and marcacite (Fe_2S), are the predominant acid-producers. In principle, pyrite oxidation is occurs under two situations. Oxygen can be supplied by advective (oxygenated) groundwater flow or by the exposure of pyrite to air. If the weathering of pyrite takes place through oxygenated groundwater, sulphate and iron concentration may increase slightly. Under these conditions, the potential for AMD is moderate to low.

If pyrite is weathered through exposure to air, very high sulphate and iron concentrations and very low pH conditions (to a pH of ±2) can be expected. Due to the low pH, other metal concentrations like aluminium (Al) as well as total dissolved solids will increase dramatically and a variety of secondary minerals like gypsum or ferric hydroxy-sulphates may precipitate. The risk of AMD is high under these conditions. The oxidation of pyrite is dependent on many factors such as the surface area or grain size of the rock, the form of pyritic sulphur, oxygen concentrations, pH conditions, catalytic agents and the presence of Thiobacillus bacteria. These bacteria can increase the oxidation of ferrous iron by 5 orders of magnitude! The reaction rate may decrease with time due to the precipitation of ferrous-hydroxide which acts as a barrier to oxygen. If no oxygen is available the oxidation process can go on through the availability of ferric iron that may be supplied by the dissolution of solid ferric hydroxide, $Fe(OH)_3$. This may explain continuing AMD after the mine has flooded or adits and discard dumps have been sealed.

2.2 Evaluation of Acid Mine Drainage with geochemical modelling

In practise an intermediate situation between the two extremities discussed above, occur. The pyrite oxidation rate limiting step is normally not well defined and depends to a large extent on the current and future conditions in the aquifer. Geochemical modelling is a tool which can be applied to address the behaviour of iron oxidation under various conditions which may arise in future times in the aquifer. Chemical reactions can be assessed with equilibrium theories or by reaction kinetics. In many situations, groundwater chemistry related to AMD cannot be fully explained by equilibrium chemistry. In many cases equilibrium does not exist in a mining environment due to changes in pH conditions and ongoing external processes such as the reaction of rain water with pyritic material in discard dumps or inside the mining area. In most cases the time scale under which AMD takes place, is too long to reach hydrochemical equilibrium during the span of a hydrogeological investigation.

The kinetics of AMD are however extremely difficult to assess or to predict. This is mainly due to the wide variety of reactions which may take place under changing pH conditions, for example. The processes that cause these reactions and their impact cannot be measured accurately under site specific conditions. It is further difficult to include adsorption, precipitation or dissolution of elements as field conditions change or to predict the future composition (e.g. the pH) of recharging water or the future composition of other groundwater bodies in the aquifer that may mix with groundwater originating from the mine. Although some progress is being made, the theories on reaction kinetics are still in development and a unifying theory does not exist. The Water Research Commission of South Africa is in the process of evaluating the various processes and methods available for evaluating the potential for AMD and will publish a guideline document in regards to AMD within the next three years.

Although equilibrium theories do not provide the ultimate answer to the assessment of spreading and future concentrations of contaminants, they may, together with sound conceptualization of the hydrogeological and hydrochemical environment and proper monitoring, help to assess the environmental impacts of AMD more realistically. An important advantage of hydrochemical modelling based on equilibrium theories is that the final concentrations of contaminants may be assessed more realistically, if the actual hydrogeological environment is considered.

In South Africa, Net Acid Generating (NAG) and element enrichment tests are commonly done on rock samples from the mining environment. During these tests the solubility of a wide range of elements are determined under water soluble conditions as well as under complete weathered conditions. If the results from these tests are evaluated in isolation, the risk associated with AMD could be overestimated. Geochemical modelling can be used to obtain more realistic results. It is often observed that contaminants resulting from AMD migrate slower than normal groundwater flow velocity. This is caused by the precipitation of sulphate and ferrous iron along the flow path due to changing geochemical conditions. The results from the NAG tests only considers the total acid generating capacity and the associated element enrichment of the rocks analysed, while in reality the mine water react with groundwater in other rock formations down gradient in the aquifer. The effect of this could be a change in pH conditions as the water mix or neutralizing and a subsequent decrease expected sulphate and ferrous iron concentrations.

To illustrate the role of geochemical modelling in the assessment of AMD, the following example is provided. The example illustrates the expected sulphate and ferrous iron concentrations under various hydrochemical conditions:

1. Case 1: The oxidation of pure pyrite *in stagnant water* (by oxygen)
2. Case 2: The same situation as in Case 1, while taking the assimilative capacity of calcite into consideration.
3. Case 3: The same situation as in Case 2, while allowing gypsum to precipitate.
4. Case 4: Oxidation of pure pyrite by oxidized *flowing groundwater*
5. Case 5: The same situation as in Case 4, while taking the assimilative capacity of calcite into consideration. Gypsum is allowed to precipitate

The results from the geochemical assessment of the expected groundwater quality under the conditions discussed above, are presented in Table 1:

Table 1 Results from the geochemical modelling

Parameter	Results in stagnant water			Results in flowing groundwater	
	Case 1	Case 2	Case 3	Case 4	Case 5
pH	<0.3	6.0	6.0	3.9	7.0
Fe^{2+}(mg/l)	>2 000	>2 000	0.37	4.68	0.12
SO_4^{2-}(mg/l)	>50 000	>50 000	972.8	8.32	7.68

Table 1 indicates that in stagnant water, AMD generation is dependent on the availability of oxygen. If there is a continuous source of oxygen, the pH may drop to very low values resulting in high concentrations of ferrous iron and sulphate. Case 1 represents the worst case and would yield similar concentrations as the results from the NAG tests discussed above. If the assimilative capacity of the surrounding rocks are taken into consideration, the pH increases (Case 2). If gypsum is allowed to precipitate, ferrous iron and sulphate concentrations are reduced dramatically (Case 3). In flowing groundwater (Case 4), the availability of oxygen is limited to the concentration of dissolved oxygen in the water. The limited available oxygen limits AMD generation. When the interaction with calcite and precipitation of gypsum is taken into consideration, the risk of AMD is a minimum.

3 WATER QUALITY MONITORING

Water quality monitoring is a very important aspect of long term prediction of groundwater quality associated with mining. Groundwater quality must be monitored on a regular basis during mining to determine quality trends. Monthly monitoring of a selected set of elements (pH, Electrical Conductivity, SO_4, Fe) can be used to determine if seasonal changes occur, what the impact of certain remediation procedures during mining are, whether the pollution control structures are sound and to determine the extent of contamination.

Information obtained through monitoring must be used to verify the geochemical and contaminant transport models. With model verification, the confidence in model results is increase, thus reducing the associated risk with over or under estimating the impact on groundwater quality. Historical monitoring data can be of great value when the mine approaches closure. If no historical groundwater quality data exists at closure, the monitoring period after closure can be up to three years longer than if quality trends could be determined from existing information.

Once the geochemical and contaminant transport models are calibrated and verified, they can be used to optimize the monitoring network by concentrating on problem areas identified through modelling. The set of elements analysed for may also be revised and/or amended by using the results from initial the geochemical modelling.

4 CONCLUSIONS

- Groundwater flow models form the basis of any study which aims at predicting future groundwater quality trends. These models are used to assess the complex flow regime during and after mining. Contaminant transport models are used in conjunction with groundwater flow and geochemical models to predict the future spreading and expected concentrations of plumes.

- Geochemical modelling can assist in obtaining more realistic concentrations of contaminants that results from AMD. Equilibrium geochemical models do not provide information on the reaction rate, but show in which direction the reaction will go and what will be the major concerns in terms of future contaminants.

- Groundwater quality monitoring is crucial to the success of the overall assessment of the long term impact of mining on groundwater quality. The data can be used to determine water quality trends which is used to verify geochemical and contaminant transport modelling.

- An old cliché goes "Prevention is better than cure." This rings especially true for remediation of contaminated groundwater, which can be very costly. It is important to think about mine closure during the planning and design of the mine. In this way, simple steps can be taken to minimize or contain the impact of mining on groundwater quality.