The groundwater interaction of a deeper lying gold mine and a shallower lying coal mine through the presence of naturally occurring as well as induced preferential flow paths

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Abstract After the closure of mines, it is expected that water in the mined-out areas will flow along preferred pathways and accumulate in lower-lying areas (Grobbelaar, 2001). Over time, these man-made voids will fill up with water and hydraulic gradients will be exerted on peripheral areas within mines, resulting in groundwater flow between mines and possibly surface. This flow is referred to as intermine flow (Grobbelaar, 2001). 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 of the most important challenges in the mining industry. Hydro-chemical and stable environmental isotope of deuterium and oxygen sampling were used to determine the interaction between the Karoo aquifer and the Witwatersrand aquifer. Comparison between the results showed that there is interaction between the Karoo and Witwatersrand aquifer, both where coal mining is present and where coal mining is absent. As the coal mine in future will cover most of the gold mining area except for the central area, it is expected that groundwater affected by the coal mining in the Karoo aquifer will move along naturally occurring structures/pathways from the base of the Karoo aquifer into the gold mine workings were preferential pathways are encountered. This interaction can directly be linked to the frequency of structures that are water-bearing in the study area. From the field work done in the underground gold mine, the number of structures that are water-bearing are the exception rather than the norm. Therefore the potential for groundwater interaction from future coal mining into the gold mine will be relatively low.

Key Words aquifer, coal, frequency, groundwater, interaction, induced, intermine flow, pathways, preferential, voids

Introduction

The objective and aim of the study was to determine potential groundwater interaction between the coal mine and the gold mine including the combined impacts on the environment. Tools used to establish whether such interaction exists comprised geological data, hydro chemical analysis, stable isotope environmental analysis, and geohydrological information. It was important to list all the various characteristic indicators identified across the various geological lithologies and different aquifers. Of interest was to briefly compare the water samples with each other, with thought given to sample location, depth, mining activity and aquifer.

General Hydrogeology and Geology

The coal mine is located in the Vryheid Formation of the Ecca Group, Karoo Supergroup. These rocks consist primarily of sandstones, shales and coal beds and are extensively intruded by dolerites of Jurassic age (Tweedie *et al.*, 1986).

The gold mining operations are situated in the Witwatersrand Supergroup, predominantly consisting of quartzite with subordinate lava, shale and conglomérate (Tweedie *et al.*, 1986). The conglomerate layer known as the Kimberley Reef, is mined for gold.

In the major part of the study area, the Witwatersrand Supergroup unconformably overlies the Archaean Basement. These Witwatersrand sediments are in turn overlain by rocks of the Ventersdorp Supergroup, Transvaal and Karoo Supergroups (Tweedie *et al.*, 1986). The study area has undergone extensive structural dislocation and faulting is the most common form of deformation with both primary and secondary fault-features being observed below the Karoo Supergroup (Tweedie *et al.*, 1986). For most of the study area, the Ventersdorp Supergroup forms a thick wedge between the Karoo/Transvaal Supergroup and the Witwatersrand Supergroup.

Early compression tectonics and later extensional tectonics affected both the Witwatersrand and Ventersdorp Supergroups in the study area, but pre-dated the deposition of the Transvaal Supergroup and hence the Karoo Supergroup (i.e. >2500 Ma). This resulted in all major faulting being "cut-off" at the base of the Karoo Supergroup and Transvaal Supergroup (Tweedie *et al.*, 1986). A conceptual model of the geology is shown in Figure 1.

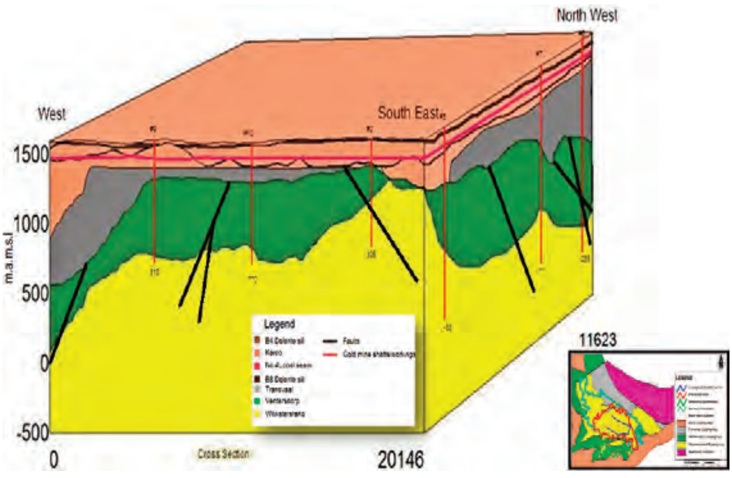

Figure 1 *Conceptual model of geology*

There is dynamic interaction between the aquifers situated in the upper Karoo Supergroup as there is a direct link with recharge from precipitation into the shallow perched aquifer and the shallow weathered aquifer (Grobbelaar, 2001). This water flows through preferential pathways from these aquifers into the deeper artificial coal mine aquifer and fractured Karoo aquifer. Therefore, the deeper Karoo aquifer is not directly recharged by precipitation but by influx from shallower Karoo aquifers. The water is prevented from moving further downward at the base of the Karoo Supergroup by the Dwyka Tillite, and further down by the Transvaal dolomites and the Ventersdorp Supergroup lavas that separate the Karoo aquifer affected by coal mining from the Witwatersrand aquifer affected by gold mining.

Recharge in the coal mine of between 5 and 7% can be expected at the subsided areas. Low recharge of between 1 and 3% can be expected where no subsidence occurs, with a tendency towards 1% where the sill is thick (Vermeulen & Dennis, 2009).

Recharge in the gold mine of a maximum of 1% can be expected in the gold mine due to the thickness of the overburden at an average of 1392 m and the lack of water-bearing structures encountered in this study. Calculated recharge from data of the gold mine was in the range of 0.5%.For the purposes of this study, the Karoo aquifers were regarded as one significant aquifer situated above the Ventersdorp Supergroup and the deeper Witwatersrand aquifer situated below the Ventersdorp Supergroup was regarded as the other significant aquifer.

The shallower Karoo aquifer is regarded as an unconfined to confined aquifer and its recharge can be linked directly to recharge by precipitation (1—3 % of annual precipitation and 5 % to 7 % where high extraction mining has occurred). The deeper Witwatersrand aquifer is regarded as a confined aquifer that has no direct link of recharge to precipitation and a very low flux from shallower Karoo aquifers though preferential pathways or where the Witwatersrand Supergroup sub-outcrops against the base of the Karoo Supergroup (>1 % of annual precipitation).

Method

The research was done as follows, literature review of previous work done in the study area, field work which consisted of visiting all boreholes and potential underground interaction areas. All boreholes and potential interaction areas were sampled for hydro chemical and stable environmental isotopes d18O and dD analysis. The sampling was done to compare samples at different depths and areas. This was done to see whether a "fingerprint" of aquifers and recharge histories could be derived from the results.

Data

To determine the origin of groundwater in both mines, sampling was done at strategic positions at each mine. Samples were taken from surface boreholes as well as underground of each mine where groundwater flow was encountered. Groundwater information was obtained for a total of 21 sampling points (Tab. 1).

Data interpretation techniques employed

In order to characterise the origin of the groundwater within the various aquifers, the following interpretation was carried out on the hydro-chemical and isotope data as shown in Figure 2 and Figure 3:

- Standard groundwater chemistry diagrams: Piper, Expanded Durov and Stiff diagrams are used to define the general study area's ground-

***Table 1** Summary of sampling locations*

	Coal & Gold Mine Surface Borehole Samples	Depth Range (Approx) in m below surface
Gold Mine	KB1D,KB5D, WB1D, WB3D, WB5D	28
Coal Mine	MHN47, MHR45, MDBCasino	100-130
	Coal & Gold Mine Underground Samples	
Gold Mine	H1,H2,H3,H4,H5,H6,H7,H10	639-2152
Coal Mine	S1,S2,S3,S4,S5	55-113

water chemistry characteristics relative to other groundwater types.

- Diagnostic chemistry diagrams: In the format of X-Y scatter plots or composition diagrams of selected pairs of measured parameters.
- d18O versus dD diagram: This "fingerprints" the different groundwater in the different aquifers, by comparing their relative isotopic ratios.

Karoo aquifer origin samples recharged by precipitation (KB1D, KB5D, WB1D, WB3D, WB5D, MHN47, MHR 45, MDBCasino and S1-S5).

The shallow Karoo aquifer samples and those affected by coal mine activities (KB1D, KB5D, WB1D, WB3D, WB5D, MHN47, MHR 45, MDBCasino and S1-S5) are generally lower in Na concentrations and higher in SO4 concentrations than the deeper Witwatersrand aquifer samples. All have relatively high concentrations of bicarbonate, suggesting they are recharged by precipitation or water from the shallow unconfined Karoo aquifer that reacts freely with the atmosphere. They all plot close to the local rainfall line, which also suggests that they have been affected in some way by precipitation either directly or indirectly (mixing). They are relatively enriched in d18O and dD, suggesting that they have had a relatively short residence time in the sub-surface (Figure 2).

Witwatersrand samples recharged by influx from shallower Karoo aquifers (H1, H4, H6, H7).

H1 and H4 are the samples most depleted in d18O and dD, both were taken from faults. This suggests that reactions with rock minerals have taken place in the water as it travelled along the fault, depleting its d18O and dD composition (Figure 2).

H6 and H7 are of Karoo aquifer origin, based on their Stiff diagram general geometry being the same as the coal mine samples and their Expanded Durov Diagram plotting position with the coal mine samples (S1-S5), which are expected to be found in high extraction coal mining. These samples have most probably undergone ion-exchange reactions in reducing conditions on the water's flow path through the Ecca shales. H6 and H7 are the samples taken closest to the coal seam. H6, H7 and H10 are also the only samples that could have been affected by coal mining as coal mining has not reached the area of the other underground gold mining sample positions.

Witwatersrand aquifer water recharged by influx from shallower Karoo aquifer with a long residence time and possibly mixed with connate

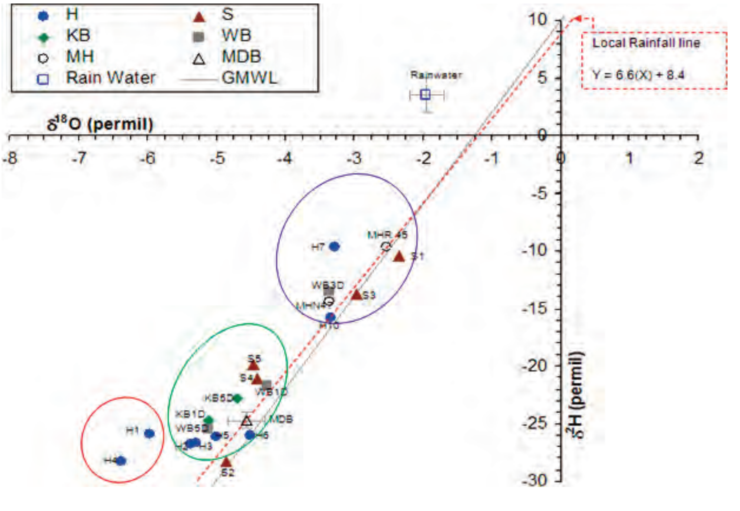

***Figure 2** $\delta^{18}O$ and δD relationship isotope plot for the samples collected in the study.*

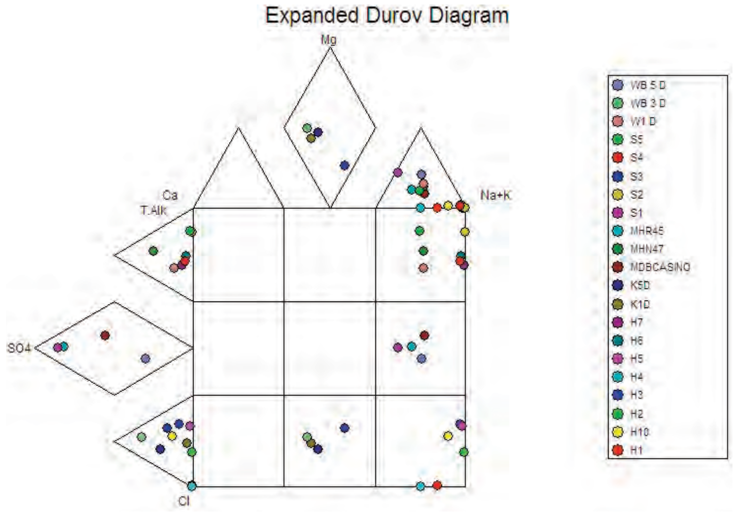

Figure 3: *Durov diagram of samples collected in study*

water or paleo-meteoric water (H2, H3, H5, H10)

Sample H2 (next to dyke), H3 (exploration borehole), H5 (out of stope) and H10 (out of mine roof) all show depleted $d^{18}O$ and dD signatures. They have relatively high Na- concentrations and low SO_4 concentrations compared to Karoo aquifer samples, but have lower Na- concentrations compared to the H1 and H4 samples (from faults), believed to be water from the base of the Karoo aquifer. H2, H3, H5 and H10 all plot within Field 9 of the Expanded Durov Diagram which is very old, stagnant or paleo-meteoric water that has reached the end of the geohydrological cycle or water and has moved a long time and/or distance though the sub-surface and has undergone significant ion-exchange (Figure 3).

H2, H5, and H10 represent a flux of confined aquifer water, as they were taken from fractures intersecting the gold mine workings. Their lower bicarbonate concentrations compared to H3 is attributed to chemical reactions in a closed system (confined aquifer) where there is no CO_2 present, resulting in the slow loss of HCO_3^- (Freeze & Cherry, 1979). This indicates that they are recharged by the shallower Karoo aquifer but that they have had a long residence time in the sub-surface.

Groundwater interaction between the Karoo aquifer and the Witwatersrand aquifer based on hydro-chemical and isotope interpretations

There is interaction between the aquifers, as seen in samples H1 H3 H4 H6 and H7, through preferred pathways such as faults and fractures. Important to note is that H1, H3 and H4 interaction occurs without the influence of the coal mine, as coal mining has not reached the areas where these samples were taken.

H6, H7 and H10 were taken near current coal mining activities. Only H6 and H7 show a “fingerprint” that is characteristic of a Karoo aquifer water. Therefore, the only current potential interaction between the coal mine and the gold mine is at sampling positions H6 and H7.

It can be stated that very little water was encountered in the gold mines- indicating that very little water seeps through from the Karoo aquifer (coal mine) into the Witwatersrand aquifer (gold mine).

Conclusions

Based on the mining activities, geology, hydrogeology, hydro-chemical and isotope interpretations relative little interaction occurs in the study area. Furthermore interaction occurs without the presence of coal mining, through faults, fractures next to dykes and exploration boreholes intersecting the gold mine workings (Although very minimal due to small volumes). Thus the coal mine is not the only contributor to the interaction between the mines, as naturally occurring structures allow for influx from the Karoo aquifer into the gold mine workings of the Witwatersrand aquifer.

The coal mine will in future cover most of the gold mining area except for the central part of the study area, it is expected that groundwater affected by the coal mining in the Karoo aquifer will only move along naturally occurring structures linking the two mines.

The possibility of interaction can therefore be directly link to the number of structures that are water-bearing in the study area as well as the area covered by coal-mining activities. From the field work done in the underground gold mine, the number of structures that are water-bearing is the exception rather than the norm. Although there is some interaction the potential for future groundwater interaction from coal mining into the gold mine will be low as the Karoo aquifer is very poorly connected to the Witwatersrand aquifer based on:

- Frequency of water-bearing structures encountered within the study area;
- Travel time of the Karoo aquifer water to reach the Witwatersrand aquifer;
- Water level in the Karoo aquifer remains relatively constant;
- Rate of inflow in the gold mine remains relatively constant;
- Recharge in the gold mine is estimated at 0.5 %, which is less than 1—7 % of that in the coal mine;
- Water-bearing structures encountered within the study area have low water volumes;
- Prevention of interaction measures of each individual mine.

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