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TECHNICAL ARTICLE

Potential Hydrological Interaction of a Gold Mine and a Coal Mine in South Africa

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Abstract In Mpumalanga Province, South Africa, an underground coal mine lies above areas of a gold mine and there are concerns that preferential flow paths might connect the two mines, allowing flow from the coal mine into the gold mine. There is also a risk that subsidence associated with the coal mining will damage existing geohydrological barriers between the shallow Karoo aquifer where the coal mining takes place and the deeper Witwatersrand aquifer where the gold is mined. Damage to these geohydrological barriers could increase groundwater influx from the surface (gold mine slimes dams), as well as from the Karoo aquifer, into the Witwatersrand aquifer. Hydrochemical sampling was used to determine interaction between the two aquifers. Certain high risk areas for potential interaction were identified after considering factors such as the depth and areas of mining, the location of tailings storage facilities, and preferential pathways.

Keywords Aquifer · Conceptual model · Inter-mine flow · Groundwater · Impact

Introduction

Coal and gold mining have co-existed for more than a century in South Africa, and more specifically, the Mpumalanga Province. Due to the scale and the duration of these operations, these activities have significantly altered the geohydrological environment of the area.

Preferential flow refers to the uneven and often rapid movement of water through subsurface media, and occurs in both unsaturated and saturated zones. The phenomenon of preferential flow between different mines (intermine flow) has been studied by previous researchers, such as Grobbelaar (2001) and Havenga (2002). After mines close, and the man-made voids fill with water, groundwater in the mined-out areas can flow along preferential flow pathways between the mines, and possibly to the surface, and can accumulate in low-lying areas (Grobbelaar 2001). Due to its potential long-term impacts on water quantity and quality, South Africa's Dept. of Water Affairs regard such intermine flow as one of the most important challenges in the mining industry.

We investigated the potential for groundwater interactions between a coal mine and a gold mine. The coal mine lies above the gold mine, so preferential pathways connecting the two mines would allow water to flow from the coal mine towards the deeper gold mine and could connect the shallow Karoo aquifer with the deeper Witwatersrand aquifer though the Ventersdorp Supergroup lavas. Potential pathways exist due to geological processes (faults/fractures) and mining (shafts/exploration boreholes and subsidence). Our aim was to understand the hydrological interactions, if any, between the two mines during operational and closure conditions, including preferred pathways created by mining, and the risk of leakage from a surface tailings facility to the mines.

Study Area

The study area is situated in the Mpumalanga Province, and involves the Area H coal deposits of the Highveld Coal

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Field, where the No. 4L coal seam is being extracted. This area overlies the deeper gold mining operations of the Kimberley reef deposits. The coal mine plans to expand its existing colliery into the Area H reserves to the west and north of its current mining operations (Fig. 1). The initial expansion will be to the west from the existing underground coal mine.

The coal mines are 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 (Fig. 2). The coal seams in the Highveld Coalfield are mainly flat to gently undulating, with a very gentle regional dip to the south. Coal seam topography and distribution, however, are commonly controlled by pre-Karoo topography on the northern and western margins of the coalfield. Steeper dips are encountered where seams are situated against pre-Karoo hills. The dolerite intrusions occur both as sills and linear dyke structures that may extend over tens of kilometers.

The gold mining operations are situated in the Witwatersrand Supergroup, predominantly consisting of quartzite with subordinate lava, shale, and conglomerate (Fig. 2). The Kimberley shale separates the two units and is marked by a basal unconformity. Immediately above this unconformity is a conglomerate layer known as the Kimberley Reef.

The Witwatersrand Supergroup unconformably overlies the Archaean Basement in most of the study area. These Witwatersrand sediments are in turn overlain by rocks of the Ventersdorp, Transvaal, and Karoo Supergroups. 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 in the study area below the Karoo Supergroup. For most of the study area, the Ventersdorp Supergroup forms a thick wedge between the Karoo/Transvaal Supergroup and the Witwatersrand Supergroup. The average thickness of the Ventersdorp Supergroup is 577 m and ranges from 0 in the southeast to 1,324 m in the central part of the study area.

Mining Methods

Bord-and-pillar and high extraction methods are used in the coal mine. High extraction consists of bord-and-pillar development followed by pillar extraction using a coal-cutting machine. The removal of the coal pillars results in the caving of the overlying strata into the mined void. This disruption of the overlying rock mass can have a significant effect on the hydrogeology, especially where high extraction has resulted in subsidence (Vermeulen and Usher 2006).

Gold mining operations in the study area take place at depths from approximately 250–2,500 m below the surface, using conventional mechanised face and gully stooping methods; the development is down the footwall of the Kimberly Reef. Stoping refers to transporting the ore from underground workings by overhead trolley lines to a metallurgical plant situated on the surface.

Aquifer Information

Two major aquifers dominate the geohydrology of the study area. The Karoo aquifer is situated above the Ventersdorp Supergroup and the deeper Witwatersrand aquifer is situated below the Ventersdorp Supergroup. The shallower Karoo aquifer is an unconfined- to confined-aquifer and its recharge can be linked directly to recharge by precipitation (1–3 % of annual precipitation, but 5–7 % where high extraction mining has occurred; Vermeulen and Usher 2006). The Witwatersrand aquifer is a confined aquifer with no direct link of recharge to precipitation. It has a very low flux from the shallower Karoo aquifers through preferential pathways, or where the Witwatersrand Supergroup sub-outcrops against the base of the Karoo Supergroup (>1 % of annual precipitation).

Karoo and Witwatersrand Aquifer Water Levels

More than 240 shallow Karoo aquifer boreholes have been drilled across the study area near the mines. The groundwater level is, on average, 3.9 m below the surface, with a range of 0–69.6 m below the surface. The Bayesian interpolation technique (i.e. water level mimics the topography, which is the norm in South Africa) was used to simulate groundwater levels over the entire study area (Fig. 3).

It is important to note that the water level of the Karoo aquifers has not been affected by the past 50 years of gold mining in the region, although large volumes of water have been pumped from the gold mines (Rison Groundwater Consulting 2007). This suggests poor hydraulic connectivity between the two aquifers, although some dewatering of the Karoo aquifer has been observed at the subsidence areas that exist to the south of the study area (Fig. 1). The subsidence areas occur where high extraction has taken place. The piezometric pressure in the deep Karoo aquifer is generally 10–50 m lower than that in the Karoo sediments (Hodgson and Grobbelaar 1998).

The Witwatersrand aquifer groundwater levels are more difficult to interpret than the Karoo aquifer water levels. The reasons for this are the great depth of the Witwatersrand aquifer and the pumping of groundwater from the underground gold mine workings to the surface, which lowers water levels within the aquifer.

The first recorded Witwatersrand aquifer water level was measured in 1962 by Pritchard-Davies at 1,533 m above mean sea level (AMSL) (Rison Groundwater Consulting

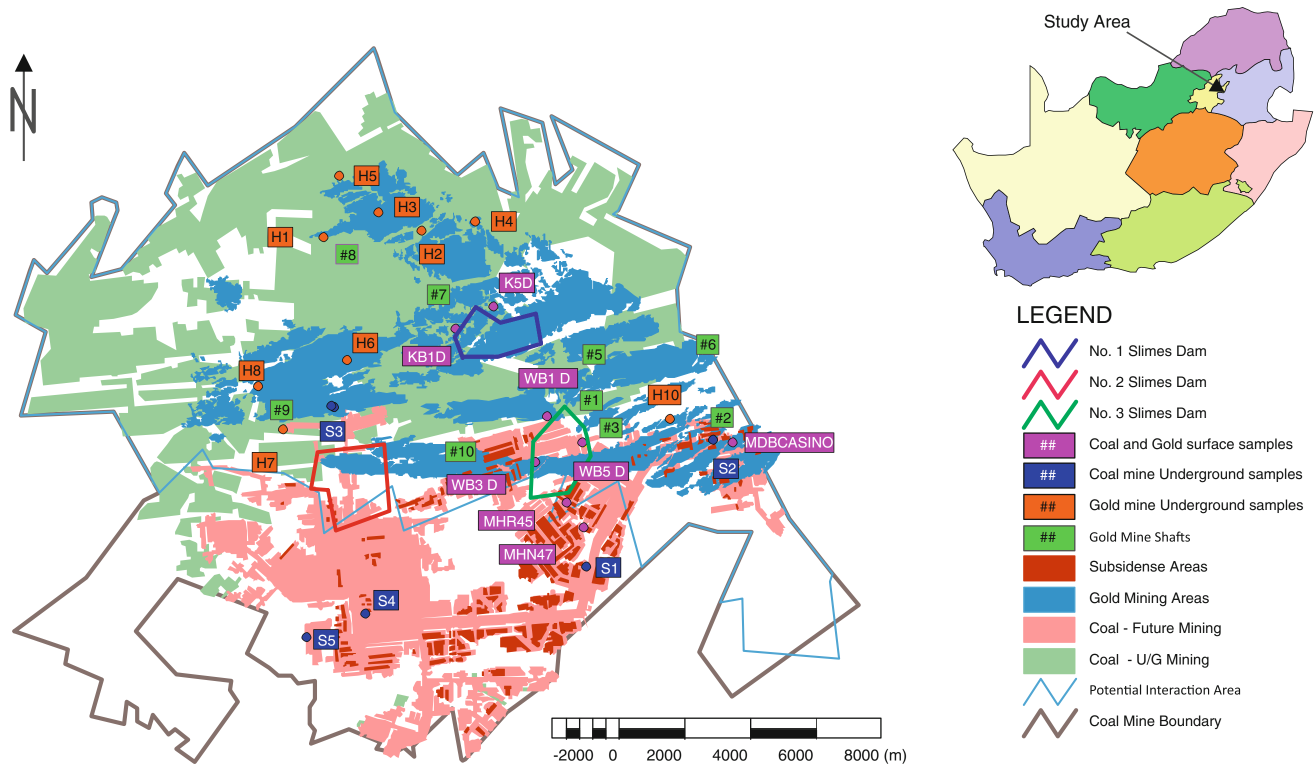

Fig. 1 Area H current and future coal mining over the gold mining activities and gold mine tailings storage facilities

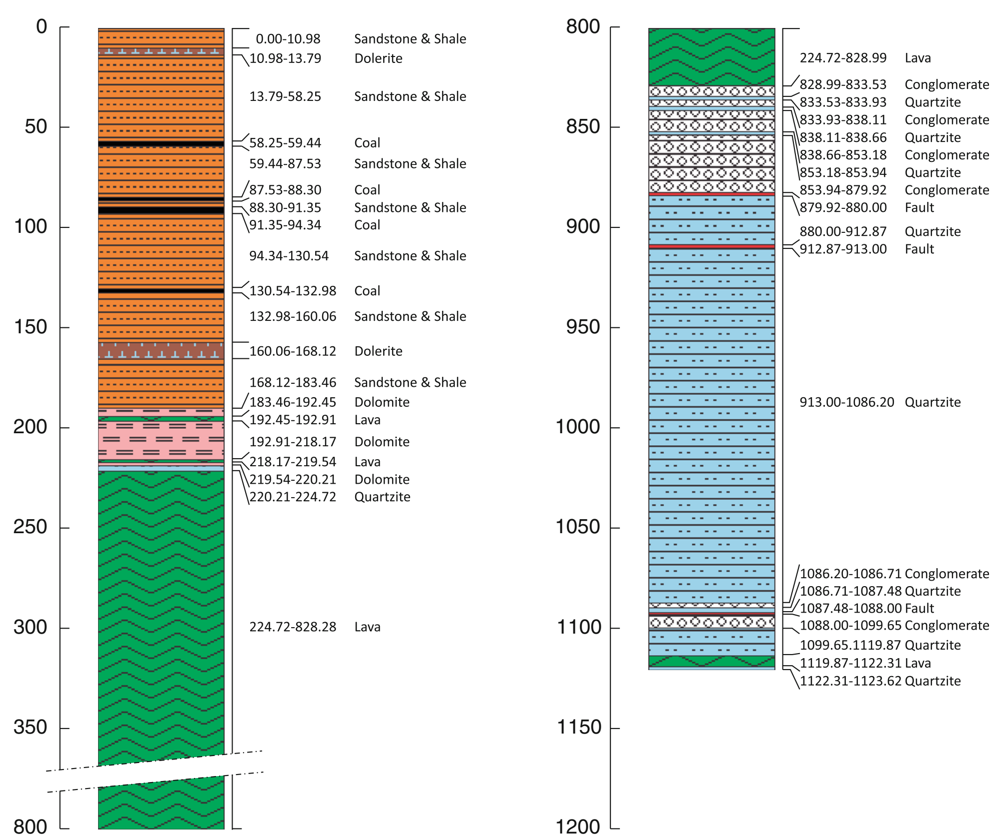

Fig. 2 Geological log for exploration borehole located at the No. 8 shaft

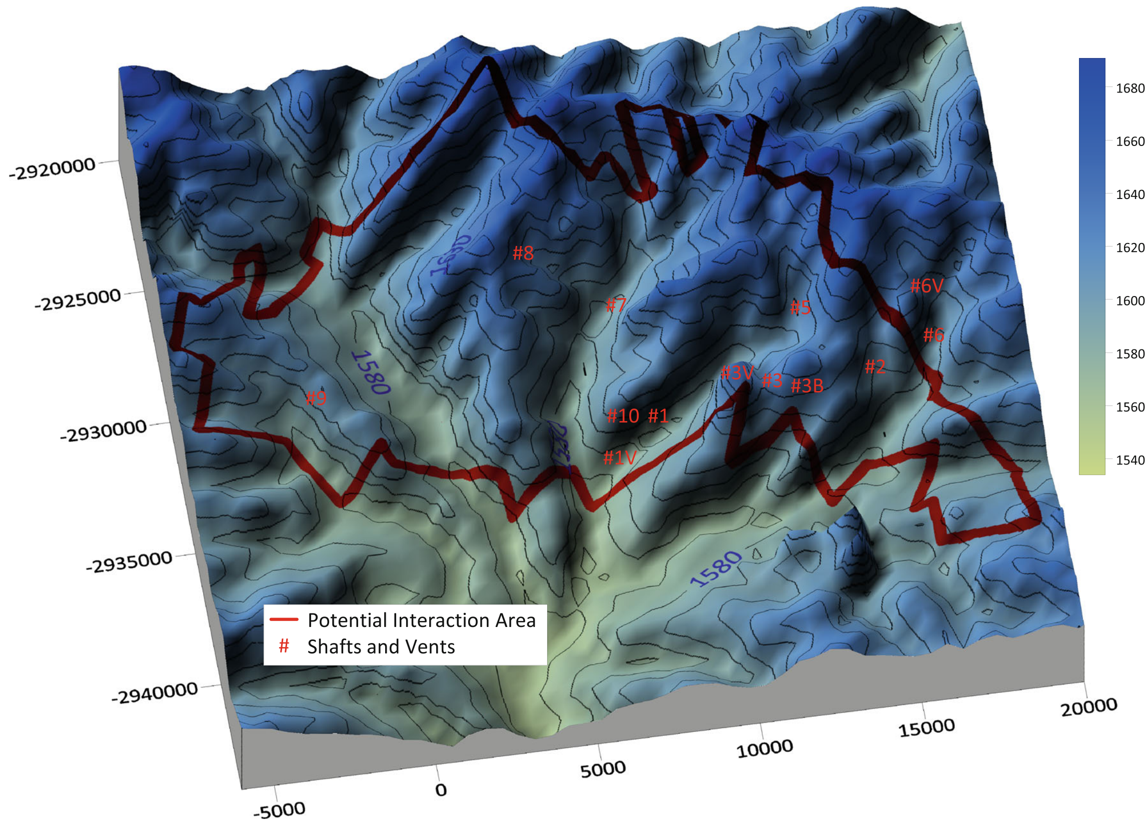

Fig. 3 Bayesian Interpolated groundwater elevation map for the Karoo aquifer water levels

Table 1 Difference in depths (m) between the No. 4L coal seam floor and the gold mine

Gold mine	Coal seam floor (m AMSL)	Gold mine operations (m AMSL)	Difference in mine depths
No. 1 shaft	1,479	1,347 (2 level)	132
No. 2 shaft	1,483	912 (9 level)	571
No. 3 shaft	1,480	1,387 (1 level)	93
No. 5 shaft	1,482	624 (13 level)	858
No. 7 shaft	1,490	849 (3 level)	641
No. 8 shaft	1,489.5	707 (8 level)	782.5
No. 9 shaft	1,461	1,380 (A level)	81
No. 10 shaft	1,470	1,345 (1 level)	125

(m AMSL) metres above mean sea level

2007). It is important to note that this elevation is within the Karoo Supergroup formation, just above the No. 4L coal seam roof, which ranges from 1,450 to 1,521 m AMSL, averaging 1,490 m AMSL. The Witwatersrand Supergroup does not outcrop on the surface of the study area and is overlain by the Ventersdorp, Transvaal, and Karoo Supergroups (Tweedie 1986). The average interpolated thickness of the overburden ranges from 2,550 to 254 m, averaging 1,400 m. This indicates that the original water level measured by Pritchard-Davies is not a water level, but a piezometric level, as there are aquicludes that confine the Witwatersrand aquifer, which produced the piezometric level of 1,533 m AMSL in the exploration borehole.

The values in Table 1, along with the top of the Witwatersrand Supergroup, were used as the current water levels around the gold mine shafts (Fig. 4). The top of the Witwatersrand was derived from the exploration boreholes covering the study area. The top of the Witwatersrand was used as a pressure level, as the base of the Ventersdorp Supergroup (aquiclude) confines the water level within the Witwatersrand aquifer.

The water levels of the Witwatersrand aquifer over the entire study area were interpolated using the inverse distance weighing method, which is deemed best for data with a large spatial variation. In Fig. 4, the effect of pumping on the Witwatersrand aquifer can be seen around the gold mine shafts.

Possible Interaction Areas within the Study Area

There is a potential risk that the coal mining will damage the impermeable geohydrological barriers that currently exist between the two aquifers. Damage to these barriers could increase groundwater influx from the surface gold

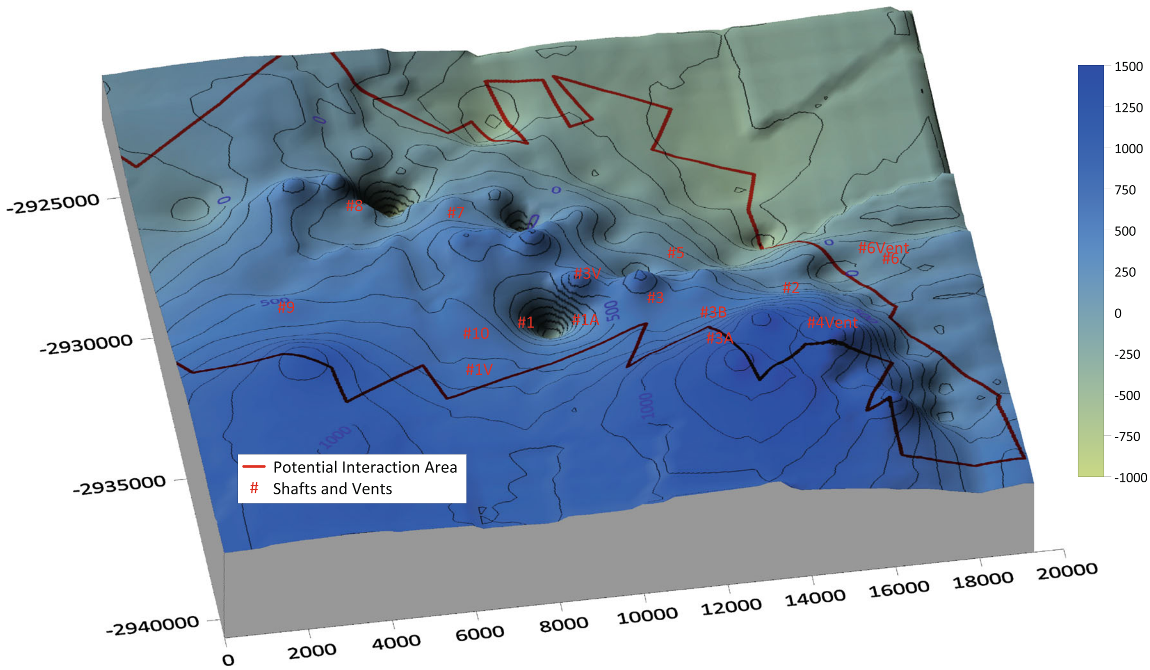

Fig. 4 Interpolated groundwater levels around the gold mine shafts

mine slimes dams and from the shallower Karoo aquifer into the Witwatersrand aquifer. The potential risk for groundwater interaction is a function of the geology, depth, and areas of mining, tailings storage facilities (TSF), and preferential pathways. By considering these factors, certain high risk areas for potential interaction were identified.

The Transvaal Supergroup dolomites and the Ventersdorp Supergroup lavas will likely act as aquicludes, restricting groundwater movement from the coal mine into the underlying gold mines. Based on published permeability values (Kruseman and De Ridder 1994), it was assumed that a cover of 50 m or more of the Ventersdorp Supergroup lavas will form an impermeable layer, restricting water movement. The Ventersdorp Supergroup lavas appear to thin towards the south-southeast of the study area, with the exception of the southern boundary of the study area where the Ventersdorp Supergroup lava is either very thin or sub-outcrops against the Karoo Supergroup (Supplemental Fig. 1; supplemental files are published with the on-line version of this paper, which can be downloaded for free by all journal subscribers). In these areas, the potential for groundwater interaction between the mines is much higher than in the areas where the Ventersdorp lava is thicker than 50 m.

Mining Depths of the Coal and Gold Mines

The No. 4L coal seam mined in the area is situated at an average depth of 80 m below the surface in the south and 150 m below the surface in the north, or at elevations between 1,450 m above mean sea level (m AMSL) and 1,521 m AMSL. Compartments are created due to the displacement of the coal seams caused by dolerite intrusion; the dolerite sills and dykes create separate groundwater compartments in which the groundwater chemistry can differ from surrounding aquifers. Groundwater compartments may receive less or more recharge than the surrounding aquifer (Vermeulen and Usher 2006). The Area H underground reserve is largely separated from the existing colliery, and is compartmentalised and sub-compartmentalised by a ±15 m thick B8 dolerite sill roughly southwest-northeast in orientation.

Geological structures such as the Kimberley Reef contain gold and platinum group metals at varying depths below the surface. The deepest operations are 2,500 m below surface, in the No. 8 shaft, and the shallowest are 240 m below surface, in the No. 3 shaft. This variable depth is due to the general dip (between16 and 24°) of the Kimberley Reef to the north and the east–west trending faults, with downthrows to the south, which results in the blocks being duplicated (Tweedie 1986).

Currently, Area H is only mining over the gold mine in the southernmost parts of the study area, with the largest area covering the southeastern part (Fig. 1). Future coal mining will cover most of the study area except for the central part around the gold mine's No. 7 and No. 8 shafts. The highest risk of groundwater interaction occurs where the mines are relatively close together (<300 m difference in mining depths). In these areas, influx of water from the coal mine into the gold mine can occur through induced

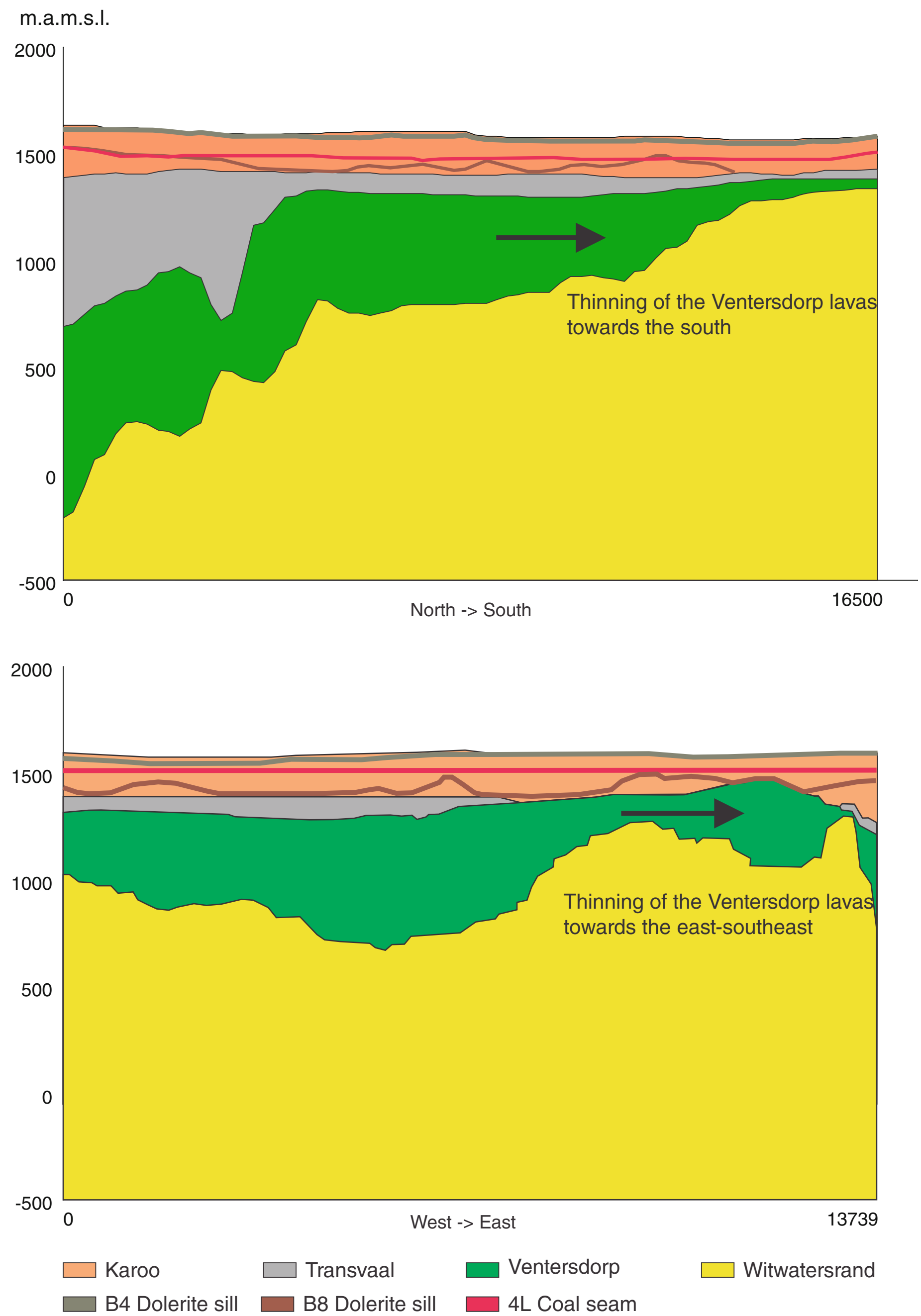

Fig. 5 Cross section through the No. 1 shaft at the gold mine

preferential flow paths. All areas throughout the gold mine where a potential for groundwater interactions may exist were physically and visually inspected and noted. Areas with the highest potential for groundwater interactions, according to difference in depth, are the areas around the gold mine's No. 1, 3, 9, and 10 shafts.

No. 1 Shaft

In the future, coal will be mined near the gold mine's No.1 Shaft, where the No. 4L coal seam floor is situated at 1,479 m AMSL (139 m below the surface). The gold mine's closest operation is 1,347 m AMSL (270 m below the surface) and 132 m below the coal seam (Fig. 5). As yet, no preferential pathways and thus no groundwater interaction from the coal mine into the gold mine could be established in this area. Also, although every haulway of the two upper levels of the gold mine was physically walked and inspected, no moisture was detected.

No. 3 Shaft

The coal mine is currently operating near the gold mine's No. 3 shaft, where the No. 4L coal seam floor is situated at

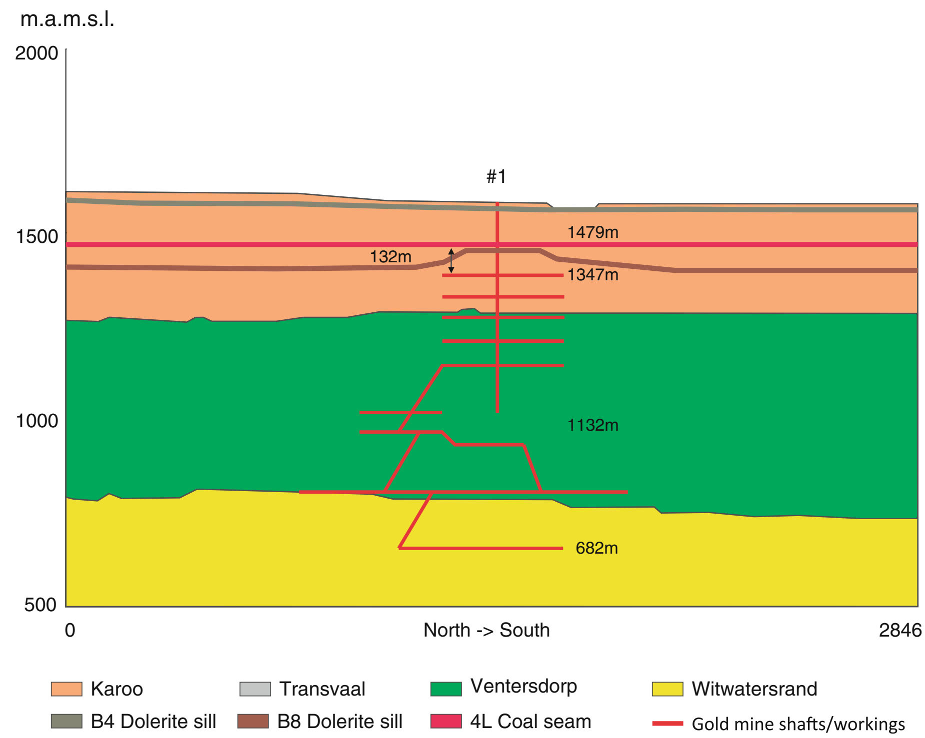

Fig. 6 Cross section through the No. 1 shaft at the gold mine

1,480 m AMSL (136 m below the surface). The gold mine's closest operation is at 1,387 m AMSL (229 m below the surface) and 93 m below the coal seam (Fig. 6). Again, no groundwater interaction from the coal mine into the gold mine could be established in the No. 3 shaft area, as no preferential pathways could be confirmed. Refer to Fig. 5 for a cross section through the gold mine's No. 2 and No. 3 shafts.

No. 9 Shaft

Future coal mining is proposed near the gold mine's No. 9 shaft where the No. 4L coal seam floor is situated at 1,461 m AMSL (126 m below the surface). The gold mine's operation at the No. 9 shaft is situated at 1,380 m AMSL (207 m below the surface), approximately 81 m below the coal seam (Fig. 7). Two preferential flow paths bearing water were found in this study during a physical inspection of the upper haulways near the No. 9 shaft (Table 1). These fractures could link the coal-mining affected Karoo aquifer to the gold mine workings in the Witwatersrand aquifer.

No. 10 Shaft

The coal mine is currently near the gold mine's No. 10 shaft where the No. 4L coal seam floor is situated at 1,470 m AMSL (119 m below the surface). The gold mine's operation closest to the No. 4L coal seam is situated at 1,345 m AMSL (244 m below the surface) and approximately 125 m below the coal seam (Fig. 8). As yet, no groundwater interaction could be established between the mines in the No. 10 shaft area, as no preferential pathways could be confirmed.

Subsidence due to High Extraction Coal Mining

As the coal seam that supports the overlying rock mass is removed, the immediate roof of the seam fails and collapses, forming rubble fill (goaf). The caved rock breaks up into blocks that vary in size from a few centimeters to tens of centimeters. These rocks pile up, partially filling the mined void. A stage will be reached when the mine workings are filled due to bulking of the rubble (Vermeulen and Usher 2006).

As the coal mining face advances, higher-lying beds fall, settle, and compress the caved layer. The stress in this secondary caving zone depends on the degree of compression of the goafed material. Typically, an extensive network of horizontal and vertical cracks develops, although the degree of displacement is not such that the beds lose their relative positions (Vermeulen and Usher 2006).

Strata overlying the secondary caving zone bend and sag under their own weight and part along bedding planes. The continuity of the beds is maintained, although some fractures develop from the stress of bending and sagging. The sagging creates tension zones, compression in the rock strata, and crack development (Fig. 9).

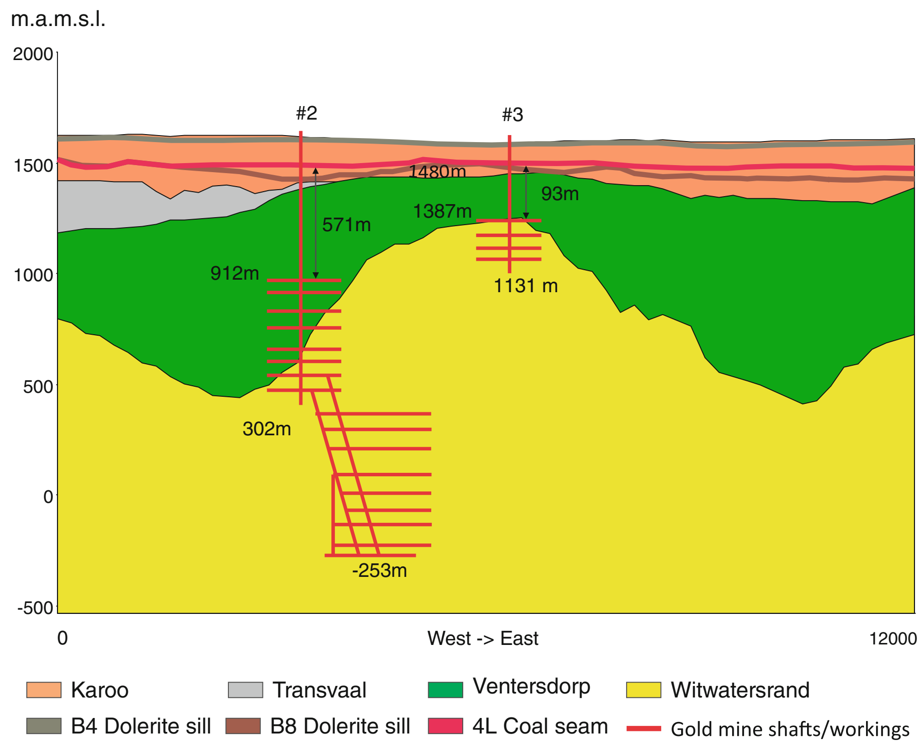

Fig. 7 Cross section through the No. 2 and No.3 shaft at the gold mine

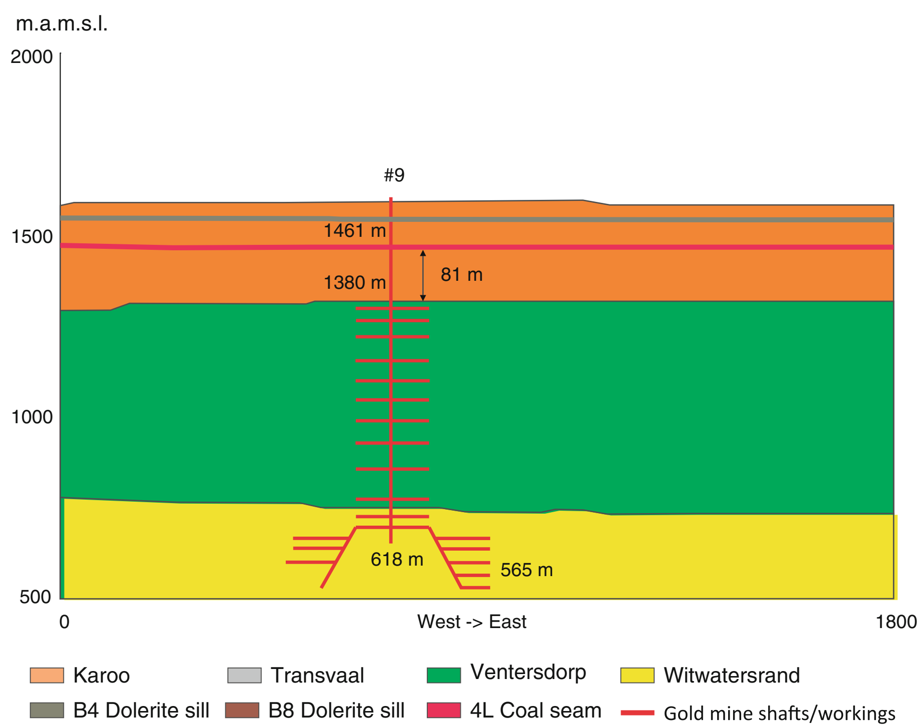

Fig. 8 Cross section through the No. 9 shaft at the gold mine

Pillar extraction presents the greatest risk of groundwater influx into the underground coal mine due to potential surface subsidence as well as the expansion of preferential flow paths such as dolerite dykes, geological contact zones, dolerite sill contact zones, faults, fissures, and unsealed exploration boreholes in the area. The influx of groundwater into mine workings will therefore be much more severe where high extraction mining has taken place.

The main contributors to the influx have been described by Vermeulen and Usher (2006): annual rainfall recharge,

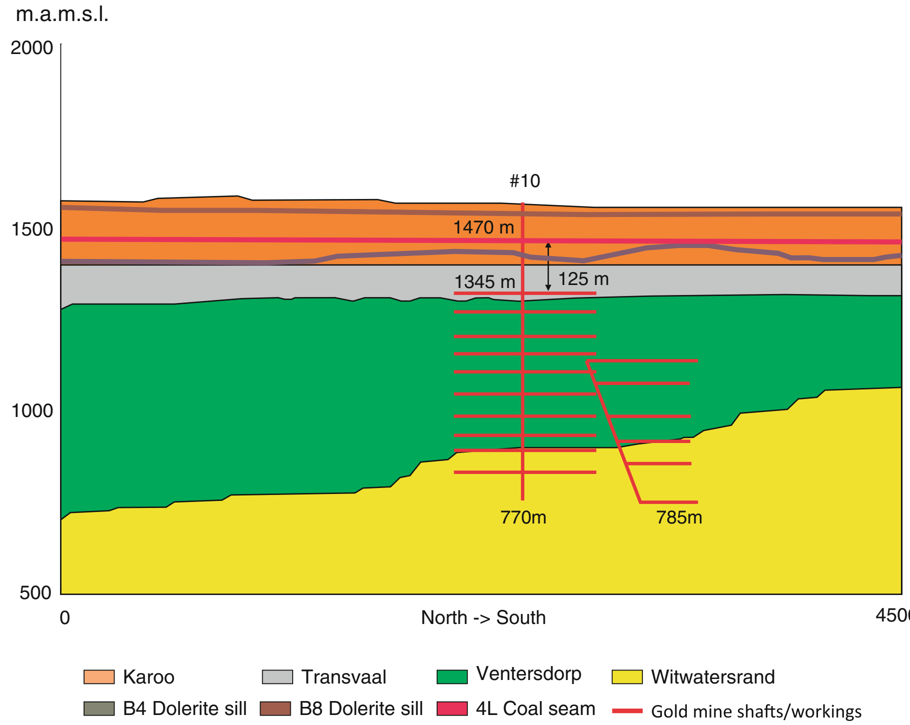

Fig. 9 Cross section through the No. 10 shaft at the gold mine

lateral inflows from the fractured Karoo aquifer, water released from storage in the overlying shallow and deep aquifers, inflows related to geological features, and inflows from mined out areas. The actual increase in groundwater influx to the coal mine will be a function of the extent of surface depressions forming ponds on the surface, the occurrence of areas with higher recharge potential (due to soil type and vegetative cover), the dimensions of apertures (cracks), and the extent of infilling of these cracks with sediment. In addition, the gold mine's surface TSF and slimes dams represent possible sources of water into the coal mine.

No. 1 Slimes Dam

The No. 1 slimes dam is situated in the centre of the study area (Fig. 1). However, mining plans for the area specifies that no high extraction coal mining will take place directly beneath or near the No 1 slimes dam (Supplemental Fig. 2), so no subsidence is expected there.

No. 2 Slimes Dam

The No. 2 slimes dam is situated to the south-southwest of the study area. Some existing high-extraction coal panels are as close as 20–50 m from the southwestern corner of the slimes dam. Also, the B4 dolerite sill, which restricts vertical groundwater movement, is very thin to the southwest of the slimes dam. Therefore, subsidence is likely to the south-southwest of the No. 2 slimes dam where high-extraction coal mining will occur, and it is expected that preferential pathways (fractures) linking the slimes dam with the underground coal mine working will be induced (Supplemental Fig. 3). Although subsidence is expected near this slimes dam, groundwater interaction could not be confirmed due to inaccessibility.

No. 3 Slimes Dam

The No. 3 slimes dam is in the south-southeast of the study area. Some existing high-extraction coal mining panels occur as close as 50–80 m to the southeastern corner of the slimes dam. The B4 dolerite sill is very thin to the south-southeast of the slimes dam (Supplemental Fig. 4). Subsidence is most likely to occur southeast of this slimes dam where high extraction coal mining will occur and it is expected that preferential pathways (fractures) linking the slimes dam with the underground coal mine working will be induced (Supplemental Fig. 4). Although subsidence is expected near the slimes dam, groundwater interaction could not be confirmed due to inaccessibility.

Interaction Areas and Preferential Pathways

All preferential flow paths intersecting the gold mine were physically and visually inspected (Table 2). It should be noted that these points were the only water-bearing structures found in the study and therefore the only known pathways potentially connecting the Karoo aquifer with the

Table 2 Preferential flow paths encountered in the study area; all were physically located and verified

Gold mine underground sites	Depth below surface (m)	Gold mine surface	Shaft or position	Description
H1	1,340	11	8	Water from fault
H2	1,340	11	8	Water next to dyke
H3	1,620	15	8	Water from exploration borehole
H4	1,830	18	8	Water from fault
H5	2,152	24	8	Water dripping from roof stope
H6	619	1	9	Water dripping from mine roof (minimal)
H7	619	1	9	Water dripping from mine roof (minimal)
H10	634	8	2	Water dripping from mine roof (minimal)
Coal mine sites		Shaft or position	Description	
S1	104	Near main shaft	Borehole into mine workings	
S2	113	Near north shaft	Water dripping from mine roof (minimal)	
S3	105	Block 38	Fissure water from mine floor	
S4	80	Near west shaft	Water dripping from mine roof (minimal)	
S5	55	Block 35	Water dripping from mine roof (minimal)	

These were the only pathways found in this study

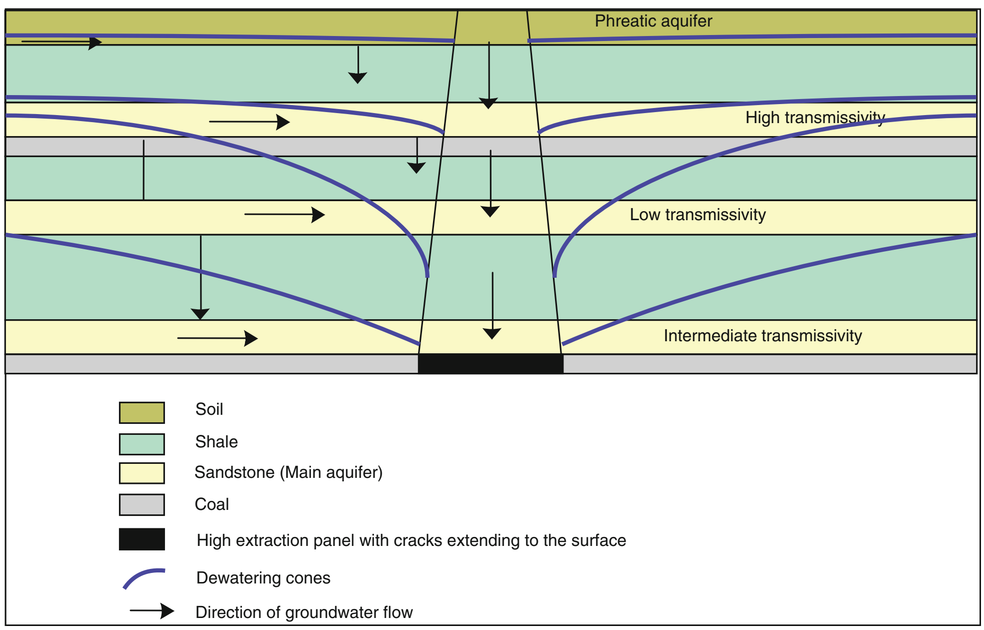

Fig. 10 Schematic cross-section of a subsided high extracted panel (Grobbelaar 2001)

Witwatersrand aquifer. Furthermore, from the mine layout and the positions of the water-bearing structures, only positions H6, H7, and H10 could be affected by coal mining, as coal mining has not yet reached the other gold mine positions; refer to Table 2 for a description of the preferential flow paths in the study area and Fig. 1 for the positions of the underground preferential flow path relative to the current and future coal mining.

H1 and H4—*Water from faults intersecting the gold mine*. The origin of this water is possibly the base of the Karoo aquifer where the Transvaal Supergroup (aquiclude) is absent and where faults pass through the Ventersdorp Supergroup (aquiclude) into the Witwatersrand aquifer. Groundwater moves along these faults until it intersects the gold mine at the No. 8 shaft, at 1,340 and 1,830 m below the surface. It is unlikely that coal mining will reach the area where these faults are and therefore it is unlikely that the coal mining will have an impact on the gold mine through these specific faults (Table 2).

H2—*Water from fractures next to a dyke exposed in the gold mine workings.* This groundwater flow is associated with fractures that may or may not be directly connected to the surface (Cook 2003); therefore, recharge may occur in the sub-surface at different depths through the influx of overlying aquifers or directly by surface precipitation. The fractures and dyke was encountered at the gold mine's No. 8 shaft, approximately 1,340 m below the surface. It is unlikely that coal mining will reach the area where this dyke is encountered and it is therefore unlikely that coal mining will impact the gold mine through this specific dyke (Table 2).

H3—*Water from exploration borehole intersecting the gold mine workings*. There are numerous exploration boreholes in the study area. In this study, one water-bearing exploration borehole was found at the No. 8 shaft, 15 level, 1,620 m below the ground level (Table 2). Refer to Fig. 2 for a full geological log. Water movement from the surface downward will be more rapid in a borehole than in faults or fractures. Exploration boreholes intersecting the Karoo aquifer will act as preferential flow paths for groundwater flow to the Witwatersrand aquifer if left unsealed. Thus, all gold mine exploration boreholes are supposed to be sealed with a non-reactive material to prevent drainage of groundwater from the coal mine to the gold mine. However, coal mining is not expected to extend to the area where this specific borehole is situated (Fig. 1), so coal mining is not expected to have an impact on the gold mine here (Fig. 10).

H5, H6, H7, and H10—*Water dripping out of the mine roof, origins difficult to determine*. The origin of water at these positions is thought to be flux from fissures/fractures and joints from overlying aquifers (Table 2). All these positions could be affected by coal mining except H5, which is at the gold mine's No. 8 shaft, where no coal mining will occur (Fig. 1).

In addition, according to the coal and gold mine personnel, an exploration borehole beneath the No. 3 slimes dam leaks water into the coal mine. This could not be confirmed as the area beneath the slimes dam is inaccessible due to flooding of the coal mine.

Preliminary Conclusions

Groundwater interaction between the shallower coal mine and the gold mine is possible through preferential pathways made by the coal mine in the areas listed below:

- The south-southeast corner of the No. 3 slimes dam, due to high extraction coal mining;
- The south-southwest corner of the No. 2 slimes dam, due to high extraction coal mining;
- South-southwest of the mine's No. 9 shaft, Level 1, as seen in samples H6 and H7.

Current interaction between the mines is minimal as water dripping out of the gold mine roof totals <1 L a day. It may increase as future coal mining extends to a much larger area around the shaft and the coal mine fills up with water.

Groundwater entry in the central part of the study area near the gold mines No. 8 shaft occurs without the presence of coal mining, through faults, fractures next to dykes, and exploration boreholes that intersect the gold mine workings. Thus, the coal mine is not the only factor to be considered as naturally occurring structures allow influx from the Karoo aquifer into the gold mine. No future coal mining is envisaged around the No. 8 shaft and therefore the potential for coal-mine-affected groundwater in the Karoo aquifer to interact with gold mine around the No. 8 shaft is very low.

The coal mine will eventually cover most of the gold mining area except for the central part near the No. 8 and No. 7 shafts. It is expected that groundwater affected by coal mining in the Karoo aquifer will only move along naturally occurring structures that link the two mines, from the base of the Karoo aquifer into the gold mine. This will only occur when structures that link the Karoo aquifer with Witwatersrand aquifer are encountered. Since few structures were found to be water-bearing in the underground gold mine, it was anticipated that the potential for groundwater interaction from future coal mining into the gold mine will be low.

However, the geochemistry of the mine waters was investigated to provide additional insight. These aspects are reported on in the accompanying paper in this issue.

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