Groundwater Source Determination of an Underground Diamond Mine Utilizing Water Chemistry and Stable Isotope Analysis

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Abstract

An underground diamond mine historically experienced periodic groundwater inflow into the underground workings of the mine, resulting in unsafe working conditions. A conceptual model was developed to better the understanding of the groundwater situation at the mine. Water samples were collected at various points. The samples were analysed for major and minor chemical constituents and the stable isotopes of hydrogen and oxygen. Three sources of groundwater inflow into the mine workings were identified. The investigation illustrates that water chemistry signatures and stable isotope signatures can successfully identify different sources of water that flows into the workings of an underground mine.

Keywords: Groundwater, Inflow, Source, Chemistry, Stable Isotopes

Introduction

The Institute for Groundwater Studies at the University of the Free State was appointed by a mining company to investigate the source/s of groundwater inflow into the underground mine workings. Periodic groundwater inflow into the underground workings result in unsafe and undesirable working conditions.

Diamond (ore) extraction was initially from the open pit and later transitioned into underground mining (block cave method). The current depth of mining ranges between 700 and 800 m below surface. The layout of the mine is presented on the map shown in Figure 1.

Materials and methods

Desktop Study

The desktop study involved the examination of available data, aerial-and satellite maps to better understand the area of investigation and to construct a conceptual model of the area. Additional information acquired from the mining company for the desktop study included, groundwater monitoring data (quantity & quality), geological maps, rainfall data, mine layout plans and previous investigations.

Water Sample Collection

Water samples were collected over a three-month period, which include various points in the underground mine workings, existing groundwater monitoring boreholes and surficial water bodies. The samples were analysed for major and minor chemical constituents (tab. 1) and the stable isotopes of hydrogen (2H & 1H) and oxygen (18O & 16O).

Data Presentation and Interpretation

The chemistry data was graphically interpreted using Piper and Stiff diagrams to identify different water types and waters from different environments. Thus, waters with the same chemical signatures can be grouped together.

Piper diagrams are trilinear representations of cation, anion, and combined cation and anion proportions (Eby 2004), whereas Stiff diagrams show the concentrations of the major cations and anions in milli-equivalents as a shape that

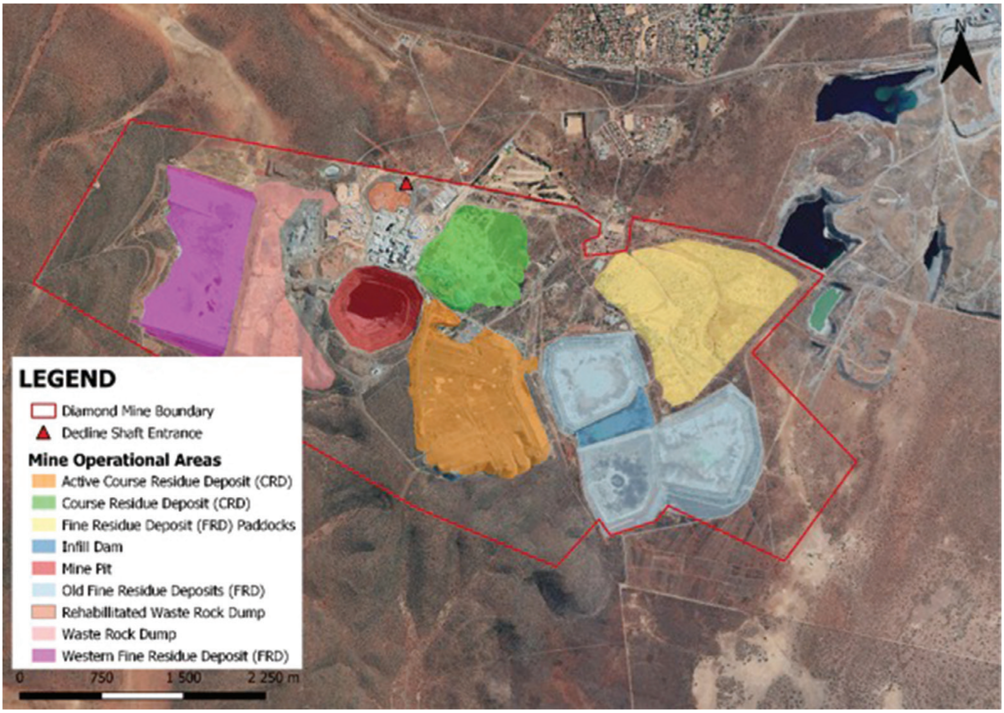

***Figure 1** Mine layout map.*

gives both the relative abundance of the various species and the total abundance (Eby 2004).

The atomic ratios of the hydrogen and oxygen isotope was plotted against the Global Meteoric Water Line (GMWL). Oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$) are constituents of water molecules and can act as conservative tracers and therefore mainly applied in geohydrology to determine the source and mixing of groundwater (Mook and Geyh 2000). The natural atomic ratios are expressed as delta values ($\delta^{18}O$ & $\delta^{2}H$). Most groundwater resources are of meteoric origin and therefor the strong relationship between the $\delta^{18}O$ and $\delta^{2}H$ values of precipitation in the Meteoric Water Line (MWL) (Mook and Geyh 2000).

Site Description

Topography and Rainfall

The regional surface elevation ranges between 1406 mamsl and 1694 mamsl. The mining area of the diamond mine is situated on a topographic high, thus the surface elevation slopes mostly away from the mine. The topographic low of the mining and the lime mining quarries of the neighbouring lime mine (northeast of the diamond mine) are clearly visible on the surface elevation map shown in Figure 2.

The annual rainfall (MAP) between 1967 and 2020 is 388.8 mm. The area received three exceptional high rainfall events over the past 53 years. These rains were received over the summer seasons of 1975, 1988 and 2012.

***Table 1** Major and minor chemical constituents analysed.*

Major and Minor Chemical Constituents
EC, pH, Alkalinity, Ca, K, Mg, Na, Br, Cl, F, NO_3(N), NO_2(N), PO_4, SO_4, Al, As, B, Ba, Cd, Co, Cr (Total), Cu, Fe (Total), Hg, Mn, Mo, Ni, Pb, Sb, Se, Si, Sr, U, V, Zn

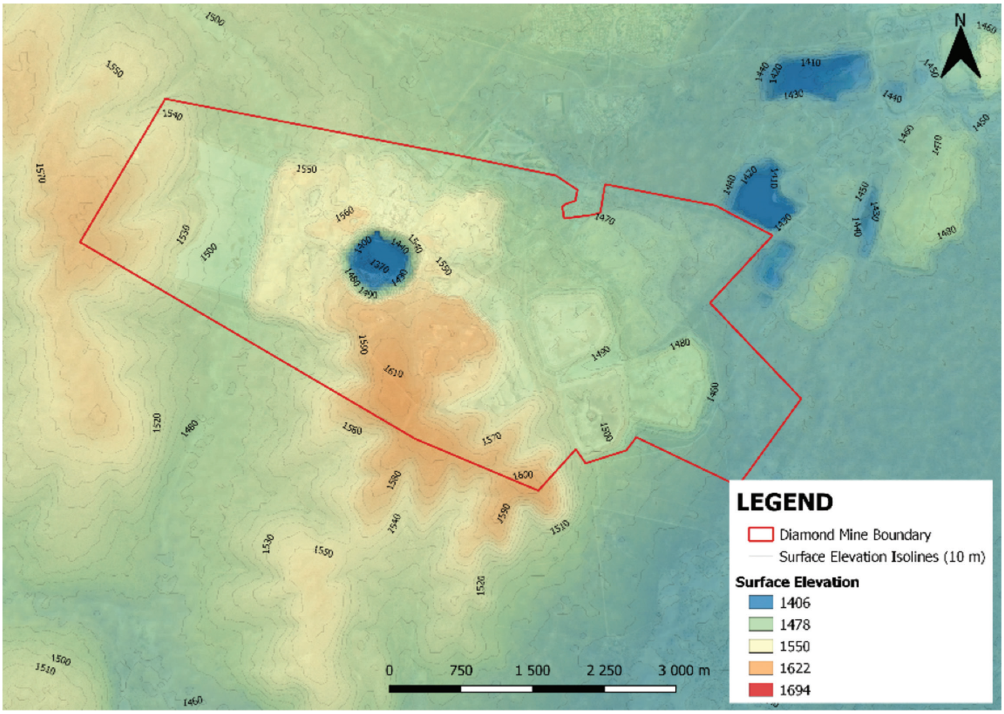

Figure 2 *Surface elevation (mamsl) map.*

The Mean Annual Evaporation (MAE) for the area ranges between 2200 and 2600 mm and the mean annual runoff (MAR) is 8 mm (Midgley *et al.* 1994).

Geology

The diamond mine consists of an 17.9 ha, 118±2.8 Ma old kimberlite pipe (Smith *et al.* 1985) which intruded through a thick sequence of Proterozoic, Griqualand West sequence of sedimentary rocks comprising of dolomites, banded iron formation and shales. There is numerous lineaments of different strike orientations, which represent structural discontinuities, such as faults and fracture zones, and are variably intruded by dykes of different composition and age (fig. 3). The area have the following primary sets off faults and fracture zones:

- NNW-SSE to N-S striking major fault zones
- NE-SW to ENE-WSW striking fault/fracture zones, commonly intruded by kimberlite precursor dykes
- WNW-ESE striking fault/fracture zones

Hydrogeology

The groundwater of the area constitutes a shallow aquifer within the weathered zone and a deeper aquifer in the fractured and karstic dolomites. The hydrogeological setting consists of partly karstic dolomites and complex zones with linear structures which create a highly interconnected fracture network. The aquifer is further compartmentalised by various dykes which impact on the groundwater regime. These structures act as conduits allowing rainfall to recharge the deeper fractured aquifer network. According to Friese and Terbrugge (2003) karst and fissure formation within the carbonaceous rocks of the Campbellrand Subgroup have been known to develop along structural discontinuities. Faults and dykes can act as either barriers of conduits to groundwater flow, and they often act as both depending on the degree of fracturing and infilling.

Dolomites are subject to solution weathering by percolating water which forms a weak carbonic acid that slowly dissolves the dolomites from the sides of

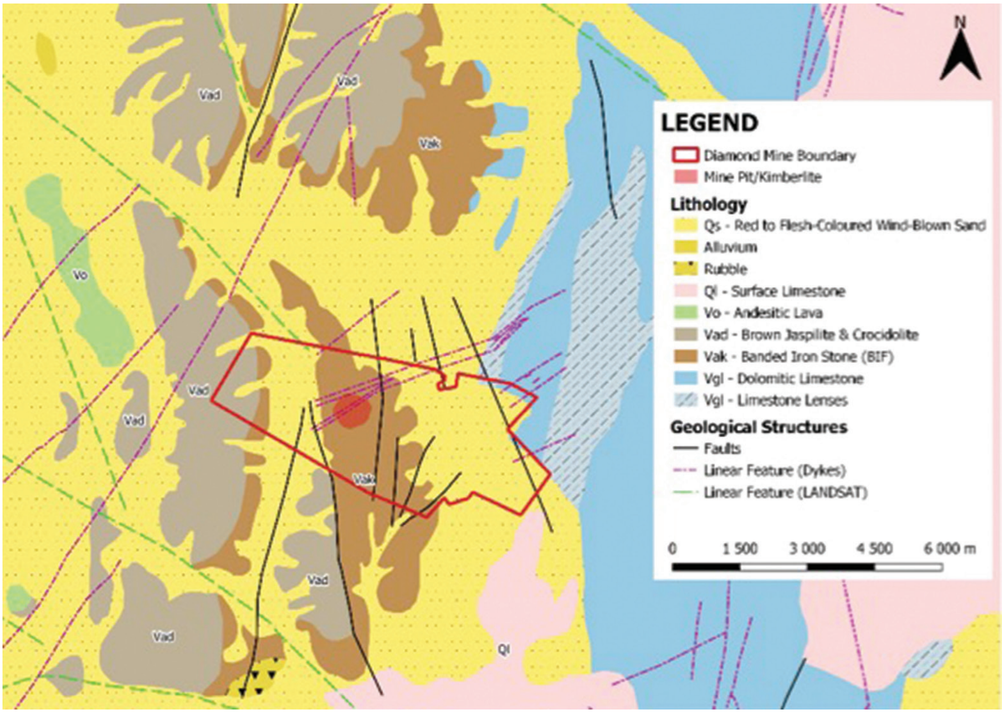

Figure 3 *Regional geology map.*

geological structures. Dolomite aquifers thus consist of a series of solution cavities. Banded ironstones contain voids created by fracture networks in the ironstones. Groundwater flow is controlled by the width, extent and the degree of interconnectedness of the fractures.

Results and Discussion

The water quality results are plotted on the Piper Diagram in Figure 4. Three water types can be identified from the Piper Diagram, namely:

- Type 1: Calcium-Magnesium-Bicarbonate type – observed for boreholes and underground sampling points
- Type 2: Calcium-Magnesium-Sulfate type – observed for boreholes, surface water bodies and underground sampling points
- Type 3: Sodium-Sulfate type – observed for surface water bodies and underground sampling points

The stable isotope results are represented in Figure 5, showing the results of δ18O versus δ2H relative to the Global Meteoric Water Line (Craig 1961). Three groups can be identified:

- Group 1: Water samples which correspond well with the GMWL, thus indicating water of meteoric origin
- Group 2: Water samples which do not correspond well with the GMWL but fall along a mixing line with water of an evaporated signature
- Group 3: Water samples which do no correspond with the GMWL but fall along the defined evaporation line

The evaporative signatures of the sampling points on 63 Level and the boreholes suggest that these sampling locations receives water inflow from surface water sources. The water quality of sampling point 63/34 on 63 Level is similar to that of the Western FRD (fig. 6). The similar water qualities and the similar isotope signature of the Western FRD and the sampling point 63/34 suggest that seepage from the Western FRD is entering the mine workings on 63 Level.

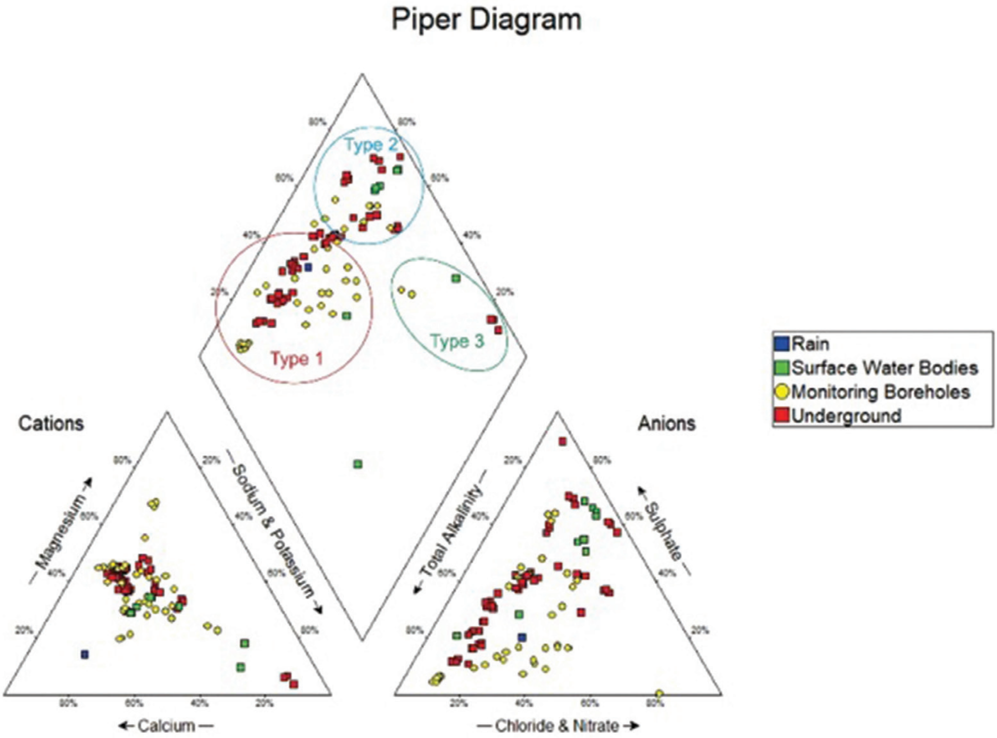

Figure 4 *Piper diagram of the samples collected.*

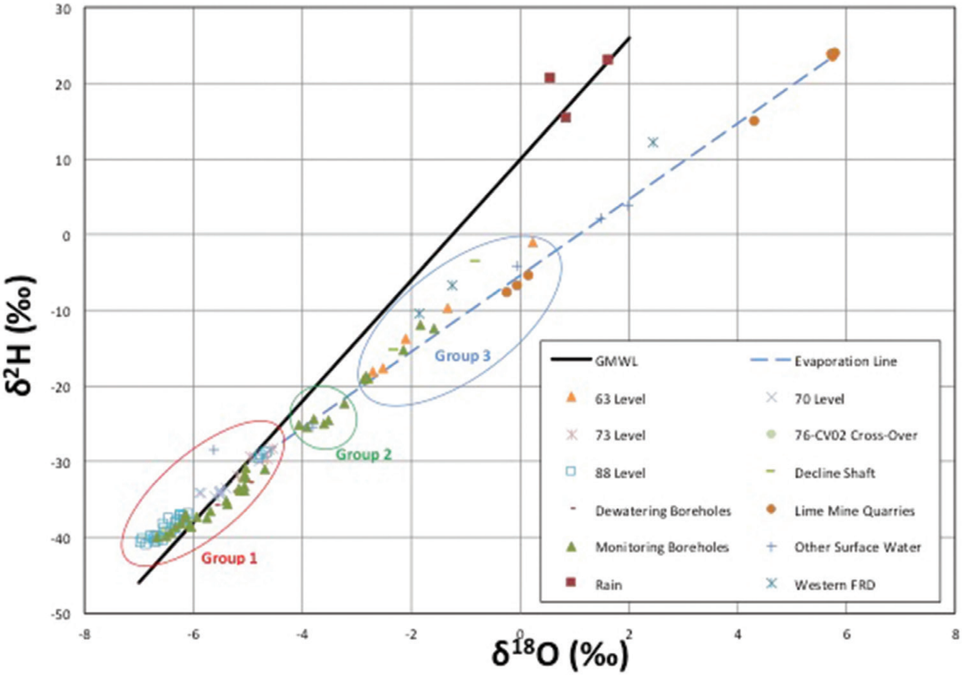

Figure 5 *Plot of stable isotope $\delta^{18}O$ versus $\delta^{2}H$ relative to the global meteoric water line (GMWL).*

The evaporative signatures of the sampling points in the decline shaft suggest that these sampling locations receive water inflow from surface water sources. The Decline Set-1 and Decline Set-2 sampling locations are situated approximately 75 m below ground level of an old waste rock dump that have been rehabilitated. There are areas on the old waste rock dump that is irrigated on a regular basis. The water quality of the samples collected in the decline shaft are similar to that of the Active CRD (fig. 6). Therefore, the calcium-magnesium-sulphate water signature and the evaporative signature of the decline shaft suggest that it is plausible that seepage from the irrigation activities on the rehabilitated waste rock dump enters the decline shaft at the two sampling locations. The calcium-magnesium-sulphate signature is probably the result of the irrigation water that interacts with the waste rock dump as it infiltrates the subsurface.

The underground water sampling points on 70 Level, 76-CV02 Cross-over and 88 Level mainly indicates waters with a calcium-magnesium-bicarbonate signature and the isotope signatures plots on the GMWL, thus suggesting water with a meteoric origin, in this case, groundwater from the dolomitic aquifer.

Conclusions

The investigation illustrates that water chemistry signatures and stable isotope signatures can successfully identify different sources of water that flows into the workings of an underground mine. The identified water sources includes the following:

- The similar water qualities and the similar isotope signature of the Western FRD and the sampling point 63/34 suggest that seepage from the Western FRD enters the mine workings on Level 63.
- The calcium-magnesium-sulphate water signature and the evaporative signature of the decline shaft suggest that it is plausible that seepage from the irrigation activities on the old rehabilitated waste rock dump enters the decline shaft.
- The water quality and isotopic signature of the underground water sampling points on 70 Level, 76-CV02 Cross-over and 88 Level mainly indicates waters originating from the dolomitic aquifer. The faults and shear zones striking NNW to SSE acts as preferential flow paths for the dolomitic water to enter the mine workings on 88 Level.

Based upon the hydrogeological, hydrochemical and stable isotope data a conceptual model was constructed (fig. 7). It is conceptualised that water from the Western-FRD infiltrates and mixes with the shallow groundwater in the banded ironstone and Passage Beds and is further transported east toward the mine pit where it infiltrates into the underground mine workings on 63 Level. The faults and shear zones striking NNW to SSE acts as preferential flow paths for the dolomitic water to enter the mine workings on 88 Level.

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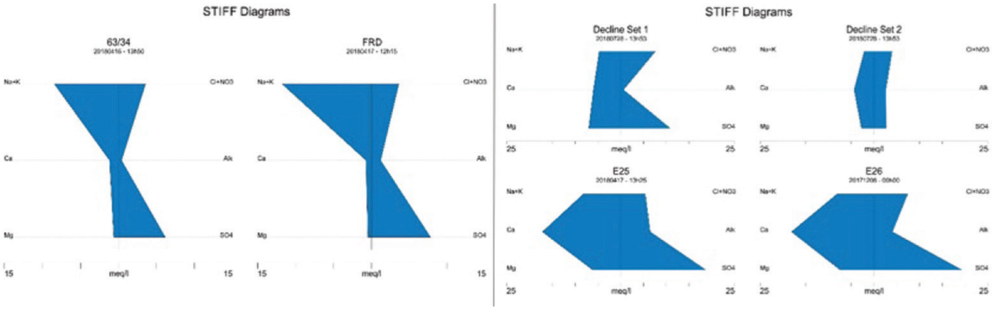

Figure 6 *Stiff Diagrams of the Western-FRD versus 63 Level (left-hand side diagrams) and the Active-CRD versus the decline shaft (right-hand side diagrams).*

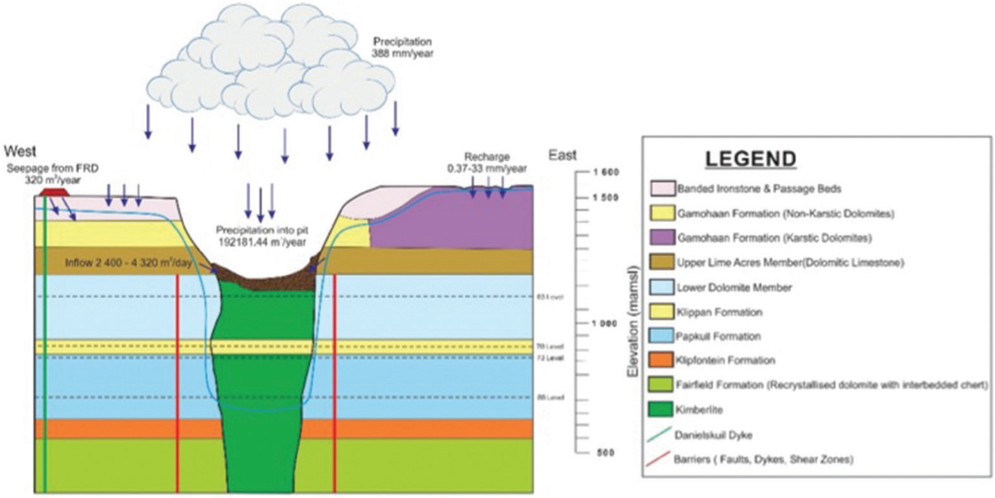

***Figure 7** Conceptual geohydrological model.*

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