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Groundwater hydrogeochemical characteristics in rehabilitated coalmine spoils

M. Gomo [a, *], E. Masemola [b]

[a] University of the Free Sate, Institute for Groundwater Studies, Faculty of Natural and Agricultural Sciences, PO Box 339, Bloemfontein, 9300, South Africa
[b] AngloAmerican, New Vaal, South Africa

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A B S T R A C T

The investigation aims to identify and describe hydrogeochemical processes controlling the evolution of groundwater chemistry in rehabilitated coalmine spoils and their overall influence on groundwater quality at a study area located in the Karoo basin of South Africa. A good understanding of the processes that controls the evolution of the mine water quality is vital for the planning, application and management of post-mining remedial actions. The study utilises scatter plots, statistical analysis, PHREEQC hydrogeochemical modelling, stoichiometric reaction ratios analysis, and the expanded Durov diagram as complimentary tools to interpret the groundwater chemistry data collected from monitoring boreholes from 1995 to 2014. Measured pH ranging between 6–8 and arithmetic mean of 7.32 shows that the groundwater system is characterised by circumneutral hydrogeochemical conditions period. Comparison of measured groundwater ion concentrations to theoretical reaction stoichiometry identifies Dolomite-Acid Mine Drainage (AMD) neutralisation as the main hydrogeochemical process controlling the evolution of the groundwater chemistry. Hydrogeochemical modelling shows that, the groundwater has temporal variations of calcite and dolomite saturation indices characterised by alternating cycles of over-saturation and under-saturation that is driven by the release of sulphate, calcium and magnesium ions from the carbonate-AMD neutralization process. Arithmetic mean concentrations of sulphate, calcium and magnesium are in the order of 762 mg/L, 141 mg/L and 108 mg/L. Calcium and magnesium ions contribute to very hard groundwater quality conditions. Classification based on total dissolved solids (TDS), shows the circumneutral water is of poor to unacceptable quality for drinking purposes. Despite its ability to prevent AMD formation and leaching of metals, the dolomite-AMD neutralisation process can still lead to problems of elevated TDS and hardness which mines should be aware of when developing water quality management plans.

1. Introduction

Spoils occur in every mining operations and their rehabilitation is an important component of post-mining waste management to prevent pollution of the environment. In coal mining which is the focus of this study, spoils can be described as the waste rock material that is removed in order to access and mine the coal resource (Merkel and Hasche-Berger, 2006). In the context of mine spoils, rehabilitation refers to their handling, utilisation and management in restoring the mined out land. Various technical facets of mine spoils rehabilitation are extensively covered in a number of studies in literature, which includes; EPA 1995; Bell 1996 and Evans 2000.

Depending on their mineralogical compositions, spoils can also pose serious threat of degrading the environment during rehabilitation. In coalfields found in the typical Karoo Basin of Southern Africa, studies have shown the existence of acid buffering minerals such as calcite and dolomite that occurs together with pyrite within the coal seams (Van Vuuren and Cole, 1979; Gaigher, 1980; Van der Spuy and Willis, 1991; Usher et al., 2001; Azzie, 2002; Pinetown and Boer, 2006).

Of particular interest to this investigation are efforts to prevent the deterioration of groundwater quality during rehabilitation. Such efforts generally include assessment and predictions of AMD potential from the spoils and in-situ monitoring of groundwater quality among other things (Eberle and Razem, 1985; Wunsch et al.,

* Corresponding author.
E-mail addresses: GomoM@ufs.ac.za (M. Gomo), eva.masemola@angloamerican.com (E. Masemola).

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1996; Ellerbroek et al., 1997; Lollar, 2005). A vital part of groundwater quality monitoring is the study of groundwater hydrogeochemistry. This mainly comprises of the identification and description of hydrogeochemical processes controlling the evolution of groundwater chemistry and their influence on groundwater quality, which is the focus of this article. Processes that controls evolution of the mine water quality has to be understood for the planning and application of post-mining remedial measures.

2. Methods and materials

2.1. Description of the study area

The study area is located in the Free State Province of South Africa (Fig. 1). Fig. 1 also shows the layout plan of the monitoring boreholes within the rehabilitated mine spoils. The spoils were used as backfill of the mined voids and dressed with alluvium sand and seeded with grass species. As part of the environmental management program, it was important to monitor the evolution of the groundwater chemistry and quality over time within the spoils in order to understand the evolution of the groundwater quality and it's implications for management options. Climatic conditions in the area are those typical to the Highveld region, which is characterised by summer rainfall and dry winter conditions. The site also consists of a dam (Fig. 1) that stores water from the dewatering activities.

2.2. General geology

The mine is located in the main Karoo Basin within the Vryheid formation of the Ecca Group. The general geology of the mine consists of a thick alluvium sand overlying a coarsening upward sequence of sandstone, shale and siltstone hard overburden followed by coal seams. The seams are underlain by Dwyka tiilite and dolomite from the Transvaal Supergroup respectively. The top seam coal is separated from the middle seam by inter-burden of coarsening upwards sequence of micaceous sandstone, shale/siltstone and carbonaceous mudstone. The bottom and middle seams are separated by a parting characterised by carbonaceous silty to gritty mudstone. Much of the rehabilitated area is covered by the clayey alluvium sand of rock mixtures from the hard overburden; inter-burden and coal discard that make up the spoil material.

2.3. Hydrogeology

The general site hydrogeology can be divided into three main aquifer systems, namely the shallow primary aquifers, Karoo aquifers and aquiclude and the pre-Karoo aquifer (Woodford and Chevallier, 2002). The primary aquifers include a shallow perched aquifer of low permeability, low yielding fine grained shallow alluvium and weathered Karoo sediments, and the artificial aquifer formed as a result of the backfill spoils. The Karoo aquifers and aquiclude are made up of a fractured aquifer of Ecca Group rocks including the coal seams; artificial aquifer formed by old underground mine workings and Dwyka aquiclude.

Previous geochemical characterisation of the site showed that there was sufficient neutralisation potential (NP) within the spoils to prevent the generation of AMD (Ochieng and Harck, 2012). However, irrespective of the spoils having been shown to have sufficient NP, groundwater quality monitoring on mine waste activities is an essential requirement (DWAF, 1998 and DWAF, 2007). Four boreholes (BH1, BH3, BH6 and BH11) were therefore installed to monitor groundwater levels and groundwater quality trends in the spoils (Fig. 1). Each borehole was drilled to different depths within the backfill material. The depth of the boreholes as meters below ground surface is as follows; BH1 − 28m, BH3 − 22m, BH6 − 15m and BH11 − 30m. Considering that the spoils are generally unconsolidated, the boreholes are cased with perforated casing throughout the entire depth to prevent the borehole wall from collapsing. The location and distribution of the monitoring boreholes was mainly influenced by the accessibility of each particular location with the drilling equipment.

Fig. 2 shows the groundwater level and rainfall measured at the study site during the monitoring period. The groundwater level trends indicate recovery from the onset of monitoring from September 2001 to November 2010 when it started to stabilise. This should be expected to occur in areas under rehabilitation that were previously dewatered during mining and are now in the recovering phase. Considering various mining dewatering activities within the mine site, it will be very difficult to determine the natural groundwater flow patterns between these monitoring boreholes. It is therefore beyond the scope of this research to determine the hydraulic patterns and groundwater flow between the mine compartments and the surroundings. The focus of the study is to investigate the groundwater hydrogeochemical characteristics of the rehabilitated coalmine spoils and not the potential offsite migration of mine water.

2.4. Groundwater sampling and ion analysis

Groundwater samples were collected from the monitoring boreholes drilled into the rehabilitated coalmine spoils and also from the dam. The duration of the reported monitoring, periods are as follows: BH1 (07/03/1995–21/05/2014), BH3 (29/04/1996–21/05/2014), BH6 (17/03/1997–21/05/2014) and BH11 (13/08/2001–21/05/2014). Samples were collected monthly with the exception of a few occasions where field conditions were difficult to access the boreholes. The other limitation is that the monitoring duration is not equal for all the boreholes. Although this could possibly affect the comparisons, it is not expected to change observed trends taking into consideration the 10 years of data for BH11 borehole which has the shortest monitored period.

Groundwater samples were obtained from the monitoring boreholes using a low flow pump rate of between 0.1 and 0.3 L/s. Temperature and electrical conductivity (EC) were continuously measured and monitored in the purged water. Samples were only collected after stabilisation of the temperature and EC. This was done to ensure to collection of groundwater that is representative of hydrogeochemical conditions in the spoils and not of the stale water in the borehole column. Samples were collected into clean 500 ml polyethylene bottles. Prior to sample collection, bottles were rinsed with hydrochloric acid at a pH of 2 to remove leachable material. After sampling, the bottles were tightly closed to protect from atmospheric gases, labelled, stored (<4 °C) and delivered to the laboratory within 24 h.

Groundwater samples were analysed for metals, major and minor ions. Analysis for cations and heavy metals was done using a PerkinElmer Optima 3000 DV Inductively Coupled Plasma (ICP) and a Dionex DX-120 Ion Chromatograph (IC) was used for the anions. Alkalinity measurements were made using a TW alpha plus titration kit. All the analyses were conducted based on the guidelines provided in the Standard Methods for the Examination *of* Water and Wastewater (American Public Health Association et al., 2005). Calculated ionic balance error for the analyses ranged between −7.6% and +14.4%.

2.5. Data analysis

Saturation indices (SI) for mineral phases were calculated using the PHREEQC hydrogeochemical model (Parkhurst and Appelo,