Mine Water approach using Tracers in South African abandoned Coal Mines

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Abstract

Surface water and groundwater quality in areas of South Africa continues to be degraded by acid mine drainage (AMD), a legacy of coal mining. The majority of abandoned coal mines consist of complex multiple level workings connected to a drainage tunnel discharging AMD, in lower lying regions. This decanting mine water poses severe problems to the receiving environment. Thus, there is a need, to define hydrologic connectivity between surface water, groundwater and mine workings to understand the source of both water and contaminants at the decanting points. South Africa has limited studies into the feasibility of using tracer techniques, especially in mine water studies to understand underground water dynamics. Locally, there are no regulations and/or standard procedures for such activities. Wolkersdorfer (2008), states that in some countries such as Germany, there are regulations that govern the use of tracers.

In a case study that is currently in progress as part of the use of tracers in mine water, water samples were collected from different discharge points in and around a flooded and abandoned coal mine, within the Witbank coal fields of the Permian Karoo Supergroup. This was done to classify the different water types as a pre-assessment for using tracer techniques. Our preliminary results demonstrated that the water samples collected have high concentrations of major elements such as SO_4, Cl, Na, Mg, Al, K, and Ca.

Key words: Mine water, tracer, discharge, South Africa

Introduction

A major environmental problem relating to mining in many parts of the world is the uncontrolled discharge of contaminated water from abandoned mines. The general consensus is that this phenomenon is responsible for costly environmental and socio-economic impacts. While South Africa has made the paradigm shift in addressing mine closures and mine water management through rigorous legislation and regulatory changes, vulnerabilities in the current system still remain. Commercial coal mining in South Africa started in about 1864 when the first colliery opened near the town of Molteno in the Eastern Cape Province (De Korte 2010). Since then, many mines were discovered and mined in different localities around the country. Subsequent to their closure, some of these were left abandoned. After the closure of the mines, many parts of the mines collapsed and subsided, resulting in a combination of problems including acid mine drainage and spontaneous combustion, eventually causing further subsidence and air pollution due to spontaneous combustion. Following mine abandonment, pumping from the active mine is terminated and mine voids are allowed to flood (Donovan *et al*. 2000).The flooding of abandoned mines will mostly continue until the groundwater achieves a new equilibrium, either by the surface discharge of mine water or by controlled pumping and treatment. The hydrodynamics controlling the flow and transport of the mine water in flooded underground mines is generally not well understood in South Africa. Much of the research carried out over the past decade in South Africa has focused on the treatment of polluted water and the prevention of water ingress, making it possible to implement certain ingress control measures immediately while other measures require minimal preparatory work. The prevention of pollution will always be more sustainable than pumping and will obviate or reduce the need for perpetual treatment of AMD.

Tracer tests are well established in groundwater studies where they are commonly used to investigate the hydraulic parameters or interconnections of groundwater (Käß 1998). Most of the techniques used are well described and, depending on the aims of the tracer test and the hydrological situation, a range of tracers or methods may be chosen. Published results of tracer tests in abandoned underground mines are not common. This is mainly as a result of the complex infrastructure of underground mine workings and poor conceptualisation of the hydrological system. However, over the past decade, a number of tracer tests in underground flooded mine workings were conducted with the aim of understanding the hydrodynamics of the subsurface and support remediation procedures (e.g. Younger *et al* 2002, Wolkersdorfer 2002,Aldous and Smart 1988, etc). A tracer is any substance (compound, trace metal, heat, micro-organism, etc.) that can be carried by water in order to provide information about the direction and velocity of the water as well as the transport of potential contaminants (Davis *et al.* 1980). Tracer tests techniques may be used to generate new knowledge, research and advancement in the field of mine water in South Africa

Methodology

The overall program that this work fits into is generally based on bringing solutions into mine water problems in South Africa. As a part of that, this task is aimed at scientifically quantifying and apportioning pollution sources from mining activities. Several methods have been proposed over the past decade, such as principal component analysis/multiple linear regression, tracer and isotopic techniques and numerical modelling (Cowie *et al* 2014). Owing to the complexity of mining water environments, regulators and decision makers are often confronted with significant challenges in their efforts to manage the full scope of water resources. Characterisation of the spatial variations and source apportionment/determination of water quality variables (analysis using piper, stiff, SAR and duvor diagrams) offers an improved understanding of the environmental conditions and can help researches to establish priorities for sustainable water management.

Tracer techniques

Tracer tests are used to investigate the hydrodynamic parameters or interconnections of groundwater flow, however, the use of tracers in flooded mines to monitor the hydrodynamics of groundwater is a field that still requires exploration. Tracers are classified into environmental/natural and artificial. Environmental tracers are ambient, natural or artificial compounds widely distributed in the earth's near-surface. They may be injected naturally into the hydrological system from the atmosphere at recharge and/or are added/lost/exchanged inherently as waters flow over and through materials (Elliot 2004). In flooded underground mines, both types of tracer tests can be used to evaluate flow paths and seepage of water, connections from the surface to the mine (Wolkersdorfer 2002).

Wolkersdorfer (2008) reported that in some countries, such as Germany, there are regulations that govern the use of tracers because water has to be managed for the security of the general public and in accordance with the welfare of individuals. Although tracer tests may have been conducted locally by academic institutions, mining houses, etc. the information is not freely available for review or is rarely published. Internationally, more and more publications on tracer tests are developing. In a tracer test review by Davis *et al*. (1994) it was noted that although there are two types of tracers, natural and artificial, it is importance to collect sufficient data in order to assess the compatibility of a tracer with the environment and tracers needs verification.

Fluorescent dyes are often used as an applied tracer, with the use of fluorescent dye to trace groundwater dating back to at least 1877 when sodium fluorescein (uranine) was used to evaluate the connection between the Danube River and the Aach spring (Käß, 1998). Fluorescent dyes are commonly chosen applied tracers for groundwater studies in areas with low clay content. Recent studies have found dye tracers to work well both in karst and fractured crystalline rock settings (Himmelsbach, *et al*, 1995). However, the use of such dyes is problematic in AMD, because below a pH of 6, the sorptivity of uranine increases and its fluorescence intensity diminishes. Smart and Laidlaw, 1977 demonstrated that the fluorescence of uranine may be reduced by as much as 50% below a pH of 5. An additional difficulty in dye tracer application in groundwater and mine systems is accurately quantifying the mixing reservoir. The reservoir represents all waters (mine pools and inflows of surface and groundwater) with which the tracer could mix between the injection point and the sampling point and which will influence the mass of tracer applied in order to produce appropriate dye concentrations in collected samples. If the mixing reservoir is overestimated, the resulting dye concentrations may become toxic or exceed the dynamic range of the instruments, whereas an underestimated reservoir will result in low dye concentrations, possibly below analytical detection. Therefore, a multiple tracer approach is often recommended for complex hydrologic settings with a limited access point and unknown flow-through times, especially when fieldwork time and logistical support are limited (Wolkersdorfer, 2008).

Isotope techniques

The variability of isotope ratios has proved valuable when studying a wide variety of geological and environmental problems. The study of Pb isotopes, in particular, has been applied to problems such as determining the source and extent of anthropogenic Pb contamination in a variety of environments (Chow and Johnstone 1965, Patterson *et al*. 1976, Monna *et al.* 2006, Coetzee and Rademeyer 2006). Stable isotope ratios in water ($\delta^{18}O$ and $\delta^{2}H$) are used to understand the origins of water in various environments (Clark and Fritz 1997). Isotopes of water are generally non-reactive in aquifers over relatively short time scales. At the surface, isotopic signatures of water can be altered by evaporation and, in the subsurface, isotopic signatures of water may be altered over long time scales by geothermal exchange and water-rock interactions (Clark and Fritz 1997). Studies have demonstrated the use of isotopes in order to understand water sources in mining environments (Cowie *et al* 2014) and in fractured-rock aquifers.

Multivariate statistical analysis

The effectiveness of the application of multivariate statistics to any problem in the geosciences field is a function of data availability. Many areas in South Africa suffer problems in respect of data scarcity, and a lack of effective monitoring of water resources remains a problem. However, the coal fields have received considerable attention over the past years and substantial amounts of data have been generated in the process of mine operations and closures. Multivariate analysis techniques are very useful in the analysis of data corresponding to a large number of variables. Analysis using these techniques produces easily interpretable results. Multivariate data consist of observations on several variables for a number of samples (sample vectors or individuals). Data of this type arise in all branches of science, ranging from physiology to biology, and methods of analysing multivariate data constitute an increasingly important area of statistics.

Various multivariate analysis techniques are available. The choice of the most appropriate technique depends on the nature of the data, the problem and objectives. The underlying theme of many multivariate analysis techniques is simplification. One fundamental distinction between the techniques is that some analyses are primarily concerned with relationships between variables, while others are primarily concerned with relationships between samples. Techniques of the former type are called variable directed, while the latter are called individual directed (sample directed) multivariate analyses. In the analysis of dependence between variables, if the variables do not arise on an equal footing, multivariate regression analysis is recommended. The multivariate statistical techniques such as cluster analysis (CA), factor analysis (FA), principal component analysis (PCA) and discriminant analysis (DA) have widely been used as unbiased methods in the analysis of water quality data for extracting meaningful information (Helena *et al* 2000). The multivariate treatment of data is widely used to characterizse and evaluates surface and freshwater quality and it is useful for evidencing temporal and spatial variations caused by natural and anthropogenic factors linked to seasonality (Helena *et al* 2000). Cluster analysis is useful in grouping objects (cases) into classes (clusters) on the basis of similarities within a class and dissimilarities between different classes. The class characteristics are not known in advance but may be determined from the analysis. The results of CA may be used to interpret the data and indicate patterns (Vega *et al* 1998). FA, which includes PCA is a very powerful technique applied to reduce the dimensionality of a data set consisting of a large number of interrelated variables, while retaining as far as possible the variability present in data set. This reduction is achieved by transforming the data set into a new set of variables, the principal components (PCs), which are orthogonal (non-correlated) and arranged in decreasing order of importance. Mathematically, the PCs are computed from covariance or other cross-product matrices, describing the dispersion of the multiple measured parameters to obtain eigenvalues and eigenvectors. Principal components are the linear combinations of the original variables and the eigenvectors (Wunderlin *et al*., 2001). In contrast to the exploratory features of CA, DA provides the statistical classification of samples and is performed with prior knowledge of membership of objects to particular group or cluster (such as the temporal or spatial grouping of a sample which is known from its sampling time or site). In addition, DA is useful in grouping the samples sharing common properties. Although not as common as CA and FA/PCA, DA has recently been applied successfully to water quality sets (Wunderlin *et al*., 2001) and other data sets.Hierarchical cluster analysis (HCA) is commonly applied to classify observations so members of the resulting groups are similar to one another but distinct from other groups (Lambrakis *et al*., 2004 and Thyne *et al*., 2004). This method possesses a small space distorting effect, uses more information on cluster contents than other methods, and has been proven to be an extremely powerful grouping mechanism (Lambrakis *et al*., 2004).

Case study

A study area has been identified in eMalahleni, about 100 km east of Pretoria in the Mpumalanga Province. The site comprises a number of coal mines that were abandoned in the early–late 1950s, including the Transvaal and Delagoa Bay Colliery, the Middleburg Steam Coal and Coke Colliery and the Douglas No. 1 and 2 Collieries. The site is found in the Upper Olifants subarea of the Olifants Water Management Area (B11 catchment) in Quaternary catchment B11K. Two major streams flow through the catchment, the Brugspruit (from south to north of the catchment passing through the Transvaal and Delagoa Bay Colliery) and the Klipspruit (which drains into the Brugspruit towards the north of the catchment. Towards the east of the catchment, the Blesbokspruit stream drains into the Klipspruit. The land has not been utilised for some time, owing to ground instability, although recently opencast coal mines have been developed on some of the previously mined sites, to extract coal left behind in the earlier mining phase. The area is covered with a grassland type biome (and alien species such as *Acacia mearnsi* and *Eucalyptus globulus*) and covered with sandy-clayey and clay soils.

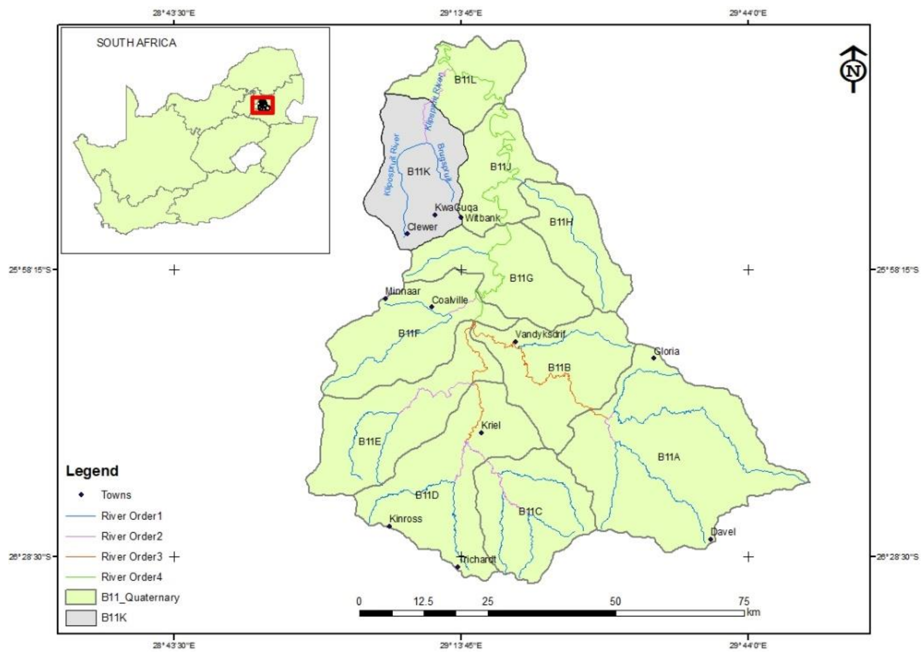

Figure 1: *Location map for B11K quarternary catchment*

The overall aims of this study are to:

- Develop an effective methodology/technique for conducting tracer tests in South African coal mine waters.
- Identify a tracer (environmental/artificial) that will be ideal to be used in mine waters characterised by high metal content and high acidity without local environmental interference.

- Determine the velocity of groundwater flow to determine possible contaminant transport and flow characteristics of the study area
- Investigate if there is any connectivity between the underground workings of site identified using tracers

Surface and groundwater sampling points were selected for the purpose of understanding the background of the study area of which preliminary water assessment and study area delineation was conducted. Physico-chemical data and water sampling is conducted quarterly and samples are analysed by ICP-MS and IC. Table 1 provides averages of physico-chemical and some major chemical data collected from different sampling points in and around a flooded and abandoned coal mine. This was done to classify the different water type as a pre-assessment for using tracer techniques. Our preliminary results demonstrated that the water samples collected have high concentrations of minerals such SO_4, Cl, Na, Mg, Al, K, and Ca.

***Table 1** Analytical results for the samples used in this study*

Sample ID	pH	EC	TDS	HCO_3	Ca	K	Mg	Na	Cl	SO_4
		uS/cm	mg/L							
SINKHOLE	7.0	3490.0	2243.5	67.7	182.8	72.9	110.4	10243.7	58.3	14494.8
BOREHOLE	5.0	4330.0	2783.5	0.000	161.3	118.4	66.2	8039.7	115.5	8637.3
7 SEEPAGE	7.5	659.0	423.6	106.2	39.9	5.9	26.7	27.5	12.0	110.6
T-DB	5.0	12423.0	7985.9	0.0	390.1	38.5	179.6	2248.5	60.1	4646.5
9 SEEPAGE	4.5	9969.0	6408.4	0.0	345.4	34.4	183.7	2881.2	146.3	-
DAM	4.0	1852.0	1190.5	0.0	106.4	3.6	70.1	9.6	1.80	247.7
14 WEIR	3.5	2404.0	1545.4	0.0	144.1	7.1	96.7	78.4	29.3	970.8
13 WEIR	3.5	2404.0	1545.3	0.00	116.4	6.	74.6	55.4	19.7	904.2

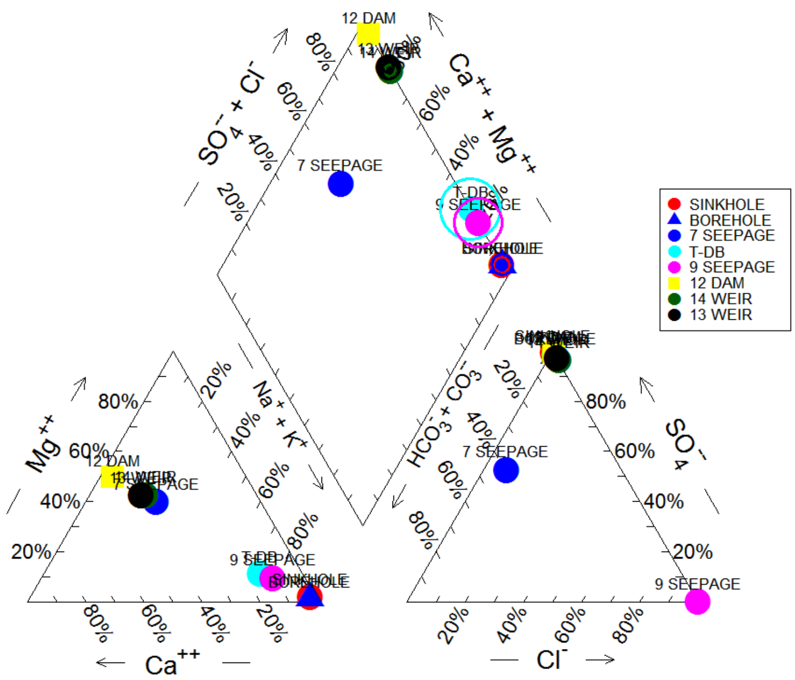

***Figure 2:** Piper diagram for samples collected in the T&DB Area.*

Preliminary water assessment and classification have demonstrated that the samples collected towards the south (13 Weir, 14 Weir and 12 Dam) of the study area, have a dominant Mg-Ca-SO_4 water type, while those collected towards the north (Sinkhole, 2Borehole and T-DB) having a Na-SO_4 water type and samples collected towards the centre displaying mixing (*fig 2*).The distribution of the water chemistry on the stiffs (*fig 3*) for the Mg-Ca-SO_4 shows a similar trend but with an introduction of magnesium and calcium at the T&DB shaft.. The water collected from the dam and weirs have a similar distribution of water chemistry with elevated magnesium and calcium concentrations.

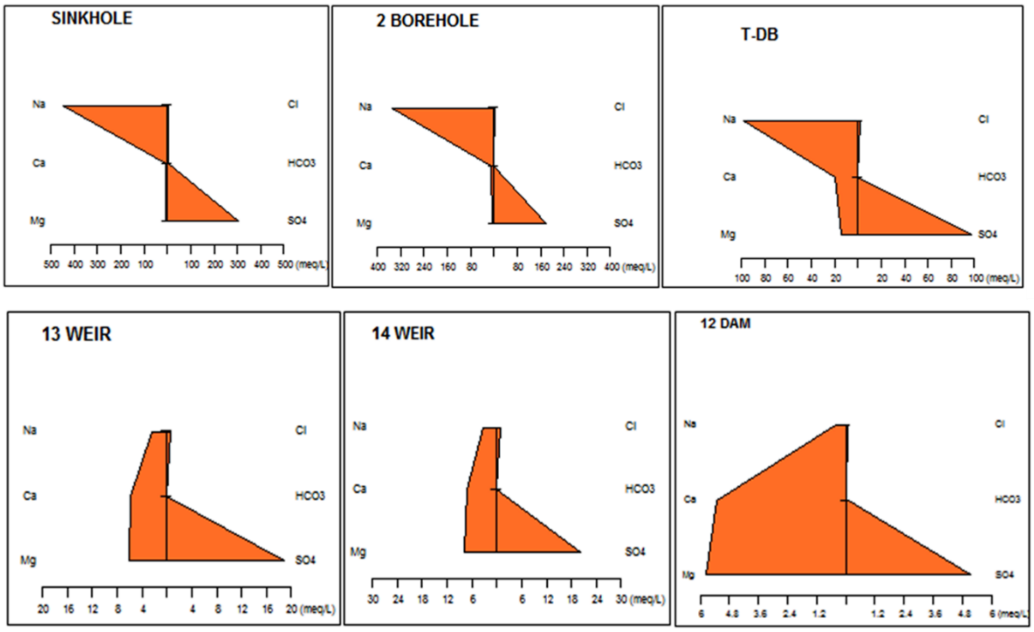

Figure 3: *Stiff diagram for samples collected from the sinkhole, borehole and T&DB which are classified as having Na-SO_4 type of water.*

The second phase will seek to scientifically quantify the environmental risks associated with existing and historical mining activities and therefore look at applying the following elements and techniques:

- Source identification using geochemical and solute mass transport modeling,
- Stable isotope analysis of $\delta^{18}O$ and $\delta^{2}H$ and multivariate statistical analysis
- The use of natural and applied tracers to guide targeted remediation efforts in acid mine drainage systems.

Conclusion

The case study is a baseline for understanding the different types of waters discharging at an abandoned coal site. Using tracer techniques we can characterize the sub-surface and surface water in terms of geochemistry, estimate its flow and storage properties, which are vital aspects in mine water management, treatment and remediation. Using tracers in a complex mining environment requires an integrated approach. This can have the added benefit of identifying targeted remediation strategies that address the feasibility of actually reducing or eliminating the generation of AMD at its source. It is critical for a mine water tracer study that the conceptual models and the associated water balance calculations are correct. These factors will be verified during phase 2 of the present project, which will deal with more data collection. The ultimate goal will be to develop a tool that can be used for mine water management at a local scale.

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