Hydrogeological investigation of the Witbank, Ermelo and Highveld Coalfields: Implications for the subsurface transport and attenuation of acid mine drainage

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Abstract A hydrogeological investigation on coalfield scale was done using available regional data and spatially spaced monitoring boreholes in order to understand the movement of Acid Mine Drainage (AMD) within the soil, vadose zone and aquifers and predict future impacts of surface coal mining activities for planners and regulators. A data-driven GIS artificial neural network was built using hydrogeological and geochemical parameters to produce AMD transport and attenuation factors for the Witbank, Ermelo and Highveld Coalfields. The transport and attenuation factors produced demarcate the coalfields in terms of the expected rates of transport and attenuation of AMD in the subsurface.

Key words Acid mine drainage, vadose zone, soil, transport, attenuation, artificial neural network

Introduction

Mining in South Africa, particularly coal mining, has been the cornerstone for economic development and has contributed significantly to the industrial development of the country. The call to decrease the world's dependence on coal as an energy source is reasonable, since lowering its use would reduce greenhouse gas emissions and environmental impacts associated with coal mining. Considering the benefits of coal mining to the South African economy and the recent global developments focused on the mitigation of environmental problems associated with coal production and use (carbon capture and storage, clean coal technologies and best practice environmental management options for mining and coal waste disposal), it is expected that coal will remain a major component of the South African energy mix for many years.

This paper focuses on coalfield-scale hydrogeological studies on the movement of acid mine drainage within the soil, vadose zone and aquifers. Hydrogeology is useful in understanding the natural subsurface movement and attenuation of Acid Mine Drainage (AMD) and for the future prediction of impacts due to the introduction of AMD on surface by future coal mining activities. The generation of AMD begins with the diffusion of oxygen into moist or wet reactive waste rock, tailings dumps or ore bodies. Sulphide minerals such as pyrite and pyrrhotite found in host rock are then oxidised to form an acidic solution with elevated sulphate concentrations and iron hydroxides. The low pH environment remobilise toxic heavy minerals in solution which can migrate both to the surface and to groundwater resources (Bell 2001).

The study area covers the Highveld, Ermelo and Witbank Coalfields located in the Mpumalanga Province of South Africa, covering an area ~ 23 315 km2 (fig. 1). The area receives an average long-term rainfall of between 600 to 1100 mm (SAWS 2016). Geological information used in this study is based on the 1:250 000 geological maps published by the Council for Geoscience (fig. 1). The study area consist eight major lithological domains namely; the Basement Complex, Witwatersrand Supergroup, Transvaal Supergroup, Bushveld Complex, Dwarsfontein Complex, Waterberg Group, Karoo Supergroup and Tertiary–Quaternary alluvial deposits. Du Toit and Sonnekus (2014) used geology to classify aquifers within the study area into four types (intergranular, fractured, intergranular-fractured and karst). The intergranular-fractured aquifer type is the most dominant type found within the Witbank, Ermelo and Highveld Coalfields and is very shallow, ranging between depths of 5 m and 20 m, making it susceptible to pollution due to coal mining (Hodgson and Krantz 1998). This high susceptibility to pollution necessitates an understanding of the processes that controls the movement and attenuation of AMD, as well as delineating spatially areas where these processes can occur.

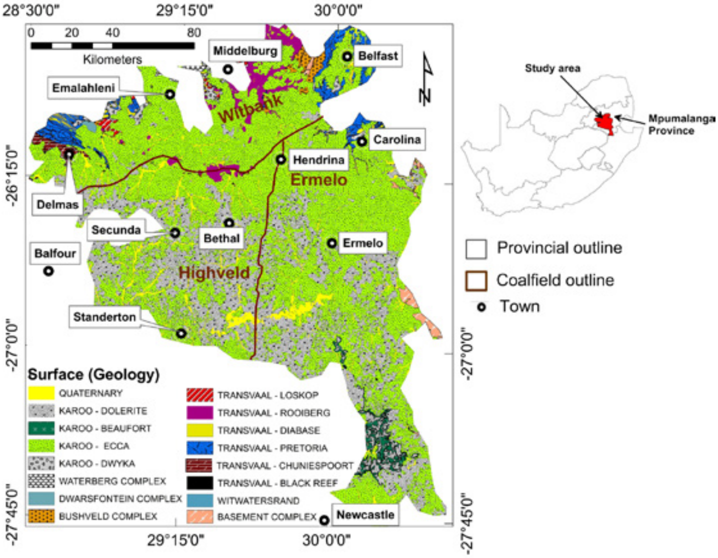

***Figure 1** Geological setting of the study area (CGS 2017).*

The aquifer system itself plays a role in transport and attenuation of AMD through processes such as dilution and other physical and chemical processes where its hydraulic conductivity controls the ease with which pollution migrate through it (Aller et al. 1987). Values for hydraulic conductivity for the various aquifers in the study area were extracted from Barnard (2000) with the fractured and intergranular-fractured types in the order of 10^{-11}, karst 10^{-4} and intergranular sandy aquifer in the order of 10^{-2} m/s.

Materials and Methods

Factors that affect AMD transport and attenuation in soil, vadose zone and aquifer were investigated in this paper. Data relating to the selected factors (soil clay content, soil thickness, preferential pathways (faults, fractures), vadose zone permeability and aquifer hydraulic conductivity) which are readily available at coalfield-scale from various government agencies was used. This paper deals only with AMD from surface sources (tailing dumps, waste-rock discard dumps) where soils controls the initial transport of AMD pollution but does not deal with underground and opencast pits sources. Aquifers underlying soils with physical, chemical and biological properties that promote the sorption of pollutants are considered less vulnerable to pollution (Mongwe and Fey 2004). The permeability and infiltration rates of soils are affected by various processes like roots, soil fauna, soil types and degree of compaction related to land-use. In this paper, only the soil clay percentage was used as clay play a vital role in pollution sorption processes. Soils with high clay content have small pore spaces that reduce permeability and infiltration rates (Mongwe and Fey 2004) which in turn increase the residence time for adsorption of pollution. Of particular importance for water quality of percolation seepage into the subsurface and groundwater is the cation exchange capacity as well as the buffer capacity and pH of the soil. According to soil studies by Lambooy (1984), there is strong positive correlation between clay content and cation exchange capacity for South African soils. For the study area, soil pH and buffering capacity could not be obtained that covers the entire coalfields, hence only clay content was used. Soil data covering the study area at a scale of 1:250 000 was obtained from the Agricultural Research Council Institute for Soil, Climate and Water (ARC-ISCW 2015).

The vadose zone is the unsaturated zone between the surface and the water table which controls the residence time available for the subsurface to interact with the water and pollution. The larger the thickness and the lower permeability of the vadose zone, the higher the possibility of natural attenuation of the pollutants. The vadose zone thickness is referred to as the depth to water table in this paper which was generated from monitoring boreholes from the South African Department of Water and Sanitation (NGA 2015). On a regional scale, zones of weakness within the subsurface include regional faults and fractures which can offer easy passage of pollutants. Information on these geological features was extracted from geological maps and geophysical interpretation maps published by Council for Geoscience on a scale of 1:250 000 (CGS 2017). Reactivity of rocks with AMD is another parameter considered as different rocks reacts differently in AMD environment. Various laboratory studies (column leach test, XRD and XRF) and kinetic simulations conducted on different types of rocks, revealed that rocks containing carbonate minerals (dolomites) buffer the acidity better than rocks without these minerals, such as silicate rocks (Lapakko 1994).

In selecting the parameters to be used for modelling, spatial association between the available map layers and boreholes with sulphate concentration (> 200 mg/L) was done. This was done based on the assumption that only those parameters which are spatial associated with high sulphate boreholes are somewhat related to AMD transport and attenuation. Spatial association test involves measuring the degree to which things are similarly arranged in space (Carranza 2002). The distance distribution method by Bonham-Carter (1994) was used for the spatial association test. In the method, cumulative frequency distribution curve for each input layer (soil clay content, distance to preferential pathways, aquifer hydraulic conductivity values, depth to water table and AMD-rock reactivity relative value) at every map location (E) is plotted against the layer value and on the same graph cumulative frequency distribution curve for every high sulphate borehole (O) plotted against the layer value. The difference between these two values at each layer value shows the spatial association where a positive difference (O>E) shows positive spatial association, negative difference (O<E) shows negative spatial association and no difference (O=E) shows independent or no association. According to Carranza (2002), only those layers with an overall positive association are statistically spatially related and negative and/or independent spatial association layers should not be used for modelling geospatial data. Of the six layers tested; soil clay content (fig. 2a), preferential pathways (fig. 2c), vadose zone permeability (fig. 2d), aquifer hydraulic conductivity (fig. 2e), depth to water table (fig. 2f) and AMD-rock reactivity (fig. 2g) show positive difference meaning there is a good positive spatial association with location of boreholes with high sulphate values. The difference curve for soil thickness is negative showing negative spatial association between soil thickness and high sulphate in groundwater (fig. 2b). Based on the spatial association tests, only these parameters that show positive spatial association (clay content, vadose zone permeability, preferential pathways, aquifer hydraulic conductivity, depth to water table and AMD-rock reactivity) were selected for modelling (fig. 3). The transport factor is a term referring to a map product generated by combining selected surface and subsurface properties that controls the movement of AMD. The attenuation factor is a term referring to a map product generated by combining selected surface and subsurface properties that attenuate AMD from reaching the groundwater.

Artificial Neural Networks

Artificial neural networks (ANNs) belong to the data-driven branch of artificial intelligence which is inspired by the biological neural system whereby the computer is trained to do the functions which at the moment humans do best like learning (Shigidi and Garcia 2005).

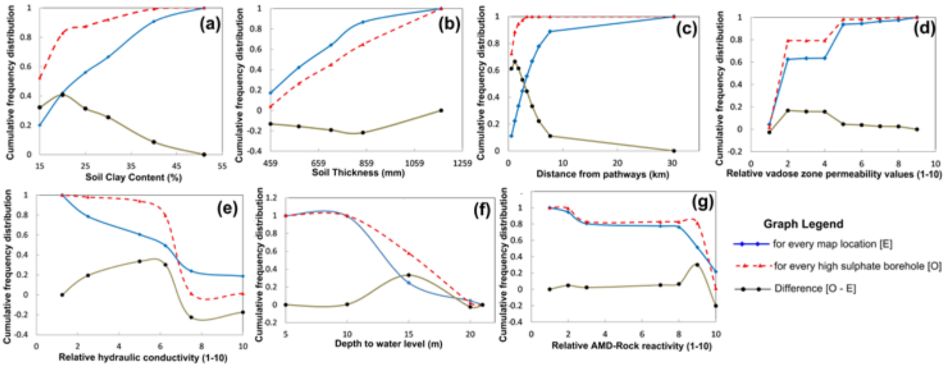

Figure 2 *Distance distribution curves for (a) soil clay content (b) soil thickness (c) distance from pathways (d) Vadose zone permeability (e) aquifer hydraulic conductivity (f) depth to water level (g) AMD-Rock reactivity.*

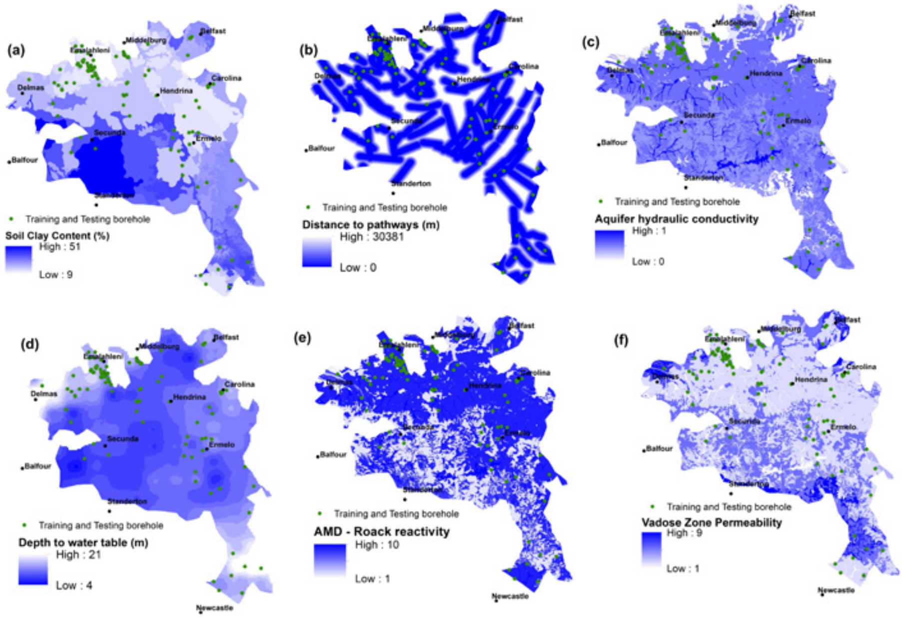

Figure 3 *Modelling input parameters (a) soil clay content (b) distance from pathways (c) aquifer hydraulic conductivity (d) depth to water level (e) AMD-Rock reactivity (f) Vadose zone permeability.*

The ANNs are trained to extract the general relationship between the input layers and given outputs by giving them a set of examples from which to learn from and store these relationships. After which, the trained ANN is given a set of input layers from which it produces an output based on the stored relationships. The ANNs are made up of input layers that are fed into hidden layers and ultimately connected to the output layer which produces an output response (fig. 4). During training, data is fed into the input layer which communicates to one or more 'hidden layers' where the actual processing is done via a system of weighted 'connections'. ANNs contain some form of 'learning algorithm' which modifies the weights of the connections according to the input patterns that it is presented with (Shigidi and Garcia 2005). In a sense, ANNs learn by example like a child learns to recognize dogs from examples of dogs. In this paper, the learning rule used was the most commonly used learning algorithm; the backpropagation algorithm which basically means that learning is done by backward propagation of the error generated when the training output value is compared with the example output. This process is done repeatedly by modifying the weights until the error is very minimum, thus the ANN would be termed 'trained' and ready for prediction of a correct output from a given a set of new input data. The efficiency in training is dependent on the number of hidden layers. For the study area, the number of hidden layers was estimated using a method by Shigidi and Garcia (2005) and seven hidden layers were found to optimum for both transport and attenuation factors (fig. 4). In the paper, parameters which are spatially associated with high sulphate concentration boreholes (soil clay content, preferential pathways, aquifer hydraulic conductivity) were used as ANN inputs for the transport factor, while the depth to water table, vadose zone permeability and AMD-rock reactivity were used as ANN inputs for the attenuation factor (fig. 4). In both cases the sulphate concentration in groundwater was used as a training output parameter.

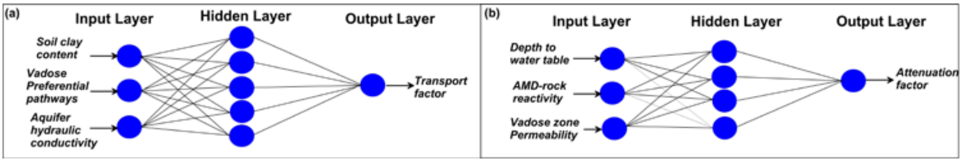

Figure 4 *Architecture of the ANN used for a) transport factor and b) attenuation factor.*

Results and discussions

The 130 groundwater samples from boreholes scattered throughout the study area were partitioned into 75 % for training and 25 % for testing of the ANN systems. The ANN was trained using sulphate concentration values in groundwater where areas with high sulphate values above 200 mg/l the target quality for drinking water (DWAF 1996) were used as polluted sites and low sulphate values below 200 mg/l as non-polluted training sites. After training, the ANN was used to predict values of the set of boreholes not used in training (testing boreholes). The difference between the predicted and the actual values of the testing samples is the testing error which is used to evaluate the accuracy of the training process and to determine the optimum number of iterations (epochs). The minimum training error of 0.0049 and 0.0034 was archived after 100 epochs for transport and attenuation factors (fig. 5a and 5b). The trained ANNs were then used to generate the transport and attenuation factors for the study area (fig. 5c and 5d).

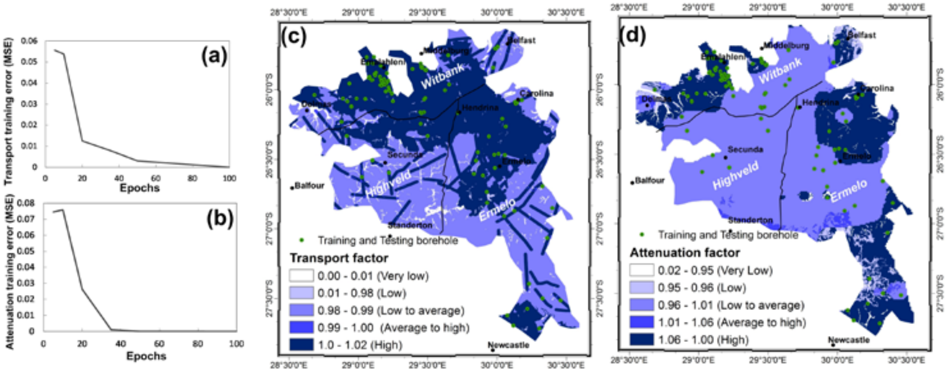

Figure 5 *Training graphs for (a) transport factor (b) attenuation factor and modelling results showing the (a) transport factor and (b) attenuation factor.*

The transport factor model shows that area between Emalahleni and Ermelo is marked by high transport factor values due to soils with low clay content, high density of pathways coupled with aquifers with higher hydraulic conductivity. Aquifer systems within the high transport factor zones are more susceptible to AMD pollution due to ease of AMD migration. The Delmas, Ermelo, Carolina areas, as well as the southern areas, are marked by high attenuation factor values due the presence of a thicker vadose zone, higher vadose zone permeability values and rocks with higher AMD-rock reactivity. This means that these parameters together reduce the likelihood of AMD from reach the groundwater, thus to say there is good AMD retention. In general the aquifer systems found in areas with high transport and low attenuation factors are more susceptible to pollution. The transport and attenuation models were validated using dataset which was not used in the modelling process i.e. pH data. Acid mine drainage is associated with high sulphate concentrations and low pH. Data from boreholes within the study area was used to produce a scatter plot of sulphate and pH. The results show a strong negative correlation; hence pH which is a sensitive indicator for AMD was used for model validation fig. 6a). The spatial association test was used to check if the generated models are spatially correlated with boreholes with pH values lower than 5. The spatial associated test reveals a very strong spatial association between pH and both transport and attenuation factors (fig. 6b and 6c).

Conclusion and recommendations

The ANNs were successfully used to produce the transport and attenuation factors for the Witbank, Ermelo and Highveld Coalfields using parameters which show positive spatial association with high sulphate in groundwater. The transport and attenuation factors demarcated areas in terms of the transport and attenuation of AMD in the subsurface. Further field verification is recommended over areas demarcated as high transport and low attenuation factors.

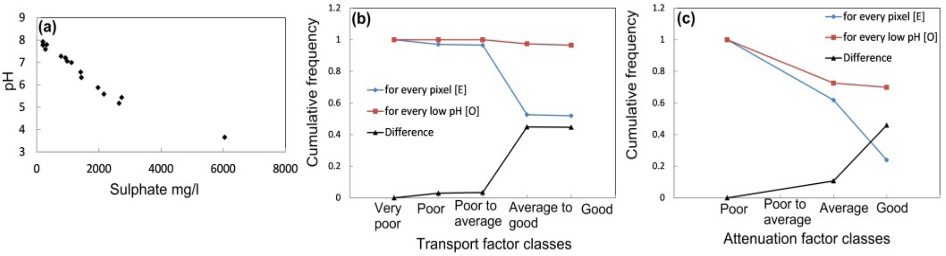

Figure 6 *(a) Sulphate – pH relationship, validation results for (b) transport and (b) attenuation factors.*

The results can be used to help policy and decision makers to make scientifically informed decisions for future land use planning of the coalfields. The datasets used in this study are readily available from various governmental agencies making the approach cost-effective in evaluating the AMD coalfield-scale subsurface transport and attenuation. The approach developed in this paper can be tested on other coalfields with similar or different hydrogeological settings to determine its robustness. The approach only considers the AMD pollution at a regional scale and cannot be used for a local point sale analysis where a specific site assessment is recommended.

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