A Source Apportionment Methodology for South African Gold Mines

Ingrid Dennis[1], Rainier Dennis[1], Michael Eckart[2] and Christoph Klinger[2]
1. *Centre for Water Sciences and Management, North-West University, South Africa*
2. *DMT GmbH & Co. KG, Germany*

ABSTRACT

South Africa is faced with the legacy of environmental impacts due to gold mining activities which have taken place over 120 years in the Witwatersrand region. Over time, as economically exploitable gold ores have been depleted, progressive cessation of mining operations has taken place. Gold mining has caused considerable changes to the surface and subsurface water flow pathways. This is due to the influence of historical surface operations, shallow sub-surface mining and deep underground mine excavations. The generation of acid mine drainage as a result of the oxidation of pyrite and other metal sulphides associated with the gold ores has caused acidic mine water with a lowered pH, elevated levels of sulphate, and elevated concentrations of mobile toxic metals. The management of the acid mine drainage poses a major challenge. A vital question is: Who is responsible for the resultant environmental management and clean-up?

The approach adopted for the study is one that involves an integrated modeling methodology. The following elements and techniques are included: source identification, geochemical, solute mass and transport modeling, geochemical speciation and kinetic modeling. Use is made of environmental cost accounting so that the scientific source identification and apportionment findings can be expressed in terms of monetary values. The current study seeks to scientifically quantify the environmental risks associated with existing and historical gold mining activities, identify the parties whose activities are responsible for impairment of water resources, and to translate these in terms of responsible parties' respective contributions according to the "polluter pays" principle.

Keywords: Source Apportionment, Integrated Modeling Approach

INTRODUCTION

South Africa is faced with the legacy of environmental impacts due to gold mining activities which have taken place over 120 years in the Witwatersrand gold mining region. Over time, as economically exploitable gold ores have been depleted and progressive cessation of mining operations have taken place. Gold mining over this period has caused considerable changes to the surface and subsurface water flow pathways. This is due to the influence of historical surface operations, shallow sub-surface mining and deep underground mine excavations. The generation of acid mine drainage as a result of the oxidation of pyrite and other metal sulphides associated with the gold ores has caused acidic mine water with lowered pH, elevated levels of sulphate, and elevated concentrations of mobile toxic metals.

The management of the acid mine drainage poses a major challenge and a vital question is: Who is to responsible for the resultant environmental management and clean-up? The source apportionment methodology is underlain by an integrated modeling approach. The impact of identified pollution sources are simulated and quantified at selected downstream points.

BACKGROUND

The South African Inter-Ministerial Committee (IMC) on Acid Mine Drainage (AMD), comprising the Ministers of Mineral Resources, Water Affairs, Science and Technology, and the Minister in the Presidency: National Planning Commission, appointed a team of experts to report on the assessment and reappraisal of the situation with respect to acid mine drainage, focusing on the Witwatersrand goldfields (Inter-Ministerial Committee, 2010).

AMD has been reported in the Western, Central and Eastern Basins (South Africa) were identified as priority areas. These areas require immediate action due to the lack of adequate measures to manage and control the problems related to AMD. The urgency of implementing intervention measures is necessary before problems become more critical. Another concern is the proximity of these problems to densely populated areas.

Pumping of groundwater from Grootvlei Mine in the Eastern Basin ceased in 2011 and mine flooding commenced. The mine historically maintained the mine water level in this basin at a depth of ~700 mbgl by pumping 75–108 Ml/d. Treatment of the mine water has not occurred for some time and an early casualty of the situation is Blesbokspruit, including a Ramsar-listed wetland (Inter-Ministerial Committee, 2010).

The South African government is compelled to provide long-term water treatment facilities for the decanting mine water. Treatment plants could include desalinization, through one of several treatment methods involving chemical precipitation, membranes (such as reverse osmosis), ion exchange or biological sulphate removal. All methods produce clean, potable water, but are costly and produce waste products of their own (Pratt, 2011). Associated cost recovery of treatment plants will have to be conducted through the "polluter pays" principle and therefore it is necessary to formulate a source apportionment methodology.

Study Area

The study area is located in the Gauteng Province of South Africa and covers the East Rand area, including the towns of Boksburg, Germiston, Brakpan, Benoni, Heidelberg, Springs and Nigel. In Mining terms the area is referred to as the East Rand Basin. Mining in the Eastern Rand portion of the Witwatersrand Goldfields started in about 1888 at the Nigel Mines and in 1892 at Van Ryn Estates, slightly later than the mines on the Central Rand. The mine lease areas in the basin cover about 768 km² as shown in Figure 1. It is important to note that the East Rand Basin is geographically, hydrologically and hydrogeologically different from the other Witwatersrand mined basins (Scott, 1995).
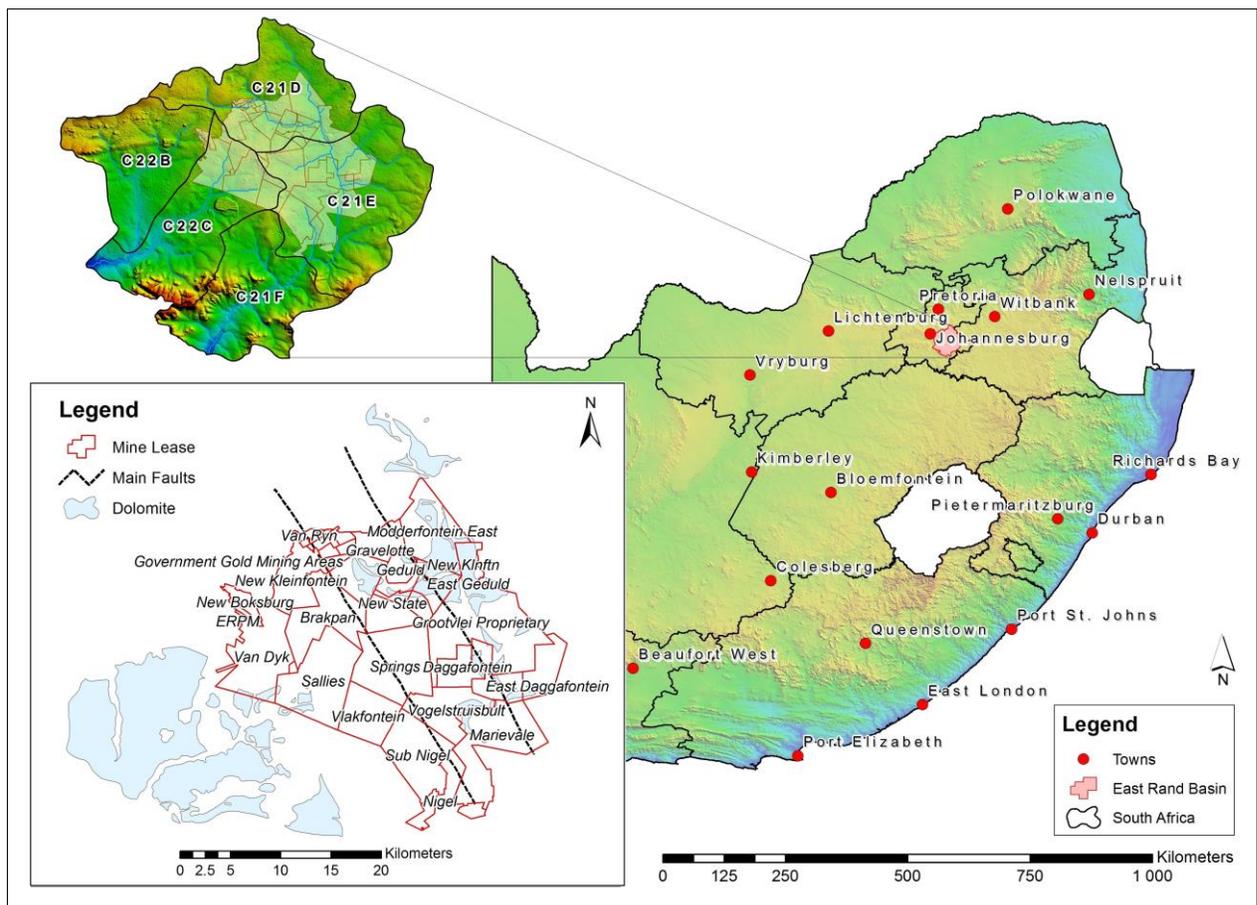
Figure 1 Locality map of the East Rand Basin

The surface catchment area considered comprises of five quaternary catchments (Figure 1): C21D, C21E, C21F, C22B and C22C. A summary of average hydrological values for each of the quaternary catchments are presented in Table 1. The two major drainage systems associated with the aforementioned catchments are the Blesbokspruit and the Natal/Rietspruit.

Table 1 Summary of average hydrological values for the study area (Middleton & Bailey (2005)

Quaternary	River	Catchment Area (km²)	MAP (mm/a)	MAR (mm/a)	MAE (mm/a)	Recharge (%MAP)
C21D	Blesbokspruit	446	698	36	1625	5.7
C21E	Blesbokspruit	628	691	35	1625	5.1
C21F	Blesbokspruit	426	704	38	1625	6.2
C22B	Natalspruit	392	692	32	1630	5.9
C22C	Rietspruit	465	684	31	1625	6.3

MAP – mean annual precipitation, MAR – mean annual rainfall, MAE – mean annual evaporation

Historic Mining

Mainly gold was mined in the area with selected coal deposits (mined via opencast pits). The gold reefs targeted were the Main, Kimberley and the Black Reef. The spatial extend of these mined-out reefs as well as a vertical profile is shown in Figure 2. Note the water level in the profile represents the shallow regional groundwater level and does not reflect the water level associated with the mine workings.
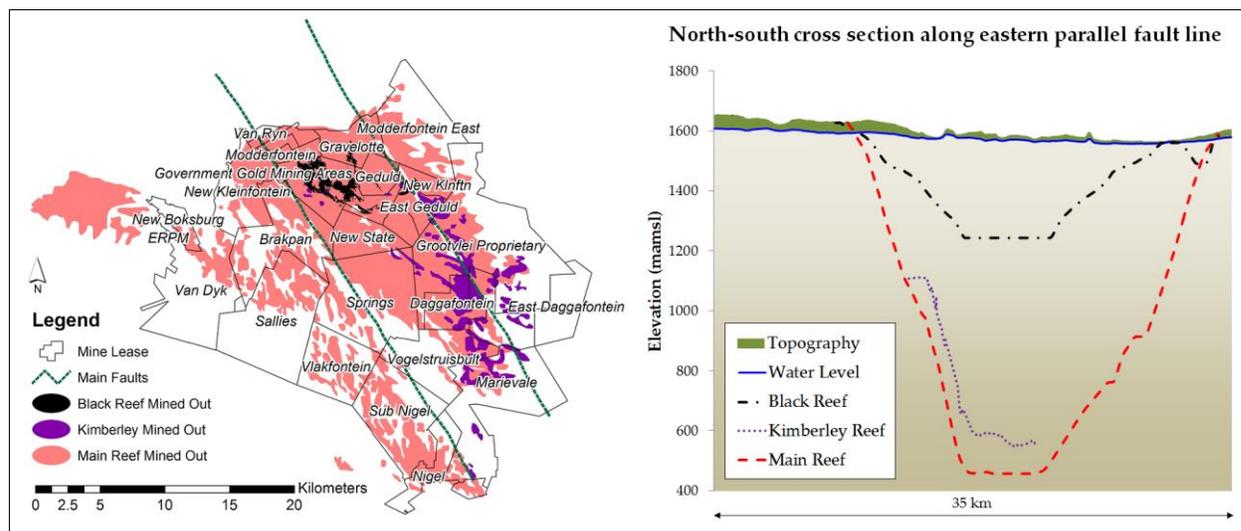
Figure 2 Mined out reefs of the East Rand Basin

METHODOLOGY

The source apportionment methodology relies on an integrated modeling approach between mine flooding, a regional groundwater model and a surface water model. Prioritization of sites and associated monitoring forms the bases of the aforementioned models. The methodology is discussed in more detail in the sections that follow.

Prioritization

A spatial approach was used to prioritize the different site types based on a site weighting given to each site. A regional model grid was used for this purpose and a layer was created for each site type e.g. tailing storage facilities (TSF), mines shafts, subsidence, dolomites, etc. A total of 13 different site types were used in the prioritization, where the resultant layer features were assigned a value of one. A zero value was assigned in the absence of these features. The priority for each grid cell was calculated as follows:

$$Priority = \left(\sum_{1}^{n} S_n W_n \right) \times DRASTIC \tag{1}$$

where n represents the number of sites types, S_n is the site value for the grid cell (zero or one) and W_n is the relative weight associated with the site type. The *DRASTIC* index (DWAF, 2006) is an index expressing the aquifer vulnerability between 1 and 200, where an index value of 200 expresses the highest aquifer vulnerability to possible groundwater pollution. Weights (W_n) applied in the prioritization is presented in Table 2. Note no weighting was assigned to the Dolomitic areas as these already form part of the DRASTIC index used.

Table 2 Summary of relative weights applied to site types in calculating priority

Site Type	W_n
Embankment	1
Pans	2
Dams, Reservoirs, Wetlands	3
Diggings, Excavations, Lineaments	5
Open Cast, Mine Shafts, TSF, Subsidence, Waste Water Treatment Works	10

The normalized prioritization map for the East Rand Basin is shown in Figure 3 together with selected pollution sources. Note that there are areas outside the mine lease area that received high prioritization. For the purpose of this study, the focus was on the prioritized areas within the mine lease area.
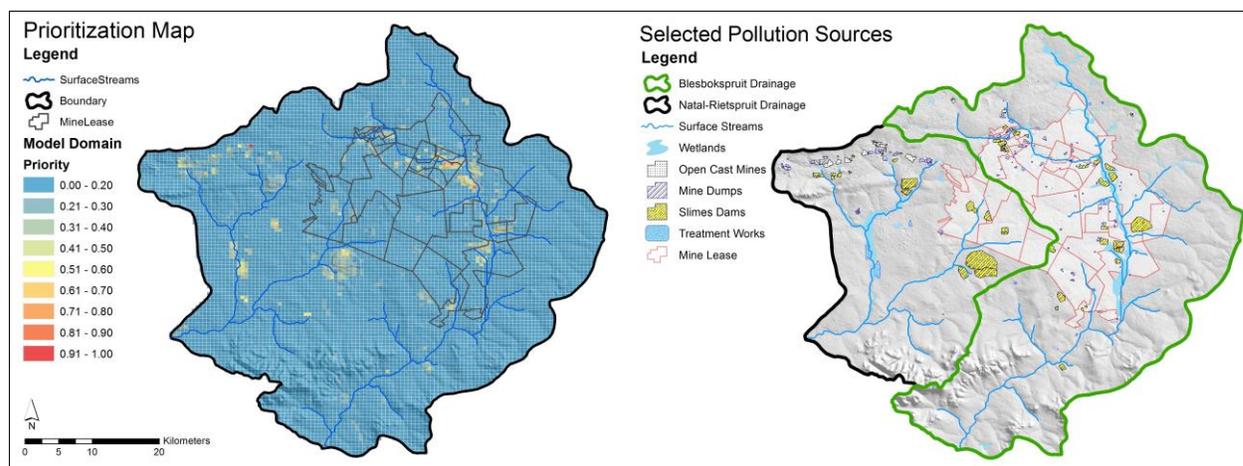
Figure 3 Normalized prioritization map and selected pollution sources of the East Rand Basin
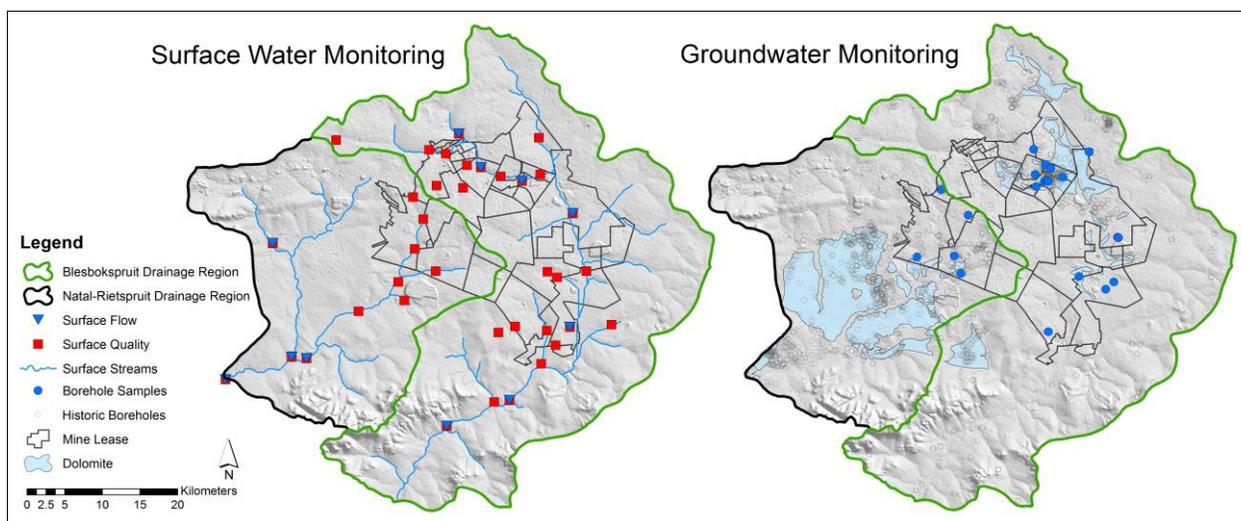
Monitoring

A monitoring network for both the surface and groundwater had to be established due to the fact that all mining operations, with the exception of the reworking of selected tailings storage facilities (TSFs), ceased and no active monitoring was taking place. Historic datasets and reports were consulted to select monitoring points that coincide as far as possible with historic monitoring points. Physical access to sites and appropriateness of sites dictated the location of monitoring points. The final monitoring networks for both surface and groundwater are shown in Figure 4.

It is clear from the groundwater monitoring network that numerous boreholes were drilled into the dolomites for water supply. The groundwater monitoring network focused on the immediate mine lease area and only few boreholes were found that formed part of the monitoring network.

Only a single weir exists within the mine lease boundary which has data from 1977 to 2004 after which monitoring of the flow gauge stopped. Surface flow measurements were conducted through surveying cross sections and measuring stage and flow velocity. The existence of large areas comprising of wetlands (Figure 3), specifically in the Blesbokspruit, posed challenges in flow measurements as the wetland acts as a buffer to flow. Often zero flow velocities were recorded within the wetland itself.

Three sampling campaigns were conducted during the course of the study, which included both a wet and a dry season. Each sampling campaign recorded surface flow and quality as well as groundwater levels and quality.

Mine flooding water levels with selected water quality measurements were being monitored at selected mine shafts by the South African Government and this data were used to calibrate the mine flooding model.

6

Figure 4 Surface and groundwater monitoring network

Source Term Determination

Material was sampled from the TSFs by making use of an auger. Samples were taken from the weathered and un-weathered zones. In storage facilities where the material is being reworked, samples were taken of the freshly exposed material. Samples were also taken from waste rock dumps.

In order to estimate the source terms that may impact on the study area, the risk sources were clustered based on their respective mineralogy. Geochemical models were developed for the various clusters types. Physical parameters of the heap that included geometry, particle size distribution, and saturation and oxygen concentration profiles formed part of the input to the geochemical models. In addition to this, the pore water composition was obtained through static leaching of the sampled materials. Humidity leach cell tests were performed in order to calibrate the numerical geochemical models.

A total of 18 TSFs and 12 waste rock dumps within the study area were sampled. A total of 9 source terms were determined for the nine cluster types determined for the TSFs and 8 source terms were determined for the waste rock dump clusters.

The spatial distribution of the TSFs and waste rock dumps are shown in Figure 3.

Model Concept

The mine hydrology, hydrogeology and surface hydrology of the area were modeled through the use of a surface run-off model, a regional groundwater model and a mine flooding model correspondingly. All three the aforementioned models are inter-connected to account for the total water balance and produce an aggregated system response. A graphic representation of the model framework is shown in Figure 5.
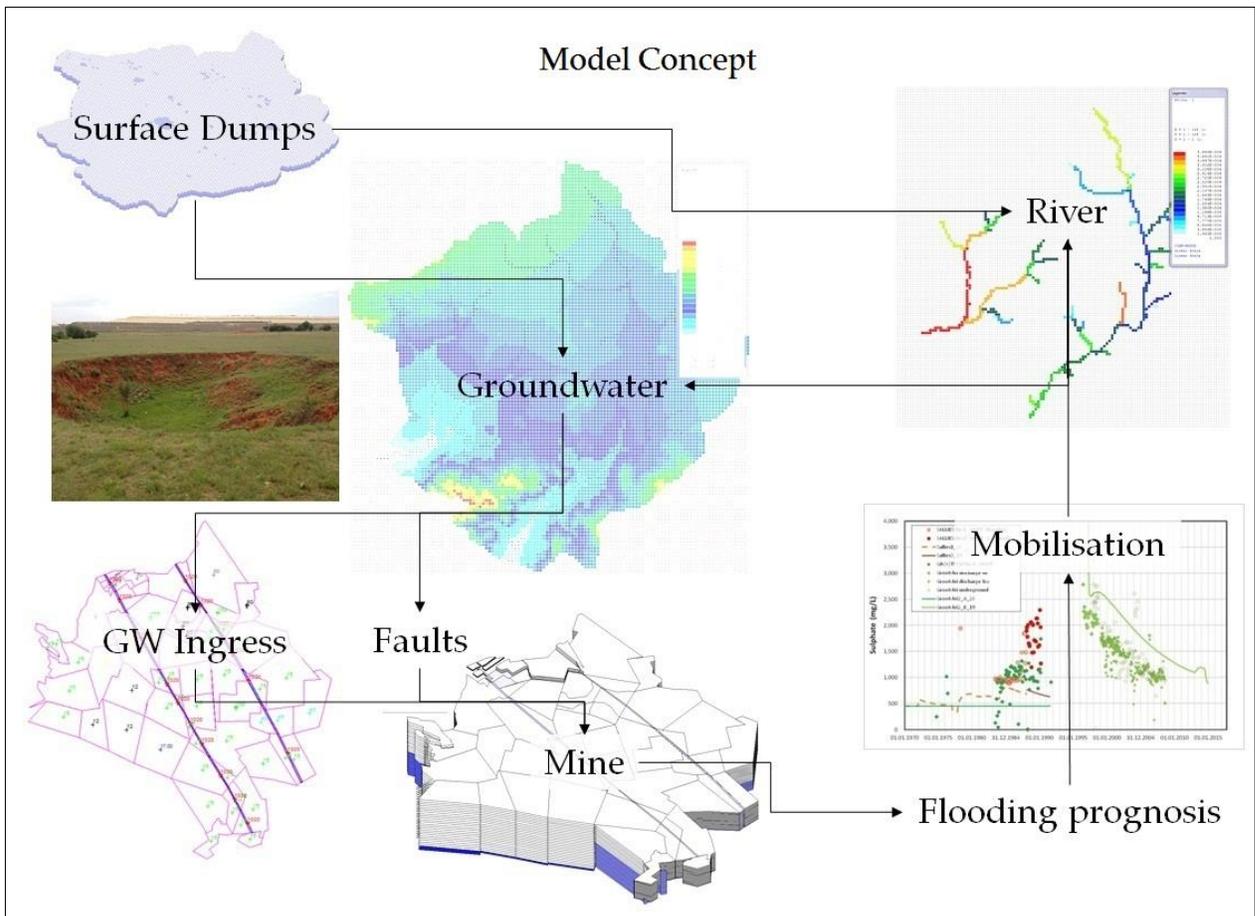
Figure 5 Source apportionment through an integrated modeling approach

The mine flooding model accounts for the two major fault lines running through the mine lease area (Figure 2) as well as areas of high ingress e.g. subsidence (Figure 5). The mine model is overlain by a multi-layer regional groundwater model onto which the surface pollution sources are added. The groundwater model grid size was chosen to ensure all TSFs and waste rock dumps were incorporated into the model.

The interface between the surface and groundwater model allows for surface-groundwater interaction which includes the decanting of mine water into the surface streams. The mine water decant to the streams can either be through surface runoff or via the shallow aquifer.

The source terms for the TSFs and waste rock dumps were included in the groundwater model.

Reactive mass transport modeling was applied in the mine flooding model and typical SO_4 results at the Grootvlei Shaft are shown in Figure 6.

In terms of the mass transport, the system was simplified to only consider sulfate as a conservative ion to track the pollution emanating from the various TSFs and waste rock dumps. The other major anion and cation movement can be modeled by making use of the associate geochemical modeling.
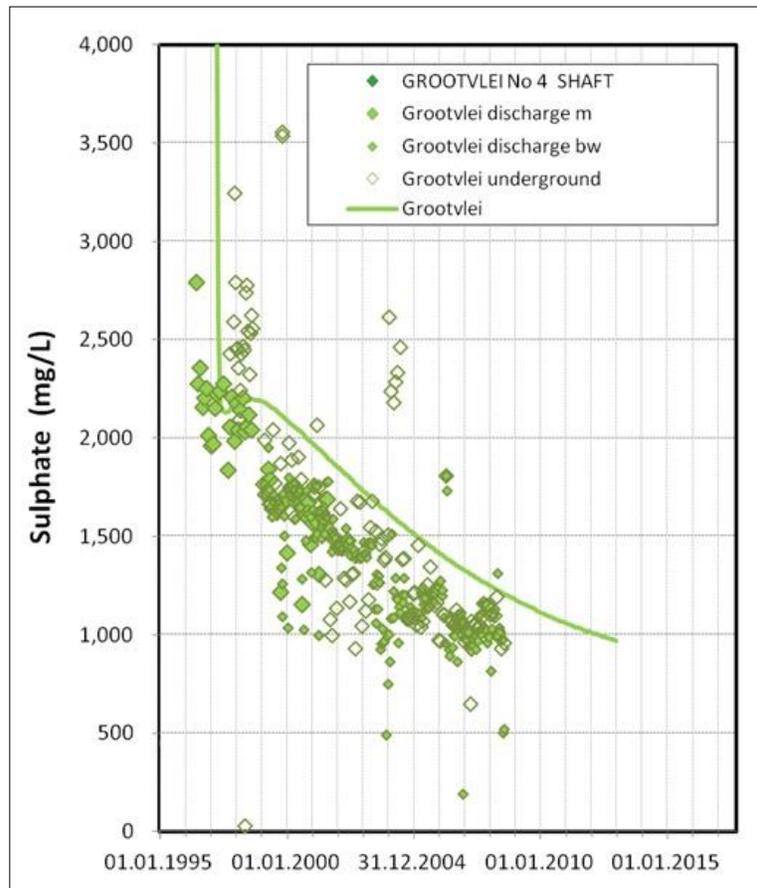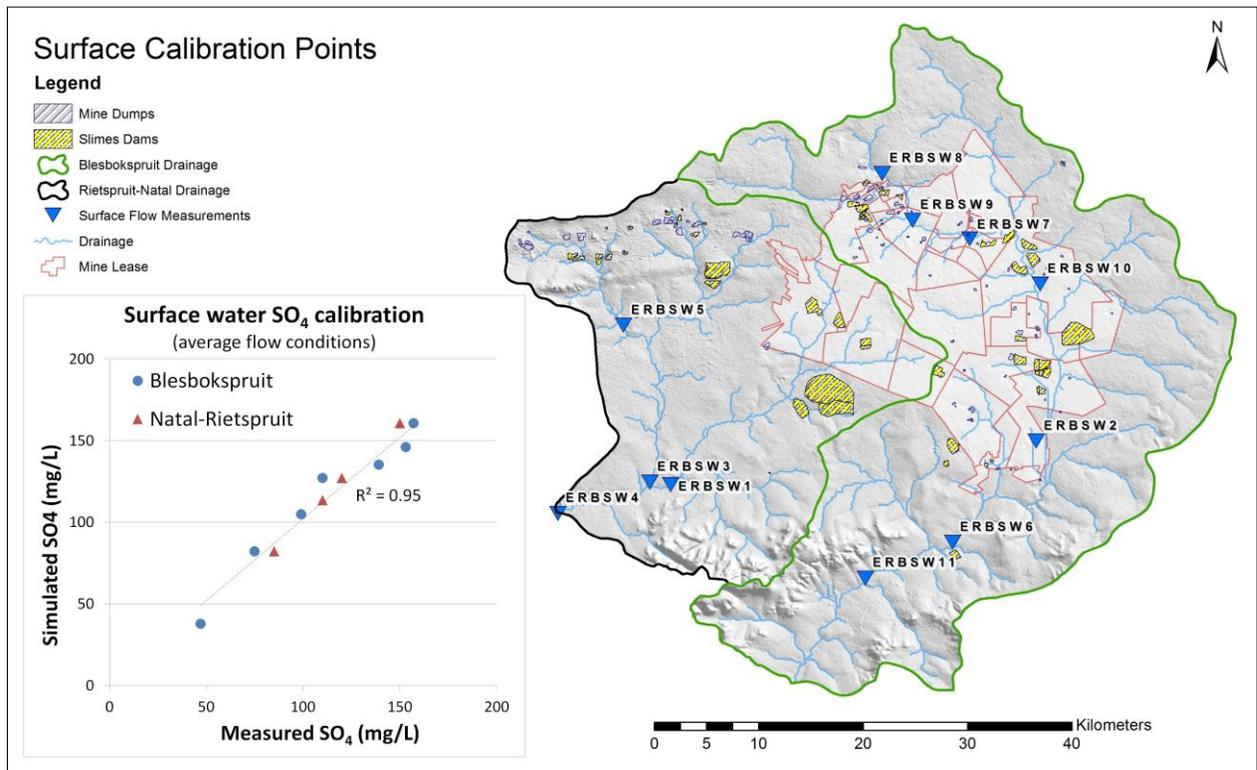

Figure 6 Model surface calibration points

Although the mine flooding model and the regional groundwater is calibrated individually, the surface water model calibration is representative of the integrated model calibration (Figure 7). The source apportionment is carried out at specified surface water points and the surface runoff model serves as a "water tree" routing all the contributions of pollution sources that report to surface water features downstream.

The groundwater model reports to the surface streams through surface-groundwater interaction and the mine flooding model reports to the surface streams through surface decant if it takes place.

The mine flooding model is also connected to the regional groundwater model and subsurface decant into the surrounding aquifer is accounted for where shafts are not hydraulically disconnected from the aquifer.

Figure 7 Integrated model surface calibration points and associated calibration

The surface water model only accounts for conservative mass transport as the surface water translates into a complex system with raw sewage (Figure 8) discharged into the water course due to faulty infrastructure or waste water treatment works running above designed capacity. Furthermore large wetlands (Figure 9) exist throughout the Blesbokspruit buffering flow and altering water chemistry.

Figure 8 Raw sewage discharged into the Blesbokspruit

Figure 9 Wetland in the Blesbokspruit

Mine Flooding Model

The mine flooding simulation was conducted using the DMT BoxModel. The BoxModel is a 3D finite volume program for modeling the flow of groundwater and mine water, heat transport and multi-component mass transport including sorption, microbial degradation and the reactions with minerals. A special feature is the highly flexible discretization, to model geological structures such as layers and faults as well as structural mining elements and mine excavations (DMT, 2011). The BoxModel also allows for interfacing to a regional groundwater model.

Regional Groundwater Model

MODFLOW was selected as choice of regional groundwater model for the study area. MODFLOW is the USGS's three-dimensional (3D) finite-difference groundwater model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions (Harbaugh, 2005).

Surface Water Model

The EPA SWMM (Storm Water Management Model) was used as primary rainfall-runoff model. The model is a dynamic and used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas. The runoff component of SWMM operates on a collection of sub-catchment areas that receive precipitation and generate runoff and pollutant loads (Rossman, LA 2010). In general SWMM is not applicable to large-scale, non-urban watersheds, but Nakamura and Villagra (2009) has shown successful application of SWMM to a natural catchment. Calibration parameters from SWMM were used to setup the secondary surface water model which forms part of the DMT BoxModel.

Source Apportionment

The technical component of the source apportionment was conducted through the use of the interconnected model representing the study area. The effect of various sources described by the model could be quantified at specific points of interest through the use of a what-if analysis. The pollution sources in question are disconnected from the model and the net effect of the detached pollution sources is recorded at points of interest.

The financial modeling based on the interconnected model relies heavily on the confidence of the model output, which is difficult to quantify considering future scenarios. The status quo confidence of the model output is related to the calibration state of the model and associated data.

The legal part of the source apportionment, which falls outside the scope of this paper, is far more challenging than the technical part due to legacy mining concerns.

DISCUSSION

The interconnected modeling approach allows for a what-if analysis to quantify the impact of various pollution sources at specified points in the network.

A challenge in model output confidence exists for the East Rand Basin as the monitoring network established only reflect the system response for a single hydrological year. Very little historic monitoring data are available to validate the model calibration.

The change of water character entering the wetland areas is contributed to the existence of Sulphate Reducing Bacteria (SRB). The surface water model employed does not explicitly account for wetlands or the effect of SRB's and this mechanism is simulated with a "treatment plant" within the surface water model. A study is currently being carried out to characterize the wetland response function particularly for the use in the surface water model.

CONCLUSION

Source apportionment in a complex mining environment requires the use of an integrated modeling approach. Model confidence on both current and future scenarios is important for the purposes of financial modeling which is the final step in the apportionment study. Continued monitoring would be required to validate the model response before final apportionment studies can be carried out.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the South African Council for Geoscience and the Department of Minerals and Resources who made this project possible.

REFERENCES

DMT GmbH & Co. KG (2011) *BoxModel Concept: ReacFlow3D,* Program description accompanying BoxModel documentation, Germany.

DWAF (2006) *Groundwater Resource Assessment II: Aquifer Vulnerability Map,* Department of Water Affairs, South Africa.

Harbaugh, AW (2005) *MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process,* U.S. Geological Survey, USA.

Inter-Ministerial Committee (2010) *Mine water management in the Witwatersrand Gold Fields with special emphasis on Acid Mine Drainage,* Council for Geoscience, South Africa.

Middleton, BJ and Bailey, AK (2005) *Water Resources of South Africa, 2005 STUDY (WR2005),* Water Research Commission, TT381/08, South Africa.

Nakamura, J and Villagra, N (2009) *Hydrologic Modeling of the Little Crum Creek Watershed with SWMM,* Swathmore College, USA.

Pratt, SE (2011) *Acid mine drainage: The toxic legacy of gold mining in South Africa,* Earth Magazine.

Rossman, LA (2010) *Storm Water Management Model User's Manual Version 5.0,* Environmental Protection Agency, EPA/600/R-05/040, USA.

Scott, R (2010) *Flooding of Central and East Rand gold Mines: an investigation into controls over the inflow rate, water quality and the predicted impacts of flooded mine,* Water Research Commission, WRC Report no 486/1/95, South Africa.