Coupled reactive mass transport for the East Rand Basin (RSA)

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Abstract

Gold mining in South Africa began in the late 1800s in the Witwatersrand area. The East Rand Basin (ERB), some 50 km east of Johannesburg is such an area of approximately 800 km^2. With gold mines in ERB having closed down over time, mine operators switched off their pumps. This has left the largely interconnected underground mines within the region to flood. In addition to mines being interconnected, there are also links to overlying aquifers and associated river systems. Therefore separate models for surface water, mine water and groundwater would not be appropriate. Another reason is seepage from tailings dams does not drain directly to the river systems and mine voids, but percolates through groundwater before reaching surface water bodies or mine voids. Furthermore a portion of polluted river water is also seeping into the groundwater system at some locations and then into the underlying mine voids.

In order to simulate the system, DMT's integrated Box Model was used. This is a reactive mass transport model which allows irregular polygons for individual mine fields, relatively regular raster elements for the groundwater layers and linear elements for the depiction of rivers. The model is then used to assist in addressing the following questions:

- Which horizons are mainly responsible for inflow into the mine voids?
- What are the dynamics of groundwater rebound?
- When is the Eastern Basin going to decant?
- How can the head differences in the interconnected mines system be interpreted during flooding?
- What contaminant loads are expected in the river systems?
- What influences does decanting mine water have on local river systems?
- What is the contribution of other surface pollution sources (e.g. tailings dams) have on mine water quality?

Key words: Reactive transport modelling; couples models; East Rand Basin

Introduction

In the Witwatersrand area, mining has taken place in the three underground mining basins of the East, Central and West Rand since the discovery of gold in 1886. During this time the more than 120 mines would have been required to pump out the water that had entered the mines in order to allow for safe mining conditions. As the mines were worked out and were abandoned, dewatering of the mine voids became the responsibility of fewer and fewer mines, and the voids (tunnels, drives and shafts) started filling with water as seen in Figure 1. Pollution generated through the ingress of water into the mine voids, is generally characterised by one or more of the following: low pH, high salt content (mostly made up of sulphates), and high levels of metals – particularly iron. In cases where uranium is present, radiological risks may also be present. There are numerous high ingress areas within the study area for example sinkholes, subsidence due to shallow mining activities, opencast mining pits etc.

As the water levels in the mine voids rise, pollution can pollute shallow aquifers. Once the polluted water reaches the surface and starts to decant, it flows down to wetlands, streams and rivers, and mortality of aquatic biota may occur. Since the rivers are inter alia used as a water source for the supply of water for agriculture, recreation and drinking purposes, polluted water potentially affects the fitness for use of such water. Polluted water can also have a cost implication further downstream due to elevated constituents that may be caused. Hence the apportionment study, to quantify the impacts and who is responsible for these impacts.

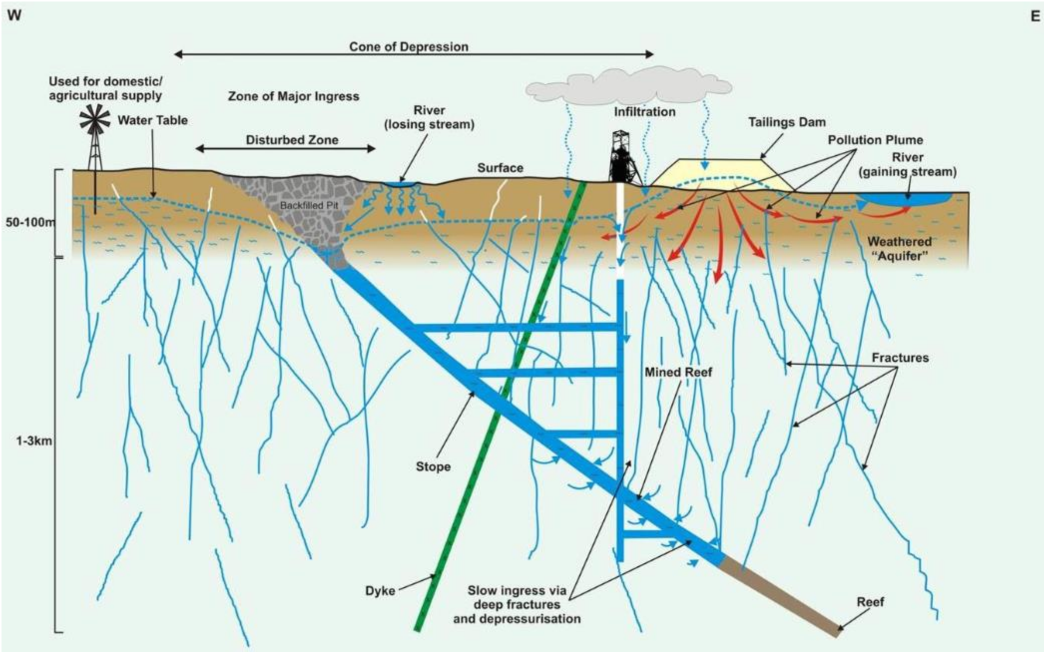

Figure 1 *Hydrogeological model showing flooding mechanisms (taken from: DWA, 2013).*

Background

The study area is located in the Gauteng Province 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 ERB. The mine lease areas in the basin are shown in Figure 2. It is important to note that the ERB is geographically, hydrologically and hydrogeologically different from the other Witwatersrand mined basins (Scott, 1995).

The climate in the study area is temperate Highveld, with short cold winters and hot summers. Most of the rainfall occurs in summer in the form of thunderstorms. The average annual rainfall is between 650 mm and 700 mm.

Gold bearing conglomerates, which were extensively mined from surface down to depths in excess of 2500 m, outcrop at two localities near Benoni and again near Nigel. For the rest of the area, the reefs sub-crop against the Transvaal or Karoo Sequences. The Main Reef was mined extensively and the Kimberly Reefs to a lesser extent. For the majority of the area, the Witwatersrand Formation is overlain by the Transvaal Sequence, which in this area comprises the Black Reef Quartzite Formation and the overlaying Malmani Dolomite Formation. The Black Reef, which was also locally mined for gold, occurs at the base of the Black Reef Quartzite Formation. Sedimentary rocks of the Karoo Sequence overlie the Transvaal Sequence. It consists mainly of shale, sandstone and mudstones of the Ecca formation. Economic coal layers, which were mined at a number of localities, occur within some of the strata. Structurally, the basin is marked by prominent folding, resulting in a number of sub-basins. These faults tend to strike east-west, while another major fault-set strikes north-west south-east. A number of diabase and syenite dykes and sills occur in the area.

Groundwater occurrences is predominantly restricted to the following types of terrains: (a) perched aquifers, (b) weathered rock aquifer in the Witwatersrand, (c) Ventersdorp and Transvaal Formations,

(d) Fractured rock aquifer in the Witwatersrand, Ventersdorp and Transvaal Formations, (e) Dolomitic and karst aquifers; and (f) Artificial aquifer created by mining.

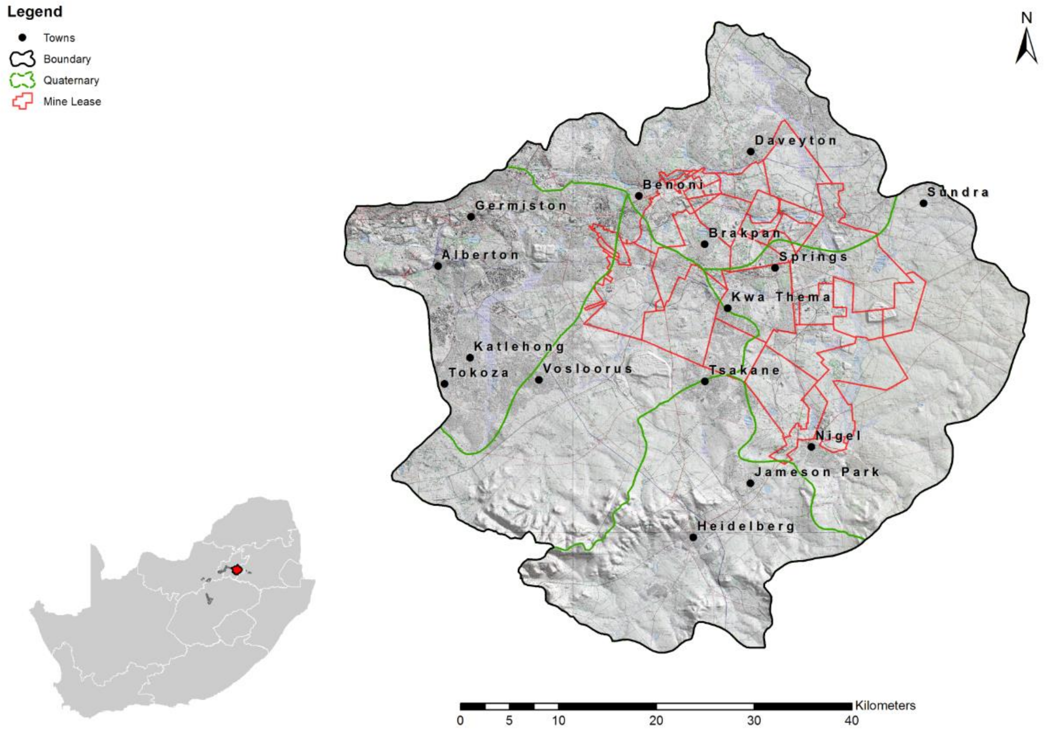

***Figure 2** Location of study area*

The watercourses within the study area predominantly north to south. In the east there is the Blesbokspruit. The Blesbokspruit flows over alluvium covered dolomite for much of its course. There are also numerous dams on the Spruit, originally constructed mainly to supply water to the mines. The water supply of the Blesbokspruit comes from a variety of sources, some of which include industrial, residential and mine discharge, several non-perennial streams and tributaries as well as urban runoff and shallow groundwater flow.

The Rietspruit drains the central and western parts of the study area, covering an area of 820 km^2. Within this area the stream is made up of numerous, small ephemeral tributaries.

Three main wetland systems are found in the study area, namely the Rietspruit, Withkspruit and Blesbokspruit wetlands. The Blesbokspruit wetlands system is a Ramsar Site.

In 2012, the then Department of Water Affairs (DWA) determined the eco-classification for the Blesbokspruit as a Class III[1] and the proposed management class was also set as a Class III.

The water levels in the ERB are rising and decant is expected within the next year or two.

Methods

This large-scale system of interconnected mines is linked with overlying aquifers and associated river systems. It is necessary to understand the systems within the area in order to answer the following questions:

- Which horizons are mainly responsible for inflow into the mine voids?
- What are the dynamics of groundwater rebound?

[1] Class III - Heavily used (configuration of ecological categories significantly altered from its pre-development condition).

- When is the ERB going to decant?
- How can the head differences in the interconnected mines system be interpreted during flooding?
- What contaminant loads are expected in the river systems?
- What influences does decanting mine water have on local river systems?
- What is the contribution of other surface pollution sources (e.g. tailings dams) have on mine water quality?

In order to understand these hydrological/hydrogeological issues/relationships and to provide answers to the questions listed above, a coupled mine water-groundwater-river-model has been developed. Due to the complexity of the system and associated interactions separate models for surface water, mine water and groundwater would not be appropriate. Another reason is seepage from tailings dams does not drain directly to the river systems and mine voids, but percolates through groundwater before reaching surface water bodies or mine voids. Furthermore a portion of polluted river water is also seeping into the groundwater system at some locations and then into mine voids.

Because of the very different geometries of the groundwater/mine voids/rivers, a flexible discretisation method is required to solve the problem of coupling the systems. Therefore DMT's Box Model (Eckart *et al.*, 2004 & 2005) was used. The Box Model is a reactive mass transport model which allows the consideration of individual mining areas in the form of irregular polygons, the groundwater layers by means of relatively regular raster elements and the rivers as linear elements. Figure 3 provides a conceptual overview of this coupled system.

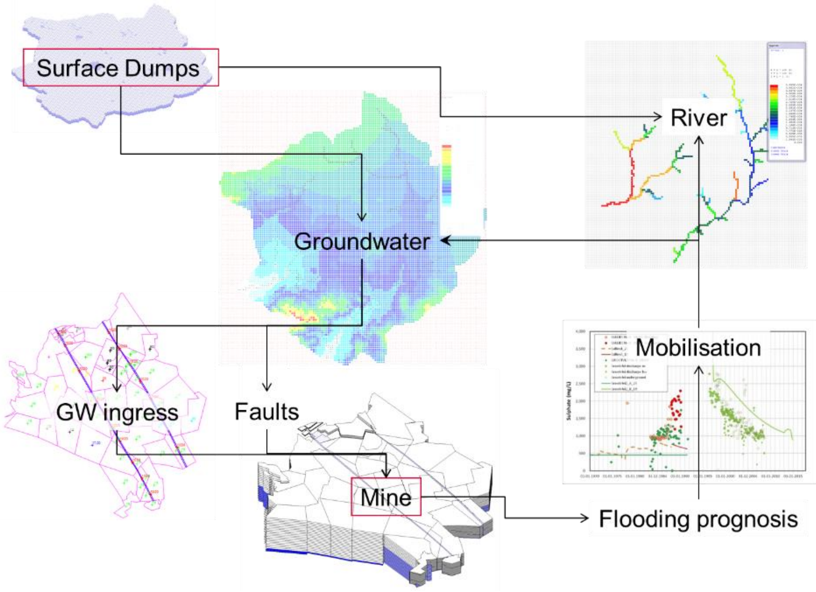

Figure 3 *Scheme of an interconnected model concept*

Once all data needed for the modelling was collected, individual models for groundwater, rivers and mine voids were developed and calibrated. Thereafter the three models were coupled and re-calibrated. The groundwater seepage rate into deeper horizons is then equal to the inflow into the mines from above.

The next step was then to set up and calibrate the multicomponent reactive mass transport model. Historic flooding data (measured rising water levels, abstraction rates and sampled chemical parameters) were used during this calibration process and the results thereof are shown in Figure 4.

Once the flow models are calibrated, the reactive mass transport model is calibrated, using water quality data collected at Grootvlei while pumping was taking place (June 1996 – January 2011). The reactive mass transport model integrates 15 main transport units with nearly 140 species. The calibration results for pH and sulphate are shown in Figure 5 and Figure 6.

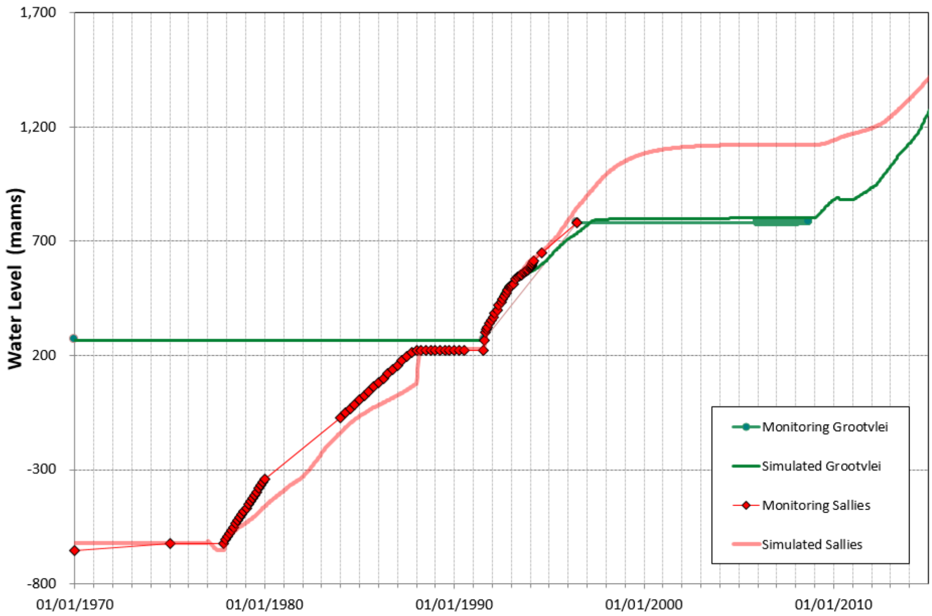

Figure 4 *Calibration results – flooding*

The ERB is expected to start decanting within the next two years. The average predicted ingress is 80 ML/d (Scott, 1995). However from the integrated model results it is clear that this ingress volume is dependent on a specific scenario. DWA (2013) estimated that the ingress would be 70 – 80 ML/d and recommended that 80 ML/d is pumped at Grootvlei #3 Shaft at a depth of 100 m (1470 metres above mean sea level). This level is referred to as the Environmental Critical Level (ECL). The coupled model indicated that the average ingress is 72 ML/d if the mine is not going to flood. It also calculated that it would be necessary to pump 19 ML/d to maintain the ECL. The model calculated the decant rate as 7 ML/d.

The calculated resulting development of sulphate after flooding for the scenarios discussed above is shown in Figure 7. The 50th, 75th and 95th percentile of the sulphate values predicted by DWA (2013) are included in Figure 7. The South African National Standard (SANS) 241:2011 drinking water guidelines are also included for comparison purposes. It is clear that these sulphate drinking water guidelines are exceeded in all scenarios. All scenarios are completed with uncertainty analysis using a monte-carlo method. The model varies the kinetic coefficient and the available mass in the source term for a range of comparable examples and experiences. The range of uncertainty for the 3 scenarios is shown in Figure 8.

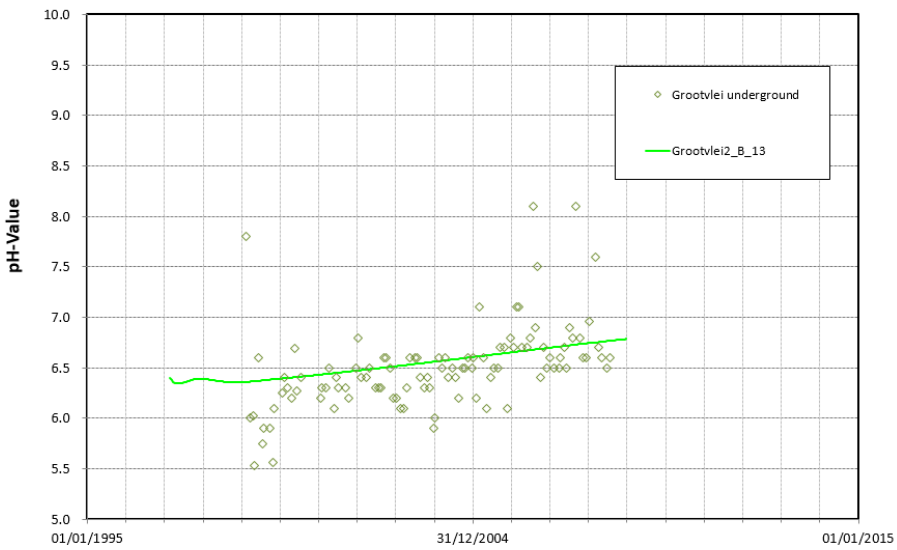

Figure 5 *Calibration results – pH*

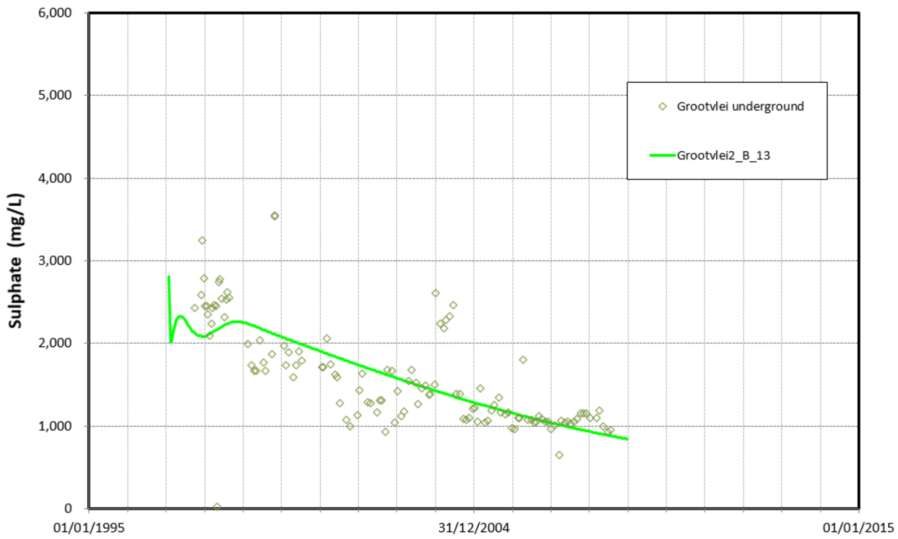

Figure 6 *Calibration results – sulphate*

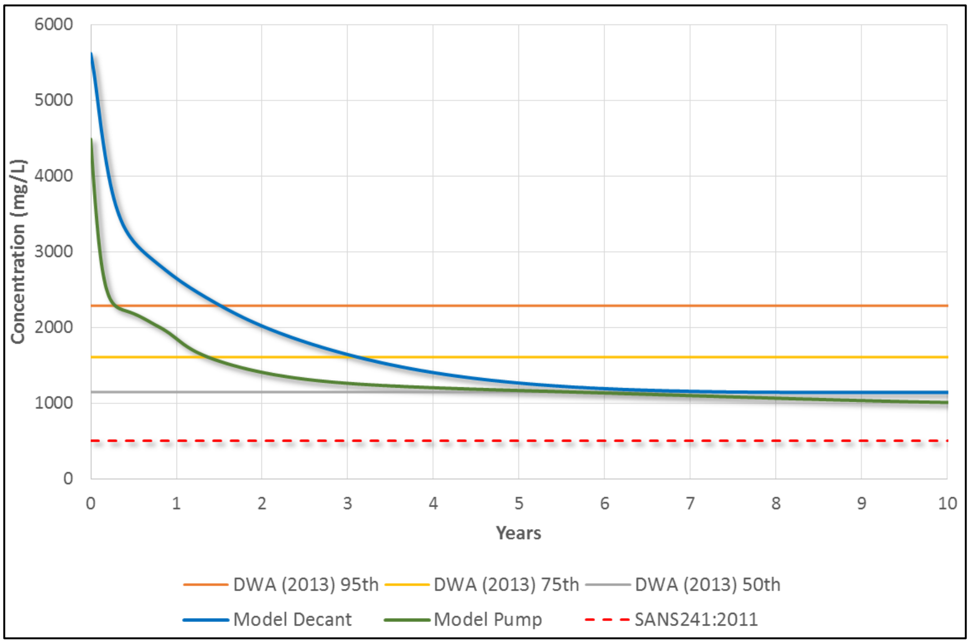

Figure 7 *Calculated sulphate development for various scenarios*

The final scenario was to determine the cumulative impacts on the Blesbokspruit if the ERB decants. This scenario takes into account the decanting mine water discharge to the river and groundwater – river water interaction. Figure 9 shows the pre-decant observed sulphate concentrations for the months April, July and November along a north - south 70 km stretch of the river. Also included in the diagram are the simulated sulphate concentrations due to decant and the average cumulative flow in the river. Included on the horizontal axis of Figure 9 are the landuse activities that can influence the sulphate load in the river. All these landuse activities are included in the coupled model.

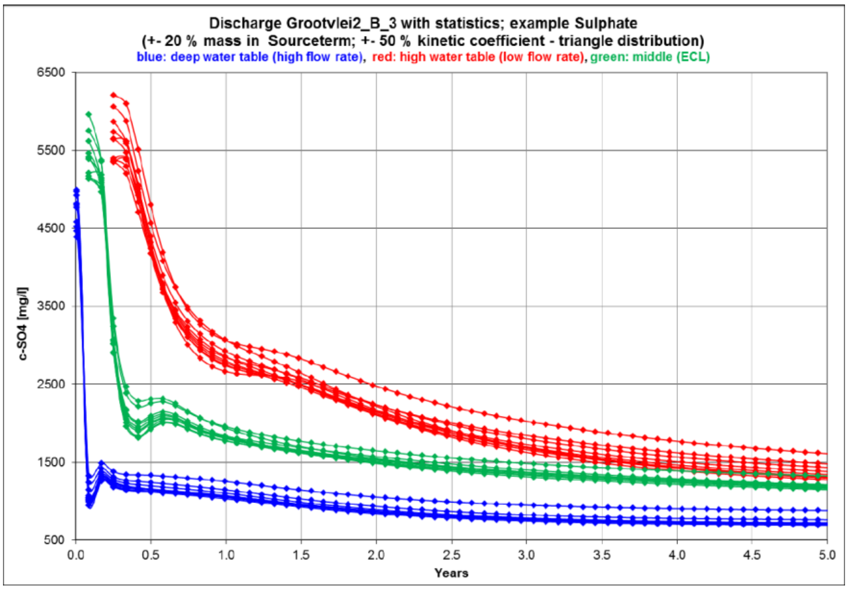

Figure 8 *Uncertainty analysis - calculated sulphate development*

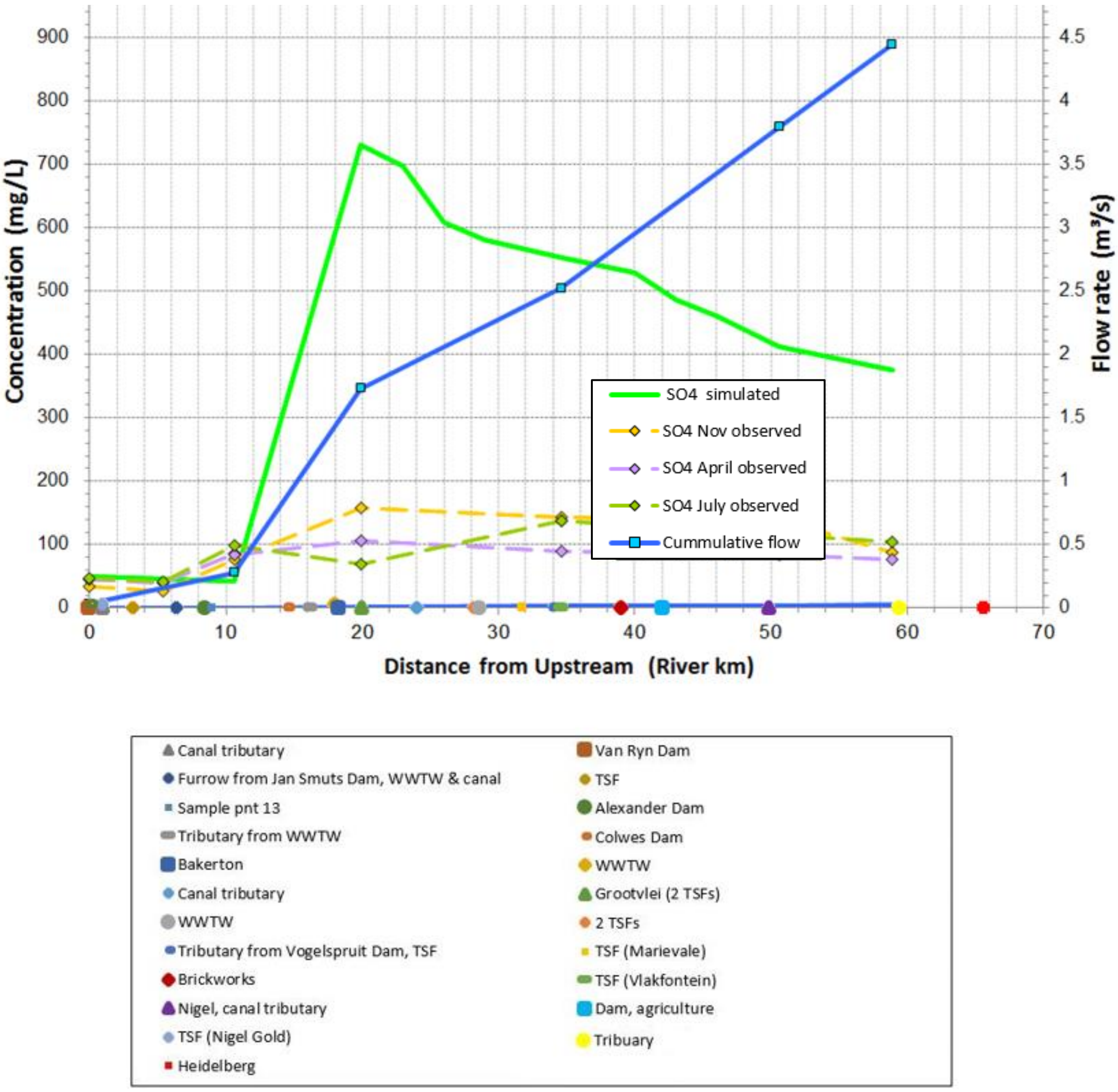

Figure 9 *Sulphate development along river course*

Conclusions

This paper summarizes some of the findings of a four year study conducted in the ERB. As the mine voids are currently flooding concerns are raised regarding the impacts the mines in the area have and are going to have (e.g. seepage from tailings dams, decant volumes and qualities) on surface water and groundwater bodies. To determine these impacts a coupled flow and reactive transport model was developed for the area.

The results of different scenarios are presented in this paper. The scenarios include: (1) Ingress if mine voids are not flooded, (2) Pumping to maintain ECL and (3) Allow total flooding and associated decanting.

The resultant sulphate values in all these scenarios are above the drinking water guidelines specified for South Africa. In the long term the sulphate values for pumping (scenario 2) is slightly better than the decanting (scenario 3). However the volumes of water that have to be treated in scenario 3 are much lower than scenario 2.

A scenario is run to determine the impacts on the Blesbokspruit. It is clear that the sulphate values increase dramatically approximately 20 km downstream due to mining activities. However the concentrations start decreasing thereafter due to the dilution effects of the river.

High ingress areas are a concern in the ERB. Former investigations estimated that the ingress can be reduced by approximately 25% by rehabilitating/sealing these areas (DWA, 2013). Though possible, sealing and stream diversion is costly and this measure require a cost-benefit analysis, should it be considered as part of the treatment solution. In addition the following should be considered with regard to sealing high ingress areas:

- Model results show that high ingress volumes result in a diluted impacting concentration (lower concentration but higher load), which will reduce treatment costs, if the dilution principle is acceptable.
- Sealing will reduce the ingress and delay the flooding process, but it is clear that the mine ingress reduce with a lower of hydraulic gradient. This would lead to higher concentrations and lower loads.

Acknowledgements

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