Modelling The Transport Of Pollutants From Mine Dump And Landfill Sites To Groundwater And Surface Water

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Abstract

Mining is important for the economies of many countries but, it results in large amount of solid and liquid waste which is released into the environment. This waste contains significant amount of toxic elements which can migrate to nearby surface waterbodies and groundwater. In this study, the transport of elements i.e. Cr, As, Cd and Pb from mine dump and landfill sites to groundwater and surface water was simulated. The highest rate of pollution occurs within 10 years of exposure. High concentrations of elements in waterbodies in the vicinity of mining areas result highly from mine dump and landfill sites.

Keywords: computational modelling, simulation, waste, waterbodies, Witwatersrand Basin

Introduction

Large amount of wastewater is discharged into the environment either directly or indirectly and groundwater and surface water are the major recipients (Whitehead et al 2019). The release of pollutants from mining sites occurs primarily through acid mine drainage (AMD), erosion of waste dumps, and tailings deposits (Salomons, 1995). AMD effluent contains high concentrations of sulfate, iron (from sulfide minerals oxidation), aluminium, and other trace elements (Salomons, 1995). When sulfide minerals in solution are exposed to oxygen, a sequence of reactions leading to the reduction of the pH (<3) results, and some of the elements such as As, Se, and Cr are released (Galhardi and Bonotto 2016). These elements from both active and inactive mining areas can end up in nearby ponds and other waterbodies and, a long period of soil exposure can lead to infiltration to groundwater. (Izah and Srivastav 2015). Plants growing in the vicinity of contaminated sites may absorb toxic elements through their rhizospheres which, can be released when the environmental conditions are acidic (Osborn et al 2011). Residents living in under-developed areas such as rural e.g. villages, usually rely on groundwater for irrigation and drinking thus, high concentrations of elements in the contaminated water can lead to many health issues. For example, arsenic and chromium are regarded as human carcinogens even in very low levels of exposure (Talabi and Kayode 2019).

Since soils and water sources in the vicinity of mining plants are susceptible to pollution, it is important to monitor the surroundings, even after the closure of some mining plants. This is because some of the elements can migrate to groundwater and negatively affect the ecosystem including living organisms (Genthe et al 2018). Moreover, residents using groundwater through boreholes do not usually have the knowledge or proper ways of cleaning the water before using it hence, they are susceptible to the negative effects of polluted water (Genthe et al 2018). Thus, it is very important to monitor the level of groundwater contamination in mining-impacted areas.

In this study, the movement of contaminants (chromium (Cr), arsenic (As), cadmium (Cd) and lead (Pb)) from landfill site and mining dumpsites to groundwater and surface water in the Central Rand of the Witwatersrand Basin, South Africa was modelled using Modular Three-dimensional Finite- Difference Groundwater model (MODFLOW) and modular three-dimensional transport model for simulation (MT3DMS) (Edokpayi et al 2018). MT3DMS simulates solute transport by using the calculated hydraulic heads and various flow terms saved by MODFLOW (Hughes et al., 2017). The distribution of the elements from their sources was studied to determine the level of contamination over the next upcoming years. The results from the study will be important for decision-making concerning groundwater remediation and the urgency of application.

Methods

The Witwatersrand Basin which is the home for the West Rand Basins in the Gauteng Province, South Africa, includes residential areas such as Fleurhof and Florida which are situated within the urban region of the Highveld grass veld-savannah (fig. 1). The Witwatersrand Basin is the world's largest gold resource and has produced more than one-third of the world's gold (Nkosi 2016). Tailings dumps are the main source of pollution in this area and are generally composed of elevated proportions of pyrite and sulfide species. The AMD in the Witwatersrand Basin is largely due to seepage from tailings storage facilities, discharge of water from the flooding of abandoned gold mines, and discharge of partially treated water from operating mines (Njinga et al 2016). The area of interest has a short mild to cold winter averaged at 15°C and a warm to hot summer averaged at 20°C. Annual precipitation ranges from 600 to over 700 mm whilst the annual potential evaporation is averaged at 1700 mm (Humphries et al 2017).

The geology of the aquifer, climate, and anthropogenic activities can influence the quality of groundwater (Genthe et al 2018). Thus, models that can incorporate all these factors are of high importance in monitoring groundwater quality. In this context, a computer-based model was used for the modeling of groundwater as an effective and rapid method to predict the rate of migration of contaminants from their sources into waterbodies.

Solid samples from mine tailings and landfills were collected from the Central Rand using polypropylene containers. Other samples were collected several distances from the tailings and landfills in order to trace the movement and transport of the elements from the point source to the residential areas and waterbodies such as the Fleurhof dam and Florida Lake. The collected samples were digested using a multiwave GO Plus microwave digestion system (Anton Paar, South Africa). About 0.5g of the solid samples were added into the digestion vessels and 6,

Figure 1 Study area and the QGIS representation of the main geographical features

Table 1 The strata main strata in the Central rand Basin.

Lithology	Thickness (m)	Porosity
Quartzite	60	~ 0.22
Conglomerate	15	~ 0.188

3, 3, and 2 mL of HNO_3, HF, H_2O_2, and HCl, respectively, were added in each of the vessels which were placed in the rotor. The system was set to digest at 180°C. Inductively coupled plasma optical emission spectroscopy (ICP-OES) (Spectro Genesis, Germany) was used to analyse the samples.

Liquid samples from the Fleurhof dam, Florida Lake, and ponds around the study area (marked with blue dots) were also collected using polypropylene containers. When collecting, the containers were filled with the solution and closed to ensure minimal or no interaction with the atmosphere. The collected samples were transported to the laboratory and stored in the refrigerator at 4°C. The samples were centrifuged and filtered before analyzing with ICP-OES. The current concentrations of the elements of interest from the collection sites as well as from previous years (i.e. obtained from previous studies) were used for the calibration of the model using parameter estimation (PEST). To do this, concentration data from over 50 years was included in the model so that the change in concentrations of the elements from the sources can be traced until the recent estimated concentrations (i.e. the rate of contamination). The calibrated model was then used to determine future concentrations of the pollutants over different years.

Computer modelling

ModelMuse, a graphical user interface simulating system for running groundwater flow and solute transport models was used. Some of its advantages include spatial data which is grid-independent and temporal data which is stress-period independent thus, giving users the flexibility to redefine the spatial and temporal discretization (Lautz and Siegel 2006). In this study, MODFLOW incorporated in ModelMuse was used. The modular structure consists of packages and programs and each package deals with a specific feature of the hydrologic system that is to be simulated. In this study, the model solves for the hydraulic head at the center of grid cells, subject to groundwater sources and sinks (e.g. recharge, pumping, evapotranspiration, discharge to surface water) and aquifer properties (specific yield, storage, hydraulic conductivity). The program has other capabilities including transport and optimization (Mosase et al 2019). MT3DMS was used to analyse the contamination transport to surface and groundwater around the pollutant source.

Some of the data required to run the MODFLOW-MT3DMS is presented in table 1. The topography of the study area was obtained from the digital elevation model (DEM) from Earth Explorer.

Model set-up and application to the study area

The Quantum Geographic Information System (QGIS) software was used to obtain the geographical information of the study area including the locations of Florida lake, Fleurhof dam, the landfills and the mine dumping sites (fig. 1). Earth explorer was used to define the coordinates of the study area and extract the SRTM 1 Arc-Second Global digital elevation model (DEM) of the study area which was exported into QGIS. The projection, EPSG:3857 – WGS 84 / Pseudo-Mercator format was used in QGIS as it contains the geographical information in MODFLOW otherwise the model would not recognize the projection, which will lead to a failed simulation.

Modelmuse version 4.3.0.0 was used to create all the MODFLOW input files. A two-layered MODFLOW model representing the underlying lithology thickness of the study area was created using MODFLOW 2005. Some of the MODFLOW parameters used are presented in table 2. The MODFLOW time was set to convert years to seconds and model the transport of the contaminants.

Table 2 Summary of MODFLOW model

Item	Details
MODFLOW version	MODFLOW-2005
GUI	Modelmuse version 4.3.0.0
Grid size	100m
No. of rows, columns, and layers	67 columns, 48 rows, and 2 layers
Total no. of cells	3126
Model simulation type	Steady-state
Length of simulation	50 years
Internal flow package	Layer property flow package
Boundary packages	CHD, RIV, and RCH

Results

Topography of the study area

The hydraulic head elevation of the study area was determined by incorporating DEM into QGIS. The resulting QGIS shapefiles and surfer grid files were transported into MODFLOW which determined the head elevation of the study area as indicated in fig. 2. The inclusion of the head elevation in the simulation is very important as the transport and the distribution of the pollutants from the source to the surroundings can be highly influenced by topography. The direction of the transport of pollutants will be from the highest elevation to the lowest elevation. According to the water mass balance, the discrepancy between the inflow and the outflow is less than 0.0001 % of the MODFLOW simulation. The study area is characterized by different elevations and most of the area has elevation greater than 1660 m. Most of the mine dumping sites in the study area are situated in elevated positions. Thus, the movement of pollutants such as As, Cr, Cd and Pb are likely to be easily transported to groundwater especially during the rainy season (Tutu et al 2008).

MODFLOW simulation results

The results of the collected samples from the mine dump and landfill sites are shown in table 3. Chromium had the highest concentration of all the elements under study. The concentrations of all the elements were found to be higher than the limits set by the world health organization (WHO) thus, the transport of these pollutants to groundwater and surface waterbodies can result in negative impacts in the ecosystem. The data obtained from the Department of Water and Sanitation (DWAS) of South Africa indicated that the groundwater of the Central Rand has high

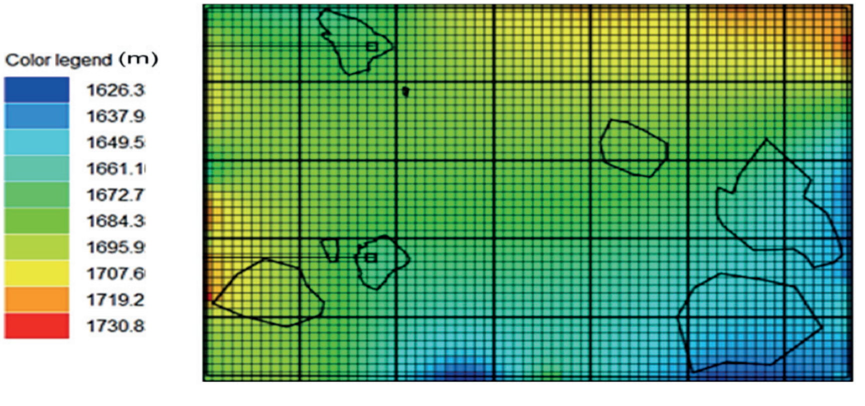

Figure 2 *Hydraulic heads of the study area.*

Table 3 *The concentrations of the elements in the mining dump sites and landfills.*

Element	Dump site A	Dump site B	Dump site C	Dump site D	Landfill A	Landfill B
Arsenic (mg L^{-1})	3.10	2.15	5.03	0.52	1.18	2.87
Chromium (mg L^{-1})	11.64	5.59	7.14	2.11	7.42	3.5
Cadmium (mg L^{-1})	0.728	0.7	0.98	0.27	1.12	0.98
Lead (mg L^{-1})						

concentrations of these elements which, may be due to the transport from abandoned and operating mines as well as from mine dump and landfill sites.

The transport of these elements to groundwater and surface waterbodies was simulated using calibrated MODFLOW model. Fig. 3 shows the transport trend of the elements from mine dump and landfill sites after 1, 10, 25 and 50 years. The transport of the pollutants from the source increased with time and spread toward the area of lower elevation. The trend of contamination was similar for all the pollutants and the difference was only in concentration. The maximum distance of transport of the pollutants was already reached within 10 years. The pollutants migrated to surface water bodies (Fluerhof Dam and Florida Lake) and groundwater. Transport to groundwater is highly influenced by recharge (rainfall) in the area.

The seepage of the pollutants through the underlying rock into the groundwater was also simulated (fig. 4). The seepage of the elements highly depends on porosity and the water table depth. As observed, mining dump and landfill sites with lower concentrations of the elements will delay the migration of the pollutants to groundwater and sites with high concentrations will lead to fast transport of the pollutants. Locations with lower elevations were polluted faster than those with higher elevations. It was clear that the high concentration of the elements in mine tailings and landfill sites can migrate to surface waterbodies and filtrate through the underlying rocks into the groundwater leading to contamination. Groundwater in the vicinity of the study area might not be safe for human consumption thus, water treatment should be applied (Chetty et al 2021).

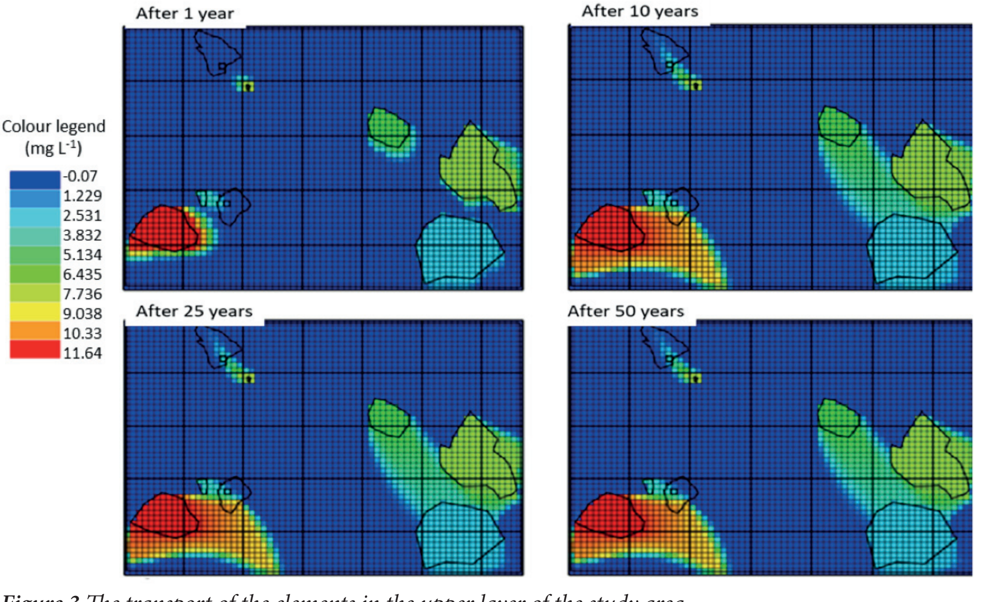

Figure 3 *The transport of the elements in the upper layer of the study area.*

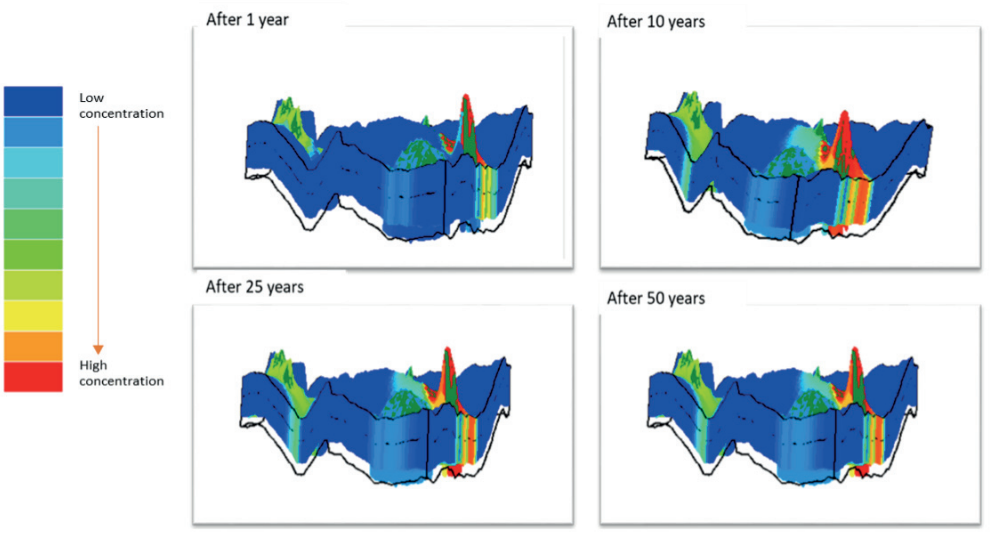

Figure 4 *The transport trend of the pollutants in the underlying rocks of the study area.*

Conclusion

Groundwater and surface water resources are important for living organisms including human beings. However, these waterbodies are prone to contamination. The transport of pollutants (As, Cr, Cd and Pb) in the sites found in the Central Rand of the Wits Basin were modeled using MODFLOW-MT3DMS model which took into account the real parameters of hydrology, geology, topography and hydrogeology. The mine dump and landfill sites had high concentrations of the pollutants which migrated to surface water and groundwater bodies. One year is enough for the concentrations for the elements to migrate and reach waterbodies. Due to the high concentrations of the elements in the water sources in the study area, residents living near mining operations and abandoned mine are prone to negative health effects due to contaminated surface water and groundwater when used for drinking, baptism or other recreational activities. There is therefore an urgent need for both groundwater and surface remediation. Moreover, the prevention of the transport of the pollutants can be achieved by phytoremediation. MODFLOW-MT3DMS is a useful tool to determine the transport of pollutants from point sources to waterbodies.

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