The transport of toxic elements from the Marie-Louise landfill site and nearby gold mine dumps to waterbodies

Alseno K. Mosai[1], Heidi Richards[2], Hlanganani Tutu[2]

[1]*Department of Chemistry, Faculty of Natural and Agricultural Science, University of Pretoria, Lynwood Road, Pretoria, 0002, South Africa, Alseno.Mosai@up.ac.za, ORCID 0000-0002-2762-9437*

[2]*Molecular Sciences Institute, School of Chemistry, University of the Witwatersrand, Johannesburg, Private Bag,Wits 2050, South Africa*

Abstract

Toxic elements such lead, cadmium, chromium and mercury have been found in concentrations higher than the WHO's drinking water limits around some landfill sites and mine dumps. These elements have the potential to migrate to waterbodies which increases the ease of access to living organisms including humans. When ingested, these elements can lead to serious health effects, some of which are fatal. In this study, MODFLOW and MT3DMS were used to simulate the migration plume of Pb^{2+} and Cd^{2+} from mine dumps and a landfill site to waterbodies in Johannesburg, South Africa. Solid and liquid samples were collected from the study area and analysed for the concentration of metals and anions. Some additional data were acquired from the Department of Water and Sanitation in South Africa. All data were added to the MODFLOW model which was calibrated before simulation. This simulation indicated that Pb^{2+} and Cd^{2+} can migrate from mine dumps and landfill sites to waterbodies, especially to groundwater. Thus, the nature and transport of toxic elements from mine dumps and landfill sites should be investigated further to determine the effects to underlying groundwater and surface waterbodies, including the characterization of dissolved organics and various pollution assessment methods. This will allow selecting appropriate treatment before usage. Moreover, to prevent further risk of negative effects from the mine dumps and landfill site, remediation techniques are required urgently.

Keywords: MODFLOW numerical modelling, transport modelling, metal toxicity, mine dumps, landfill site

Introduction

Many developing countries have been faced with the negative effect of landfills on the environment (Vaverková 2019). This is because, landfills are associated with the release of contaminants including toxic elements, greenhouse gases and microplastics into the environment. The release of contaminants from landfills occurs mainly because of the lack of appropriate landfill bottom liners and leachate treatment systems (Hussein et al. 2021). Thus, the produced leachate easily percolates to nearby soils and groundwater (Talalaj 2014). Toxic elements such as lead (Pb^{2+}), cadmium (Cd^{2+}), mercury (Hg^{2+}) and arsenic (As^{2+}) have been detected in landfills. Consequently, these elements have been detected in nearby waterbodies as a result of the escaped leachate (Hussein et al. 2021).

The Marie-Louise landfill site in Johannesburg, South Africa, is one of the largest landfills in the country. It is lined with a geomembrane called geosynthetic clay liner which only covers 0.61 km^2 of the waste footprint (Sibiya et al. 2017). It is near gold mine dumps which have been existing for decades. The mining industry is known as one of the sources which continue to degrade the quality of the environment because of the large amounts of waste that is produced during the processing of minerals (Vareda et al. 2019). More specifically, the Fleurhof dam and the Florida lake, considered in this study, are used for recreational purposes and some ceremonies such as baptisms. The groundwater is used by community members for agricultural and domestic purposes. Very low concentrations of these metals can lead to serious health effects in living organisms including kidney and liver damage, anaemia and cancer (Ebrahimi et al. 2020). This study aims at evaluating the risk for residents to be negatively affected by the landfill/mine site.

In this study, Modular Three-dimensional Finite- Difference Groundwater model (MODFLOW) and modular three-dimensional transport model for simulation (MT3DMS) were calibrated and used to simulate the migration of Pb^{2+} and Cd^{2+} from the Marie-Louise landfill site and nearby mine dumps to waterbodies.

Methodology

Study area

The location of the Johannesburg area considered in this study includes the Marie-Louise landfill site which is surrounded by gold mine dumps (Fig. 1). Mine dumps, tailings were left by former mines and acid mine drainage still occurs (Harrison and Zack 2012; Turton 2015). The landfill was granted permission to operate in 1993 and is located near residential areas (Mohlala 2006). Moreover, it has been suggested that the landfill has reached its 20 years lifespan (Mohlala 2006). Many sanitary landfills have been found to readily release leachates into the environment when the lifespan has been reached, due to worn-out liners. It is also close to dams and a lake which are used for recreational activities. Residents living in the vicinity of the landfill site have often complained about the smell and the dust from the landfill site. It is therefore possible that some of the toxic elements travel to the residential areas through the air.

Sample collection and analysis

Sediments were collected from seven mine dumps and the landfill site using drill augers according to standard procedures. The samples were collected using polypropylene containers and digested using a multiwave GO Plus microwave digestion system (Anton Paar, South Africa). Inductively coupled plasma optical emission spectroscopy (ICP-OES) (Spectro genesis, Germany) was used to determine the concentration of metals and ion chromatography was used to determine the concentration of anions.

The groundwater data for the chosen study area was obtained from the Department of Water and Sanitation in South Africa. Surface waterbodies were collected using polypropylene containers which were washed and rinsed with 10% nitric acid and deionized water prior to sampling. The collected samples were preserved at 4 °C during transportation and for laboratory storage. The concentrations of metals and anions were analysed. Soil samples were collected between the surface waterbodies and the mine dumps in order to trace if the elements of interest are present. Landfill leachate was also collected and analysed.

MODFLOW coupled to parameter estimation (PEST) was used to model the transport of the pollutants to waterbodies. The main purpose of the transport modelling was to predict the concentration of Pb and Cd in the next 1, 5, 10 and 20 years based on the calibrated model.

Numerical modelling

The migration of Pb^{2+} and Cd^{2+} from the landfill and mine dumps to groundwater and surface waterbodies was simulated using MODFLOW numerical modelling. MODFLOW 2005 computer code was used to develop a numerical representation of the hydrogeologic environment of the study site (Brunner et al. 2010). The software is considered as a standard code to simulate and predict groundwater conditions and ground and surface water interaction. Model Muse graphical user interface which incorporates MODFLOW was used. It allows for the link between MODFLOW and other programs such as MT3DMS. The interface also allows for the activation and deactivation of MODFLOW packages. The program requires output data from external programs such as QGIS and input analytical data.

Quantum Geographic Information System (QGIS) software was used to visualize, create, and analyze geospatial information. The geographical features of the study area such as mine dumps, waterbodies (Fleurhof dam, Florida lake, and Hennie Hugo dam) and the landfill site were demarcated in QGIS along with the digital elevation model (DEM) obtained from Earth Explorer.

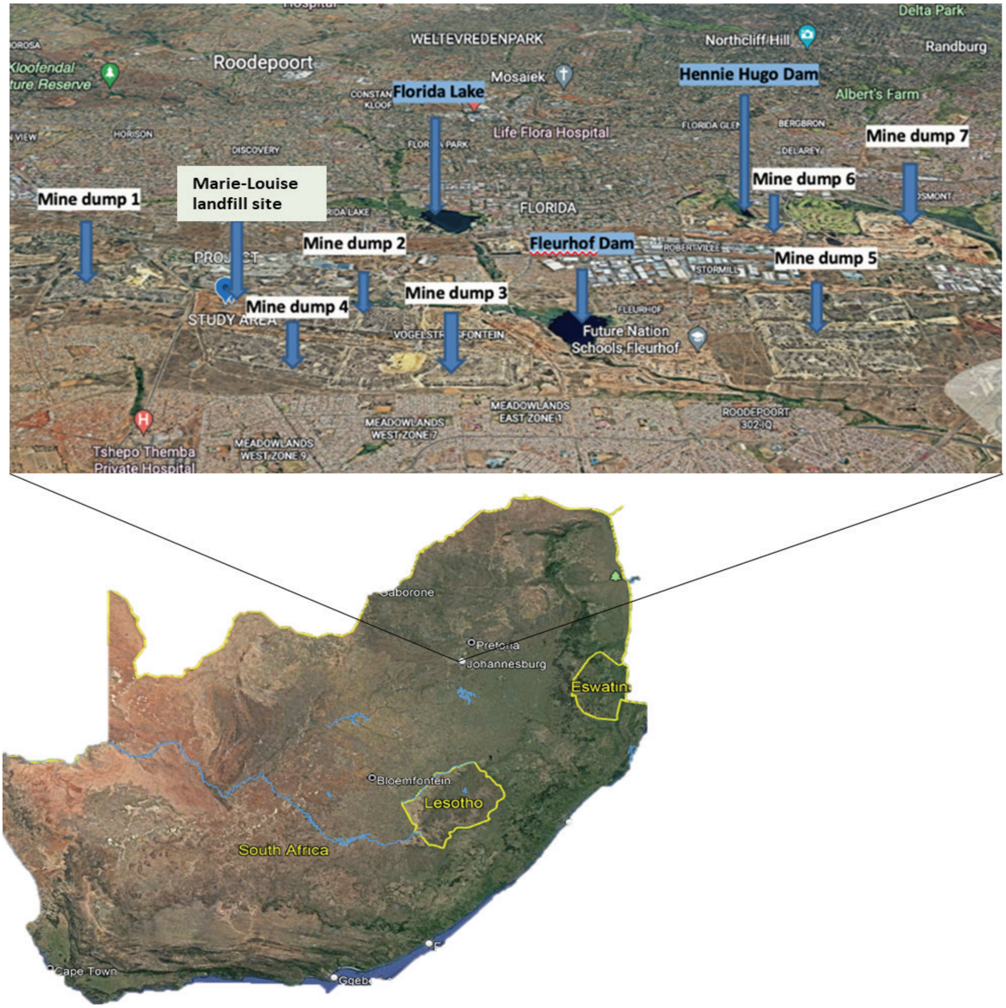

Figure 1 Map of the study area and the geographical features considered (Google Earth)

The geographical features were saved as shapefiles. Moreover, the area of interest was demarcated and saved as a grid file so that the elevation of the study area could be included in MODFLOW.

To create the MODFLOW numerical model, the grid file and shapefiles from QGIS were imported into model muse. The Constand Head (CHD) boundary conditions which allows the user to specify the value of the head, the Recharge package (RCH) that specifies the amount of precipitation received in the area per year, the Well package (WELL) that allows user to define the concentrations and behavior of the contaminants and the Evapotranspiration package (EVT) that allows for the specification of the rate of transpiration in the area per year were specified in MODFLOW. The view of the MODFLOW model of the study area is shown in Fig. 2. The model was run for 1 year, 5 years, 10 years, and 20 years after calibration in order to trace the movement of metals during these periods. MODFLOW was run first before simulating the transport and dispersion of pollutants using MT3DMS.

The speciation of the elements in waterbodies and the landfill leachate was determined using PHREEQC geochemical code. To do this, conditions such as pH, concentration of cations and anions, pe, temperature, density and redox were specified.

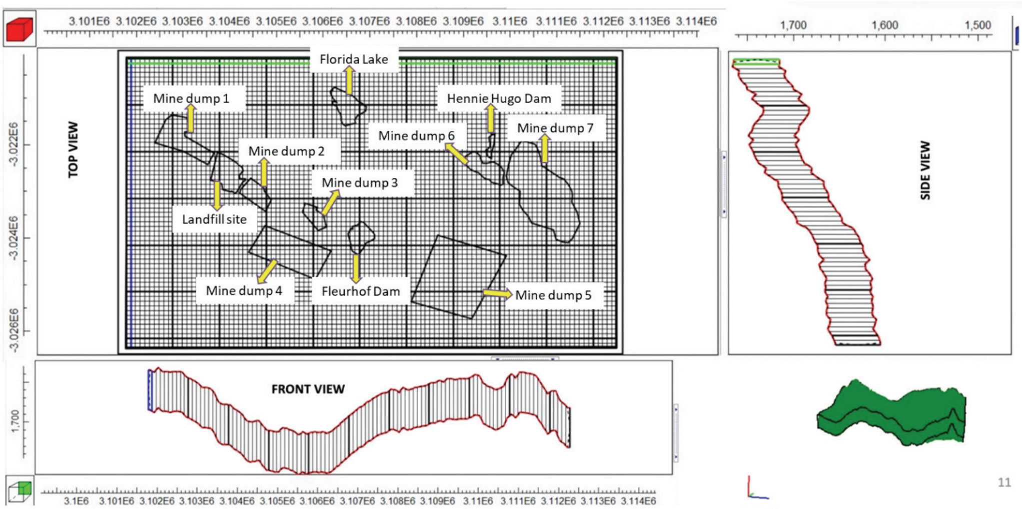

Figure 2 *MODFLOW groundwater and surface water model views of study area*

The output is the proportion of major species for each element. It was estimated in each waterbody. This contributes to evaluating the toxicity level.

Results

Different dissolved elements including Fe^{2+}, K^{+}, SO_4^{2-}, Cl^{-}, NO^{3-}, Mg^{2+}, Mn^{2+}, Zn^{2+}, Cu^{2+}, Na^{+}, Pb^{2+} and Cd^{2+} were detected in mine dumps and landfill site. Moreover, the Department of Water and Sanitation found that these elements were present in groundwater in the vicinity of the study area. The elements were also detected in surface waterbodies. It is highly possible that the elements in mine dumps and landfill site can migrate to waterbodies through the air and soil. Moreover, high concentrations of the elements are transported to groundwater during rainfall. Table 1 shows the current concentrations of Pb^{2+} and Cd^{2+} from mine dumps and the landfill site. The concentrations were found to be higher than the permissible limits in drinking water as determined by the World Health Organisation (WHO). This means that the migration of the elements to waterbodies should be prevented since some of the toxic elements can lead to severe effects in living organism including humans and livestock even when in very low concentrations (Ebrahimi et al. 2020).

The concentrations in Table 1 were added to MODFLOW so that the migration of Pb^{2+} and Cd^{2+} could be simulated using MODFLOW-MT3DMS (Fig. 3 and 4). The results showed that the contaminants do not travel far within the first year of the simulation, however after five years, the concentrations of the contaminants are likely to be detected several kilometres from the sources. The level of contamination depends on the concentration of the contaminants i.e., the higher the concentration, the further the distance travelled and the higher the negative effects (Chowdhury and Rahnuma 2023). The results also indicated that the Fleurhof Dam, which is very close to mine dumps will be severely affected within the first five years of the release of contaminants from mine dumps (Fig. 3a and 4a). Thus, using this water for

Table 1 *Concentrations of Pb2+and Cd2+ in mine dumps and Marie-Louise landfill site*

Element	Dump site 1	Dump site 2	Dump site 3	Dump site 4	Dump site 5	Dump site 6	Dump site 7	Landfill site	Permissible limits in drinking water (Aloke *et al.*, 2019
Pb^{2+} (mg L^{-1})	0.24	0.07	0.07	0.07	0.05	0.21	0.20	0.62	0.01
Cd^{2+} (mg L^{-1})	0.02	0.10	0.34	0.54	0.44	0.66	0.32	0.28	0.003

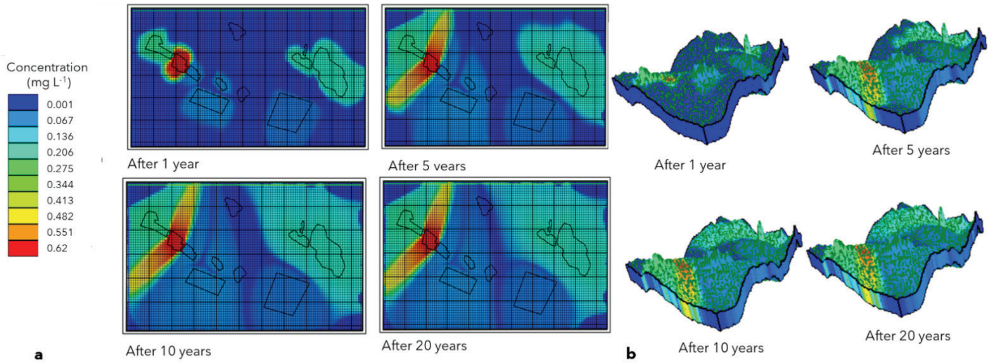

Figure 3 *The (a) horizontal and (b) vertical transport of Pb2+ in the study area*

any purpose may not ideal. The simulation indicated that the surface waterbodies are not affected by the contaminants from the landfill site, but other factors such as pollutant transport through dust should be considered. The study also showed that the elevation of the area has high influence on the transport of the pollutants. The simulation also indicated that there is a vertical transport of the contaminants (Fig. 3b and 4b). Meaning that Pb^{2+} and Cd^{2+} is likely to reach groundwater by seepage through the underlying rock (Naicker et al. 2003). The vertical transport is more efficient than the horizontal one, thus contaminants travel faster to groundwater than to surface waterbodies. This means that the elements detected in groundwater are either from the mine dumps, landfill site or saturated and unsaturated zones surrounding the groundwater.

PHREEQC geochemical modelling indicated that most of the elements including lead and cadmium exist as free cations (e.g., Pb^{2+} and Cd^{2+}) and other species (i.e., associated other elements) in groundwater and surface waterbodies due to the conditions of the water. The data collected indicated that the pH of groundwater has been decreasing over the years which could the result of the high concentration of sulfate from mine dumps and tailings in the area. Lower pH leads to the dissolution of most metals hence free cations will be in high quantities (Huang et al. 2017). This induces the toxicity levels of the elements under consideration. Thus, the groundwater in the vicinity of mine dumps and landfill site should be treated before usage especially for domestic and agricultural purposes. The results indicated that the

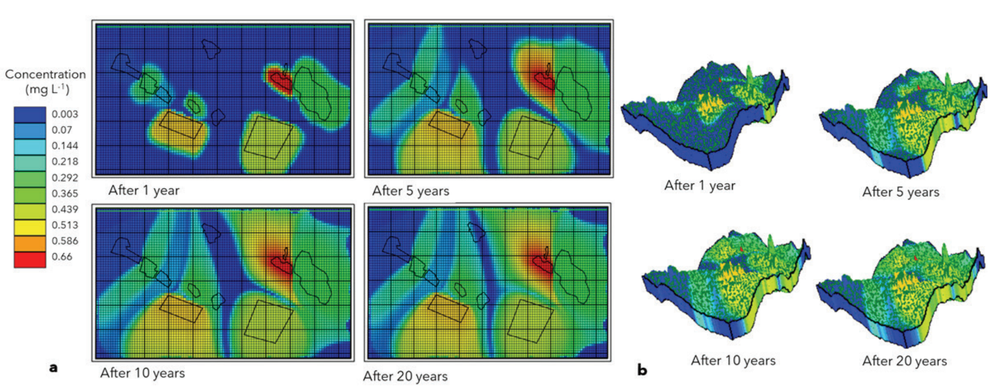

Figure 4 *The (a) horizontal and (b) vertical transport of Cd2+ in the study area*

situation would worsen if the transport of the elements is not controlled.

The study indicated that the waterbodies in the vicinity of point sources are contaminated with toxic elements and sulfate. MODFLOW coupled to PEST can accurately determine the transport of elements from point sources. Water treatment technologies should be applied in affected surface water and groundwater due to high concentrations of toxic pollutants.

Conclusion

The transport of Pb^{2+} and Cd^{2+} from mine dumps and the Marie-Louise landfill site was simulated using MODFLOW-MT3DMS. The concentrations of the elements were determined and included in the model. The results of the study showed that the waterbodies in the vicinity of the Marie-Louise landfill site and mine dumps were contaminated by toxic elements (Pb^{2+} and Cd^{2+}) whose concentrations were above the threshold limits for drinking waters (0.001 mg/L and 0.003 mg/L respectively) as set by the World Health Organisation (WHO). The modelling results indicated that the transport of elements will continue if not prevented. This means that local residents depending on the waterbodies for different purposes are prone to negative side effects as a result of the high concentrations of elements, some of which are toxic in very low concentrations. Other elements such as Fe^{2+}, K^{+}, SO_4^{2-}, Cl^{-}, NO^{3-}, Mg^{2+}, Mn^{2+}, Zn^{2+}, Cu^{2+} and Na^{+} were also found to be in high concentrations in the waterbodies as a result of the mine dumps. MODFLOW-MT3DMS can be used to simulate the transport of contaminants from their sources. This is important for determining the role of mine dumps and landfill sites on the environment. Moreover, future prediction of the level of transport of the contaminants using MODFLOW-MT3DMS will help with identifying areas that require urgent remediation strategies.

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References

Aloke, C., Uzuegbu, I. E., Ogbu, P. N., Ugwuja, E. I., Orinya, O. F., & Obasi, I. O. (2019). Comparative assessment of heavy metals in drinking water sources from Enyigba Community in Abakaliki Local Government Area, Ebonyi State, Nigeria. African Journal of Environmental Science and Technology, 13(4), 149–154.

Brunner, P., Simmons, C. T., Cook, P. G., & Therrien, R. (2010). Modeling surface water-groundwater interaction with MODFLOW: Some considerations. Groundwater, 48(2), 174-180.

Chowdhury, A., & Rahnuma, M. (2023). Groundwater contaminant transport modeling using MODFLOW and MT3DMS: a case study in Rajshahi City. Water Practice and Technology, 18(5), 1255–1272.

Ebrahimi, M., Khalili, N., Razi, S., Keshavarz-Fathi, M., Khalili, N., & Rezaei, N. (2020). Effects of lead and cadmium on the immune system and cancer progression. Journal of Environmental Health Science and Engineering, 18, 335-343.

Harrison, P., & Zack, T. (2012). The power of mining: the fall of gold and rise of Johannesburg. Journal of contemporary African studies, 30(4), 551–570.

Hussein, M., Yoneda, K., Mohd-Zaki, Z., Amir, A., & Othman, N. (2021). Heavy metals in leachate, impacted soils and natural soils of different landfills in Malaysia: An alarming threat. Chemosphere, 267, 128874.

Huang, J., Yuan, F., Zeng, G., Li, X., Gu, Y., Shi, L., ... & Shi, Y. (2017). Influence of pH on heavy metal speciation and removal from wastewater using micellar-enhanced ultrafiltration. Chemosphere, 173, 199–206.

Mohlala, T. (2006), Dumping ground, Mail and Guardian, https://mg.co.za/article/2006-06-13-dumping-ground/ [Accessed: 19 December 2023]

Naicker, K., Cukrowska, E., & McCarthy, T. S. (2003). Acid mine drainage arising from gold mining activity in Johannesburg, South Africa and environs. Environmental pollution, 122(1), 29–40.

Sibiya, I. V., Olukunle, O. I., & Okonkwo, O. J. (2017). Seasonal variations and the influence of geomembrane liners on the levels of PBDEs in landfill leachates, sediment and groundwater in Gauteng Province, South Africa. Emerging Contaminants, 3(2), 76–84.

Talalaj, I. A. (2014). Assessment of groundwater quality near the landfill site using the modified water quality index. Environmental monitoring and assessment, 186, 3673–3683.

Turton, A. (2015). When gold mining ends: An environmental catastrophe for Johannesburg. New South African Review 5: Beyond Marikana, 120–142.

Vareda, J. P., Valente, A. J., & Durães, L. (2019). Assessment of heavy metal pollution from anthropogenic activities and remediation strategies: A review. Journal of environmental management, 246, 101–118.

Vaverková, M. D. (2019). Landfill impacts on the environment. Geosciences, 9(10), 431.