ENVIRONMENTAL IMPACT ASSESSMENT OF ABUNDANT LEAD LANDFILL ON GROUNDWATER AND SOIL QUALITY

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ABSTRACT

Soil contaminated with lead poses high risk to human health through direct ingestion or drinking contaminated groundwater. Hence, monitoring and prediction of lead migration is a major public health concern. A three dimensional finite difference model using Modflow-MT3DMS mass and contaminant transport modules was developed to assess groundwater and soil quality in the area of the abandoned landfill of the Awadallah lead (Pb) smelter located in northeastern of Greater Cairo, Egypt. The dimensions of the landfill extend for 190 m length, 100 m width, 1.0–3.5 m depth and located in the core of the over populated residential area of Shoubra El Kheima city with 160 m separating distance from Ismailia Canal. The studied area is characterized by silts and sandy clay deposits overlaying a graded sand and gravel. The main aquifer belongs to the Quaternary formation (Nile-recharged formation). The numerical model was verified using collected geophysical and subsurface investigations data. Contaminants concentration in ground and surface water were predicted using the verified numerical model. The Lead contamination affects the unsaturated zone and the phreatic aquifer up to a depth of about 10 m. Predicted concentrations of Lead in groundwater was slightly exceeding the safe limits identified by the US-EPA. Lead in soil samples revealed elevated concentrations around the landfill, whereas a gradual decrease in concentrations was predicted in the northwestern direction. Different mitigation scenarios were carried out to prevent further migration of lead, and the best scenario was to convert the landfill into a sanitary land fill.

Keywords: Modflow-MT3DMS, Lead Migration, Soil Quality, Groundwater Quality

1 INTRODUCTION

Lead, which has been recognized as one of the most hazardous heavy metal among environmental pollutants, is quite harmful to human beings and the environment (Finzger et al., 2004). Not only can Lead in soil reduce the output of crops, but also affect human health through the food chain, inhalation, and ingestion (Ricardo et al., 2003). As a kind of toxicant to the central nervous system, lead is much more serious to health and intelligence of children (Cui et al., 2011). Meanwhile, lead will pollute underground water by leaching. Lead is not biodegradable and will remain in the ecosystem for a long time, so it is hard to totally remediate lead-contaminated soil since the harmfulness of lead are long-term and latent (Xia et al., 2012). Therefore, remediation of lead-contaminated soil is always considered as an important environmental issue.

During the early 1990s, lead was one of the main pollutants affecting the lives of Egyptian residents. Diagnosed cases of lead poisoning and measurable levels of lead in the blood were more than twenty times higher than for adults in the United States. In addition, lead levels in the air of Cairo neighborhoods were more than thirty times higher than world health standards. Most of the lead in Cairo's air was coming from uncontrolled emissions of secondary lead smelters in the densely populated area of Shoubra El Kheima which was responsible for more than 70% of the lead pollution in the air [1]. Shoubra El Kheima is the fourth largest city in Egypt; it is located in the Al Qaliubyia governorate with total population of 1,099,354 at the 2012 Census [2]. The city was primarily inhabited by workers (and their families), who have worked in surrounding factories since the 1940s.

Awadallah Lead Smelter is one of the smelter located in Shoubra El Kheima; this smelter began operations in 1979 and ceased smelting in August, 2001. The main raw material for the plant was used batteries. Approximately, 20,000 tons of batteries were recycled per year producing 11,000 tons of lead ingots. The smelter has area of approximate 1550 m^2 with a total volume of building material of about 553 m^3 equipped with few environmental controls equipment as shown in Fig. 1. After the smelting process stopped, the plant was used only in refining and manufacturing lead products (USAID Report, 2003).

The smelter used to dispose its waste in the studied landfill which distant 500m northwest of the smelter. The landfill is located within the flood plain of the Nile River. The topography of the area is almost flat with an average altitude of 17 meters above mean sea level. The climate of the site is considered arid. Annual rainfall is about 25 mm/year. The smelter lies within a mixed industrial and residential area. The site is located approximately about 210 meters north of a soccer field, and about 10 meters south of housing block. Underlying the landfill, there are two hydro-geologic units, an upper silt and clay layer and a major alluvial aquifer. The water table is between 5.0 – 6.0 meters below the ground surface. One hundred and sixty meters to the south of the site is the Ismailia Canal, which is a source of recharge to the aquifer.

Figure 1. Old lead smelting operation in Awadallah Lead Smelter (USAID Report, 2004).

To stop the leaching toxic of lead in soil below the limit values prescribed in the standards, and meet the requirements of the corresponding land use types and water quality, some physical, chemical, biological and composite methods can be used to stop, absorb, fix, degrade, and transform the lead in soil (Li et al., 2013).

The aim of this paper is to achieve a well knowledge of the present hydrogeological and hydro-chemical conditions of the landfill site and to evaluate the efficiency of possible scenarios to achieve the environmental limits in the pollutant concentration both in soil and groundwater. The proposed scenarios are construction of cut-off wall between Ismailia Canal and the landfill, covering the existing landfill to prevent water recharge, and converting the landfill to sanitary landfill. The proposed scenarios were investigated numerically using visual Modflow-MT3DMS software. The numerical model results were first verified using field measurements, and then different scenarios were carried out.

2 SITE DESCRIPTION

The study area is located in a mixed industrial and residential area of Shoubra El Kheima, northeastern Cairo, south of Al Qaliubyia Governorate, 3300 m east of the Nile River, 160 m north of Ismailia Canal as shown in Fig. 1. The topography of the area is characterized by gentle slope with gradual increase in altitude ranging from 16 to 27 m amsl as shown in Fig. 2. The area is characterized by arid climatic conditions (Atta, 1979), USAID Report (2005) describe the climatic features of the area as:

- Annual mean air temperature of 19.9 °C and the average monthly temperature reach its maximum value in July and August (26.9 °C) and its minimum value in January (11.2 °C).
- Average annual relative humidity is approximately 68 percent.
- Rainfall is very limited. The average annual rainfall is about 25.5 mm. The majority of the rainfall is limited to three months (December through February).
- The dominant winds over the year have a northern component with an annual mean velocity of 12.27 km/h. The dominant winds over the winter season trend SSW, S, and SW. The affecting dominant winds over the summer period are multidirectional and trend NNW, N, and NNE.

Figure 2. Location of the studied area (Google Earth).

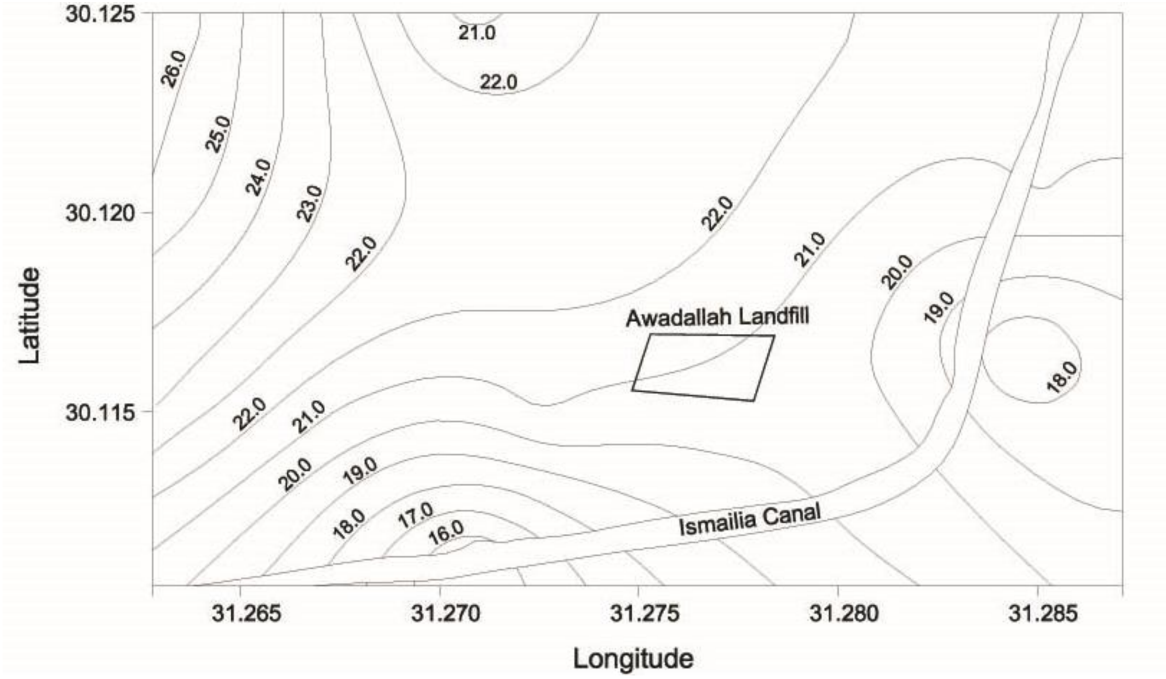


Figure 3. Site Topography (reproduced from Khalil, 2012)

3 SITE ENVIRONMENTAL ISSUES

The abundant lead landfill poses a multitude of health and safety hazards to nearby residents, and the environment. Exposure to toxic elements associated with batteries such lead, cadmium, arsenic, antimony, and selenium can have a profound effect on long-term human health. Children and young adults can be exposed to lead through inhaling or ingesting high levels of contaminated fugitive dust. Fugitive dust from the landfill could be blown and deposited on agricultural products; onto the waters in the Ismailia Canal; and on the water treatment plant of Amiriya which is located about 300 meters downwind of the landfill.

Among all the contaminants found at the site, lead is of most concern. Lead exposure affects many organ systems, including cardiovascular, renal, and hepatic. The most sensitive is the central nervous system and it can damages kidneys and the immune system, particularly in children (USAID Report, 2005). Unborn children can be exposed to lead through their mothers; causing harmful effects include premature births, smaller babies, decreased mental ability in the infant, learning difficulties, and reduced growth in young children. High lead and other metals were found at high levels in soil samples, and water samples at the site. Soil samples showed up 3000 mg/L/kg concentration of lead (Khalil, 2013) which is more than five times the U.S. Environmental Protection Agency (US EPA) limits (600 mg/L/kg). Groundwater sampling from wells drilled on and near the site showed a lead concentration ranges between 0,033 mg/L to 0,036 mg/L (Khalil, 2013) which is more than double the US EPA limits.

4 HYDROGEOLOGICAL SETTING

4.1 Geology

The area, in general, is a part of the Northern tip of the Nile Delta and alluvial plain (Atta, 1979). Such silty and sandy clay deposits (Holocene-Q3) are overlaying graded sand and gravel Pleistocene aquifer (Pleistocene-Q1). The main aquifer belongs to the Quaternary formation (Nile-recharged formation) (Maha, 1984). Boreholes in the study area indicated four subsurface layers, from top to bottom as follows:

1. A surface layer characterized by a mixture of silty and sandy clay cap (Holocene-Q3) and different building wastes. This layer characterized by thickness ranges from 0.1 to 1.5 m.
2. A second layer of silty and sandy clay cap (Holocene-Q3). This layer characterized by thickness ranges from 1.5 to 11.5 m.
3. A third layer of mixed sand and gravel (Pleistocene-Q1). This layer represents the aquifer and characterized by thickness ranges from 100 to 130 m.
4. A fourth layer exists below the aquifer and consists of very impermeable rigid clay.

4.2 Hydrodynamic parameters

In the study area, the predominant flow of the groundwater is from the south to the north and from the west to the east (Atta, 1979; Maher, 1996). There are some secondary movements due to some depletion in the groundwater level due to excessive pumping (Safar et al., 2007). The main source of groundwater recharge is the River Nile and Ismailia canal (Fig. 2). The secondary recharge source is seepage from sewage system and drainage networks. The groundwater discharge is mainly from water wells (Safar et al., 2007).

The main aquifer belongs to the Quaternary formation that is a Nile River recharged formation. The Holocene (Q3) layer is about 15 m thick and the thickness of the Pleistocene (Q1) is not definitely known but extends beyond 200 m deep. The layers forming the aquifer can be classified into the following (USAID Report, 2005):

1. A clay cap that is the surface layer over the aquifer was formed from clay precipitants that belong to the Holocene Era. The thickness of this layer ranges from 2 to 10 m. This semi-permeable layer allows for water penetration to the aquifer.
2. Sand and gravel layers of the aquifer follow the contour of the surface layer. The thickness of this layer ranges from 100 to 130 m. Previous studies indicated that the average hydraulic conductivity is 30 m/day and the average transmissivity is 1000 m^2/day.
3. The lower clay layer, where it exists, below the aquifer consists of very rigid clay and is considered to be impermeable.

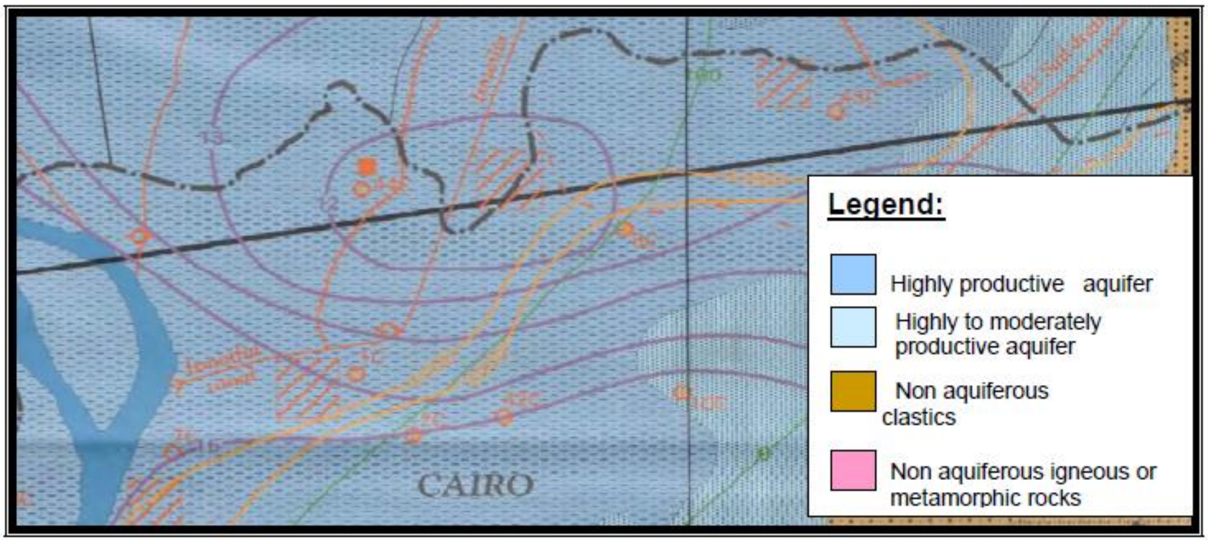


Figure 4. Hydrological map of Shoubra El Khiema (after USAID Report, 2005)

5 NUMERICAL SIMMULATION

5.1 Model Domain

The modeling study covers an area of 2440m by 1420m within which the landfill site is located. The numerical representation of the site created as a 2440m by 1420m grid in the X and Y direction (corresponding with east-west and north-south, respectively), with a general uniform grid spacing of 50m between grid nodes, refined to 25m uniform spacing at the landfill as shown in Figure 5. Three hydro-stratigraphic layers were defined at the Site based on the data given in Section 4, soil anisotropy was assumed, thus vertical conductivity (K_z) was established as $0.1(K_x=K_y)$.

Elevations for each layer were recorded in coordinates and placed into separate spreadsheets, then imported as layers in the model. For the initial attempt at importing elevation data, missing elevation values were not provided where layers were not present. This yielded cross-sections appearing not representative of the Site geology. The process was then performed using a value of 0.5 m for missing layers which yielded cross-sections appearing to be more representative of the conceptual model. In order to provide uniform cell sizing in the z direction for the model, the thicker sand and gravel layers were subdivided into roughly equivalent layers, exhibiting the same hydrogeological properties. All the available information about the geology of the area has been used to set up the geological model. The upper three geological layers have been accounted for. The overall simulated thickness is 100m.

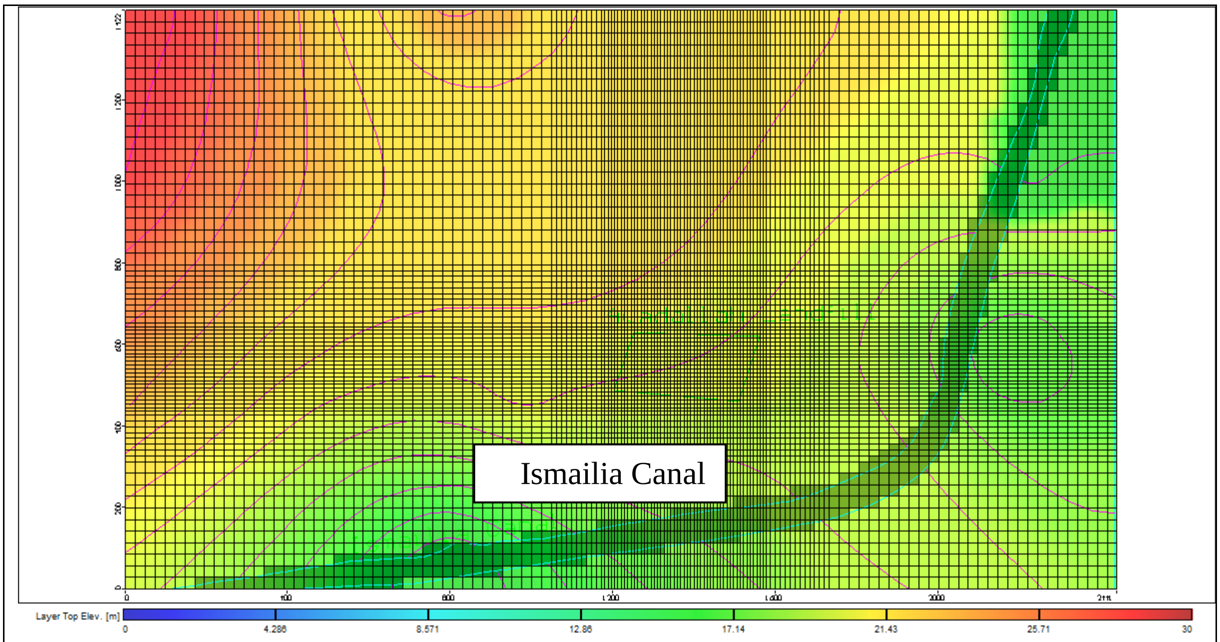


Figure 5. Visual Modflow model grid, showing surface layer elevations and model boundary

5.2 Boundary Conditions

As shown in Figure 5, Ismailia canal was modeled as a river boundary (Waterloo, 2005). The source of groundwater contaminant under this research study is the lead in the landfill, which will infiltrate the soil surface and recharge into the groundwater aquifer with rainfall and any surface water recharge. The infiltration pattern in the area is complex and influenced by industrial activities. The better description of recharge pattern has been obtained using information regarding areas in which groundwater may be recharged. The rainfall recharge was taken 25.5mm/yr.

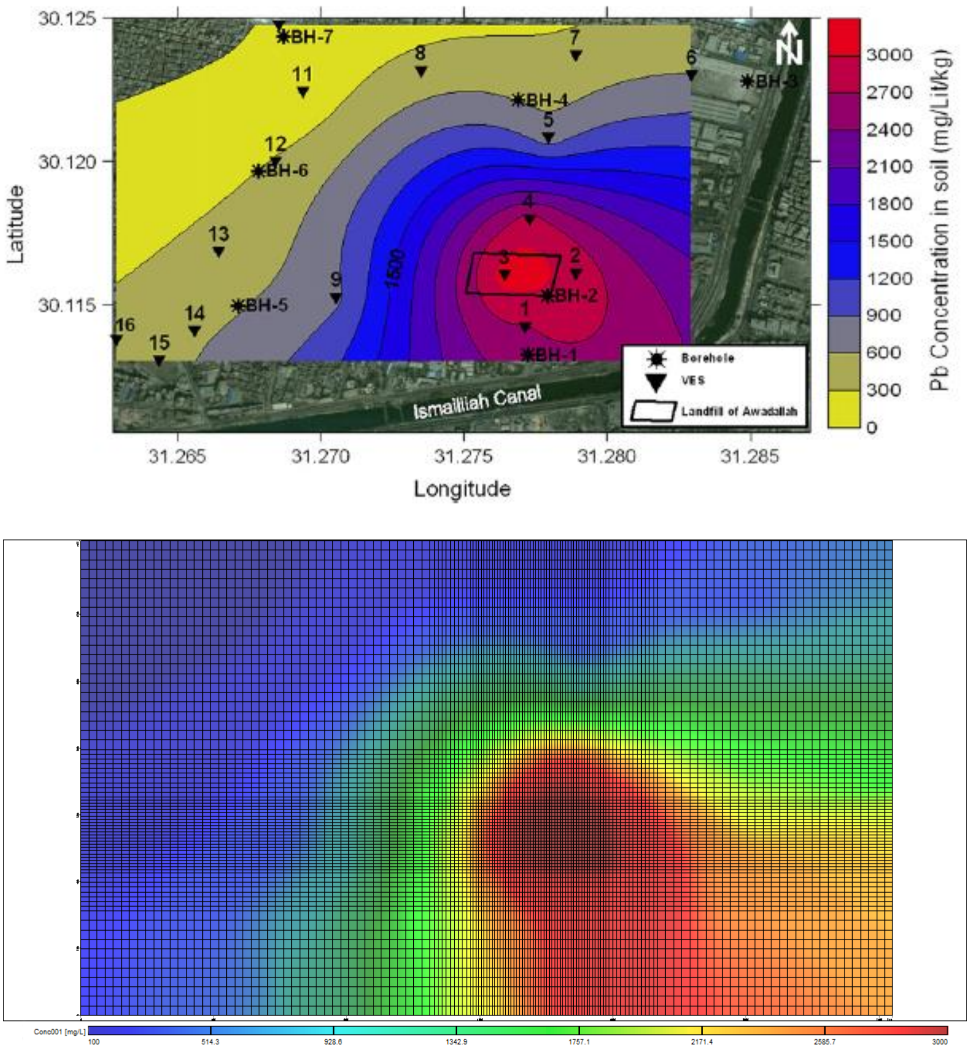
No flow boundary has been applied, but this has been verified the possibility that there should be flux across parts of these boundaries. The lower clayey horizon has been selected as the lower model boundary.

5.3 MT3DMS Contaminant Transport Simulation

High concentration of lead has been detected both in the soil and water samples collected in the study area. The major problem is to evaluate the possible migration of the heavy metals into the groundwater aquifer. With this aim, a set of transport simulations have been addressed, describing the contaminant movement in the subsurface for different scenarios. Preliminary advection-dispersion transport simulations mainly for lead that have a lower affinity for the aqueous phase, the simulation of the behavior described above would require the knowledge of the distribution coefficient K_d to simulate the reactive nature of the metal with a linear isotherm, Baes et al. (1983) recommend a value of 4.6 ml/g as a mean value. Longitudinal and transversal dispersivities have been set to 50 and 5.0m, respectively (Fetter, 1993). Due to the lack of data to implement an accurate adsorption/de-sorption model; only preliminary simulation has been run using the Modflow-MT3DMS contaminant transport module. Hence, model results have been used for the purpose of evaluating the possible "best" scenario to stop the migration of lead from the landfill.

5.4 Model Validation

The MT3DMS simulation was incorporated into the transient MODFLOW simulation model. The MT3DMS model was validated by comparing numerical model predictions with the results of geotechnical and geophysical investigation carried by Khalil (2013), the results of the numerical model prediction in line with the observed data are presented graphically in Figure 6.



a.

b.

Figure 6. Soil lead concentrations: a. Observed data (after Khalil, 2013), b. predicted results

From Figure 6, it can be noted that:

1. The observation of 3000 mg/L at landfill site was predicted which is very near the observed data (3130 mg/L). The percent error is less than 5%.
2. The migration of lead is very similar as the observed data, the lead concentration decreases in the north-west direction.
3. Lead is leaching and it may contaminate Ismailia Canal.

5.5 Remediation Scenarios

Several scenarios were numerically investigated to increase the environmental quality of the study area and to prevent further migration of lead into groundwater aquifer, however, problems related to the aquifer are not completely solved by these scenarios. To reserve space, the proposed scenarios can be summarized (without detailed simulation results) as follows:

1. Construction of Cut-off wall to prevent groundwater recharge from Ismailia Canal. The cut-off wall was modeled as impermeable with depth of 20m and thickness of 0.35m and surrounds the landfill from the south and east side. The numerical simulation results show that the cut-off wall has a limited effect on the migration of lead into the groundwater aquifer.
2. Covering the landfill to prevent the surface recharge which was simulated by assuming no surface recharge. The numerical simulation shows that it has a minor effect due to the effect of groundwater recharge on lead migration.
3. Converting the landfill into a sanitary landfill which was simulated by assuming zero initial concentration and zero recharge. The numerical simulation shows that no further migration of lead into groundwater, also the concentration of lead will be decreased dramatically to reach to safe limit after eight years.

6 CONCLUSIONS

A hydrogeological model was performed using Modflow-MT3DMS to study the effect of abundant lead landfill located in Shoubra El Kheima city on soil and groundwater. All the available hydrological and geological data have been used to set up, and validate the numerical model. Within the limitation of the present research paper and study area, it can be concluded that:

- The landfill poses a harmful health effect due to high concentration of lead soil and in groundwater.
- The landfill contaminates the groundwater aquifer due to leaching of lead.
- The best remediation action to prevent lead leachate from the landfill into the aquifer is to transfer the landfill into a sanitary landfill.
- Numerical simulations have served as a preliminary evaluation tool to indicate that there is a possibility of the contaminants distributed in the area to reach the Ismailia Canal.
- Numerical simulations have proved to a powerful toll to improve our knowledge of the main features of the flow field that acts as the forcing factor of the transport of lead in the subsurface.

The study highly recommended the implementation of the best remediation scenario to prevent leachate from the landfill to reach the groundwater aquifer.

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