Mathematical modeling of heavy metals contamination from MSW landfill site in Khon Kaen, Thailand
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ABSTRACT

Kham Bon landfill site is one of many municipality waste disposal sites in Thailand which are in an unsanitary condition. The site has been receiving municipality wastes without separating hazardous waste since 1968. Heavy metals including, Pb, Cr and Cd are found in soil and groundwater around the site, posing a health risk to people living nearby. In this research, contamination transport modelling of Pb, Cr and Cd was simulated using MODFLOW for two periods, at the present (2010) and 20 years prediction (2030). Model results showed that heavy metals, especially Pb and Cr migrated toward the north-eastern and south-eastern direction. The 20 years prediction showed that, heavy metals tend to move from the top soil to the deeper aquifer. The migration would not exceed 500 m radius from the landfill centre in the next 20 years, which is considered to be a slow process. From the simulation model, it is recommended that a mitigation measure should be performed to reduce the risk from landfill contamination. Hazardous waste should be separated for proper management. Groundwater contamination in the aquifer should be closely monitored. Consumption of groundwater in a 500 m radius must be avoided. In addition, rehabilitation of the landfill site should be undertaken to prevent further mobilization of pollutants.

Key words | contamination, heavy metals, landfill, landfill leachate

INTRODUCTION

In communities where hazardous waste is not properly separated from MSW (municipal solid waste), hazardous waste in the form of paint containers, insecticide containers, used oil, mercury-containing waste, used batteries, and many other diffuse products are co-disposed with MSW in landfills. These landfills are releasing toxic substances, such as heavy metals, into groundwater, although, the majority of heavy metals would remain in the landfill since they have strong attenuation by sorption and precipitation in the plume (Baun & Christensen 2004). However, there are several reports on the dispersion of Pb and Cd with leachate found in and around sanitary landfill sites (Anuluxtipun 2002; Kasassi et al. 2008).

Kham Bon landfill site in Khon Kaen province, Thailand, has been operating for more than 30 years receiving community waste. Hazardous wastes are being disposed of along with MSW, causing heavy metals contamination (PCD 1998). Heavy metals including cadmium (Cd), chromium (Cr) and lead (Pb) were found in monitoring wells, private wells, wells used for community water supply (Kayandee 1999; Chuangcham et al. 2008) and soil around the site (Promlao et al. 2007). The Thai Government is aware of the problem and has a plan to solve the environmental issues. However, before the environmental planning of the landfill can be performed and mitigation measures can be implemented, it is necessary to comprehensively characterize heavy metals in the landfill. Understanding the migration behaviour of pollutant in groundwater is the key issue that can be used to devise the groundwater management of the aquifer system.

The study of groundwater contamination using mathematical models has become a popular tool for a decision maker to access the site condition. In the last few decades, hundreds of computer programs for simulating various aspects of soil groundwater systems have been developed. The great advantage of the computer is that large amounts of data can be processed promptly so that many possible situations for a given problem can be studied.

Thus, this research focuses on employing groundwater and a heavy metals transportation model for prediction of
heavy metals concentration in groundwater. MODFLOW (three-dimensional block-centred finite-difference groundwater flow model), a computer program, developed by Waterloo Hydrogeologic Software (WHS) is used to simulate groundwater flow and contamination transport of heavy metals around Kham Bon Landfill Site. The results are used to explain the contamination pathway and to predict heavy metals concentration in groundwater in the future.

SITE DESCRIPTION

Site characteristic

The study area lies within the boundaries of the Kham Bon Sub District, Khon Kaen Province, Thailand. The center of the site is at UTM Zone 48 Q 266,125 m E 1,835,999 m N. It is about 17 km north of Khon Kaen city along national highway A2 (Friendship Highway) as shown in Figure 1. The site covers an area of 156,800 sq. m. The community closest to the landfill is Kham Bon Noi community with approximately 70 households and a population of 200 persons. It is located about 200 m south of the site. The community makes their living by sorting garbage in the landfill to collect and sell recyclable items to recycle shops nearby.

The landfill receives approximately 200 tons/day of MSW from Khon Kaen municipality along with 15 nearby communities. Waste disposed of at this site consists of food, plastic, paper and cardboard, wood, glass, metals and related municipal garbage. The site has problems caused from poor operational conditions and an inadequate disposal area. Wastes are mixed together without proper sorting or compacting and are piled on the ground for natural decomposition. In addition to the MSW, hazardous waste such as batteries, used fluorescent lamps, used aerosol spray cans, insecticide containers and paint containers are also being co-disposed (Kirathithorn 2004). Leachate from the site containing various pollutants and toxic substances, especially heavy metals, are migrating, infiltrating and descending via surface runoff and seepage to the surrounding area. Heavy metals from this site have been leaching into the soil, surface water and groundwater to the nearby area.

Site geology

The site is on Khorat plateau. The geological features are the Khorat group of sedimentary rocks, Phu Phan and Khok Kruat formation. Phu Phan formation consists of conglomeratic sandstones. Khok Kruat consists of red silt stones, sandstones and conglomerates. Alluvial sediments of the Quaternary age are also found on top of the Phu Phan formation in some areas.

Surface and groundwater direction

The site is situated on top of elevated land, surrounded by crop cultivation, typically cassava, sugar cane, eucalyptus and rice. It is located on a ridge about 180 to 220 m above mean sea level between Mak Ngo Creek at the North and Kham Bon Creek at the South. The soil surface slopes gradually down eastwards to the Phong River at the east.

Surface water drains in 2 pathways. First, surface runoff drains northwards from the site into Sam Chan reservoir and then flows eastwards to Mak Ngo Creek before discharging to Phong River. Second, runoff drains southwards into Kham Bon Creek and then flows to Bung Kae Reservoir and

Figure 1 | Location of Kham Bon landfill site.
the Phong River. Groundwater aquifer depth in the area is less than 1.0 m in some areas during the wet season and about 3–8 m during dry seasons. Groundwater flows from east to west toward the Phong River.

**GROUNDWATER MODELING**

In this research, 3D groundwater flow and transport models were selected based upon the hydrogeological characterization and model conceptualization. Computer program, Visual MODFLOW 3.1 developed by Waterloo Hydrogeologic Software (WHS), was used to determine the contaminant distribution pathway and to assess the possible impact of heavy metals contamination on the groundwater. The study area covered a 2 km radius from the landfill center. The groundwater flow model was calibrated under steady-state conditions. Details about parameter input, model calibration and contamination prediction results are as follows.

**Parameter input**

**Topographic Data**

The topographic data used is based on Thai’s Military map scale 1:50,000. The map was digitized using the AutoCAD program. The AutoCAD file extension was changed from a .dxf file to a text file before importing to Visual MODFLOW.

**Geologic Data**

The data was obtained from a soil boring test following ASTM D-1587. Ten undisturbed sample type soil test borings, each drilled to a depth of 100 m, around 2 km from the center of the landfill, were performed during November–December 2009. The boring results show that soil in the area can be divided into 3 layers based on soil characteristics. The soil mainly consist of 3 soil types; sand, clayed sand and sandstone with a thickness of 10, 15 and 25 m, from the top soil respectively.

**Hydrologic Data**

Precipitation data from Thai Metrologic Department for 30 years from 1978 to 2009 was used. Base on topography and land use, recharge in this model was divided into 2 zones which are the general area (15% of precipitation values) and the landfill area (85–90% of precipitation values). Hydrology data from field measurement in seven monitoring wells used for the model input is shown in Table 1.

**Dispersivity**

Dispersivity values input into the model is from Karlheinz & Moreno (1996). Sand longitudinal, horizontal and vertical dispersivity ratios are 3, 0.1 and 0.1, respectively. Clayed sand and sandstone longitudinal, horizontal and vertical dispersivity ratios are 1, 0.1 and 0.1, respectively.

**Distribution coefficient 
\( K_d \)**

This parameter affects the mobility of contaminant in soil. It depends on type of soil and is site specific. Distribution coefficient values input are from Chuangcham et al. (2008). \( K_d \) values for silty clay loam for Pb, Cr and Cd are 83.4, 16.5 and 32.3 l/kg, respectively. \( K_d \) values for sand for Pb, Cr and Cd are 8.8, 4.4 and 10.7 l/kg, respectively.

**Table 1 | Hydraulic head of seven monitoring wells**

<table>
<thead>
<tr>
<th>Name</th>
<th>East</th>
<th>North</th>
<th>Borehole elevation (m)</th>
<th>Groundwater level (m)</th>
<th>Observation head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KK1</td>
<td>265,705</td>
<td>1,835,893</td>
<td>194.627</td>
<td>5.6</td>
<td>189.027</td>
</tr>
<tr>
<td>KK2</td>
<td>266,119</td>
<td>1,836,284</td>
<td>182.399</td>
<td>1.35</td>
<td>181.05</td>
</tr>
<tr>
<td>KK3</td>
<td>266,113</td>
<td>1,836,087</td>
<td>185.103</td>
<td>2.24</td>
<td>182.86</td>
</tr>
<tr>
<td>KK4</td>
<td>266,192</td>
<td>1,836,060</td>
<td>190.393</td>
<td>7.55</td>
<td>148.89</td>
</tr>
<tr>
<td>KK5</td>
<td>266,317</td>
<td>1,836,110</td>
<td>192.507</td>
<td>4.7</td>
<td>187.807</td>
</tr>
<tr>
<td>KK6</td>
<td>265,911</td>
<td>1,835,899</td>
<td>192.876</td>
<td>7.3</td>
<td>185.576</td>
</tr>
<tr>
<td>KK7</td>
<td>266,185</td>
<td>1,835,931</td>
<td>187.702</td>
<td>3.25</td>
<td>184.452</td>
</tr>
</tbody>
</table>
$K_d$ values for silty loam sand for Pb, Cr and Cd are 30.8, 9.7 and 17.2 l/kg, respectively.

**Constants**

Hydraulic conductivity of soil specific storage ($S_s$), specific yield ($S_y$), total porosity ($n$) and effective porosity ($n_e$) were obtained from the values recommended by Karlheinz & Moreno (1996). Input parameter, hydraulic conductivity of waste is from PCD (1998) in the Kham Bon landfill site. Constants for input parameters used in the model are shown in Table 2.

**Initial concentration**

Initial concentrations from field sampling during February 2010, as shown in Table 3, were assigned in the model cell. Other boundaries are convective flux boundaries, adjusted until concentration of contaminants in the model are equal to the real concentration from the field data. The transport model was run at 180-day time intervals for a total of 20 years.

**Discretization**

The study covers an area of $2.36 \times 3.11$ km$^2$. The area was divided into 118 rows, 155 columns that followed the soil characteristics of the site. The location and width of the constant head boundary were designated based on an aerial photograph of the site, coupled with elevation data from direct surveys that were imported into Visual MODFLOW.

**Model opportunity, sensitivity and limitations**

Input data includes, hydraulic head, hydraulic conductivity, recharge/discharge, and contaminant sources were tested for sensitivity by comparing the partial $R^2$. It was found that hydraulic head had the most impact on the hydraulic gradient of groundwater simulated from the model. Other parameters provide low $R^2$ indication that they are not significant. Thus, it is important to calibrate the hydraulic head to be as close to the field measurement as possible. In this study, hydraulic field data was used to calibrate with model simulation.

The model was developed to investigate potential contamination of heavy metals from community landfill. Thirty years average annual precipitation data was used for model calibration. A large amount of data allows confidence in the model results. The model was developed based on the soil and hydrology characteristics of the site. Significant changes in groundwater would require revised calculations of recharge and perhaps additional calibration.

**Model calibration**

Model calibration was done by adjusting parameters until the degree of fit between the simulated and observed water levels was less than 10%. Average differences between simulated and measured head is commonly expressed by

Table 2 | Constants used in groundwater model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Layer 1</th>
<th>Layer 2</th>
<th>Layer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Hydraulic conductivity of soil</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 $K_x$</td>
<td>m/d</td>
<td>1</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>1.2 $K_y$</td>
<td>m/d</td>
<td>1</td>
<td>0.01</td>
<td>1</td>
</tr>
<tr>
<td>1.3 $K_z$</td>
<td>m/d</td>
<td>0.1</td>
<td>0.001</td>
<td>0.1</td>
</tr>
<tr>
<td>2. Hydraulic conductivity of waste layer $K_x = K_y = K_z$</td>
<td>m/d</td>
<td>0.864</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Specific storage ($S_s$)</td>
<td></td>
<td>0.01</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>4. Specific yield ($S_y$)</td>
<td></td>
<td>0.2</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>5. Total porosity ($n$)</td>
<td></td>
<td>0.33</td>
<td>0.29</td>
<td>0.2</td>
</tr>
<tr>
<td>6. Effective porosity ($n_e$)</td>
<td></td>
<td>0.22</td>
<td>0.2</td>
<td>0.15</td>
</tr>
<tr>
<td>7. Recharge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1 General area</td>
<td>mm/yr</td>
<td>0</td>
<td>35.73</td>
<td></td>
</tr>
<tr>
<td>7.2 Landfill area</td>
<td>mm/yr</td>
<td>100</td>
<td>426</td>
<td></td>
</tr>
<tr>
<td>8. Evapotranspiration</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8.1 General area</td>
<td>mm/yr</td>
<td>100</td>
<td>120</td>
<td></td>
</tr>
<tr>
<td>8.2 Landfill area</td>
<td>mm/yr</td>
<td>50</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>9. Extinction depth</td>
<td>m</td>
<td></td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>10. Contaminated area</td>
<td>m$^2$</td>
<td></td>
<td>$2.36 \times 3.11$</td>
<td></td>
</tr>
<tr>
<td>11. Simulation time</td>
<td>Years</td>
<td></td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Table 3 | Metals concentration for contaminant transport model

<table>
<thead>
<tr>
<th>Location of samples</th>
<th>Pb</th>
<th>Cr</th>
<th>Cd</th>
</tr>
</thead>
<tbody>
<tr>
<td>KK1</td>
<td>0.04</td>
<td>0.018</td>
<td>0.01</td>
</tr>
<tr>
<td>KK2</td>
<td>0.24</td>
<td>0.027</td>
<td>Name</td>
</tr>
<tr>
<td>KK3</td>
<td>0.08</td>
<td>0.027</td>
<td>N/D</td>
</tr>
<tr>
<td>KK4</td>
<td>0.21</td>
<td>0.026</td>
<td>N/D</td>
</tr>
<tr>
<td>KK5</td>
<td>0.32</td>
<td>0.038</td>
<td>N/D</td>
</tr>
<tr>
<td>KK6</td>
<td>0.17</td>
<td>0.027</td>
<td>0.01</td>
</tr>
<tr>
<td>KK7</td>
<td>0.17</td>
<td>0.028</td>
<td>0.01</td>
</tr>
</tbody>
</table>

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standard error, the root mean square (RMS) and correlation coefficient. From the calibration, the maximum residual obtained was 1.65 m and the absolute residual mean obtained was 0.908 m. The normalized residual mean square error of the model was 13.11%. The normalized residual mean was 0.675 m. The observation versus predicted head values had a correlation coefficient of 0.995 m. In general, the model-simulated heads were slightly higher than the observed heads. Model results revealed that groundwater flow direction from landfill is from west to east.

**Contamination prediction results**

After calibration, the model was used to predict contaminant transport conditions in the future. The migration pathway and concentrations of contaminants in groundwater were elucidated using the model. Results are shown in Figures 2–4.

Figures 2(a) and (b) showed contamination of Pb in year 2010. From the figure, contamination of Pb is higher in the northeast direction. This is due to the site geology where water drains northwards from the site into Sam Chan reservoir and flows eastwards to Mak Ngo Creek. Concentration in Layer 1 (0–10 m from surface) is higher than in Layer 2 (10–25 m from surface). Figures 2(c) and (d) are a prediction of Pb contamination in year 2030. From the results, heavy metals tend to move from the top soil to the deeper aquifer. The horizontal distance does not expand while the vertical distance goes further down. The migration does not exceed 500 m after 20 years and can be considered a slow process. The results herein correspond to simulation results reported by Tiwary et al. (2005). This is because, Pb tends to accumulate in the soil surface. Soil organic matter may immobilize Pb via specific adsorption reactions (Yong et al. 2001; Sharma & Reddy 2004).

Contamination plumes of Cr are displayed in Figure 3. The directions of Cr migration are the same as Pb. Cd migration covers the smallest area and lowest concentration due to its low solubility (Figure 4). Cd migration also shows a similar pattern to Pb and Cr. Usually, concentration of Pb and Cr in landfill soil is similar (less than 2,000 mg/kg) where concentration of Cd found was very low (less than 6 mg/kg) (Anuluxtipun 2002; Ösman et al. 2006; Xiaoli et al. 2007; Kasassi et al. 2008; Vijukrattana 2009).
Figure 3 | Plume of Cr from MODFLOW simulation. (a) Year 2010 (0–10 m underground). (b) Year 2010 (10–15 m underground). (c) Year 2030 (0–10 m underground). (d) Year 2030 (10–15 m underground).

Figure 4 | Plume of Cd from MODFLOW simulation. (a) Year 2010 (0–10 m underground). (b) Year 2010 (10–15 m underground). (c) Year 2030 (0–10 m underground). (d) Year 2030 (10–15 m underground).
From the field survey, it was found that contamination occurred mainly from surface runoff. The 20 years simulation was run under the assumption that the leachate collection system is constructed and well operated. From the assumption of the simulation, it can be concluded that even when the leachate collection system is applied, contamination still migrates to the aquifer. Thus, a mitigation measure is required.

**Proposed mitigation measures**

From the simulation results, it was found that it is likely to be contaminated with a high level of heavy metals in a 500 m radius. In addition, there is a possibility of further metals contamination in the future. Thus, mitigation measures are proposed as follows.

**Short-term strategies:**
1. Inform villagers to avoid the consumption of groundwater in a 500 m radius.
2. Find alternative clean water source for the villagers.
3. Separate hazardous waste from MSW.
4. Apply liner/cover to prevent leachate and runoff from the landfill.

**Long-term strategies:**
1. Rehabilitate the landfill site to prevent further mobilization of pollutants.
2. Monitor for groundwater contamination.

**CONCLUSIONS**

In this study, a Visual MODFLOW model was used to predict the distribution pathway of heavy metals contamination from Kham Bon landfill site for the next 20 years. Hydrology model calibration provided maximum residual at 1.65 m and the absolute residual mean is 0.908 m. The normalized residual mean square error of the model is 13.11%. The normalized residual mean is 0.675 m. The observation versus predicted head values has a correlation coefficient of 0.995 m. Model results revealed that groundwater flow direction from landfill is from west to east.

The model was generated to show the Pb, Cr and Cd migration pathway, which showed that heavy metals especially Pb and Cr migrate to northeast and southeast more than other parts. Base on site geology, water drains northwards from the site into Sam Chan reservoir and flows eastwards to Mak Ngo Creek. The degree of migration was Pb > Cr > Cd. In the next 20 years, heavy metals predictions tend to move from the top soil to the deeper aquifer. The horizontal distance does not expand while vertical distance goes further down. The migration would not exceed 500 m after 20 years and the migration is considered a slow process. Even when the leachate collection system is applied, contamination still migrates to the aquifer. Thus, mitigation measures such as avoiding consumption of groundwater nearby the landfill, sorting hazardous waste, monitoring groundwater and rehabilitation of the landfill site are required.

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