BIO-GEOCHEMICAL SIMULATION FOR SOLUTE TRANSPORT IN PIYUNGAN LANDFILL, YOGYAKARTA SPECIAL PROVINCE, INDONESIA

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Abstract

Piyungan Landfill is the largest in Bantul Regency. According to water quality sampling taken from a leachate pond, there are significant contaminant issues resulting from landfill leachate. The objectives of this research were achieved by applying a two-dimensional bacteria mediated reduction numerical model was applied. Method of characteristic was applied to solve the advection part of the solute transport equation. Three bacteria (X_1, X_2, and X_3) groups were defined in the redox model. In the conceptual model, bacterial X_1 utilizes oxygen under aerobic conditions and nitrate, NO_3^- under aerobic conditions as electron acceptors. Consequently, under aerobic conditions bacteria X_2, and X_3 utilize MnO_2, and $Fe(OH)_3$ respectively as electron acceptors. In the redox model organic carbon which was defined as CH_2O was considered as the electron donor for all bacteria mediated reduction reactions. The results of research are to improve the understanding of biogeochemical processes in aquifer.
Keywords: *landfill leachate, hydrogeological factors, numerical model, redox modeling.*

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1 Introduction

Piyungan landfill is a dumping site of waste disposal from human activities' products, which has operated since 1995 and is the biggest landfill in Bantul Regency. Day by day the wastes are increasing in Yogyakarta and dumped in Piyungan landfill that can produce leachate (wastewater from leachate), which gives value of contaminant concentration. Based on Putra *et al.* (2001), the research for two-dimensional horizontal solute transport had been done; the plume was extended along the flow which moves from southern to northern part (Putra, 2001).

Furthermore, the existing of sanitary landfill still can bring a negative impact to the surrounding environment. The problems of groundwater contamination from leachate leakage always occur on the aquifer on the landfill area. Issue of groundwater contamination such as heavy metal and dissolved organic carbon, caused by leachate leakage in Piyungan Landfill has been reported by the local communities of Banyakan village (Putra *et al.*, 2001). Banyakan village is located more or less 700 m northern of Piyungan landfill (Figure 1).

Beside that there are still many researches of groundwater in Yogyakarta which are being performed. Some graduation papers of undergraduate and postgraduate students of Gadjah
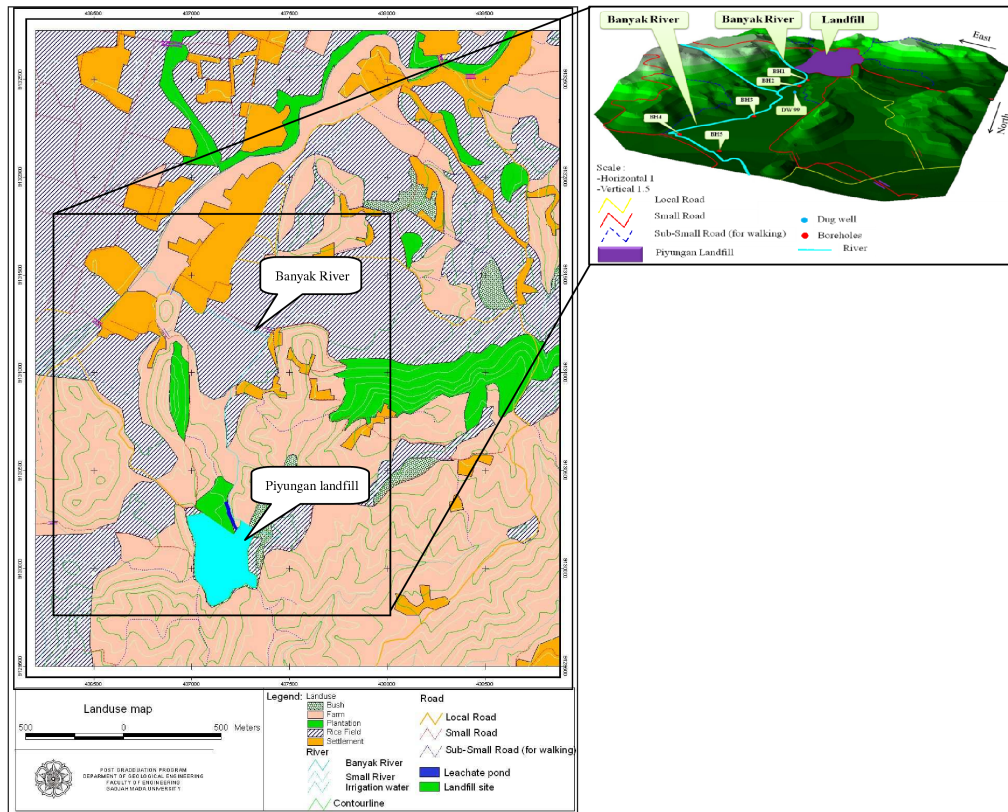
Figure 1: Location map and tree-dimensional view of the study area (North-South)

Mada University are contributed to groundwater problem in Bantul regency. Although many researches of groundwater had been done in this landfill, the study about contaminant transport from Piyungan landfill must be continued to give more understanding about redox reaction in groundwater systems.

Therefore, in order to give more understanding of contaminant transport from landfill, the modeling of redox from landfill will be focused on this research works must be simulated.

2 Site condition

This study area occupies the morphology of the river plains of the railroad. It is the result of fluvial deposition of Opak river. This unit spreads widely about 10.58% of the total mapped area. As well as alluvial deposits, outcrops of this unit found along river banks of Opak (Putra, 2001). Description and the characteristics of Opak fluvial deposit is as follows: spreading along the flow of Opak river, brown-

gray, clayey sand-sized further down the coarse grain size and gravel, sorting is quite good, layered with changes not clear, and below are the tuffaceous sandstones and agglomerates. The thickness on the river bank of Opak river reachs approximately 12-15 meters (see Figure 2).

3 Theoretical Background

Based on the research of Perera *et al.* (2009), the model explains the utilization of O_2, NO_3^-, MnO_2, $Fe(OH)_3$ and SO_4^{2-} as electron acceptors for oxidation of organic carbon in the aquifer under aerobic and anaerobic conditions. The conceptual model consists of three different phases named as bio phase, mobile phase and matrix phase. Model parameters are adopted from literature on bacteria mediated multi-component modelling and bioremediation processes. Monod kinetic equation is used to formulate the bacterial growth (Perera *et al.*, 2009). The model explains the behaviours of aerobic and anaerobic bacteria under the avail-
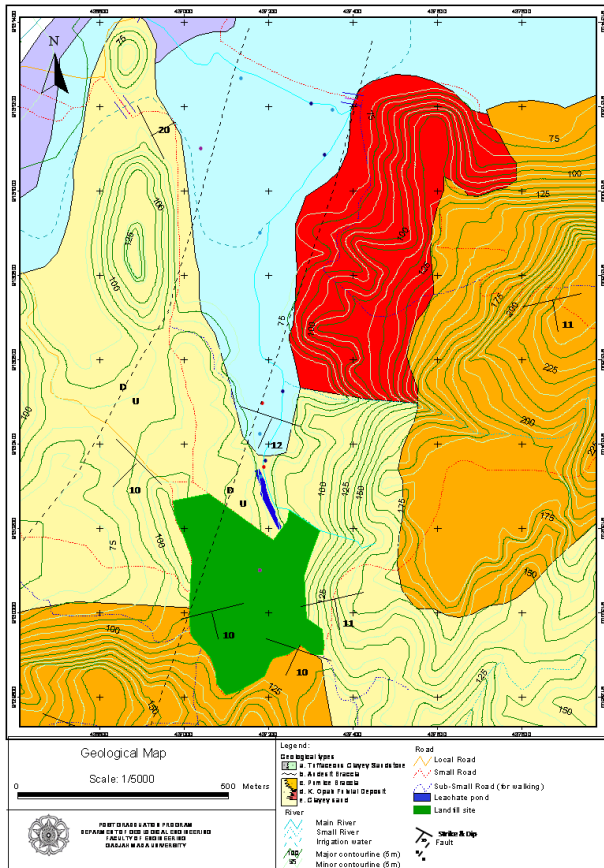
Figure 2: Geological map of study area (redrawn and modified from Putra, 2001)

growth, precipitation of $Fe(OH)_3$ in the mixing zone of the water region source.
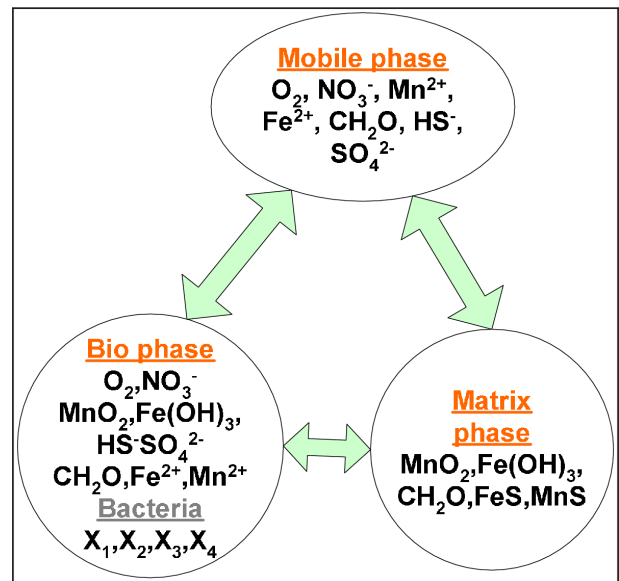
Figure 3: Conceptualization of redox model (Perera *et al.*, 2009)

ability of organic carbon. The redox simulation of this research focuses on the possibility of the simulation of the formation of reduced environments in groundwater aquifers which purpose to know and understand the redox reaction in groundwater environment (Figure 3).

Bacteria group X_1 uses oxygen under aerobic conditions and NO_3^- under anaerobic conditions as electron acceptor. Anaerobic bacterial groups X_2, X_3 and X_4 use MnO_2, $Fe(OH)_3$ and SO_4^{2-} as electron acceptors respectively (Perera *et al.*, 2009). Organic carbon which behaves as the electron donor is considered as the most important factor for the bacteria mediated reduction processes (Figure 3). On the Figure 3 shows the chemical species considered in the redox model and species exchange between different phases. The redox model describes the interactions between O_2, NO_3^-, MnO_2, $Fe(OH)_3$, SO_4^{2-}, organic carbon concentrations, bacterial

Exchange processes considered between the different model phases can be summarized as; (a) the mobile phase and the bio phase; (b) the mobile phase and the matrix phase; and (c) the bio phase and the matrix phase. The redox model describes the biological degradation of organic carbon by different bacterial groups and the precipitation of $Fe(OH)_3$ and FeS (Perera *et al.*, 2009). Microbial mediated redox sequences of reactions as shown in Figure 4, (aerobic oxidation, NO_3^- reduction, MnO_2 reduction, $Fe(OH)_3$ reduction and SO_4^{2-} reduction) are modelled with four bacteria groups (X_1, X_2, X_3, and X_4).

The general form of contaminant transport equation for the mobile components in the aqueous phase with the reaction term can be written as follow (Perera *et al.*, 2009):

$$\frac{\partial C_{mob}}{\partial t} + \frac{u'\partial C_{mob}}{\partial x} + \frac{v'\partial C_{mob}}{\partial y} =$$
$$\frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C_{mob}}{\partial x} + D_{xy}\frac{\partial C_{mob}}{\partial y}\right) +$$
$$\frac{\partial}{\partial y}\left(D_{yy}\frac{\partial C_{mob}}{\partial y} + D_{yx}\frac{\partial C_{mob}}{\partial x}\right) + \sum_{i=1}^{3} S_i \quad (1)$$

Where Cmob is the mobile phase species concentration. u' and v' are the components of real
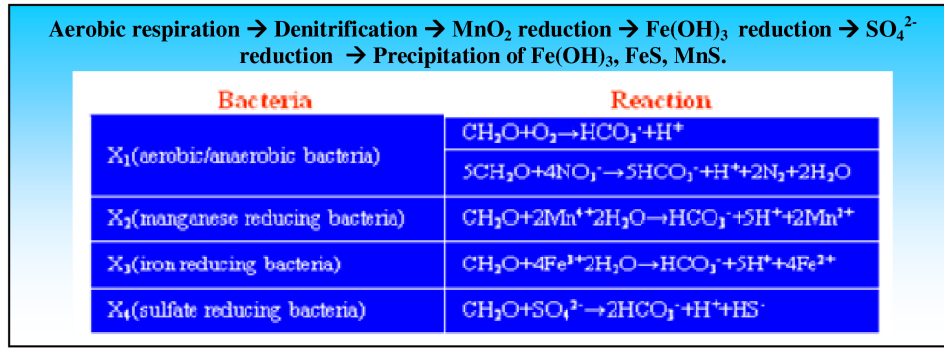
Figure 4: Sequence of major biological reactions considered in the biogeochemical model (Perera *et al.*, 2009)

pore velocities in x and y directions. S_i is the source/sink term which represents the solute exchange between different phases.

The dispersion coefficients, dependent on the real pore velocity, are represented as follows (in Perera *et al.*, 2008):

$$
\begin{aligned}
D_{xx} &= \frac{\alpha_L u'^2}{V} + \frac{\alpha_T v'^2}{V} + \tau \cdot D_M \\
D_{yy} &= \frac{\alpha_T u'^2}{V} + \frac{\alpha_L u'^2}{V} + \tau \cdot D_M \quad (2)\\
D_{xy} &= D_{yx} = \frac{(\alpha_L - \alpha_T) u' v'}{V}
\end{aligned}
$$

Where α_L and α_T are the microscopic dispersion lengths related to the sand particle diameter, $v = \sqrt{(u'^2 + v'^2)}$, and D_M is the fluid molecular diffusion coefficient. τ is the tortuosity (Perera *et al.*, 2008).

The source-sink term (S_i) of Equation (3) describes the solute exchange between model phases. The solute exchange driving force is the difference between the concentrations of the species in different phases. The following equations describe the solute exchange between model phases (Perera *et al.*, 2009).

The exchange of solute between the mobile phase and the bio phase S_1 is defined as:

$$
\begin{aligned}
S_1 &= \frac{\alpha(1-\varepsilon_0)}{a} \cdot \frac{\theta_{bio}\sqrt{D_L}}{\theta_{bio}+\theta_w} \left(C_{bio} - C_{mob}\right) \\
&= \alpha' \left(C_{bio} - C_{mob}\right) \quad (3)\\
\alpha' &= \frac{\alpha(1-\varepsilon_0)}{a} \cdot \frac{\theta_{bio}\sqrt{D_L}}{\theta_{bio}+\theta_w}
\end{aligned}
$$

The exchange of solute between the mobile phase and the matrix phase S_2 is defined as:

$$
\begin{aligned}
S_2 &= \frac{\beta(1-\varepsilon_0)}{a} \cdot \frac{\theta_{mat}\sqrt{D_L}}{\theta_{mat}+\theta_w} \left(C_{mat} - C_{mob}\right) \\
&= \beta' \left(C_{mat} - C_{mob}\right) \quad (4)\\
\beta' &= \frac{\beta(1-\varepsilon_0)}{a} \cdot \frac{\theta_{bio}\sqrt{D_L}}{\theta_{bio}+\theta_w}
\end{aligned}
$$

The exchange of solute between the bio and matrix phases S_3 is defined as:

$$
\begin{aligned}
S_3 &= \frac{\gamma(1-\varepsilon_0)}{a} \cdot \frac{\theta_{mat}\sqrt{D_L}}{\theta_{bio}+\theta_{mat}} \left(C_{bio} - C_{mat}\right) \\
&= \alpha' \left(C_{bio} - C_{mat}\right) \quad (5)\\
\gamma' &= \frac{\gamma(1-\varepsilon_0)}{a} \cdot \frac{\theta_{bio}\sqrt{D_L}}{\theta_{bio}+\theta_w}
\end{aligned}
$$

Where C_{mob}, C_{bio} and C_{mat} are the concentrations of solute in the mobile phase, bio phase and matrix phase respectively. α is the exchange coefficient between bio phase and mobile phase. β is the exchange coefficient between matrix phase and mobile phase. γ is the exchange coefficient between bio phase and matrix phase. α', β' and γ' are the simplified exchange coefficients. ε_0 is the initial porosity, a is the diameter of uniform soil particle and bio, mat and w are the specific volume of bio, matrix and mobile phases respectively. D_L is the dispersion coefficient (Perera *et al.*, 2009).

4   Methods

Finite different approximation is used to solve the problem. The finite difference approximations are derived from the fundamental definition of derivative and Taylor series expansion of a function $f(x)$. When a function $f(x)$ and

its derivatives are single valued, finite, and continuous function of x, then by Taylor's series (in Jinno *et al.*, 2001).

The method of characteristic is one of the solution technique used to solve the solute transport in porous media. It was originally applied by Garder *et al.* (1964) for calculation of miscible displacement in reservoir simulation

5 Results and Discussions

The some parameters to input the redox model were show in Keophousone *et al.* (2010a). Based on Keophousone *et al.* (2010b), the research of two-dimensional groundwater flow was simulated; therefore the flow modeling has been simulated again for satisfying with parameters data and site situation. Beside the flow simulation, the solute transport has been simulated either (in Keophousone *et al.*, 2010c), and the calibration of parameter were edited afterward to make the model in reality.

The redox model was applied to the selected cross section under the following chemical species distribution which is shown in Table 1. Redox model was applied for two years of simulation and results are shown for bacteria growth, mobile phase species and matrix phase species along the borehole BH1 were chosen. Thus, the organic carbon supply from the matrix phase was kept constant and the velocity profile was followed as done for flow simulation (Keophousone *et al.*, 2010). Moreover, constant supplies of MnO_2 are also assigned. The organic carbon (1.0 mg/L; Perera *et al.*, 2009) is continuously supplied from the top soil layer where cocist of sandy silt. Oxygen is infiltrated from the ground surface at the constant concentration of 8 mg/L with the infiltrated water (Perera *et al.*, 2009).

On Table 1 shows the initial conditions assigned for redox model and the assigned boundary conditions for the simulation. The initial bacterial concentrations for aerobic and anaerobic bacteria were kept as 0.001 mg/L. Redox model was applied for two years simulation and results are shown for bacteria growth, mobile phase species and matrix phase species along the borehole BH1.

As shown on Figure 6 to 8, the obtained numerical results show the formation of two reduced zones. One reduced zone has been formed at depths between 0.0 m and 0.7 m, and another one has been formed below 2.3 m depth, this result can be observed by matrix phase (Figure 7). The reason for the redox zone is obvious.

Aerobic Oxidation, Denitrification and Growth of Bacteria X_1

According to Figure 6, bacteria X_1 growth is dominant in the freshwater region (Figure 6) and no or less growth can be seen in the anaerobic source region of the aquifer. The gradual decrease of CH_2O in the aerobic freshwater region is the main reason for the decrease of bacteria X_1 growth after 30 days.

Due to the consumption of CH_2O in the freshwater region of bio phase by bacteria X_1, CH_2O in the freshwater region of the matrix phase is decreased and it is correctly simulated and shown in Figure 7. The growth of bacteria X_1 in the freshwater region is controlled by the available CH_2O. As a result of continuous infiltration of rainwater with the 8 mg/L of O_2 concentration, there is enough O_2 for bacteria X_1 to grow. However, there is no constant CH_2O supply for the freshwater region. Therefore, when the available CH_2O is consumed, the growth of bacteria X_1 hinders. Moreover, in Figure 8, NO_3^- concentration decreases gradually due to the denitrifying (NO_3^- reduce to bacteria X_1) process of bacteria X_1. The concentration variations of O_2 and NO_3^- with the metabolism of bacteria X_1 imply that the redox model can simulate the growth of aerobic and denitrify bacteria under the available CH_2O appropriately.

Reduction of MnO_2 and growth of bacteria X_2

Formation of Mn^{2+} and Fe^{2+} could be observed as a result of the reduction of MnO_2 and $Fe(OH)_3$ below 2.3 m. Bacteria X_2 reduce MnO_2 to Mn^{2+} under anaerobic conditions. Figure 7 shows the growth of MnO_2 reducing bacteria X_2. The decrease of MnO_2 in the matrix phase (Figure 7) corresponds well with the bacteria X_2 growth which is shown in Figure 6.

Table 1: Initial chemical species distribution for redox model

Chemical Species	Mobile phase (mg/L)		Bio phase (mg/L)	Matrix phase (mg/L)
	Fresh water	Source water		
O_2	0.0	3.4	0.0	-
NO_3^-	0.05	0.002	0.0	-
MnO_2	-	-	0.0	5.0
$Fe(OH)_3$	-	-	0.0	1.5
Fe^{2+}	0.0	0.0	0.0	-
Mn^{2+}	0.0	0.0	0.0	-
CH_2O	0.6	0.5	0.0	0.5
SO_4^{2-}	12.0	500	-	-
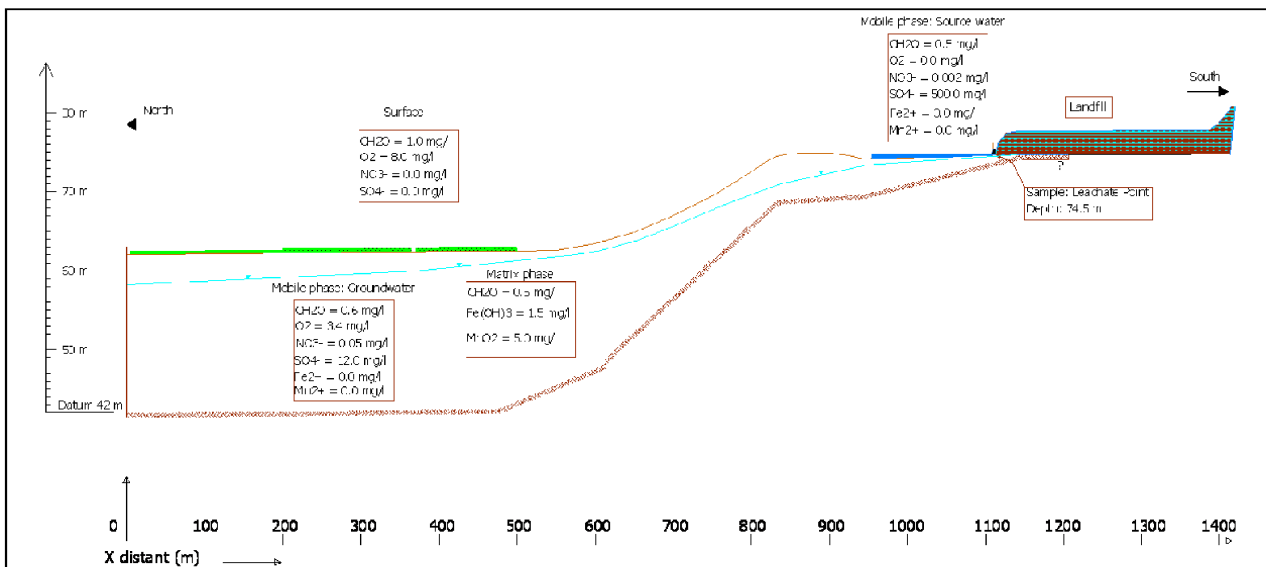
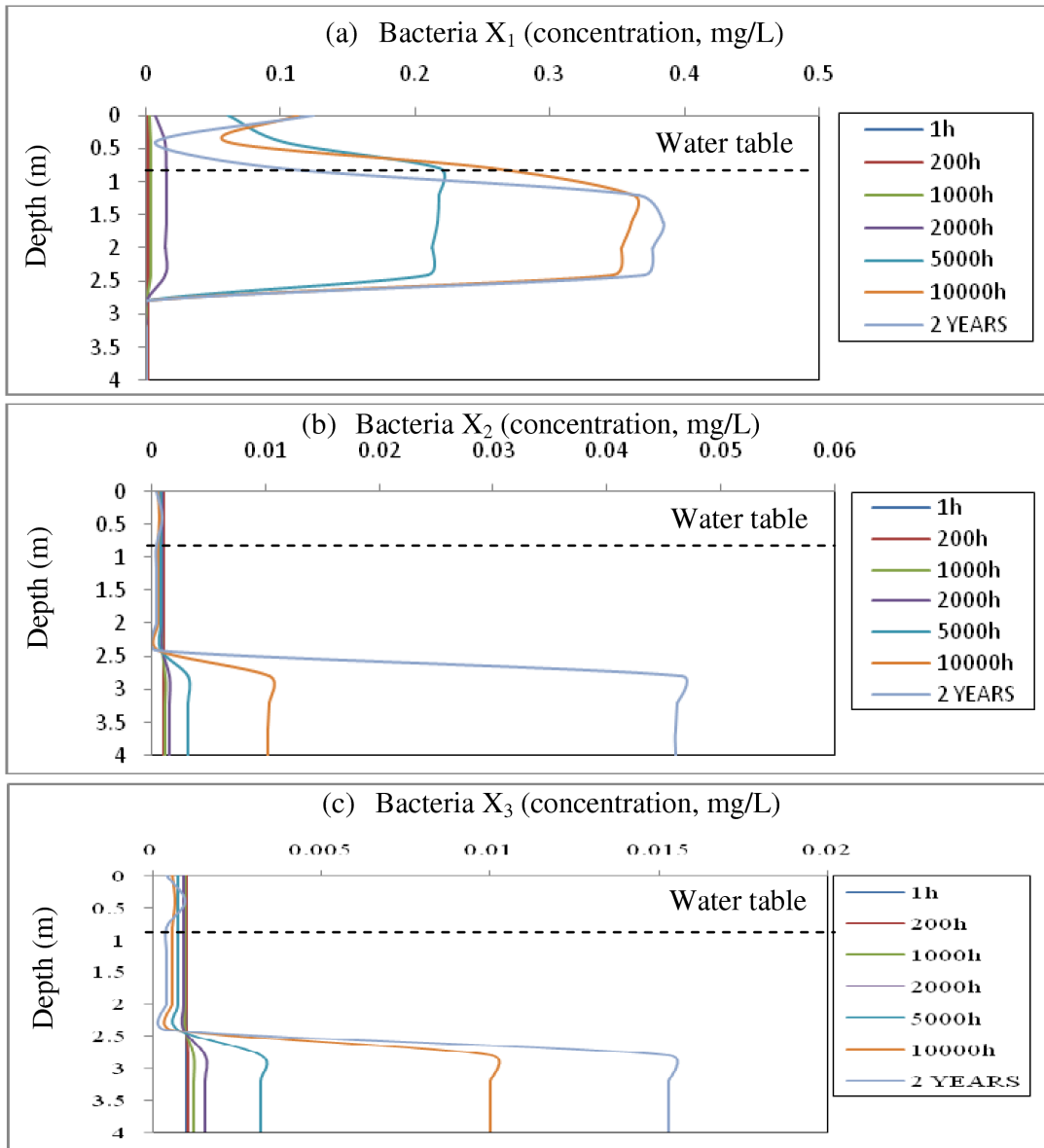Figure 5: Initial and boundaries of chemical species distribution for redox model

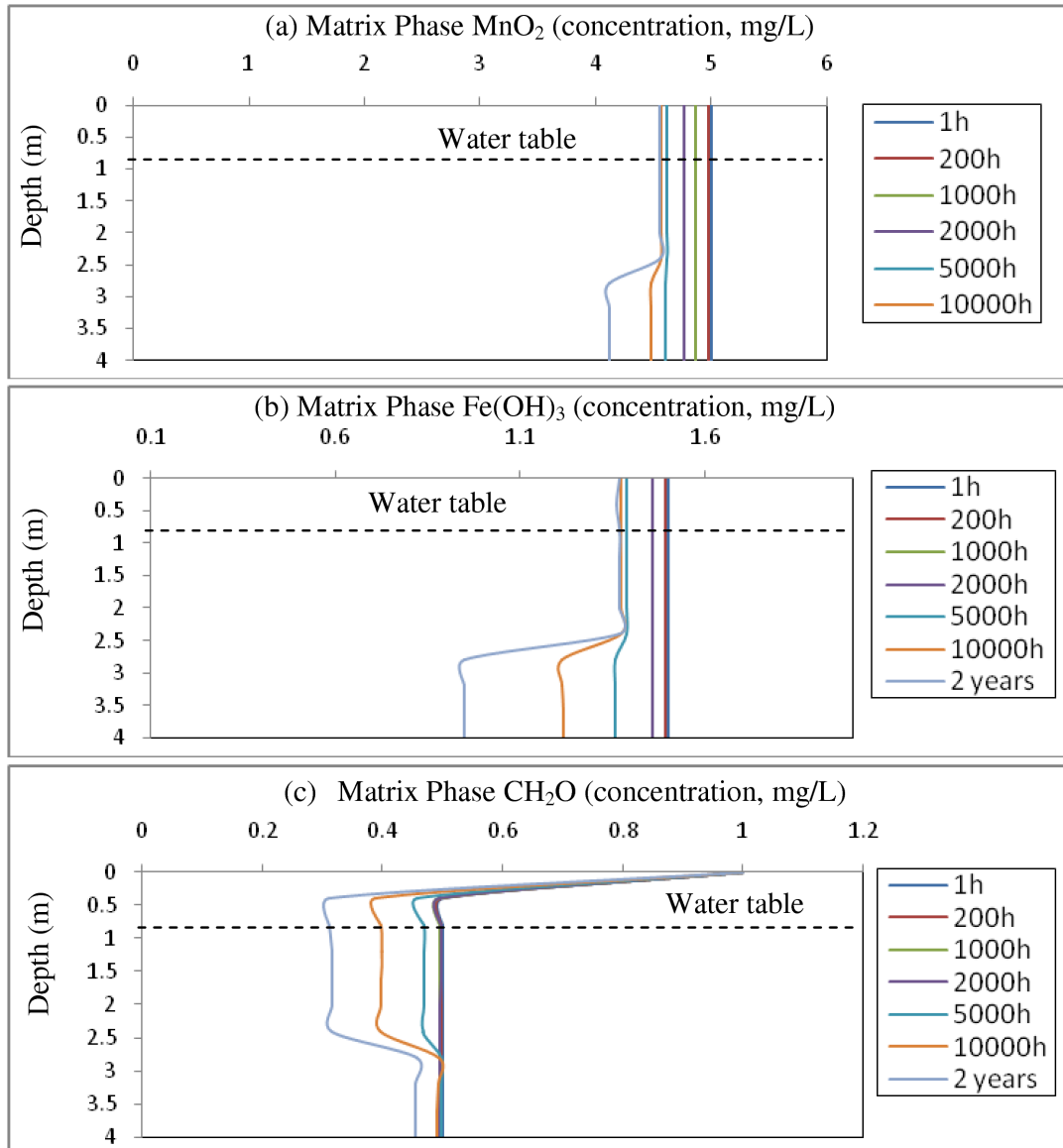Figure 6: Numerical results for aerobic and anaerobic bacterial growth (at BH1)

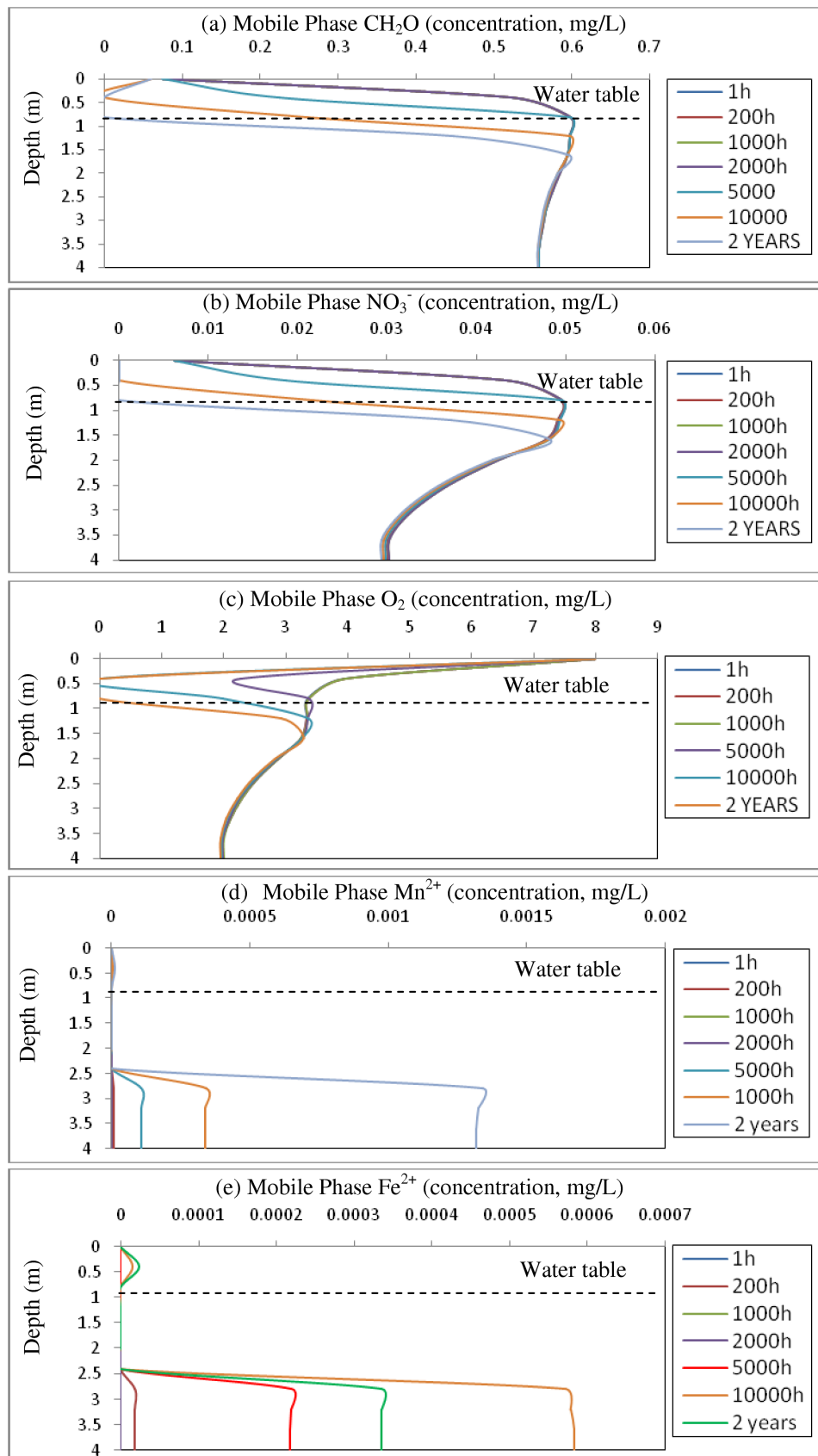Figure 7: Numerical results for concentration variations of the matrix phase species (at BH1)

Figure 8: Numerical results for concentration variations of the mobile phase species (at BH1)

Figure 8 shows the concentration of formed Mn^{2+} in mobile phase. Bacteria X_2 growth is significant in the anaerobic source region of the aquifer. Constant CH_2O layer provides abundant electron donor environment which is favorable for bacterial growth. According to Figure 6 growth of bacteria X_2 increases up to 2 years. The reason for that is the availability of MnO_2. Bacteria X_2 use available MnO_2 in the organic carbon region. Availability of CH_2O and MnO_2 under anaerobic condition is favorable for the growth of bacteria X_2. Availability of CH_2O and MnO_2 in the anaerobic region are the determining factors for bacteria X_2. Redox model is able to simulate the growth of bacteria X_2 appropriately under the assigned conditions.

Reduction of Fe(OH)₃, the growth of bacteria X₃ and precipitation of Fe(OH)₃

The reduction of $Fe(OH)_3$ occurs in the anaerobic region due to the metabolism of bacteria X_3 in the redox model. On Figure 8 shows the formation of Fe^{2+} in mobile phase due to the reduction of $Fe(OH)_3$ in the bio phase. Figure 6 shows the bacteria X_3 growth for ten years while in Figure 7 shows the concentration changes of $Fe(OH)_3$ in the matrix phase.

The decrease of the growth of bacteria X_3 in the constant CH_2O layer is due to the consumption of $Fe(OH)_3$ in the bottom of the aquifer. Therefore, bacteria X_3 grows in that region until all the $Fe(OH)_3$ is reduced by bacteria X_3. The precipitation of formed Fe^{2+} takes place in the mixing zone area, where O_2 is available. The reduction of $Fe(OH)_3$ takes place in the lower part of mixing zone and anaerobic source region of the aquifer at different rates according to the availability of CH_2O and $Fe(OH)_3$. High concentration of dissolved Fe^{2+} is a common water quality problem associated with groundwater. Therefore, the reduction of $Fe(OH)_3$ is an important process to be considered in numerical simulations to enhance the understanding of biological involvement in groundwater.

The formed Fe^{2+} moves to the mixing zone with the advective flow and meets O_2 and precipitates as $Fe(OH)_3$. The precipitation of $Fe(OH)_3$ is highlighted as the increase of

$Fe(OH)_3$ concentration in the matrix zone. In Figure 7, the gradual increase of $Fe(OH)_3$ concentration in the mixing zone region (elevation between 2.1 m to 2.3 m) depicts the precipitation of $Fe(OH)_3$. The Fe^{2+} concentration increases around the 2.3 m elevation in the mobile phase (Figure 8) is due the reduction of precipitated $Fe(OH)_3$ in bottom edge of the mixing zone.

6 Conclusions

The calculation result shows that biochemical processes are important and must be taken to be considered in groundwater quality problem. The simulation results show the trends of groundwater quality alteration such as denitrification, MnO_2 reduction and $Fe(OH)_3$ reduction. Therefore, due to the limitations in the field measurements and difficulties in the biogeochemical parameter identification, it was impossible to simulate the exact situation which is prevailing in the Piyungan landfill area. Further efforts are needed to modify the redox model parameters in the case where more accurate groundwater chemistry is needed.

Acknowledgements

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