Bulletin of the Geological Society of Malaysia, Volume 58, December 2012, pp. 23 – 27

Influence of variable fluxes and sorption properties on Mn^{2+} transport under single, binary, and multiple metals through lateritic aquifer

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Abstract: Contamination of underlying aquifers in gold mining areas is usually a great concern and prevention plans need to be implemented. To assess the potential risk of heavy metal contamination, the simulation of heavy metal transport was carried out using variable leachate fluxes and chemical nonequilibrium two-site sorption parameters derived from column experiments. This study applied a numerical model, called the HYDRUS-2D, to simulate the transport of Mn^{2+} under a single metal and multi-metal systems with 2 variable leachate fluxes (0.002 and 0.0026 m/day) through a lateritic aquifer approximately 5 km downgradient of the tailing pond. This model could be used as an environmental monitoring tool for gold mining management. The model assumed that the compacted clay layer of the tailing storage facility (TSF) has cracked and this led to Mn^{2+} and some other elements to contaminate the shallow groundwater. The simulations showed that the time needed to reach from contamination to the Thailand drinking water standard at a specific location for Mn^{2+} in a multi-metal system was faster than those in the binary metal system and single metal system, respectively. With increasing leachate flux from 0.002 to 0.0026 m/day (30% increase), the time to reach the drinking water standard at well no. 1 (1 km downgradient, the nearest well to the source) was about 57 and 106 years (17 and 19% decrease, respectively) for Mn^{2+} under the multi-metal and single metal systems. In addition, the timing of the heavy metal contamination leached from the tailings may be a source of pollution for over hundreds to thousands of years. As indicated by the simulation results, the predicted impacts of contamination of the TSF on the groundwater quality in the lateritic aquifer indicate that sorption parameters and leachate fluxes should be carefully monitored. These visible descriptions should be used as management tools for planning well installations under field conditions.

Keywords: lateritic aquifer, chemical nonequilibrium sorption, HYDRUS-2D, modeling

INTRODUCTION

The transport of heavy metals leached from the mine tailings to the groundwater system needs to be realistically predicted to assess the risk (Pang, 1995; Van der Grift & Griffioen, 2008). To predict the risk, one needs to develop and select the most appropriate strategies in monitoring and remediating the contaminated site. According to the study of Chotpantarat (2008), the chemical nonequilibrium two-site model described the heavy metals transport in lateritic soil better than the equilibrium convection-dispersion models. Consequently, the parameters obtained from chemical nonequilibrium two-site model were applied for field-scale metal transport simulations.

Moreover, one of the most important parameters is water flux from a tailing pond due to clay liner cracking. Mn^{2+} was chosen as the representative heavy metal because it leaches from tailings higher than other metals (Chotpantarat, 2008). The numerical model used for field-scale simulation in this study was HYDRUS-2D (Šimůnek *et al*., 1999) which can evaluate the potential transport and contamination of heavy metals in groundwater. The objective of this study was to simulate the movement of heavy metals leached from mine tailings through shallow groundwater systems with variable leachate fluxes and different sorption parameters.

STUDY AREA

The Akara mining site located about 280 km north of Bangkok in Phichit Province, central Thailand was selected for the study (Figure 1). A tailing storage facility (TSF) in the mine has been designed to safely store the mine tailings. The TSF is located on the southern portion of the mining site (Figure 1). It covers an area of approximately 320,000 m^2.

Groundwater levels typically conform to the surface topography. A north-south orientated hydraulic groundwater divide is located through Khao Mo and Khao Pong. Natural

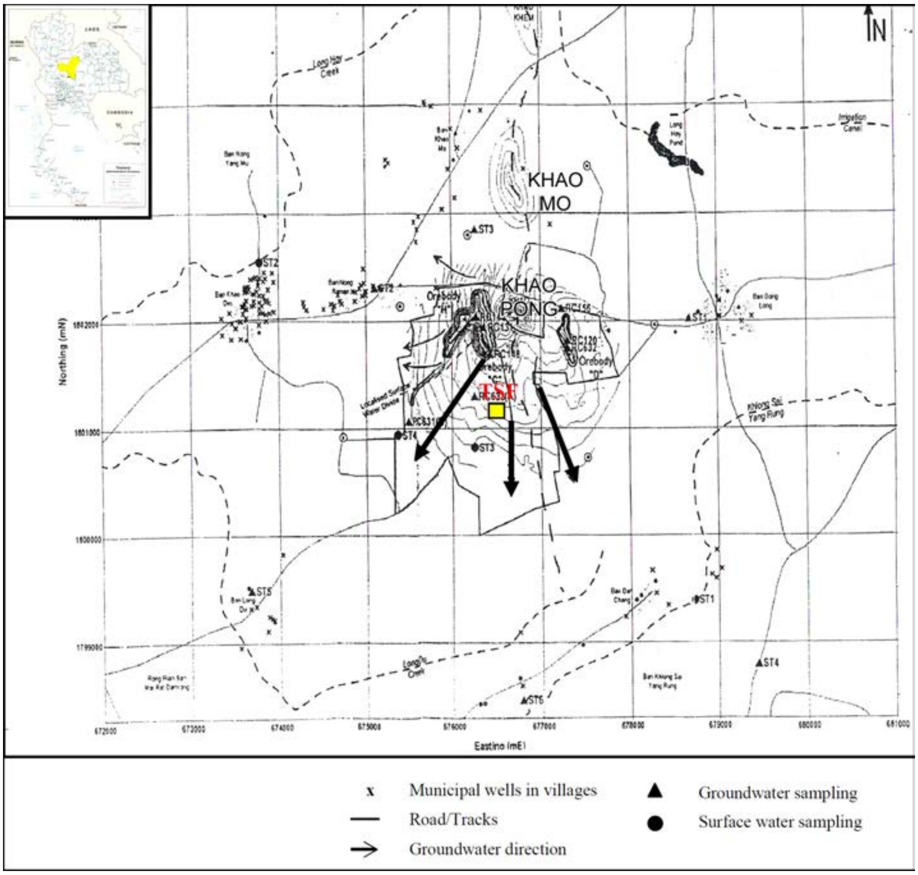

Figure 1: Map showing location and groundwater flow in the Akara mining site (from URS, 1999).

groundwater flows from the ore bodies in C-H mining pit in a southwest direction to the adjacent areas (Figure 1).

The shallow groundwater wells in the nearby villages were mainly dug into the aquifer of the lateritic layer at depths between 1.5 and 7 metres. The soil profile in the surrounding area consists of a top soil layer over the whole area with a thickness of approximately 20 to 40 cm, a lateritic layer with about 1.5 to 7 meter thick and a thick clay layer between 4.3 - 11 meter thick forming at the bottom of soil sequence.

The simulations assumed that heavy metals were leaked under acidic condition (pH 5) from the tailing storage facility passing through the cracked liners and then through the lateritic soil reaching the shallow groundwater system. Although it may not happen in the real situation, the result can be also used for monitoring and prevention plans.

FORECAST OF LONG TERM IMPACTS

Effect of simultaneous metals on groundwater quality

To investigate the importance of proper sorption parameters obtained from column studies under different environmental conditions, the sorption parameters (Table 1) are derived from different environmental conditions (Chotpantarat, 2008) were applied to a field scenario where the compacted clay liner was assumed to be cracked.

Figure 2 shows the schematic simulation of the heavy metals transport from the TSF. For simplicity, it was assumed that the lateritic layer has a uniform thickness of 7 meters and hydraulic gradient is 0.001 m/m. It was assumed that the maximum concentrations of heavy metals leached from the column desorption experiments (Chotpantarat, 2008) were transported continuously to the lateritic soil.

The input parameters are listed in Table 1. The background concentrations of Mn^{2+} in the lateritic aquifer layer were assumed to be zero. With the assumed initial concentration C_0, and the sorption parameters obtained from chemical nonequilibriuim two-site model (Table 1), the predicted heavy metal concentration in the municipal shallow wells are shown in Figure 2**.** These wells were located at 1, 2, 3 and 4 km from the source, respectively.

The computer simulation using HYDRUS-2D shows the results from the influence of simultaneous presence of other metals on the transport of Mn^{2+} in lateritic soil in Figure 3 which the Mn^{2+} concentrations detected for each well (y-axis) versus the time to reach required Mn^{2+} concentrations (x-axis). The time needed to reach the Thailand drinking water standard of Mn^{2+} at well no. 1 (nearest well from the source) was about 70, 114 and 130 years under multi-metal, binary and single metal systems, respectively (Table 2). For the wells located further away from the source (TSF), the time to reach the standard in well nos. 2-4 was increased respectively. Mn^{2+} under multi-metal systems seems to move faster than those under single and binary metal systems and it would exceed the standard in approximately 70 years. In the multi-metal system, the times to reach the standard for

Table 1: Input parameters for heavy metal transport for HYDRUS-2D simulation.

Parameter	value
Longitudinal dispersivity, m	500
Transverse dispersivity, m	50
Bulk density (g cm^{-3})	1.23
Residual water content	0.1035
Saturated water content	0.5233
Saturated hydraulic conductivity, m day^{-1}	0.76
Water flux, mm day^{-1}	0.02 and 0.026
Sorption parameters#, Q_{max}, mM g^{-1} and b, L mM^{-1}	0.12 and 0.80 for Mn^{2+} (single system) 0.05 and 1.61 for Mn^{2+} (binary system) 0.04 and 0.88 for Mn^{2+} (multi-metal system)
Nonequilibrium parameters#, f (-) and α (hr^{-1})	0.33 and 0.02 for Mn^{2+} (single system) 0.47 and 0.04 for Mn^{2+} (binary system) 0.48 and 0.05 for Mn^{2+} (multi-metal system)
Initial concentration, C_0, mg L^{-1}	40 for Mn^{2+}
Thailand drinking water standard, mg L^{-1}	0.3 for Mn^{2+}

#Derived from previous study (Chotpantarat, 2008)

Mn^{2+} at specific locations appear to reduce about two times as compared with those in single metal system. This has potential impact for the shallow groundwater and should be of concern in monitoring and prevention strategies. Moreover, the transports of Mn^{2+} in multi-metal system compared to those in single and binary metal systems may be a result of the competition of heavy metals on the sorption sites. This result is supported from data of a previous column study (Chotpantarat, 2008). Where lower values of maximum sorption capacity and retardation factor (R_f = 6.95) of Mn^{2+} in multi-metal system was recorded as compared with those in the single (R_f = 19.22) and binary metal systems (R_f = 10.40) (Chotpantarat, 2008).

Effect of variable fluxes on groundwater quality

During the mining processing, enormous amounts of tailings are generated and dumped into the TSF, which could cause clay liner cracking. As a consequence, when it rains, the water flux infiltrates through the mine tailings with a relative high potential increase in the Mn^{2+} concentration in the mine tailings leachate. In addition, during the post-closure of the mine, an increase in the head difference between the leachate in the TSF and the water table might be one of the major factor affecting an increasing water flux through the clay liner (Du & Hayashi, 2006).

Figure 4 shows the computer simulation results of variable fluxes of leachate with a 30% increase from base case (0.002 m/day) to 0.0026m/day. The leachate is assumed to be infiltrating through lateritic aquifer as a result of the cracking of the compacted clay liner.

Increasing the water flux from the base case by 30%, the time needed to reach the Thailand drinking water standard of Mn^{2+} at well no. 1 (nearest well from the source) was reduced from 58 years (a 17% decrease) in a multimetal system to 106 years in a single metal systems (Table 3). In well nos. 2-4, the time needed to reach the

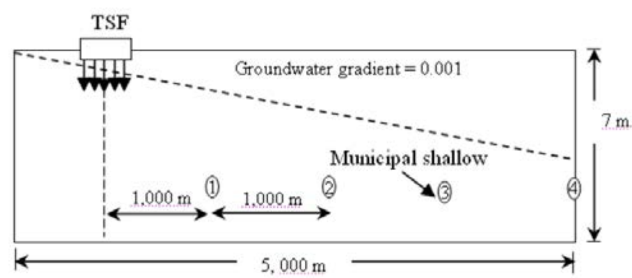

Figure 2: Schematic of the heavy metals transport leached from TSF through lateritic aquifer and positions of the assumed well nos 1-4 with 1 km distance between each well.

Table 2: Arrival times at well nos.1 to 4 under single metal, binary metal and multi-metal systems for Mn^{2+} concentration exceeding the drinking water standards of Thailand.

Well	Time exceeding the Thailand drinking water standard for Mn^{2+} (years)		
	Metal systems		
	Single	Binary	Multiple
1	130	114	70
2	340	292	190
3	560	478	310
4	770	650	430

Thailand drinking water standard of Mn^{2+} decreased about 20% compared with base case scenario for both single and multi-metal systems. When increasing the water flux by 30% from base case, the times needed to reach the standard for Mn^{2+} in the multi-metal system, appears to reduce about two times as compared with those in single metal system.

As mentioned above, it was concluded that the selection of the proper sorption parameters derived from column studies with the simultaneous presence of other heavy metals is very crucial. Moreover, to provide accurate infiltration

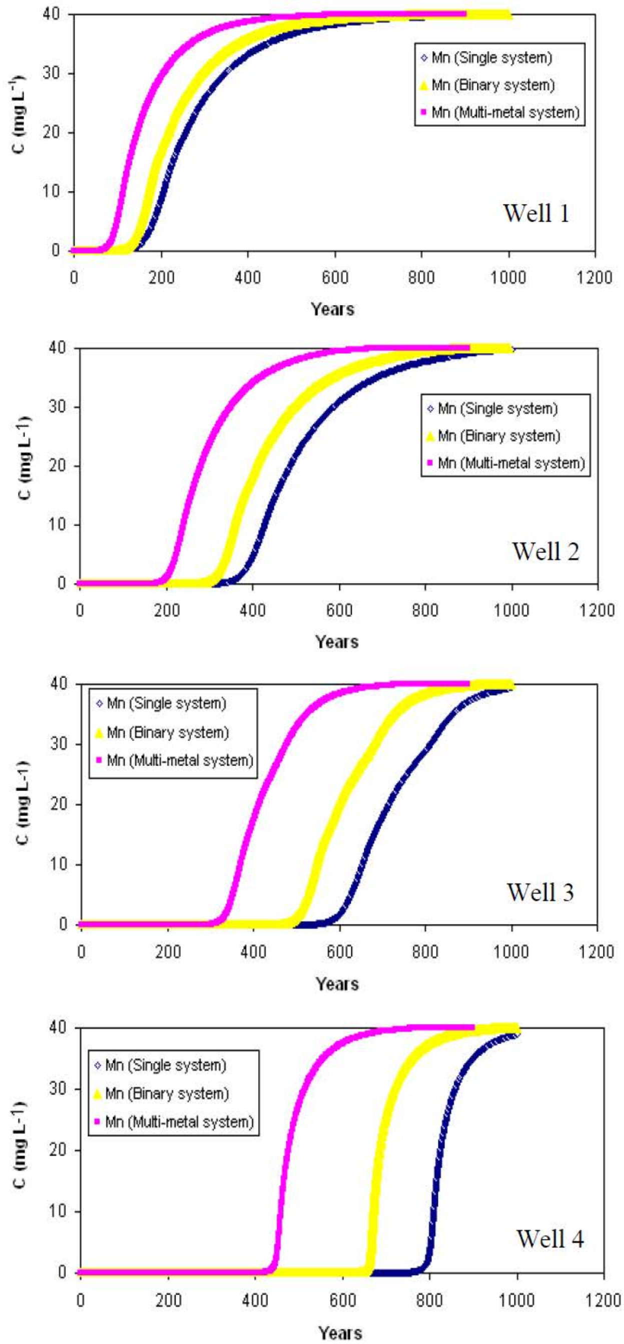

Figure 3: Concentrations of Mn^{2+}in the lateritic aquifer under single metal, binary metal and multi-metal systems in four wells representing various distances from the contaminant source (see Figure 1).

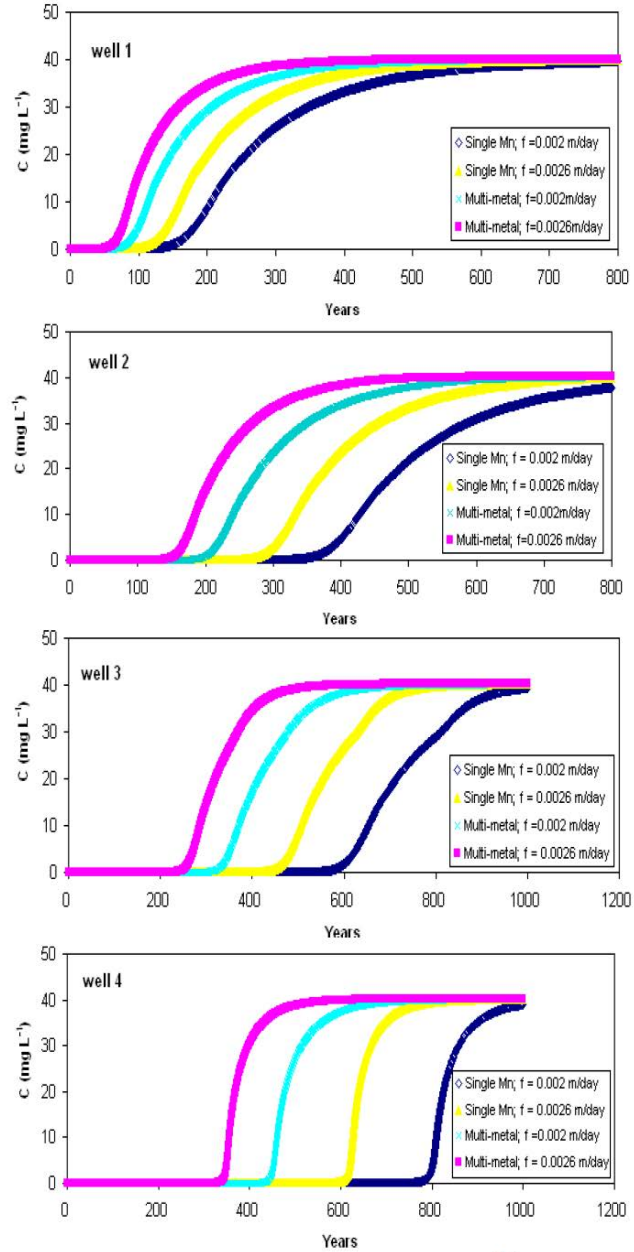

Figure 4: Concentrations of Mn^{2+}in the lateritic aquifer under single metal and multi-metal systems under variable flux in four wells representing various distances from the contaminant source (see Figure 1).

rates of water from the tailing ponds, the monitoring wells underneath the compacted clay liner of the tailing ponds should be monitored even after mine closure. The design and construction of compacted clay liner is critical due to high loading of the mine tailings and the long-term aging of the clay liner. If the clay liner was to crack, it will probably lead to high metal leachate through the subsurface environment. Moreover, the head difference in the TSF after mine closure might increase the risk that the leachate flux will migrate through the underlying aquifer. Therefore, predicting the potential impact with variable water fluxes and proper sorption parameters can help understand heavy metal transport through the subsurface. Further use of the model could help design the installation of the monitoring wells in field conditions.

However, these predicted simulations were initiated for simple cases. The simulation could be more accurate in its prediction if information from the field conditions is used for the model. For example, water levels or metal concentrations in the monitoring wells should be taken

Table 3: Arrival times at well nos.1 to 4 under single metal and multi-metal systems for Mn^{2+} concentration exceeding the drinking water standards of Thailand under variable fluxes.

well	Time exceeding the Thailand drinking water standard for Mn^{2+} (years)			
	Single system		Multi-metal system	
	f=0.002 m/d	f=0.0026 m/d (+30%)	f=0.002 m/d	f=0.0026 m/d (+30%)
1	130	106 (-19%)	70	58 (-17%)
2	340	271 (-20%)	190	149 (-22%)
3	560	444 (-21%)	310	248 (-20%)
4	770	602 (-22%)	430	340 (-21%)

into account. Moreover, the heavy metal transports may be affected by the other processes such as precipitation and dissolution of Fe-oxides and other chemical and biological processes. Further work should be carried out in detail for better prediction of the heavy metal transport under the field conditions.

CONCLUSION

The application of HYDRUS-2D model provided visible descriptions of heavy metal movement in lateritic aquifer under different environmental conditions. The sorption parameters and variable fluxes derived from column studies can be used as important parameters to predict heavy metal transport in field conditions. However, these sorption parameters obtained from different models and different environmental conditions are the critical effect for the prediction.

ACKNOWLEGDEMENTS

The authors are very grateful to the Ratchadapisek scholarship and Geology Department, Faculty of Science, Chulalongkorn University for the research funds provided during this study.

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Manuscript received: 15 March 2010