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SIMULATION OF PHOSPHORUS MIGRATION IN AN UNCONFINED AQUIFER: UNIVERSITI PUTRA MALAYSIA

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The distribution of phosphorus in groundwater was simulated on the University Putra Malaysia campus, within which a pond and a sludge area are located. The results show that the concentration of phosphorus in the sludge area is higher than those set by the National Water Quality Standard for Malaysia (NWQSM). The sludge is the dominant source of phosphorus within the study area. The phosphorus transport during 10 and 50 years was simulated and the probability of pollution of the pond was assessed. The results showed that the migration of contaminant in the first and second layers are not similar due to different hydraulic conductivity and other properties of soils. Results also indicated that vertical migration can be the most important aspect of phosphorus movement toward the pond.

INTRODUCTION

One of the critical and significant environmental problems caused by human activities in the world is the intensifying loading of nutrients into surface water and groundwater (Liu et al., 2008; Smil, 2000). Phosphorus is one of the inorganic nutrients that was released widely through activities such as mining, farming, animal husbandry, field erosion, and household consumption (Liu, 2008; Ismail, 2001).

Liu (2005) stated that one half of phosphorus (10.5 million metric tons) is lost in the world's croplands. This amount of phosphorus input to cropland cannot compensate for the phosphorus loss due to the considerable amount of total phosphorus being carried by groundwater (Smil, 2000). The loss of phosphorus needs to be controlled to ensure good water quality in the environment.

In Malaysia many plants, including oil palms, which are the primary crops in many areas, are not able to grow to maturity without application of phosphorus fertilizers due to deficiency of soil nutrients. Ninety percent of phosphorus in oil palm is derived from fertilizers (Zaharah et al., 1997). Due to the wide use of chemical fertilizers the Malaysian government has taken steps to protect and improve the water quality by defining the required standard for this parameter. The National Water Quality Standard for Malaysia (NWQSM) expresses values of phosphorus in groundwater for class IIA/IIB and III as 0.1 mg/l and 0.2 mg/l respectively (DOE, 2004). The main problem associated with increasing phosphorus is eutrophication which has adverse effects on ocean water and fresh water (Hauer, 2006; Smil, 2000). It can destroy fish and aquatic plants that are living in ponds and lakes due to reduction of dissolved oxygen. In the case of small lakes and most ponds, it causes adverse changes in the terrestrial and aquatic environments (Khan and Ansari, 2005).

It is well recognized that shallow lakes are almost always hydraulically connected to aquifer systems (Rahim et al., 2006). The interaction between surface waters and the groundwater in the study area had been investigated through the use of an integrated computer package, Visual MODFLOW, including MODFLOW (Harbaugh, 2005) and MT3DMS (Zheng, 2006). The models were used to simulate the groundwater flow and phosphorus concentration in the surface water and groundwater and the transportation of leached phosphorus in subsurface. The application of Visual MODFLOW has an important role for the effective protection and management of the high environmental values, especially in sites connected to lakes (Rahim et al., 2006).

The campus of University Putra Malaysia, Serdang, Selangor, Malaysia was chosen as the study area in the present research. A sludge pit and a pond are located at this site. The objective of the present research was to assess the likelihood that sludge was the main source of phosphorus to the pond and groundwater when the groundwater level dropped two meters inside the pond.

Investigation of the concentration of phosphorus will help to determine the distribution of this compound in groundwater, the pond, and sludge, as well as the possibility of eutrophication and change in the aquatic environment. This investigation is helpful in developing a plan to control the pollution in groundwater and the transportation of phosphorus to the pond.

METHODOLOGY

Study area

The study area covers 16.03 hectares inside the University Putra Malaysia, Serdang, toward the south of Kuala Lumpur (Figure 1). The land is gently sloping with elevations that range from38.0m

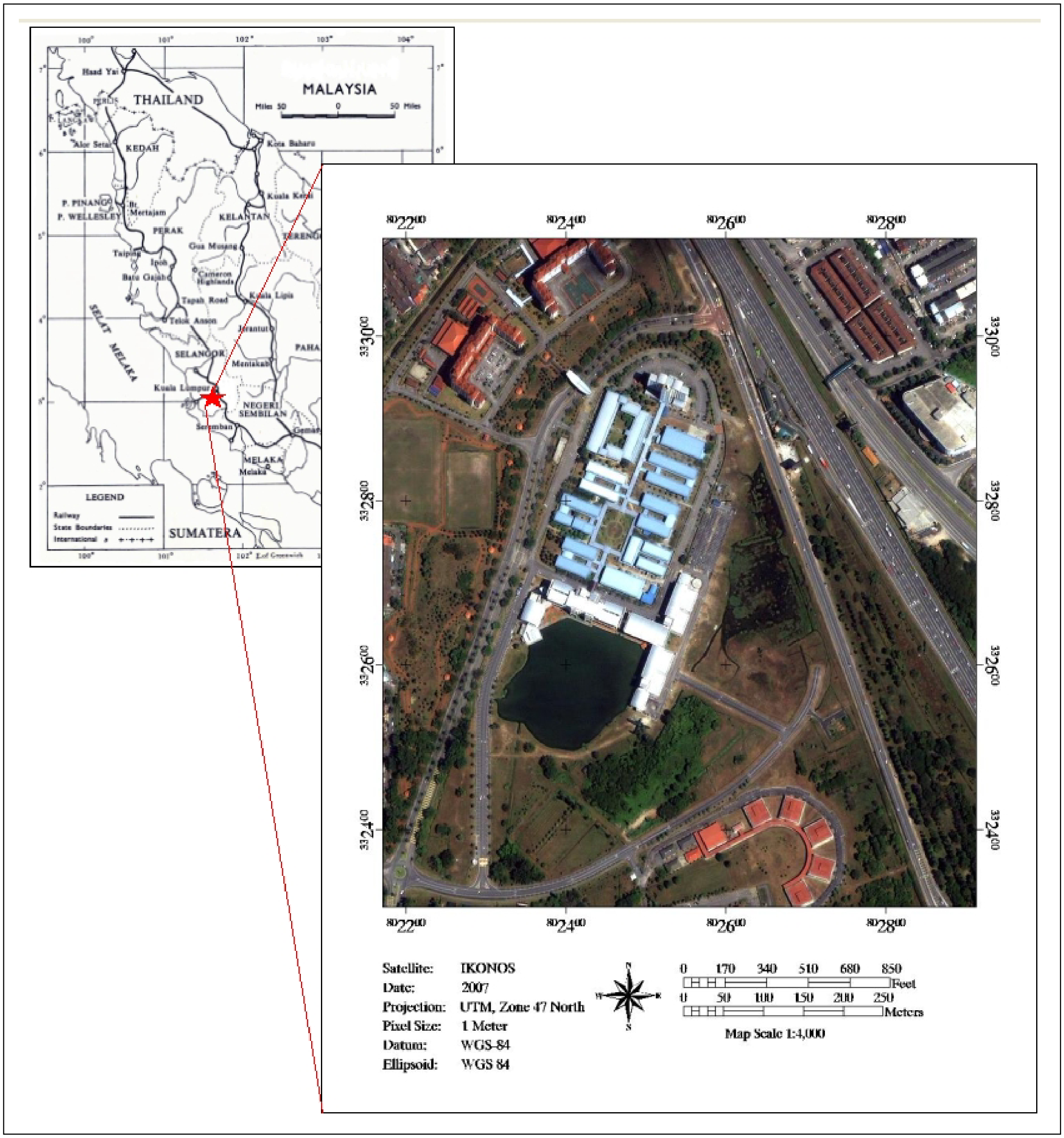

Figure 1. Location of the study area.

to 39.5m above mean sea level. The study area is located in a tropical climate with annual average rainfall of 2990 millimeters. Soil and rock classification indicates that the top layer of the aquifer consists of clay loam while the lower layer is made up of limestone. The average thickness of the upper aquifer within the study area is about 10 meters (Saghravani, 2009). The first layer is known as Kajang formation and the second layer as Kuala Lumpur limestone (Gobbett and Hutchiston, 1973; Huat et al., 2004).

Groundwater data

The present research was planned to assess groundwater flow and fate of phosphorus within 20 meters from the ground surface using well data.

Orthophosphorus as a dominant form of phosphorus was measured in the study area using the ascorbic acid method (Hach, 1988). Then the concentration of phosphorus within the study area was simulated for 3650-days and 18250-days periods. These long periods were chosen due to low hydraulic conductivity of Layer 1 and also slow phosphorus movement in soil. Within the soil, some phosphorus may be adsorbed by the soil aggregate but when the phosphorus adsorption capacity of the soil is exceeded then the mobility of phosphorus is resumed (Knapp et al., 2002). The required parameters used in the simulation include hydraulic conductivity, porosity, dispersivity, thickness and type of soil, evapotranspiration, and recharge. These data were collected from January 2007 to March 2008 (Saghravani, 2009).

Model principles

The integrated model consists of MODFLOW as groundwater flow simulator and MT3DMS for assessing the concentration of phosphorus leached from the sludge into the pond by groundwater.

MODFLOW Model

MODFLOW (Three-Dimensional Block-Centered Finite-Difference Groundwater Flow Model), a computer program, has been developed for groundwater surveys in the form of a modular three-dimensional groundwater flow model (Harbaugh, 2005). It solves the groundwater flow equation by finite-difference methods and is designed to simulate aquifer systems in which saturated flow conditions exist and Darcy's law applies. In this method the aquifer will be divided into finite number of cells. Three dimensional groundwater flows equation for a confined or unconfined aquifer use in MODFLOW is:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

where, K_{xx}, K_{yy}, K_{zz} are values of hydraulic conductivity along the x, y, and z that are assumed to be parallel to the major axes of hydraulic conductivity; h is piezometric head; W is volumetric flux per unit volume that is represented for pumping, recharge or other sources such as sinks; S_s is specific storage coefficient; *x, y, z* are coordinate direction and *t* is time.

MT3DMS Model

Different theories and approaches have been developed to express the transport of contamination by groundwater. Among them, Equation 2 is the most important relation for simulation and handling equilibrium sorption or non-equilibrium sorption (Zheng, 2006). MT3DMS is able to simulate advection, dispersion, and chemical reactions of contamination in 3-D groundwater flow. It uses the cell-by-cell data that is computed and output by MODFLOW to establish the results. Groundwater flow systems can be written as follows:

$$\frac{\partial(\omega C^k)}{\partial t}=\frac{\partial}{\partial x_i}\left(\omega D_{ij}\frac{\partial C^k}{\partial x_j}\right)-\frac{\partial}{\partial x_i}\left(\omega v_i C^k\right)+q_s C_s^k+\sum R_n \quad (2)$$

where, *w* is subsurface porosity; C^k is concentration of parameter in dissolved form (ML^{-3}); *k* is parameter; *t* is time (T); $X_{i,j}$ is distance (L); D_{ij} is diffusion and dispersion coefficient (L^2T^{-1}); V_i is seepage (LT^{-1}); q_s is Volumetric flow rate per unit volume of aquifer (T^{-1}); C^k_s is concentration of source for *k* (ML^{-3}) and S*Rn* is the chemical reaction ($ML^{-3}T^{-1}$). The MT3DMS transport model follows the same spatial discretization convention as MODFLOW.

Model Boundaries

Boundary conditions of the model include a constant head boundary (CHB) that is located by the pond to simulate the movement and fate of phosphorus if the water table is dropped by two meters during 10 years and 50 years. Other boundaries include i) a wall boundary or horizontal flow barrier (HFB) that was used to show thin, vertical, low permeability features which obstruct the movement of groundwater, ii) recharge boundary conditions were used to simulate the recharge into groundwater system, iii) an evapotranspiration boundary was needed to assign the evapotranspiration rate and extinction depth. Visual MODFLOW requires the input of evapotranspiration for the first layer.

Model Calibration

Within Visual MODFLOW 45 columns and 30 rows were assigned and each column and row of the model represents 13-m wide strips of aquifer within the study area. The total thickness of aquifer system under investigation was 20 meters measured from ground surface and includes two isotropic layers, the upper clay loam and the limestone bedrock. The model was initially calibrated under transient conditions by adjusting the input data. The result of normalized Root Mean Square for concentration of phosphorus was given as 28.6%, root mean squared was 0.14 mg/l, residual mean was 0.059 mg/l, and standard error of the estimate was 0.057 mg/l.

Model Limitations

There are several limitations that may potentially decrease the model predictive capability. The most important is the accuracy of software predictions which is widely dependent on the availability and accuracy of the input data. The accuracy of prediction will be reduced when the input parameter is based on average or estimated conditions. For computation evapotranspiration and recharge are assumed constant but these are variable and have no constant pattern during the months and years.

RESULTS AND DISCUSSION

Transient flow was considered to simulate the transportation of contamination for both simulation periods (3650-days and 18250-days). The flow direction of groundwater was observed to be toward the pond due to the placement of the boundary. In this case the water level dropped 2 meters in the pond. This causes a change in groundwater flow direction and water from other part of study area; including the sludge area.

The simulation results show that the phosphorus does not spread in the first layer that consists of clay loam. This is due to the low hydraulic conductivity of the layer. Vector graphs are shown in Figure 2 and Figure 3. The magnitude of the vectors represents the velocity of flow which is an indication of the magnitude and the direction of groundwater flow toward the pond from the sludge. Figure 2 presents the concentration of contamination in clay loam layer of the study area. It seems that a longer simulation period is needed to find the characteristics of the movement of phosphorus groundwater contamination plume emanating from the sludge via Layer 1.

Figure 3 shows the direction of phosphorus movement in Layer 2 after 10 years. It should be noted that X and Y axis in figures are expressed in meters.

In Figure 3, the magnitudes of vectors are longer which means the water velocity is higher through the Layer 2 and phosphorus is also spreading faster due to higher hydraulic conductivity. In other words, phosphorus moves a longer path through Layer 2 in comparison with Layer 1 during

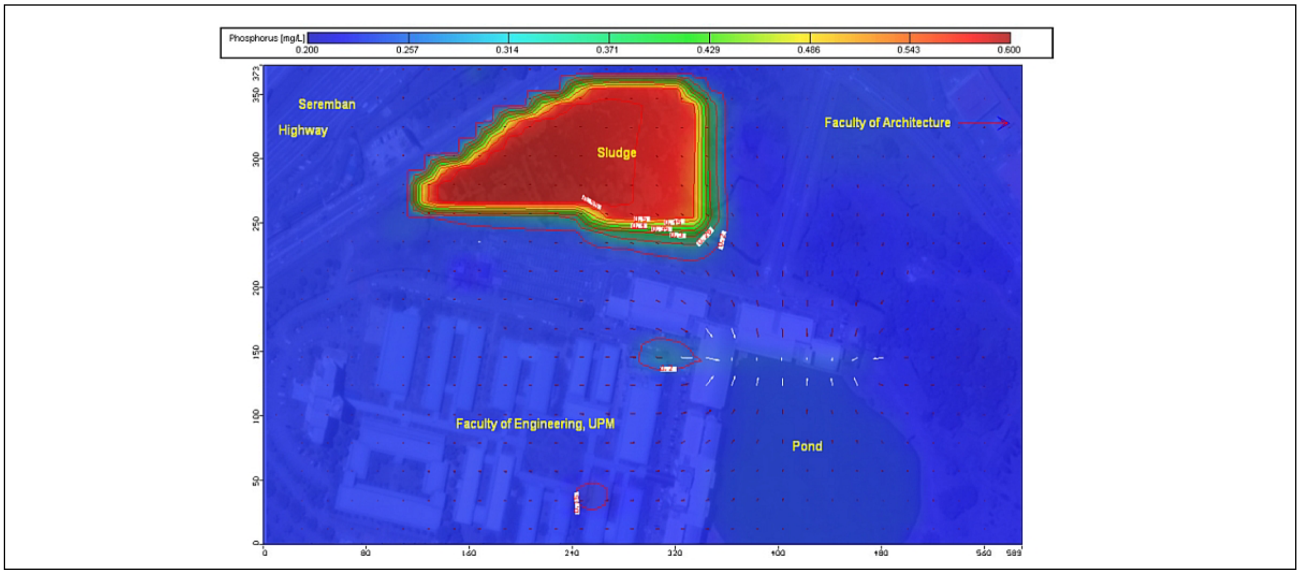

Figure 2. Spreading of phosphorus in layer No.1 (3650-days of simulation period).

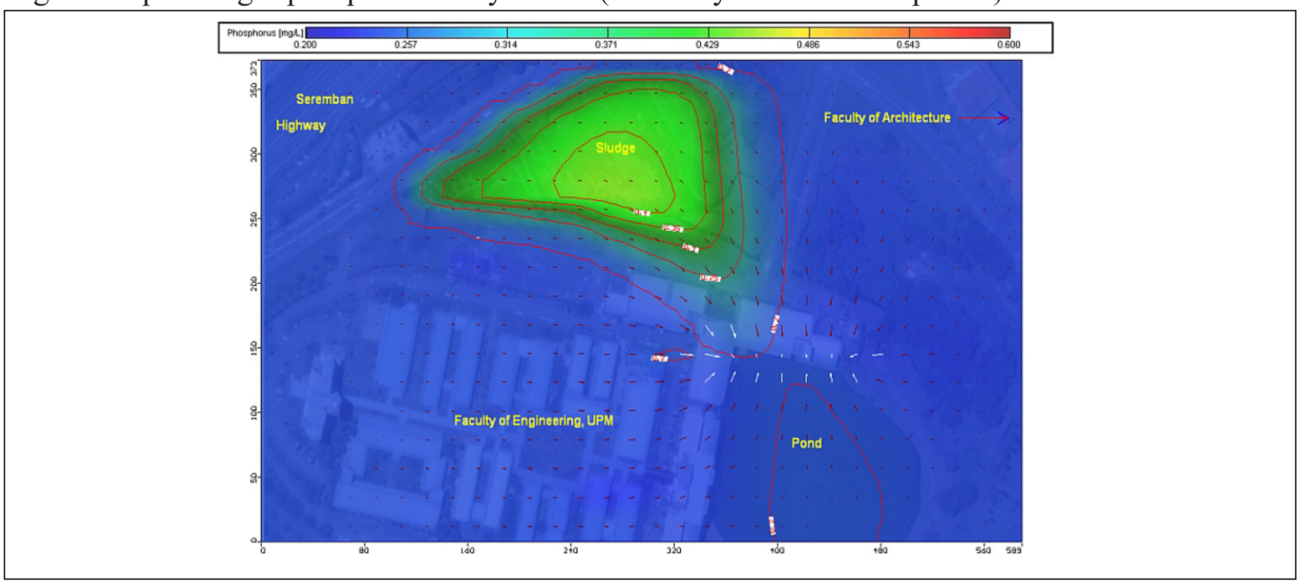

Figure 3. Spreading of phosphorus in layer No.2 (3650-days of simulation period).

the same time. Conditions of layers during simulation periods shows that the pollution would not transfer from sludge to pond through Layer 1 but it will be received by the pond via Layer 2. This can only occur if a vertical migration of the phosphorus from the sludge area occurs to Layer 2.

Figure 4 shows the cross-sectional view of two layers, concentration of phosphorus, layers boundary, constant head boundary (CHB), and groundwater flow direction.

Figures 5 and 6 illustrate the concentration of groundwater contamination after simulation of 18250-days. From these two figures, one can conclude that vertical migration can be responsible for the occurrence of phosphorus within the second layer because the direct horizontal movement of pollutant through the first layer to the pond is limited due to its very low hydraulic conductivity.

After a period of 18250-days the highest phosphorus concentration in Layers 1 and 2 were calculated at 0.55 mg/l and 0.35 mg/l respectively. This clearly shows that horizontal migration of phosphorus to point further away from the source is through Layer 1 via vertical migration of the contaminant from the sludge point (i.e. the source).

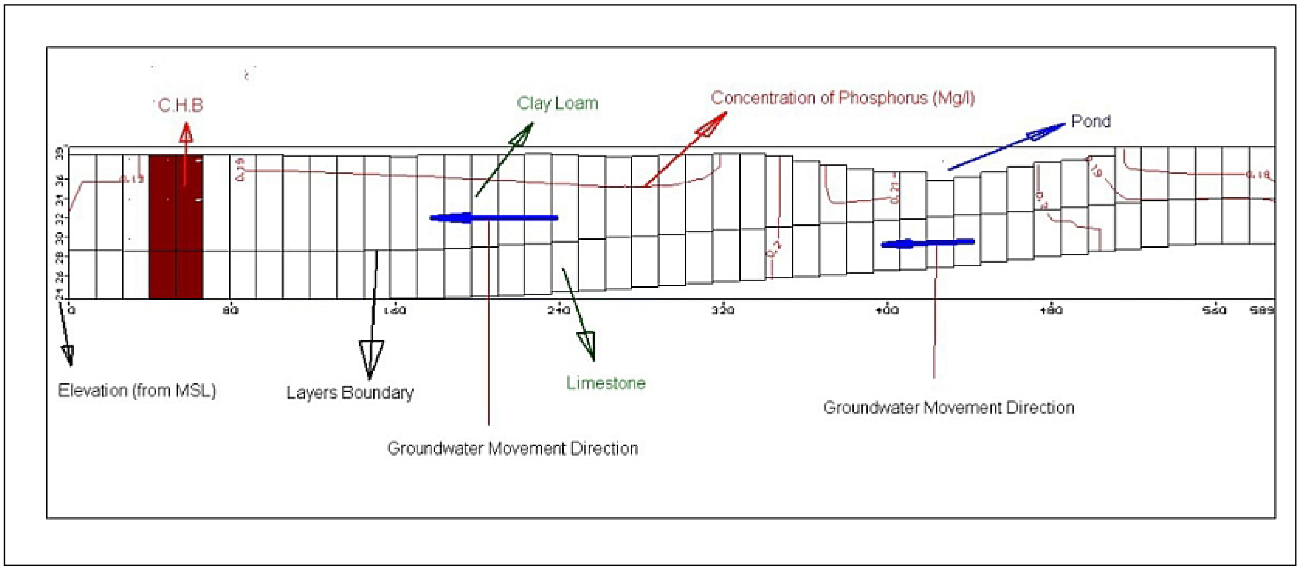

Figure 4. Cross-sectional view of study area in Visual MODFLOW.

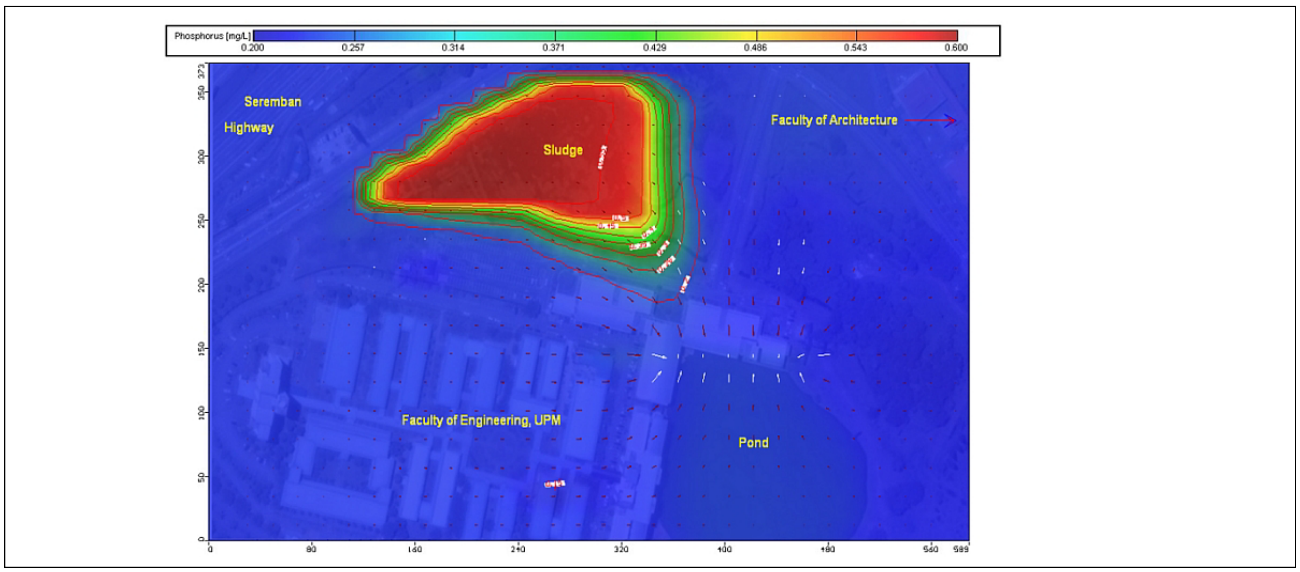

Figure 5. Phosphorus concentration in layer No.1 (18250-days of simulation period).

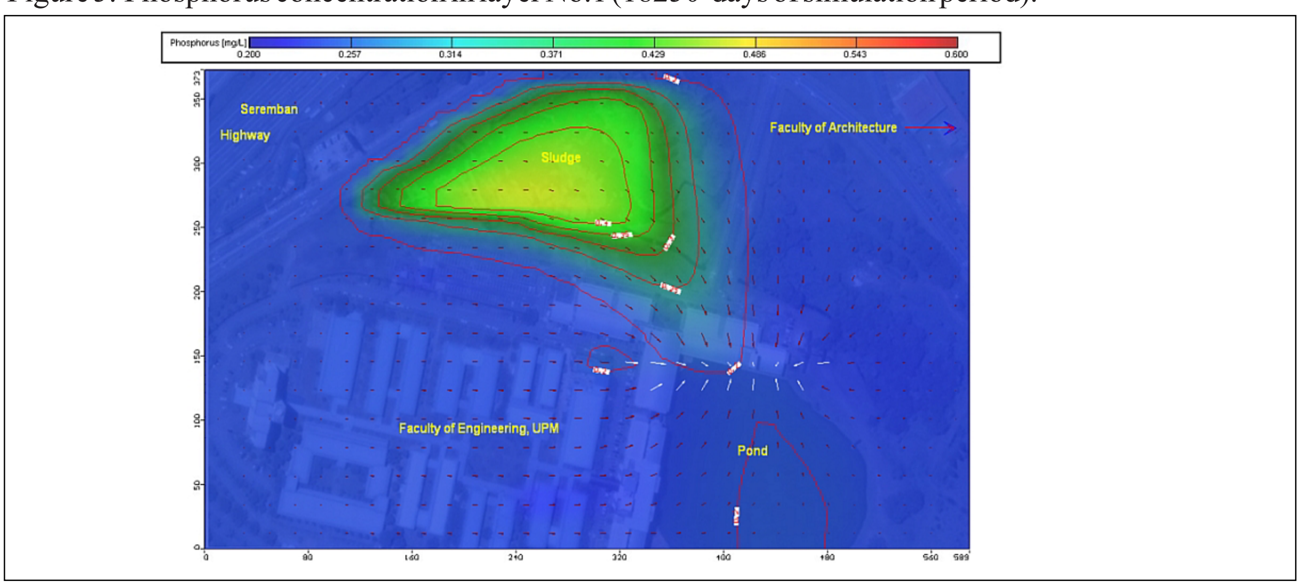

Figure 6. Phosphorus concentration in layer No.2 (18250-days of simulation period).

CONCLUSION

(1) Visual MODFLOW can be used to model groundwater movement and MT3DMS is able to find the fate of leached phosphorus from the sludge into the subsurface. The combination of these two was used to predict and estimate the conditions and concentration of contamination and assess water quality.

(2) The proposed methodology for modeling the groundwater flow of the study area and the fate of phosphorus shows that along with the reduction of the water level in the pond, the direction of local groundwater can be changed from northeast-southwest to be toward the pond and it causes a slight increase in phosphorus concentration. As a result, the use of fertilizers should be reduced to control the concentration of phosphorus in groundwater.

(3) It has also been noticed that factors such as soil type, phosphorus source management, and rainfall were significant in contributing to the estimation of transport and concentration of phosphorus using Visual MODFLOW. To prevent the increase of concentration of phosphorus in the study area specifically in the pond, further studies should be implemented to assess and control the source of contamination and water quality in future.

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