River Pollution Attenuation in Aquifers Using Bank Infiltration Technique

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Abstract

Riverbank filtration (RBF) is a natural technique for surface water treatment, based on the natural removal of pollutants from water during its transfer through the aquifer to pumping well. In this report a mathematical model is used to simulate three major processes related to RBF which are: (1) Groundwater flow and contaminants transport from river towards the pumping well (2) arrival time needed by contaminants to reach the well and (3) evolution of water chemistry due to microbial activity. While the first and second problems were solved numerically by using MODFLOW, the third problem was solved analytically. MODFLOW simulation highlighted the capture zone influenced by each pumping well. Also it was found that the contaminant needs 75 days to reach the pumping well. Furthermore, the analytical model for third problem showed that NO_3 and O_2 were consumed within 10 cm of the aquifer while SO_4 consumed within 30 cm.

1.1 Introduction

The population of Selangor has now reached around 6 million as of 2010 (Department of Statistic Malaysia, 2010). The rapid population growth in Selangor, along with unplanned urbanization and industrialization, overstrains the water supply infrastructure of the capital. In report of Malaysia Water Guide 2005, the water consumption in the state is very high. In 2003, metered domestic water consumption in Selangor was recorded at 478,995,217 cubic meters, while metered non-domestic water consumption was at 245,490,214 cubic metres. The total consumption of metered domestic and non-domestic water in Malaysia in 2003 was 1,609,574,693 cubic meters and 843,388,420 cubic meters respectively. In Selangor, domestic demand grew at an average compounded rate of 5.9% from 1960 to 2006. That year, water demand was divided between the domestic and non-domestic sectors by a ratio of 61 to 39. The projected domestic and industrial demand for peninsular Malaysia up to 2050 based on study by Economic Planning Unit, under the National Water Resources Study (Government of Malaysia, 2000), is about 4,753 million liters per day (MLD), and in 2008, it had almost tripled to 12,468 MLD and projected to reach 24,485 MLD by the year 2020. Demand projections for the Kuala Langat and Sepang districts shown the water demand is 330 MLD in 2010, but increase to 524 MLD in 2020. From the statistic of water consumption in Malaysia from 2008 until 2009 shows that there are about 12,418 water intakes in 2008, taking water directly from rivers for the water supply. The number of the water intakes and has risen to 12,583 in the year 2009 due to increased demand for water of the high demand for water, was feared that the incident would occur if the closure of water intakes are too dependent on the water surface. To meet future water requirements in the country, there has been a recommendation to build 47 new dams, besides three new inter-state water projects that include the Pahang-Selangor Inter State Raw Water Transfer. But, the infrastructure such as dams to treatment plants and distribution systems entails high investments. Operational costs such as energy and labour cost, and cost of maintaining the dams, treatment plants, distribution network, and pumps are no less costly.

Langat River Basin is an important water supply source in the Klang Valley. There are two main dams that stored water from Langat River basin which are Langat and Semenyih Dams. Since the last 20 years, there were several occasions where water intakes and treatment plants have been closed as a result of serious river pollution. The closure of water intakes and water treatment plants has impacts on water supply and thus on economic activities for industries and other sectors. The main sources of river water pollution were discharge of domestic sewage, pollutants from agro-based industries/farming, run-offs from earthworks and land clearing and effluent discharge from manufacturing activities. According to Khairuddin and Abd Malek (2002) the sources of the Langat River pollution coming from industrial discharge (58%), domestic sewage from treatment plants (28%), construction projects (12%) and pig farming (2%). Department of Environment (DOE) of Malaysia, Ministry of Natural Resources and Environment of Malaysia, monitors the water quality of river in Malaysia based on water quality index (WQI) to evaluate the water quality status and river classification. The water quality in the basin has been deteriorating over the years, as evidenced from the water quality database compiled for 15 years. The recorded WQI ranged from 58.1 to 75, which corresponds to pollute (WQI, 0–59) and moderately polluted (WQI, 60–80). Based on the average values taken from the 2002 survey, the major pollutants in the Langat River Basin expressed as percentage of stations exhibiting quality corresponding to class 3 and above are as follows (figures in parenthesis indicate percent sampling stations): AN (94%), TSS and BOD (71%), COD (65%), and DO (53%; UPUM (2002)). Data on the contamination of the Langat River has been published by various authors: for instance, in Malaysia, Zakaria and Mahat (2006) reported the sources and concentration of polycyclic aromatic hydrocarbon (PAHs) in the river sediment in the Langat Estuary, and that this area is dominated by pyrogenic sources which means that most of the PAH compounds are coming from the atmosphere such as street dust. Farizawati et al. (2005) reported a study of Cryptosporidium and Giardia from cattle farms located near Sungai Langat and Semenyih River showed that out of 24 samples of water taken from Sungai Semenyih, 4.2% was positive for Giardia cysts with a concentration of 1.3 cysts/l and 20.8% were positive with Cryptosporidium oocysts with a range of 0.7–2.7 oocysts/l. In Langat River, from the 43 samples taken, 23.3% were positive for Giardia cysts with a range of 1.5–9.0 cysts/l whereas 11.6% were positive with Cryptosporidium oocysts with a range of 2.5–240.0 oocysts/l. This shows that wastewater was discharged into the river signifying contamination of oocycts from the cattle farms into the river system. Liza (2010) identify the point source (PS) and non-point source (NPS) pollution using Geographical Information Systems during the base and storm flow event using the DOE data from 2004-2008 and ranked using the violation analysis which showed that E.Coli (NPS) > E.Coli (PS) > TSS (NPS) > COD (NPS) > NH_3-N (NPS) > BOD (NPS) > COD (PS) > TSS (PS) > NH_3-N(PS) > BOD (PS). It also found that the presence of E.Coli in Langat river can reach 44 times higher than limiting standard of 2000cfu/100ml. The strong concentrations of BOD and COD are related to anthropogenic pollution sources from sewage treatment plants and industrial effluents. Lee and Omar (2006), examining organochlorine insecticides from sediment and water of lake and Langat river. The results showed that endrin, chlordane and aldrin were present in all water samples with concentrations for endrin: 0.02-0.21 µg/L, chlordane: 0.05-0.16 µg/L and aldrin 0.03-0.13 µg/L. Lindane and heptachlor were rarely detected in the water samples. For sediment, lindane, endrin and heptachlor were detected in all sediment samples. Their levels in sediments were 0.28-0.53 µg/kg for lindane, 0.06-0.53 µg/kg for heptachlor and 1.06-2.06 µg/kg for endrin. The source would be from the river upstream flow through an area of oil palm plantation, where these insecticides might have been used for pest control in the past. Osman et al. (2012), identified sources of organic contaminants using chemometric techniques to classify the pollution sources in Langat river basin based on the analysis of water and sediment samples collected from 24 stations, monitored for 14 organic contaminants from polycyclic aromatic hydrocarbons (PAHs), sterols, and pesticides groups. They obtained from chemometric techniques indications that sterols (coprostanol, cholesterol, stigmasterol, β-sitosterol, and stigmastanol) are strongly correlated to domestic and urban sewage, PAHs (naphthalene, acenaphthene, pyrene, benzo[a]anthracene, and benzo[a]pyrene) from industrial and urban activities and chlorpyrifos correlated to samples nearby agricultural sites. Othman and Gasim (2005) reported that heavy metal concentrations such as mercury (Hg), cadmium (Cd), zinc (Zn), lead (Pb), copper (Cu), nickel (Ni), iron (Fe), cobalt (Co) and manganese (Mn) in water of Semenyih river watershed were determined in the water samples. Al-Odaini et al. (2010), observed pharmaceuticals in Langat river indicate that samples collected from the remaining sampling stations along the Langat river were found to contain 15 out of the 19 targeted pharmaceuticals. However, chlorpheniramine, lovastatin, simvastatin, and amlodipine were never detectable in any samples. The frequencies of detection for each pharmaceutical in all thirty samples are depicted. Mefenamic acid, glibenclamide, and salicylic acid were present in samples from all the sampling sites, suggesting both their widespread use and their high degree of persistence in the environment. Metformin, chlorothiazide, and atenolol were detected in 83%, 80%, and 73% of the samples, respectively. On the other hand, nifedipine and loratadine have the lowest frequency of detection (6.6 %). The overall high pollution of the river has alarmed Malaysian scientists, population and authorities. In the past 20 years, judicial intervention and huge financial investment were undertaken to save the Langat river, but despite all attempts both the contamination upstream of Langat river and the contaminant load from the urbanisation itself are still rising and need the Strategic Planning and Management for the Langat River Basin (United Nations 2005). Based on the previous study by some researchers in Malaysia, surface waters are not generally safe for human consumption unless they are properly treated.

In tropical countries like Malaysia where the rainfalls continuously recharge river flow, the main source of dependable water supply is essentially river water. However, as development and economic activities spreads, the management of water resources can be very critical due to increase demand as well as environmental degradation. Pollution of rivers has made surface water unsuitable for sources of raw water for treatment and in certain cases has caused the treatment costs to rise unexpectedly. One of the alternative ways to improve dependable clean portable water supply that is being considered is through Riverbank filtration (RBF) technology as a second source of water supply to guarantee clean and dependable watersupply solution without neglecting the polluted surface water.

Riverbank filtration (RBF) is a natural technique for surface water treatment, based on the natural removal of pollutants from water during its transfer through the aquifer to pumping well. This technology is applied in USA and several European countries. Recently, RBF technique has been applied for the first time in Malaysia in Pilot project conducted in Jenderam Hilir, located in Langat Basin, Selangor, Malaysia (Shamsuddin et al., 2013). This approach had been approved to be a very effective technology that reduces pollutants concentration and it has potential benefits for drinking water supply in Malaysia. To manage and operate RBF system efficiently, it is extremely important to evaluate the potential for contamination of drinking water wells by river pollution.

1.2 Problem Statement

To manage and protect the water supply, transport processes need to be predicted by using the RBF method. To date, the method has mostly been studied by using mathematical solutions. This research specifically simulates the groundwater flow and contaminants transport induced by pumping well and investigates the evolution of the water chemistry during bank-filtrations systems.

1.3 Methodology – Assumptions, Mathematical model, Algorithm

Numerical modelling by using MODFLOW code is developed to simulate groundwater flow and arrival time for pollutants transport induced by pumping well in the river bed sediments where water infiltrates. Shallow homogenous aquifers are assumed in this model. Under the steady state and 1-dimensional saturated flow in infiltration zone, the governing equation of ground flow model in MODFLOW software is:

$$\frac{\partial}{\partial x}K_x\frac{\partial h}{\partial x}+\frac{\partial}{\partial y}K_y\frac{\partial h}{\partial y}+\frac{\partial}{\partial z}K_z\frac{\partial h}{\partial z}=S\frac{\partial h}{\partial t}+R \qquad (1)$$

where K_x, K_y and K_z are the hydraulic conductivity of the aquifers in x, y and z directions respectively. h is the head, S is storage coefficient, R is the source sink term. Finite Difference Method is used in solving the governing equations includes the initial and boundary conditions.

To simulate the arrival time required by contaminants to reach the well, MT3D MODFLOW package is used. A 2-dimensional governing equation that describes the fate and transport of pollutants in RT3D code is

$$R_d\frac{\partial C}{\partial t}=D_x\frac{\partial^2 C}{\partial x^2}+D_y\frac{\partial^2 C}{\partial y^2}-U_x\frac{\partial C}{\partial x}-U_y\frac{\partial C}{\partial y}-kC \qquad (2)$$

where C solute concentration, D diffusivity of mass transport, U_x and U_y are Darcy velocity in x and y directions, D_x and D_y are the diffusivity in x and y directions, k is the degradation rate and R_d is the retardation factor.

On other hand, analytical modelling is developed to simulate the evolution of water chemistry occurs during the water movement from river to the pumping well due to bacterial activity. Equation (2) is used with some modifications to include the microbial activity in the model as follow:

$$\frac{\varphi R_d}{q}\frac{\partial C}{\partial t}=D_x y\frac{\partial^2 C}{\partial x^2}-U_x y\frac{\partial C}{\partial x}-\beta C \qquad . \qquad (3)$$

With the following initial and boundary conditions:

$$C(x,0)=0 \quad \text{for} \quad x \geq 0 \quad \text{and } t=0$$

$$C(0,t)=C_0 \quad \text{for} \quad t \geq 0 \quad \text{and } x=0$$

$$C \to 0 \text{ as } \quad x \to \infty$$

where φ is the effective porosity, q is decay rate, y is degradation of dissolved organic matter and β is the growth rate of bacteria. The final solution is:

$$C(x,t)=C_0 \exp\left(\frac{q\alpha}{\varphi R_d} t\right) \exp\left(\left(\frac{yU_x - \sqrt{(yU)^2 + 4D_x y(\beta+\alpha)}}{2D_x y}\right)x\right). \quad (4)$$

This solution can be used to determine the concentration of pollutants via distance *x* at any time *t.*

1.4 Results and Discussion.

Results of implementation of MODFLOW

Numerical model is tested by data for a river flows through a valley which is bounded to the north and south by impermeable granitic intrusions. The river forms part of a permeable unconfined aquifer system horizontal hydraulic conductivity K_h = 5 m/day, vertical hydraulic conductivity K_v = 0.5 m/day, specific yield S = 0.05 effective porosity φ = 0.2 which overlies a confined aquifer of a variable thickness (K_h = 2 m/day, K_v = 1 m/day, specific storage S = 5 × 10 -5, φ = 0.25). A 2 m thick silty layer (K_h = 0.5 m/day, K_v = 0.05 m/day, φ = 0.25) separates the two aquifers. Three pumping wells pumping at 500m^3/day each abstract water from the confined aquifer. This data is applicable for the *National Hydraulics Research Institute Malaysia (NAHRIM)* situation. Fig 1 illustrates the data for the well DW2 in

Selangor site such as the distance between river and well, river width and type of soil in different layers in the aquifers.

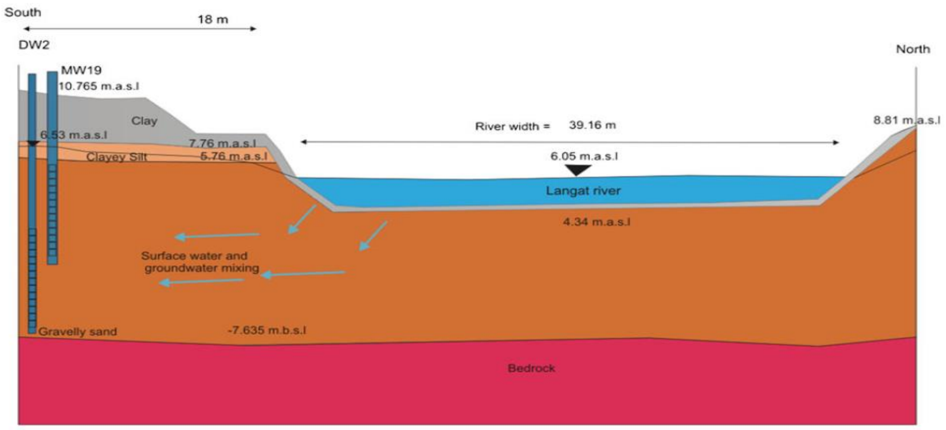

Fig (1): summarized some data for the well DW2 in the pilot project conducted in Malaysia.

By using equation (1) in MODFLOW package we can simulate the hydraulic conductivity at any location in the aquifer as shown in Fig (2). Moreover, the capture zone where the water infiltrates towards each well under the influence of pumping process is illustrated in Fig (3).

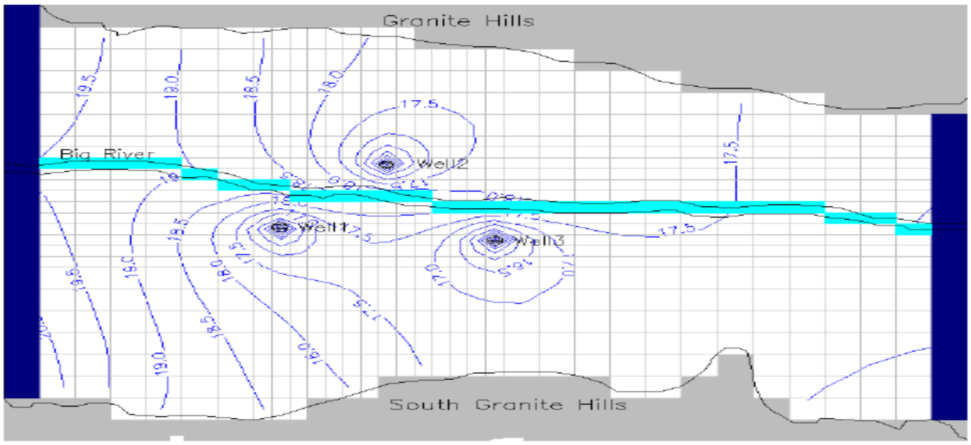

Fig (2): The hydraulic conductivity contours in aquifer surrounding the river

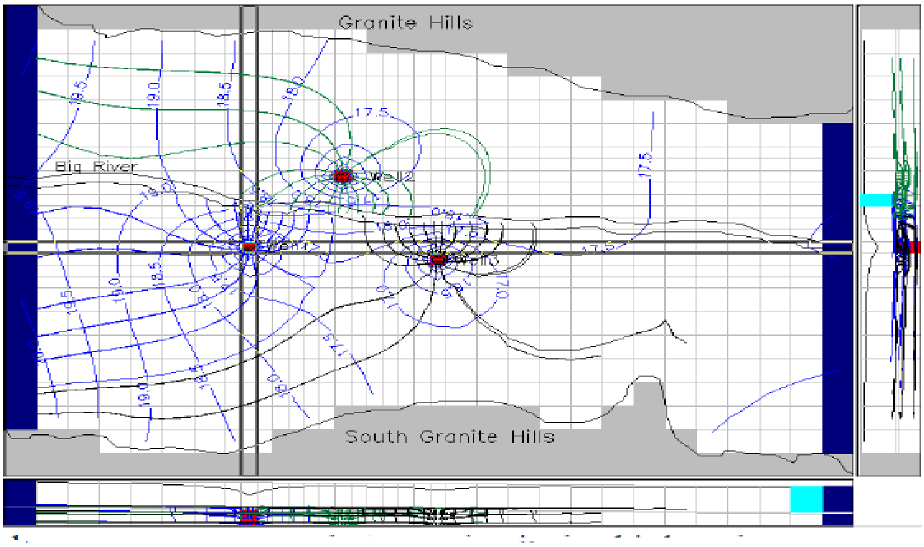

Fig (3) the capture zone of each pumping well

Also by using MT3D MODFLOW packages which depend on equation (2) we can estimate the contaminate transport and the arrival time of pollutants to reach the aquifer. It is found that contaminants in the location A1 illustrated in Fig (4) needs 75 days to reach the well 2. Furthermore, the area influenced by pollutants due to pumping process can be determined as shown in Fig (5).

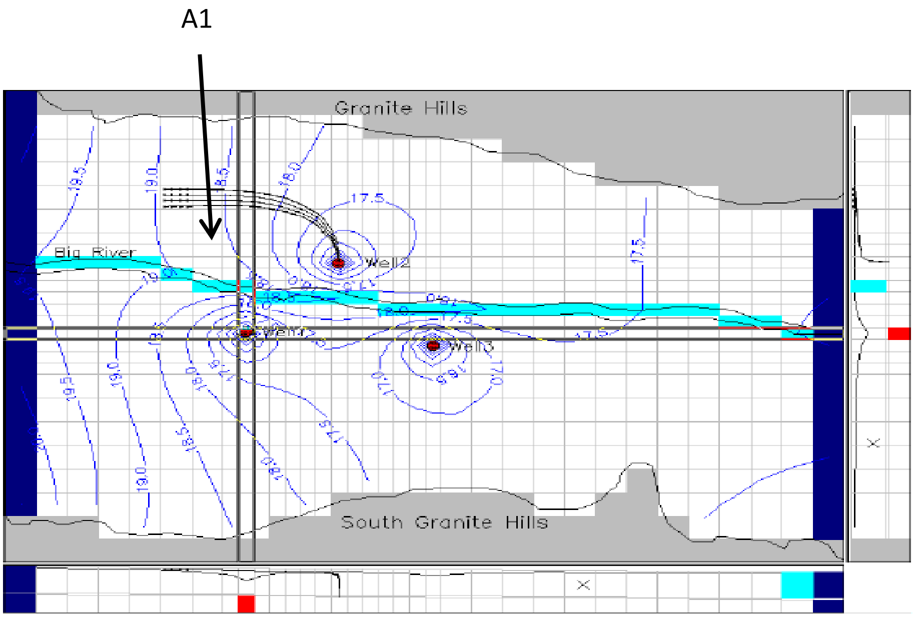

Fig (4): The transport path of pollutants from the location A1 towards the well 2

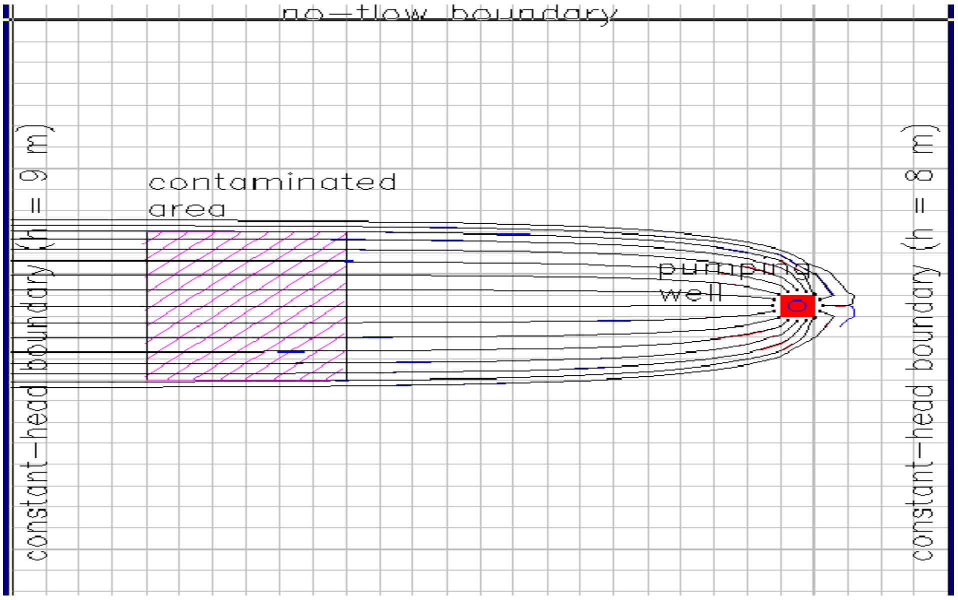

Fig (5) the contaminant area influenced by pumping well

Although MODFLOW is the most popular software used to simulate groundwater process and it can give a satisfactory result, there are some limitations for using it in RBF systems.

Limitations of MODFLOW (Brunner et al., 2010**)**

- Neglecting negative pressure gradients leads to an underestimation of the infiltration flux.
- Because rivers are assigned to only one grid cell, the infiltration flux under a river is uniform while in reality this is only true for disconnected systems.
- The size of the single grid cell of a river is assigned to influence the infiltration flux.
- The vertical discretization of the aquifer affects the infiltration flux.

Results of the Analytical model

The model (referring to equation (3) and analytical solution (4)) is tested for three different nutrients: NO_3, O_2 and SO_4. The model is compared with experimental data of Doussan et al. (1997) for NO_3, O_2 (Fig 6) and SO_4 (Fig 7), and showed that NO_3 and O_2 are consumed within 10 cm of the aquifer while SO_4 is consumed within 30 cm.

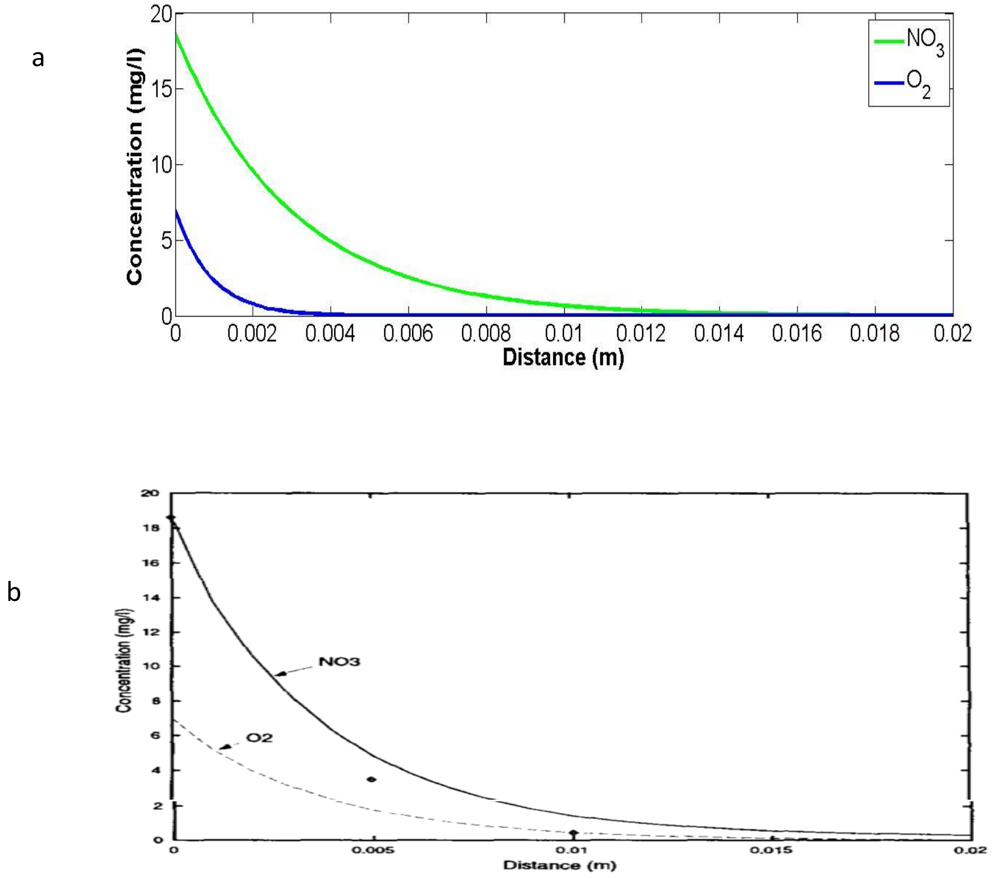

Fig (6): (a) illustrates the simulation of NO_3 and O_2 in an analytical model, (b) shows simulated lines and experimental data points for (Doussan et al., 1997)

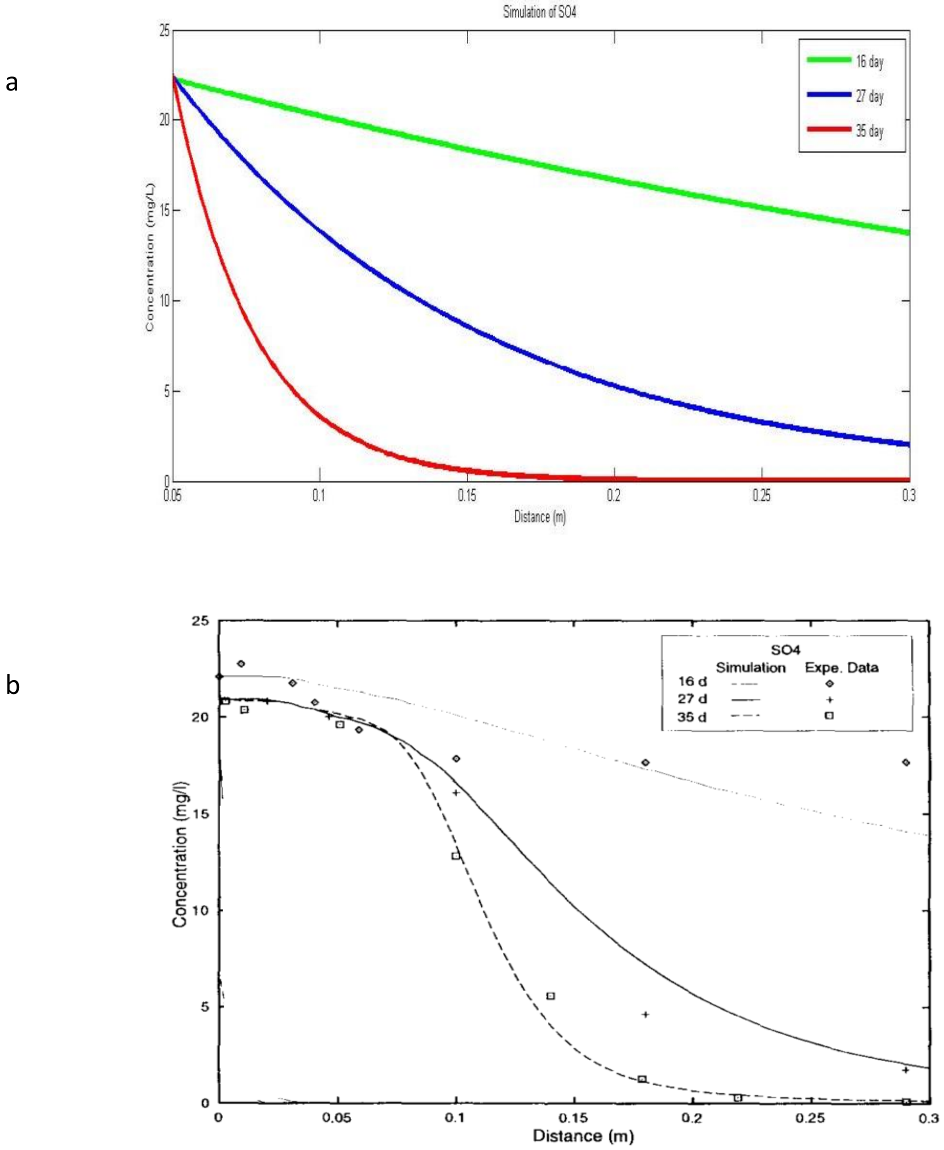

Fig (7): (a) illustrates the simulation of SO_4 after 16, 27 and 35 days, (b) shows simulated lines and experimental data points for (Doussan et al., 1997) in the same time.

1.5 Conclusion and Recommendation

Both of the numerical and analytical modelling methods are used in this report to simulate the contaminants transport and water flow in the riverbank filtration site. The numerical code MODFLOW is used to simulate water flow, hydraulic head and capture zone of each pumping well near the river. Also the particle tracking based Eulerian-Lagrangian method in MODFLOW is used to simulate the travel time taken by contaminants to reach the well. The result is calculated under the pumping rate equal 500m^3/day for each well. Although MODFLOW software is used by researchers to simulate most processes which occur in groundwater dynamics, further mathematical modelling should be developed to get more accurate results and to overcome the limitations of MODFLOW that are mentioned previously. Also, in this report, MODFLOW is only used for computing the hydraulic head and the travel time needed for contaminant to reach the pumping well. In further development of theses result, MODFLOW can be implemented to simulate:

1- The drawdown of groundwater and stream depletion rate due to pumping process.
2- The contaminant concentration in surrounding aquifer.
3- The optimum pumping rate needed so that the contaminated area lies within the capture zone of the pumping well.

On other hand the analytical model is used for evolution of water chemistry due to microbial activity. The model is compared with data collected from the literature which is applicable for the *National Hydraulics Research Institute Malaysia (NAHRIM)* situation. The model concerned only microbial activity, thus, for further development of this model, water flow process (water movement induced by pumping well) should be considered.

1.6 References

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