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Modelling The Effect of Hydraulic Conductivity on One Dimensional Contaminant Transport in RBF System

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Abstract Riverbank filtration (RBF) system is a surface water technology that is based on the natural treatment of filtration instead of the use of chemicals, to pre-treat surface water and provides public water supplies. Hydraulic conductivity value is one of the significant factors affecting the water quality in RBF systems. In this article, an analytical modelling is developed to investigate the effect of this parameter on one dimensional contaminant transport in RBF system. The model is solved by using Green's function approach. The model is applied for the first RBF system conducted in Malaysia. Generally, the results show that increasing the hydraulic conductivity value lead to an increase in contaminant concentration in pumping well area.

Keywords Analytical modelling; hydraulic conductivity; riverbank filtration systems.

Mathematics Subject Classification 35J08, 35K57, 91B76.

1 Introduction

Riverbank filtration (RBF) technology is a natural treatment process of infiltrating river water. The pumping process induced the water to move from the river towards the pumping well located adjacent to the river. Through the water passage from the river to the pumping well, the contaminants are removed due to the chemical, physical and biological processes occurred in riverbed sediments [1, 2].

Different mathematical models are developed in literature to describe 1D, 2D and 3D contaminant transport in aquifer [3-17]. Some of these modelling studies concerned about the role of microbial activity on the fate of solute transport [10, 13, 14]. Also, some authors developed numerical solutions to investigate the effect of pumping process on contaminant transport especially by using MODFLOW software [18-22]. Some mathematical modelling studies were focused on groundwater flow, the drawdown of water due to pumping process and stream depletion rate [23-26]. Some models produced solutions to determine the drawdown of water in pumping wells located near river and to determine the change of hydraulic conductivity [27, 28] .

The hydraulic conductivity K value measures the soil ability to transmit water. This value is an important factor in groundwater modelling. If the hydraulic conductivity is too low, the percentage of infiltration river water in pumping well will be low as well [2]. On the other hand if the hydraulic conductivity value is high, the velocity of water will increase and consequently will decrease the quality of produced water. There is a wide range of methods for calculating$K$.The effect of hydraulic conductivity on contaminant transport was also studied by researchers. The Kozeny-Carman equation is the most common formula that used for estimating conductivity [29]. .Urumovic and Urumovic Sr [30] showed the significant effect of grain size and effective porosity parameters on the permeability and hydraulic conductivity values. They confirmed the validity of applying Kozeny–Carman model up to the limits of validity of Darcy's law Zhu, Gong [29] estimated the conductivity distributions by developing a new method that combines astochastic hydrofacies model with geophysical methods. Soldi, Guarracino [31] presented a mathematical model for unsaturated flow that provides a relationship between permeability and porosity. Moreover, some common and reliable methods for determining K are slug/bail and pumping tests [32-34] . Based on the equation formulas of these methods, the Kvalue is affected by several transport parameters such as porosity. The pervious methods were tested on soil samples extracted from the aquifer in the laboratory. In fact, some researchers had performed field measurements to determine Kvalue. They found that Kvalues measured at laboratory were underestimated, compared to those calculated at the field measurements. Generally, the parameters measured at laboratory samples cannot be applied at larger aquifer volumes, nor to the whole aquifer. Fallico [35] investigated the relation between K value and porosity at field scale. The relationship obtained by his experiments was tested at sandy confined aquifer in south Italy.

Although the mathematical models for the effect of hydraulic conductivity on contaminant transport has been solved numerically, the analytical models still can be valuable tools to investigate solute transport in porous media. It is usually used to verify numerical solutions because of its accuracy and simplicity. In this article an analytical model is developed to study the effect of hydraulic conductivity on contaminant transport in riverbank filtration systems. In this model, the formula obtained by Fallico [35] is used to relate the hydraulic conductivity with the porosity value.

2 Mathematics Formula and Equations

The hydraulic conductivity value is important for the investigation of the transport processes in RBF systems. Alluvial sand and gravel aquifers are usually found in RBF systems with hydraulic conductivity values greater than 8.64 m/d (1E-4 m/s) [2]. According to .Oosterbaan and Nijland [36], the Kvalues of the gravelly coarse sand range from 10-50 m/day. By using the following Theis Equation, the transmissivity T for the wells was calculated as follows [37]

$$T = \frac{Q}{4\pi \Delta s}, \tag{1}$$

where Δs is the draw down change and Q is the pumping rate. Based on the calculated value for T, the value of $K$was then estimated according to:

$$K = \frac{T}{d}, \tag{2}$$

where d is the aquifer thickness. By substituting equation (2) into equation (1) and rearrange we got:

$$Q = 4dK\pi\Delta s. \tag{3}$$

Ground water pumping rate has significant impact on riverbank system efficiency. In particular, increasing the pumping rate can increase the water velocity which leads to decrease in the traveling time of contaminants to reach the well. Consequently, the contaminant adsorption will be less. Also increasing the pumping rate lowers the water table and distorts the groundwater flow. In this model the influence of pumping rate was taken into account through Darcy velocity value as follows [1]

$$U_x = \frac{3Q}{\phi 2\pi dL}, \tag{4}$$

where $\phi$is the porosity and L is the distance between river edge and pumping well. Substitute equation (3) in equation (4) to obtain

$$U_x = \frac{6K\Delta s}{\phi L}, \tag{5}$$

Since the dispersion $D_x = aU_x$ [38], then by using equation (5) we had:

$$D_x = a\frac{6K\Delta s}{\phi L}, \tag{6}$$

where a is the dispersivity value.

The porosity value ϕ was assumed to be changed at different values of hydraulic conductivity. The following equation which was developed by Fallico [35] was used to calculate the porosity based on the K value

$$K = 1.52E - 4\phi^{1.418}. \tag{7}$$

This equation was obtained in a field scale in sandy confined aquifer in south Italy and it could be applied in the porous sites with same properties. In our study area, the type of aquifer is also confined sandy aquifer but with different depth. In particular, the determination of K at field scale is required in practical applications since the formulas that are related to the laboratory scale are not representative of the large aquifer volumes or the whole aquifer. In equations (5) and (6), the value of ϕ was determined by using equation (7). To calculate the travelling time t_1, the following equation which was derived from equation (5) was used

$$t_1 = \frac{L}{U_x} = \frac{\phi L^2}{6K\Delta s}. \tag{8}$$

The governing equation of one dimensional contaminant transport in riverbank filtration systems under the effect of pumping well was developed by Mustafa *et al.* [39] :

$$C(x,t) = \frac{1}{\alpha\sqrt{\pi}R}\frac{q}{Q}C_o \exp(-\frac{1}{R}\beta t_1)(2\sqrt{\frac{U_x t_2}{d}}\exp(\frac{-R(x-\frac{U_x}{R}t_1)^2}{4D_x t_2}) - \sqrt{\pi}\sqrt{\frac{U_x R}{dD_x}}(x-\frac{U_x}{R}t_1)$$
$$erfc(\frac{\sqrt{R}}{2\sqrt{D_x t_2}}(x-\frac{U_x}{R}t_1))), \quad (9)$$

where β is the degradation rate, R is the linear retardation factor, t_2 is the pumping time, $C_0$is the initial concentration at the river and q/Q is the percentage of river water at the pumping well.

To show the effect of K value on the contaminant transport, equations (5), (6), and (8) were substituted in to the contaminant concentration equation (9).

3 Results and Discussion

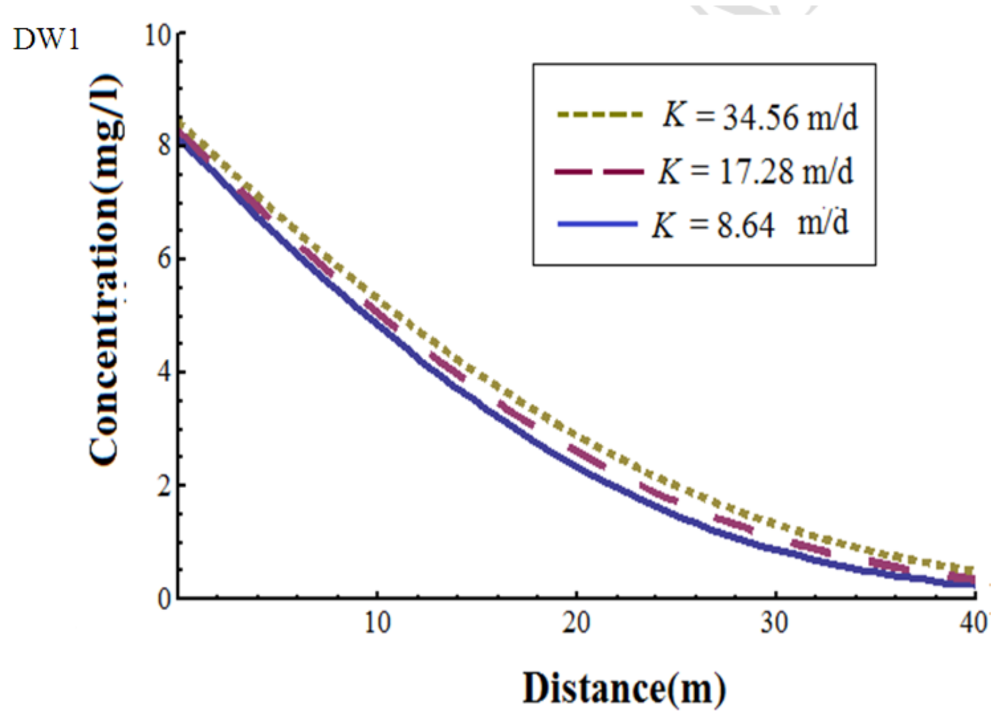
Our study area is the first riverbank filtration pilot project that has been conducted in Jenderam Hilir, located in Langat Basin, Selangor, Malaysia [40]. The site has two pumping wells DW1 and DW2 which are located at 40m and 18m from the river respectively. The initial contaminant concentration was assumed 16mg/l. Figure 1 presents the impact of hydraulic conductivity on contaminant concentration for both pumping wells DW1 and DW2. The initial value of Kused during simulation was 8.64 m/d based on the minimum acceptable value for RBF sites [2] and we increased this value to 17.28 m/d and 34.56 m/d which is still within the specified range by .Oosterbaan and Nijland [36] for gravelly coarse sandy aquifer. For the draw down Δs, we assumed two values Δs_1 which represents the drawdown in water in DW1 well and Δs_2 for DW2 well. A 3 days pumping time have been used for DW1 well while 7 days pumping time have been used for DW2 well. At these pumping times, the drawdown Δs_1 for DW1 was 4.2 m while the Δs_2 for DW2 was 2.02 m respectively [40].

For both wells, the increasing of Kvalue led to a slight increase on contaminant concentration. For DW1, the concentration was around 8 mg/l near the river, and it fell to less than 1 mg/l near the well after 3 pumping days at all values of K. However, after 7 pumping days for DW2, the contaminant concentration was 5.5mg/l near the river and it fell to 3 mg/l at $K =$ 8.64 m/d. After increasing the K value to 34.56 m/d, the concentration of contaminant fell from 7 mg/l near the river to 4mg/l near the well. These higher concentration values measured for DW2 well in comparison with DW1 were justified, because the DW2 well is nearer to the river edge than from DW1 well.

4 Conclusions

An analytical model was developed in this article to study the effect of hydraulic conductivity on one dimensional contaminant transports in RBF systems. From this study it can be concluded that:

1. The model suitability to simulate the effect of hydraulic conductivity values on one dimensional contaminant transport in Sandy aquifer.



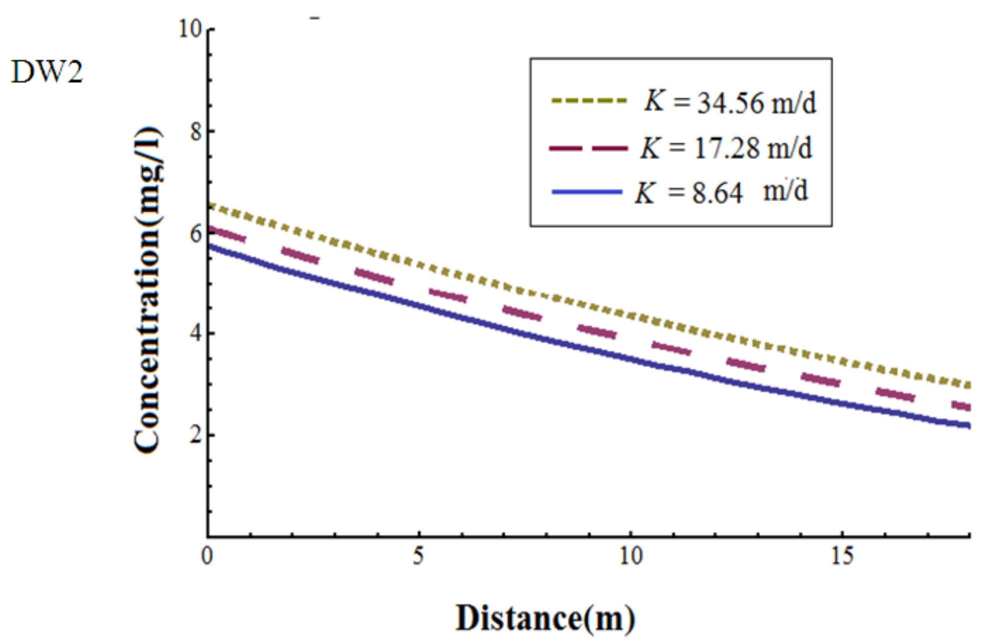


Figure 1: Contaminant Concentration at the RBF Site in Malaysia as a Function of Hydraulic Conductivity at Different K Values

2. Equation (7) which was developed by Fallico [35] is suitable only for sandy aquifer. For another type of aquifer, equation (7) should be changed or adapted to be suitable for the new type.

3. If the hydraulic conductivity values increased, the quality of the water produced from pumping well would decrease. Additionally, it was noticed that if the pumping well is very close to the river edge then the contaminant concentration at the pumped water will be high.

4. The proposed model is helpful in investigating the contamination degree in the aquifer with different K values, which is useful for managing and planning the well site.

5. The model can be applied in RBF systems and several other applications including pumping and treatment systems or contaminant recharge from lakes and landfills.

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