Asian Journal of Water, Environment and Pollution, Vol. 19, No. 6 (2022), pp. 1-9.
DOI 10.3233/AJW220082

Effect of Hydraulic Conductivity on Three Dimensional Contaminant Transport in Riverbank Filtration System

Shaymaa Mustafa and Mohamad Darwish[1]*
UTM Centre for Industrial and Applied Mathematics, Ibnu Sina Institute for Scientific and Industrial Research, Universiti Teknologi Malaysia, Johor Bahru – 81310, Malaysia
[1]School of Civil Engineering, Faculty of Engineering, Universiti Teknologi Malaysia (UTM) Skudai, Johor Bahru – 81310, Malaysia
✉ sjmohamad@utm.my

Received June 27, 2022; revised and accepted August 18, 2022

Abstract: Riverbank filtration system is a technique used for surface water treatment that is based on biological activities to attenuate the contamination in water through its movement from the river to the adjacent pumping well. Hydraulic conductivity is a critical parameter that affects the efficiency of riverbank filtration systems. In this study, an analytical model, using Green's function approach, is developed to investigate the effect of hydraulic conductivity on contaminant transport and RBF system efficiency. The model is applied at the RBF site in Malaysia. The outcomes show that increasing the hydraulic conductivity values results in lowering the quality of the pumped water produced from the well, in which the contamination area around the well increase. Additionally, the distance from well to the river that should be considered when establishing a new RBF site is significantly affected by the hydraulic conductivity value.

Key words: Hydraulic conductivity, analytical solution, Green's function, riverbank filtration, groundwater modelling.

Introduction

Surface water pollution is a significant matter of concern specifically in countries that depend on surface water, such as rivers and lakes, as the main source of water supply (Shamsuddin et al., 2013). The increasing demand for these sources, as well as environmental degradation, are due to the development and growth of economic activity in the last decade. The high pollution rate of river water made it unsuitable for use and requires expensive and multi-phases treatment processes. Nevertheless, one of the cheapest and most sustainable solutions is to drill a pumping well next to the stream, a system that is well-known as the riverbank filtration (RBF) system.

Extracting water from wells in RBF induces the water to transport from the stream to the adjacent well. Generally, the contaminants are attenuated because of physical, microbial and chemical activities in the aquifer. The hydraulic conductivity K of the aquifer that measures how easily water can pass through soil plays a significant role in groundwater modelling and RBF systems. If the K value is too low, a less amount of water can only pass through the aquifer, which reduces the ratio of surface water inside the pumping well and most of the pumped water will be generated from native groundwater (Maliva and Missimer, 2012). In contrast, if the K value is high, then higher amounts of water will transport to the well which will increase the contaminants' concentration in the

*Corresponding Author

extracted water, and hence, the quality of produced water will be less. Therefore, the value of K should be determined accurately to investigate its effect on the contaminants' transport. Several parameters can affect the hydraulic conductivity values such as the effective porosity and grain size (Urumovic and Urumovic Sr, 2016). Consequently, there are several approaches for estimating K values. The Kozeny Carman formula is one of the popular equations for estimating conductivity. Zhu et al. (2016) identified a new approach by using both a stochastic model and geophysical methods to estimate the K value. Also, Soldi et al. (2017) suggested a relationship between permeability and porosity in an unsaturated flow. Since laboratory values for hydraulic conductivity were underestimated, in comparison with those evaluated in the field, many researchers calculated the K values in the field. For example, Fallico (2014) produced a formula at field scale that relates the porosity and K value and his results were applied in south Italy in an area that has a confined sandy aquifer.

Several modelling studies have been done in the literature to investigate the effect of hydraulic conductivity values on solute transport. In order to simulate and estimate representative heterogeneous field distributions of hydrogeological properties, stochastic methods had been widely applied for groundwater models based on a limited number of groundwater samples. He and Wu (2009) modelled the distribution of sand and clay in glacial deposits. Validation analysis showed that the geophysical data significantly improved the accuracy of lithology predictions for the sand units, for which there was a lack of direct observations. Bianchi et al. (2015) generated conditional stochastic realizations of the spatial distribution of geological categories that account for geological structure. Rwanga and Ndambuki (2020) produced a comprehensive methodology applied in the development of a stochastic groundwater model under uncertain recharge. The methodology includes two steps. The first step is to develop a groundwater flow model using MODFLOW 2000. The second is the development of a stochastic solution; a stochastic groundwater flow model where the recharge is considered an uncertain parameter. The methodology demonstrated the significance of considering the existence of recharge uncertainty in groundwater flow models and hence considering it in the development of groundwater management solutions.

Several models in the literature were solved numerically, especially by MODFLOW software. However, analytical solutions are still required to investigate the fate of contamination in groundwater. One common analytical method in groundwater modelling is Green's function approach. This technique is known for its simplicity and flexibility in dealing with several groundwater problems with several boundary conditions. Leij and van Genuchten (2000) provided several solutions based on Green's function for various plane sources and produced three solutions for a semi-infinitive aquifer. Wang and Wu (2009) and Park and Zhan (2001) also produced a library of solutions based on Green's functions to simulate the three-dimensional transport of contaminants. Mustafa et al. (2016) and Mustafa et al. (2020) simulated one and two-dimensional contaminant transport released from line river sources by using Green's function, respectively. Until recent years, efforts of developing analytical solutions for subsurface solute transport by using Green's function approaches were continued (Chen et al., 2016; Mustafa et al., 2019; Paladino et al., 2018; Stanev et al., 2018). Mustafa et al. (2016) developed a mathematical model using Green's function to investigate one-dimensional contaminant transport under the effect of the pumping process. In the current research, the Green's function method is used to determine the impact of hydraulic conductivity values on the movement of contaminants in the systems of riverbank filtration. The formula attained by Fallico (2014) is used in this model to come out with a relation between the values of hydraulic conductivity and porosity.

Mathematics Formula and Equations

Modelling Contaminant Transport

The 3D equation that describes the contaminants transported in groundwater is:

$$R\partial C/\partial t - D_x\partial^2 C/\partial x^2 - D_y\partial^2 C/\partial y^2 - D_z\partial^2 C/\partial z^2 + U_x\partial C/\partial x + \nu RC = S_0 - C_w(t) \quad (1)$$

where the initial and boundary conditions are as follows:

$C(x, y, z, t) = 0 \quad -\infty \leq y \leq \infty,\ x \to \infty,\ 0 \leq z \leq d$ and $t > 0$

$C(x, y, z, t) = 0 \quad y \to \pm\infty,\ 0 \leq x \leq \infty,\ 0 \leq z \leq d$ and $t > 0$

$C(x, y, z, t) = S_0 f(t, y) \quad \to -M \leq y \leq M,\ x = 0,\ z = 0,$ and $t \geq 0$ (2)

$$\frac{\partial C(x,y,0,t)}{\partial z} = \frac{\partial C(x,y,d,t)}{\partial z} = 0,\ -\infty \leq y \leq \infty,\ 0 \leq x \leq \infty$$
and $t \geq 0$,

$C(x,y,z,0)=0 \quad 0\le x\le\infty\,,\quad -\infty\le y\le\infty\,,\quad 0\le z\le d$ and $t=0$

$C(x, y, z, t)$ is solute concentration, d is the aquifer depth (L), U_x is the velocity, D_x, D_y, D_z are the dispersion components along the x, y and z axis respectively, ν represents the degradation constant, S_0 denotes the mass of the initial pollutant produced from the river and dissolved within a unit of time in a unit volume of water, R is the linear retardation factor, and $f(t, y, z)$ denotes non-dimensional unknown function. In Equation (1), it is noticeable that the velocity is assumed only in one direction because the aquifer is isotropic and homogeneous and the uniform flow of groundwater (Batu, 2005).

The dispersion values are depending on velocity U_x where the subscript x is omitted as follows (Batu, 2005):

$$D_x = a_l U$$
$$D_y = a_t U$$
$$D_z = a_v U \tag{3}$$

where a_l, a_t and a_v are the dispersion components coefficient (L). The value $C_w(t)$, used to calculate the concentration of contaminants in the pumped water, is obtained using the following equation (Dillon et al., 2002):

$$C_w(t_w) = q/Q\ [S_o \exp(-\nu\ t_w)], \tag{4}$$

where t_w denotes the travelling time of contaminants, q is the stream depletion rate and Q represents the constant pumping rate. The infiltration flow rate of river water to the pumping rate q/Q is evaluated using the equation of Hunt (1999):

$$\frac{q}{Q} = erfc\left(\sqrt{\frac{S_x L^2}{4Tt_p}}\right) - Exp\left(\frac{\lambda^2 t_p}{4S_x T} + \frac{\lambda L}{2T}\right)$$
$$erfc\left(\sqrt{\frac{\lambda^2 t_p}{4S_x T}} + \sqrt{\frac{S_x L^2}{4Tt_p}}\right), \tag{5}$$

where L represents the distance from the pumping well to river edge, λ is the stream bed leakage coefficient, t_p is the period of pumping, T is the transmissivity and S_x is the storage coefficient. Equation (1) is converted to a non-dimensional equation according to the following dimensionless and transformations:

$x^* = x - Ut/R$; $\bar{C}(x,y,t) = C(x,y,t)\exp(\nu t)$; and $\bar{C}_w(t) = [S_0 - C_w(t)]\exp(\nu t)$

$$t_D = Ut/d \quad C_D = U\bar{C}/(S_0 d) \quad C_{w_D} = \bar{C}_w / S_0 R$$

$$x_D^* = x^*\sqrt{UR/(dD_x)} = x^*\sqrt{R/(da_l)}$$

$$y_D = y\sqrt{UR/(dD_y)} = y\sqrt{R/(da_t)};\quad d_D = \sqrt{Rd/a_v};$$

$$z_D = z\sqrt{UR/(dD_z)} = z\sqrt{R/(da_v)};$$

$$U_D = \sqrt{Ud/(RD_x)} = \sqrt{d/(Ra_l)};\quad f_D(t) = f(t)\exp(\nu t)$$

$$M_D = M\sqrt{UR/(dD_x)} = M\sqrt{R/(da_l)};$$

Thus, the non-dimensional equation is:

$$\partial C_D/\partial t_D - \partial^2 C_D/\partial {x^*_D}^2 - \partial^2 C_D/\partial y^2_D$$
$$-\partial^2 C_D/\partial z^2_D = C_{w_D}(t_{w_D}) \tag{6}$$

With the following non-dimensional initial and boundary conditions:

$$C_D(\infty, y_D, z_D, t_D) = 0 \quad -\infty \le y_D \le \infty,\ 0 \le z_D \le d_D$$
and $t_D \ge 0$

$$C_D(x^*_D, \pm\infty, z_D, t_D) = 0 \quad -U_D t_D \le x^*_D \le \infty,\ 0 \le z_D \le d_D$$
and $t_D \ge 0$

$$C_D(-U_D\tau_{0D}, y_D, z_D, t_D) = f_D(t_D, y_{0_D})$$
$$= -M_D \le y_{0_D} \le M_D,\ 0 \le z_D \le d_D \text{ and } t_D \ge 0 \tag{7}$$

$$\frac{\partial C_D\left(x^*_D, y_D, 0, t_D\right)}{\partial z_d} = \frac{\partial C_D\left(x^*_D, y_D, d_D, t_D\right)}{\partial z_d} = 0$$

$$-\infty \le y_D \le \infty,\ -U_D t_D \le x^*_D \le \infty, \text{ and } t_D \ge 0$$

$$C_D(x^*_D, y_D, z_D, 0) = 0 \quad -U_D t_D < x^*_D < \infty,\ -\infty \le y_D \le \infty,$$
$$0 \le z_D \le d_D$$

where τ_0 represents the time that the contaminant was generated at the source. Initially, to get the Green's function G the following equation should be solved:

$$\partial^2 G/\partial {x^*_D}^2 + \partial^2 G/\partial {y_D}^2 + \partial^2 G/\partial {z_D}^2 - \partial G/\partial t_D$$
$$= \delta(x^*_D - L_D)\delta(y_D)\delta(z_D)\delta(t_D) \tag{8}$$

where δ represents the Dirac delta function. Then the following integral is solved to get the solution of Equations (6):

$$C_D = \int_0^{t_D} C_{w_D}(\tau_{w_D}) G(x_D^*, y_D, z_D, \tau_D) d\tau_D \quad (9)$$

To get the 3D Green's function for Equation (8), the 1D Green's functions in *x*, *y* and *z* directions will be multiplied as follows (Park and Zhan, 2001; Wang and Wu, 2009):

$$G(x_D^*, y_D, z_D, t_D) = G(x_D^*, t_D) G(y_D, t_D) G(z_D, t_D) \quad (10)$$

The 1D Green's function in *x* direction is equal to (Park and Zhan, 2001, Wang and Wu, 2009):

$$G(x_D^*, t_D) = 1/(2\sqrt{\pi t_D}) \exp(-(x_D^* - L_D)^2 / (4t_D)) \quad (11)$$

Since the river extends $-M$ to M along y axis, then the dimensionless Green's function along y axis is defined as a source function $S(y_D - \xi_D, t_D)$ and is obtained as follows:

$$\mathrm{S}(y_D, t_D) = \int_{-M_D}^{M_D} G(y_D - \zeta_D, t_D) d\zeta_D$$

$$= \int_{-M_D}^{M_D} 1/(2\sqrt{\pi t_D}) \exp(-(y_D - \zeta_D)^2 / (4t_D)) \, d\zeta_D$$

$$= \frac{1}{2}(\mathrm{erfc}\,(\frac{y_D - M_D}{2\sqrt{t_D}}) - \mathrm{erfc}(\frac{y_D + M_D}{2\sqrt{t_D}}) \quad (12)$$

Vertically, at *z* direction, the image of theory is implemented since the aquifer has finite depth (Zhan, 1999). Thus the vertical Green's function *G* is (Park and Zhan, 2001, Wang and Wu, 2009):

$$G(z_D, t_D) = 1 + 2\sum_{n=1}^{\infty} \cos n\pi z_0 \cos n\pi z_D \exp(-n^2\pi^2 t_D) \quad (13)$$

Since the stream is located at $z_0 = 0$ then:

$$G(z_D, t_D) = 1 + 2\sum_{n=1}^{\infty} \cos n\pi z_D \exp(-n^2\pi^2 t_D) \quad (14)$$

By using Equations (10), (11), (12) and (14), The 3D- Green's function is:

$$G(x_D^*, y_D, z_D, t_D) = 1/(4\sqrt{\pi t_D}) \exp(\frac{-(x_D^* - L_D)^2}{4t_D})$$

$$(\mathrm{erfc}\,(\frac{y_D - M_D}{2\sqrt{t_D}}) - \mathrm{erfc}(\frac{y_D + M_D}{2\sqrt{t_D}})$$

$$[1 + 2\sum_{n=1}^{\infty} \cos n\pi z_D \exp(-n^2\pi^2 t_D)] \quad (15)$$

Based on Equation (9), the final non dimensional solution is:

$$C_D(x_D^*, y_D, z_D, t_D) = \frac{1}{4\sqrt{\pi}} \int_0^{t_D} C_{w_D}(\tau_{w_D}) \frac{1}{\sqrt{\tau_D}}$$

$$\exp(\frac{-(x_D^* - L_D)^2}{4\tau_D})(\mathrm{erfc}\,(\frac{y_D + M_D}{2\sqrt{\tau_D}})$$

$$-\mathrm{erfc}(\frac{y_D - M_D}{2\sqrt{\tau_D}})$$

$$[1 + 2\sum_{n=1}^{\infty} \cos n\pi z_D \exp(-n^2\pi^2 \tau_D)] \, d\tau_D \quad (16)$$

Which is equivalent to the following dimensional equation:

$$C(x, y, z, t) = \frac{S_0}{4R\sqrt{\pi}}(1 - \frac{q}{Q} e^{-\upsilon t_w}) \sqrt{d/U}$$

$$\int_0^t \frac{1}{\sqrt{\tau}} e^{-\upsilon(t_w - \tau)} \exp(\frac{-R(x - L - U\tau/R)^2}{4\tau D_x})$$

$$(\mathrm{erfc}(\frac{\sqrt{R}(y + M)}{2\sqrt{D_y \tau}}) - \mathrm{erfc}(\frac{\sqrt{R}(y - M)}{2\sqrt{D_y \tau}})$$

$$[1 + 2\sum_{n=1}^{\infty} \cos n\pi z \sqrt{R/(a_v d)} \exp(-n^2\pi^2 U\tau/d)] d\tau \quad (17)$$

Modelling Hydraulic Conductivity

Most RBF sites are established at alluvial sand and gravel aquifers since the hydraulic conductivity in these aquifers varies from 10-50 m/d which is more than 8.64 m/d (Maliva and Missimer, 2012). The following Theis Equation for the transmissivity *T* is used (Theis, 1935):

$$T = \frac{Q}{4\pi \Delta s} \quad (18)$$

where Δs denotes the change of draw down. Based on the evaluated value for *T*, the *K* value was then determined:

$$K = \frac{T}{d}, \quad (19)$$

If Equation (19) is substituted in Equation (18) we got:

$$Q = 4dK\pi\Delta s \quad (20)$$

Since the rate of groundwater pumping significantly affects the water velocity and riverbank filtration system efficiency, its influence was assumed into consideration as follows (Dillon et al., 2002):

$$U = \frac{3Q}{\varphi 2\pi dL} \tag{21}$$

where φ is the porosity. Thus by using Equation (20) we get:

$$U = \frac{6K\Delta s}{\varphi L} \tag{22}$$

From Equation (3) we have:

$$D_x = a_l \frac{6K\Delta s}{\varphi L}$$

$$D_y = a_t \frac{6K\Delta s}{\varphi L}$$

$$D_z = a_v \frac{6K\Delta s}{\varphi L} \tag{23}$$

Since the hydraulic conductivity values change according to porosity values then, the following equation was used:

$$K = 1.52E - 4\varphi^{1.418} \tag{24}$$

This equation was developed by Fallico (2014) on a field scale in a sandy aquifer. The aquifer in our study area is also sandy but with different depths. In Equations (22) and (23), we used Equation (24) to determine the porosity value:

The relation between the travelling time t_1 and K value is derived from Equation (22) as follows:

$$t_w = \frac{L}{U} = \frac{\varphi L^2}{6K\Delta s} \tag{25}$$

Equations (22), (23), and (25) were substituted in Equation (17) to simulate the hydraulic conductivity effect on the pollutant's transport.

Results and Discussion

Our model is applied at a site of riverbank filtration in Malaysia that consists of two pumping wells DW1 and DW2. The site is located in Langat Basin, Selangor, Malaysia (Shamsuddin et al., 2013). The DW1 well is located 40m from the river edge while the distance from DW2 to the shore is 18m. The solute concentration at the river was set at 16 mg/L. The values of K used during the simulation start from 8.64 m/day and this is the minimum value that is acceptable for riverbank filtration sites (Maliva and Missimer, 2012). Then the values increased to 17.28 m/day and then to 34.56 m/day. Figures 1 and 2 present the impact of K values on contaminant concentration for the DW1 and DW2 wells. The DW1 well was pumping for 3 days and the draw down in DW1 is represented by Δs_1. For DW2 the drawdown is denoted by Δs_2 and 7 days pumping time is applied. At these periods pumping, the values of Δs_1 and Δs_2 were 4.2 m and 2.02 m respectively (Shumsuddin et al., 2013). The influence of K values on the concentration were simulated on the region $\{D = (x, y, z) | 0 \le x \le L, -30 \le y \le 30, 0 \le z \le 20\}$ where L is the distance between DW1 and DW2 wells and river edge.

Generally, by raising the K values, more area is influenced by contamination. For DW1, at K = 8.64 m/d, the concentration value was 0.84 mg/L near the river. However, this measurement of concentration increased to 0.91 mg/L and then to 1.05 mg/L when the hydraulic conductivity values raised from 17.28 m/day to 34.56 m/dy. Additionally, at 30 m from the edge of stream, the values of solute concentrations enlarged from 0.12 mg/L to around 0.15 mg/L by raising the hydraulic conductivity values from 8.64 m/day to 34.56 m/day. For DW2, the contaminants concentration values increased after 7 pumping days from 2.04 mg/L to 2.2 mg/L near the river by raising the K values from 8.64 m/day to 34.56 m/day. However, it is noticed that, for all values of hydraulic conductivity values, the pumped water is contaminated with concentration values around 0.5 mg/L. This is due to the short distance from DW2 to the stream. This indicates that the quality of water produced from the DW1 well is better than DW2.

Our results are consistent with the results obtained by Sanskrityayn et al. (2017) who investigated one-dimensional pollutant transport in groundwater and riverine flow analytically using both Green's Function Method (GFM) and the pertinent coordinate transformation method. They assumed in their study that the water flow is affected by several factors such as the heterogeneity of the medium and velocity fluctuations that are influenced by hydraulic conductivity values. Their results showed that the concentration decreased with increasing the distance from the source. In particular, they agreed with our results that the contamination is attenuated in the first meters from the river.

The hydraulic conductivity K impact on the fate of pollutants with different pumping time periods is also simulated and the results were plotted in Figure 3. During the simulation, the K values were assumed to equal 8.64, 13.24, 17.82, 25.13 and 34.5 m/day.

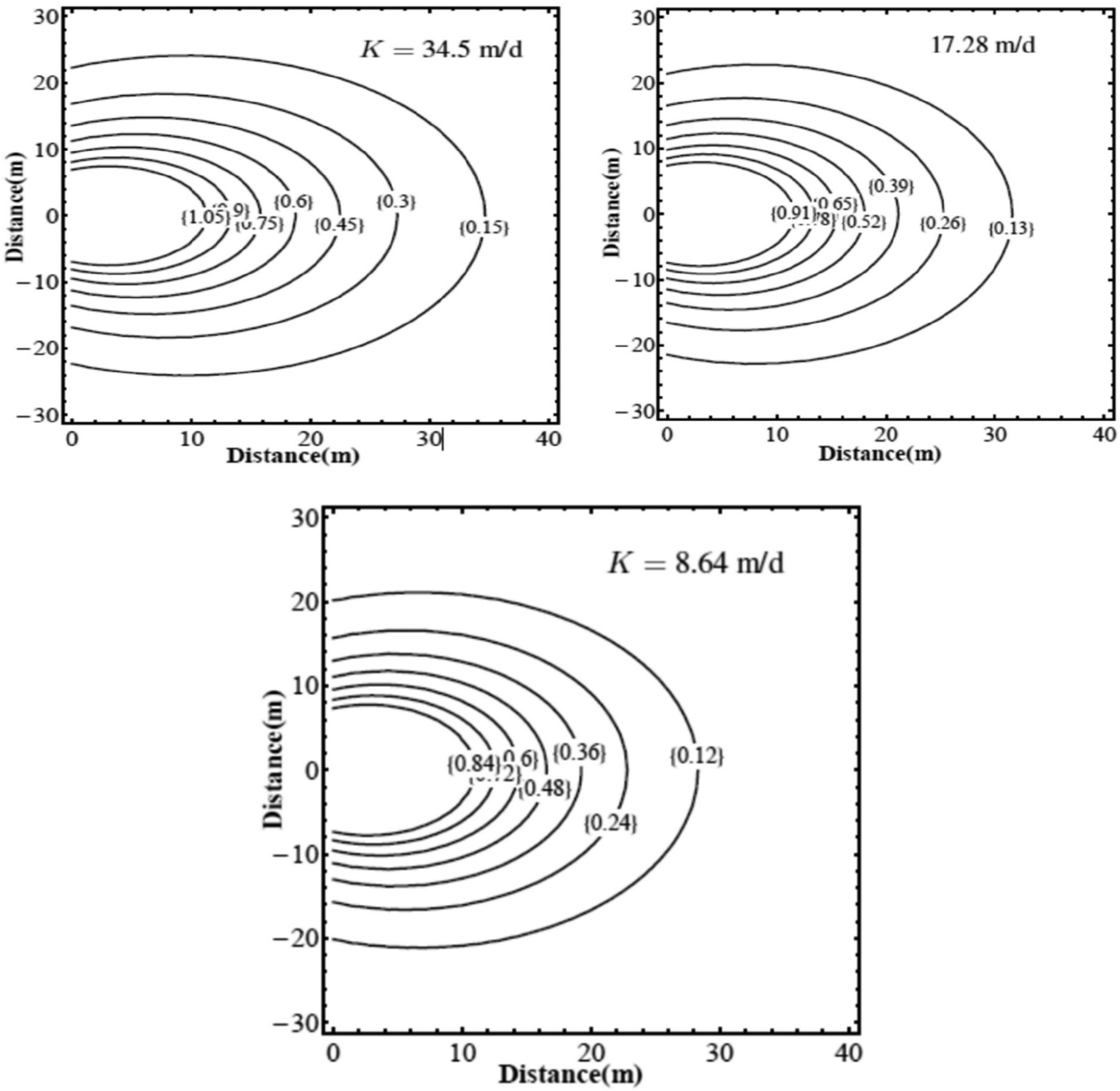

Figure 1: The effect of different *K* values on contaminant transport in DW1.

From Figure 3, it can be noticed that the concentration of contaminant raised to more than 0.11 mg/L when *K* enlarged to 34.5 m/day. In general, raising *K* values allows more amount of water to enter the aquifer and consequently more dense contamination. Also, Figure 3 indicates that the long time use of the pumping well leads to an increase in the contamination in the well area.

It is required for riverbank filtration system efficiency to drill the pumping well at the minimum distance between the river and well that produces more amount of high quality infiltrating river water. This distance is affected by the hydraulic conductivity value *K* values and this effect is investigated in Figure 4 for three pumping days with drawdown $\Delta S_1 = 4.2$ m and at seven pumping days with drawdown $\Delta S_2 = 2.02$ m. The value of *K* started from 8.64 m/day and it increased until $K = 40.13$ m/day. From Figure 4, it is found that increasing the hydraulic conductivity can enlarge the distance between the pumping well and the edge of the stream. At $\Delta S_1 = 4.2$ m, the distance increased from 33.5 m to around 40.68 m when the hydraulic conductivity changed from $K = 8.64$ m/day to $K = 40.13$ m/day. On the other hand, at $\Delta S_2 = 2.02$ m, the distance between well and the river increased from 35.2 m to around 42.6 m due to the raising of hydraulic conductivity

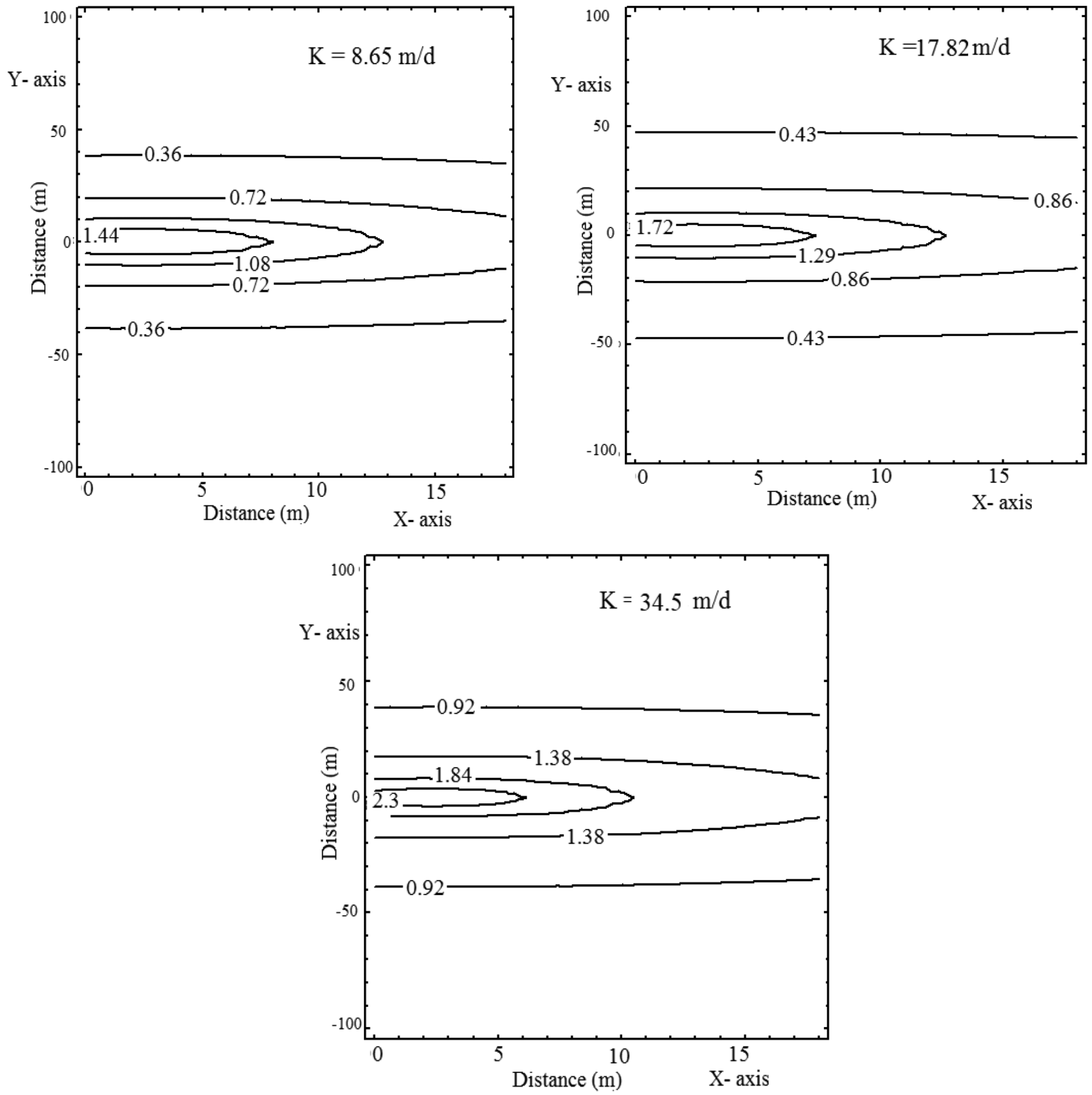

Figure 2: The impact of different *K* values on solute transport in DW1.

value from 8.64 m/day to 40.13 m/day. It is also found that when the drawdown increased from 2.02 m to 4.2 m, there was approximately a 3 or 2 m difference in distance that should be taken into consideration between the extracting well and the edge of the river.

Müller et al. (2010) estimated the concentration of pharmaceutical substances in groundwater by using a new approach that considered not only the hydraulic and hydrogeological characteristics of bank filtration sites but also the transport processes. The study conducted by them showed that the hydraulic conductivity values changed from 1E-2 to 1E-4 m/s while the distance from shore varies from 1.5 to 1200 m. the pumping rates and times were in the range 500-5000 m^3/d and 1 to 1100 days, respectively. They calculated the concentration based on the initial concentration on the river and the flow time to the well that is influenced by hydraulic conductivity values. Their result is matched with our finding the pumping processes (rates and time), as well as the distance between well and shore, are the main

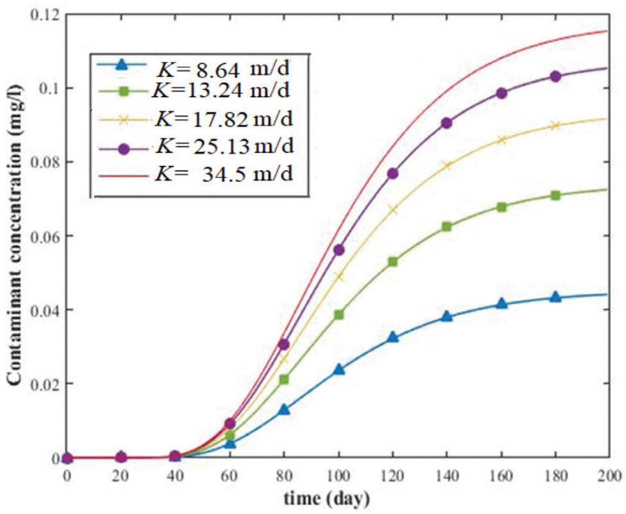

Figure 3: Contaminant concentration at different hydraulic conductivity values.

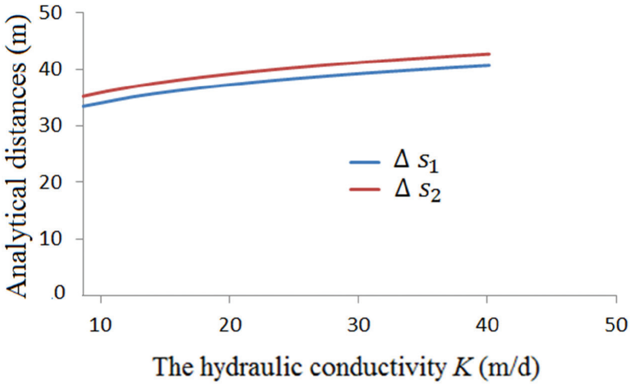

Figure 4: The impact of hydraulic conductivity on the distance from well to the river.

factors in controlling the riverbank filtration efficiency. For high pumping rates, more water and contaminants flow to the well so the distance should be increased or less pumping rate should be used.

Conclusion

The effect of hydraulic conductivity values on contaminant transports in RBF systems is modelled analytically by using Green's function approach. Generally, it is found that the high values of hydraulic conductivity led to increasing the area of contamination around the well and consequently the quality of water produced from the well is decreased, especially if the well is close to the river. It is noticed that based on the hydraulic conductivity and porosity in the area, the contamination degree in the aquifer can be investigated and consequently the riverbank filtration system can be managed. For existing riverbank filtration systems, the proposed model can be used to control the pumping rate and time values that produce high quality water from the well. For establishing new systems, the distance between the well and river edge can be changed according to the hydraulic conductivity values. The results confirm that with decreasing the drawdown of water in the well, the distance that should be considered between the well and the river is less. Thus, this model can be used to manage and operate RBF sites and to monitor pumping and treatment systems or contaminant recharge from landfills and lakes.

Acknowledgement

The authors would like to thank Universiti Teknologi Malaysia for supporting this research through the Collaborative Research Grant (CRG) No. 09G82 and Fundamental Research Grant Scheme (FRGS) No. 5F249.

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Asian Journal of Water, Environment and Pollution

Volume 19 Number 2 **March, 2022**

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