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Modelling Well Location Between River and Second Contaminant Source in Riverbank Filtration Systems

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Extracting water from pumping well near to river in riverbank filtration systems leads to the natural treatment for surface water. To increase the system efficiency, the well should be located at a distance from the river in which the well can produce high percentage of river water that satisfies the requirements of water quality. In case the well is located between river and a contaminant source, its location should be relocated to a suitable place between the two sources. In this article, an analytical solution is produced to specify the suitable distance of pumping well and polluted river in a riverbank filtration systems if there is a contaminant source to the present well. The analytical solution is obtained by using Green's function. This approach is chosen because of its simplicity for solving multidimensional problems, and its flexibility to deal with arbitrary initial and boundary conditions. The model is compared with numerical one obtained by using MODFLOW software. The results indicate that the location obtained from proposed model is suitable for use to determine the well location. Additionally, the results show that increasing either the pumping rate or initial contaminant concentration leads to an increment to the distance between river well.

Keywords: riverbank filtration systems; Green function approach; pumping well; Analytical modelling

I. INTRODUCTION

Surface water pollution problems are of obvious national and economic importance, and they attract government and academic attention. Tropical countries such as Malaysia face more risk than, since they depend basically on surface water (rivers, lakes, etc.) as a main source of potable water supply. However, surface water, mainly river water, is exposed to threats of permanent and sudden pollution by wastewaters, chemical industrial wastes, agricultural fertilisers, landfill leachates, land transportation and many other contaminant sources. High levels of pollutants in surface water may lead to expensive treatment, so efficient riverbank filtration systems is one of the economic and sustainable solutions when river water cannot be used directly.

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Riverbank filtration (RBF) is a process where the wells are located adjacent to the stream to capture a portion of the river water either naturally or induced by pumping from the wells. The extraction of the groundwater near the river provides clean water for public use or for agricultural areas. The success of such schemes and the quality of the produced water are dependent on several factors such as microbial activity, chemical transformations that are commonly occurred in the collation layer within the riverbed, site hydrogeology, well type and location, and the degree of contamination of river water.

RBF technology is applied in USA and several European countries such as Germany, Slovak Republic, Hungary and Netherlands (Dash *et al.,* 2010). In Malaysia, the first RBF pilot project was Jenderam Hilir to determine the possibility of implementing RBF system. Their study has shown a significant increase in the quality of the infiltrated water can be achieved. Also, they found that RBF systems can support a high-water demand and can reduce the cost of river water treatments in Malaysia. Nowadays, Malaysia is going forward to build new sites of RBF systems especially in high polluted states such as Selangor. However, these states are very crowded and have a lot of rivers.

Establishing and managing new RBF sites require a variety of important decisions such as the selection of RBF design (well types and location). The fundamental issue in designing RBF system is obtaining an optimal balance between the quality of water improvement, cost, system yield and accuracy. Different types of wells can be found in RBF systems including horizontal wells, vertical wells, or collector wells (Ranney collectors). On the other hand, the pumping well should be drilled at an appropriate distance far from the river satisfying the quality requirements of pumped water. At the same time this distance is preferred to be as near to the river as possible to have high percentage of infiltrated rate of the river water into the aquifer and acceptable pumped water quality.

Mathematical modelling for different process in RBF has been investigated well in literature (Doussan *et al.,* 1997; Dillon *et al.,* 2002; Abdel-Fattah *et al.,* 2008; Bakker, 2010; Malaguerra *et al.,* 2013; Shamsuddin *et al.,* 2014). However, most mathematical model's studies of river aquifer interaction do not focus on calculating the shortest distance between rivers and well that can produce water with high quality.

Usually, the previous mathematical models are developed for existing RBF systems (i.e., the wells is already drilled). Sometimes it is needed to determine the nearest location to the river where the well can be drilled to have drinking water that can be used for public consumption. The share of river water at the pumping well in the specified location is supposed to be the highest amount that can be obtained. Moreover, by calculating the nearest point to the river, the drawdown of water inside the well is supposed to be less.

The image well theory and graphical method was applied by many researchers to solve such problems (Barry *et al.,* 2009; Asadi-Aghbolaghi *et al.,* 2013; Galvão *et al.,* 2017). However, these studies focused on the capture zone delineation, based on groundwater flow, pumping rates and position of pumping well. Holzbecher (2013) determined the location of pumping well based only on the discharge ratio value of the river water in the well. Mustafa *et al.* (2019) used Green's function approach to determine the well location based on two factors, the rate of bank filtration share and the level of contamination at the pumped water.

The situation becomes more difficult if there is another contaminant source coming to the well. Usually, the contaminants reach the pumping well in riverbank filtration systems not only released from the river but also from other sources such as river or house or building that can be considered as another contaminant source. Thus, the location of the well should be chosen carefully between the river and the other sources. Based on the literature, there is as yet no exact analytical model developed to determine the location of pumping well if it is located between two contaminant sources. For numerical models, MODFLOW software can be used to solve this problem by using trial and error approach. In particular, the well location is specified in one cell and then the MODFLOW simulation is run to see the contaminant concentration at this location if it is suitable or not. The contaminant concentration values at the well are determined in MODFLOW by using finite difference approach.

This article presents an analytical model developed to specify the suitable location of pumping well between the river and another pollutants source from opposite side. It is expected that the water pumped from the well at this location has a low level of contamination and large amount of river water. The model calculates the distance value based on the pumping rate value and on how many years the pumping well is used. The solution is obtained analytically by implementing Green's function approach to solve different groundwater problems in literature (Chen & Woodside 1988; Leij *et al.,* 1993; Leij & van Genuchten, 2000; Leij *et al.,* 2000; Park & Zhan, 2001; Mustafa *et al.,* 2018; Mustafa *et al.,* 2019; Mustafa *et al.,* 2020).

II. MATHEMATICAL FORMULATION

In this model, the place where the pumping well should be drilled between the river and another contaminant source is determined. Particularly, the model calculates the values of $x_{\min_1}$ and $x_{\min_2}$ that represent the distance far from river and second source, respectively. At these distances it is supposed that the contaminant reaches its maximum allowable concentration C_s (Figure 1). In other words if the well drilled within the interval $(x_{\min_1}, x_{\min_2})$ then the quality of produced water is expected to be acceptable. In contrast if

$$x \le x_{\min_1} \quad \text{or} \quad x \ge x_{\min_2} \implies \quad C \ge C_s,$$

then the concentration of contaminant is not satisfactory.

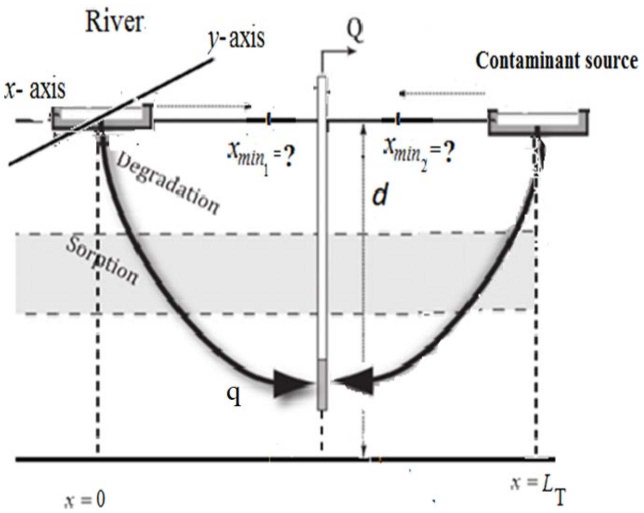

Figure 1. A general diagram of the problem

The model is formulated based on the following assumptions;

1. The aquifer is homogeneous, isotropic and has finite depth.
2. The well has a constant pumping rate and located between the two contaminant sources.
3. The river is at the origin and the total distance between river and other contaminant source equals to L_T (Figure 1).
4. The other contaminant source has an infinite dimension along y-axis such as river, lake or wastewater from houses. Otherwise, the well can be drilled far from the second source.
5. The contaminant coming to the well only from the river and the second contaminant source.

Initially, we supposed that there is a pumping well positioned at distance $x_{\min_1}$ from the river. The method used to determine $x_{\min_1}$ and $x_{\min_2}$ is based on the solution for the following equation relating the solute transport from river to well (Mustafa *et al.,* 2016):

$$R\frac{\partial C}{\partial t} - D_x\frac{\partial^2 C}{\partial x^2} + U_x\frac{\partial C}{\partial x} + \beta C = m_0(t) \tag{1}$$

where C is the concentration of pollutants (M/L³); β is the decay rate of contaminants, U_x is the velocity (L/T) and D_x is the diffusion coefficient (L²/T). The function $m_0(t)$ describes the pollutants concentration at the pumping well which can be calculated as follows (Dillon *et al.,* 2002):

$$m_0(x,t) = \frac{q}{Q}S_o\, exp(-\frac{1}{R}\beta t) \tag{2}$$

q is the stream depletion flow rate (L³/T) and R is the retardation factor. By the following transformations:

$$\bar{x} = x - \frac{U_x}{R}t;\ \ \bar{C}(x,t) = C(x,t)\, exp(\frac{1}{R}\beta t); \quad \text{and}$$

$$\overline{C}_w(t) = C_w(t)\, exp(\frac{1}{R}\beta t)$$

and the dimensionless variables:

$$t_D = \frac{U_x}{d}t;\ C_D(x,t) = \frac{U_x}{S_0 d}\bar{C}(x,t);\quad C_{w_D}(t) = \frac{1}{S_0 R}\overline{C}_w(t);\ \ x_D = \bar{x}\sqrt{\frac{U_x R}{d D_x}}$$

We get:

$$\frac{\partial C_D}{\partial t_D} - \frac{\partial^2 C_D}{\partial x^2{}_D} = C_{w_D}(t_D) \tag{3}$$

The solution of the homogenous of Equation (3) is called Green's function. In our situation, the Green's function represents the concentration of pollutants at the aquifer. Here, the Green's function that satisfy the homogeneous equation of Equation (3) is (Carslaw & Jaeger, 1986):

$$G(x_D, \tau_D) = 1/(\alpha\sqrt{\pi\tau_D})\, exp(-{x_D}^2/4\tau_D), \tag{4}$$

Suppose that t_1 is the solute travelling time towards the pumping well and t_2 is the pumping time from the well. Thus, the solution of Equation (3) is obtained as follows:

$$C_D = \int_0^{t_{D_1}} \int_0^{t_{D_2}} m_{0_D}(\tau_{D_1})\, G(x_D, \tau_{D_2}) d\tau_{D_2} d\tau_{D_1} \tag{5}$$

The initial and boundary conditions are:

$$C(x,t) = 0 \quad \text{for} \quad x \to \infty \quad \text{and} \quad t \geq 0 \tag{5A}$$

$$C(x,t) = S_o f(t) \quad \text{for} \quad x = 0 \text{ and} \quad t \geq 0 \tag{5B}$$

$$C(x,t) = 0 \quad \text{for} \quad x \geq 0 \quad \text{and} \quad t = 0, \tag{5C}$$

Where C_0 is the initial concentration of a contaminant at the river (M/L3). Solving Equations (5) with the condition (5A-5C) implies:

$$C(x,t) = \frac{1}{\alpha\sqrt{\pi}R}\frac{q}{Q} C_0\, exp(-\frac{\beta t_1}{R}) \\ (2\sqrt{\frac{U_x t_2}{d}}\, exp(-\frac{R}{4D_x t_2}(x - \frac{U_x t_1}{R})^2) - \\ \sqrt{\pi}\sqrt{\frac{U_x R}{dD_x}}(x - \frac{U_x t_1}{R}) erfc(\frac{\sqrt{R}}{2\sqrt{D_x t_2}}(x - \frac{U_x t_1}{R}))), \tag{6}$$

Now to calculate the value of x_{min_1} , Equation (6) is converted to one variable equation of x_{min_1} . To do this, the following variables are written in terms of x_{min_1} . The Darcy velocity U_x can be measured based on pumping rate value Q from the well (Dillon *et al.,* 2002):

$$U_x = \frac{3Q}{2\pi\phi d x_{\min_1}}, \tag{7}$$

where ϕ is the porosity and d is the aquifer depth. The value of D_x is computed as follow (Batu, 2005):

$$D_x = a\ U_x\ , \tag{8}$$

where a is the dispersivity [L] and consequently,

$$D_x = a\frac{3Q}{2\pi\phi d x_{\min_1}}, \tag{9}$$

Moreover, the travelling time required by the contaminant to reach the well is also based on pumping rate and distance:

$$t_1 = \frac{x_{\min_1}}{U_x} = \frac{2\pi\phi d\,(x_{\min_1})^2}{3Q} \tag{10}$$

By substituting Equations (7), (9) and (10) in Equation (6) and replace x by $x_{\min_1}$ we get:

$$C(x_{min_1}, t) = \frac{1}{\alpha\sqrt{\pi}R}\frac{q}{Q} C_0 \\ exp(-\frac{2\beta\pi\phi d(x_{min_1})^2}{3QR})(2\sqrt{\frac{3t_2 Q}{2\pi\phi d^2 (x_{min_1})^2}} \\ exp(-\frac{\pi\phi d x_{min_1} R}{6a t_2 Q}(x_{min_1} - \frac{x_{min_1}}{R})^2) \\ -\sqrt{\pi}\sqrt{\frac{R}{ad}}(x_{min_1} - \frac{x_{min_1}}{R}) \\ erfc(\frac{\sqrt{R}}{2\sqrt{\frac{3aQ}{2\pi\phi d x_{min_1}} t_2}}(x_{min_1} - \frac{x_{min_1}}{R}))), \tag{11}$$

If we substitute $C(x_{\min_1}, t) = C_s$ in Equation (11), then we get equation in one variable $x_{\min_1}$. The solution form Equation (11) can be approximated to the smallest greatest integer. Since the contaminant concentration decreases by increasing the distance between river and well then for any distance x after $x_{\min_1}$ we have $C(x,t) \leq C_s$. The same calculation is repeated for $x_{\min_2}$ by assuming the other contaminant source.

Remarks

1. Case 1: If the other pollutants source is not a river, then the location should be closed to $x_{\min_1}$. This can facilitate obtaining higher amount of infiltrated river water.
2. Case 2: If the second contaminant source is also a polluted river the well can be drilled within the interval $(x_{\min_1}, x_{\min_2})$ and closed to the river that has less contamination degree.
3. case 3: If $x_{\min_2}$ is greater than $x_{\min_1}$ that means this area is not sufficient to drill the well. Using the model, the values of $x_{\min_1}$ and $x_{\min_2}$ are calculated separately. In this situation, the well should be drilled in the area satisfying the following condition:

$$L_T > x_{\min_1} + x_{\min_2}$$

III. RESULTS AND DISCUSSION

A. Model Validation

1. Comparison with data related to riverbank filtration site in Malaysia

The project that is established in Langat Basin, Selangor, Malaysia (Shamsuddin *et al.,* 2013) includes two pumping wells. The first well DW1 located at 40m from the river while the second one DW2 at 18m from the river. Initially, to validate the model, it is implemented to validate the position of the two pumping wells for the project site and to predict the pumping well location for the new site. In the beginning, it is assumed that there is no pumping well in the area. Then the proposed model was applied to calculate the distance that should be considered away from the river to drill the pumping well. Beyond this distance, the contaminant concentration should be less than C_s. Finally, the results obtained were compared with the real locations of DW1 and DW2 wells in the site (see Table 1). The model is performed for pumping rate 3075 m³/d and two pumping time periods: 3 years and 10 years. The initial concentration of contaminant was assumed 16 mg/L during the model test. The values of $x_{\min_1}$ and $x_{\min_2}$ are calculated using Equation (11) by considering that the concentration of pollutants around the well is expected to be less than 0.5 mg/L.

Table 1. Location results from analytical model for both DW1 and DW2 in Malaysia

t_2 (d)	Q (m³/d)	Well number	C_s (mg/L)	x_{min} (m)	Real location (m)
9.7	3075	DW1	0.5	22	40
4.6	3075	DW2	0.5	15	18

From Table 1, the analytical results showed that during 9.7 pumping days, the distance between Dw1 well and river edge should be more than 22 m which agrees with its real location at 40 m from the river. However, the analytical results also show that if the DW1 well was drilled at a distance less than 40m from the river such as 25 m, then a greater proportion of river water would be produced from the well. For DW2, the results indicated that the real location of the well at 18 m from stream, which is greater than the 15 m obtained from the model, is good enough to have a high percentage of high quality river water.

2. Comparison with model developed by Holzbecher (2013)

Holzbecher (2013) calculated the distance to shore based only on the aimed discharge ratio and he didn't considered the quality of the water produced in his model. The model is performed for pumping rates 292.8 m³/d, 2164 m³/d and 3075 m³/d for 3 and 7 days pumping periods. Two values of $\frac{q}{Q}$ was considered :33 % and 38 %. The results obtained in this comparison are summarised in Table 2.

Table 2. Location results from the proposed analytical model and Holzbecher (2013) model

t_2 (d)	Q (m³/d)	C_s (mg/L)	x_{min} (m)	x_{min} (m) (Holzbecher 2013)
3	292.8	0.5	10	9.01
7	2164	0.5	16	12.3
3	3075	0.5	12	10.46

From Table 2, in the pumped water when we calculated is noticeable that there is around 2 to 4 metres differences between the two models. This is because our model considered the contaminant concentration level in the pumped water when calculating the distance to river edge.

B. Model Applications

In this section, the effects of pumping time and rates on the well location were simulated if there were two polluted rivers. Three cases of the initial values of concentration from the river C_{0_1} and the second source C_{0_2} are taken:

Case 1: C_{0_1} and C_{0_2} are same and equal to 16 mg/L,

Case 2: the initial concentration at one of the sources is increased to 50 mg/L (here it is taken at the river), and

Case 3: both C_{0_1} and C_{0_2} are the same but multiplied 3 times to reach around 50 mg/L which is considered a little high.

After obtaining the positions results from analytical model, a numerical simulation is conducted to calculate the concentration at these positions. The numerical simulation is performed using Processing MODFLOW software which depends on the finite difference approach. The concentration values at pumping wells C_w are estimated by using the MT3D package in MODFLOW. According to concentration values obtained from the numerical simulation, the well position can be validated. The values of all input parameters used in both analytical and numerical simulation are related to RBF pilot project in Malaysia by Shamsuddin *et al.* (2013, 2014). According to Mohebbi Tafreshi *et al.* (2019), the maximum time required by pollutants to transport from the river to the well is 508,952.5 days, which is more than 1000 years while the minimum time taken is 144 days. In their study, the model assumes a single-layer unconfined aquifer with an annual average rainfall of 112 mm and an annual average temperature of 26.9 °C. On the other hand, Johnson *et al.* (2011) recommended a 40-year travel time for contaminant to transport to public water supply wells in order to differentiate semiconfined and highly confined conditions. Also, they mentioned that if the well is close to the contamination source, the travel time may be become 5 years. In this model, the simulation is conducted for 3 and 10 years pumping periods and it is assumed the aquifer is confined and initially free of contaminants. Thus the contamination at the well originated only from the river and the other source in the opposite site. Table 3 summarised the following values:

1- The results of $x_{\min_1}$ and $x_{\min_2}$ were obtained by analytical model for each pumping period and three cases of C_{0_1} and C_{0_2}.

2- The distance between river and well L_1 and the distance between the second contaminant source and well L_2 that are used during the numerical simulation of MODFLOW. The values of L_1 and L_2 are chosen such that $L_1 > x_{\min_1}$ and $L_2 > x_{\min_2}$. Consequently, the pumping well is located between $x_{\min_1}$ and $x_{\min_2}$.

3- The total distance L_T that are considered at MODFLOW simulation at the area of pumping well.

The concentration of contaminants around the well C_w is computed by MODFLOW. If the concentration values are less than 0.5 mg/L as expected from analytical model, then the analytical model is suitable for use.

Table 3. The values of $x_{\min_1}$, $x_{\min_2}$, C_{0_1}, C_{0_2}, L_1, L_2, L_T and C_w at 3 years and 10 years pumping time periods

t_2	C_{0_1}	C_{0_2}	$x_{\min_1}$ (m)	$x_{\min_2}$ (m)	L_1 (m)	L_2 (m)	L_T (m)	C_w (mg/L)
3	16	16	158	158	175	175	350	0.00129
	50	16	188	158	225	175	400	0.00123
	50	50	188	188	225	225	450	0.00145
10	16	16	253	253	275	275	550	0.0173
	50	16	294	253	325	275	600	0.026
	50	50	294	294	325	325	650	0.0616

According to the results listed in Table 3, it is noticed that the concentration values near the well lie in the range of 0.0012 mg/L to 0.0616 mg/L in all observed cases. These small concentration values validate the well location which is specified based on analytical results for $x_{\min_1}$ and $x_{\min_2}$. Also, it is found that increasing either the initial contaminant concentration at the contaminant source or pumping period leads to an increment of $x_{\min_1}$ and $x_{\min_2}$ values. The increase in $x_{\min_1}$ and $x_{\min_2}$ values due to change of C_{0_1} or C_{0_2} are considered small. By multiplying C_{0_1} or C_{0_2} from 16 mg/L to 50 mg/L the value $x_{\min_1}$ or $x_{\min_2}$ increased from 158m to 188m only after 3 years pumping period. After 10 years pumping period the value of $x_{\min_1}$ or $x_{\min_2}$ increases from 253 m to 293 m at 16 mg/L and 50 mg/L, respectively for C_{0_1} or C_{0_2}. In both pumping periods the difference of distance values occurred due to increasing the initial concentration was 30 m or 40 m only. On the other hand a noticeable increasing of $x_{\min_1}$ and $x_{\min_2}$ values as shown due to change of pumping period. When C_{0_1} or C_{0_2} was equal 16 mg/L, the results of $x_{\min_1}$ or $x_{\min_2}$ increased from 158 m to 253 m by increasing the pumping period from 3 years to 10 years. In the meanwhile, at 50 mg/L for C_{0_1} or C_{0_2}, the distance values changed from 188 m to 294 m by increasing the pumping period from 3 years to 10 years. In both value of initial concentration, the difference of distance results was around 100 m.

Figure 2 represents the relation between the periods of pumping and the total distance that should be found between the two rivers L_T that at least should be found to drill the pumping well. The value of L_T was calculated by using the following equation:

$$L_T = x_{\min_1} + x_{\min_2} + E\,; \tag{13}$$

where E is the extra distance that is used to drill the pumping well (i.e. the length of the interval ($x_{\min_1}$, $x_{\min_2}$)). In Figure 2, the value of E was assumed to be equal 5m. It was found that, by increasing the pumping time periods, the L_T value between the two contaminant sources is increased.

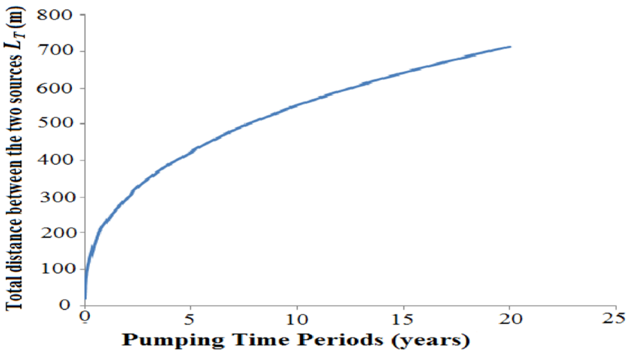

Figure 2. The effect of pumping time period on the total distance that should be exist between the two rivers

For example, by using 5 years pumping time, L_T equals approximately 400 m while this value was around 500m after 10 years pumping period. The total distance between the stream and the second contaminant source continues to increase by increasing the pumping period until reaching 700m after 20 years.

Figure 3 shows the $x_{\min_1}$ and $x_{\min_2}$ values at different pumping time periods. The $x_{\min_1}$ was calculated by using C_{0_1} at the river equals 16 mg/L while $x_{\min_2}$ was calculated by using C_{0_2} at the second river equals 50 mg/L. Generally, increasing the pumping time period may increase the distance between pumping well and contaminant source. Additionally, the difference between $x_{\min_1}$ and $x_{\min_2}$ becomes a little higher when the pumping time period increased. In particular, after 3 years pumping, the difference between $x_{\min_1}$ and $x_{\min_2}$ was around 30 m. However, by duplicating the time period to 6 years, this difference becomes around 36 m. After 20 years pumping this value reaches 50 m. This shows that, despite the initial concentration at second river was 3 times more than the first one, the differences between the $x_{\min_1}$ and $x_{\min_2}$ were not so big.

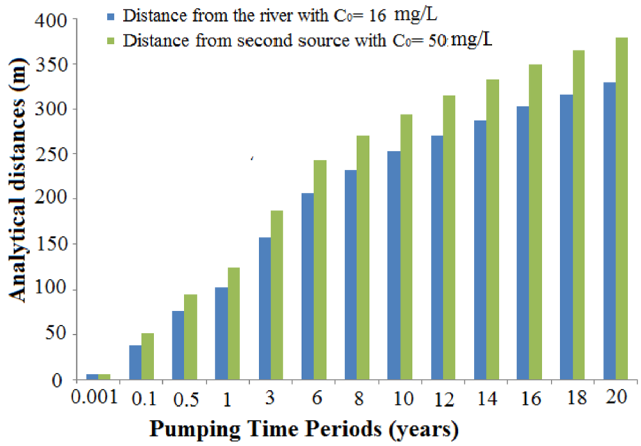

Figure 3. The locations of the pumping well between the two rivers at different pumping periods

The efficiency of analytical model results is also investigated for different pumping rates. Table 3 showed $x_{\min_1}$ and $x_{\min_2}$ values at different pumping rates.

Table 3. The values of $x_{\min_1}$, $x_{\min_2}$, C_{0_1}, C_{0_2}, L_T and C_w at different pumping rates

Q	C_{0_1}	C_{0_2}	$x_{\min_1}$	$x_{\min_2}$	L_T	C_w (mg/L)
1500	16	16	120	120	250	0.00132
	50	16	144	120	300	0.00894
	50	50	144	144	350	0.0011
3072	16	16	158	158	350	0.00129
	50	16	188	158	400	0.0012279
	50	50	188	188	450	0.00145
4072	16	16	177	177	450	0.00114
	50	16	208	177	400	00.002233
	50	50	208	208	450	0.00438

At all observed pumping rates, the concentration values do not exceed 0.004 mg/L at the well location determined by the analytical model. Generally increasing the pumping rates increases the values of $x_{\min_1}$ and $x_{\min_2}$. For example, when C_{0_1} or C_{0_2} was equal 16 mg/L, the values of $x_{\min_1}$ or $x_{\min_2}$ increases from 120 m to 158 m until 177 m by using 1500 m3/day, 3072 m3/day and 4072 m3/day, respectively. By multiplying C_{0_1} or C_{0_2} to 50 mg/L, the values of $x_{\min_1}$ or $x_{\min_2}$ increases from 144 m to 188 m until 208 m by using 1500 m3/day, 3072 m3/day and 4072 m3/day, respectively.

IV. CONCLUSION

An analytical model is developed to investigate the best location for the pumping well in Riverbank filtration system in the case if there is another contaminant source located on the other side of the well. The derivation of the model equation based on advection dispersion equation which is solved by using Green's function method. The results are validated for different values of initial concentration at the river and the other contaminant source and for different pumping rates. Also, two pumping periods: 3 years and 10 years were observed. A numerical MODFLOW simulation is performed to calculate the concentration value at the pumping well located at a distance far from the river obtained from the analytical model. Generally, the concentration values measured at the pumping well in different cases do not exceed 0.05 mg/L. This means that the well location obtained from the proposed analytical is suitable for use in RBF systems. Moreover, it was noticeable that the effect of pumping periods on the distance values far from the river was bigger than the effect of pumping rate or initial contaminant concentration at the river or other contaminant source. However, the effect of pumping rate and initial contaminant concentration is still significant and should be considered during the model run. The proposed model can be used in managing and operating new sites of riverbank filtration systems in which the well location is determined based on how much high-quality water is needed to pump (i.e. pumping rate), how long the well is supposed to be used (i.e. pumping period), and initial concentration of pollutants at the river and other contaminant sources.

V. ACKNOWLEDGEMENT

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