

Analytical Modeling for Water Chemistry Changes in River Bank Filtration Systems

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Abstract: Riverbank filtration system is considered one of the economic and sustainable solutions to river water pollution especially in tropical countries such as Malaysia. In this work, an analytical model is developed to simulate the contaminant attenuation in riverbank filtration systems by using the separation of variables method. The basic aim of the model is to understand the role of microbial activity that occurs in riverbed sediments on reducing the concentration of the contaminant in the aquifer and changing the water characteristics. Graphically, it is found that the model can simulate the infiltration process of polluted river water effectively. Also, the analytical model results, as well as experimental data, show that nitrate (18.6 and 34.1 mg-NO₃/L) and sulphate (20.9 – 22.1 mg-SO₄/L) can be consumed by bacteria in the first 0.5 m of the aquifer, and reduced by more than 95% for both compounds. The model is applied for the first riverbank filtration system in Malaysia. Sensitivity analysis results highlight the importance of dissolved organic matter (DOM) concentration (ranged from 1.0 to 12.4 mg/L) for RBF efficacy in which a higher concentration of DOM leads to faster consumption of pollutants.

Key words: Analytical modelling, riverbank filtration, ammonia pollution, bacterial process, wastewater.

Introduction

Surface water pollution is a significant public health problem that encourages governments to make more efforts to prevent it. Tropical countries such as Malaysia are more risk-facing than the others since they depend basically on surface water (rivers, lakes, etc.) as the main source of water supply where rainfall continuously recharges the surface water streams (Libera et al., 2017). However, most of these sources are polluted to significant degrees by various pollutants. Pollution of river water with multiple sources such as industrial wastes, agricultural fertilisers, landfill leachates, transportation, manure runoff or sewage can cause microbial contamination of drinking water (Mekuria et

al., 2021). These results in many dangerous diseases that can be fatal for individuals. For example, the usage of synthetic fertilisers in agriculture can cause contamination of surface water by nitrates (Mayo et al., 2019), which can cause blue baby syndrome for infants. Moreover, high levels of pollutants in surface water rise the treatment cost. Currently, tropical countries are moving toward using groundwater as a supplementary source of water supply. One optional technique is riverbank filtration (RBF).

RBF is a surface water treatment technique that depends on the natural removal of pollutants from water during its transfer to the aquifer (Figure 1). This technology can occur naturally or induced by several pumping wells near the stream. RBF is applied

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effectively in the USA and several European countries (D'Alissio et al., 2018; Paufler et al., 2018). RBF technique had been applied for the first time in Malaysia in a Pilot project conducted in Jenderam Hilir, located in Langat Basin, Selangor, Malaysia (Shamsuddin et al., 2013).

The quality of produced water in RBF systems is usually influenced by several factors: the degree of pollution in the river, site hydrogeology, well type and location, chemical reactions and stream depletion rate. This technology can effectively reduce different contaminants concentrations such as dissolved organic carbon, suspended solids, turbidity, pathogens, and many organic and inorganic compounds without negative effects on the surrounding environment (Mustafa et al., 2021). The water pumped from RBF systems can be used directly for potable water supply or can serve as the final treatment just before disinfection.

Mathematical models that are related to pollutants transportation from the river to wells and changes in water chemistry due to the natural process in the first few meters in the RBF system have been studied by many researchers (Doussan et al., 1997; Hantush and Mariño, 1996; Kim et al., 2003; Kim, 2005; Malaguerra et al., 2013; Natarajan and Suresh Kumar, 2011; Schäfer et al., 1998a; Schäfer et al., 1998b; Sen et al., 2005). Most studies mentioned earlier dealt with the problem numerically. In particular, most researchers used finite difference and finite element approaches to solve the transport equation. On the other hand, analytical solutions are more useful in the quick estimation of concentrations, simplicity of input parameters and free from numerical errors. In literature, four analytical approaches were mainly used to estimate solute transport in aquifers: Laplace transform and Fourier transform (Chen et al., 2012; Chen, 2010; Connell, 2007; Singh et al., 2012; Singh, 2013), Hankel transforms (Massabó et al., 2006; Singh et al., 2010) and Green function (Park and Zhan, 2001). However, all of these analytical methods have numerical summation or integration, which needs complex further calculations. In this study, a new analytical method is

presented to simulate the degradation of contaminants. The significance of the current solution is that it is based on the separation of variables method, which can be easily applied in spreadsheets and it does not require a numerical integration using advanced software. To the best of our knowledge, the separation of variables method has not been applied in RBF system problems.

Mathematical Modelling Formulation

Analytical modelling is developed to simulate the unsteady flow to pumping wells near rivers in confined aquifers. In this model, it is assumed that the river penetrates the aquifer partially. Under the unsteady state, the 1D advection dispersion equation for solute transport is given as:

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

where C is the concentration of pollutants, U_x is the Darcy velocity, ϕ is the porosity, D_x is the diffusivity of mass transport, C_w is the concentration of pollutants at the pumping well, β is the decay constant and R is the linear retardation factor. The following equation is used to describe the calculation of D_x (Ingebritsen and Sanford, 1998):

$$D_x = a U_x \quad (2)$$

where a is the dispersivity. The initial and boundary conditions are written as follows:

$$\begin{aligned} C(x, t) &= f(x) \text{ for } x \geq 0 \text{ and } t = 0 \\ C(x, t) &= C_0 \text{ for } t \geq 0 \text{ and } x = 0 \\ C(x, t) &\rightarrow 0 \text{ as } x \rightarrow \infty \end{aligned} \quad (3)$$

where C_0 is the initial concentration at the river. The value of C_w can be computed as follows (Dillon et al., 2002):

$$C_w(t) = \frac{q}{Q} C_o \exp\left(-\frac{1}{R} \beta t\right) \quad (4)$$

where q is the stream depletion flow rate, and $\frac{q}{Q}$ is the percentage of infiltrated river water to the pumped water. The partial connection between the river and the aquifer due to the clogging layer under the streambed decreases $\frac{q}{Q}$ the value. To describe the effect of clogging of riverbed in the model formulation, the value of $\frac{q}{Q}$ will be computed as follows (Hunt, 1999):

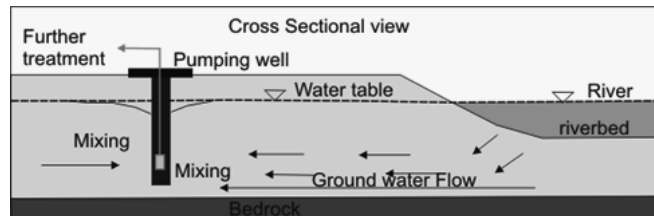


Figure 1: A simple river bank filtration system (modified from Kim et al., 2003).

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

where t_p is the pumping time, L is the distance between the pumping well and river edge, λ is the stream bed leakage coefficient, S_x is the storage coefficient, and T is the transmissivity.

The nonhomogeneous Equation (1) is solved analytically by finding the solution of the homogenous equation $C_h(x, t)$ and the particular solution $C_p(x, t)$. Then the general solution of Equation (1) is a linear combination of homogenous and particular solutions as follows:

$$C(x, t) = C_h(x, t) + C_p(x, t) \quad (6)$$

Firstly, we will solve the homogenous Equation (7) by using the separation of variables method.

$$\phi R \frac{\partial C}{\partial t} - D_x \frac{\partial^2 C}{\partial x^2} + U_x \frac{\partial C}{\partial x} + \beta C = 0 \quad (7)$$

Consider $C_h(x, t) = T(t) X(x)$. Thus Equation (7) becomes:

$$\phi R T'(t) X(x) = D_x T(t) X''(x) - U_x T(t) X'(x) - \beta T(t) X(x), \quad (8)$$

where the initial and boundary conditions will be transformed into

$$\begin{aligned} T'(0) &= 0 \\ X(0) &= C_0, \text{ and } X(\infty) = 0 \end{aligned} \quad (9)$$

Dividing both sides of Equation (8) by $T(t) X(x)$ gives the following:

$$\phi R \frac{T'(t)}{T(t)} = D_x \frac{X''(x)}{X(x)} - U_x \frac{X'(x)}{X(x)} - \beta \quad (10)$$

Then, Equation (10) is divided into two separate equations:

$$\phi R_d \frac{T'(t)}{T(t)} = \alpha \quad (11)$$

and

$$D_x \frac{X''(x)}{X(x)} - U_x \frac{X'(x)}{X(x)} - \beta = \alpha, \quad (12)$$

where $\alpha > 0$. If $\alpha = 0$, then the equation will be steady state. The solution for Equation (11) is obtained as:

$$T(t) = M \exp\left(\left(\frac{\alpha}{\phi R}\right)t\right), \quad (13)$$

Additionally, Equation (12), under the previous boundary conditions, can be solved as follows:

$$X(x) = C_0 \exp\left(\left(\frac{U_x - \sqrt{(U_x)^2 + 4D_x(\beta + \alpha)}}{2D_x}\right)x\right). \quad (14)$$

Combining the two solutions of Equations (13) and (14), the final solution of Equation (8) becomes:

$$C_h(x, t) = C_0 \exp\left(\left(\frac{\alpha}{\phi R}\right)t\right) \exp\left(\frac{U_x - \sqrt{(U_x)^2 + 4D_x(\beta + \alpha)}}{2D_x}x\right). \quad (15)$$

To find the particular solution C_p , assume that $C_p(x, t) = A \exp\left(-\frac{\beta}{R}t\right)$ then

$$-\phi \beta A \exp\left(-\frac{\beta}{R}t\right) = -\beta A \exp\left(-\frac{\beta}{R}t\right) + \frac{q}{Q} C_0 \exp\left(-\frac{\beta}{R}t\right) \quad (16)$$

which implies that

$$A = \frac{q}{Q} \frac{1}{(1 - \phi)\beta} C_0 \quad (17)$$

and

$$C_p(x, t) = \frac{q}{Q} \frac{1}{(1 - \phi)\beta} C_0 \exp\left(-\frac{\beta}{R}t\right) \quad (18)$$

Applying the initial condition

$$C_h(x, 0) = c_i - \frac{q}{Q} \frac{1}{(1 - \phi)\beta} C_0 \quad (19)$$

Based in Equation (6), our final solution is

$C(x, t) =$

$$\begin{aligned} &C_0 \exp\left(\left(\frac{\alpha}{\phi R}\right)t\right) \exp\left(\frac{(U_x - \sqrt{(U_x)^2 + 4D_x(\beta + \alpha)})}{2D_x}x\right) \\ &+ \frac{q}{Q} \frac{1}{(1 - \phi)\beta} C_0 \exp\left(-\frac{\beta}{R}t\right) \end{aligned} \quad (20)$$

The pumping process from the well affects the velocity of water and the travelling time of pollutants to reach the well significantly. To consider this effect we used the following equation to calculate the seeping velocity (Dillon et al., 2002):

$$U_x = \frac{3Q}{\phi 2\pi dL}, \quad (21)$$

where Q is the pumping rate. The transmissivity value T is calculated as follows (Theis, 1935):

$$T = \frac{Q}{4\pi\Delta s}, \quad (22)$$

where Δs is the drawdown change. The value of hydraulic conductivity (K) can be estimated based on the calculated value for T as follows:

$$K = \frac{T}{d}, \quad (23)$$

where d is the aquifer thickness. From equations (22) and (23), the following is obtained:

$$Q = 4dK\pi\Delta s. \quad (24)$$

By substituting Equation (24) into Equation (21), the following equation is obtained:

$$U_x = \frac{6K\Delta s}{\phi L}. \quad (25)$$

Consequently, from Equation (2), the following is produced:

$$D_x = a_l \frac{6K\Delta s}{\phi L}, \quad (26)$$

The ϕ value is assumed to depend on the hydraulic conductivity values K according to the following formula developed by Fallico (2014) from a field scale in a sandy confined aquifer, South Italy:

$$K = 1.52E - 4\phi^{1.418} \quad (27)$$

Equation (27) can be applied in similar porous sites that have the same properties. Thus, we applied the formula in Equation (27) to calculate the value of ϕ in Equations (25) and (26). The travelling time t is calculated based on Equation (25):

$$t = \frac{L}{U_x} = \frac{\phi L^2}{6K\Delta s}. \quad (28)$$

To take into account the effect of the K in the proposed model, Equations (25), (26), and (28) were substituted into Equation (20).

Results and Discussion

Simulation of Column Experiments

The model is proposed to simulate the unsteady 1D contaminant transport in an aquifer where riverbank filtration is implemented. To investigate the behaviour of the proposed analytical model for simulating the biological process described previously, it is applied to the column experiments of von Gunten and Zobrist (1993). The importance of these experiments is that it

is designed to simulate infiltration of an organically polluted river into an aquifer. The model is checked for three mineral compounds; NO_3 , O_2 and SO_4 , and compared with numerical model results obtained by Doussan et al. (1997). Furthermore, the statistical measure R^2 is computed to show how the data points fit with the analytical model. Actually, the two-column experiments (a) and (b) are conducted by Doussan et al. (1997). In the column experiment, the only substrate of bacteria was NO_3 , and the model is compared with the numerical results obtained after 14 days, where the bacteria are expected to enter the stationary phase. In contrast, column (b) includes three different nutrients of bacteria: NO_3 , O_2 and SO_4 , and the comparison are conducted after 35 days. Tables 1 and 2 summarise the values of different parameters that are required for the model test.

Figure 2 represents the contamination by NO_3 in column (a) after 14 days on the interval $0 \leq x \leq 1$ m. It is clear that the contamination is decreasing rapidly

Table 1: Physical parameters used in the simulation of column experiments conducted by Doussan et al. (1997)

Parameter	Comments
$K_c = (\text{m}^3/\text{kg})$	Linear distribution coefficient
$R_d = 8.96$	Retardation factor
$\phi = 0.37$	Porosity
$U_x = 1.8$ (m/day) (Column a) $= 0.37$ (m/day) (Column b)	Darcy velocity
$a = 0.001$ (m)	Dispersivity
$C_d = 43.2$ (mg/L)	Initial concentration of DOM at $x=0$
$\alpha = 0.002$	Solution constant

Table 2: Microbiological parameters used in the simulation of column experiments conducted by Doussan et al. (1997)

Parameter	O_2	NO_3	SO_4
Maximum specific growth rate constant (day^{-1})	10	1.44	0.26
Half- saturation constant of electron acceptors (mg/L)	0.77	7	5.35
Half- saturation constant of electron donor (mg/L)	3	3	3
Microbial yield F	0.5	0.4	0.4
Initial concentration for $x = 0$, Column (a)	0	34.1	0
Column (b)	7	18.6	20.9-22.1

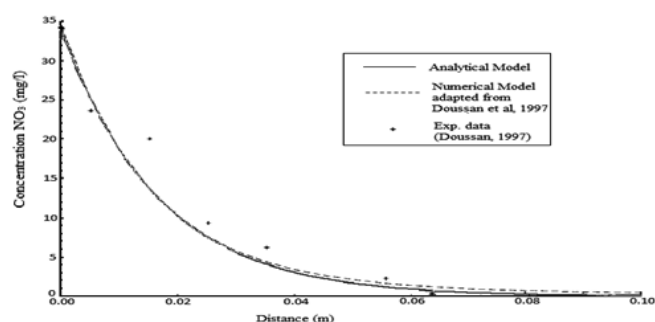


Figure 2: Profiles of NO_3 concentration in column (a) after 14 days by an analytical model, and numerical simulation lines and experimental data points of Doussan et al. (1997).

during the first meters from the aquifer. Comparing analytical and numerical solutions, a strong resemblance between the two graphs is noticed. Both analytical and numerical simulations indicate that the concentration of NO_3 is approximately consumed after 10 cm. This result is consistent with the experimental data.

Similar results are obtained for the period after 35 days for NO_3 and O_2 in column *b* (Figures 3a and 3b, respectively). In this period the bacteria is expected to enter the stationary phase where the growth rate is very small. The difference of time period for a stationary phase in both columns (a) and (b) can be interpreted by the existence of O_2 and SO_4 in column (b) in which they act as inhibition factors. Since there are no experimental points data recorded for O_2 and NO_3 in this period of time, the analytical model is compared with the numerical simulation. Graphically, it is found that the concentration of NO_3 and O_2 are reduced rapidly to reach zero before 0.05 m. Also, it is clear that the consumption of O_2 is faster than the consumption of NO_3 , which is coherent to the numerical results curve that has similar behaviour. Thus, the results obtained from comparison with the data of columns (a) and (b) show the high accuracy of the analytical solution.

For SO_4 reduction by bacterial activity, it was simulated after 35 days in column (b) on the distance ranges from 0.05 m to 0.3 m. Basically, the analytical model can simulate the degradation of contaminants when the bacteria start their work. Referring to Doussan et al. (1997) and Schäfer et al. (1998b), the bacteria begin to consume SO_4 at the sulphate reduction zone, which is located approximately at 0.05 m distance from the river surface. Consequently, we use the difference $(x-0.05)$ instead of (x) in Equation (20). It is worth noting that after 35 days the sulphate simulation in the analytical models show that SO_4 concentration goes to zero during the first 30 cm (refer Figure 4). This

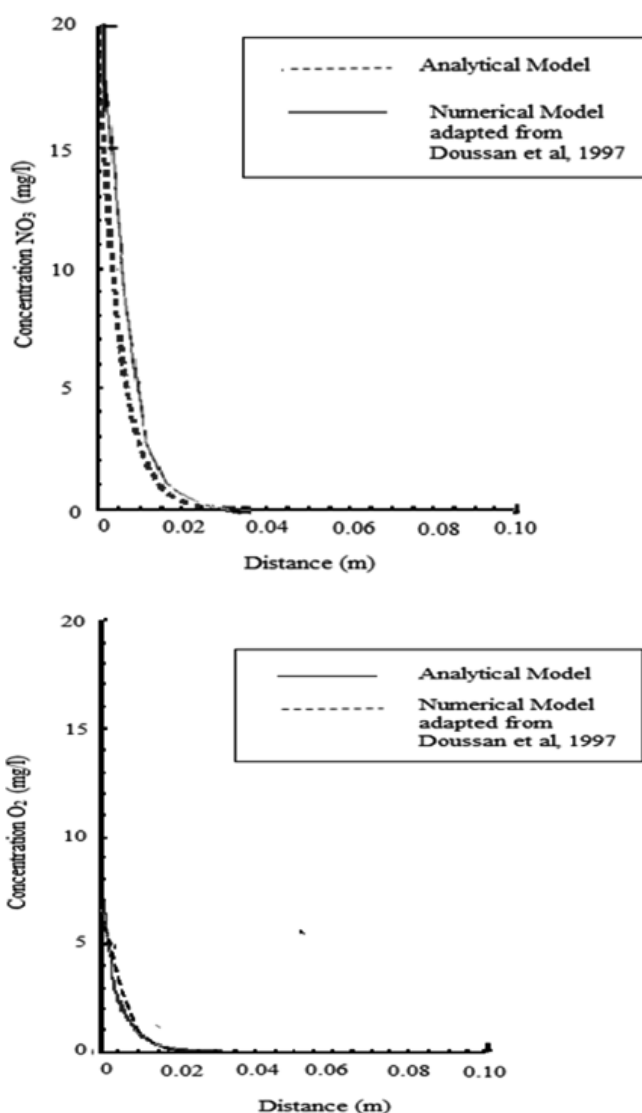


Figure 3: Analytical and numerical simulation in column (b) after 35 days (i) for NO_3 (ii) for O_2 .

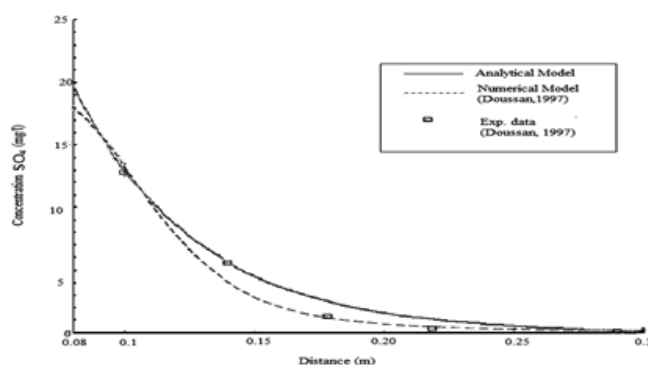


Figure 4: Analytical and numerical simulation in column (b) after 35 days for SO_4 .

showed that the bacteria can absorb both NO_3 and O_2 before SO_4 . In addition, SO_4 decreasing rate in the numerical model is within the distance between 0.1 and 0.25 m. This rate is a little higher than the decreasing rate in the analytical model within the same interval. However, these differences do not affect the accuracy of the analytical model results, as both models give approximately equalled values after 0.25 m. Generally, in RBF all nutrients can be consumed by bacteria in the first few meters from the aquifer.

Although the graphs show a good match between the analytical model and numerical data, we further investigate the R^2 measures for the analytical model against the observed data. This implementation would ensure the actual performance of the analytical model. This refers to the closeness of the analytical model to the observed data distribution. R^2 values are computed for NO_3 in column (a) (refer Figure 5) and SO_4 in column (b) (refer Figure 6). Since there is no plotted experimental data for NO_3 in column (b), R^2 values are calculated for analytical model with respect to the numerical simulation (refer Figure 7). It is interesting

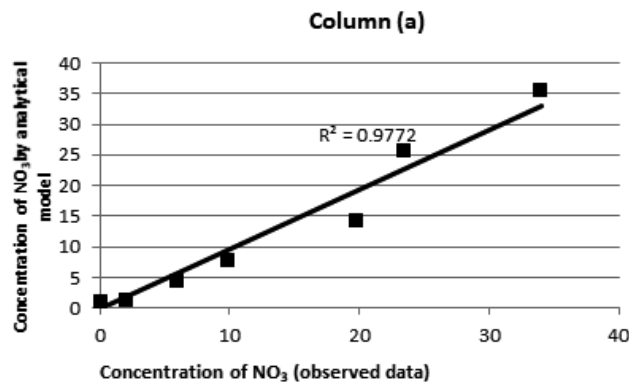


Figure 5: R^2 values for NO_3 in column (a).

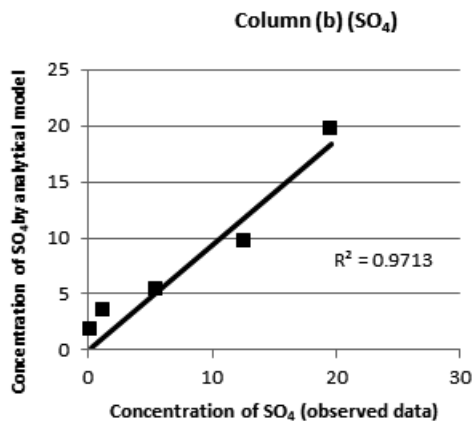


Figure 6: R^2 values for SO_4 in column (b).

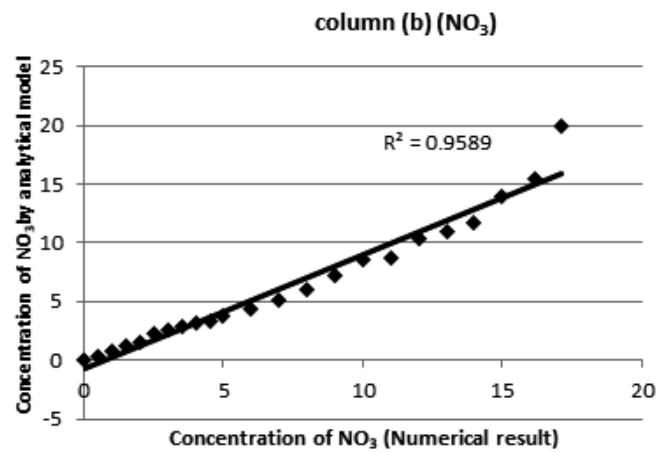


Figure 7: R^2 measured values for NO_3 in column (b).

to see that the recorded R^2 values for analytical model lies in the range from 0.92-0.95, which means that the model performance is significantly close to the experimental results.

Applying the Model to the Experimental Site Data

Here, we examine whether the model can give similar results with the simulation of the column experiments. Also, we check if the model is suitably matched with the numerical simulation that is related to the RBF site in France (Doussan et al., 1997). The parameters used in this simulation are listed in Tables 3 and 4.

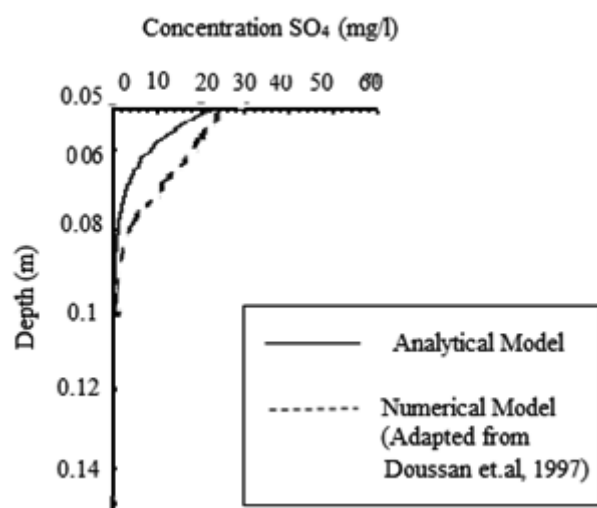
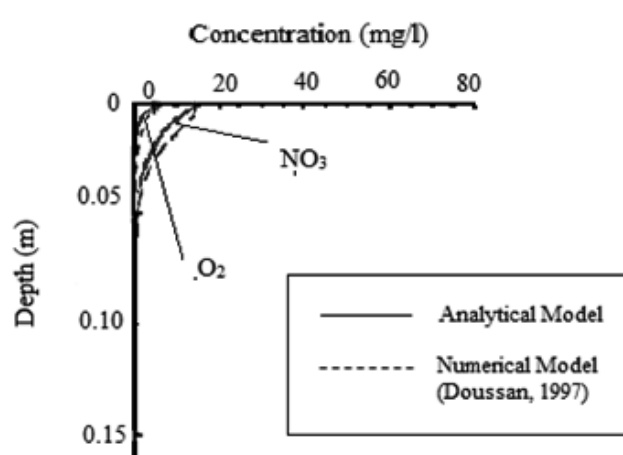
The analytical model that is carried on for NO_3 , O_2 and SO_4 in the experimental site is presented in Figure 8. The concentration of NO_3 and O_2 are found to be consumed during 5 cm in the site, while SO_4 concentration goes to zero during the first 10 cm. As

Table 3: Physical parameters used in the simulation of experimental site data conducted by Doussan et al. (1997)

Parameter	Comments
$K_c = 2.10^{-3} \text{ (m}^3/\text{kg)}$	Linear distribution coefficient
$R_d = 8.96$	Retardation factor
$\phi = 0.6$	Porosity
$U_x = 0.004 \text{ (m/day)}$	Darcy velocity
$a = 0.001 \text{ (m)}$	Dispersivity coefficient
$C_d = 6.2 \text{ (mg/L)}$	Initial concentration of DOM at $x = 0$
$\alpha = 0.002$	Solution constant

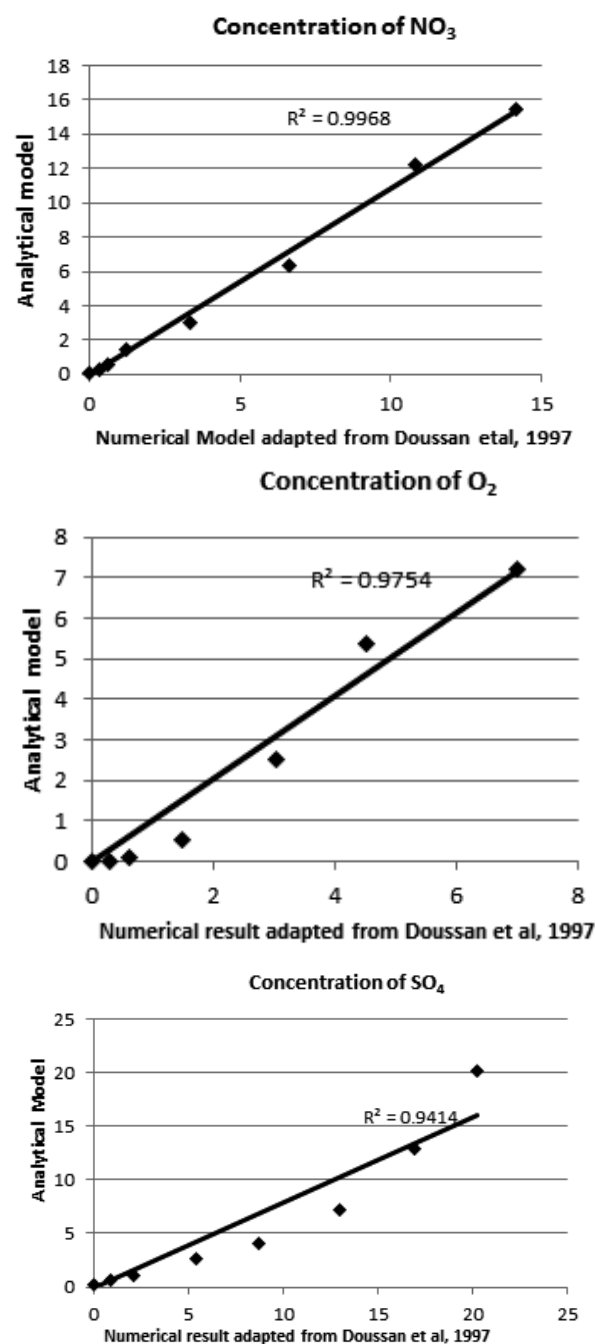
Table 4: Microbiological parameters used in the simulation of experimental site data conducted by Doussan et al. (1997)

Parameter	O_2	NO_3	SO_4
Maximum specific growth rate constant μ_{max} (day^{-1})	10	10	5
Half- saturation constant of electron acceptors S_c (mg/L)	0.77	65	1
Half- saturation constant of electron donor S_d (mg/L)	15	20	20
Microbial yield F	0.5	0.4	0.1
Initial concentration for $x = 0$, C_0	7	15	52

**Figure 8: Concentration profiles in real site (a) for NO_3 and O_2 ; (b) for SO_4 .**

mentioned before, the simulation of SO_4 began from 5 cm and consumed before 10 cm. These results are coherent with numerical simulation.

To have strong evidence for a worthy fitness of data by the analytical model, R^2 measures are examined for NO_3 , O_2 and SO_4 between the analytical model and numerical results that are adapted from Doussan et al. (1997) in the experimental site (Figure 9 a-c). It is noticed that the model matches the numerical result,

**Figure 9: R^2 measured values for the experimental site.**

especially for NO_3 and O_2 . The R^2 values lie within the range 0.8912 for SO_4 and 0.9585 and 0.9942 for O_2 and NO_3 , respectively.

Sensitive Analysis for DOM Concentration

The sensitive analysis is performed to observe the effect of DOM concentration on the model's behaviour (Figure 10). All parameters implemented in the sensitive analysis test are taken from the experimental site, except for Darcy velocity, which is set to be 0.04 m/day. The result is observed for NO_3 concentration with four different values of DOM concentration: 1 mg/L, 3 mg/L, 6.2 mg/L and 12.4 mg/L. As the behaviour of SO_4 change is similar to NO_3 , sensitive analysis was not repeated to the SO_4 model. Generally, the increase of DOM in the aquifer leads to a decrease in the distance where NO_3 concentration goes to zero. For example, for a DOM concentration of 6.2 mg/L, the distance required for NO_3 consumption is 0.2 m. When the DOM concentration is doubled (i.e. 12.4 mg/L), the distance is decreased to 0.1 m, while by decreasing the DOM concentration to 3 mg/L, the distance is increased to 0.3 m. Also, for 1 mg/L, the distance is found to be equal to 0.7 m. Clearly, based on these results, it is concluded that the increase of DOM decreases the travelled distance of contamination and consequently, increases the RBF efficiency.

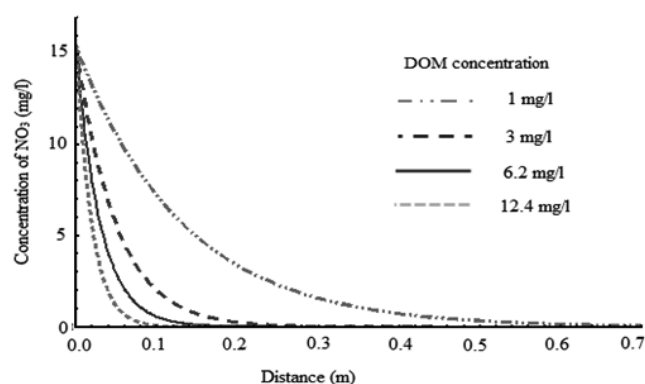


Figure 10: Simulation of NO_3 profiles with different values of DOM concentration.

Conclusion

RBF technology is applied in several countries around the world as one of the main sources of drinking water supply. Therefore, it is important to know the chemical changes that may occur in the water during its pathway from the river to the pumping well through the aquifer. In this work, an analytical model is

developed to simulate the water chemistry change and microbial activity in the RBF system by evaluating the decrease in concentration of NO_3 , O_2 and SO_4 . The model focusses on the microbial process in the area of riverbed sediments where most of the bacteria are accumulated. In this area, most of the contaminants concentrations are reduced. The model is compared with the experimental data and numerical simulation of Doussan et al. (1997). It is found that NO_3 and O_2 are consumed in the first 10 cm from the aquifer, while SO_4 is consumed in the first 30 cm. These results are consistent with those of the other studies (Doussan et al., 1997, Schäfer et al., 1998b). Furthermore, R^2 values are computed to examine the performance of the model. It is found that the model matches well with the numerical results and experimental data. Sensitive analysis results highlight the importance of DOM concentration in aquifers where a higher concentration of DOM leads to faster consumption of contaminants. The present model can help to achieve an in-depth understanding of the behaviour of bacteria and its important role in the evolution of contaminant concentration in the RBF system, despite the limitation in fully describing the whole processes occurring during water transport from the river to the surrounding aquifer. Furthermore, this study could assist in accurately estimating the well location in riverbank filtration zones.

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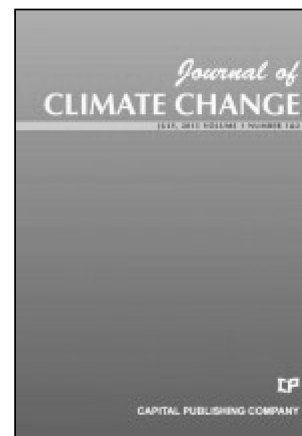
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