MATHEMATICAL MODELLING OF CONTAMINANT TRANSPORT IN RIVERBANK FILTRATION SYSTEMS

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To my beloved parents, the strong and first teachers
To my brother and sisters, lightening hope candles in my life
To my dear husband and children, the source of peace and love everyday
To my country Palestine, the place that I will always sacrifice for
ACKNOWLEDGEMENT

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ABSTRACT

Analytical study of contaminant transport in riverbank filtration (RBF) systems is significant in providing a guide for managing and operating drinking water supplies from pumping wells. The pumping process and the distance of the pumping well from the river are two important factors for producing permissible drinking water from the system. Simulation of the impact of pumping rate and pumping time on contaminant transport based on analytical studies are not yet extensive. Thus, there is a lack of mathematical models for RBF systems to determine the shortest distance of the pumping well to the river, that produces quality water. This research aimed to provide a mathematical model based on advection dispersion equation and Green’s function approach to determine the potential effects of pumping rate and pumping time, on one and two-dimensional contaminant transport models in RBF systems. The model would be able to show how the pumping time and pumping rate affect the contaminant concentration in RBF systems. By considering an inverse problem, the Green’s function solution was applied to the problem in order to determine the shortest distance from the pumping well to the river, to increase the percentage of the quality of river water. This distance was computed when the contaminants were released from a few scenario which include a single polluted river and two polluted rivers. The distance evaluated was based on three simulated scenarios containing the varying pumping times, pumping rates and different initial concentrations from the river. The model was assessed using parameters related to nitrate (NO$_3$) compound obtained from RBF pilot project which had been conducted in Malaysia. The results confirmed the suitability of the proposed model in simulating the effect of pumping process on the quality of the produced water and in locating the pumping well. The proposed model is helpful in providing guide to manage the existing RBF systems as well as in establishing new sites.
**ABSTRAK**

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LIST OF ABBREVIATIONS

ADE - Advection dispersion equation
AEM - Analytical element method
BEM - Boundary element method
BVP - Boundary value problem
DBPs - Disinfection by-products
DOM - Dissolved organic matter
DW1 - The first pumping well in the study area
DW2 - The second pumping well in the study area
EFT - Exponential Fourier Transform
FDM - Finite Difference Method
FEflow - Finite Element subsurface FLOW system
FEM - Finite Element Method
FEMLAB - Software based on MATLAB for solving PDE via FEM
FLexPDE - A finite element model builder and numerical solver
HP1 - HYDRUS-PHREEQC-1D
HYDRUS-1D - Water, heat, and solute movement in 1D simulator
LBM - Lattice Boltzmann Method
MODFLOW - Modelling Groundwater Flow and Pollution software
MT3DMS - Modular Transport Three Dimensional Model Simulator
MMP - Modified moment propagation
ODE - ordinary differential equation
PAT - Pump and treat system
PDE - Partial differential equation
PHREEQC - pH-Redox-Equilibrium Calculator
PF - Pumping function
RBF - Riverbank filtration system
RC - Radial collector
RMSE - Root Mean Square Error
RT3D - Reactive Transport Three Dimensional Model
SDR - Stream depletion rate
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<td>TCE</td>
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<td>WHO</td>
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\( Q_{m_{adv}} \) - advection flux
\( Q_{m_{dp}} \) - Diffusion flux
\( q \) - Stream depletion flow rate
\( q_n \) - Water flux normal to the boundary surface
\( \frac{Q}{Q} \) - The proportion of river water at the pumping well
\( R \) - Retardation factor
\( r_0 \) - Radius of influence
\( r_w \) - Radius of the main pumping well
\( S_x \) - Specific storage
\( \Delta s \) - Water drawdown in pumping well
\( \Delta s_1 \) - Water drawdown in DW1 well
\( \Delta s_2 \) - Water drawdown in DW2 well
\( T \) - Transmissivity
\( t_1 \) - Travelling time of contaminants
\( t_2 \) - Pumping time period
\( U \) - Darcy velocity
\( U_s \) - Settling velocity of bacteria
\( U_x \) - Darcy velocity in \( x \) direction
\( U_y \) - Darcy velocity in \( y \) direction
\( U_z \) - Darcy velocity in \( z \) direction
\( W \) - Well function
\( w_r \) - Width of the river
\( x_{min} \) - The shortest distance of the pumping well from river edge
\( x_{min_c} \) - The shortest distance at the case of clogging
\( \delta(x) \) - Dirac delta function
\( \lambda \) - Stream bed leak coefficient
\( \rho \) - Water density
\( \rho_b \) - Bulk density
\( \rho_s \) - Density of bacteria
\( \phi \) - The effective porosity
\( \beta \) - Degradation rate
\( \varepsilon \) - Empirical correction factor
\( \alpha_s \) - Sticking factor
\( \eta_0 \) - Collision factor
\( \ell_T \) - Laplace Transformation
\( \xi \) - Fourier transform variable
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CHAPTER 1

INTRODUCTION

1.1 Problem Background

Aquifers occupy around 2.5% of freshwater on earth and only, less than 1% of Earth’s water can be found in lakes, rivers, or atmosphere layers (Figure 1.1) (Environment and climate change Canada, 2013). Despite this small percentage, many countries depend heavily, or often exclusively, on the river water as a source of clean water for agriculture and drinking water supplies. (Pimentel et al., 2004; Kallioras et al., 2006; Schwarzenbach et al., 2010; Arie et al., 2012).

Figure 1.1: Groundwater and the world’s freshwater supply (Environment and climate change Canada, 2013)
As a result of development and increasing of economic activities, the demand and the degree of contamination in raw water sources have significantly increased (Schwarzenbach et al., 2010; Hogan, 2014; Juma et al., 2014). The high demand of river water cannot be overcome by existing dams. In fact, building new dams is too expensive and causes negative impacts on the natural ecology. (Azhar, 2000). Additionally, the high levels of pollutants in river’s water make it unsuitable for direct use, and affects the quantity of potable water supply, hence increases the river treatment cost. In the past decades, several water treatment plants in Malaysia have been closed as a result of high percentages of different kinds of pollutants in the rivers (Shamsuddin et al., 2013). Moreover, the presence of contaminants in river water may cause detrimental effects on the environment, human health and crop productivity (Kan, 2009; Schwarzenbach et al., 2010). Consequently, different diseases that can be fatal for individuals may occur. For example, the usage of agriculture fertilizers can cause contamination of river water by nitrates chemicals (Kowal and Polik, 1987). These compounds have harmful effects on human health, especially for infants, young children, elderly individuals, pregnant and nursing women (U.S. Environmental Protection Agency, 2009). For infants, the nitrate compounds can cause blue baby syndrome where the blood cannot properly carry oxygen (Comly, 1987; U.S. Environmental Protection Agency, 2009). This situation leads to infant death if there is no immediate medical attention. (Schwarzenbach et al., 2010). Therefore, governments are making more efforts to solve surface water pollution problem and supplying healthy drinking water.

Most of river water treatment methods are generally based on pre-chlorination of river water before it is subjected to the treatment processes sequence (Singh et al., 2010b). Chlorination is considered the most common, economical and simple chemical approach for river water treatment (Singh et al., 2010b). However, chlorination of river water that is polluted by organics forms disinfection by-products (DBPs), thus its use is being controlled. Reducing or eliminating pre-chlorination and minimizing formation of DBPs by removing organics are regulatory requirements in developed countries. Riverbank filtration (RBF) is considered as one of the alternatives of the pre chlorination process that can be used to attenuate organic, microbial and other pollutants (Singh et al., 2010b). Moreover, RBF is a sustainable approach for providing clean river’s water and groundwater.
1.1.1 Riverbank filtration systems

A riverbank filtration system (RBF) is a natural technology for surface water treatment. Instead of using chemicals to treat water directly after obtaining it from the river, the infiltrated water can be extracted from one or a system of pumping wells adjacent to the stream (Hiscock and Grischek, 2002; Ray, 2002; Maliva and Missimer, 2012). RBF systems have the advantage of natural degradation of contaminants from river water during its passage through the aquifer. The contaminants are removed due to chemical, physical and biological processes that occur in riverbed sediments. The movement of water from the river to the surrounding aquifer can occur naturally or induced by using pumping wells. The pumping process lowers the pressure (head) in the aquifer and river bed sediments, which creates a difference in hydraulic gradients between surface water and the aquifer. This difference in the hydraulic head will induce the water to move from the river towards the pumping well. (Figure 1.2). The downward flow of water into the underlying aquifer caused by pumping process is called an induced infiltration or induced recharge (Maliva and Missimer, 2012).

![Figure 1.2: A simple river bank filtration system (modified from (Kim et al., 2003))](image)

The major advantage of RBF technology is that it can produce better quality of water with lower cost treatment than other river water treatment methods (Dalai and Jha, 2014). Using conventional river water treatment methods incur higher costs where it requires higher volumes of chemicals particularly with higher contaminant concentrations. Additionally, the volume of DBPs that is added to river water to eliminate microbial contamination is also high. On the other hand, reducing the pre-treatment requirements by using RBF technology lowers the operational costs (Maliva and Missimer, 2012; Dalai and Jha, 2014). Basically, RBF system can serve as the final treatment just before disinfection. However, sometimes additional treatment may be needed before water distributed. This can be determined according to the quality of
the produced water. As a minimum, RBF systems can act as a pre-treatment step for drinking water production (Maliva and Missimer, 2012; Ray, 2002).

In general, RBF systems have no harmful effects on surrounding environments. This technique can reduce the concentrations of particulates (suspended solids, turbidity), pathogens, Gardai, dissolved organic carbon, and many (but not all) organic and inorganic compounds (Maliva and Missimer, 2012).

Many previous modelling studies had described 1D, 2D and 3D contaminant transport in aquifer (Pantelis, 1988; Doussan et al., 1997; Neupauer and Wilson, 1999, 2001; Kim et al., 2003; Kim, 2005; Massab et al., 2006; Connell, 2007; Chen, 2010; Praveena and Aris, 2010; Singh et al., 2010a; Chen et al., 2012; Singh et al., 2012; Malaguerra et al., 2013; Singh, 2013; Chen et al., 2015). Some of these studies were concerned about the effect of microbial activity on solute transport, but without considering the role of groundwater pumping (Doussan et al., 1997; Kim et al., 2003; Kim, 2005). Also, most of the models that described the impact of pumping process on solute transport were based on numerical modelling (Wail and Hatamleh, 2007; Belcher and Sweetkind, 2004; Ghoraba et al., 2013; Yang et al., 2011; Zhou and Li, 2011). Precisely, modelling groundwater flow and pollution software (MODFLOW) that was developed by McDonald and Harbaugh (1988) is the most used software by researchers for this purpose (Zhou and Li, 2011). Analytical models are considered as valuable tools for investigating solute transport in porous media and for verifying the numerical solutions due to its accuracy and simplicity (Leij and van Genuchten, 2000). Besides, Green’s function approach can facilitate the analytical solution for 1D or 2D contaminant transport equation in uniform porous media with unsteady flow. This is due to its simplicity in solving multi-dimensional problems and flexibility in dealing with arbitrary initial and boundary conditions (Leij and van Genuchten, 2000). This method had been implemented previously by many researchers to investigate contaminant transport (Chen and Woodside, 1988; Adams and Viramontes, 1993; Leij et al., 1993; Leij and van Genuchten, 2000; Park and Zhan, 2001). Some of these studies were concerned solely on contaminant transport without any adsorption or degradation (Chen and Woodside, 1988), while some other studies focused on natural contaminant movement without any effect of pumping well (Leij and van Genuchten, 2000; Park and Zhan, 2001). Furthermore, some researchers simulated the radial transport of pollutants towards a single, fully penetrating pumping well using Green’s function method (Adams and Viramontes, 1993).

Managing and planning to establish new RBF projects has a wide variety of
previous important decisions that should be taken before starting to establish the new site. One of these decisions is the RBF design selection that includes: the type of the aquifer, the well type and location. Regarding aquifer type, most of the RBF systems around the world (e.g. Canada, northern Europe and the northern United States) were established in confined aquifers (Maliva and Missimer, 2012) which is bounded both at the top and bottom by impervious or semi impervious layers, thus hydraulically isolated from other geological formations. This kind of aquifers is often preferred to bank filtrate so as to prevent contaminants seeping from the surface due to its disconnection with the surface (Malaguerra et al., 2013). For the well type, a variety of different well technologies can be used in RBF systems including: vertical wells, horizontal or inclined wells and collector wells (Ranney collectors)(Maliva and Missimer, 2012) based on the hydrological properties of site and river, cost and the amount of infiltrated water needed to be supplied (Yeh and Chang, 2013). The radial collector well is a central well with horizontal sections of screened collector pipe called laterals and arranged radially to increase yield. The radial orientation of laterals in radial collector wells (RC) leads to unsteady groundwater flow inside the laterals. For calculating the location of pumping well, the three-dimensional finite-difference ground-water model is one of the most popular available techniques that can be used for this purpose. This technique is available in MODFLOW software which is widely used in such groundwater models to simulate steady-state or transient flow in confined or/and unconfined aquifers (McDonald and Harbaugh, 1988). However, MODFLOW was developed to capture the groundwater flow, not to determine the pumping well location. Therefore, it is required to develop an analytical model to determine the distance between the river and production well in order to get high percentage of infiltrating river water that satisfies the quality requirements of chemical contaminant concentration. Despite the strong relation between distance and contaminant concentration, most of the previous studies did not concerned about calculating the shortest distance of the pumping well from river edge. (Abdel-Fattah et al., 2008; Shankar et al., 2009; Orban et al., 2010).

An improved understanding of contaminants behavior, and the factors controlling their transport in RBF systems, is important in planning and managing RBF sites. The pumping process is one of the crucial factors that could change subsurface water behavior. In particular, increasing the pumping rate leads to an increase in groundwater flow velocity. Consequently, the travelling time required by pollutants to reach the well may be decreased, which may raise the contamination in the area around the well. To assess the influence of pumping well on pollutant transport successfully, various means, such as mathematical modelling, are required. Despite the significance of Green’s function method, most of the Green’s function models in groundwater
did not consider the effects of both pumping time and pumping rate on contaminant transport.

About the well location, it should be drilled within a suitable distance from the river. At this distance, the produced river water satisfies the quality requirements of contaminant removal which is sufficiently fresh for potable supplies. Depending on the two factors: the degree of contamination in the produced water and the expected river infiltration rate, the wells should be drilled within a suitable distance from the river. The values of these two factors will increase when the well is close to the river, accordingly starts to decline by increasing distance from the river (Dillon et al., 2002). So, it is necessary to calculate the shortest location of the pumping well from the river to have potable water for public use. At this location, higher percentage of infiltrating river water can be obtained, at which the water drawdown inside the well is expected to be less.

The problem of determining the location of the well becomes more difficult if there is another polluted river on the opposite side. Any location for the well may not be adjacent to only one river, but sometimes it may be located between two polluted rivers. In this case, the well location should be adjusted in a suitable place between the river and the other pollution source. So, the previous analytical model is needed to be enhanced to specify the best location to drill the well between the two rivers. At this distance, the water produced from the well is expected to be with high quality and have a high percentage of infiltrating river water.

1.2 Research objectives

In this study, we used the Green’s function approach and we extended the contaminant transport model which was based on the advection dispersion equation. The model was developed for different purposes:

1. To determine the effect of pumping well on one and two dimensional contaminant transport in RBF systems
2. To calculate the shortest distance of the pumping well from the river edge to produce water that satisfies the quality requirements of contaminant concentration.
To calculate the nearest location of the pumping well from river edge, taking into consideration the existence of other rivers in the opposite side.

Finally, the model was applied by using RBF pilot project parameters which had been conducted in Malaysia.

1.3 Research scope

The current study was concerned about three major RBF problems: one and two dimensional contaminant transport under the influence of pumping well, the shortest distance of the pumping well from the river edge, and; the shortest location of pumping well to the river edge by considering the existence of another polluted rivers. These problems were solved in this research by using the mathematical modelling techniques. The models were developed based on advection dispersion equation for solute transport and solved by using Green’s function approach. The confined homogeneous and isotropic aquifer was chosen in our research, since it is preferred and common in RBF sites. Also, the study focused on the sandy and gravelly alluvial aquifer. This type of aquifer was common in RBF sites due to its ability to contain excessive amounts of water. The effects of initial contaminant concentration at the river and hydraulic conductivity on contaminant transport was also investigated. The models were applied and tested with data related to the nitrates NO$_3$ compound. Data were taken from the first RBF pilot project conducted in Malaysia (Shamsuddin et al., 2013, 2014), because of the abundance of data from this site.

1.4 Research significance

RBF technique is one of the best solutions for surface water pollution, which provides better water quality with lower costs (Maliva and Missimer, 2012). By solving the first problem, it is then can be used to determine the effect of pumping process on contaminant transport. In particular, we can investigate to what extent the pumping rate and the pumping period affect the pumped water quality. Consequently, the pumping process can be managed carefully to produce water meet the quality requirements as long as possible.
Solving the second and third problem is helpful mainly in managing and building a new RBF site. It helps to decide locating the pumping well if there are one or two polluted rivers. This will lower the cost without losing time and efforts. This decision will be taken based on the quality degree of pumped water and the percentage of infiltrating river water. Based on our knowledge, there is no model developed before that can help to specify the well location.

Moreover, completing the objectives of this research can save a lot of effort and time that will consume in collecting data and monitoring water quality (Wexler, 1992). Also, this model can be verified by the industrial and engineering communities and be used for their relevant applications in groundwater systems.

1.5 Thesis organization

The present study was organized into eight Chapters and two Appendices. The first chapter gave a general background on: surface water pollution, types and sources of pollution, attenuation processes implemented for its control and prevention and RBF system. Also, it produced an overview of RBF system including its definition, efficiency, design, its importance comparable with other conventional water treatment approaches. This background was followed by the problem statements, objectives of this research, the scope of the present study and the significance of the research.

The second chapter was a general literature review. This review covers most of the previous mathematical models which were developed for RBF problems. This included the basic RBF subjects described by these models, main governing equations, different analytical and numerical solutions and comparison between these models.

The third chapter described the methodology used in this study, and the details of the analytical approaches implemented to achieve the research objectives. The fourth and fifth chapters presented the analytical models developed in this study to simulate the influence of pumping well on one and two-dimensional contaminant transport respectively. Also, the sensitivity analysis results for different pumping time, and rates were presented.

The sixth and seventh Chapters produced the theoretical calculations and the results of the developing models obtained to determine the shortest distance from
pumping well to the river edge. In chapter 6, the distance was calculated when the river
was the only source of contaminant while in chapter 7 we considered the existence of
other sources. The conclusion and the future work of this study were given in the
eighth chapter.

This thesis included two Appendices: Appendix A produced the derivation of
the basic physical laws and equation implemented in this study. Appendix B showed
the main papers that have been published /accepted/submitted in journals and presented
in international conferences.
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