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Studying the effect of design parameters on riverbank filtration performance for drinking water supply in Egypt: a case study

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ABSTRACT

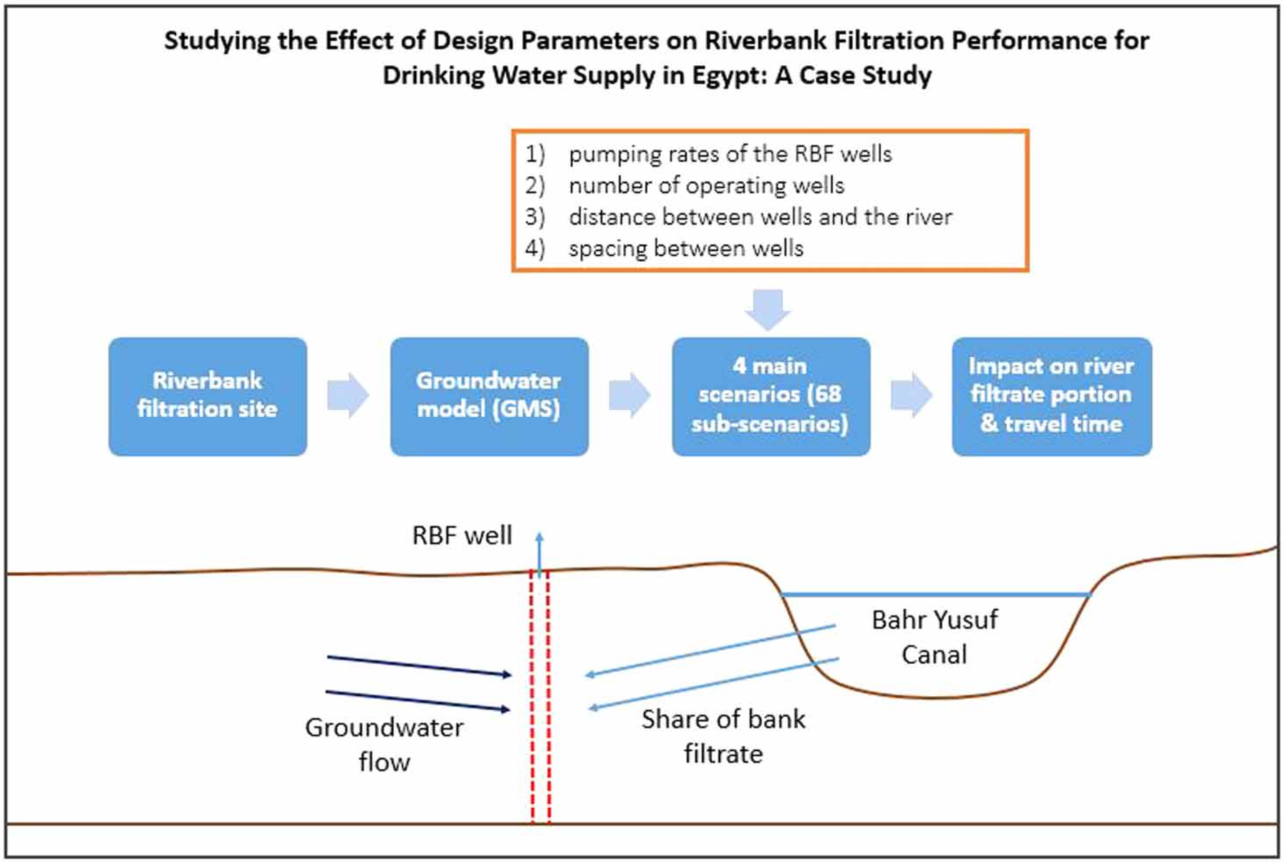
Riverbank filtration (RBF) is an affordable technique to provide drinking water with adequate quality. The ultimate objective of this study is to facilitate the transferability and application of this sustainable technique in Egypt. In this work, a numerical model was constructed using Groundwater Modeling System (GMS) to study the effect of four design parameters on the RBF performance parameters (i.e., river filtrate portion and travel time) with the aid of MODPATH and ZONEBUDGET. The design parameters were: (1) the pumping rates of the RBF wells, (2) number of operating wells, (3) distance between wells and the river, and (4) the spacing between wells. This study was focused on the hydraulic aspects of the technique. The results demonstrated that: (1) the river filtrate portion exceeds 75% regardless of the design conditions, and (2) the hydraulic performance of the RBF technique is highly controlled by the production capacity of the wells and their positions relative to the surface water systems; the spacing between wells has a minimum effect. Two equations were developed to estimate the river filtrate portion and minimum travel time as functions of pumping rate and distance between the pumping well and the river.

Key words: groundwater modeling, hydraulics of riverbank filtration, model calibration, riverbank filtration, river filtrate portion

HIGHLIGHTS

- Hydraulic aspects of riverbank filtration.
- Impact of design parameters on river filtrate portion and travel time.
- The relation between over-pumping and river filtrate portion.
- Multi-regression analysis for RBF performance.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Egypt encounters great challenges in meeting the rapidly growing water demand due to high population increase, in addition to the decreasing quality of surface water. The annual per capita consumption dropped to 600 m^3/year in 2017, and it is expected to be 350 m^3/year by the year 2050. Egypt has diverse water resources: the Nile River provides the country with 55.5 billion cubic metres per year, groundwater (6.9 BCM/y), precipitation (1.8 BCM/y), and desalination (0.04 BCM/y). The domestic demand equals approximately 13.5% of the total demand. Thus, with all the challenges that Egypt encounters regarding both quality and quantity of surface water, come the many advantages of riverbank filtration (RBF). RBF is the process of extracting water from a river by pumping wells located nearby, where river water is purified through natural physical, biological, and chemical filtration mechanisms (Hiscock & Grischek 2002).

RBF is considered to be a green, sustainable and an economic technology. Removal of pollutants, turbidity, suspended solids, pathogens, biodegradable compounds, non-polar organic compounds, and heavy metals from surface water has been approved in the locations where RBF has been implemented around the world (Irmscher & Teermann 2002; Weiss *et al.* 2003; Massmann *et al.* 2008; Dash *et al.* 2010; Sandhu *et al.* 2011; Gutiérrez *et al.* 2017). The flow through the aquifer dilutes the concentration peaks that may result from sudden spills in the river or during floods (Hiscock & Grischek 2002; Abdel Wahaab *et al.* 2019). Furthermore, the cost of construction, operation and maintenance is very low compared with the conventional water treatment plants (WTPs) (UN-Habitat 2018; Abdelrady *et al.* 2020). The required area for the RBF system is relatively smaller than the required area for conventional WTPs. In addition, a regulation in temperature has been observed in RBF systems, as the river filtered water temperature is more adequate in both summer and winter rather than the river water (Hiscock & Grischek 2002).

The selection of RBF site location depends on several factors so that the system will be economic and effective. First, potential locations should be investigated and evaluated. This process includes site visit and assessment, construction of exploratory wells and observing piezometers, and determining both aquifer and river characteristics. Then, a model simulating the groundwater flow should be developed to predict travel time, river filtrate portion, and catchment zones. The extracted water from the well is a mixture of the river water, the groundwater, and other recharge sources such as precipitation and irrigation. River filtrate portion is the ratio of the extracted water from the river through the well to the total extracted water from the well. A high river filtrate portion indicates the success of the RBF process, where the river water share is more than the groundwater share. Travel time is the time required for a water particle to travel from the river to the well in a specific path. The catchment zone is the area of the aquifer that contributes water to the well. Finally, the potential location should be evaluated according to the aims, which are to extract the required amount of water, achieve the maximum river filtrate portion, and achieve the maximum removal of pathogens and micropollutants (Gutiérrez *et al.* 2017; Abdel Wahaab *et al.* 2019).

The selection of RBF site location criteria depends on the following aspects so that the well yield can be maximized (Gollnitz 2002; Grischek *et al.* 2002; Schubert 2002; Ray *et al.* 2003; Caldwell 2006; Grischek & Ray 2009; Brunner *et al.* 2011):

1. Aquifer characteristics:
   a. Thickness of the aquifer: the saturated thickness should not be less than 6 m. In general, the increased screen length decreases the entrance velocity, leading to lower clogging at the screen.
   b. The lithology of the site and soil characteristics (porosity, hydraulic conductivity, transmissivity, storage coefficient, etc.), which control the yield of the RBF system, water flow through it, and the area of the catchment zone.
   c. Groundwater level: when it is lower than the river stage, it induces infiltration from the river (Abdel Wahaab *et al.* 2019). A hydraulic gradient towards the river means that the aquifer is originally recharged from sources other than the river, leading to lower river filtrate portions. A hydraulic gradient from the river towards the aquifer leads to higher river filtrate portions (Hiscock & Grischek 2002) In addition, groundwater quality parameters affect the quality of the extracted water from the well. The contamination of groundwater from sewage disposal and agricultural activities will affect the RBF water.
   d. High hydraulic conductivity ($K > 1 \times 10^{-4}$ m/s) that induces the river to recharge the aquifer.
2. River characteristics:
   a. Good hydraulic connection between the river and the aquifer is required, so that the yield of the aquifer is increased (Ray *et al.* 2003). The hydraulic connection describes the exchange relationship between the river and the aquifer. The river can be gaining, losing, throughflow, or disconnected from the aquifer. Moreover, this relation can vary with time according to the river stage and groundwater level. For the losing type, the connection is mandatory for a successful RBF. For higher river filtrate portion, a losing connected river to the aquifer is preferred.
   b. Cross-section of the river: where the larger wetted riverbed area allows greater quantities of water to infiltrate to the aquifer (Gollnitz 2002). Moreover, the slope of the water surface is an indicator for the shear stress that can resuspend the sediments that cause clogging at the riverbed.
   c. Erosive river flow to prevent riverbed clogging.
   d. Flow (maximum, minimum, average) or stage (max, min, avg): a higher river stage provides a higher hydraulic gradient.
   e. Water quality, various parameters: as they affect the yield by causing mechanical, biological, and chemical clogging at the riverbed (Caldwell 2006).
   f. Riverbed characteristics (hydraulic conductivity): the riverbed is the direct connection between the river and the aquifer. Since clogging and renewing of the riverbed affect the RBF system, the riverbed characteristics affect the system too and the ability of the river to recharge the aquifer. The vertical hydraulic conductivity, particle distribution of sediment, D10, D50, and D90 sizes, and the presence or absence of an armor layer can express the riverbed (Caldwell 2006).
3. Available area and land acquisition.
4. Water supply demand that should be met.

The design of an RBF system is site-specific as it depends on the site characteristics. RBF wells can be vertical, horizontal collector wells (for higher extraction rates), or siphon tube wells (Ray *et al.* 2003; Bartak & Grischek 2018) (Figure 1).

The design of RBF wells includes determining the number of wells (which are 24/7 operated), a constant pumping rate of each well, the distance between the wells and the river, and the spacing between the wells that decreases the interference between them. The implementation of an effective RBF site achieves the maximum river filtrate portion, in a suitable

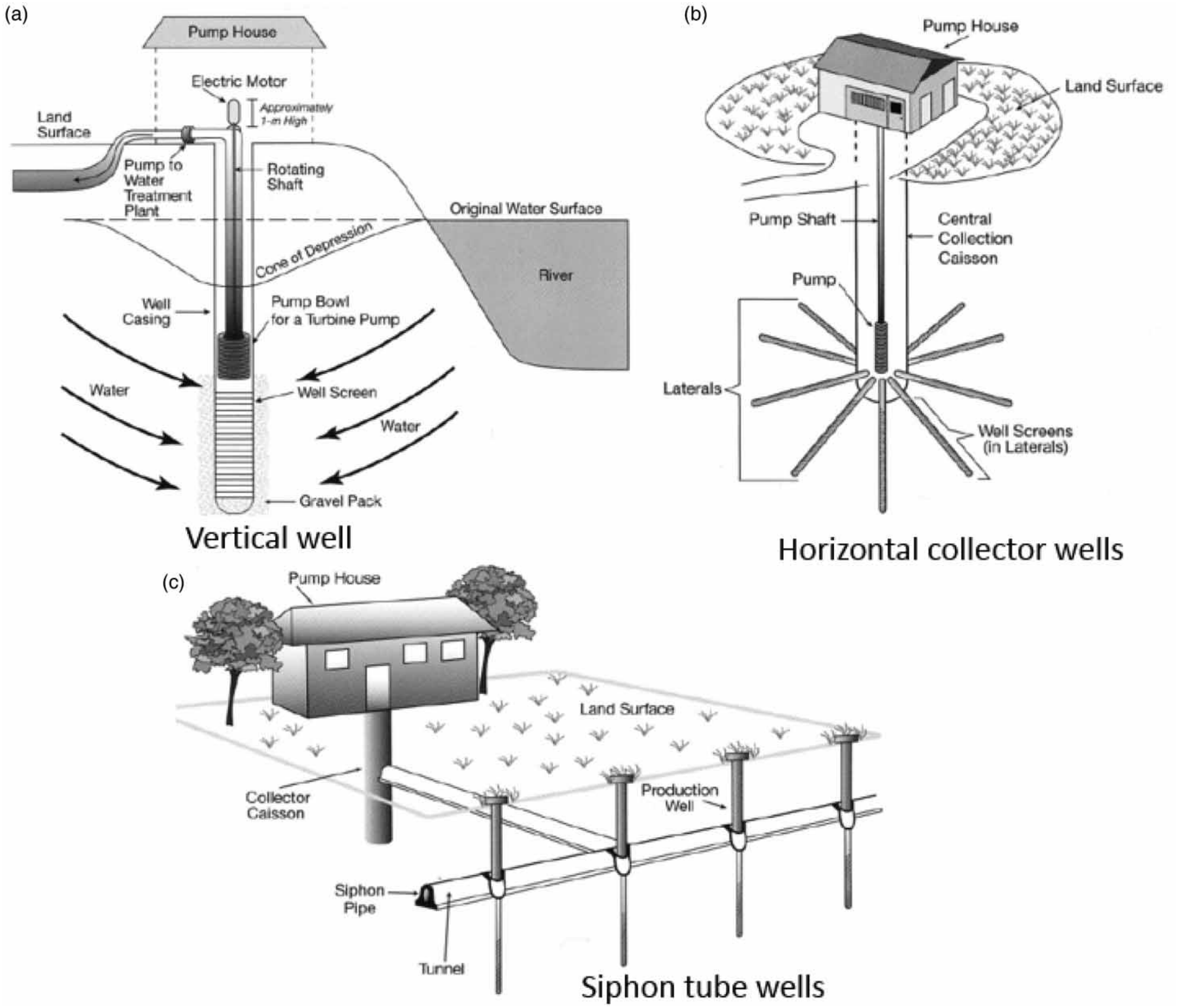


Figure 1 | Types of RBF wells (Ray *et al.* 2003).

travel time that allows the treatment process to be effective and the extracted water to comply with quality standards (Grischek *et al.* 2002; Abdelrady *et al.* 2020).

RBF wells are already located in several locations in Egypt, and there are more potential locations (UN-Habitat 2018). Numerical modeling is one of the most crucial tasks to determine the efficiency of an RBF system at a specific site. In this work, a groundwater model was constructed to simulate Idrasiya RBF site in Beni Suef governorate, Egypt, to study the effect of four design parameters on the RBF process. These design parameters are: (1) the pumping rate of the RBF wells, (2) the number of operating wells, (3) the distance between wells and the river, and (4) the spacing between wells.

2. METHODS

2.1. Groundwater flow model

A groundwater flow model was developed to simulate the current situation at the study area and to simulate the design scenarios.

2.2. Data preparation

The following data were collected from site investigation, direct communication with administrators of Beni Suef Water and Sanitation Company (BWSC), official reports by the Holding Company for Water and Wastewater (HCWW), and publications.

The study area in this work is Idrasiya Compact and RBF water plant, which is located in Ihnasiya region, 30°52′39.856″E and 29°3′50.576″N, Beni Suef governorate, Egypt (Figure 2(a)). The intake of this compact plant is on Bahr Yusuf Principal Canal (the river), located at the east of the site, and it is one of the longest irrigation canals in Egypt and diverts water from the Ibrahimia Canal at the Dirout Group of Regulators and runs downstream as far as Fayoum, stretching over 313 km (JICA & MWRI 2018). Bahr Yusuf is a natural earth canal that was enlarged over the years by Old Egyptians. At the west of the site, Alriva Canal, a man-made earth canal, is located at approximately 100 m from the RBF wells. Prior to this study, three RBF units, i.e. three vertical wells (Well 1, Well 2, and Well 3), were constructed at this site with a total capacity of 120 l/s, to serve 86,400 capita, in addition to a fourth well, GW Well (30 l/s), that is used to extract groundwater to increase the river filtrate portion (Figure 2(b)). The total required production from the RBF wells is 60 l/s to meet consumer demand in the served area. The output drinking water meets the Egyptian standards.

The ground surface elevations for the study area were obtained from HCWW as a GIS point shapefile, and then they were compared with Shuttle Radar Topography Mission (SRTM) data version 4.1, WGS84 in ArcMap 10.1. The elevation at the RBF site was found to be 28 m above sea level (asl). The ground elevations in the study area range between 25 and 30 m asl. The ground surface was interpolated in GMS using the inverse distance method. The attributes for both Bahr Yusuf and Alriva Canal were collected from official reports by HCWW and site visits. The annual rainfall is 6 mm (National Oceanic and Atmospheric Administration, NOAA). Consequently, the recharge of the aquifer due to precipitation was ignored. The source of the aquifer recharge is the infiltration of irrigation and seepage from canals. The recharge into the water table is 0.85–1.3 mm/day at Sidfa site, Assiut Governorate (Shamrukh *et al.* 2001). Thus, compared with Beni Suef, which has the same conditions of irrigation, recharge was assumed to be in the same range (taken as 1 mm/day). Only one exploratory well (at the location of Well 2) was drilled at the site to investigate the soil layers by Beni Suef Water and Sanitation Company (BWSC). The soil layers were simplified to six main layers (8 m clay, 1 m fine to medium sand, 1 m fine sand with clay, 1 m sand with gravel, 2 m medium sand, and 10 m coarse sand with gravel) as shown in Figure 3. Due to the insufficient number of boreholes, soil layers were considered to be at the same constant elevation as at the executed borehole at the exploratory well location (Well 2), and the aquifer was assumed to be a homogeneous aquifer.

However, the report did not mention the properties of each layer such as hydraulic conductivity and porosity. Thus, hydraulic conductivities were assumed for each layer according to both Freeze & Cherry (1979) and Heath (1983) (Table 1), and these assumptions were confirmed by the model calibration process. For model simplification purposes, the fourth, fifth, and sixth layers were grouped into one equivalent layer with an equivalent hydraulic conductivity $K_{h(EQ)}$ and $K_{v(EQ)}$. The equivalent hydraulic conductivity for the horizontal direction $K_{h(EQ)}$ (Equation (1)), and the equivalent hydraulic conductivity

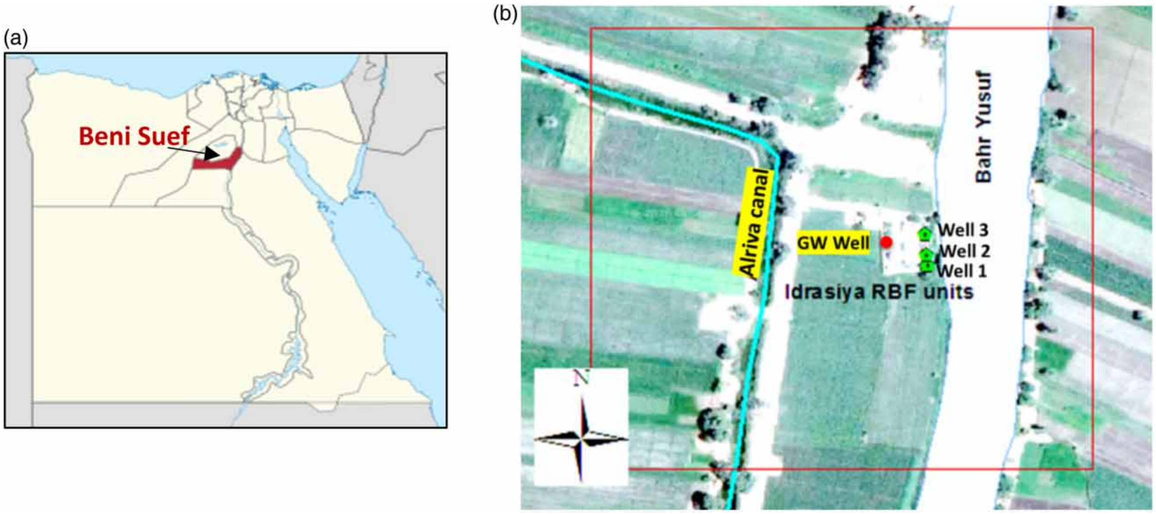


Figure 2 | Location of RBF and GW wells. (a) Location of Beni Suef governorate, (b) RBF wells and GW Well at Idrasiya site.

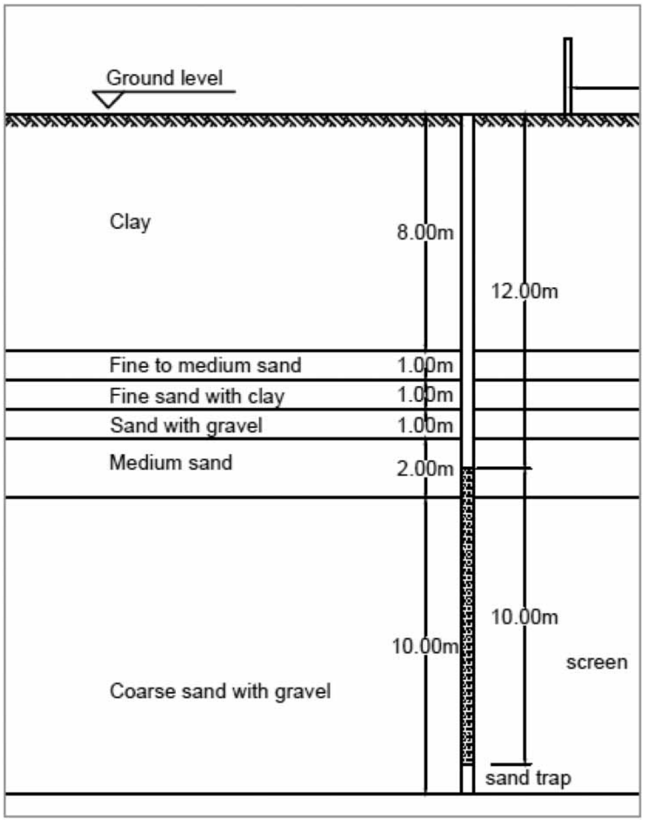


Figure 3 | Soil layers at the site.

Table 1 | Hydraulic conductivity assumptions

Layer	Type	Depth (m)	K_h (m/d)	K_v (m/d)
1	Clay	8.00	0.001	0.0001
2	Fine to medium sand	1.00	1	0.1
3	Fine sand with clay	1.00	0.1	0.01
4	Sand with gravel	1.00	100	10
5	Medium sand	2.00	10	1
6	Coarse sand with gravel	10.00	100	10

for the vertical direction $K_{\mathrm{v(EQ)}}$ (Equation (2)), for number of layers (n), were calculated as follows (Das 2013):

$$K_{\mathrm{h(EQ)}} = \sum (H_i K_i)/H_{\mathrm{total}} \tag{1}$$

$$K_{\mathrm{v(EQ)}} = H_{\mathrm{total}}/\sum (H_i/K_i) \tag{2}$$

where H_i is the depth of layer number i.

After the model calibration and first run, another grouping to a single layer model was needed. The final equivalent hydraulic conductivities were calculated; $K_{\mathrm{h(EQ)}}$=57 m/d, and $K_{\mathrm{v(EQ)}}$=0.0003 m/d.

The RBF site has three vertical wells; Well 1, Well 2, and Well 3 (each of diameter 0.2 m) aligned parallel to the river at distance 10.5 m from it, in addition to a fourth well (GW Well) at distance 31.5 m from the river, which is used to extract groundwater to increase the river filtrate portion. The pumping rate of the wells, Well 1, Well 2, Well 3, and GW Well, are 60, 30, 30, 30 l/s, respectively. The ground elevation at the site is 28 m, and the static head is located at a depth of 1.5 m from the surface. The RBF wells are operated to produce 60 l/s. There is no data concerning the drawdown occurring at the wells during operation, as the wells are sealed and no data logger for measuring water level is attached.

2.3. Numerical model development

A conceptual model (Figure 4) was constructed using Groundwater Modeling System (GMS) version 10.3.6 (GMS 10.3.6, 2018), by AQUAVEO, as a graphical user interface (Gogu *et al.* 2001) for MODLFOW (Harbaugh *et al.* 2000) using the finite difference method. In order to simulate the different components of the conceptual model, i.e. the river, the wells, and the recharge, supporting packages such as RIV1 (McDonald & Harbaugh 1988; Harbaugh *et al.* 2000), WEL1 (Harbaugh *et al.* 2000), and RCH1 (Harbaugh *et al.* 2000) were used to simulate river, wells, and recharge, respectively. Also, the Layer-Property Flow (LPF) package (Harbaugh *et al.* 2000) was selected for defining soil layers' properties, such as hydraulic conductivity values, and performing flow calculations. Preconditioned Conjugate Gradient (PCG2) (Harbaugh *et al.* 2000) was used as a package for solving simultaneous equations based on the finite difference method. By using the available data and the assumptions, the model was calibrated. Then, the model was used to simulate the existing situation and three design

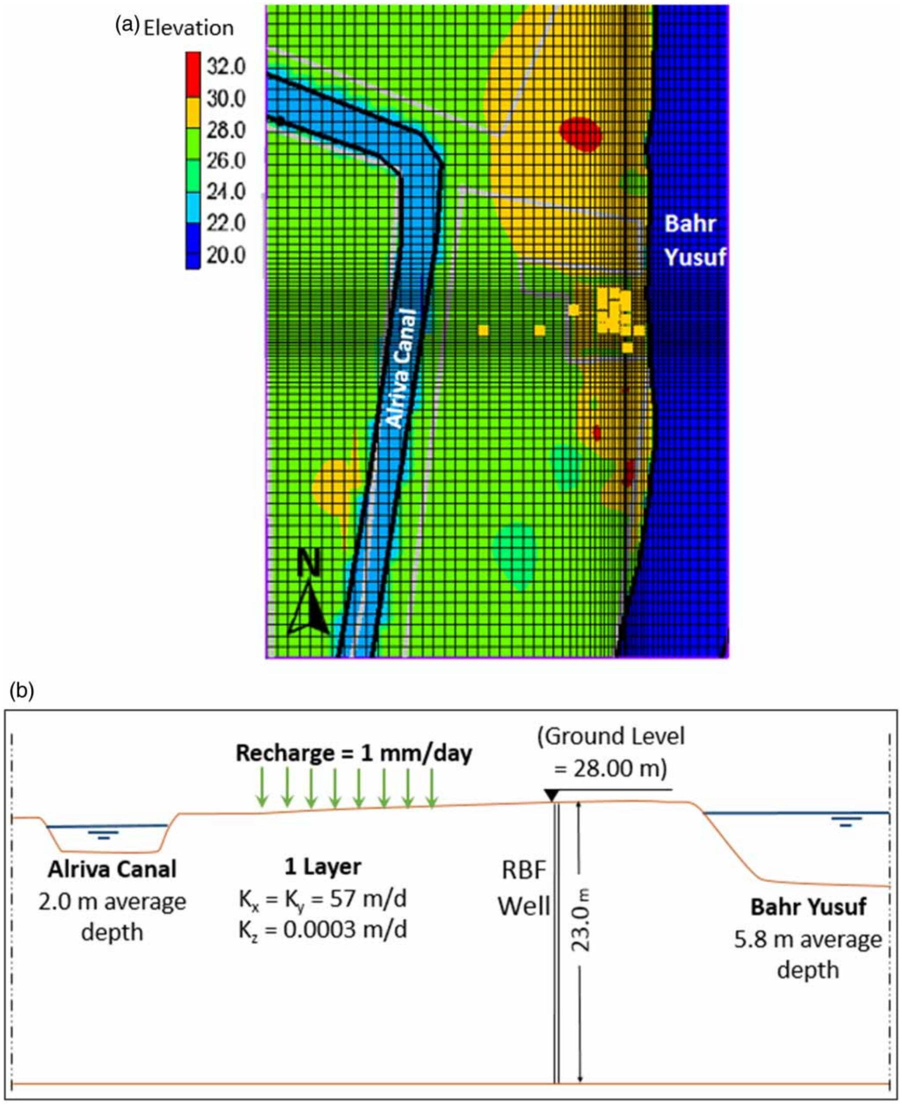


Figure 4 | Conceptual model and cross-sectional view. (a) Conceptual model, (b) cross-sectional view at Well 2.

scenarios with a total number of 68 sub-scenarios in order to study the effect of the four design parameters on both river filtrate portion and travel time, assuming that the extracted water quality is improved by increasing the river filtrate portion.

MODFLOW produces cell-to-cell flow data, which can be read by ZONEBUDGET, a code developed by USGS, and then ZONEBUDGET (Pollock 1989) calculates budgets for pre-defined regions in the model area, and this can determine the source of flow portions in each cell. The river filtrate portion was calculated for each scenario by applying the following equation (Equation (3)):

$$\mathit{River\ filtrate\ portion} = \frac{\mathit{River\ share\ of\ water\ (from\ Bahr\ Yusuf)}}{\mathit{Total\ extracted\ water\ from\ the\ well}} \tag{3}$$

MODPATH (McDonald & Harbaugh 1988; Pollock 1989) is a particle tracking code that is used in conjunction with MODFLOW. After running a MODFLOW simulation, the user can designate the location of a set of particles. The particles are then tracked through time, assuming they are transported by advection using the flow field computed by MODFLOW. Particles can be tracked either forward in time or backward in time. Particle tracking analyses are particularly useful for delineating capture zones or areas of influence for wells, and calculating travel time.

The eastern boundary of the model domain is the river (Bahr Yusuf Canal). The western boundary is Alriva Canal as shown in Figures 2(a) and 4, and both of them were simulated as river boundary condition (RIV1). At the northern and southern boundaries, a no-flow condition was used. In addition, a recharge boundary condition (RCH1) was applied with value equal to 1 mm/day at the areas of irrigation inside the model domain. A rectangular boundary (200 × 290 m) was created to define the model domain and to create the cells within it. A three-dimensional finite difference grid was constructed, consisting of 90 rows, 60 columns and one layer, and the total number of cells was 5,400. The starting size of a cell was 5 × 5 m to be refined to 1 × 1 m at each of the three well locations, with a bias of 10% to control how the cell size varied from one cell to the next.

2.4. Model calibration

Due to lack of data, as only the static head at the RBF wells was known, the model was manually calibrated at no pumping condition by a trial-and-error procedure. The purpose of the calibration was to find the hydraulic conductivity of the aquifer soil and riverbed conductance values that make the calculated head at the well locations meet the static head measurements that were obtained from the site (1.5 m below ground level). The results of the model calibration were as follows: (K_h=57 m/d), (K_v=0.0003 m/d), and riverbed conductance for the river (Bahr Yusuf) and Alriva Canal is 5 and 0.2 (m^2/d)/m^2, respectively. Riverbed conductance refers to infiltration resistance that occurs at the riverbed due to clogging (Grischek & Bartak 2016). In Darcy's Law, the terms (KA/L) are grouped together and called conductance. Since the rivers were simulated as polygon-feature objects in this model, the conductance values were entered per unit area, as the area differed from cell to cell in the grid. In this model, the clogging effect was ignored, because the riverbed is dredged each three months.

2.5. Scenario definition

Four main scenarios with a total number of 68 sub-scenarios were developed to study the effect of the four design parameters on both river filtrate portion and travel time. These design parameters are: (1) the pumping rate of the RBF wells, (2) the number of operating wells, (3) the distance between wells and the river, and (4) the spacing between wells.

2.5.1. Scenario CS: current situation

In this scenario, the current situation at the RBF site was modeled with four different operation scenarios to extract 60 l/s from the RBF wells as shown in Table 2. The purpose of this scenario was to study the effect of different pumping rates with different well combinations on both river filtrate portion and travel time within the existing situation of the RBF wells. In two of these scenarios, the well that is used at the site to extract groundwater (GW Well) to reduce groundwater share was operated, to simulate the existing operation at the site, and to study the effect and feasibility of this GW Well.

2.5.2. Scenario 1: single well, various pumping rates, constant distance from the river

The purpose of this scenario was to study the effect of different pumping rates of a single well on both river filtrate portion and travel time. In the simulation of this scenario, a single continuously operated well (Well 2) was used, at distance 10.5 m from the river. By varying the pumping rate of this well, four cases (30, 60, 90, 120 l/s) were studied as shown in Table 3.

Table 2 | Scenario CS

Sub-scenario no.	No. of wells	Total pumping rate (l/s)	Distance from RBF well to river (m)
1	Well 1	60	10.5
2	Well 1 + GW Well	90	10.5
3	Well 2 + Well 3	60	10.5
4	Well 2 + Well 3 + GW Well	90	10.5

Table 3 | Scenario 1

Sub-scenario no.	No. of wells	Pumping rate (l/s)	Distance from RBF well to river (m)
5	1	30	10.5
6	1	60	10.5
7	1	90	10.5
8	1	120	10.5

2.5.3. Scenario 2: single well, various pumping rates, different distances

The purpose of this scenario was to study the effect of distance between a single pumping well and the river, for different pumping rates, on both river filtrate portion and travel time. A single continuously operated well was used at different distances between the well and the river for each pumping rate. Six different distances (5, 10.5, 15, 20, 50, 75 m) were studied for each of four pumping rates (30, 60, 90, 120 l/s) as shown in Table 4.

2.5.4. Scenario 3: Two wells, equal pumping rates, different distances and spacing

The purpose of this scenario was to study the effect of spacing between two pumping wells, for different pumping rates and different distances between wells and the river, on both river filtrate portion and travel time. Two continuously operated wells were operated simultaneously with equal pumping rates, at different distances from the river (10.5, 15, 20 m), and different spacing between the wells (5, 10, 15 m). In each sub-scenario, the two wells were located at the same distance from the river. Four cases of pumping rate (30, 60, 90, 120 l/s) were studied as shown in Table 5.

Table 4 | Scenario 2

Sub-scenario no.	No. of wells	Pumping rate (l/s)	Distance to river (m)	Sub-scenario no.	No. of wells	Pumping rate (l/s)	Distance to river (m)
9	1	30	5	21	1	90	5
10			10.5	22			10.5
11			15	23			15
12			20	24			20
13			50	25			50
14			75	26			75
15	1	60	5	27	1	120	5
16			10.5	28			10.5
17			15	29			15
18			20	30			20
19			50	31			50
20			75	32			75

Table 5 | Scenario 3

Sub-scenario no.	No. of wells	Pumping rate (l/s)	Distance to river (m)	Spacing (m)	Sub-scenario no.	No. of wells	Pumping rate (l/s)	Distance to river (m)	Spacing (m)
33	2	30	10.5	5	51	2	90	10.5	5
34				10	52				10
35				15	53				15
36			15	5	54			15	5
37				10	55				10
38				15	56				15
39			20	5	57			20	5
40				10	58				10
41				15	59				15
42	2	60	10.5	5	60	2	120	10.5	5
43				10	61				10
44				15	62				15
45			15	5	63			15	5
46				10	64				10
47				15	65				15
48			20	5	66			20	5
49				10	67				10
50				15	68				15

3. RESULTS AND DISCUSSION

3.1. Scenario CS: current situation

It was found in this scenario that the river filtrate portions for different operation scenarios were approximately 97%. However, the operation of the GW Well decreased the catchment zone for the RBF wells (Figure 5). The catchment zone for Well 1 (Sub-scenario 1) was decreased when the GW Well was operated (Sub-scenario 2), and the catchment zones for Well 2 and Well 3 (Sub-scenario 3) were decreased in Sub-scenario 4. A larger catchment zone means that the river-filtered water is exposed to more pollutants from fertilizers and pesticides that are infiltered to the soil with the irrigation water. The minimum travel time was very low (two days); this was calculated for the shortest path line for a water particle to move from the river to the RBF well through the soil. This low residence time could reduce the potentiality of removing pathogens during the infiltration process. According to Grützmacher *et al.* (2010) a minimum of ten days of travel time is required to remove pathogens (e.g. cyanobacteria) during the RBF process. In addition, hydrophobic micropollutants (e.g. pyriproxyfen, pendimethalin) were documented to be highly persistent during the infiltration process and required longer travel time (at least 30 days) to be removed (Maeng *et al.* 2010; Abdelrady *et al.* 2019). Therefore, the quality of the river filtrate should also be monitored regularly and post-treatment procedures might be needed. Sub-scenario 1 and Sub-scenario 3 are alternatives for operation; when a well is taken out of service for maintenance, the alternative can be operated, to guarantee the continuous operation of the facility. However, if contamination of groundwater is observed, then the alternatives Sub-scenario 2 and Sub-scenario 4 would be better for operation in terms of water quality.

3.2. Scenario 1

The results of Scenario 1 revealed that the aquifer is principally recharged from Bahr Yusuf, therefore, the river filtrate portion was high (>95%). Moreover, the infiltration from irrigation was very low compared with the river seepage. In the same regard, the higher pumping rate induces the river to flow into the RBF well in a faster way and hence decreases the travel time. The minimum travel time was four days at pumping rate equal to 30 l/s, and dropped to one day at pumping rate 120 l/s. The maximum travel time was determined for the longest path line for a water particle moving through the soil from the river to the RBF well. For wells located at 10.5 m from the river, it was found that the river filtrate portion increased considerably with

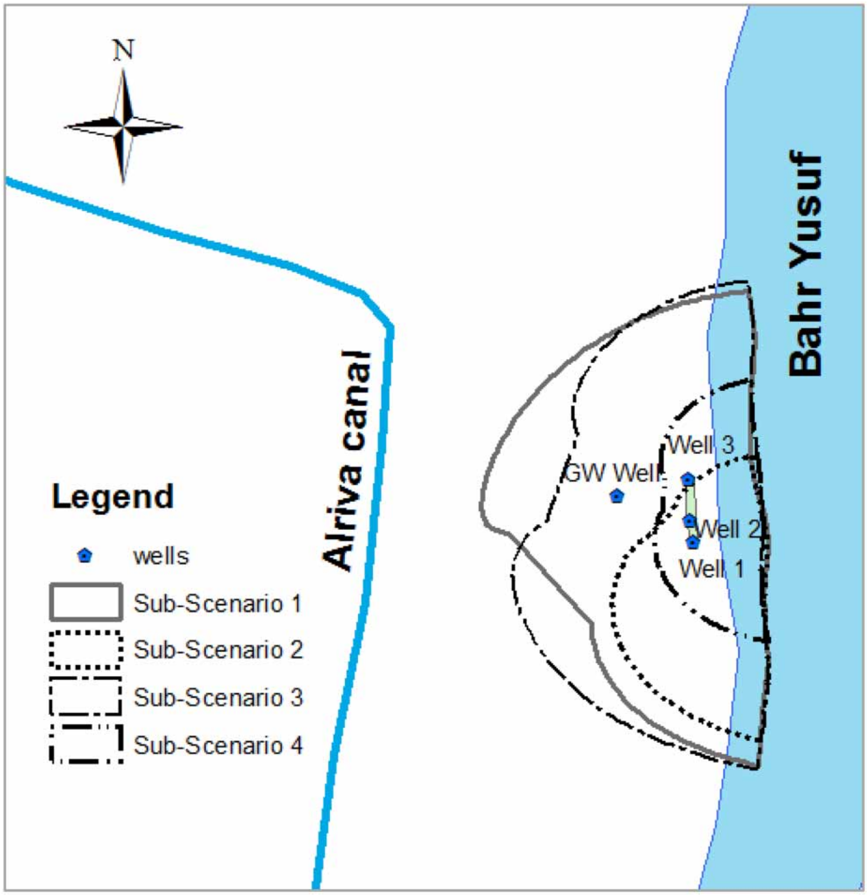


Figure 5 | Catchment zones for Scenario CS for RBF wells.

raising the pumping capacity. However, at a pumping rate of 120 l/s, the ambient contaminated groundwater was highly induced to flow toward the RBF wells, and subsequently, the river filtrate portion declined. Therefore, it can be concluded that the over-pumping practices have an adverse effect on the sustainability of the RBF technique and considerably affect the quality of bank filtrate.

3.3. Scenario 2

The outcomes of Scenario 2, which was illustrated in Table 3, demonstrated that the distance of the RBF wells to the river significantly affects the technique's performance and sustainability (Figure 6(a)); installing the wells further from the river would significantly reduce the river-filtered portion. At all the tested pumping rates, it was apparent that the construction of the RBF wells within 20 metres of the river bank has no significant effect on the proportion of the infiltrated water. Conversely, placing the RBF wells at further distance could lead to a sharp decline in the river filtrate portion particularly at high pumping rates (>30 l/s).

Figure 6(b) indicates that the longer distance from the river required longer travel time for water particles to reach from the river to the well, while the higher pumping rate induced the river to recharge the aquifer faster than the lower recharge rate. The highest travel time (38 days) was obtained when the RBF wells were situated at a distance of 75 m from the river and a pumping rate of 30 l/s was applied. This prolonged infiltration time could strongly increase the potentiality of turning the infiltration environment anaerobic where the microbial reduction of undesirable and toxic metal elements (e.g., As, Cd and Pb) into the bank filtrate is high (Grischek & Paufler 2017).

3.4. Scenario 3

The model results for Scenario 3 indicated that for each pumping rate, there was a negligible decrease of the river filtrate portion for the longer distance from the river ranging between 10.5 to 20 m; also, the higher the pumping rate, the lower

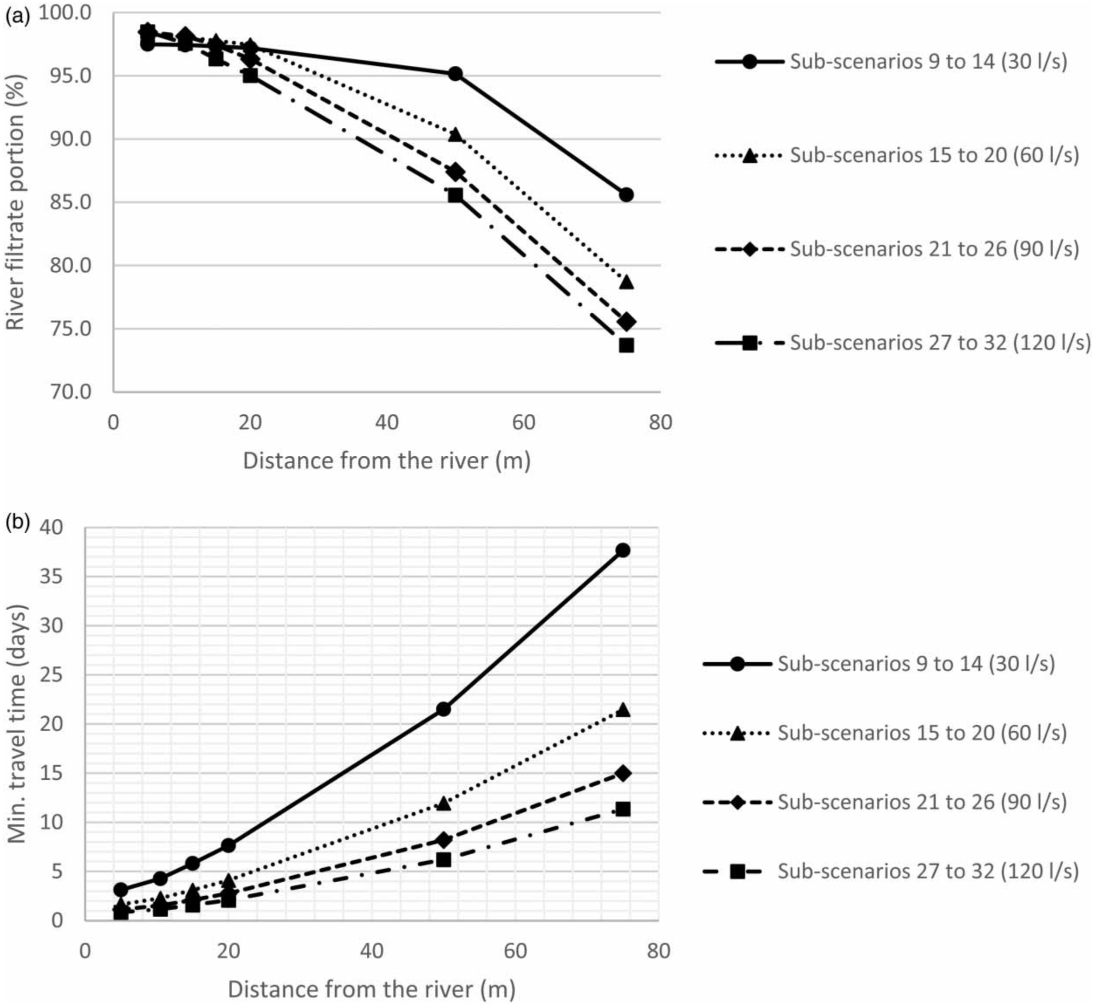


Figure 6 | Results of Scenario 2. (a) Impact of distance from the river on the river filtrate portion, (b) impact of distance from the river on the minimum travel time.

the river filtrate portion. The spacing between the wells (5, 10, 15 m) for each pumping rate at each distance to the river (10.5, 15, 20 m) did not affect the river filtrate portion, but it had a slight impact on the minimum travel time. The minimum travel time increased with the longer distance to the river and bigger spacing (Figure 7), while with the larger spacing between the two wells, the drawdown decreased as the interference between the wells was lower. In addition, as previously mentioned, the higher value for pumping rate corresponded to a lower river filtrate portion and less travel time. The average river filtrate portions for pumping rates 2 × 30 l/s, 2 × 60 l/s, 2 × 90 l/s, and 2 × 120 l/s were 97.8%, 96.3%, 94.8%, and 93.8%, respectively.

By comparing the results of all sub-scenarios, it was noticed that both the number of wells and spacing between wells did not affect the river filtrate portion or the minimum travel time, for the same extracted quantity of water at the same distance from the river. However, the most significant design parameters were pumping rate and distance from the river. Table 6 shows examples for this conclusion.

3.5. Influential length of the river

MODPATH was used to estimate the length of the river that is influenced by a pumping well for different cases of pumping rates for one operated well at different distances from the river. This can be used to determine the protection area of the river from effluent pollutants or sudden spills. The distances between the well and river were 5.0, 10.5, 20.0, and 75.0 m. For each distance, three pumping rates were studied as follows: 30, 60, and 90 l/s. As shown in Figure 8, the influential length is directly proportional to both the pumping rate and the distance.

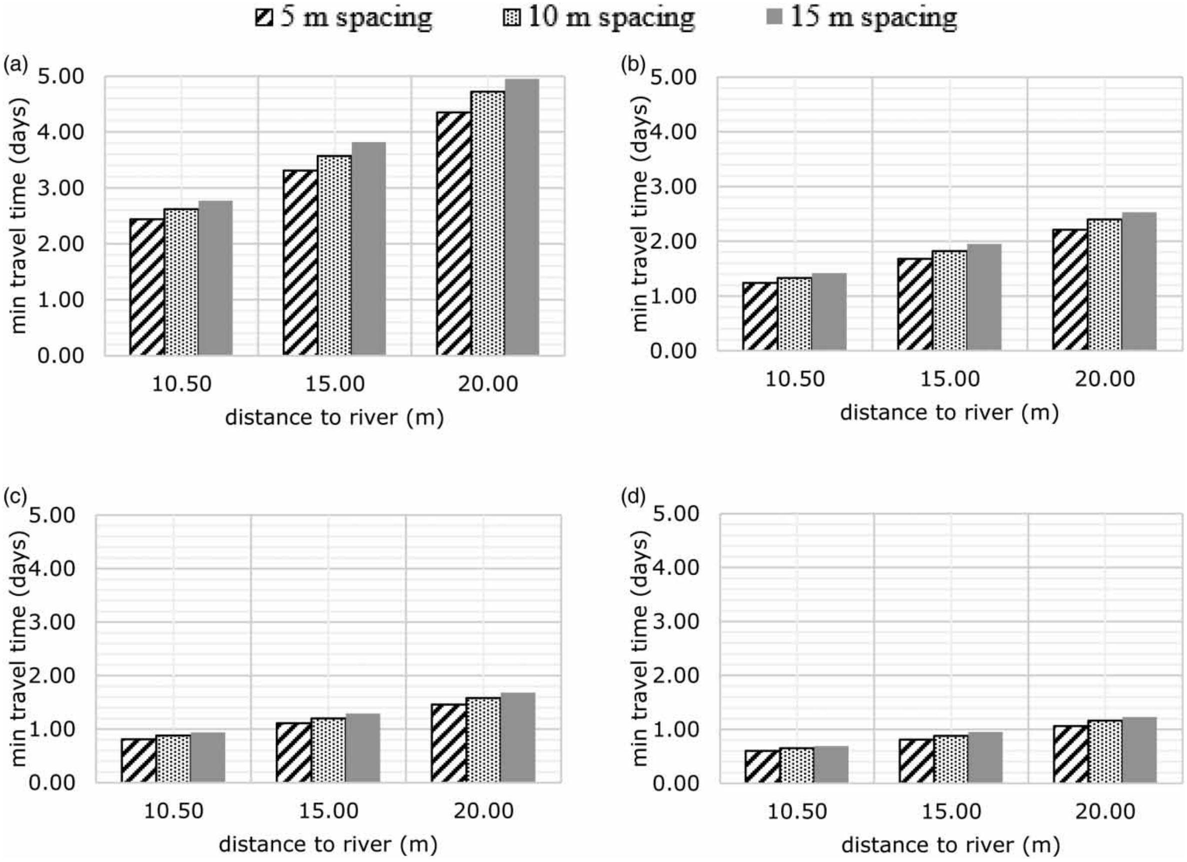


Figure 7 | Relation between distance to river, spacing between wells, and min. travel time. (a) Two wells, 30 l/s each, (b) two wells, 60 l/s each, (c) two wells, 90 l/s each, (d) two wells, 120 l/s each.

Table 6 | Comparison between some sub-scenarios

Sub-scenario	No. of wells	Pumping rate (l/s)	Distance from river (m)	River filtrate portion (%)	Min. travel time (days)
1, 6, and 16	1	1 × 60	10.5	98.0	2.5
3, 33, 34, and 35	2	2 × 30			
18	1	1 × 60	20.0	97.5	4.2
39, 40, and 41	2	2 × 30			
30	1	1 × 120	20.0	95.0	2.0
48, 49, and 50	2	2 × 60			

3.6. Multi-Regression analysis

Regression analysis was used to predict groundwater levels (Sahoo & Jha 2013; Yan *et al.* 2018; Kommineni *et al.* 2020), recharge (Lorenz & Delin 2007), and groundwater quality (Chenini & Khemiri 2009). In this work, a multi-regression analysis was used to estimate both river filtrate portion (Equation (4)) and minimum travel time (Equation (5)) as functions of pumping rate and distance between the pumping well and the river (Figure 9), as these two design parameters have the highest impact on RBF performance as concluded from the results of the studied scenarios. This procedure can be used as a guideline for similar RBF projects.

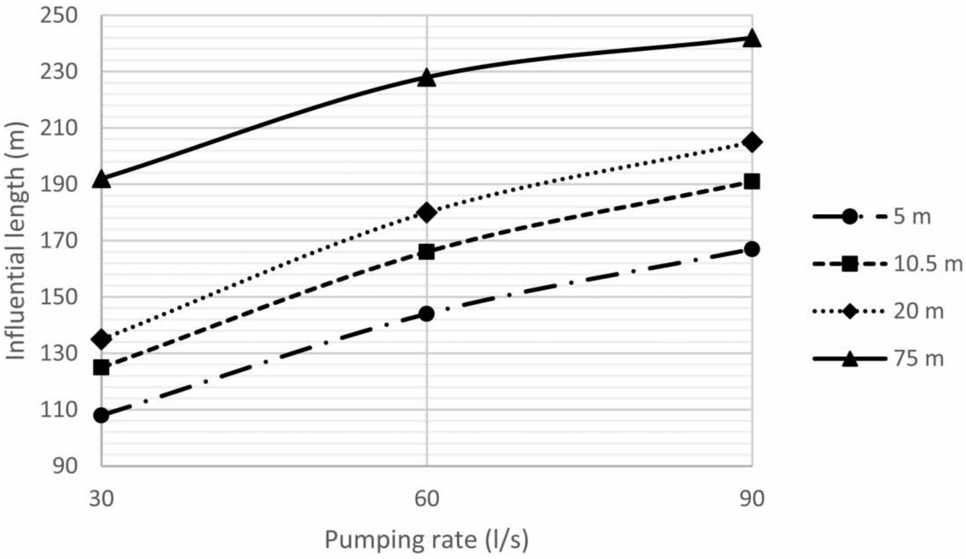


Figure 8 | Influential length of the river.

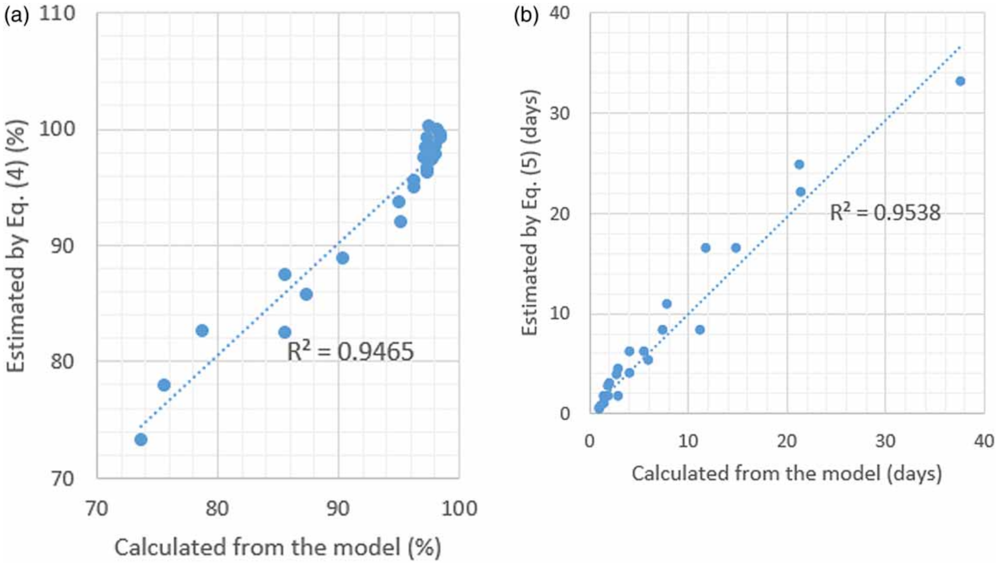


Figure 9 | Model results vs equations' estimations. (a) River filtrate portion, (b) min. travel time.

The regression analysis was established according to the results of Scenario 1 and Scenario 2, and within the studied range of pumping rates and distances from the river. These two equations are limited to this site and the previously mentioned assumptions. The assumption and limits can be summarized as follows:

1. Homogeneous aquifer with calibrated K_h=57 m/d, and K_v=0.0003 m/d.
2. Riverbed conductance for the river (Bahr Yusuf) and Alriva Canal are 5 and 0.2 (m^2/d)/m^2, respectively. Riverbed clogging effect was neglected.
3. Recharge from irrigation=1 mm/day, and recharge from precipitation was neglected.
4. Operating one RBF well with pumping rate ranges from 30 to 120 l/s.
5. Distance from the well to the river ranges from 5 to 75 m.

The normalized root mean square error (NRMSE) was calculated for both river filtrate portion and minimum travel time and found to be 0.02 and 0.25, respectively. These two equations can be used for this site for any future projects.

$$\%R = (-0.002\,Q - 0.12)D + 101.1,\ RMSE = 1.74\% \tag{4}$$

$$T_{\min} = (-0.004\,Q + 0.56)D - 0.8,\ RMSE = 1.87\ \text{days} \tag{5}$$

where

$\%R$: river filtrate portion (%)
Q: pumping rate (l/s)
D: distance between river and well (m)
$T_{\min}$: min. travel time (days).

4. SUMMARY AND CONCLUSIONS

4.1. Summary

Riverbank filtration (RBF) has become a promising solution for Egypt, which offers potable water with a low cost. RBF is the process of extracting water from a river by pumping wells located nearby, where river water is purified through natural physical, biological, and chemical filtration mechanisms. In this work, a groundwater model was constructed to simulate the Idrasiya RBF site, which contains three RBF units, in Beni Suef, Egypt, using MODFlOW, to study the effect of four design parameters on both river filtrate portion and travel time, assuming that the extracted water quality is improved by increasing the river filtrate portion. These parameters are: (1) the extraction rate of the RBF wells, (2) the number of operating wells, (3) the distance between wells and the river, and (4) the spacing between wells. MODPATH and ZONEBUDGET were used for determining travel time and river filtrate portion for each scenario. Only hydraulic aspects were taken into consideration. The model was manually calibrated. This calibrated model was used to simulate the existing situation and three design scenarios with a total number of 68 sub-scenarios. In the first scenario, a single continuously operated vertical well was used, at a constant distance from the river, and variable pumping rates. In the second scenario, a single continuously operated vertical well was used, at a variable distance from the river, and variable pumping rates. In the third scenario, two continuously operated vertical wells were operated simultaneously with equal pumping rates, different distances from the river, and different spacing between them. From the scenario results, the most significant design parameters were found to be pumping rate and distance from the river. Hence, two equations have been developed to estimate the river filtrate portion and minimum travel time as functions of pumping rate and distance between the pumping well and the river. This procedure can be used as a guideline for similar RBF projects.

5. CONCLUSIONS

- The outcomes of the model indicated that the RBF technique is a promising technique to be implemented in the field under investigation. The percentage of river-infiltrated water in the overall abstracted water was high (>74%) in all scenarios. The major recharge source of the aquifer was the river infiltration from Bahr Yusuf, while the infiltration from agriculture was very limited relative to the infiltration from the river.
- Based on the studied scenarios, the most significant design parameters for the RBF process were the distance between the river and the well, and the pumping rate.
- Placing the RBF at a further distance from the river bank could prolong the infiltration time and increase the potentiality of making the infiltration environment anaerobic. In contrast, it was observed that the spacing between the RBF wells had a minor impact on the efficiency of the RBF technique.
- From a hydraulic perspective, constructing one well at distance 10.5 m from the river, with pumping rate equal to 60 l/s, produced the highest river filtrate portion (98%). From a water quality perspective, it would be required to investigate the relationship between the distance from the well to the river and water quality parameters.
- Two equations were developed to estimate the river filtrate portion and minimum travel time as functions of pumping rate and distance between the pumping well and the river. They can be used for this site for any future projects. This procedure can be used as a guideline for similar RBF projects.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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