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Article

Analysis of the Performance of Bank Filtration for Water Supply in Arid Climates: Case Study in Egypt

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Abstract: Bank filtration (BF) is acknowledged as a sustainable and effective technique to provide drinking water of adequate quality; it has been known for a long time in Europe. However, this technique is site-specific and therefore its application in developing countries with different hydrologic and environment conditions remains limited. In this research, a 3-discipline study was performed to evaluate the feasibility of the application of this technique in Aswan City (Egypt). Firstly, a hydrological model was developed to identify key environmental factors that influence the effectiveness of BF, and to formulate plans for the design and management of the BF system. Secondly, water samples were collected for one year (January 2017 to December 2017) from the water sources and monitoring wells to characterize the bank-filtrate quality. Lastly, an economic study was conducted to compare the capital and operating costs of BF and the existing treatment techniques. The results demonstrated that there is high potential for application of BF under such hydrological and environmental conditions. However, there are some aspects that could restrict the BF efficacy and must therefore be considered during the design process. These include the following: (i) Over-pumping practices can reduce travel time, and thus decrease the efficiency of treatment; (ii) Locating the wells near the surface water systems (<50 m) decreases the travel time to the limit (<10 days), and thus could restrict the treatment capacity. In such case, a low pumping rate must be applied; (iii) the consequences of lowering the surface water level can be regulated through the continuous operation of the wells. Furthermore, laboratory analysis indicated that BF is capable of producing high quality drinking water. However, an increase in organic matter (i.e., humics) concentration was observed in the pumped water, which increases the risk of trihalomethanes being produced if post-chlorination is implemented. The economic study ultimately demonstrated that BF is an economic and sustainable technique for implementation in Aswan City to address the demand for potable water.

Keywords: bank filtration; modelling; bank filtrate quality; economic feasibility; arid climate

1. Introduction

Access to potable drinking water is a major challenge confronting water service providers in arid and semi-arid countries owing to dwindling water quantity and quality. This issue is more pressing in Egypt, where the annual growth rate of the population is high (1.9%) [1]. The population increased to approximately 82 million in 2012 from 28 million in 1960, and is predicted to be 120–150 million by 2050. Egyptian water treatment plants produce approximately 22.1 million m³ of drinking water daily; however, the production capacity of potable water remains ten times less than the consumption rate [2]. Consequently, more than 20% of Egyptian villages continue to have restricted access to drinking water [3]. Moreover, the current conventional water treatment plants cannot produce drinking water with adequate quality owing to the pollution of the surface water systems. One hundred and twenty eight agricultural and industrial drains discharge water with a high load of chemical pollutants to the Nile River (NR) [4]. The concentration of organic matter ranges between 2.3 and 11.3 mg/L in the Nile Delta [5]. Therefore, the Egyptian government has recently relied on bank filtration (BF) as a robust and economical technique to replace or integrate with existing waterworks to provide drinking water of adequate quality [4].

BF is an affordable natural treatment technique, where river water naturally flows through the riverbanks to an aquifer. A sequence of chemical, physical, and biological processes occurs during the sub-surface flow and reduces pollutant concentrations. It is a water treatment process that is environmentally sound and attenuates majority of the contaminant concentrations to acceptable limit and increases its biological stability [6]. Sandhu [7] reported a 50% removal of dissolved organic matter (DOM) and 13–99% of the micropollutants at BF fields along the Yamuna River (India). The BF principle has evolved in Europe and has been extensively used over hundred years along the Elbe and Rhine rivers for domestic water production. Recently, the application of this technique has been extended in countries such as India [8], China [9], Brazil [10], and Egypt [4] with different hydrological and environmental conditions. However, bank filtrates contribute less than 0.1% to Egypt's national water supply system [2]. Thus, there is a requirement to assess the performance of this sustainable technique under these local hydrological conditions to propose guidelines to promote its application.

The effectiveness of BF is highly influenced by the hydrological and hydrogeological conditions of the surface water system and aquifer. Different studies [2,3,11,12] demonstrated the hydrological conditions at NR are favorable for the application of the BF technique. Such conditions were defined by Wahaab [4] as follows: (i) The aquifer has high hydraulic conductivity ($K > 1 \times 10^{-4}$ m/s) and appropriate thickness (>10 m), reflecting a high water transmission capacity. (ii) The flow of the NR is erosive, which reduces the riverbed's clogging development, and thus, (iii) the NR is well connected with the adjacent aquifer. However, the interaction between the NR and the aquifer is projected to change shortly due to the anthropogenic activities (e.g., construction of the Renaissance dam in Grand Ethiopia (GRED) and the impacts of climate change which could reduce the availability of surface water and consequently impact the performance of BF. Recent studies [13,14] have demonstrated that the construction of GRED will reduce the storage capacity of the Aswan High Dam (AHD) by 14.8–60.7%. In comparison, as a consequence of the decrease in the discharge of the AHD by 10%, the NR water level is estimated to decline by 0.45–0.75 m. Regarding climate change, Beyene [15] reported that precipitation in the Nile Basin is projected to decrease up to 40% by the end of the 21st century. Hence, the annual inflow to the AHD Lake is expected to decrease by 16%. The decline in the availability of surface water could influence the BF performance parameters, such as travel time and drawdown, and reduce the effectiveness of treatment process.

The quality of the bank filtrates is highly dependent on the source water quality, environmental conditions of the infiltration zone, and the design parameters of the BF system (i.e., the distance between the wells and river, number of wells, production capacity and travel time). Grützmacher [16] stated that the elimination of cyanobacteria toxins during the BF process requires at least ten days of residence. Wintgens [17] demonstrated that a subsurface travelling time of 50 days is adequate to remove pathogens and provide high-quality drinking water. Maeng [18], conversely, found a negative

relationship between the travel time and redox potential of the bank filtrate. This suggests that longer travel increases the potential for environmental anaerobic conditions. This enhances the reduction of undesirable and toxic elements (e.g., Fe, Mn, and As), and consequently has an adverse effect on the bank-filtrate quality. Based on these assumptions, a travel time of 10 to 50 days was regarded as acceptable.

The identification of the correct position to install the BF wells is a critical factor for the successful application of the BF technique [4]. However, the major drawback of BF is that it is a site-specific technique, and therefore an extensive investigation must be conducted to determine the site's viability for BF application. Sandhu [19] proposed a four-stage investigation plan for site selection; this plan can be described as follows: (i) A preliminary evaluation of the potential sites by conducting field studies to collect information on the hydrogeological and hydrological properties of the water systems and collecting samples from the wells and surface systems; (ii) an in-depth assessment of the potential sites to identify the appropriate locations for installing the BF wells, to determine the groundwater elevations at the investigated areas and to construct monitoring wells; (iii) determination of the hydrological parameters of the aquifer and monitoring of the surface water levels and quality; and (iv) development of an analytical or numerical model to estimate travel time and determine the bank-filtrate proportion in the total water pumped.

The main objective of this study was to analyze the performance of BF in Aswan City (Egypt) as an example of an arid climate region and to use the results to suggest guidelines to facilitate the application of BF in Egypt and countries with a similar hydrological regime. However, another environmental benefit of implementing the BF technique is addressing the groundwater rising problem in the area under investigation. In 2009, 40 productive wells were shut off, and the groundwater head increased resulting in creation of ponds of depths ranging from 8–15 m in the low-lying areas. These ponds have detrimental environmental impact as they endanger the public health and city's infrastructure. Therefore, the government was obligated to pump water from the aquifer and re-operate some of the wells [20]. Hence, it is required to install BF wells to produce high quality drinking water and maintain groundwater level to avoid environmental problems.

The study was conducted in three phases including (i) the development of a hydrological model for the study area to assess the appropriate locations for BF-well installation and propose different scenarios to manage the BF fields under different environmental conditions; (ii) a water quality assessment—the quality characteristics of the surface water resources and observation wells were monitored for an extended period to predict the bank-filtrate quality; and (iii) an economic analysis conducted to compare the costs of BF systems with existing conventional surface water treatment systems.

2. Study Area

Aswan City is located in the south of Egypt on the eastern bank of the NR between 32°53' and 32°56' E longitudes and 24°01'30" and 24°04'30" N latitudes (Figure 1). The area under investigation was bounded from the east and west by the basement rocks and the NR, respectively. It covered approximately 19.43 km², with a maximum width of approximately 4.5 km. The area has a dry climate, without rain, except for one event every 10 to 15 years [20]. The maximum and minimum air temperatures are 49.5 °C and 27.3 °C in summer, and 30 °C and 15 °C in winter, respectively, and the average annual temperature is 26 °C. The relative humidity in May is the lowest (18%); the maximum occurs in December (40.3%). The ground elevation of the study area ranged from 88–211 m above sea level with an average of 112 m. The study area included three geological units (basement rocks, Nubian Sandstone, and Quaternary sediments). The Quaternary sediments consist of sands, gravels, and clays of the Pleistocene age [21]. In the southern region of the study area, the aquifer is composed mainly of fine to medium sand intersected by thin intercalations of clay; the thickness of these intercalations typically increases from the south to the north. The study area was bounded from the west and east boundaries by complex Precambrian igneous and metamorphic rocks, mainly of granites and schists. Nubian Sandstone strata overlaid the basement rocks with a thickness ranging

between 20 and 85 m [20,22]. This study area included 76 pumping wells; however, the majority of these were not in operational mode. Currently, 11 wells pump approximately 23,700 m³/day for irrigation, industrial, and drinking purposes.

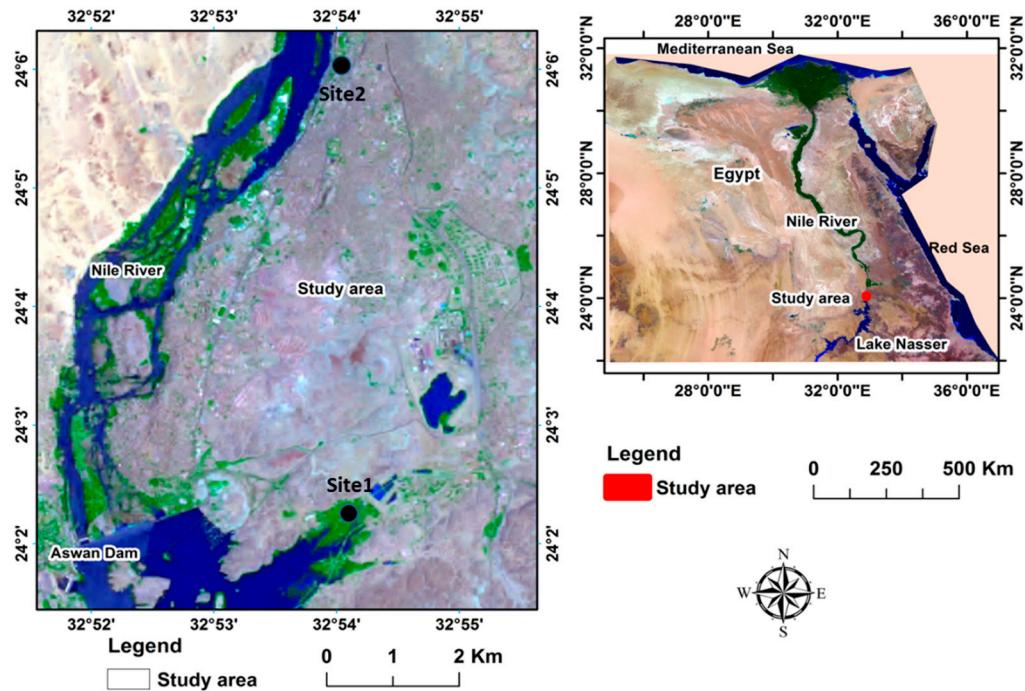


Figure 1. Location of study area in Egypt (right) and detailed features (left).

3. Research Methods

3.1. Hydrological Model

A hydrological model was developed to simulate the current situation of the Aswan's aquifer and propose different scenarios to manage the BF technique.

3.1.1. Data Preparation

This study focused on the development of a 3-dimensional model to characterize the groundwater flow system and levels in the area adjacent to the NR at Aswan City, Egypt, by coupling MODFLOW (finite difference code) [23] and Geographic Information System (ArcGIS) [24]. The developed model was used to identify the current hydrological situation of the aquifer, define the proper positions to install BF wells, and assess the effects of design and operation conditions on the efficiency of BF systems. A geodatabase for the Nubian Sandstone Aquifer Aswan was developed from different data sources using ArcGIS. The model data included model geometry, river stage levels, cross sections, pumping test, observation heads (42 observation wells), and borehole data. A digital elevation model (DEM) was derived from the SRTM-3 (Shuttle Radar Topography Mission) [25]. The geometric surfaces, initials, and the hydraulic parameters were developed using ArcGIS as point data features with their spatial references and appropriate attributes. This dataset was interpolated using Surfer software and a kriging technique with a proper variogram model, and prepared as input for the model development [26].

3.1.2. Model Development

In MODFLOW, the aquifer was discretized using an array of finite different cells and nodes. The study area was simulated horizontally with a grid mosaic of 71 rows and 90 columns with a cell dimension of 100 m × 100 m resulting in 3014 active cells. The model boundaries were identified as follows (Figure 2). (i) The river boundary: the study area was bounded from the west and south by the

NR and Aswan Dam Lake (ADL). These natural boundaries were simulated in MODFLOW using the River package. (ii) The aquifer was bounded from the north and east with basement rocks where the lateral groundwater flow was negligible or non-existent, and thus these outer features were considered as no-flow boundaries. The aquifer base was assigned as a no-flow boundary (basement rocks).

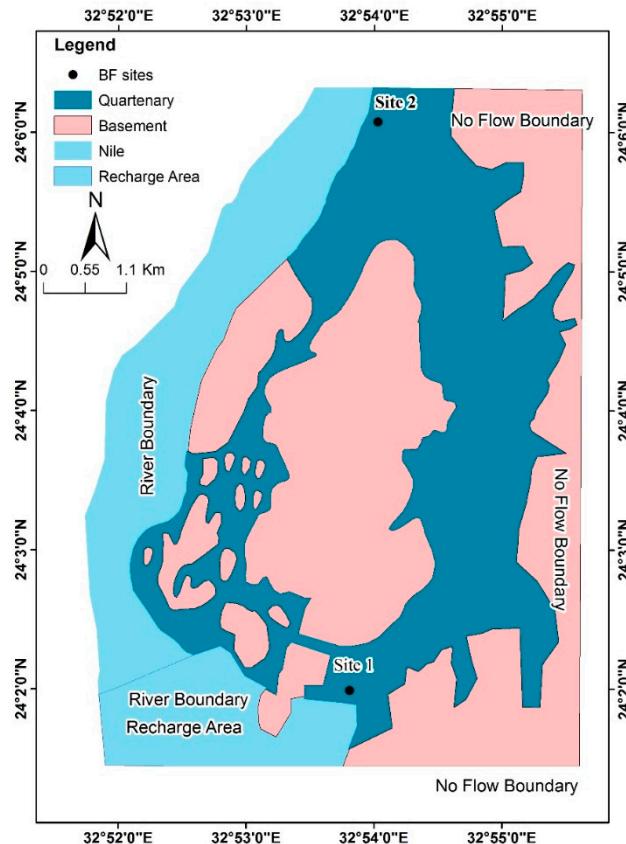


Figure 2. Geological units and model boundary conditions.

The aquifer was mainly recharged from ADL (the lake confined between the AHD and Aswan dam). Areal recharge from the surface was considered negligible as no or minimal rain occurs yearly in the study area. Based on the available hydraulic heads, the general groundwater flow direction in this area is from south to north corresponding to the NR flow [20]. The outflow of the aquifer occurs at the northwest of the model area where the water flows from the aquifer into the NR. The NR conductance was estimated for a bed thickness of 1.6 m and hydraulic conductivity of 0.0004 m/s [6].

The pumping rates from the production wells were simulated as constant values. Public drinking water network leakage was represented with injection wells with positive charge and capacities based on the data provided by the Aswan Water and Wastewater Company, then validated during the calibration process. The unconfined aquifer was simulated with one layer with variable thickness starting from 130 m in the south and decreasing gradually in a northerly direction. This permeable layer was composed mainly of sand and gravel and demonstrated insignificant horizontal variations in its hydraulic parameters along the scale of the modelled area. Moreover, it was assumed to be internally homogenous anisotropic with equal hydraulic conductivity (K) in the X and Y directions ($K_x = K_y$), and one order less in the Z direction ($K_z = K_x/10$), this is in agreement with other modelling studies that have been conducted in upper Egypt [12,27]. The $K_{x,y}$ values were assigned as 0.001 m/sec based on the aquifer test and laboratory analysis estimations. The hydraulic parameters, including transmissivity, storage coefficient, and leakage rate of the porous layer were estimated from the pumping tests conducted during this research and were consistent with the values determined by

different authors such as Hamdan [21]. These hydrological parameters were calibrated during the simulation period.

3.1.3. Model Calibration

The model was primarily developed and executed under steady-state conditions using the initial estimates of the hydraulic parameters (e.g., hydraulic conductivity). To reproduce the preliminary configuration of the aquifer water table prior to pumping, the hydraulic parameters and stresses were adjusted by a trial and error technique. A calibrated output hydrological map (2008) was used as an initial head map to execute and calibrate the model in the transient condition. Although the steady-state results were reasonable, the steady-state condition was not proven completely. Therefore, a “warming-up period” technique was used in this research to avoid the accumulative error that could appear during the calculation process due to inaccurate initial conditions imposed on the model software [28]. The transient model was initiated with a warming period (365 days). Then, for another five years (from 1 January 2009 to 31 December 2013), the model was executed and calibrated under the stress of eight pumping wells and 33 observation wells with variable hydraulic heads, distributed in the study area. The simulation time was discretized into daily stress periods; each had two-time steps. The model was executed repetitively and recalibrated until field-observed values were matched with the modelled values within an acceptable level of accuracy. Then, the model was subsequently executed and validated for a further five years (2014–2017) as a validation period.

3.2. Development of BF Management Scenarios

A calibrated hydraulic simulation was used to optimize the hydraulic capacity of the BF system and assess the influence of the design conditions including well spacing, distance from the well to the river, and pumping capacity, and to determine the effect of surface water level on the efficiency of the BF technique. In this research, two proposed BF sites (Site 1 and 2,) were examined. Site 1 was located at the recharge region of the aquifer (specifically at longitude 24°01'56" N and latitude 32°53'48" E); this site was 100 m farther from the lake reservoir confined between the Aswan Dam and AHD. Site 2 was located at 24°06'05" N, 32°54'01" E. This site was characterized by its proximity to an urban area (Figure 2).

Drawdown refers to the decline in water table within the aquifer due to pumping. %BF refers to the share of each water source (surface water or ambient groundwater) that reaches the BF-well during the BF-process. For each hydraulic simulation, the share of bank filtrate BF% and the drawdown were estimated in a grid cell in the center of each site and the best options were determined based on three criteria: (i) Appropriate travel time, (ii) greater bank-filtrate share, and (iii) less drawdown. The MODPATH particle-tracking code [23,29] was used to estimate the travel time of water particles to the BF pumping wells. MODPATH is a 3-dimensional tool designed for collaborating with MODFLOW to determine the advective transport of particles that mimic pollutants (or tracers). During this research, a set of particles were identified at the interface between the surface water system and adjacent aquifer. Then, the MODPATH code was applied in the forward function to simulate the migration of the water particles toward the wells. In this research, the travel time along the meridian and angled lines were estimated and used as an approximation for the minimum and maximum travel times.

The ZoneBudget (ZONBUD) code [30] was applied to estimate the bank-filtrate share for each hydraulic simulation. ZONBUD is post-processing code that facilitates the determination of a sub-region water budget based on the MODFLOW flow model results. First, a set of fictitious particles were placed at the locations of the extraction wells. Then, the MODPATH code was execute in the backward mode to delineate the pathlines of these particles from the aquifer and surface water system toward the abstraction wells and determine the size of each zone. Then, the ZONBUD code was applied to estimate the contribution of the ambient groundwater and infiltrated water to the total pumped water.

3.3. Water Quality Characterization

To predict the quality characteristics of the bank filtrate, water samples were collected from a pumping well (BF1) placed at 24°02'28" N and 32°54'35" E near the first potential BF site and 1.2 Km from the surface water system. There are 12 extraction wells in the BF field, which operated mutually. Second set of samples were collected from an observation well (BF2) situated at 24°06'03" N and 32°54'08" E near the second potential BF field (Site 2) and 600 m from the Nile. As it was previously mentioned, the aquifer is mainly recharged from the lake of Aswan Dam, therefore, samples were collected from the surface water systems (NR and ADL) to assess the efficiency of the BF process. Moreover, samples were collected from a well located at 24°03'26" N and 32°54'33" E and at a distance of 4.5 km of the ADL system; this well was considered as a source for ambient groundwater. The samples were collected on a monthly basis from the different sources (bank filtrating wells, surface water and groundwater systems) for one year (from January 2017 to December 2017), filtered using a 0.45- μm membrane filter (Whatman, Dassel, Germany) and analyzed. The physical parameters (temperature, electric conductivity, pH, and turbidity) were determined onsite using portable (HACH, USA) instruments. The main inorganic parameters were quantified using an ion chromatograph (881 Compact IC pro, Metrohm, Swiss); the metals were analyzed by ICP-OES (Optima 8300 from Perkin Elmer Company, USA).

The bulk organic concentration of the raw and infiltrated water was determined using a total organic carbon (TOC) analyzer (TOC-VCPN (TN), Shimadzu, Japan). The water absorbance in the ultraviolet range at the 254 nm wavelength (UV_{254}) was used as a predictor for the aromaticity and potential formation of trihalomethane during the treatment process [31]. The UV_{254} (cm^{-1}) absorbance was monitored using a UV/Vis spectrophotometer (UV-2501PC Shimadzu). Then, the specific ultraviolet absorbance (SUVA_{254}) ($\text{L/mg}\cdot\text{m}$) was calculated by dividing the UV_{254} absorbance [m^{-1}] by the dissolved organic carbon (DOC) concentration (mg/L). The measurements were conducted at the laboratories of the Holding Company for water and wastewater (Cairo, Egypt).

Fluorescence excitation-emission measurements (F-EEM) were conducted following the procedures described in Abdelrady [32] to classify the bulk organic matter into different constituents. The fluorescence measurements were performed once at the IHE-(Delft, Netherlands) using a Fluoromax-3 spectrofluorometer (HORIBA Jobin Yvon, Edison, NJ, USA). The fluorescence characteristics were determined at an excitation wavelength (λ_{ex}) between 240–452 nm (interval = 4 nm); the emission wavelengths (λ_{em}) were from 290–500 nm with an interval of 2 nm. In this study, three fluorescent peaks were identified at definite excitation and emission wavelengths representing three different organic substances. These peaks included primary humic-like P1 ($\lambda_{\text{ex}} = 250$ –260 nm and $\lambda_{\text{em}} = 380$ –480 nm), secondary humic-like ($\lambda_{\text{ex}} = 300$ –370 nm and $\lambda_{\text{em}} = 400$ –500 nm), and protein-like ($\lambda_{\text{ex}} = 270$ –280 nm and $\lambda_{\text{em}} = 320$ –350 nm) [33,34]. To gain insight into the organic characteristics of the bank filtrate and raw water, the fluorescence indices (Humification index (HIX), fluorescence index (FIX), and biological index (BIX)) were estimated following the equations presented in Gabor [35].

The percentage of the infiltrated water from the surface water systems captured by the two BF wells was determined using chloride as a conservative chemical parameter based on the following equation [36,37]:

$$BF\% = \frac{C_{BF} - C_{GW}}{C_{SW} - C_{GW}} \times 100 \quad (1)$$

where C_{BF} , C_{SW} , and C_{GW} are the concentrations of the conservative parameter in the BF well, surface water, and native groundwater, respectively.

3.4. Cost Analysis

The extended application of BF in developing countries is highly dependent on its capacity to provide a sufficient quantity and quality of drinking water. Nonetheless, the economic cost is also a decisive factor that must be considered. Two methods (Net Present Value (NPV) and Payback Period (PBP)) were used in this research to evaluate the economic feasibility of using the BF technique in

Aswan City compared to other existing treatment techniques. *PBP* calculates the minimum time (in years) required to recover the total investment cost. This can be calculated as follows:

$$PBP = \frac{\text{Total capital cost}}{\text{Annual income} - \text{Annual outcome}} \quad (2)$$

The *NPV* is used to assess each project's profitability by offsetting all future income and expenses to the present (Equation (3)):

$$NPV = \sum_{n=1}^N \frac{B - C}{(1+r)^n} - I_0 \quad (3)$$

where B and C are income and expenses of each year, r is the discount rate, and I_0 is the capital cost. Whereas, n is the project's lifetime (in years).

4. Results and Discussion

4.1. Calibration of the Model

The calibrated results demonstrated an acceptable agreement between the modelled and observed groundwater heads with $R^2 = 0.90$. The mean absolute error (MAE) was 0.37 m, and the root mean square error (RMSE) was 0.47 m (Figure 3a), which indicates reasonable model performance. The validated results also indicated that the modelled and observed heads were well aligned ($R^2 = 0.90$, MAE = 1.02 m, and RMSE = 1.31 m) (Figure 3b). Moreover, observed and simulated heads in both cases were virtually aligned around the mean of the observed heads.

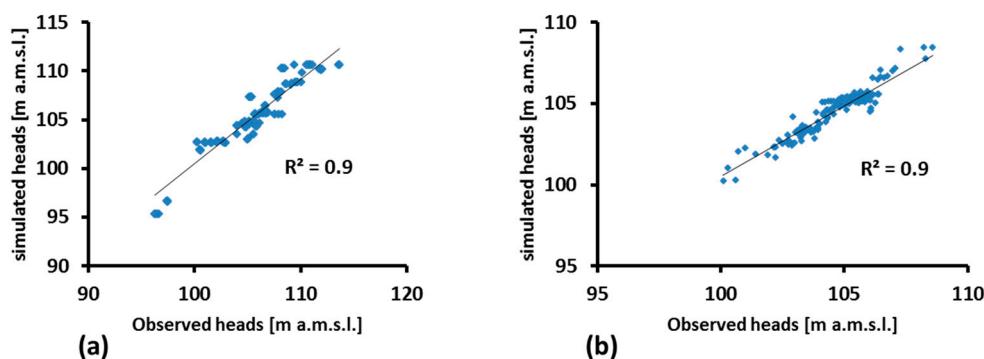


Figure 3. Model simulated vs. field observed water level: (a) Calibration period and; (b) validation period.

4.2. Aswan Aquifer Model (Current Situation)

The model was developed to simulate the current situation (2009–2017) of the Aswan city aquifer and assess the influence of the proposed stresses on the interaction between the surface water and groundwater systems and consequently on the water quantity of the BF wells. The ultimate goal was to provide different scenarios to manage the bank fields under different hydrological conditions. The results revealed that the ground and infiltrate water flow from the south to the north direction, paralleling the NR. The total water penetration from the ADL into the aquifer was highly dependent on the lake and river stages and aquifer's water head; its value ranged from 683,710 m³/day in summer to 551,030 m³/day in winter. The groundwater had the same general flow path as the NR from the south to the north. Conversely, discharging water from the aquifer toward the NR (baseflow) was the main outflow component and occurred in the northern region of the aquifer. The total water discharge into the surface water system ranged from 528,410 to 603,500 m³/day. The aquifer exhibited a high capacity to store the water. The model results revealed that the groundwater head increased by 1–3 m during the period from January 2009 to July 2013 (Figure 4a,b), mainly attributed to the shutting off of 40 productive wells by the Egyptian government. In 2013, eight abstraction wells were re-operated to

pump 17,280 m³/day from the aquifer. Consequently, the groundwater level decreased by 0.3 m and 0.5 m by the end of 2013 and 2017, respectively (Figure 4c–e).

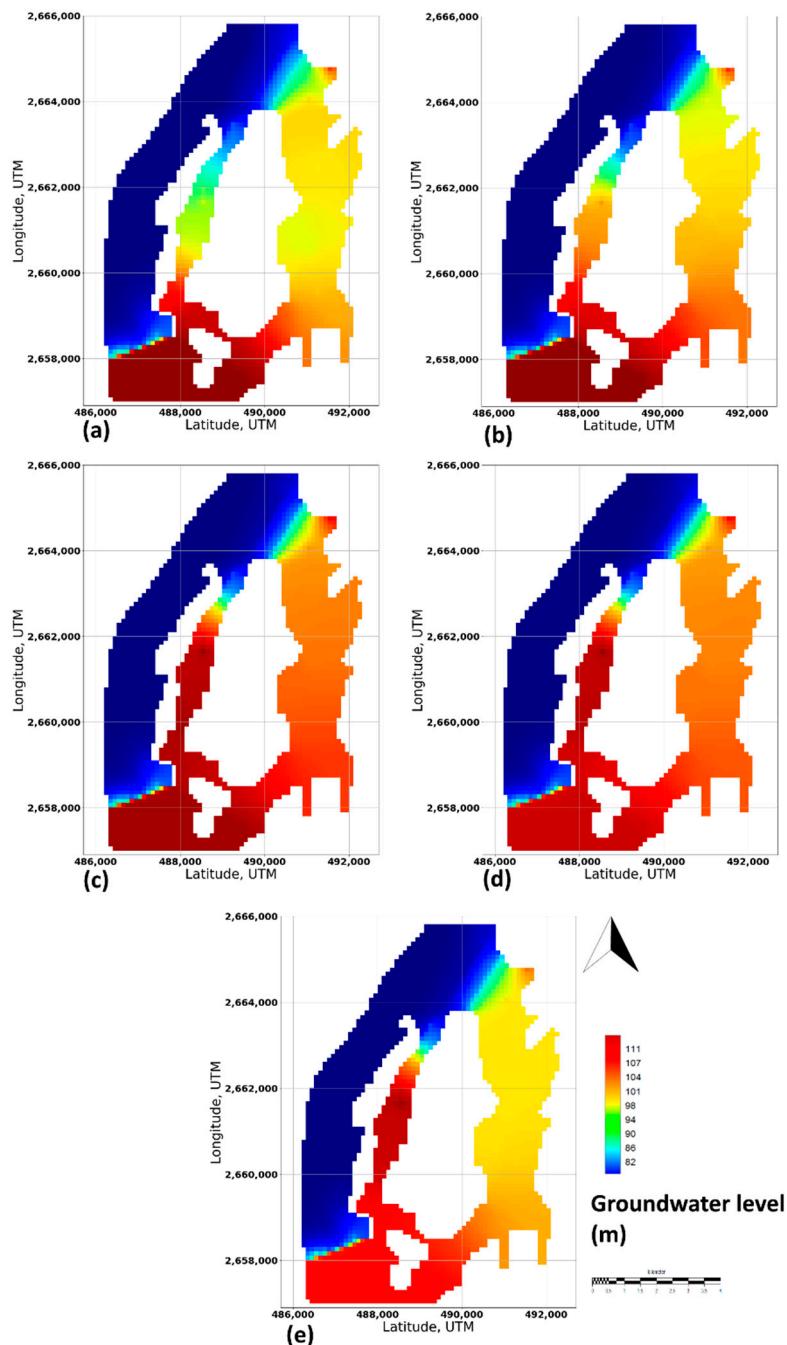


Figure 4. Simulated groundwater levels of Aswan aquifer for years (a) 2008, (b) 2009, (c) 2013, (d) 2014, and (e) 2017.

4.3. Bank Filtration Management Scenarios

Different hydraulic simulations were performed to assess the influence of the well design parameters and identify the optimum operating conditions for managing the BF technique at two different sites in Aswan City.

4.3.1. Effect of Number of Wells and Pumping Rate on BF Performance

Three scenarios were proposed to evaluate the influence of the number of wells and pumping rate on the BF performance:

- Scenario 1 (effect of the number of wells): Four simulations were conducted based on the number of wells; 5, 10, 15, and 20 wells, where the production capacity was the same ($35,000 \text{ m}^3/\text{day}$) in each simulation. The production capacity was divided equally on the number of wells, so that, in each simulation, each well has the same pumping rate.
- Scenario 2 (effect of pumping rate): Three simulations were conducted based on the pumping rates ($35,000$, $17,770$, and $70,000 \text{ m}^3/\text{day}$). The number of wells in each simulation was constant (10 wells).
- Scenario 3 (effect of increasing the number of wells and pumping rate simultaneously): A different groups of 5, 10, 15, and 20 wells were simulated with production capacity of $17,500$, $35,000$, $52,500$, and $70,000 \text{ m}^3/\text{day}$, respectively.

For all the scenarios the wells were aligned parallel to surface water system at 100 m far from the surface water system, and the space between the wells was 50 m.

The Scenario 1 results (Figure 5a) illustrated that increasing the number of wells, while maintaining the production capacity constant ($35,000 \text{ m}^3/\text{day}$), could influence the BF efficiency. After an operation period of 365 days, the bank-filtrate share was increased from 73 to 97% and from 65 to 70% when the number of extraction wells increased from 5 to 20 at Sites 1 and 2, respectively. Nonetheless, no noticeable influence on the drawdown was observed. The drawdown was increased marginally from 1.4 to 1.5 m at Site 1 and decreased from 5.6 m to 3.7 m at Site 2. Conversely, travel time along the meridian pathline increased from 13 to 19 days and 12 to 23 days when the number of wells were increased from 5 to 20 in the two planned areas. However, travel time along the angled pathlines declined from 60 to 48 days and 72 to 40 days. Hence, it can be deduced that installing a low number of wells (less than 10) at the proposed sites could increase the risk of developing an anaerobic environment during the infiltration process.

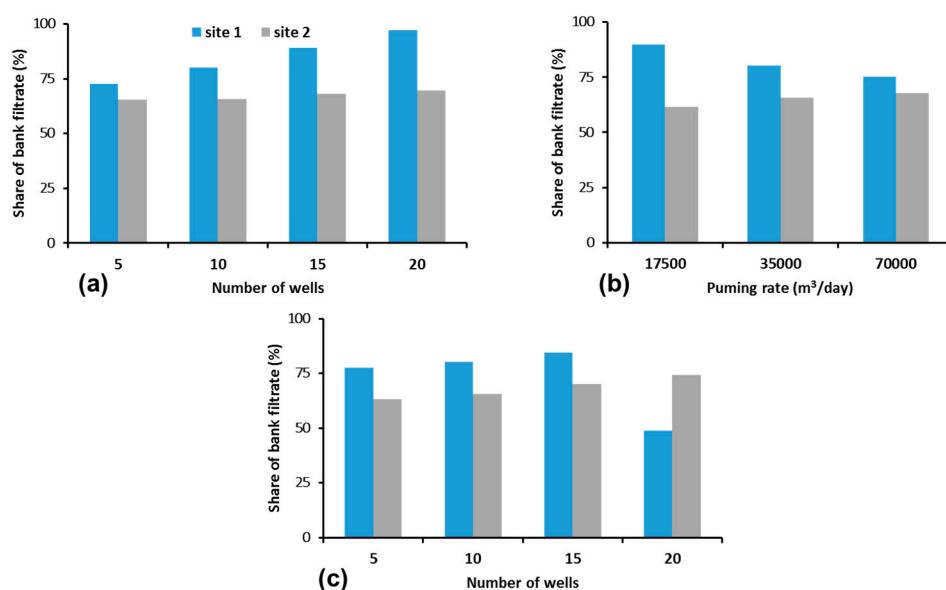


Figure 5. Effect of number of wells and pumping rate on bank-filtrate share (BF %): (a) Scenario 1, (b) Scenario 2, and (c) Scenario 3.

The results obtained from Scenario 2 (Figure 5b) demonstrate that increasing the pumping rate considerably influenced the BF efficiency. For Site 1, a double increase in the abstraction rate of

the extraction wells decreased the bank-filtrate share of the pumped water by 5–10% and dropped the drawdown by 1–1.5 m. Furthermore, the travel times were 95, 50, and 30 days for the particles travelling along the angled pathlines and 21, 11, and 7 days for the particles tracking the meridian pathlines when the abstraction capacity was 17,500, 35,000, and 70,000 m³/day, respectively. The same findings were observed at Site 2, that increasing the production capacity of the wells could increase the drawdown and reduce the travel time. However, a slight increase in the proportion of bank filtrate was noted which may attribute to the induction of surface water to infiltrate into the extraction wells as the level of the groundwater table dropped. As the pumping capacity increased by 17,500 m³/day, the bank-filtrate share improved on average by 2%. Moreover, the drawdown estimated was 2.1, 5.2, and 11.6 m at an abstraction capacity of 17,500, 35,000, and 70,000 m³/day. Similarly, the travel time was decreased from 40, to 15, and to 8 days as the production capacity increased from 17,500, to 35,000, and 70,000 m³/day, respectively. This inferred that a higher production capacity (>35,000 m³/day) could cause a severe increase in drawdown values and reduce travel time to a level (<10 days) that influences the efficiency of the BF processes at the proposed BF sites.

The outcomes of Scenario 3 (Figure 5c) revealed that increasing the abstraction capacity and number of wells simultaneously at Site 1 had a notable influence on the bank-filtrate share of the pumped water. It estimated that the river-infiltrated water contributed to the pumped water with 78%, 80%, and 84% when the number of abstraction wells was 5, 10, and 15, respectively. However, this value decreased to 49% when the number of wells increased to 20, with a total production capacity of 70,000 m³/day. This implies that an over-pumping process induces the ambient groundwater to flow toward the BF wells and thus promotes the groundwater's contribution percentage to the produced water and reduces the share of the bank-filtrate percentage. This is in agreement with the drawdown results, which indicated a gradual decreased behavior with an increased the number of wells. The groundwater table was depleted by approximately 0.7 m when the number of wells increased from 5 to 20. Conversely, it was observed that doubling the number of wells and their pumping intensities concurrently enhanced the bank-filtrate share by approximately 4% at Site 2 and reduced the groundwater level by 1.5 m on average. This procedure has also been demonstrated to have a substantial effect on the travel time of the infiltrating water. The results indicate that it required 10 and 20 days for the water particles following the meridian pathlines to reach the pumped wells in Sites 1 and 2 when the number of wells was 15 and 20, respectively. Whereas the particles following the angled pathlines converged at the pumping wells after 100 days of infiltration time when five wells were simulated. This infers that both low and high pumping procedures adversely influence the travel time and ultimately reduced the BF efficiency of at the two proposed areas.

From all scenarios, from a hydrological perspective, it was determined that the BF performance at Site 1 was superior to that at Site 2. For a production capacity of 35,000 m³/day (with a number of wells ranged between 5–20 and at the spacing of 50 m), the contribution of river infiltrated water to the total pumped water ranged between 73 and 97% at Site 1, whereas it ranged between 65 and 70% at Site 2 under the same design conditions. Further, the maximum estimated drawdown was 1.8 and 5.6 at Site 1 and 2, respectively. It was also noticed that the production capacity of the wells had a greater influence than the number of wells. Increasing the number of wells, maintaining the total production capacity constant, could improve the bank-filtrate's share without a major change in travel time and drawdown. The bank-filtrate proportion exceeded 80% at Site 1 and 65% at Site 2 when ten or more extraction wells with an abstraction capacity of 35,000 m³/day were installed. Furthermore, the travel time varied between 10 and 50 days, which is sufficient to enhance BF efficiency. Higher production capacity, however, could shorten the travel time to the limit, reducing the treatment efficiency of the BF processes.

4.3.2. Effect of Distance of the Well from River on BF Performance

Several hydraulic simulations were developed to analyze the influence of the distance between the surface water system and abstraction wells on the BF performance at the two potential sites.

The production wells were modelled at different distances (i.e., 50, 100, and 200 m from the river) parallel to the surface water systems. The effect was assessed at different well-pumping rates (17,500, 35,000, and 70,000 m³/day). The results (Figure 6) indicated that the distance of the wells to the river did not have a remarkable influence on the bank-filtrate share and drawdown. After 365 days of operation, the bank-filtrate percentage in the abstraction wells (with a production capacity of 35,000 m³/day) situated at a distance of 50 m from the river was 81% and 66%, and the drawdown was 1.7 m and 4.4 m at Sites 1 and 2, respectively. In comparison, placing the BF wells at 200 m from the river changed the proportion of infiltrated water in the total pumped water by 1% and depleted the groundwater table by 0.3 and 2.2 m at the two proposed sites, respectively. The same finding of a minor effect of the distance between the BF well and river on the bank-filtrate share and drawdown was determined at other pumping rates. Conversely, travel time was the most influenced parameter of changing the distance from the wells to the river. When the wells were positioned at 200 m from the river, and the pumping rate was low (1750 m³/day), the water particles converged at the abstraction wells at a time ranging between 135–195 days at Site 1 and 83–110 days at Site 2. As the pumping rate doubled, the travel time at both sites decreased to 72–150 and 43–65 days, respectively. Consequently, there is a high potential of the infiltration environment becoming anaerobic under these hydrological conditions. Conversely, the proximity of the wells to the surface water system reduced the time of interaction between the soils and infiltrated water and therefore influenced the efficiency of the treatment processes. At a distance between the wells and river of 50 m, the travel time varied between 13–35, 7–35, and 3–17 days at pumping rates of 1750, 3500, and 7000 m³/day, respectively. This indicates that low pumping rates should be employed when the BF wells are close (50 m or less) to the surface water system at the proposed sites.

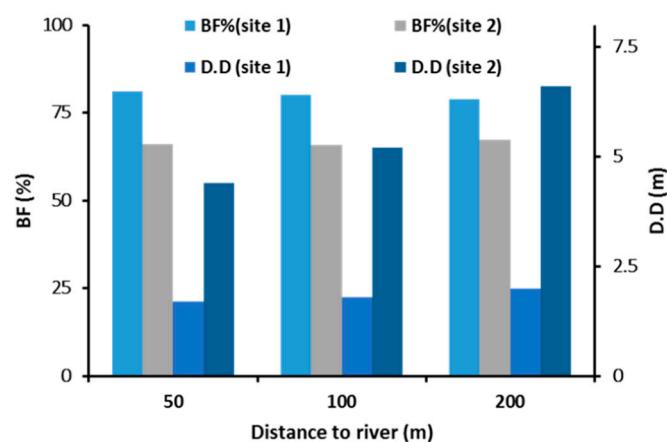


Figure 6. Impact of the distance between BF wells and surface water system on the bank filtrate share (BF %) and drawdown (D.D.) at the two potential BF sites of Aswan City.

4.3.3. Effect of Well Spacing on BF Performance

The space between the wells has a significant influence on the level of the groundwater and its interaction with the surface water system and subsequently affects the efficiency of the BF system. In this research, two well spacing options (i.e., 25 and 50 m) were assessed under different design and operation conditions, including different pumping rates and distances to the river. From a hydrological perspective, it was observed that the space between the pumping wells had a positive effect on the BF performance at the two investigated sites (Tables 1 and 2). In all hydraulic simulations, it was observed that an increase in space between the wells from 25 to 50 m could enhance the proportion of infiltrated water in the total produced water by approximately 10% at both sites. Furthermore, it reduced the drawdown, thereby prolonging the travel time. This effect can be attributed primarily to the expansion of the radius of influence of the wells when they are close [38]. When the well spacing increased from 25 to 50 m, the drawdown reduced by an average of 0.2 m at Site 1 and 3 m at Site 2. In comparison,

the travel time at both sites increased by, respectively, 5–25 and 5–10 days. However, inappropriate travel time was recorded when the wells were installed 200 m from the surface water system with a low pumping rate ($1750 \text{ m}^3/\text{day}$), as reported in earlier sections.

Table 1. Effect of well spacing on BF performance modelled parameters (i.e., bank-filtrate share BF%, drawdown D.D., and travel time) for wells placed at different distances to surface water system.

Well Spacing (m)	Distance to River (m)	Site 1			Site 2		
		D.D (m)	BF%	Travel Time (day)	D.D (m)	BF%	Travel Time (day)
50	50	1.3	91	12–25	3.4	70	15–30
	100	1.6	92	22–47	4	71	25–35
	200	1.8	92	103–175	5.5	73	53–70
25	50	2	81	7–25	6.6	66	7–30
	100	1.8	80	11–50	5.2	66	18–40
	200	2	79	72–150	6.6	67	43–65

Table 2. Effect of well spacing on BF performance modelled parameters (i.e., bank-filtrate share BF%, drawdown D.D., and travel time) for wells operating at different pumping rates (m^3/day).

Well Spacing (m)	Pumping Rate (m^3/day)	Site 1			Site 2		
		D.D (m)	BF%	Travel Time (day)	D.D (m)	BF%	Travel Time (day)
50	1750	1.2	99	36–90	2.1	63	47–60
	3500	1.6	92	22–47	4	71	25–35
	7000	1.8	84	14–45	5.2	75	12–17
25	1750	1.3	90	21–95	2.6	62	40–80
	3500	1.8	80	11–50	5.2	66	18–40
	7000	2	75	7–40	8.7	68	25–35

4.3.4. Effect of River Stage on BF Performance

Several hydraulic simulations were performed to determine the influence of decreasing the river stage on BF performance at Aswan City. Within these simulations, surface water levels were reduced by 0.5, 1 m, and 1.5 m as the worst scenario. The results (Figure 7) indicated that reducing the surface water level could decrease the bank-filtrate contribution to the total pumped water, particularly at the onset of the BF wells' operation. However, after a period of approximately 100 days, the effect of surface water levels became minor. When the river stage decreased ($\Delta R.S.$) by 1.5 m, the bank-filtrate share at Site 1 and Site 2, respectively, was reduced by 14% and 5% after a 10-day operating period. However, after 90 days, the variance in the bank-filtrate share due to the decline of the river stage was less than 2%. Lowering the surface water level reduces the water table at the BF field, diminishes the hydraulic gradient between the wells and surface water stages, and ultimately reduces the flow velocity of the infiltrated water to the wells. Decreasing the river stage in the model by 1.5 m triggered a 1.2 m reduction of the drawdown at Site 1 and 1.7 m at Site 2. This was followed by an 11–12-day and 2–4-day decrease in the travel time at both sites, respectively. A decrease of the river stage by 0.5 m reduced the subsurface water table by 0.5 m at Site 1 and 0.4 m at Site 2 and lengthened the travel time by 4 and 7 days at the two sites, respectively. Therefore, it can be concluded that the continued functioning of the BF wells can minimize the influence of the reduction of the surface water level and thus improve the BF efficiency. Bartak [12] investigated the BF performance at the Dishna site along the NR and reported that the intermittent operation of the BF wells was one of the major drawbacks reducing the efficiency of the BF technique. This study demonstrated that the bank-filtrate share in specific BF wells did not exceed 10% after construction and operation of BF abstraction wells for 1.5 years, primarily due to the 8-h daily interruption in the operation of the wells. Moreover, the water pumped did not meet drinking water requirements. Therefore, it can be concluded that the continuous operation of BF wells is a prerequisite for the successful application of the BF technique in Egypt.

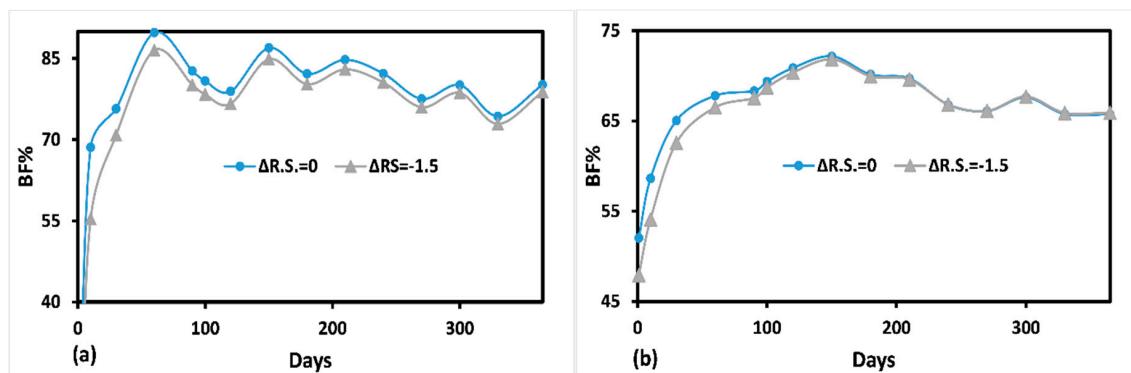


Figure 7. Influence of river stage dropping on bank-filtrate share (BF %) at two proposed sites: (a) Site 1 and (b) Site 2 at Aswan City (Egypt).

4.4. Bank-Filtrate Chemistry

The chloride was used as conservative elements to estimate the percentage of infiltrated water from the surface water systems to the total pumped water at the two BF wells. The average chloride concentrations for NR, ADL, BF1, BF2, and GW were 6.7 ± 1.7 , 7 ± 2 , 16.5 ± 3 , 38 ± 9 , and 56 ± 7 mg/L, respectively. Therefore, the bank-filtrate share for BF1 and BF2 was estimated to be 81% and 36%, respectively.

The physical and chemical characteristics of the raw, infiltrated, and groundwater at the study area are summarized in (Table 3 and Tables S1–S3). The minimum and maximum temperatures were 17.8 and 28.6 °C for the surface water systems, respectively, and 16.8 and 25.7 °C for the BF wells, primarily due to the low buffer heat capacity of the soil and short distance between the surface water sources and wells. Moreover, it was observed that the banks acted as a robust barrier to the elimination of suspended matter. The turbidity was low (<0.3 NTU) at the BF wells, regardless of the corresponding value at surface water systems.

Table 3. Quality parameters of surface waters, bank filtrates, and groundwater sources.

Parameter	Unit	MDL	River Nile	Aswan Dam Lake	BF (Site1)	BF (Site2)	GW	Egyptian Standards
pH			8.2 ± 0.6	7.9 ± 0.5	8.41 ± 0.3	8.3 ± 0.5	8.4 ± 0.3	6.5–8.5
Conductivity	$\mu\text{s}/\text{cm}$	2	234 ± 12	225 ± 8	288 ± 25	376 ± 38	438 ± 26	-
turbidity	NTU	0.1	1.5 ± 0.6	1.2 ± 0.7	0.23 ± 0.1	0.28 ± 0.1	0.75 ± 0.2	1
NH_4^+	mg/L	0.2	n.d.	n.d.	0.42 ± 0.2	0.61 ± 0.1	0.64 ± 0.2	0.5
NO_2^-	mg/L	0.02	0.14 ± 0.1	0.1 ± 0.08	0.05 ± 0.02	0.28 ± 0.1	0.37 ± 0.1	0.2
NO_3^-	mg/L	0.2	2.63 ± 0.4	2.22 ± 0.6	0.71 ± 0.1	5.8 ± 1.3	4.3 ± 0.8	45
Fe	$\mu\text{g}/\text{L}$	3	n.d.	n.d.	20 ± 3	145 ± 21	330 ± 37	300
Mn	$\mu\text{g}/\text{L}$	5	42 ± 9	n.d.	14 ± 5	211 ± 27	432 ± 41	400
DOC	mg/L	0.5	3.90	3.60	4.30	4.90	5.50	-
SUV ₂₅₄	L/mg.m	-	1.56	1.33	2.16	2.04	2.73	-
P1	R.U.	-	0.32	0.20	0.41	0.74	1.10	-
P2	R.U.	-	0.12	0.09	0.14	0.25	0.46	-
P3	R.U.	-	0.23	0.22	0.11	0.14	0.19	-

MDL: minimum detection limit; n.d.: not detected; R.U.: Raman Unit.

The concentrations of major cations (Na, K, Ca, and Mg) and anions (Cl, SO_4^{2-} , and HCO_3^{-}) demonstrated increased behavior during the infiltration process. For example, the average concentrations of Ca were 24 ± 3 and 19 ± 5 mg/L for the NR and ADL surface water systems and increased to 36 ± 5 and 55 ± 8 mg/L for the BF1 and BF2 wells, respectively. Similarly, an increase in the concentrations of heavy metals was detected at the BF wells. Fe, Mn, Al, and Cu were not detected in the surface water systems, yet were 20 ± 3 , 14 ± 5 , 837 ± 116 , and $14 \pm 7 \mu\text{g}/\text{L}$ at BF1 and 145 ± 2 , 211 ± 27 , 511 ± 32 , and $24 \pm 9 \mu\text{g}/\text{L}$ at BF2, respectively. This is mainly attributed to the (i) dissolution of minerals during the filtration process and/or (ii) mixing of infiltrated water with the contaminated native groundwater [39]. The dissolved oxygen ranged between 5.1–7.3 mg/L at the surface water sources and decreased to 2.7–5.4 mg/L at the BF wells. It is therefore expected that microbial reduction

does not have a major role in increasing the concentration of metals in the pumped water at the BF wells. However, the concentrations of these elements in the pumped bank filtrates did not exceed the threshold levels of drinking water quality guidelines proposed by WHO [40] and therefore they do not pose a risk to human health. Similarly, other toxic metals (As, Cd, Co, Ni, Pb, and Zn) were not found in either the surface water systems or bank filtrates.

BF is recognized as an effective technique to reduce nutrient concentrations significantly [31]. However, higher concentrations of nitrogen and phosphorus were found in the BF wells relative to the concentrations of the surface water bodies during this study. The concentration of ammonia was less than the detection limit at the surface water sources; however, its concentration increased to 0.54 mg/L at BF1 and 0.73 mg/L at BF2. Similarly, the average concentration of phosphate was 0.05 ± 0.02 and 0.03 ± 0.01 mg/L at the NR and ADL systems and increased to 0.1 ± 0.04 and 0.14 ± 0.05 mg/L at the BF1 and BF2 wells, respectively. The principal reason for this increase is the mixing of infiltrated water with contaminated groundwater [20,21].

Organic matter is the main factor influencing the process that occurs during the BF process. The bulk and constituents of the organic matter were monitored during this study using different analytical techniques. BF is regarded as an effective technique for reducing the organic matter concentration [41,42]. Maeng [43] conducted column studies to simulate BF processes and demonstrated that more than 50% of the organic matter was removed during the top 50 cm of the column. However, in this research, a marginal increase in the concentration of bank-filtrate organic matter was observed. The concentration of organic matter in the NR and ADL surface water systems was 3.9 and 3.6 mg/L, whereas the concentrations in the pumped water of the BF1, BF2, and GW wells were 4.3, 4.9, and 5.5 mg/L, respectively. Moreover, SUVA₂₅₄ values of NR, ADL, BF1, BF2, and GW were 1.56, 1.33, 2.16, 2.04, and 2.73 L/mg·m, respectively, which indicates that the bank filtrate and ambient groundwater had relatively higher aromatic characteristics than the surface water sources. This observation could be attributed to the (i) dissolution or desorption of soil organic matter into the filtrate water, which is significantly increased at high temperatures [44,45], (ii) accumulation and subsequent degradation of particulate organic matter (e.g., Phytoplankton) during the filtration process that augments the organic concentration in the bank filtrate [46], and (iii) effect of mixing the infiltrated water with the ambient groundwater, which has a higher concentration of organic matter. The phenomenon of enrichment of the organic content of the bank filtrate was also reported at BF wells along the Lot River (France) and Lagoa do Peri Lake (Brazil) [10,47].

The organic fluorescence characteristics of the surface water, bank filtrates, and groundwater were determined to provide insight into the organic composition of the water sources. The F-EEM spectra of the measured samples are presented in Figure S1. The protein-like components were considerably attenuated during the filtration process. The fluorescence intensity results (Table 3) indicated that the protein-like compounds were reduced by 33–55% in the bank filtrates compared to their intensities in the surface water systems. Therefore, it can be concluded that BF enhances the biological stability of pumped water [31]. Conversely, bank filtrates had a relatively higher content of humic compounds than surface water sources. This can be mainly attributed to the mixing effect of the infiltrated water with groundwater with high humic content, and the dissolution of soil humic compounds into the infiltrate water as mentioned above. The fluorescence indices verified these findings. The results indicated that the bank filtrates had higher humic content (higher HIX) and lower microbial-derived compounds (lower BIX). The FIX was 1.67 and 1.36 for the NR and ADL surface water systems and decreased to 1.09 and 1.07 for bank filtrates BF1 and BF2, respectively. This infers that the bank filtrates retained a higher content of humic compounds of terrestrial origin than the surface water sources. The increase of humic compounds in the bank filtrates could enhance the formation of trihalomethane compounds during the post-treatment process (i.e., post-chlorination) [48]. Consequently, the BF design process in Aswan city must focus more on reducing the proportion of groundwater in the overall pumped water. Moreover, a post-treatment process (e.g., coagulation and filtration) might be needed to minimize the humic concentration in the bank filtrate.

To conclude, the produced bank filtrates meet the drinking water quality standards proposed by the Egyptian government [4]. However, the infiltration of untreated wastewater and drainage waters into the pumped water deteriorates its quality [21].

4.5. Economic Analysis

The primary sources of drinking water in Aswan City are conventional water treatment plants (WTPs) and groundwater wells. High-capacity WTP (production capacity ranges between 17,000 m³/day and 1 million m³/day or more) employs coagulation, flocculation, sedimentation, sand filtration, and disinfection combination to provide potable water to the public. Low-capacity WTP (compact units, a production capacity of ~2160 m³/day) is mainly used to provide drinking water to small villages. The treatment processes are similar to that of high-capacity WTPs, but on smaller-scale [4]. BF and GW plants consist of extraction wells and a chlorine-disinfection unit, no post-treatment procedures are presently implemented. The depth of the GW wells ranged from 90 to 110 m. However, the BF wells are drilled at a depth of about 20–60 m. The existing treatment techniques produce drinking water quality meeting the Egyptian standards.

This section presents an economic comparison between the existing treatment techniques and BF in Aswan city. The capital and operation costs (including chemicals costs) of each treatment technique were estimated based on expenditure and revenue field data for five years (2015–2019) from the Aswan Water and Wastewater Company, Egypt. The water tariff is 2.09 EGP per cubic meter. The operation costs of BF and GW wells were assumed to be the same. The results (Table 4) revealed that NPV and PBP were 6.2 million EGP (project's life = 10 years) and 0.5 years for BF, 5.9 million EGP (project's life = 10 years) and 0.7 years for GW, 0.9 million EGP (project's life = 15 years) and 8.2 years for a low-capacity WTP, and 7.6 million EGP (project's life = 25 years) and 6.3 years for a high-capacity WTP, respectively. This indicates that the BF technique had a relatively high NPV and low PBP values, and therefore, the BF technique is economically feasible to implement in Aswan City.

Table 4. Economic comparison between current treatment techniques and BF in Aswan City, Egypt.

	Unit	BF	GW	Low-Capacity WTP	High-Capacity WTP
Production capacity	(m ³ /day)	2160	2160	2160	8640
Capital cost	(Million EGP/Unit)	0.5	0.8	5.0	35.0
Chemicals, operation and energy cost/year	(Million EGP/Unit)	0.5	0.5	1.0	1.8
NPV	(Million EGP)	6.2	5.9	0.9	7.6
PBP	(years)	0.5	0.7	8.2	6.3

5. Conclusions

The feasibility of implementing the BF technique in an arid environment (Aswan, Egypt) was investigated in this study. The overarching objective was to establish guidelines for the management of BF systems under these environmental conditions. A 3-discipline research was undertaken to achieve this objective, including (i) the development of a hydrological model to determine the impact of environmental variables on the performance of this technique. (ii) A water quality monitoring study has been conducted to characterize the quality of bank filtrate. (iii) An economic viability analysis was conducted to compare BF with existing treatment techniques. From a hydrological perspective, BF is a favorable technique under the local environmental conditions of Aswan City. However, the design parameters (e.g., number of wells, production capacity, and spacing between wells) should mainly be identified based on minimizing the contribution of contaminated groundwater to the total pumped water. The water level of the Nile River is projected to decline in the foreseeable future owing either to the construction of the Renaissance dam in Grand Ethiopia or to the consequences of climate change. The model results revealed that dropping of Nile River level (by 0.5–1.5 m) has a substantial effect on the BF parameters (e.g., travel time, the share of bank filtrate) in the onset operation of the wells.

Nevertheless, the continued operation of BF wells for long period (approximately 100 days) could mitigate these consequences.

The water quality study demonstrated that BF in Aswan City is an effective technique for eliminating the chemical contaminants and ensuring decent quality drinking water. However, there was an increase in the humic compounds (terrestrial) in the pumped water, which may be due to the dissolution of these compounds from the soil into the infiltrating water or to the impact of mixing infiltrated water with the polluted groundwater. If the post-chlorination process is implemented, this rise in humic compounds in the pumped water may increase the potential for the formation of trihalomethane compounds.

Ultimately, the Net Present Value (NPV) and the Payback Period (PBP) were used as economic analysis tools to determine the viability of BF relative to other treatment technique. The results pointed out that BF had lower NPV and PBP values, indicating sound economic viability.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4441/12/6/1816/s1>, Figure S1: F-EEM spectra: (a) NR, (b) ADL, (c) BF1, (d) BF2, and (e) GW, Table S1: Physical and inorganic characteristics of the surface waters, bank filtrates and groundwater sources, Table S2: The concentrations of heavy metals in the surface waters, bank filtrates and groundwater sources, Table S3: Organic characteristics of the surface waters, bank filtrates and groundwater sources.

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