Challenges and Possible Solutions for Riverbank Filtration: Case Studies of Three Sites in Egypt

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ABSTRACT: In response to Egypt's escalating water scarcity and pollution, Riverbank Filtration (RBF) technology is emerging as an effective solution to enhance water quality and simplify drinking water provision. This study evaluates RBF at three sites in Upper Egypt by assessing hydrogeological conditions and water quality based on 36 parameters from 2022 to 2023. Findings indicate that RBF efficiently treats infiltrated river water, with all sites meeting turbidity and microbiological standards (Total Bacterial Count and Coliforms), achieving removal rates of approximately 90% and 99%, respectively. Despite these successes, challenges persist in reducing manganese to safe levels, with concentrations at Alsaayda site reaching 0.51 mg/L, over the drinking water safe limit of 0.4 mg/L. To address this, further post-treatment strategies are proposed to remove the excess manganese. A practical application of an Oxidizer at the Bani Murr groundwater treatment plant has demonstrated the effective removal of iron and manganese, bringing their levels down to safe drinking water standards. This case exemplifies a successful solution for iron and manganese removal. This research highlights RBF's potential in water treatment in developing countries, while emphasizing the need for supplementary measures to manage specific contaminants.

KEYWORDS: Riverbank filtration, iron and manganese removal, Egypt, non-conventional water treatment

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Introduction

Riverbank filtration (RBF) refers to water abstraction from aquifers that are located close to the riverbank and recharged through the adjacent river water (Wahaab et al., 2019). The bank and bed of the river act as treatment zones for river water (Hunt et al., 2002). Lowering the groundwater table by pumping induces river water infiltration towards the production wells through the aquifer sediments (Osman et al., 2022; Wahaab et al., 2019). RBF has been widely applied worldwide owing to its efficiency and cost-effectiveness; it reduces chemical usage by providing natural pretreatment (Jiang et al., 2019). However, the design of an RBF system is difficult and complex, and many factors must be taken into consideration during the design step (Jiang et al., 2019). The main factors that must be considered during the design step to ensure the sustainability of the RBF system include groundwater quality and surface water quality, hydrogeological and hydrological conditions, length and location of the filter pipe, well depth and distance to the river, layout and distance between wells, chemical and physical characteristics of the RBF system and its structure, water yield and the allowable groundwater table drawdown (Hester et al., 2017; Jiang et al., 2019). The Nile valley has more favourable hydrogeological conditions for RBF applications than the Nile delta. The River Nile in the Nile valley is fully or partially connected with the quaternary aquifer (Osman, 2022).

RBF has been shown to improve the abstracted water quality utilizing ecosystem services and has been used for a long time in Europe along cities over the Rhine, Elbe and Danube Rivers (Abdelrady et al., 2018; Hiscock & Grischek, 2002; Tufenkji et al., 2002), particularly in Budapest where it has been used over 150 years along the Danube River (Laszlo, 2003; Nagy-Kovács et al., 2019). Improvements in water quality have been demonstrated in several areas around the world where RBF is utilized, particularly for emerging organic micropollutants (OMPs) in surface water bodies (Glorian et al., 2018; Jährig et al., 2018). Moreover, RBF technology utilizes self-renewing natural treatment processes, which means that well-designed RBF systems can maintain a high efficiency for an indefinite period of time. In addition, the fact that RBF relies on the groundwater table, which is generally shallow in proximity to rivers, is cost-effective and requires less excavation and drilling, while still yielding a high productivity (Boving et al., 2018; Ray et al., 2003; Schubert, 2002). This has incentivized many countries to explore and adopt such a system as a cost-effective treatment technique in both developed and developing countries (Abdelrady et al., 2018; Boving et al., 2018; Cady et al., 2013; Dehariya & Verma, 2023; Kumar et al., 2023; Sandhu & Grischek, 2012; Schubert, 2002; Stahlschmidt et al., 2016).

In particular, for our case of interest, Egypt started adopting such technology to provide safe drinking water (Abdelrady et al., 2018; Bartak et al., 2015). This new direction and paradigm shift in water treatment stems from two primary underlying factors. The ever-increasing demand for freshwater outpaces the available production level, with no sign of increasing production levels and the Nile River still comprises approximately 95% of all freshwater used (Central Agency for Public Mobilization and Statistics [CAPMAS, 2017; Deutsches Wissenschaftszentrum Cairo, 2016; Grischek & Bartak, 2016). This is exacerbated by the high population growth rate, which estimates that the population would will reach approximately 150 million people by 2050 (CAPMAS, 2017). The increasing population has created a higher pressure on current water resources. A higher pollution load is discharged into the Nile River, due to the increased domestic, industrial and agricultural effluents at a very low treatment level (Wahaab, 2006). In fact, there are 56 main drainages that discharge directly into the Nile River from industrial and residential areas, and another 72 agricultural drainages. In addition, frequent accidental spills and increasing flash flood occurrences compounded with climate change deteriorate the Nile River water quality significantly, affecting conventional Water Treatment Plants (WTPs) infrastructure (Aly et al., 2022; M. Abdeldayem et al., 2020; Yehia et al., 2017; Yousry et al., 2009).

Furthermore, during winter, the irrigation canals undergo maintenance, and the released water from the main High Aswan Dam is reduced significantly, decreasing the dilution effect and adversely affecting conventional water treatment plant operations (Holding Company for Water and Wastewater, 2018; Wahaab et al., 2019; Yehia et al., 2017). Therefore, different technologies, such as RBF systems, to provide safe drinking water are of interest, particularly for remote communities.

The objective of this paper is to explore the challenges that developing countries, such as Egypt, face in implementing RBF systems. This study assesses the effectiveness of RBF by comparing treated RBF water with untreated Nile River water. A novel aspect of this research is its review of post-treatment solutions from various literature sources, coupled with an examination of a real-world application in Egypt, to achieve drinking water quality standards. It has already been demonstrated that there are several possible solutions for maintaining a good quality level of water for drinking water purposes from RBF systems (Jährig et al., 2018). Three sites in Egypt were selected as cases studies in this study, and workable post-treatment solutions were investigated based on feasibility and suitability to obtain the required water quality level.

Materials and Methods

Site description

Three sites have been investigated in Upper Egypt (Figure 1); Abu Tieg WTP in Assiut Governorate, Altawael WTP in Sohag Governorate and Alsaayda WTP in Luxor Governorate. The capacity of these three sites is planned to be increased by implementing RBF plants. All these plants provide acceptable drinking water (according to the Egyptian standards) and are managed by the Holding Company for Water and Wastewater (HCWW). They have been selected following the Guidelines on Riverbank Filtration in Egypt (UN Habitat, 2021). These locations were specifically selected to be in an already existing WTP to use available state-owned land instead of acquiring plots from private owners. The RBF well locations were selected to be in close proximity to the Nile River shoreline, at a setback distance of 15 to 20 m, with the intentional trade-off of sacrificing the extended travel distances and flow path lengths, which are characteristic of bank filtrate. This trade-off aims to maximize the extraction of a significant portion of bank filtrate rather than groundwater, mainly because of concerns over possible polluted groundwater sources or the need for more complex post-treatment of groundwater rather than RBF water.

Abu Tieg City is a densely populated urban area with around 80,000 residents. It is bounded by the Nile River on its eastern side and is surrounded by land used for intensive farming on its other side. The drinking water treatment plant, which serves not only the city but also nearby towns, pilot villages and scattered settlements, is situated in the northern section of the city along the Nile riverbank. On February 10, 2021, a field visit was conducted in Abu Tieg to evaluate baseline conditions. The WTP total capacity for water treatment, prior to the addition of the RBF wells, was approximately 135 L/s.

Since February 2021, three RBF wells have been installed and operational in Abu Tieg WTP. These wells are located in proximity to the Nile River shoreline, with a spacing of approximately 20 m between each other and a distance of approximately 15 to 20 m from the Nile River shoreline. All water abstracted from the RBF wells is subjected to chlorine dosage for water disinfection and then pumped to the consumers.

Figure 2a shows the location of Abu Tieg WTP, Assiut (N 27° 03′ 15″, E 31° 19′ 00″), while Figures 2b and 3 illustrate the geological cross-section located south of Abu Tieg City and the site RBF cross-section and its utilized portion of the aquifer, respectively. The cross-section revealed that the aquifer thickness in Assiut spans a range of 200 to 300 m, with the utilized thickness around 20 to 35 m. The aquifer comprises a top layer consisting of sand and gravel, underlain by a layer of sand and gravel with clay interbeds. Situated above the aquifer is a relatively thin semi-confining silty clay layer representing agricultural lands. The clay layer lies directly beneath a productive aquifer. Notably, aquifer permeability ranges from 20 to 40 m per day, indicating highly favourable conditions for the RBF project (Ministry of Water Resources and Irrigation [MWRI], 1998).

Altawael Town is situated in Saqulta, on the eastern side of the Nile River, approximately 15 km north of Sohag City. Altawael WTP is positioned on the Nile River bank, roughly 1,500 m to the west of Altawael Town, facing Al-Buha Island.

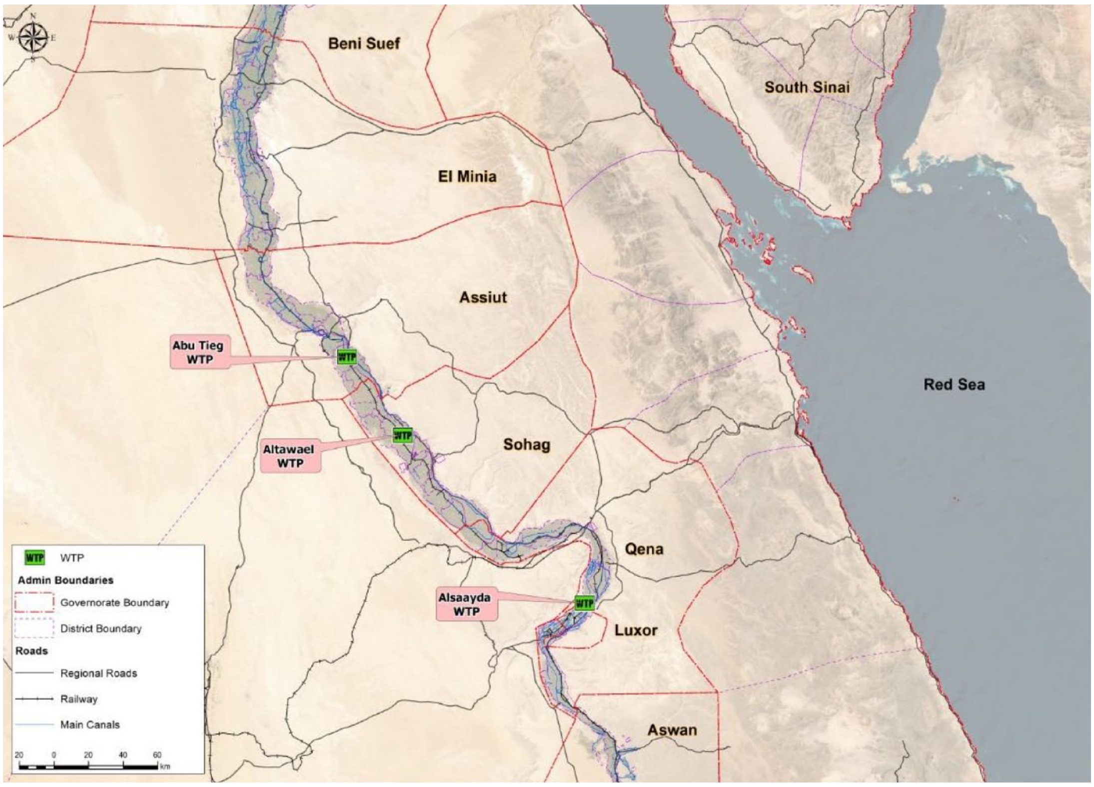

Figure 1. Selected WTP locations as case studies in Upper Egypt along the Nile River; Abu Tieg in Assiut in the north, Altawael in Sohag in the middle and Alsaayda in Luxor in the south.

The plant provides service to the towns of Altawael, Saqulta and Al-Quarametah, as well as part of Nag El-Saquia in the village of Awamiya, in addition to various surrounding dispersed settlements. On February 11, 2021, a field visit was conducted in Altawael in order to evaluate the baseline conditions. Table 1 illustrates the WTP components prior to the addition of the RBF well. The WTP total capacity for water treatment, prior to the addition of the RBF well, was approximately 215 L/s.

An RBF well has been installed and in operation at the Altawael WTP since February 2021. The newly installed RBF well is located close to the Nile River bank at a distance of approximately 15 m. This has increased WTP capacity by an additional 30 L/s, which is equivalent to an increase of approximately 14% from the current treatment capacity. All water abstracted from the RBF wells is subjected to chlorine dosage for water disinfection and then pumped to the consumers.

Figure 4a shows the location of Altawael WTP, Sohag (N26°38′51″, E31°38′51″), while Figures 4b and 5 illustrate the geological cross-section located north of Altawael Town and the site RBF cross-section and its utilized portion of the aquifer, respectively. The cross-section revealed that the aquifer thickness ranges between 200 and 300 m, with the utilized thickness around 30 to 35 m. The aquifer comprises a top layer consisting of sand and gravel, underlain by a layer of sand and gravel with clay interbeds. Situated above the aquifer is a relatively thin semi-confining silty clay layer representing agricultural lands. The clay layer lies directly beneath a productive aquifer. Notably, aquifer permeability ranges from 20 to 40 m per day, indicating highly favourable conditions for the RBF project (MWRI, 1998). However, the observed groundwater level gradient indicates that the groundwater flow directions are towards the project site and the river. This natural movement of groundwater is further enhanced by the seepage of excess irrigation water from surrounding agricultural lands (Ahmed, 2009). As a result, the portion of the bank infiltrate in the RBF well is reduced owing to the influence of this additional groundwater flow, reducing the bank filtrate portion, to mitigate this risk, all RBF wells operate continuously 24/7 to minimize the influence of the groundwater towards the RBF abstraction zone, following the Guidelines on Riverbank Filtration in Egypt (UN Habitat, 2021).

Alsaayda WTP is located on the riverbank about 1.25 km northwest of Alsaayda Village, which is situated on the eastern agricultural Aswan-Cairo Road area approximately 15 km north of Luxor City. The WTP is mostly surrounded by agricultural land and serves the areas of Alsaayda, Madamud, Monshaet El-Amary and the surrounding scattered settlements. A field visit was conducted on February 16, 2021, to assess the baseline conditions. Table 2 illustrates the WTP components prior to the addition of RBF wells. The WTP total capacity for water treatment prior to the addition of the RBF plant was approximately 290 L/s. Three RBF wells were installed, each with a capacity of about 30 L/s. This has increased the existing capacity by approximately 31%.

Figure 6a shows the location of Alsaayda WTP, Luxor (N25°46′31″ and E32°42′14″), while Figures 6b and 7 illustrate the geological cross-section located south of Alsaayda and

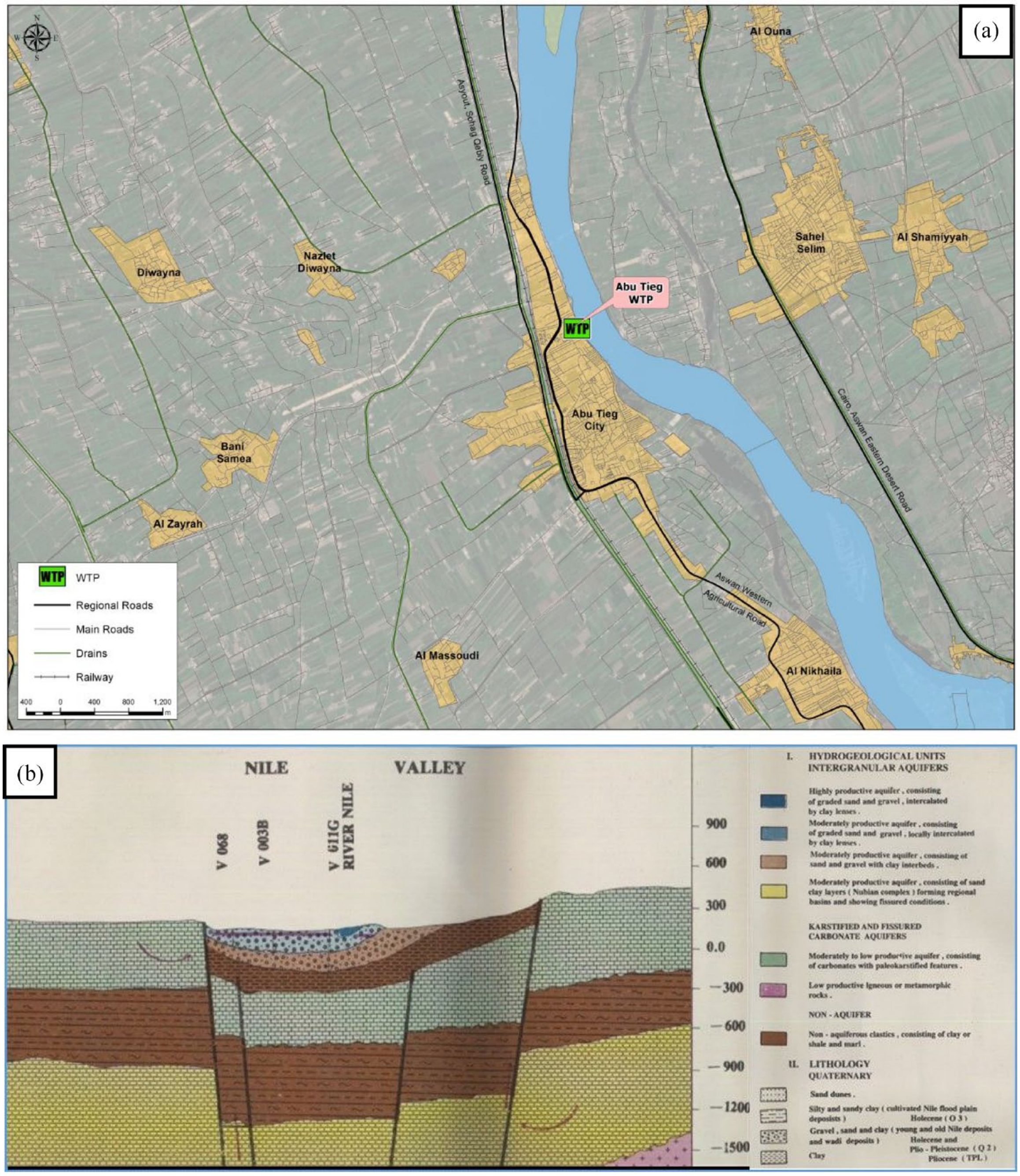

Figure 2. (a) Map showing the location of Abu Tieg WTP and (b) geological cross-section adapted from (MWRI, 1998).

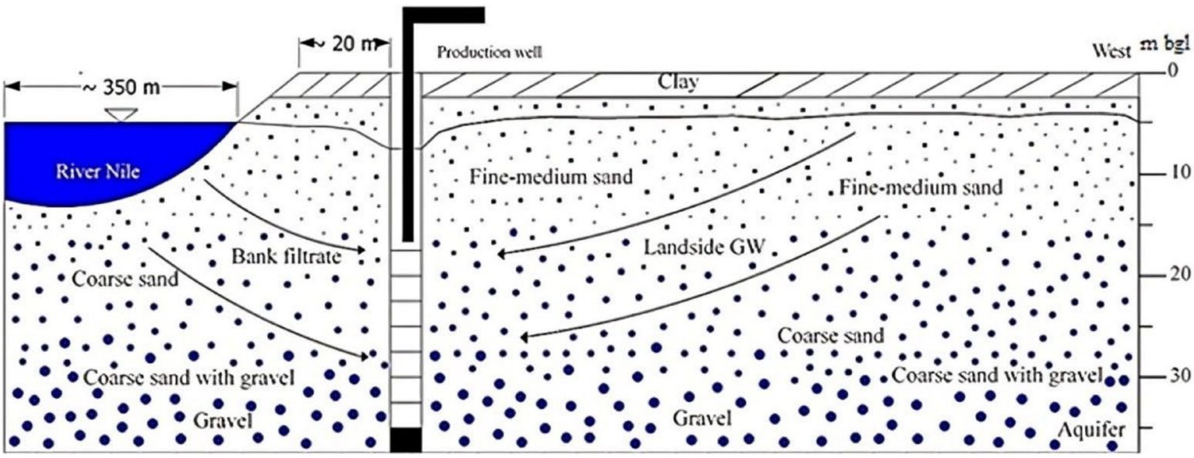

Figure 3. A generalized RBF cross-section for Abu Tieg site.

Table 1. Altawael WTP Capacity.

WTP COMPONENT	CAPACITY (L/S)	REMARKS
3 Deep wells	Up to 25 each	–
2 Compact units	Up to 25 each	–
3 Existing riverbank filtration wells	Up to 30 each	2 wells started operation in 2015, 1 well started operation in 2018.

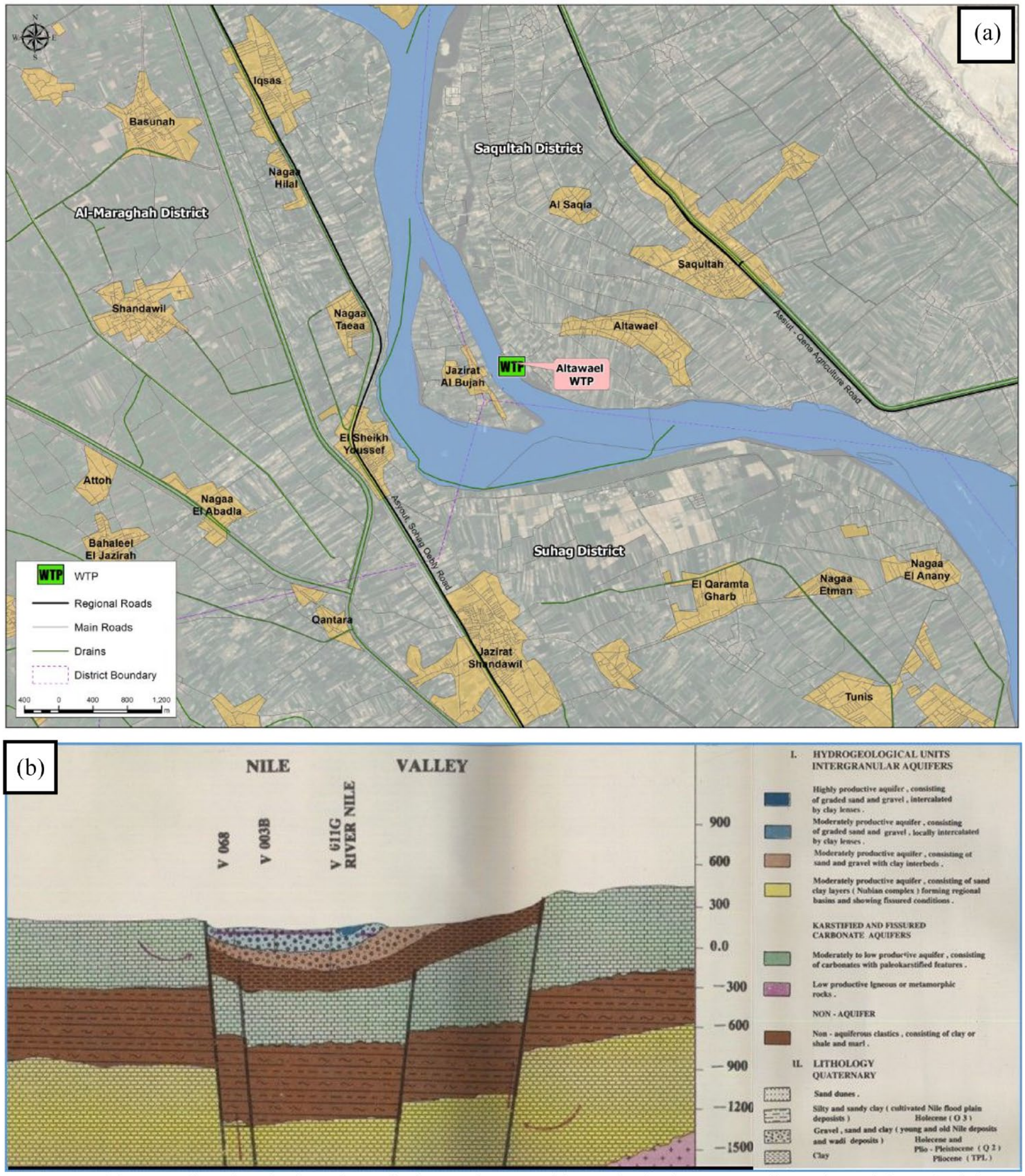

Figure 4. (a) Map showing the location of Altawael WTP and (b) geological cross-section adapted from (MWRI, 1998).

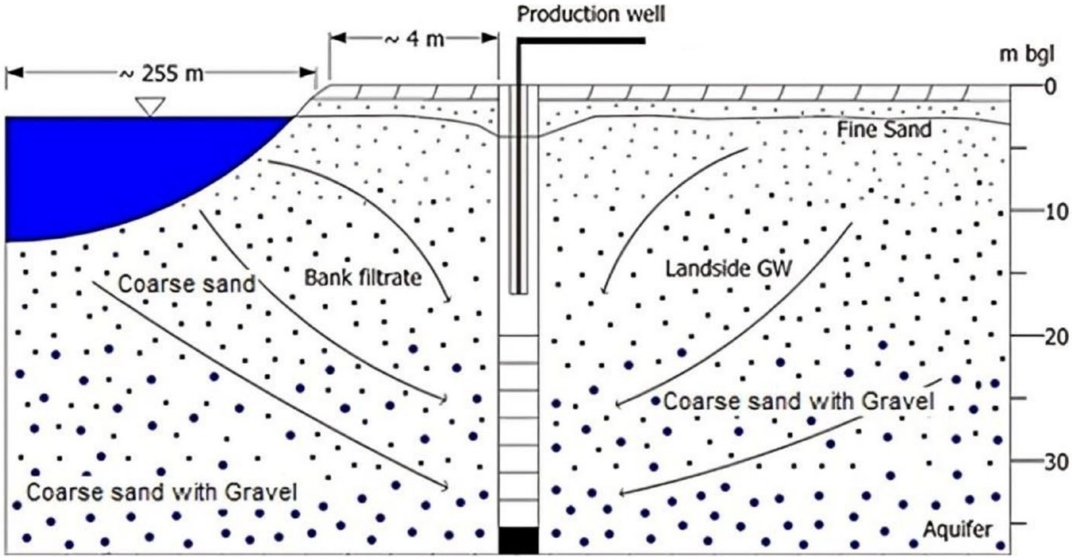

Figure 5. A generalized RBF cross-section for Altawael site.

Table 2. Alsaayda WTP Capacity.

WTP COMPONENT	CAPACITY (L/S)	REMARKS
1 Compact unit	Up to 200	–
3 Existing riverbank filtration wells	Up to 30 each	–

Luxor City and the site RBF cross-section and its utilized portion of the aquifer, respectively. The cross-section revealed that the aquifer thickness in Luxor reached approximately 100 m, with the utilized thickness around 20 to 25 m. The aquifer structure features a top layer of sand and gravel, followed by a similar layer with interbedded clay, and beneath it, a thick clay layer underlies the productive aquifer. Notably, with aquifer permeability ranging from 30 to 40 m/day, conditions are highly favourable for the RBF project (MWRI, 1997). However, the groundwater level gradient suggests that groundwater flows towards both the project site and the river. This flow is exacerbated by seepage from excess irrigation water on surrounding agricultural lands, leading to higher groundwater levels and subsequently diminishing the proportion of bank filtrate in the well. To counteract this effect and minimize the influence of local groundwater on the RBF abstraction zone, it is crucial that all RBF wells operate continuously, in accordance with the Guidelines on Riverbank Filtration in Egypt (UN Habitat, 2021).

Water sampling and analysis

Water samples from the Nile River were collected by the HCWW at Bani Murr groundwater plant in Assiut which is adjacent to the Nile River (N 27° 12′ 58″, E 31° 11′ 01″). The HCWW uses the water samples from Bani Murr station as a representative station for Upper Egypt Nile River water quality. The Nile River water was sampled regularly (at least weekly) from November 2022 to November 2023, according to Egyptian guidelines and standards (Ministry of Health and Population, 2007).

The new RBF wells were continuously operated for an adequate amount of time before being put into service. Initially for 30 days the filtrate is flushed to the river, with samples taken two to three times a week and analysed fully until a satisfactory water quality fulfilling drinking water limits was maintained and stabilized, following (Wahaab et al., 2019). After the new RBF wells are put into service to the water supply network, water samples were collected regularly (at least weekly) from November 2022 to November 2023 from a water tap before the disinfection unit, according to Egyptian guidelines and standards (Ministry of Health and Population, 2007).

Due to resource constraints, it was impractical to install additional monitoring wells for groundwater. Consequently, all samples were collected from the RBF production wells. Therefore, it should be considered that the sampled RBF water might include a combination of bank filtrates and landside groundwater. However, this impact is anticipated to be minimal, as the RBF wells were selected and constructed in compliance with the Egyptian Riverbank Filtration Guidelines that maximizes for abstracting a significant river bank filtrate portion (UN Habitat, 2021).

Physical, chemical and microbiological parameters were evaluated in an authorized laboratory at the HCWW (ISO 17025). The methods used for each parameter are listed in Table 3, following Standard Methods (American Water Works Association [AWWA] et al., 2017).

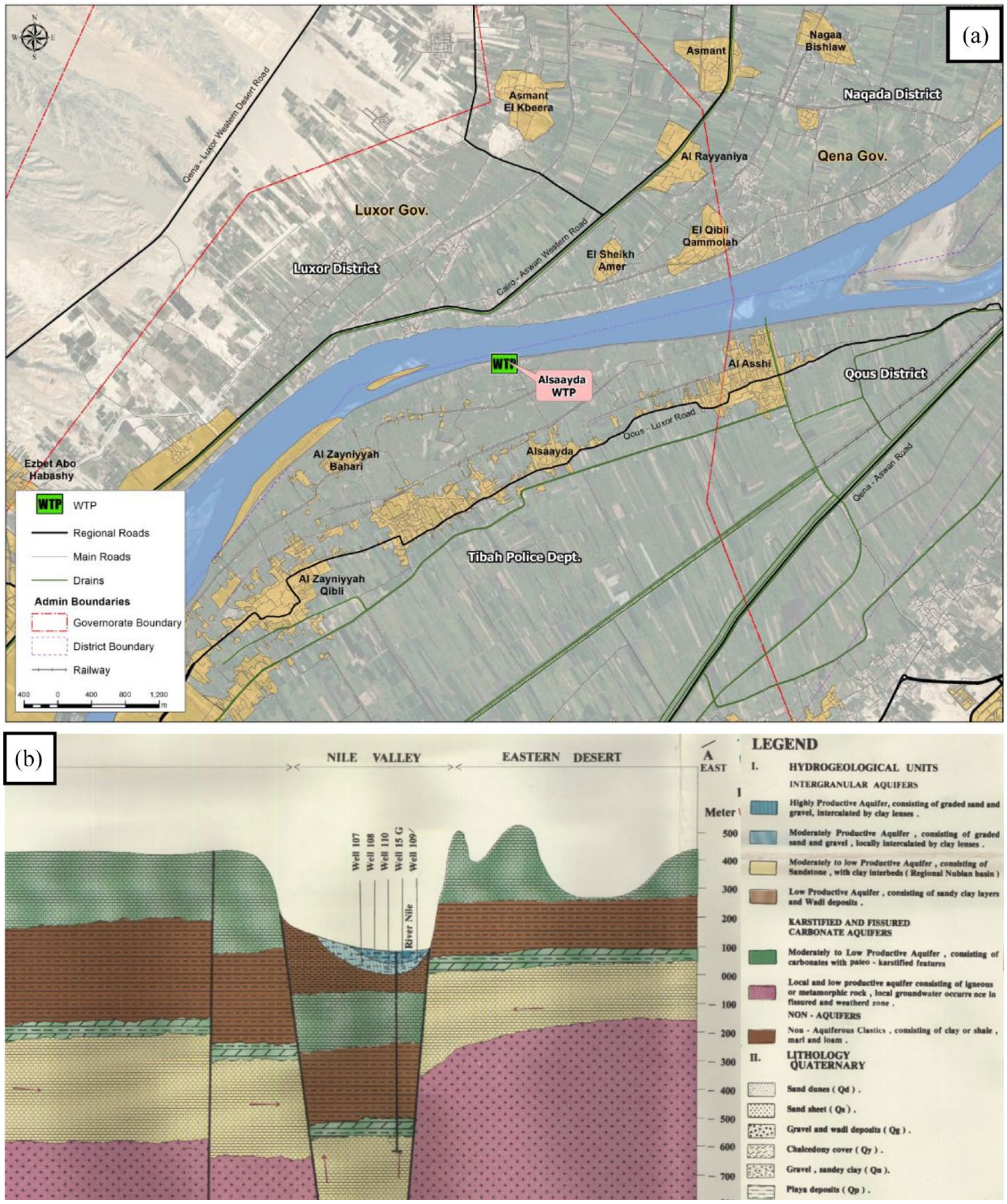

Figure 6. (a) Map showing the location of Alsaayda WTP and (b) geological cross-section adapted from (MWRI, 1997).

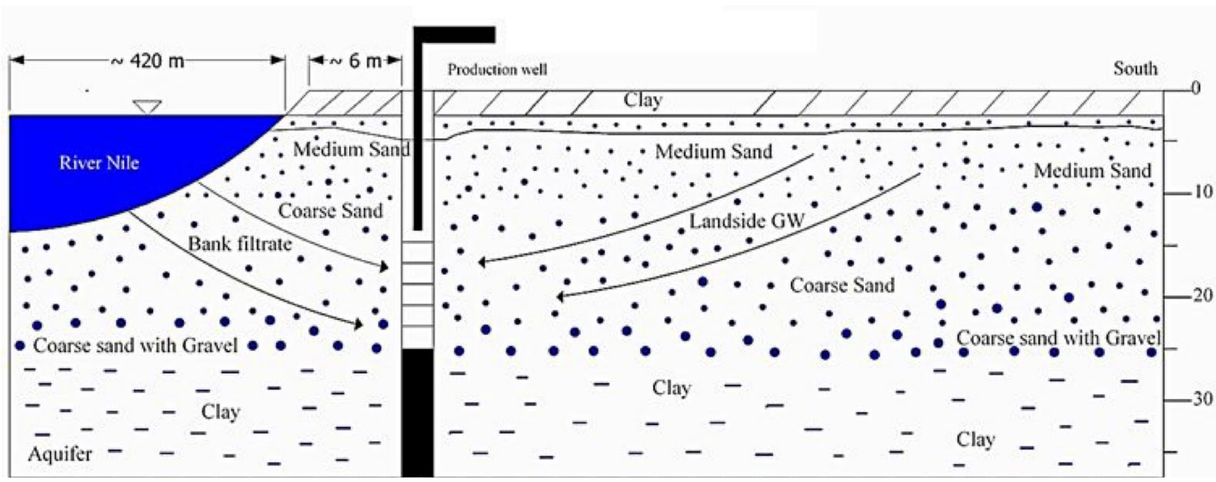

Figure 7. A generalized RBF cross-section for Alsaayda site.

Table 3. Adopted Methods for Water Analysis (AWWA et al., 2017). .

NUMBER	WATER QUALITY PARAMETERS	METHOD
1	pH	pH (4500-H^+)/Electrometric method/Thermo Scientific (Orion 3 STAR), 4–95
2	Temperature (°C)	Temperature (2550), 2–74
3	Total Dissolved Solids (ppm)	TDS (2540), 2–66
4	Dissolved Oxygen (mg/L)	Dissolved Oxygen (4500-O)/Membrane-Electrode Method, 4–144
5	Turbidity (N T U)	Turbidity (2130)/Nephelometric method/Turbidimeter (Hach), 2–12
6	Chemical oxygen demand COD (mg/L)	Chemical oxygen demand (5220-COD)/Closed Reflux, Colorimetric method, 5–17
7	Biological oxygen demand BOD (mg/L)	Biological oxygen demand (5210-BOD)/Ultimate BOD Test, 5–11
8	Ammonia (mg/L)	Ammonia (4500-NH_3)/Phenate method, 4–114
9	Nitrate (mg/L)	Nitrate (4500-NO_3)/Ultraviolet spectrophotometric method/Cecil 2041 UV/VIS, 4–126
10	Nitrite (mg/L)	Nitrite (4500-NO_2)/Colorimetric method, 4-124
11	Phosphorus (mg/L)	Phosphorus (4500-P)/In-line UV/Persulfate Digestion, 4–169
12	Oil and Grease (mg/L)	Oil & Grease (5520)/Gravimetric method, 5–42
13	Chlorides (mg/L)	Chloride (4500-Cl^-)/Argentometric method, 4–75
14	Sulphate (mg/L)	Sulfate (4500-SO_4^{2-})/Turbidimetric method, 4–197
15	Total Alkalinity (mg/L)	Alkalinity (2320)/Titrimetric method, 2–36
16	Total Hardness (mg/L)	Calcium (3500-Ca)/EDTA Titrimetric method, 3–69
17	Ca Hardness (mg/L)	Calcium (3500-Ca)/EDTA Titrimetric method, 3–69
18	Mg Hardness (mg/L)	Magnesium (3500-Mg), 3–86
19	Calcium (mg/L)	Calcium (3500-Ca)/EDTA Titrimetric Method, 3–69
20	Magnesium (mg/L)	Magnesium (3500-Mg), 3–86
21	Sulphides (H_2S) (mg/L)	Sulphides (4500-S_2)/Iodometric Method, 4–187
22	Fluoride (mg/L)	Fluoride (4500-F)/ SPADNS Method, 4–90
23	Aluminium (mg/L)	Aluminium (3500-Al)/ Eriochrome Cyanine R Method, 3–63
24	Iron (mg/L)	Iron (3500-Fe)/Phenanthroline method/Cecil 2041 UV/VIS, 3–79
25	Manganese (mg/L)	Manganese (3500-Mn)/Persulfate method/Cecil 2041 UV/VIS, 3–87
26	Arsenic (mg/L)	Arsenic (3500-As)/Silver Diethyldithiocarbamate method, 3–67
27	Total Bacterial Count (35°C) (CFU/1 mL)	Heterotrophic plate count (9215)/Pour Plate Method, 9–56
28	Total Bacterial Count(22°C) (CFU/1 mL)	Heterotrophic plate count (9215)/Pour Plate Method, 9–56
29	Total Coliform (35°C) (CFU/100 mL) (MF)	MFT (9222)/B-D, endo agar method, 9–81 for drinking water, MTFT 9221 B-C-E for intake water
30	Fecal Coliform (44.5°C) (CFU/100 mL) (MF)	MFT (9222)/Membrane filter procedure for coliform group D, thermotolerant (fecal) coliforms
31	Fecal Streptococci (35°C) (CFU/100 mL) (MF)	Fecal Enterococcus/Streptococcus groups (9222)/Membrane filter techniques, 9–119
32	Free Living Amoeba (amoeba/L) (MF)	Detection of Pathogenic Bacteria (9260)/ J, 9–177
33	Total Algal Count (cell/L)	Plankton (10200)/C, E and F, 10–11, 10–15, 10–17
34	Blue Green algae (cell/L)	Plankton (10200)/C, E and F, 10–11, 10–15, 10–17
35	Green Algae (cell/L)	Plankton (10200)/C, E and F, 10–11, 10–15, 10–17
36	Diatoms (cell/L)	Plankton (10200)/C, E and F, 10–11, 10–15, 10–17

Table 4. Nile River Water Samples Analysis at Bani Murr Station.

NUMBER	WATER QUALITY PARAMETERS	BANI MURR, ASSIUT NOVEMBER 2022–NOVEMBER 2023	LIMITS[a]
1	pH	8.1 ± 0.1 (50)	6.5–8.5
2	Temperature (°C)	22.8 ± 3.1 (49)	–
3	Total Dissolved Solids (ppm)	208 ± 10 (50)	1,000
4	Dissolved Oxygen (mg/L)	9.4 ± 0.9 (50)	–
5	Turbidity (N T U)	**5.7 ± 0.5 (50)**	1
6	Chemical oxygen demand COD (mg/L)	5.6 ± 0.6 (50)	-–
7	Ammonia (mg/L)	0.042 ± 0.013 (50)	0.5
8	Nitrate (mg/L)	0.82 ± 0.2 (50)	45
9	Nitrite (mg/L)	0.012 ± 0.007 (50)	0.2
10	Chlorides (mg/L)	13.4 ± 1.6 (50)	250
11	Sulphate (mg/L)	17.8 ± 2.8 (50)	250
12	Total Alkalinity (mg/L)	140 ± 4 (50)	–
13	Total Hardness (mg/L)	115 ± 5 (50)	500
14	Ca Hardness (mg/L)	73 ± 5 (50)	350
15	Mg Hardness (mg/L)	42 ± 2 (50)	150
16	Fluoride (mg/L)	0.46 ± 0.04 (50)	0.8
17	Aluminium (mg/L)	0.041 ± 0.017 (50)	0.2
18	Iron (mg/L)	0.15 ± 0.04 (50)	0.3
19	Manganese (mg/L)	0.16 ± 0.03 (50)	0.4
20	Total Bacterial Count (35°C) (CFU/1 mL)	**4,014 ± 290 (50)**	<50
21	Total Coliform (35°C) (CFU/100 mL) (MF)	**1,085 ± 643 (50)**	<2
22	Fecal Coliform (44.5°C) (CFU/100 mL) (MF)	**61 ± 79 (50)**	<1
23	Total Algal Count (cell/L)	3,791 ± 2,020 (50)	–
24	Blue Green algae (cell/L)	180 ± 162 (50)	–
25	Green Algae (cell/L)	593 ± 241 (50)	–
26	Diatoms (cell/L)	3,056 ± 1,855 (50)	–

Note. Mean ± standard deviation (number of samples; highlighted in **bold** are values above Egyptian drinking water standards).
[a]Egyptian Drinking Water Standards Declaration No. 458 of 2007 (Ministry of Health and Population, 2007).

Results and Discussion

Analysis of Nile River water samples

Water samples from the Nile River were collected at least weekly at the Bani Murr groundwater plant and analysed, with results summarized in Table 4. This data will serve as the foundation for assessing the effectiveness of the RBF system as a treatment method. Overall, the analysis indicated that all measured parameters in the Nile River water were within Egyptian drinking water standards, with the exceptions of turbidity and microbiological parameters significantly exceeding the drinking water limits. Sampling throughout the year accounted for seasonal variations that could influence the analysis results.

Analysis of RBF water samples

Water samples were collected from November 2022 to November 2023 from the RBF wells after continuous operation since 2021, as described in the methodology section. All RBF water samples were collected before disinfection. The sampled water from the RBF wells represents a mixture of bank filtrate and groundwater, with the bank filtrate constituting the biggest proportion as the RBF well design follows the Guidelines on Riverbank Filtration in Egypt (UN Habitat, 2021).

Table 5 shows a summary of the different water quality parameters tested. Across all sites the RBF produced water complied with every drinking water standards parameter (Ministry of Health and Population, 2007), except for Alsaayda site where manganese exceeded the limits. Nevertheless, turbidity and microbiological parameters, which are the main parameters of concern from Nile River water, have shown a significant decrease across all sites with a percentage decrease of around 90% and 99%, respectively, reaching safe drinking water levels.

Several other parameters have shown a decrease across all sites. However, other parameters have mainly increased, including TDS, ammonia, chlorides, sulphates, total alkalinity, hardness and manganese, while iron varied from one site to the other. The increase has been reported in the literature where infiltrating water through the soil dissolve minerals and mineralization of organic components in the soil (Abd-Elaty et al., 2021; Covatti & Grischek, 2021), although they are still within safe drinking water limits.

RBF produced water in all sites are pumped to a disinfection unit as part of the treatment train of the whole plant, this is done as a protection measure for the water network operation and to ensure safe drinking water delivered to the consumers through the water network.

However, to ensure that Alsaayda the RBF wells' drinking water quality meets Egyptian drinking water standards (Ministry of Health and Population, 2007), an additional manganese removal unit is needed as a post-treatment step after the RBF well.

Overall, the RBF-treated water sample results are consistent with those of similar studies conducted worldwide (Dehariya & Verma, 2023; Kumar et al., 2023; Maeng & Lee, 2019; Mossad et al., 2022; Sandhu et al., 2019; Wahaab et al., 2019). The analysis of the results illustrates the capability of the RBF system to effectively treat river water at a low cost and is easily integrated within existing WTPs (Wahaab et al., 2019).

Iron and Manganese removal

Iron and manganese removal at Bani Murr plant, Assiut, real case study

Bani Murr WTP (N27°12′58″ and E31°11′01″) is directly adjacent to Assiut city, on the eastern side of the Nile River. Its location is characterized by both urban and agricultural use. Assiut Company for Water and Wastewater established a groundwater treatment plant in Bani Murr and uses Oxidizer followed by filtration system to remove excess iron and manganese. Figure 8 shows the main design for the oxidizers and Figure 9 the main design for the compact rapid sand filters.

Average concentrations of iron and manganese in the groundwater wells at Bani Murr plant are 0.4 and 0.65 mg/L, respectively. The main design for the treatment process is to expose the water containing iron and manganese to a vacuum compacted air pressure inside the Oxidizers, where iron and manganese can be oxidized into insoluble state which is passed to the compacted rapid sand filters to be removed. The treated water is then delivered to a water tank to be injected with post-chlorine dosage to protect the water pumped to the consumers throughout the water network pipelines. Figure 10 shows the concentrations of iron and manganese (before and after) removal recorded from January 2020 till June 2021, where the red and black lines represent manganese and iron concentrations, respectively, in raw water before removal, blue and green lines represent manganese and iron concentrations, respectively, in treated water after passing through Fe/Mn removal system. It can be seen that the Oxidizer have significantly decreased the iron and manganese concentrations well below the drinking water standards of 0.3 and 0.4 mg/L, respectively.

Literature review

Iron and manganese derive from minerals and sediments in the earth. While iron and manganese concentrations in surface water are usually low, much higher concentrations can be encountered in groundwater where water spends a longer period of time in contact with rocks. Iron and manganese within the soil sediments can be dissolved and remobilized, particularly under anoxic conditions, due to the degradation of TOC in the riverbed sediments. This releases iron and manganese into the bank filtrate water and passes through riverbank filtration wells (Ghodeif et al., 2022; Grischek et al., 2017; Otter et al., 2019). Although natural and common, when present in a water supply, iron and manganese suspensions cause aesthetic problems including metallic taste and discolouration of water fittings and laundry. High dissolved iron and manganese concentrations can also increase chlorine demand, due to oxidation and thus reduce the efficiency of chlorine disinfection. Additionally, where iron and manganese deposits build up within a water system, tank or pipe, the pressure of the water system can decrease – leading to an increase in energy costs as a result of inefficiency.

Iron and manganese can be present in groundwater and surface water, most usually as the soluble Fe^{2+} and Mn^{2+} and the insoluble Fe^{3+} and Mn^{4+} forms, but occasionally in different oxidation states depending upon water conditions, principally pH and microbial levels. Iron is easily oxidized by atmospheric

Table 5. RBF Produced Water Samples Before Disinfection .

NUMBER	WATER QUALITY PARAMETERS	ABU TIEG, ASSIUT NOVEMBER 2022–NOVEMBER 2023	ALTAWAEL, SOHAG NOVEMBER 2022–NOVEMBER 2023	ALSAAYDA, LUXOR NOVEMBER 2022–NOVEMBER 2023	LIMITS[a]
1	pH	7.6 ± 0.05 (*n* = 30)	7.51 ± 0.06 (*n* = 45)	7.5 ± 0.06 (*n* = 35)	6.5–8.5
2	Total dissolved solids (ppm)	341 ± 27 (*n* = 30)	396 ± 43 (*n* = 45)	215 ± 8 (*n* = 35)	1,000
3	Turbidity (N T U)	0.8 ± 0.15 (*n* = 30)	0.59 ± 0.18 (*n* = 45)	0.45 ± 0.21 (*n* = 35)	1
4	Chemical oxygen demand COD (mg/L)	ND (*n* = 1)	ND (*n* = 1)	ND (*n* = 1)	–
5	Biological oxygen demand BOD (mg/L)	ND (*n* = 1)	ND (*n* = 1)	ND (*n* = 1)	–
6	Ammonia (mg/L)	0.31 ± 0.13 (*n* = 30)	0.32 ± 0.1 (*n* = 45)	0.21 ± 0.12 (*n* = 35)	0.5
7	Nitrate (mg/L)	0.2 ± 0.25 (*n* = 1)	0.14 ± 0.91 (*n* = 1)	0.09 ± 0.24 (*n* = 1)	45
8	Nitrite (mg/L)	ND (*n* = 1)	ND (*n* = 1)	ND (*n* = 1)	0.2
9	Phosphorus (mg/L)	0.13 (*n* = 1)	ND (*n* = 1)	NA (*n* = 0)	–
10	Oil and grease (mg/L)	0.001 (*n* = 1)	ND (*n* = 1)	NA (*n* = 0)	–
11	Chlorides (mg/L)	34 ± 3 (*n* = 30)	28 ± 4 (*n* = 45)	18 ± 2 (*n* = 35)	250
12	Sulphate (mg/L)	43 ± 4 (*n* = 30)	29 ± 6 (*n* = 45)	28 ± 3 (*n* = 35)	250
13	Total alkalinity (mg/L)	198 ± 19 (*n* = 30)	291 ± 26 (*n* = 45)	140 ± 8 (*n* = 35)	–
14	Total hardness (mg/L)	244 ± 14 (*n* = 30)	228 ± 17 (*n* = 45)	212 ± 13 (*n* = 35)	500
15	Ca hardness (mg/L)	128 ± 11 (*n* = 1)	160 ± 10 (*n* = 1)	70 ± 18 (*n* = 1)	350
16	Mg hardness (mg/L)	110 ± 7 (*n* = 1)	65 ± 10 (*n* = 1)	NA (*n* = 0)	150
17	Calcium (mg/L)	53 (*n* = 1)	70 (*n* = 1)	NA (*n* = 0)	–
18	Magnesium (mg/L)	35 (*n* = 1)	18 (*n* = 1)	NA (*n* = 0)	–
19	Sulphides (H_2S) (mg/L)	ND (*n* = 1)	ND (*n* = 1)	NA (*n* = 0)	–
20	Fluoride (mg/L)	0.01 (*n* = 1)	0.05 (*n* = 1)	0.03 (*n* = 1)	0.8
21	Iron (mg/L)	0.1 ± 0.05 (*n* = 30)	0.19 ± 0.1 (*n* = 45)	0.14 ± 0.06 (*n* = 35)	0.3
22	Manganese (mg/L)	0.38 ± 0.04 (*n* = 30)	0.25 ± 0.18 (*n* = 45)	**0.51 ± 0.1 (*n* = 35)**	0.4
23	Arsenic (mg/L)	ND (*n* = 30)	ND (*n* = 45)	ND (*n* = 35)	0.01
24	Total bacterial count (35°C) (CFU/1 mL)	8 ± 17.96 (*n* = 30)	10 ± 12.18 (*n* = 45)	5 ± 19.65 (*n* = 35)	<50
25	Total coliform (35°C) (CFU/100 mL) (MF)	<1 ± 0.51 (*n* = 30)	<1 ± 1.27 (*n* = 45)	<1 ± 4.85 (*n* = 35)	<2
26	Fecal coliform (44.5°C) (CFU/100 mL) (MF)	<1 (*n* = 30)	<1 ± 0.21 (*n* = 45)	<1 ± 2.58 (*n* = 30)	<1
27	Fecal Streptococci (35°C) (CFU/100 mL) (MF)	<1 (*n* = 30)	<1 (*n* = 45)	<1 (*n* = 30)	<1
28	Free living amoeba (amoeba/L) (MF)	ND (*n* = 30)	ND (*n* = 45)	ND (*n* = 30)	–
29	Total algal count (cell/L)	ND (*n* = 30)	ND (*n* = 45)	ND (*n* = 30)	–
30	Blue green algae (cell/L)	ND (*n* = 30)	ND (*n* = 45)	ND (*n* = 30)	–

Note. mean ± standard deviation (number of samples), ND (Not Detected), NA (Not Applicable; highlighted in **bold** are values above Egyptian Drinking Water Standards).
[a]Egyptian Drinking Water Standards Declaration No. 458 of 2007 (Ministry of Health and Population, 2007).

oxygen; manganese less so, but aeration can provide the dissolved oxygen needed to convert both the iron and manganese from their soluble to insoluble forms. Oxidation of iron and manganese with air is the most cost-effective method as there is no chemical cost. However, it is not without disadvantages. If there are high levels of manganese, the oxidation process can be slow and the reaction tank is generally required to be quite large. In addition, small changes in water quality may affect the pH of the water and the oxidation rate may slow to a point where the plant capacity for iron and manganese removal is reduced (Abdel-Lah et al., 2002). Additional treatment step maybe used for the excess of Mn concentrations such as chemical reagents, green sand, anthracite sand etc.

Figure 8. Oxidizers at Bani Murr WTP.

Figure 9. Rapid sand filters following the Oxidizer at Bani Murr WTP to filter out the oxidized iron and manganese.

There are several methods used in the deironing/demanganization process. The iron/manganese removal unit is designed to remove and reduce excess iron, manganese and other heavy metals loadings from water using a variety of options, whether physical or chemical using filter media, ion exchange or sorption technology (Tobiason et al., 2016). Due to resource limitations, the possibility of testing a pilot scale version of an iron/manganese removal unit for the case presented in our study was not feasible. However, the selection of the optimum technology for developing countries with the minimum treatment required was further investigated. The combination of the two systems (RBF and Fe/Mn removal) would provide an effective and environmentally friendly approach to produce drinking water free of iron, manganese and other contaminants.

The most common method for removing iron from water is oxidation followed by filtration (Maeng & Lee, 2019). This can be achieved through several means, the most prevalent and suitable for developing countries is oxidation by aeration and utilizing rapid sand filtration to remove the residues, reducing the need for chemicals, complexity and achieving cost-effectiveness (Sharma et al., 2005). Two possible post-treatment trains based on oxidation and filtration are discussed further below.

Air is introduced after water extraction from RBF wells through open aeration with waterfall aerators such as spray aerators, cascade aerators and cone aerators. It can also be introduced through pressure aeration using direct injection

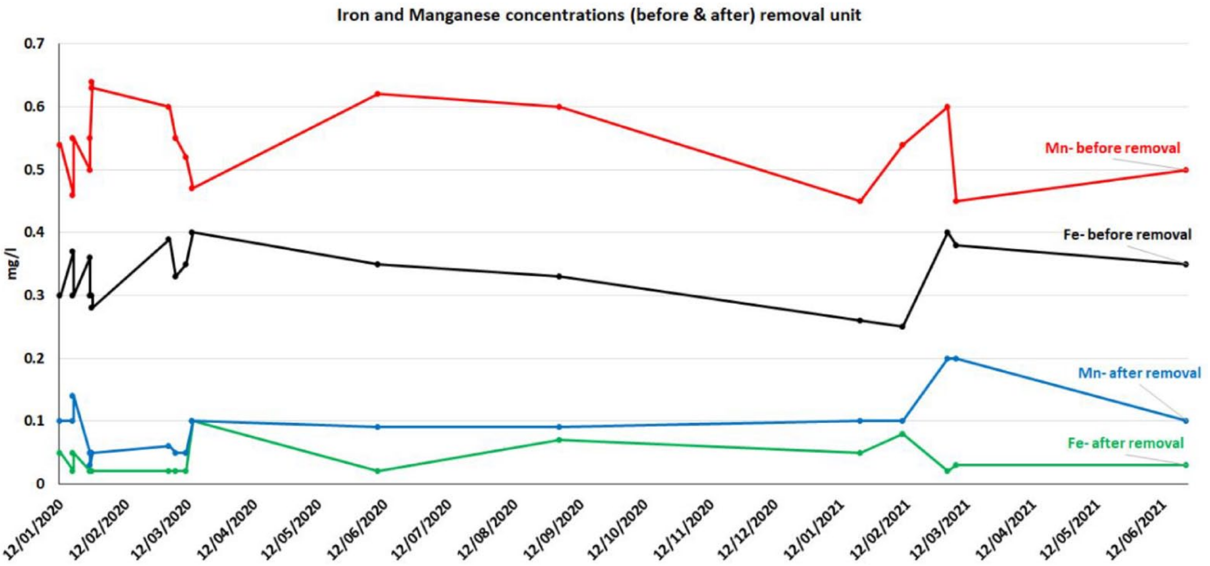

Figure 10. Iron and manganese concentrations (before and after) passing through Fe/Mn removal unit at Bani Murr WTP.

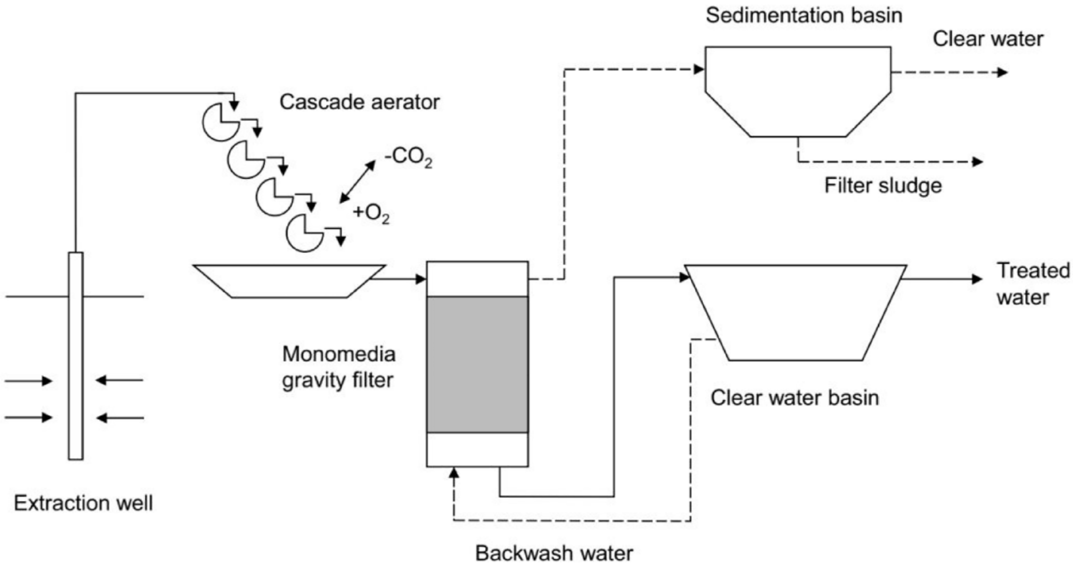

Figure 11. Process scheme of single stage deironing/demanganization with open cascade aeration. The dashed lines show the flow regime during backwashing (Worch, 2019).

into a pipeline or closed spray reactors supplied with compressed air. The former option of open aeration has the additional benefit of stripping dissolved gases like CO_2, CH_4 and H_2S. The core component of this process is the filter responsible for capturing the oxidation byproducts from aeration. The accumulated solids within the filter bed serve as catalytic surfaces for further oxidation while also supporting the growth of biofilms formed by iron and manganese bacteria. Quartz sand or gravel is a commonly used filter material.

Over the operating time of the filter, oxidation products accumulate and increase the resistance of the filter. Therefore, periodic backwashing is necessary to remove the deposited oxidation products from the filter material. It is essential to use disinfectant-free water for backwashing to prevent killing the bacteria in the biofilm (UN Habitat, 2021; Worch, 2019). The exact design of the treatment process varies based on the metal concentrations in the water being treated, and other constituents that may affect the treatment process. For instance, water with low redox potentials, indicating low iron and manganese concentrations, and the presence of hydrogen sulfide and methane, can be effectively treated through open aeration to strip dissolved gases, followed by a single-stage mono-media filter (Figure 11).

Water with moderate redox potentials, indicating higher iron and manganese concentrations, can essentially be treated using the same process as before. It is recommended to use a dual-media filter, consisting of sand and anthracite, or a two-stage filtration, employing two mono-media filters (Figure 12). This would separate iron and manganese oxidation and enable tuning the process conditions to meet specific requirements for each process element, such as different filter run times, filter conditioning and pH adjustment (UN Habitat, 2021; Worch, 2019). A variation of this treatment process is used for RBF post-treatment in the Wabash River in Indiana, USA, where a dual-media pressure filter is used to remove iron and manganese (Weiss et al., 2003).

Membrane filtration has been proposed for the treatment of very high concentrations of heavy metals. Membrane filtration is used in Germany as part of coupling RBF technology with a more sophisticated membrane technology. As part of the AquaNES project, a new technology of inline electrolysis has been used in conjunction with ultrafiltration membranes to remove 100% of manganese concentration and fulfilled the required water quality standards. However, this results in increased operational expenses and lower energy efficiency (Haas et al., 2018).

Capillary nanofiltration membranes have also been used in the AquaNES project as post-treatment for RBF filtrates with very high concentrations of iron and manganese around 1.8 and 0.5 mg/L, respectively. It achieved a high iron reduction of 48% and a reduction of 42% for manganese without any further pre-treatment. However, if the limits of safe drinking water are not achieved, further treatment would be necessary. The permeate water can be diverted to other available treatment trains within the WTP that contain aeration and filtration to remove any remaining iron and manganese residues (Jährig et al., 2018).

Conclusions and Recommendations

The findings of this study demonstrate that RBF technology is an effective and cost-efficient solution for providing drinking water that meets the drinking water standards. For Upper Egypt, where major water infrastructure is often lacking, a modular, integrated and easy-to-implement solution is preferred, similar to RBF systems. This investigation highlights the favourable hydrogeological conditions of the surrounding

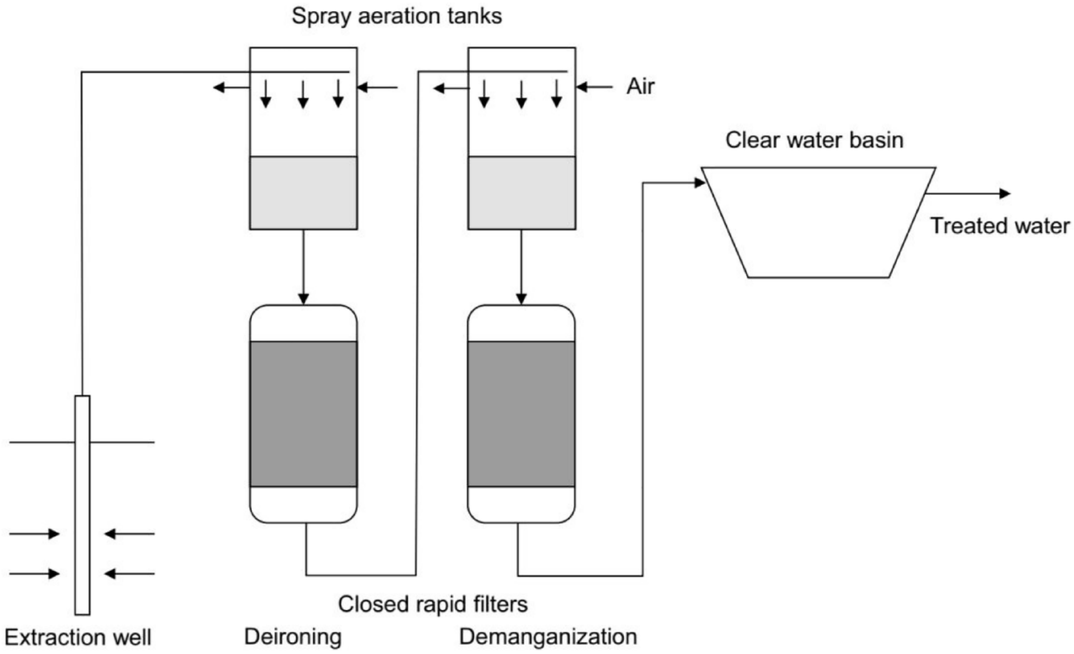

Figure 12. Two-stage deironing/demanganization process with intermediate aeration (backwashing not shown; Worch, 2019).

productive aquifer at the three investigated sites for RBF. The results of the water quality analysis from the RBF plants show that the produced water is of high-quality water according to the Egyptian water standards for most of the water quality parameters. All sites are complying with the microbiological drinking water standards and would need disinfection to secure the water network before delivered to the consumers. However, one site out of the three studied sites, Alsaayda WTP, have a mean manganese concentration of 0.51 mg/L exceeding the maximum permissible concentration of 0.4 mg/L. This highlights the need for further post-treatment for manganese.

Several iron and manganese removal treatment options based on metal concentrations have been proposed. The most optimal option in the Egyptian context is a two-stage filtration system. It is favoured over simple filtration and complex filtration membranes as it has been implemented before in several HCWW's WTP and is familiar within the adopted technologies in the Egyptian water sector and can be easily operated and maintained. A WTP in Bani Murr has used Oxidizers to remove excess iron and manganese from groundwater wells. This provided an example of an implemented iron and manganese removal system in Egypt, where a significant decrease of both metals has been recorded to safe drinking water levels.

In conclusion, RBF technology provides a non-conventional water treatment method that can supply high-quality treated water in large capacity. However, further post-treatment may still be necessary, particularly for iron and manganese. It can be easily installed within existing WTPs, given that the surrounding aquifer provides favourable conditions. As part of future work to expand on the research achieved here, it is recommended that a pilot-scale system for the Fe/Mn removal unit be tested at one of the sites to identify the viability and fine-tune the design parameters to suit the abstracted and desired water quality. It is also recommended that additional monitoring wells to be installed to record the influence of landside groundwater on RBF system water quality and performance.

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Mohamed ElHadary, Mohamed K. Mostafa, Amgad S. Elansary and Ashraf Ghanem: research, conceptualization, methodology, Validation and data analysis. Mohamed ElHadary and Mohamed K. Mostafa: original draft writing and editing. Amgad S. Elansary, Ashraf Ghanem and Robert W. Peters are responsible for reviewing the first draft of the manuscript. Ahmed Salah and Rifaat A. Wahaab are responsible for field-work and data collection and support in final draft writing. Ahmed Salah and Rifaat A. Wahaab are responsible for reviewing the final draft after addressing all reviewers' comments. Mohamed ElHadary is responsible for drafting the final copy of the manuscript. Beshoy Mikhail is responsible for GIS data collection and Maps creation. Amgad S. Elansary, Ashraf Ghanem, Robert W. Peters and Mohamed K. Mostafa are responsible for reviewing the final draft of the manuscript. Mohamed K. Mostafa, Amgad S. Elansary, Ashraf Ghanem, Robert W. Peters and Rifaat A. Wahaab: Supervision and Project Administration.

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