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River bank filtration for sustainable drinking water supply in Sohag, Egypt

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Abstract: The Egyptian Holding Company for Water and Wastewater and its affiliated companies have started a programme to develop riverbank filtration (RBF) sites in all Egyptian governorates trying to cover all hotspots due to drinking water shortage in these areas. The paper gives an overview of water quality parameters as a result of RBF, during continuous operation in Sohag, Upper Egypt. Two RBF sites were developed in Sohag. Whereas water quality changes during RBF, redox-zonation and removal rates have been discussed by many authors, little information is available on the initial phase of new RBF schemes. The new RBF sites in Upper Egypt can provide low-cost, green and sustainable drinking water supply for many studied hotspot areas.Between 2018 and 2021, significant changes were observed for total dissolved solids, chloride, sulfate, iron, manganese and ammonium concentrations, and bacterial counts. The results showed that RBF wells should be operated continuously, to maintain the advantage of lower Fe and Mn concentrations achieved by the wash-out effect in the aquifer zone between the riverbank and the RBF wells. A Water Safety Plan Approach was applied to the site to reduce the opportunity of hazards from the surroundings.

Keywords: Riverbank filtration– water quality– microorganisms– Water Safety Plan

1Introduction

Egypt's aquifers, which contain large amounts of fossil water that experiences little to no replenishment, cannot be abstracted easily. While desalination of seawater is slowly picking up in the country, it still represents a very negligible amount of freshwater production overall, and comes with its own set of environmental issues and high cost. New strategies have to be developed by the governorates to overcome water shortages. One strategy is to opt for riverbank filtration, which has been used for over 150 years in Germany and other European countries, to produce large quantities of drinking and industrial water at low cost and high quality, even during floods and droughts [1].

The water quality of the River Nile mainly depends on the water quality in the Lake Nasser reservoir and the volume of water released from it. Despite the overall water quality of the River Nile being suitable for drinking water production using conventional treatment, accidental (oil) spills and flash floods occur frequently, which affect the operations of water treatment plants [2].

Additionally, from December to January, irrigation canals are put under maintenance (winter closure) and the water released from the Aswan dam is reduced, such that less dilution of sewage inputs occur, and some large water treatment plants suffer from higher siltation at the intake points. During this period, several small surface water abstraction units suffer from the lower river water level and use that time for maintenance, resulting in a decrease in drinking water supply [3].

The demand for high-quality drinking water is growing dramatically throughout the world, particularly with a rise in urbanization and population growth. However, contamination of surface water resources through the discharge of municipal and industrial wastewaters necessitates intensive water treatment [4].

The aim of this study is to prove the possibility / potentiality of application of riverbank filtration in Sohag for sustainable drinking water supply. Water quality was analyzed and interpreted to show the efficiency of these schemes for water production depending on some specific parameters (electric conductivity EC, iron Fe, manganese

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Mn, chloride Cl^-, ammonium NH_4^+, and bacteriological parameters).

2 River Bank Filtration

Riverbank filtration (RBF) is the abstraction of water from aquifers that are hydraulically connected to the river, through pumping wells adjacent to the river [5]. The pumping lowers the groundwater table, such that the river water infiltrates into the aquifer. The bank filtrate percolates through the aquifer sediments towards the production wells, where it mixes with landside groundwater. Alluvial aquifers are the most suitable sites given their high production capacity, high connectivity to surface water sources, and accessibility to regions of demand [6].

Figure 1 shows an RBF cross-section with typical conditions from Upper Egypt. Favorable conditions include a good hydraulic connection between the river and the aquifer, erosive river flow conditions to prevent riverbed clogging, sufficient aquifer thickness (>10 m) and hydraulic conductivity ($K > 1 \times 10-4$ m/s), and a low natural (pre-RBF) gradient of groundwater flow towards the river [5] and [7]. Such favorable hydrogeological conditions for RBF have been identified for Upper Egypt [8].

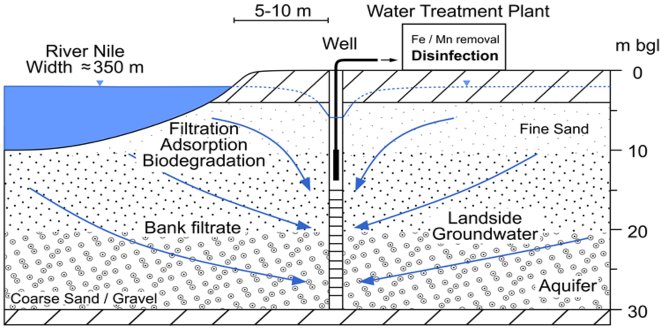

Fig.1: RBF cross section with typical conditions for Upper Egypt, ©Grischek [9].

RBF is regarded as a simple and sustainable technique that can provide good quality drinking water. During industrialization, European surface water resources became heavily contaminated with industrial and municipal wastewater and slow sand filtration and RBF were found to be able to secure drinking water of acceptable quality and at acceptable cost [10]. It has been shown that under suitable hydrogeological conditions, well-operated RBF facilities may require little further treatment [11]. The effectiveness of RBF in the production of high-quality drinking water is dependent on a multiple of variables, including raw water quality, hydrological characteristics, and geological setting. Hydrological characteristics have substantial effects on the travel time and redox conditions of the infiltration zone, which have direct influences on BF efficiency and pumped water quality [5].

As water infiltrates through the riverbank into the aquifer, it experiences chemical changes described by four general types of reactions: electron transfer, weathering, ion exchange, and gas exchange. In numerous studies, the most significant chemical changes were related to microbial activity, such as degradation of organic matter or organic pollutants, and were found to occur in the early stages of infiltration [4] and [12]. RBF also equilibrates temperature and dampens accidental chemical load peaks. It can be used to replace or support existing water treatment techniques by providing a robust barrier and reducing the cost of treatment [13].

Another advantage of RBF is that it may be used in regions with seasonally variable precipitation and run-off regimes (e.g. monsoon-, flood-, and drought-prone regions) as a means of increasing water-storage capacity [14]. The technology itself is quite simple, is often cheaper than conventional water treatment systems, and requires little maintenance [15].Identifying the right location for an RBF site is a key issue. Therefore, water quality tests of river and groundwater need to be conducted at each specific site, and the composition of the riverbed and thickness and hydraulic conductivity of the adjacent aquifer need to be examined to assess the viability of a site.

A precondition of RBF is a good hydraulic connection between the river and the aquifer. However, RBF is vulnerable for clogging. Clogging of the riverbed is seen as one of the most crucial parameters determining the volume of bank filtrate by altering the hydraulic conductivity of the riverbed [1].

According to [15], four stages of site investigation should be followed:

1. Initial site assessment, including visual reconnaissance by site visits, documentation of verbal and archived information, and in-situ sampling of river water and groundwater.
2. Basic site survey and installation of basic infrastructure: Identifying possible well locations, determining ground elevations and datum, river and groundwater monitoring locations, and construction of exploratory and monitoring wells.
3. Monitoring and determining aquifer parameters: Monitoring of river and groundwater levels and quality, river channel geometry and grain size analysis, and pumping tests.
4. Analytical or numerical groundwater flow modeling: Determining flow paths, travel times, and portions of bank filtrate and groundwater in the extracted water.

A continuous well operation can cause a wash-out effect of the aquifer resulting in a continuous reduction of Mnand Fe [17].

The Nile valley has more favorable hydrogeological conditions for RBF applications than the Nile delta. The River Nile in the Nile valley is fully or partially cutting through the clay cap and thus is hydraulically connected with the Quaternary aquifer. The riverbed materials are sandy in Upper Egypt and composed of silt and clay in Lower Egypt. Eight bank filtration sites were evaluated in terms of bank filtrate share and produced water quality. Of these sites, five are distributed along the River Nile in Upper Egypt and three along canals [1].

Based on the survey and investigated data from previous studies regarding the geological, hydrogeological, and hydrology aspects as well as other indicated criteria, the main selection criteria are: Quaternary geology, young alluvial plains, TDS <500 ppm, and a location on the main stream of the River Nile. Accordingly, eight governorates along the Nile valley from Aswan to Giza have been selected to evaluate the applicability of RBF: Aswan, Luxor, Qena, Sohag, Assiut, Minya, BeniSuif and Giza [18].

3 Sites of Investigation, Materials and Methods

Results from investigations at three production sites in Upper Egypt will be presented – Almaragha site (M) and Alshoranya site (S), (**Tab. 1**). Sohag Company is an affiliated body of the Holding Company for Water and Wastewater (HCWW) that provides drinking water (according to the Egyptian Standards for drinking water) from different water treatment plants (surface water, groundwater and riverbank filtration).

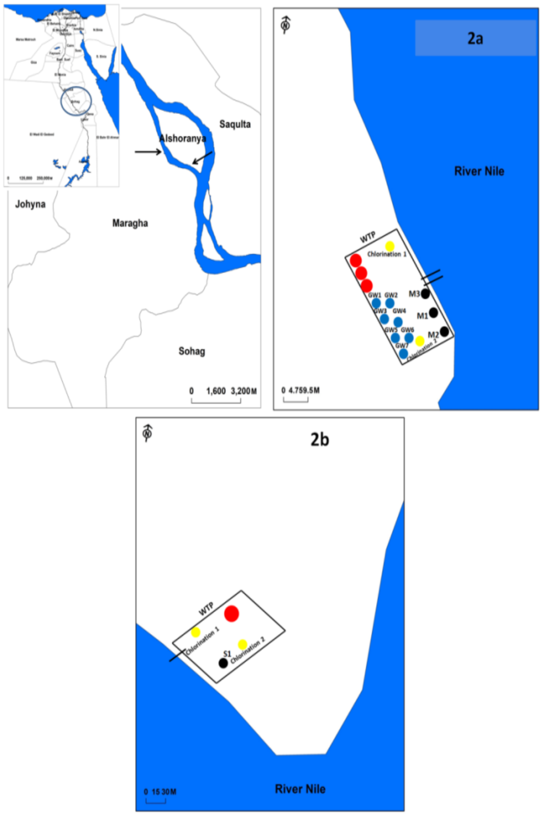

Fig 2: Location of the RBF sites, Almaraghawtp (a) and Alshoranyawtp (b) in Sohag.

Tab. 1: Design parameters of RBF units for the study sites

Site	**Almaragha(M) wtp****			**Alshoranya (S) wtp**
Well No.	M1****	M2****	M3***	S1***
Depth of well (mbgs)*	36	36	36	36
Location of the filter screen (mbgs)	18-35	18-35	18-35	18-35
Borehole diameter (inch)	20	20	20	20
Well diameter (inch)	14	14	14	14
Distance from riverbank (m)	5	5	7	10
Distance from neighboring well (m)	12	12	12	
Pumping rate (L/sec)	35	35	35	35
Static level (m)	2.6	2.5	2.5	2.8
Drawdown (m)	2.1	2.4	2.6	1.78

**mbgs - meter below ground surface,* ***water treatment plant,******Feb. 2018,and*****Dec. 2019*

3.1 Site description of Almaragha site (M)

Almaragha site (Site M) (26_41028 N, 31_36048 E), one exploratory was drilled in December 2017 and two production wells were drilled in February 2018. The wells were located at a distance of 5 m from the right river bank (**Tab. 1, Fig. 2a**), where black circles represent the RBF unit (wells), red circles represent the water treatment plant and yellow circles represent chlorination system. The distance between wells M1 and M2 was 12 m. The static groundwater depth was 2.5 mbgs, but when the wells pumping is 6 mbgs[9]. A new RBF well was drilled (M3) in December, 2019 in cooperation with the United Nations Human Settlements Programmme (UN-HABITAT).

All water abstracted from the wells is subjected to chlorine dosage for disinfection and water network protection and then pumped directly to the consumers. One exploratory well was drilled in December, 2017 to describe the geological and hydrogeological settings of the area [9],(**Fig. 3**).

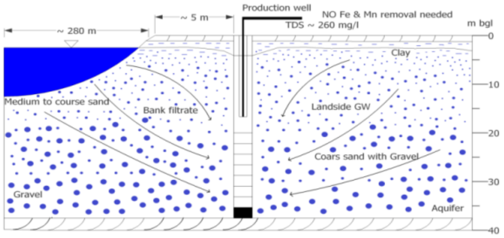

Fig 3: RBF cross section for Almaragha site, ©Ahmed Salah.

3.2 Site description of Alshoranya site (S)

Alshoranya site is located in the Alshoranya water treatment plant in GaziratAlshoranya (**Fig. 2b**), where black circle represents the RBF unit (wells), red circle represents the water treatment plant and yellow circle represents chlorination system, at coordinates 26° 41” 12’ N, 31° 37” 43’ E. One exploratory well was drilled in December, 2017 to investigate the geological and hydrogeological site conditions (**Fig. 4**). One production wells were drilled in December 2019.

RBF wells in the study sites were drilled to overcome the water shortage in the areas due to the following reasons:

1. Flash floods with high turbidity load, e.g. the flash flood 2014 [2].
2. Inadvertent chemical releases into the water way, e.g. oil spills, petroleum raw materials, phosphates etc. In 2015 a barge carrying 500 tons of phosphate upstream from Upper Egypt hit a bridge in the city of Qena, before capsizing into the River Nile waters, sparking environmental and health fears [3].
3. Additional water supply to meet peak water demands during rush hours in summer.
4. Reduce the cost of chemical doses, electricity and running cost for maintenance, as the water is abstracted with no microbial and algal contents and low turbidity ranging from 0.6 to 1 NTU.

All water abstracted from the wells is subjected to chlorine dosage for disinfection and water network protection and then pumped directly to the consumers. This site represents the typical conditions for constructing an RBF well as described in [7].

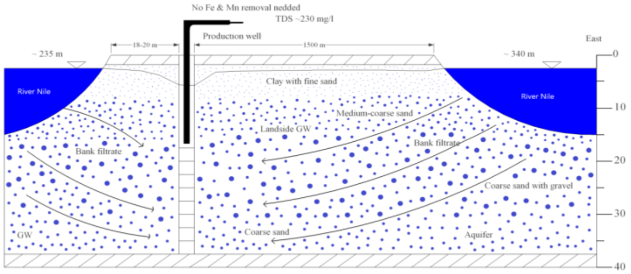

Fig 4: RBF cross section for Alshoranys site, ©Ahmed Salah.

3.3 Geological and Hydrogeological settings

The aquifer has a thickness of about 36m, as shown in (**Fig. 3 and Fig. 4**), where they illustrate the lithological profiles from drilling with a very good succession of sands and gravels with small clay cap at site M and some clay intrusions at site S. The hydrogeology of Upper Egypt has been subject of investigation by many authors [19]; [20]; [21]; [22], [23], [24]; [25]; [26]; [27] and [28]. According to these studies the Quaternary aquifer is formed by the alluvial deposits of the River Nile and can be categorized into two hydrogeological units, each with its distinct hydraulic properties. The upper unit consists of a semi-permeable clay-silt layer (Holocene) with low horizontal and vertical conductivity. The clay-silt layer has its greatest thickness near the river channel and tapers towards the edges of the valley. The second unit consists of Pleistocene fluviatile sediments with high horizontal and vertical hydraulic conductivity due to its sand and gravel characteristic.

Values for the hydraulic conductivity of the Pleistocene layer range from 40 to 120 m/day [1]. Consequently, the aquifer can be described as a semi-confined or leaky aquifer [29].Where the Holocene layer is absent, the water is found under unconfined conditions. A high heterogeneity of the aquifer with variations in hydraulic conductivity represents the study area due to interfingering and the presence of clay lenses [30].

3.4 Water sampling and analysis

Water sampling from RBF wells and the River Nile at Sohag was carried out following the Egyptian Guidelines for Drinking Water and Standard Methods for Water and Wastewater [31] and [32]. All samples are from production wells already pumping to the water network after a series of continuous monitoring according to [33]. Sampling was carried out weekly or monthly from all sites and the River Nile at Sohag.

4 Results and discussion

4.1 Long term monitoring for Site (M)

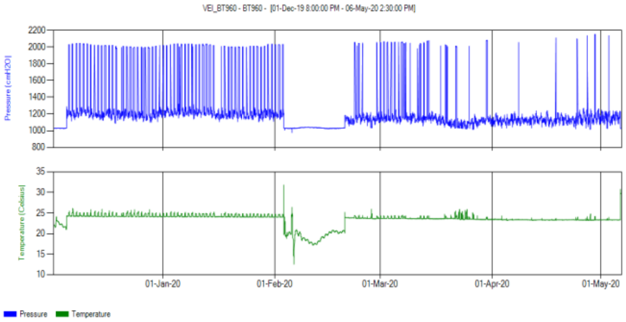

Fig. 5: Long-term water level measurements inside M2.

Long-term water level measurements with automatic pressure logger (Mini Diver, Van Essen Instruments B.V., Delft, The Netherlands) were used to explain how often and for how long the RBF well (wells) was switched on/off. If there is a rapid peak rise in the water level (pressure readings) in a well, it can be concluded that the pump was switched off. From this the still water levels in the wells can be read.Figure 5 shows a systematic switching on/off of the pump during the day, which –in most cases – affects the fluctuation of Fe and Mn concentrations in the abstracted water.

The straight blue line in (**Fig. 5**) represents the pressure readings for the period between 2-18 February, 2020, indicates that the data loggerwas removed/lifted from the well during this periodand re-put again, where the data logger for this purpose only reads pressure under the water table.

4.2 Water quality

Table 2 gives average values of major water quality parameters for River Nile water and water pumped from RBF wells (mainly bank filtrate).

Tab. 2: Standard water quality parameters, average values, River Nile water at Sohag and bank filtrate (BF) at Sohag (*n* = number of samples)

Parameter	Unit	WHO, 2017	EHCW, 2007	Nile water, Sohag	BF Site M 2018-2021**	GW site M 2018-2021	BF Site S 2019-2021	GW site S 2018-2021
EC*	µS/cm	-	-	480 (n=720)	533 (n=144)	620 (n=245)	337 (n=50)	829 (n=45)
pH	-	-***	6.5-8.5	8.1 (n=1080)	7.6 (n=96)	7.51 (n=245)	7.5 (n=50)	7.5 (n=45)
Turbidity	NTU	-***	1	3.7 (n=1080)	0.8 (n=144)	0.59 (n=243)	0.45 (n=50)	0.73 (n=45)
TDS	mg/L	-***	1000	307 (n=720)	341 (n=144)	396 (n=245)	215 (n=50)	530 (n=45)
Alkalinity	mg/L	-	-	132 (n=360)	198 (n=48)	291 (n=209)	140 (n=50)	377 (n=35)
Total hardness	mg/L	-***	500	115 (n=360)	NA	212 (n=208)	NA	365 (n=35)
Fe*	mg/L	-***	0.3	< 0.001 (n=48)	0.2 (n=144)	0.19 (n=207)	0.14 (n=50)	0.43 (n=45)
Mn*	mg/L	-***	0.4	0.01 (n=48)	0.38 (n=144)	0.25 (n=180)	0.22 (n=50)	0.56 (n=32)
NH_4^+*	mg/L	-***	0.5	0.01 (n=48)	0.31 (n=144)	0.78 (n=209)	0.21 (n=50)	0.52 (n=37)
Cl^- *	mg/L	-***	250	14 (n=360)	34 (n=96)	28 (n=239)	18 (n=50)	47 (n=45)
SO_4^{2-}	mg/L	-***	250	20 (n=360)	43 (n=96)	29 (n=233)	28 (n=50)	43.7 (n=44)
HPC*	CFU/ml	-	50	2100 (n=360)	6 (n=90)	30 (n=229)	2 (n=50)	20 (n=44)
Total coliform*	CFU/100 ml	Free	< 1	2400 (n=360)	0 (n=72)	0 (n=50)	0 (n=44)	
Fecal coliform*	CFU/100 ml	Free	< 1	200 (n=360)	0 (n=72)	0 (n=250)	0 (n=50)	0 (n=44)

*main parameters of bank filtrate analysis, **after [9], ***not of health concerns at levels found in drinking water, except for Mn is normally causing acceptability problems in drinking water, and NA -not analyzed*

At Site M, EC in the pumped water is slightly higher than in river water due to a high EC of landside groundwater. Figure 6 shows Electrical Conductivity (EC) for all sites. Mixing with a higher portion of landside groundwater is also obvious from a higher chloride and sulfate concentration observed in pumped water compared to river water. Low chloride and EC concentrations at site S indicate a high portion of bank filtrate (river water) in the pumped water.

As expected, the pH is higher in surface water (pH 8.1, also as an effect of algae growth) and a bit lower in BF at all sites with pH 7.5-7.6 as a result of degradation processes in the aquifer and formation of CO_2. CO_2 is further reacting with the minerals in the aquifer and resulting in increased values of alkalinity.Fe and Mn concentrations are slightly high at site M where the portion of Fe/Mn rich landside groundwater is higher.

Figure 7 shows the iron concentrations for all sites. On average, Fe and Mn concentrations at all sites are below the threshold for drinking water of 0.3 mg/L and 0.4 mg/L respectively.

From previous investigations of the initial phase of RBF it is known that the “wash-out effect” in the aquifer takes longer for Mn than for Fe [9]. If Mn concentrations do not further decrease, the riverbed has to be checked for high contents of silty, organic rich material which can cause release of Mn under anoxic conditions. If there is a longer retention time of the infiltrating river water in the riverbed, organic matter degradation may result in oxygen depletion and release of Mn from the riverbed.

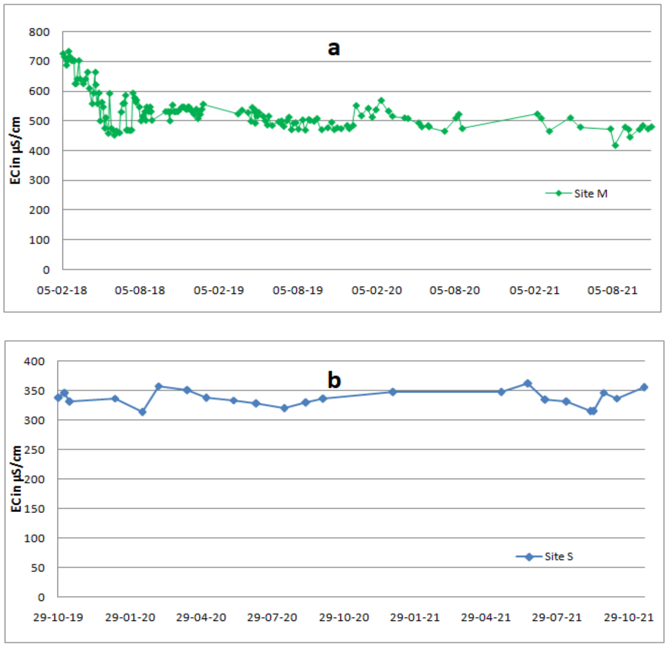

Fig.6: ECin RBF well waterin Site (M^a, after [9]) and S^b.

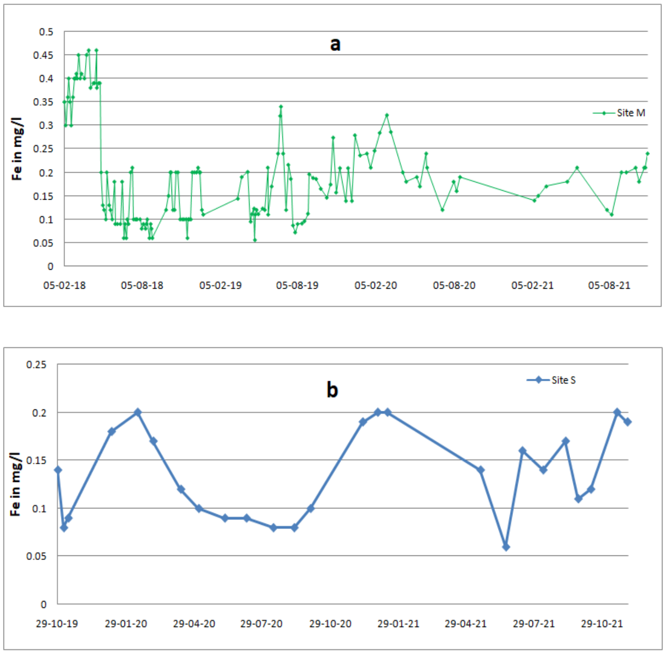

Fig. 7: Fe concentration inRBF well water in Site (M^a, after [9]) and S^b.

Ammonium concentrations are also increasing compared to river water but remain on average below the threshold value of 0.5 mg/L. As ammonium reacts with chlorine, additional dosage of chlorine for disinfection has to be checked. Ammonium may be released from organic-rich riverbed sediments and could be controlled by abstraction rates causing higher infiltration velocities [34].

No coliforms and fecal coliforms were detected in RBF well water. Removal of turbidity and pathogens is a major advantage of RBF, fully proven at all sites. Also, the decrease in colony forming units of heterotrophic bacteria (HPC) is impressive, (**Fig. 8**).

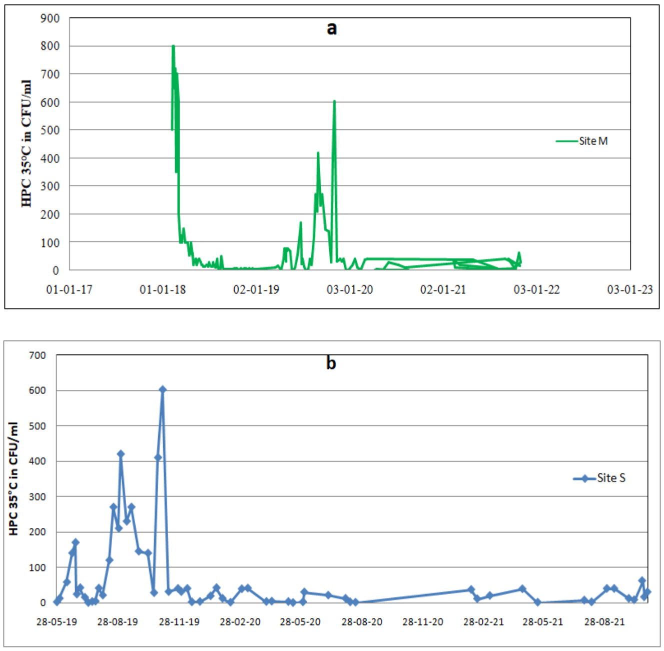

Fig. 8: Heterotrophic Plate Count in RBF wellin Site (M^a, after [9]) and S^b.

5 Water Safety Plan (WSP)

Water safety plans are the most effective way to ensure the safety of drinking water resources at all times, and rely on a comprehensive approach to risk assessment and management that covers all stages of the water supply from source to consumer the following graph summarizes the steps that have been carried and considered during the implementation phase of WSP [35].

The evaluation of the drinking water supply system is the basis for the next stages in the preparation of a water safety and security management plan under which effective strategies for monitoring sources of risk are planned and implemented. Risk analysis and assessment in the drinking water supply system can be improved through the preparation of a risk assessment chart. The charts provide a general description of the drinking water supply system, including source characterization, identification of possible sources of pollution, resource and resource protection measures, processing processes, and storage and distribution infrastructure. It is very important that the drinking water supply system be represented accurately" in the imaging of the system components. If the chart is not correct," it could lead to the omission of potentially significant sources of risk [36] and [37].

The guideline of WHO named Water Safety plan was a lead way in order to come with the results. It was found that however, RBF is considered a well-established water technology with a low cost it still could be vulnerable to different kinds of potential hazards [38]. Table 3 refers to the risk assessment procedures, while (**Tab. 4**) refers to the risk based matrix for the hazardous assessment and evaluation.

Tab. 3: Risk Assessment [39]

Value	**Frequency of the risk**	**Value**	**Severity of the hazard**
5	Almost certain (once per day)	1	Insignificant (No impact)
4	Likely (once per week)	2	Minor (Compliance impact)
3	Moderate likely (once per month)	3	Moderate (Aesthetic impact)
2	Unlikely (once a year)	4	Major (Regulatory impact)
1	Rare (once every five years)	5	Catastrophic (Impact on public health)
Risk Score (factor)= Risk frequency * Severity of Hazard			

Risk score	< 6	6 – 9	10 – 15	>15
Risk rating	Low	Medium	High	Very high

Tab. 4: Risk matrix ranking [39]

Likelihood	**Severity of sequences**				
	Insignificant	**Minor**	**Moderate**	**Major**	**Catastrophic**
Almost certain	5	10	15	20	25
Likely	4	8	12	16	20
Moderate likely	3	6	9	12	15
Unlikely	2	4	6	8	10
Rare	1	2	3	4	5

By using risk ranking, control measures can be prioritized in relation to their significance. A variety of semiquantitative and qualitative approaches to ranking risk can be applied. An example of a semiquantitative approach is given in (**Tab. 4**) Application of this matrix relies to a significant extent on expert opinion to make judgements on the public health risk posed by hazards or hazardous events.

An example of descriptors that can be used to rate the likelihood of occurrence and severity of consequences is given in (**Tab. 3**). A "cut-off" point must be determined, above which all risks will require immediate attention. There is little value in expending large amounts of effort to consider very low risks

5.1 Risks identification and management

The description and assessment of the system allow indicating the following potential hazards which were prioritize according to the risk assessment matrix ranking and summarized in the table in (Tab. 5), whereas (Tab. 6) shows the corrective actions and responsibilities to eliminate/reduce the effect of these hazards

Tab. 5: Potential hazards which was prioritize according to the risk assessment matrix ranking

Section	Location	Risk / causes	Frequency/ degree	Severity Impact	Risk score
Site M / S	Monitoring openings	The possibility of contamination by microbiological pollutants	Likely – 4	Major - 4	16 Very high
	Chlorination	The possibility of non chlorine dosage to the abstracted water to the network.	Moderate likely - 3	Major - 4	12 High
	Power source	The possibility of power cut action within the day which lead to shutdown the RBF wells	Moderate likely - 3	Major - 4	12 High
	The surrounding environment – buffer zone	The area is not served with a wastewater system. Septic tanks are used for the sewage discharge which may lead to potential microbiological contamination of the groundwater.	Unlikely - 2	Major - 4	8 Medium
	Staff	Lack of capacity of the staff about the SOPs of the RBF technology	Unlikely - 2	Moderate - 3	6 Medium

Tab. 6: Corrective actions and responsibilities

Section	Corrective action	Time	Responsible	Impact	KPI
Site M / S	Provide a screw cap cover to the monitoring openings	Short time (one month)	District manager – water company	Reduce/eliminate the chance of microbiological pollution	Percentage of non-compliance samples abstracted from RBF wells %
	Draft protocol with the local government to regularly evacuate the septic tanks of the communities close to the RBF system	Short term (Six months)	Localities – water company	Reduce the chance of microbiological pollution	Percentage of non-compliance samples abstracted from RBF wells %
	Provide a spare chlorine dosage line	Short term (three months)	Technical support dep. – water company	Continuity of Safe drinking water supply	No. of complaints related to non chlorinated water
	Installing a spare power resource	Short term (six months)	Technical support dep. – water company	Service continuity and high pressure in the water network	No. of complaints related to water cuts
	Capacity building of the staff	Short term (six months)	Training center – water company	Enhance customers satisfaction and reduce the number of non-compliance samples	Customers satisfaction %

6 Conclusions

During the low-flow period in December/January (called the winter closure), the changing water levels affect the water quality parameters in the River Nile such as EC and chloride concentration. Water quality from the RBF wells may take longer time to be stable, and this is highly related to continuous operation of the wells 24/7.

Thus, RBF technology is being approved as a sustainable drinking water supply in Sohag. RBF can provide large quantities of water at high quality and low cost.

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Symbols and Abbreviations

RBF	Riverbank Filtration	NA	Not Analyzed
BF	Bank Filtrate	SCWW	Sohag Company for Water and Wastewater
TDS	Total Dissolved Solids	HTP	Heterotrophic Plate Count
NTU	Nephelometric Turbidity Unit	EC	Electrical Conductivity
mbgs	meter below ground surface	WTP	Water Treatment Plant

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