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ORIGINAL ARTICLE

Potential of river bank filtration (RBF) in Egypt

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Abstract Drinking water supply in Egypt is based on surface water abstraction (91.4 %), groundwater (8.3 %) and desalination (0.24 %). As Egypt is currently facing problems with the pollution of surface water by industrial, agricultural and municipal inflows, riverbank filtration would offer a low cost alternative for pre-treatment of raw water for potable use. The objective of this paper is to evaluate the potential of riverbank filtration in Egypt based on drilling at potential sites and monitoring of both water level and water quality parameters. The evaluation of six sites receiving a bank filtration share of more than 50 % and producing drinking water has proven the feasibility of riverbank filtration in Egypt. Favorable hydrogeological conditions exist both along the river Nile in Upper Egypt and on main canals in the desert fringes. Key issues for the feasibility of riverbank filtration in Egypt were found to be the hydraulic connection between surface waters and the adjacent aquifer and the landside groundwater quality. The river Nile in Upper Egypt has fully to partially cut through surficial clayey sediments and is in hydraulic connection with a Quaternary aquifer that is comprised of sandy riverine sediments. The sandy riverbed and coarse aquifer materials have a sufficient hydraulic conductivity for riverbank filtration. Islands and stretches of the river channel that have convex sides are favorable for siting RBF schemes to receive a high portion of bank filtrate and limit mixing with land-side groundwater, which contains high concentrations of iron and manganese. The main benefits of RBF would be the removal of pathogens, algae and turbidity. It is recommended that wells are constructed at short distances from the river bank, to get a high share of bank filtrate.

Introduction

Drinking water supply in Egypt depends mainly on surface water treatment through sand filtration techniques followed by chlorine disinfection (91.46 %) while groundwater and desalination represent 8.3–0.24 %, respectively, (HCWW 2014). Surface water pollution, increasing treatment costs and the potential for the formation of disinfection byproducts justify the assessment of other sources. For example, more than 100 years ago direct river water abstraction in Germany was widely replaced by riverbank filtration (RBF) as a reaction to increased surface water pollution. Public water supply in Germany depends mainly on groundwater (61.1 %). Bank filtration and artificial groundwater recharge account for 17 % while surface water (lakes, reservoirs) and other sources represent 21.9 % (Destatis 2015). In Egypt, RBF use is still less than 0.1 % but could be developed at a wider scale.

RBF is a managed surface–groundwater interaction where surface water is induced by pumping to flow into wells installed along the banks of rivers or canals (Fig. 1). The subsurface passage of surface water through the riverbed and aquifer material provides several natural treatment processes

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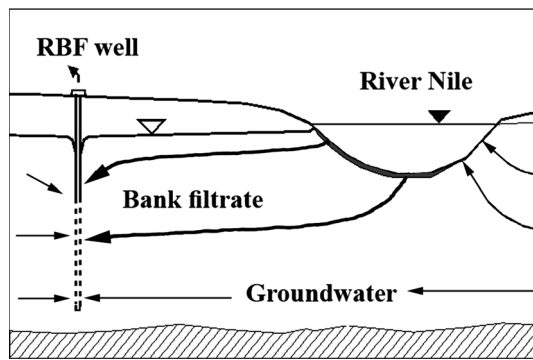
Fig. 1 Schematic of riverbank filtration (RBF)

Fig. 2 Location map for the investigated sites for riverbank filtration (RBF) in Egypt

including filtration, biodegradation, adsorption, chemical precipitation and amending water quality through redox processes (Hiscock and Grischek 2002). RBF is used as a means of primary and pre-treatment by water utilities throughout the world, especially in Europe and North America. At many sites in Europe, RBF schemes have been successfully operated for several decades (Sontheimer 1980). RBF is safe, green and low cost technology that means no addition of pre-chlorination, coagulation and flocculation chemicals (Kuehn and Mueller 2000; Eckert 2011). Bank filtration is a highly effective method for removing turbidity and providing a significant barrier to microorganisms (Gollnitz et al. 2003; Dash et al. 2008). It can also effectively remove trihalomethane (THM) precursors such as organic contaminants (Grünheid et al. 2005). Although in Europe the development of new RBF sites is rare due to the decreasing water demand, there has been a renaissance of RBF technology in the USA, India, South Korea, and other countries (Grischek et al. 2007). In the United States, RBF has been receiving increased attention especially with regard to the removal of parasites and the prevention of disinfection byproduct precursors (Tufenkji et al. 2002; Gollnitz et al. 2004; Weiss et al. 2005).

In Egypt, large amounts of untreated or poorly treated sewage are discharged into surface waters (Wahaab 2006). The total organic carbon concentration (TOC) in surface waters is reported to be range of 3.6–4.9 mg/l and thus has a high potential for the formation of disinfection byproducts when this water is chlorinated (Ghodeif and Fritz 2007). The River Nile is also used for navigation and water quality in the river is frequently affected by accidents and oil spills.

Groundwater from surficial Quaternary aquifers in Egypt typically contains high iron and manganese concentrations (Ghodeif 2011). It can contain ammonium and nitrate originating from sewage leakages and irrigation water (Shamrukh et al. 2001; Abdalla et al. 2009). The mixture of bank filtrate groundwater needs therefore special attention to prevent negative effects on raw water quality and as well as on well screen clogging.
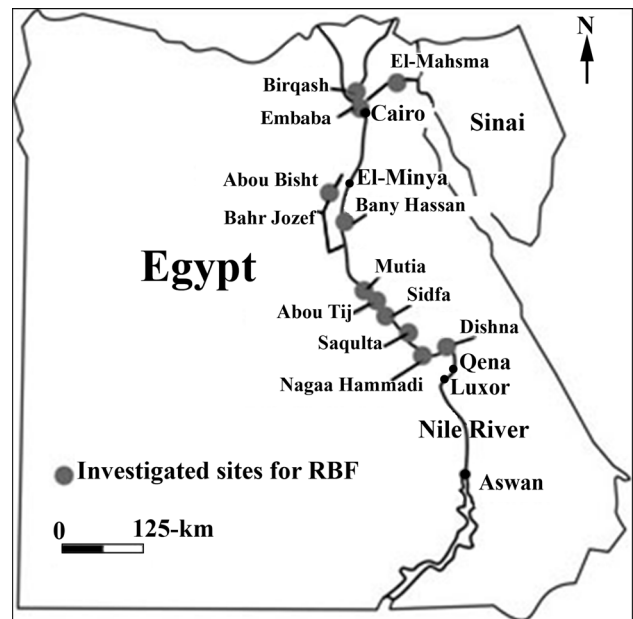
RBF in Egypt aims to achieve the strategic goals of improving drinking water production including an improved availability and increased sustainability of drinking water supply at high quality, at low cost and with a limited generation of waste products. Based on the experiences from Europe and North America, RBF can confront the problems that conventional treatment techniques in Egypt are currently facing. These problems include increasing contaminants loads at the source, closure of plants during shock loads from flash floods, accidents and contaminant spills, seasonal algae blooms and their toxins and disposal of treatment plants backwash wastes.

A number of RBF test-sites in Egypt that have been previously constructed and designed by local water companies as groundwater wells along the river Nile and main canals banks (Fig. 2). Some of these sites were successful and others have either failed to deliver a substantial amount of bank filtrate or failed after short term operation at very high abstraction rates due to canal bed clogging. The main reasons for the failure were insufficient hydrogeological investigations, incorrect well design and/or the absence of guidelines and operation procedures for operating the system.

Fortunately, a number of RBF schemes have also been successfully constructed along the river Nile in Upper Egypt that receive a substantial amount of bank filtrate share and produce water that complies with the Egyptian drinking water standards for organic, inorganic and microbial parameters (Shamrukh and Wahaab 2008; Abdalla and Shamrukh 2011; Abdel-Lah 2013).

In Egypt, the average surface water temperature ranges from 15.6 °C in January to 29.6 °C in August; such temperature variation may affect both the infiltration rate (Lin et al. 2003), redox conditions (Greskowiak 2006) and subsequent treatment processes. Cyanobacteria toxins have also been found in the river Nile and associated canals (Mohamed et al. 2006). The high ability of sediments to remove cyanobacteria toxins has suggested that bank filtration could be used safely provided water has at least 10-day residence time in the bank sediments (Gruetzmacher et al. 2009).

Currently there are limited guidelines worldwide to support engineers in identifying favorable hydrogeological conditions and the appropriate RBF design. Guidelines for the investigation and implementation of RBF schemes at sites in Egypt were recently proposed together with guidance on a generalized RBF well design in Egypt for sites with limited data or for areas where groundwater is of low quality and unsuitable for potable supply (Bartak et al. 2015a). A comprehensive risk assessment approach, which is consistent with the WHO Water Safety Plans (WHO 2011), was applied to a well-investigated RBF site in India (Bartak et al. 2015b). Typically, a comprehensive assessment of hydrological, hydrogeological, hydrochemical aspects together with state-specific regulations, land use, cost and other issues is necessary for optimal RBF siting (Grischek et al. 2003; Ray 2008; Dash et al. 2010; Lorenzen et al. 2010).

The objective of this paper is to investigate the potential of RBF along the River Nile and its main canals in Egypt and to provide guidance for optimum siting of these water treatment systems based on hydrogeology and water quality information. In order to achieve a high percentage of bank filtrate and to prevent a system failure due to clogging, river hydrology and site hydrogeology must be carefully considered when designing new RBF systems.

# Hydrogeologic setting of the Nile system Quaternary sediments

The upper layers of the Quaternary sediments in the Nile valley and delta are of main interest for RBF use in Egypt. The geological evolution of the river Nile within the boundaries of Egypt was well investigated by Said (1981) based on borehole data and field observations. The Quaternary sediments in the Nile valley and delta were investigated in detail by Butzer and Hansen (1968), Wendorf and Schild (1976) and Said (1981). The middle (Q2) and late (Q3) Quaternary sediments in the Nile delta are represented with both MitGamr Formation and Bilqas Formation, respectively. The upper layer, Bilqas Formation (Q3), is made up of alternating fine to medium grained sand, silt and clay inter-beds. The clay beds include organic matter and peat beds (Said 1981). The MitGhamr Formation (Q2) is made up of sand and pebble beds with a few minor clay inter-beds in the lower part of the formation (Ghodeif et al. 2013). It is coeval with the Qena Formation (Q2) in the Nile valley while the Bilqas Formation is coeval with the top layers (Q3) of the Qena Formation. The top layers (Q3) in the Nile valley are composed of clay, silts and fine sands with a number of thin limestone inter-beds and occasional lenses of locally derived gravel. The Qena Formation (Q2) is made up of cross-bedded fluvial sands with minor conglomerate and clay beds. At its type locality (Wadi Abou Manaa quarry face, east bank, Dishna, Qena), the base is unexposed and has thickness exceeding 20 m. The Qena and MitGamr Formations are the main aquifers in the Nile valley and Nile delta, respectively, and are collectively known as the Nilotic aquifer. The Nilotic aquifer overlies Tertiary clays. The relationships between these lithologies are shown schematically in a geological cross section extending S-N through the Nile valley and Nile delta (Fig. 3). The greatest thickness of the Quaternary basin in the Nile valley is found at Sohag (about 400 m)and then almost disappears at both Aswan in the south and Cairo in the north. The smallest thickness is found at Maghagha (about 30 m), North El-Minya.

The greatest thickness of the Quaternary sediments in Egypt is found in the Nile delta (Hefny and Shata 2004). The thickness of the main aquifer (Q2), in the center of the Nile delta, is about 500 m (Shahin 1987). The thickness of the top clay layer (Q3) in the center of the Nile delta is about 20 m (Shahin 1987; Ghodeif 2011) and increases to the north along the coast (30–50 m) and decreases to the south (<10 m) (Dawoud et al. 2005). Along the Nile valley, the thickness of the clay cap layer in the flood plain of the Nile is between 3 and 20 m (Table 1). To the east and west, the thickness of the clay cap decreases with increasing distance from the Nile to the edge of the desert, where it completely disappears (Shahin 1987).

The shallow groundwater in the uppermost layer (Q3) of these sediments is generally semi-confined while the main aquifer (Q2) has confined and unconfined conditions (Shahin 1987; RIGW 1991; Dawoud et al. 2005, 2006; Brikowski and Faid 2006). The horizontal and vertical hydraulic conductivity of the Holocene sediments (top cap layer) in the Nile valley ranges between 0.06 m/d and 1.5 m/d and 0.002 m/d and 0.04 m/d, respectively (Warner et al. 1991; Shamrukh et al. 2001; Ahmed and Ali 2009). In the Nile delta, the vertical hydraulic conductivity value ranges from 1×10^{-8} to 6×10^{-6} m/s (Shahin 1987; Fadlelmawla and Dawoud 2006). Due to the low permeability no bank filtrate can be recovered through the Holocene top layer. The hydraulic conductivity of the sand and gravel aquifer (Q2) is anisotropic. In the Nile delta, it ranges from 25 to 100 m/d and in the Nile valley from 40 to 120 m/d (Table 1). The thickness of the Quaternary deposits in the Nile valley varies from 16 to 400 m and is on average 125 m. The thickness of the poorly permeable

Fig. 3 Longitudinal hydrogeological cross section along the river Nile extending from south to north (1 clay and silt layers, 2 main Quaternary aquifer (sand and gravel), 3 Tertiary clay, Tertiary gravel, 5 Fractured carbonate, 6 Nubian sandstone, 7 Fractured basement rocks) (modified after Hefny and Shata 2004)
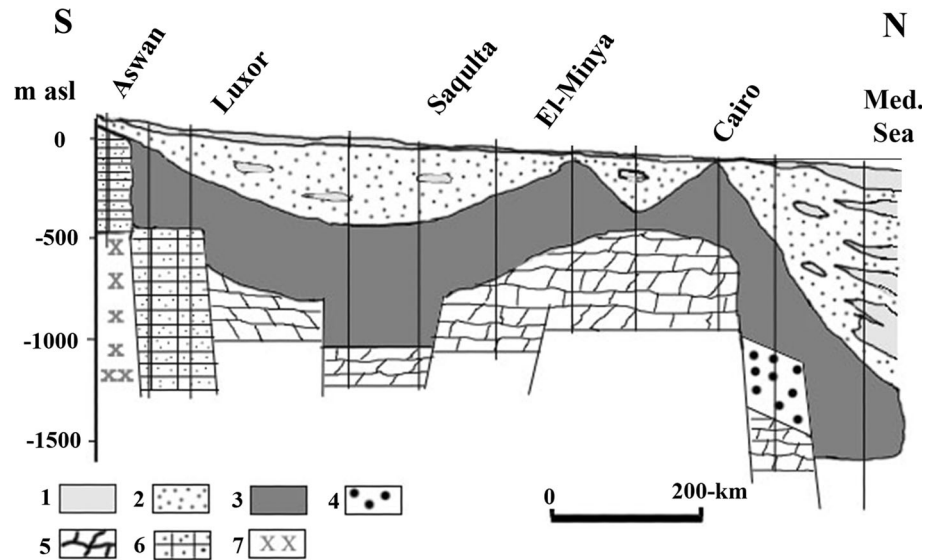
Table 1 Hydrogeological parameters of the Nile aquifers and clay cap

Aquifer type	Aquifer horizontal hydraulic conductivity m/d	Transmissivity 10^3 (m^2/d)	Clay cap thickness m	Clay cap vertical hydraulic conductivity m/d
Nile delta				
Unconfined desert fringe	50–80	2.5–15		
Confined central areas	25–100	2.5–25	8–50	0.001–0.5
Nile valley				
Unconfined desert fringe	40–80	2–5		
Confined/semi-confined central areas	40–120	1.5–30	3–20	0.002–0.04

top layer in the Nile valley is up to 20 m and in the Nile delta up to 50 m (RIGW 1991; Geirnaert and Laeven 1992).

The groundwater gradients in the Nile valley aquifer range from 0.0008 to 0.007 and the groundwater flow is generally towards the river Nile, which drains the aquifer and acts as a discharge boundary (Brikowski and Faid 2006; Hamdan 2013). Exceptions are found behind dams and barrages where the river Nile water level is above the water table and Nile water is infiltrating locally in the aquifer (Dawoud and Allam 2004; Dawoud et al. 2006). The main recharge to the aquifer is through irrigation canals and seepage of irrigation water and in some areas by the Nile (Attia 1985; Shamrukh et al. 2001; Dawoud et al. 2005, 2006; Brikowski and Faid 2006). At specific sites along faults, the aquifer receives highly mineralized artesian groundwater from the Nubian Sandstone aquifer from several hundred meters depth (RIGW 1994; Brikowski and Faid 2006). The seepage of irrigation water from the fertile top layer in the flood plain of the Nile valley is on average 1 mm/d (0.65–1.1 mm/d) (Warner et al. 1991; Shamrukh et al. 2001) and 2.5 m/d on reclaimed land, where the

Holocene clay cap is absent (Warner et al. 1991). Accordingly, the main aquifer properties are favorable for the construction of RBF sites.

Materials and methods

The potential to use RBF in Egypt was investigated based on a literature review and a regional survey of potential sites, and exploratory drillings and monitoring programs of both water levels and water quality at different sites. General characteristics such as the surface water geometry, hydrology, hydrogeology, surface and groundwater quality, potential sources of contamination and adjacent aquifer hydraulic parameters were obtained from literature values, the Ministry of Water Resources and Irrigation (MWRI) and from local water companies.

Exploratory wells (with a diameter of 0.075–0.25 m) were drilled with and without mud (both) to depths of 7–60 m depth at four sites along the river Nile and its main canals in the desert fringes of both Nile valley and Nile delta. Riverbed and aquifer sediments were collected and

investigated for their grain size distribution and to estimate hydraulic properties. Additional bore logs that provided information about the thickness of the aquifer and the clay cap were obtained from drilling reports or community well owners. Within a 1.5-year long site investigation and monitoring program starting in 2012, one abstraction well and three monitoring wells were installed at Dishna in Upper Egypt (Bartak et al. 2015a). A detailed investigation of the river Nile riverbed sediments and its elevation was carried out along three profiles (east, middle, west) of the River. The elevation of the riverbed was determined by sounding and samples were collected from a boat using a Petersen grab sampler and a scuba diver. In October 2014, two new monitoring wells (MW) were drilled in Dishna at 5 and 130 m distance from the riverbank for further investigations with a 12″ hand rotary drill without fluids through the clay cap to a depth of 12 and 16 m below ground. Sediment samples were taken from different depths and analysed for grain size distribution. Ground levelling was carried out for both new and old monitoring points including the pilot well and the intake well.

Water quality was monitored in surface waters and production wells at eight different locations along the river Nile during years 2012/2014. Monthly grab samples for water quality analysis were taken from the river Nile and the adjacent groundwater at Dishna and El-Mahsma. Water quality monitoring at other sites was carried out by local operators and scheduled according to their monthly monitoring program. The monthly monitored parameters included field parameters (T, O_2, pH, EC/TDS), inorganic species (SO_4^{2-}, NH_4^+, NO_3^-, Cl^-, Fe, Mn) and microbiological indicators (total coliforms). The organic sum and group parameters (DOC, UV_{254}), strontium (Sr) and algae total count are based on event-based analyses. All analyses were done at HCWW central and reference labs according to APHA standard methods for the examination of water and wastewater (APHA 2005). Event-based samples for specific parameters were analyzed at the Institute of Water Chemistry, TU Dresden, Germany.

The ambient groundwater quality at both the Nile valley and Eastern Nile delta aquifers was defined based on analyses done by water companies for their drinking water wells. The Qena water company has monitored 23 drinking water wells during years 2013/2014. The Canal water company has monitored 26 drinking water wells during years 2013/2014. Water quality data were statistically analysed using the Statistica program (Statsoft 1995).

Two sites (Dishna and El-Mahsma) were instrumented with data loggers for measuring water levels, water temperature and electrical conductivity (Baro-Diver, Mini-Diver and CTD diver, Schlumberger Water Service). The degree of hydraulic connection between the river and adjacent aquifer was assessed based on the riverbed

sediment analysis, the elevation of the river Nile bottom with respect to the bottom edge of the clay cap as well as water level response of the aquifer fluctuations in the river Nile stage. Hydrological data for the river Nile and canal stages data were obtained from MWRI monitoring points.

The bank filtration share (BF %) was calculated using mean value of conservative species (chloride, strontium, EC). The percentage of bank filtrate (BF %) in the pumped water was calculated with the following equation:

$$\text{BF \%} = \frac{c_{\text{sample}} - c_{\text{Groundwater}}}{c_{\text{Surfacewater}} - c_{\text{Groundwater}}} \times 100\,\%$$

BF % bank filtrate share in %; C concentration (or EC) of conservative species used; c_{sample} concentration (or EC) in the pumped water; $c_{\text{Groundwater}}$ concentration (or EC) in groundwater; $c_{\text{surfacewater}}$ concentration (or EC) in surface water.

Results

Hydrology

River Nile discharge data were extracted from about 12 years' worth of records (1976 to 1987) for Esna, Nagaa Hammadi, Assuit and Aswan Dam (Fig. 4). The average discharge ranges from 750 m^3/s (during December at Assuit station) to 2639 m^3/s (during July at Aswan Dam station). The mean Nile out flow at the Aswan Dam is 1750 to 1900 m^3/s (Agrawala et al. 2004). The seasonality of river Nile flow was regulated after construction of Aswan High Dam (AHD). Meanwhile there is still a clear variation between summer and winter flow (Fig. 4) but without serious flood and drought events. The monitored stations, Esna, Nagaa Hammadi and Assuit are at about 166, 346 and 544 km downstream of Aswan Dam, respectively. The average discharge (Q) is decreasing downstream as more and more water is taken from the Nile for irrigation and other purposes.
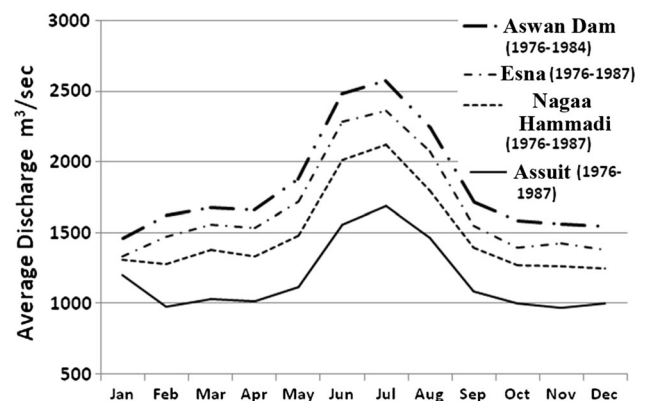

Fig. 4 Average discharge of the river Nile (m^3/s) at four sites in Upper Egypt (Source: http://www.sage.wisc.edu/riverdata/)

For storage management of the AHD, the discharge is increased from June to August. As the river Nile flows downstream towards Cairo, four barrages regulate and distribute a portion of the total discharge to the main irrigation canals. The river Nile discharge is reduced at the dam to its minimum in December for about 4 weeks (winter closure) for bank embankment and canal bed works (dredging).

Riverbed morphology and permeability

The average river Nile depth along three profiles in the stretch between Esna and Nagaa Hammadi barrages ranged from 5.0 to 8.0 m during minimum and maximum flow (Ismail and Samuel 2011). Riverbed profiles at four sites (Aswan, Luxor, Qena and El-Minya) in Upper Egypt (MWRI internal reports 2014) show river geometry and riverbed bathymetry (Fig. 5). The average depths of the River Nile at three segments (Aswan, Luxor, Qena) ranged from 3.3 to 6.3 m while at El-Minya it ranged from 2.3 to 5.0 m. A detailed investigation at Dishna using riverbed sounding and a diver from a boat was done along three profiles at 25, 250 and 450 m distance from the eastern riverbank. The riverbed depth ranged from 4.5 to 12 m with average width of about 500 m (Bartak et al. 2015a). The river depth was identified to be a critical parameter for RBF application along the river Nile. If the river depth is less than the thickness of the clay cap, RBF will not be feasible.

The riverbed sediments at Dishna were comprised of fine and medium sand with few shells and no smell. Sediments collected from the middle profile were mainly medium and coarse sand and of light colour. The sediments along the western bank were mainly fine sand with silt and of almost black colour. The average horizontal hydraulic

conductivity of the samples was estimated according to Hazen's formula to about 17.3 m/d (Bartak et al. 2015a). Upon the new investigations, the Nile river at Dishna was found to cut through the clay layer and is in hydraulic connection with the aquifer. However, the borehole data in 5 m distance from the riverbank shows the presence of a transitional zone of silt and fine sand to 4.5 m underneath the Nile riverbed at the intake side of the riverbank. This layer consists of a large fraction of silt and clay (20–30 %) and limits river infiltration as indicated by recent water level measurements. Mica found in the riverbed in front of the intake is similar to that found in the transitional zone. However, silt and clay were not found in the riverbed samples as they were probably washed out during in-river-sampling at 4.5–5 m water depth.

Groundwater–surface water interaction

A good hydraulic connection between the river and the aquifer is a prerequisite for the bank filtrate recovery. The Nile riverbed must cut into the aquifer or be lower than the bottom edge of the top layer. The average water depth of the river Nile varies from 2.30 to 6.25 m (MWRI internal reports 2014). The thickness of the clay layer in the middle Nile Delta (Birqash site) is too thick for the river to cut through and the shallow surficial sandy top layer has an insufficient thickness for the abstraction of water (Fig. 6). These conditions prevent the hydrologic connection and thus are unfavorable for the riverbank filtration. Hydrogeological profiles in Upper Egypt (Fig. 6) at El-Minya and Abou Tij show full penetration of the Nile through the clay cap layer while at Dishna show partial penetration. Full penetration through the clay cap layer is also observed at two sites along main canals in the desert border areas (Fig. 7). These are at the Abou Bisht site along Bahr Jozef west of the Nile valley and the El-Mahsma site along Ismailia Canal to the east of the Nile delta.

The water level of the main aquifer (Q2) is confined in the central region of the Nile valley and is unconfined in its peripheral areas (desert fringes), where the clay cap layer is missing. Detailed site investigations concerning the main aquifer in the Nile valley show moderate hydraulic gradient of values range from 0.008 to 0.0001. The groundwater flow at the main aquifer is towards the River Nile. The main aquifer is composed mainly of sand and gravel deposits that have relatively high hydraulic conductivity values that range from 75 to 100 m/d. Such hydrogeological conditions of relatively high hydraulic conductivity and hydraulic gradients require special design for RBF schemes.

Nile river and adjacent groundwater levels were continuously monitored at Dishna from Oct. 2012 to Nov.
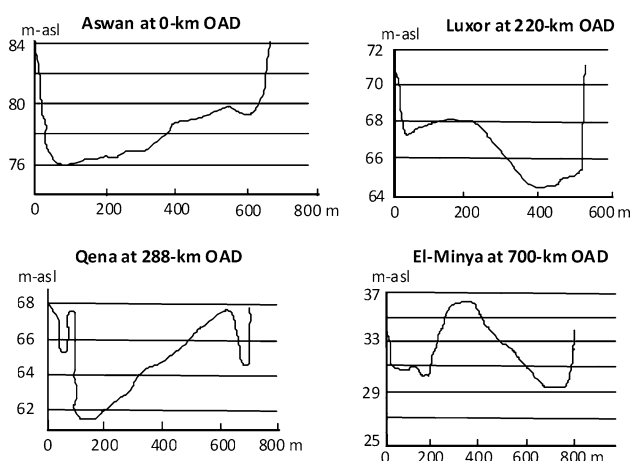
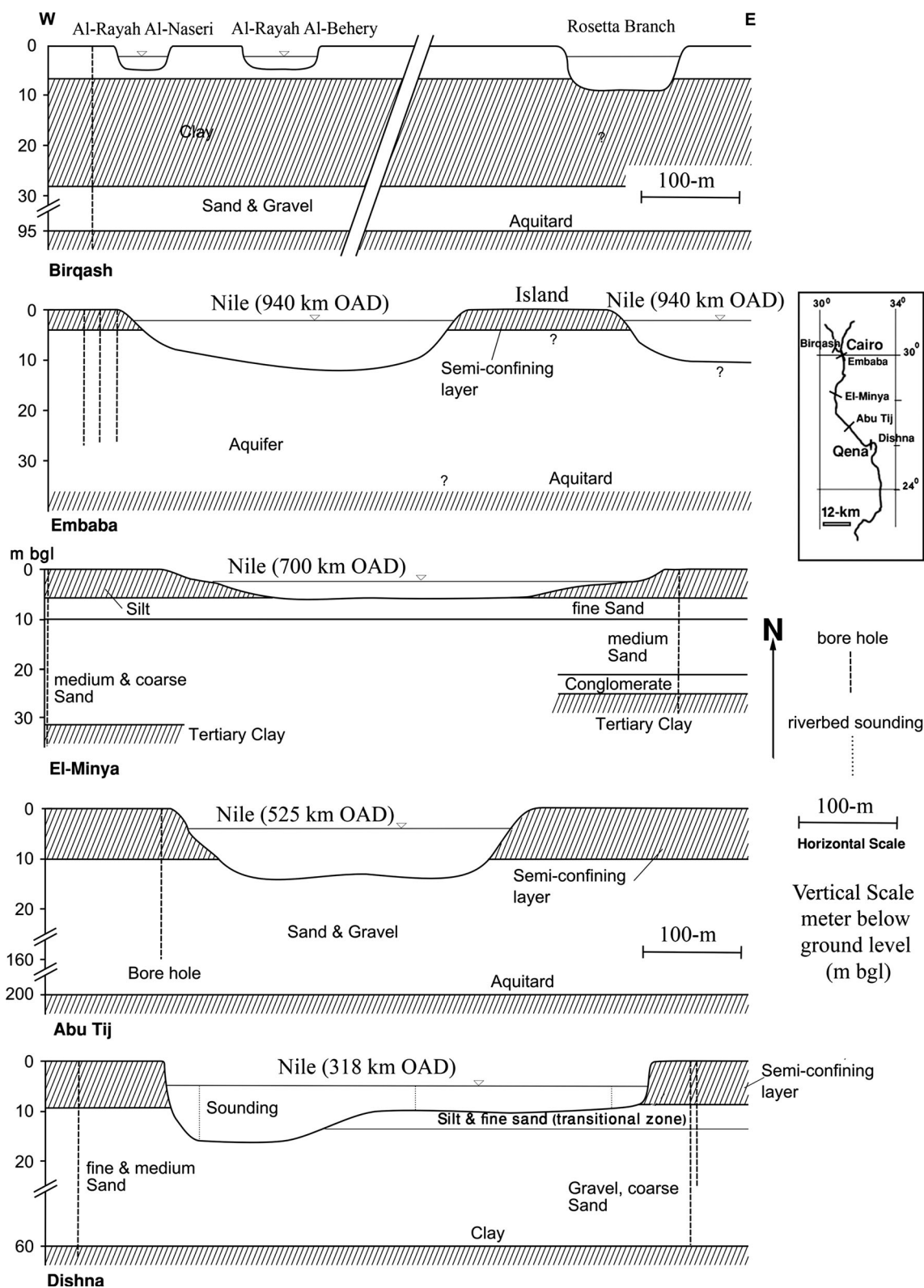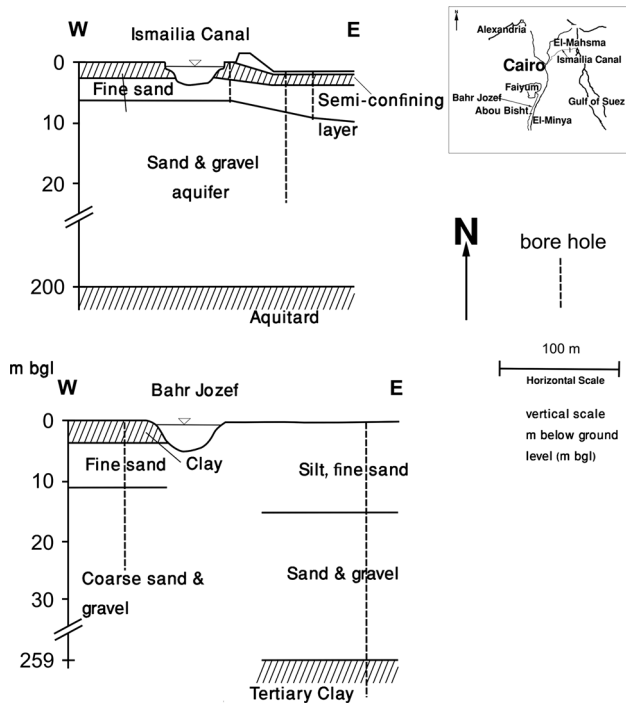**Fig. 5** Nile river cross sections (Source: Internal reports from MWRI 2014)

Fig. 6 Hydrogeological profiles along the Nile river (OAD Old Aswan Dam)

Fig. 7 Hydrogeological profiles along the Nile system desert fringes; El-Mahsma along Ismailia canal and Abou Bisht along Bahr Jozef

2013 (Fig. 8) to analyze the impact of the seasonal River Nile water level fluctuations on the groundwater flow regime. Water levels in the shallow aquifers are highest in summer when water levels in the river are also at a maximum. Variations in water levels over time are similar for both the aquifer and the Nile, thus indicating a direct hydraulic connection. Note, the pilot well represents water level during pumping. Water changes during non-operational hours were removed from the data for clarity but are visible in the observation well.

The Nile valley has more favorable hydrogeological conditions for RBF applications than the Nile delta. The river Nile in the Nile valley is fully and 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. Regarding the stability of the river channel, the River Nile canals and banks are stable in most of its flow path in Upper Egypt except for a few sites at Sohag. Islands such as El-Towabya island nearby Qena and convex sides of the river Nile as at Sohag are also favorable locations to receive a high share of bank filtrate and thus are better protected from polluted, shallow groundwater.

Nile river, main canals and ambient groundwater quality

Mean values for water quality parameters of both the river Nile in Upper Egypt and its main canals are presented in Table 2. The River Nile water quality is described at three sites (Dishna at 318 km downstream Old Aswan Dam (OAD); Abou Tij at 525 km downstream OAD, and El-Minya at 700 km downstream OAD) in Upper Egypt. The average water temperature in the River Nile generally varies from summer to winter. Mean water temperatures vary from 20 to 28 °C. The average content of dissolved oxygen at Upper Egypt varies from 8.2 at Dishna to 10.2 mg/l at El-Minya. The salinity of the River Nile shows increase in downstream direction; the average electric conductivity (EC) ranges from 315 to 394 µS/cm and the average chloride (Cl^-) concentrations range from 17 to 23 mg/l. Water in the main canals have the same chemical composition as water in the river. Nevertheless, their water quality deteriorates in a downstream direction due to the disposal of municipal and industrial effluents, the inflow of agricultural drainage as well as the decreasing water flow. This can be seen from the higher chloride concentrations.

Turbidity is relatively low but above drinking water limits and ranges from 2.8 at Dishna to 23 NTU at Bahr Jozef. During flash floods, turbidity can increase a hundred fold. This has happened during a flash flood in March 2014, where a shock load has extended for about 11 days and affected severely all drinking water companies in Upper Egypt. During this period, the level of turbidity in the River

Fig. 8 Comparison of river Nile and groundwater level fluctuations at Dishna, Qena (modified from Bartak et al. 2015a)
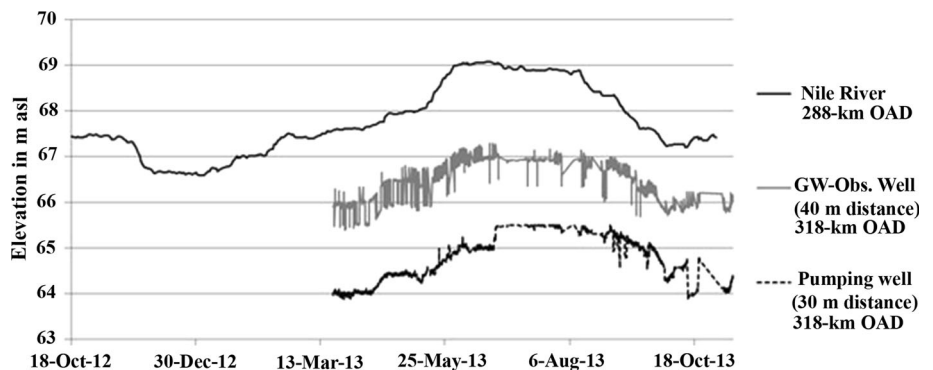
Table 2 Mean water quality of the Nile River in Upper Egypt and its main canals (2012–2014)

| Parameter | Unit | Nile river in Upper Egypt | | | | | | Main canals | | | | | |
| | | Dishna | | Abou Tij | | El-Minya | | Bahr Jozef at Abou Bisht | | Al-Rayah Al-Naseri at Birqash | | Ismailia Canal at El-Mahsma | |
		n	Mean	n	Mean	n	Mean	n	Mean	n	Mean	n	Mean
T	°C	32	20	6	23	12	24	6	24	12	25.8	33	24.1
O_2	mg/l	24	8.2	5	8.8	8	10.2		NA	7	10.2	25	8.6
pH	–	36	8.3	6	8.25	12	8.16	6	8.15	12	8.3	36	8.2
EC	µS/cm	36	315	6	324	12	394	6	365	12	376	36	376
Turbidity	NTU	36	2.8	6	7.6	12	8.82	6	23	9	4.9	29	8.9
NH_4	mg/l	28	<0.05	6	0.05	7	0.26		NA	6	0.12	18	<0.1
Cl	mg/l	33	17	6	18	12	23.3	6	28	12	25	25	26
NO_3	mg/l	28	<1	6	0.7	7	4.5		NA	6	<1	19	5
HCO_3	mg/l	36	160	6	169			6	160	12	148	36	182
Fe_{total}	mg/l	36	<0.06	5	0.05	12	0.03	3	0.08	6	0.1	26	0.08
Mn	mg/l	36	<0.04	5	0.07	12	0.03	3	0.07	6	0.21	26	0.1
Sr	Mg/l	6	0.21	3	0.21	3	0.26	3	0.36			5	0.3
DOC	mg/l	6	3.6	3	3.3		NA		NA	3	4.5	5	4.0
UVA_{254}	m^{-1}	6	5.5	3	5.6		NA		NA	3	6.6	5	6.1
TC	MPN/100 ml	28	2.819	6	1200		NA		NA	8	1.700	26	700
Algae total count	ml^{-1}	13	6.118	3	3030		NA		NA		NA		NA

Mean values calculated as arithmetic means using limits of quantification for low values

NA data not available

Nile reached a maximum of about 2000 NTU. This has caused the temporary closure of a number of conventional drinking water treatment plants while RBF sites in Upper Egypt stayed in operation (HCWW internal reports 2014).

All major ions in Nile water are generally within the limits for drinking water supply. The Nile water is alkaline and predominantly of the bicarbonate type. Alkalinity ranges from 160 to 169 mg/l with calcium as main hardness constituent. The main problem comes from a high load of microbiological contaminants. Mean total coliform (TC) numbers of 2819 MPN/100 ml and total algae count of 6118 org/ml at Dishna exceeded drinking water limits (EHCW 2007). Due to the high dilution potential of the River Nile for sewerage and other inflows, dissolved organic carbon (DOC) concentration is moderate and ranges from 3.3 to 3.6 mg/l. The main canals (Bahr Jozef and Ismailia canal) and Rayahs (main canals, branching directly from the River Nile) such as Al-Rayah Al-Naseri have similar water qualities to that of the River Nile (Table 2).

The ambient groundwater in the Nile valley, nearby the current River Nile track, has EC values of range from 344 to 1510 µS/cm with an average value of 875 µS/cm (Table 3). Mean iron (Fe) and manganese (Mn) concentrations are 0.43 and 0.49 mg/l, respectively. Values range between <LOQ (0.06 mg/l) and 1.05 mg/l for Fe and <LOQ (0.04 mg/l) to 0.84 mg/l for Mn. RBF targets the aquifer that is in contact with the surface water body and wells are usually shallow. In Egypt risks arise from the targeted part of the aquifer as it is subject to contamination mainly from unsecure conventional systems for sewage disposal in villages (latrines and septic tanks) but also from seepage of irrigation water containing nitrogen fertilizers. Mean Values for ammonium (NH_4^+) and nitrate (NO_3^-) are 0.20 mg/l and 4.53 mg/l. The ammonium and nitrate have maximum contents 0.94 mg/l and 25 mg/l, respectively. Total coliform (TC) counts in some wells exceeded the drinking water standards. It has a mean value in the Nile valley aquifer of 14 MPN/100 ml.

The ambient groundwater in the Eastern Nile delta is characterized by a wide range of salinity values, measured as EC. Values in the vicinity of surface water courses range from 376 to 2067 µS/cm with a mean value of 959 µS/cm. Iron and manganese concentrations range from 0.06 to 1.52 mg/l and 0.06 to 2.63 mg/l, respectively. Ammonium in the shallow aquifer has a mean value of 0.56 mg/l and nitrate concentrations range from 0.3 to 65 mg/l. The main aquifer in the Nile delta is also subject to contamination from sewage disposal and agricultural activities.

Table 3 The ambient groundwater quality in the Nile valley and Eastern Nile delta (2013/2014)

Variable	Unit	Nile valley (Qena drinking water wells)					Eastern Nile delta (Ismailiya drinking water wells)				
		n	Mean	Min.	Max.	SD	n	Mean	Min.	Max.	SD
pH	–	30	7.45	5.99	8.04	0.42	107	7.59	7.17	8.18	0.23
EC	µS/cm	34	875	344	1510	321.64	105	959	376	2067	352
Turbidity	NTU	29	0.59	0.08	2.15	0.44	84	1.23	0.20	6.28	1.06
HCO_3	mg/l	31	422	212	618	116.79	NA	NA	NA	NA	NA
Cl	mg/l	29	52	10.6	125	38.06	24	52	14	120	28
NO_3	mg/l	29	4.53	<LOQ	25.00	5.64	56	19	0.3	65	18.29
NH_4	mg/l	26	0.20	<LOQ	0.94	0.29	66	0.56	<LOQ	5.49	0.83
Fe_{total}	mg/l	31	0.43	<LOQ	1.05	0.31	85	0.41	0.06	1.52	0.35
Mn	mg/l	31	0.49	<LOQ	0.84	0.26	99	0.41	0.06	2.63	0.35
TC	MPN/100 ml	26	14	<1	300	58.74	15	70	<1	700	182

Mean values calculated as arithmetic means using limits of quantification for low values

NA data not available, *LOQ* limit of quantification

Table 4 Bank filtration share (BF%) at the investigated sites using mean values of various tracers

Site	Tracer	Pumped water	Groundwater	Surface water	BF %
Dishna	EC (µS/cm)	1094	1166	315	8.5
	Cl (mg/l)	50	54	17	10.8
	Sr (mg/l)	0.55	0.66	0.21	24.4
Nagaa Hammadi	EC (µS/cm)	416	725	345	81.3
	Cl (mg/l)	18.5	28	18	95.0
Saqulta	EC (µS/cm)	486	901	328	72.4
	Cl (mg/l)	35.5	58	18	56.3
Abou Tij	EC (µS/cm)	445	730	324	70.2
	Sr (mg/l)	0.3	0.66	0.21	80.0
Bany Hassan	EC (µS/cm)	597	893	394	59.3
Abou Bisht	EC (µS/cm)	414	1550	365	95.9
	Sr (mg/l)	0.38	0.66	0.36	93.3
El-Mahsma	EC (µS/cm)	399	780	376	94.3
	Cl (mg/l)	27	52	26	96.2
	Sr (mg/l)	0.3	0.57	0.3	100.0
Birqash	Modeling (Ghodeif and Grischek 2015)				<1 %

Evaluation of bank filtration sites

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. The bank filtration share (BF %) at all sites was calculated using mean values of conservative tracers concentrations except for the Birqash site (Table 4). The BF % at Birqash site is estimated from modeling (Ghodeif and Grischek 2015). The BF % at successful sites ranges from >50 to 100 %. Two sites were evaluated to have very low bank filtrate share (BF % < 10 %) because of their unfavorable hydrogeology. At both sites, infiltration of surface water is limited by the presence of a clayey or clay layer with a low hydraulic conductivity below the riverbed. The discharged water quality from both sites is mainly groundwater.

The other four existing RBF sites along the river Nile in Upper Egypt with BF >50 % prove the feasibility of RBF in Egypt if the hydrogeological conditions are favorable. Two sites are located along the eastern bank of the River Nile in Qena governorate (Dishna and Naga Hammadi); one were able to deliver about 80 % bank filtrate while the other has failed to deliver >10 % so far. Hence, RBF is site-specific and every new site development usually requires exploratory drillings and a feasibility study. These

Table 5 Average water quality of RBF wells at different sites, number of samples (n) is variable from site to site and for variables within sites

Site	Unit	EDWS 2007[a]	Dishna Qena	Nagaa Hammadi	Saqulta	Abou Tij	Bany Hassan	Abou Bisht	Birqash	El-Mahsma
Region					Sohag	Assiut	El-Minya		Giza	Ismailia
Source			River Nile					Main canals		
Date			(2012/ 2014)	(Oct. 2014)	(Oct. 2014)	(Nov. 2013)	(Jun. 2014)	(Year 2014)	(Year 2012)	(2012/ 2014)
pH	–	(6.5–8.5)	7.6	7.7	8.2	7.68	7.56	7.68	7.5	7.6
Temperature	°C	NS	23.4	26	26	25	23.7	25.7	26.4	25.8
Conductivity EC	µS/cm	NS	1094	416	486	445	597	414	620	399
Turbidity	NTU	1	0.2	0.4	0.60	0.5	0.6	0.4	0.6	0.4
Alkalinity	mg/l	NS	578	195	287	274	255	230	244	176
Total Hardness as $CaCO_3$	mg/l	500	302	180	244	NA	194	138	258	NA
Chloride	mg/l	250	50	18.5	35.5	7.3	12.3	22	22.3	27
Nitrate	mg/l	45	18	0.12	0.1	<5	0.16	4.0	<1	7
Nitrite	mg/l	0.2	0.18	<0.04	<0.04	NA	NA	NA	<0.04	NA
Ammonia	mg/l	0.5	0.21	<0.05	0.3	NA	0.32	<0.05	0.06	0.05
$Iron_{total}$	mg/l	0.3	<0.06	<0.06	0.29	0.04	0.22	0.18	0.43	0.18
Manganese	mg/l	0.4	0.66	<0.04	0.43	0.43	0.12	0.28	0.51	0.21
Sr	mg/l	NS	0.55	NA	NA	0.3	NA	0.38	NA	0.3
TOC	mg/l	NS	NA	1.81	NA	NA	NA	2.16	NA	3.29
DOC	mg/l	NS	1.7	NA	NA	1.8	NA	NA	1.8	1.8
UVA_{254}	m^{-1}	NS	1.9	NA	NA	4.0	NA	NA	2.2	3.7
TC	MPN/ 100 ml	<2	3	<1	1	<1	NA	NA	3	1

NS not specified, NA data not available

[a] EDWS 2007 Egyptian Drinking Water Standards Year 2007

sites produce drinking water that meets the permissible limit of Egyptian drinking water standards (Table 5). Turbidity is consistently reduced below <1 NTU. Iron and manganese concentrations range from <0.06 to 0.29 mg/l and from <0.04 to 0.43 mg/l, respectively.

RBF was also found to be successful along main canals. For example, the Abou Bisht and El-Mahsma sites were both found to have a bank filtration share of more than 90 % (Table 4). Values for EC, chloride and strontium are almost similar to that of the nearby surface water. The water quality meets drinking water limits (Table 5). The risk of canal bed clogging is generally higher than that of the riverbed of the river Nile as flow velocities are lower. The canals are often subject to sedimentation of silt and clay and dredged every 3 months. This mud layer can significantly decrease infiltration rates and enhance the release of iron and manganese. Risks may be reduced by low abstraction rates. In Abou Bisht and El-Mahsma, abstraction rates are in balance with the canal hydrology and maintenance. Clogging did not decrease the share of BF yet and mean iron and manganese concentrations are

still below Egyptian drinking water standards (EDWS 2007).

General recommendation for siting RBF wells

First of all the hydraulic connection between the river and the aquifer has to be proven by preliminary site investigations. Only if the riverbed level is sufficiently lower than the lower boundary of the clay overbank and the hydraulic conductivity of the riverbed is similar to the aquifer material, the site is suitable for RBF.

Alluvial sediments in the Nile river valley are characterized by a good hydraulic conductivity to place wells at various distances to the riverbank. However, at many potential RBF sites the natural groundwater flow gradient towards the river appears to be relatively high. Hence, abstraction wells should be placed in short distance from the riverbank to cause sufficient drawdown and a high portion of bank filtrate. According to Bartak et al. (2015a), a flow distance between 20 and 70 m from the Nile to the abstraction wells was found sufficient to remove coliform

bacteria and algae. Islands or locations inside a meander bend naturally favor a higher portion of bank filtrate.

Despite the Egyptian regulations that wells for potable supply have to be drilled to a depth of 60 m (Egyptian Ministry of Health and Population decree No. 1 1994, High Water Committee decisions year 1997), RBF wells should be designed to abstract water from the upper layer of the aquifer to increase the portion of bank filtrate. For example, if the clay overbank is 6 m thick and the water table is found 4 m below ground surface (mbgs), the filter screen may be placed between 12 and 24 mbgs. A typical vertical well could have a diameter between 300 and 600 mm, a screen length of 6–12 m, a drilling depth of not more than 25 mbgs and a continuous abstraction rate between 40 and 100 m^3/h. It is advised to design abstraction schemes with more than two wells. Well galleries parallel to the riverbank allow the abstraction of a higher portion of bank filtrate. They also decrease the risk of changes in redox conditions between the river and the wells in case one of the wells cannot be operated continuously due to pump failure or maintenance. Even a well gallery could be constructed within the vicinity of an existing surface water works as the abstraction wells could be placed at a minimum spacing of 10–30 m relative to each other. It is of vital importance that the pumps in the wells are operated continuously. Discontinuous pump operation will significantly reduce the infiltration of bank filtrate into the aquifer and likewise the percentage of bank filtrate in the final abstracted water, causing problems with water quality (iron, manganese, ammonium).

Conclusions

The main challenge for drinking water supply in Egypt is the increasing treatment cost due to increasing contamination of conventional sources. RBF is a sustainable and low cost technology that can help. It is not viable everywhere in Egypt; it needs favorable hydrogeological conditions and thorough investigations. Our regional survey indicated a high potential for RBF along surface waters in the desert fringes in both the Nile valley and the delta as well as in the flood plain in the Nile valley of Upper Egypt. Fully penetrating sections, islands and meanders of the river Nile profile are the best sites for RBF applications. Four RBF sites along the river Nile and two along main canals have proved ability to produce drinking water with more than 50 % bank filtrate. Nevertheless, RBF sites along the main canals deserve further detail investigations regarding clogging and its impact on the produced bank filtrate water quality. RBF in Egypt is site-specific and every new site requires detail hydrogeological investigations.

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