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Groundwater aquifer recharge with treated wastewater in Egypt: technical, environmental, economical and regulatory considerations

Nahed E. El Arabi, Mohamed A. Dawoud*

Research Institute for Groundwater, National Water Research Center, El Kanter El Khairia, Kalubia, Egypt
Email: mdawoud@ead.ae

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ABSTRACT

The economic development in Egypt and the rapid growth rate in various development sectors are dependent on the availability of water resources. Surface water is used to supply approximately 82% of the Egyptian water demand, while the groundwater is used to supply about 12%. The remaining about 6% comes from the reuse of agriculture drainage water and treated wastewater. Increasingly, Egypt has turned to use the groundwater to satisfy the growing demand, at the expense of exceeding the safe yield and overexploiting the aquifer systems in some areas, such as the western Nile Delta and along the desert fringes in the Nile Valley. Egypt has launched the Environmental Management of Groundwater Resources program which include examination of the feasibility of artificial recharge for the augmentation of groundwater supply. Through this program a detailed study has been carried including an investigation of potential sites for an artificial recharge experiment using treated wastewater. Through this pilot project, a detailed hydrogeological investigation and engineering design were carried out. Many scenarios for the aquifer storage and recovery were evaluated for technical environmental, economical and regulatory consideration. Results indicated that artificial recharge of the groundwater aquifer using treated wastewater is promising. However, more detailed studies are needed to assess how aquifer characteristics influence the recharge with treated wastewater. The health risks associated with wastewater recharge are a function of the physical and chemical conditions prevailing in the aquifer, the limited adsorption capacities of the aquifer materials and the rate of microorganisms die off and toxic pollutants degradation to other toxic compounds.

Keywords: ASR; TSE; Groundwater; Infiltration; Recharge; Artificial recharge; Unsaturated flow; Egypt

1. General background

Where soil and groundwater conditions are favorable for artificial recharge of groundwater through infiltration basins, a high degree of improvement in water quality can be achieved by allowing partially-treated sewage effluent to infiltrate into the soil and move down to the groundwater. The unsaturated or "vadose" zone acts as a natural filter and can remove essentially all suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms. Significant reductions in nitrogen, phosphorus, and heavy metals concentrations can also be achieved.

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*Corresponding author.

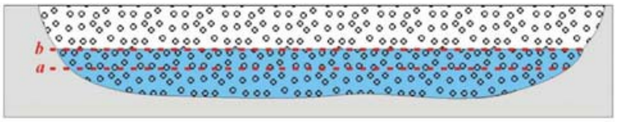
Present address: Water Resources Department, Environment Agency–Abu Dhabi, Abu Dhabi, P.O. Box. 45553, United Arab Emirates.

Aquifer storage and recovery (ASR) using treated sewage effluent (TSE) appears to be a viable option of both storing and improving the quality of water. Conventional surface disposal of wastewater can cause significant deterioration in surface water quality. Direct disposal of TSE into rivers and drains often leads to eutrophication due to the presence of contaminants, such as nitrate and phosphate [1]. A common indicator of eutrophication is increased phytoplankton density resulting in green turbid and foul-smelling water. After such a bloom, the algal biomass is broken down both chemically and biologically, resulting in greater chemical and biological oxygen demands (COD, BOD). Alleviating such a situation requires a reduction in water-borne nitrate, phosphate and pathogenic bacteria in the river or drain water.

ASR was defined by Pyne [2] as “the storage of water in a suitable aquifer through a well during times when water is available, and the recovery of the water from the same well during times when it is needed.” This definition has been found to be inadequate in that the operational requirement for injection and recovery to be performed using the same well is overly restrictive. The essential, defining feature of ASR is that it involves the injection, storage, and recovery of the same or similar quality water with perhaps some mixing with regional groundwater. An alternative modified definition of ASR that captures the essence of the technology is “the storage of water in a suitable aquifer through a well during times when water is available, and the recovery of the same or similar quality water using a well during times when it is needed.”

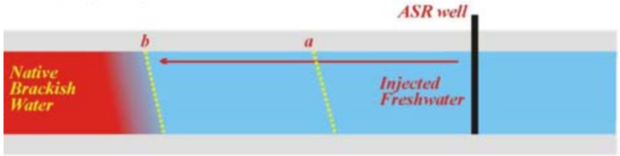
The above definition recognizes that there are distinctly different types of ASR systems that vary in how they achieve useful storage of water [3,4] as shown in Fig. 1. The injection of water into physical storage-type ASR systems actually increases the amount of water physically present in the aquifer, as manifested by an increase in aquifer water levels or pressure. For physically bound ASR systems, injection and recovery could be performed at separate locations. Chemically bound ASR systems store freshwater by displacing poorer quality (usually saline) water. A third type of ASR system, which is referred to as interface management systems, uses the injection of freshwater to prevent or reverse the migration of the interface with poorer-quality water. An interface management system, such as illustrated in Fig. 1, would allow for the seasonal recovery of freshwater without causing or contributing to the intrusion of saline water.

Physical storage ASR systems are uncommon because they require an aquifer of limited areal extent and the presence of effective confinement on all sides to prevent the stored water from leaking out. Brackish-water aquifers are often present in coastal areas, which may be suitable for use as storage zones for chemically bounded ASR systems. In aquifers that are prone to saline-water intrusion, either interface management ASR systems or salinity barriers are options. A salinity barrier system involves injection near the saline-water interface in order to allow for the continued or expanded withdrawals of freshwater using production wells located farther inland. ASR systems storing reclaimed water face the same technical issues as ASR systems that store other types of water such as potable water. For chemically bounded ASR systems, local hydrogeological conditions must be favorable for the recovery of a high percentage of the injected water. Clogging (plugging) of the well and aquifer can also be an important operational issue. Most ASR wells require periodic back-flushing and more intensive rehabilitation in order to maintain their injection and recovery capacity.



Physical storage ASR system. Storage is achieved by increasing aquifer water levels from (a) to (b).

Chemically bounded ASR system. Storage is achieved by the injected freshwater laterally displacing the native brackish water.



Interface management ASR system. Freshwater in injected landwards of the saline-water interface in order to push the interface seawards. Useful storage is achieved by allowing sustainable freshwater production during high demand periods without causing saline-water intrusion.

Fig. 1. Schematic diagram of the main ASR system types.

ASR systems used to store TSE may also involve additional regulatory and technical issues related to the nature of the water. If the ASR system could potentially result in indirect potable reuse, then TSE may have to be treated to a higher level. The major health concern associated with indirect potable reuse is the potential presence of pathogenic microorganisms. The introduction of nutrients may also promote the growth of opportunistic pathogens indigenous to the aquifer [5].

TSE may contain a variety of microbiological and chemical contaminants. The contaminants of greatest concern are pathogenic microorganisms because a one-time exposure can cause serious illness [6–8]. Microorganisms associated with waterborne disease are primarily enteric pathogens (i.e. originate within the intestines of humans or other animals), which have a fecal-oral or fecal-dermal route of infection (either human-to-human or animal-to-human) and can survive in water (National Research Council, 1998). Chemical contaminants usually exist in TSE at very low concentrations and prolonged ingestion would be necessary to produce detrimental effects on human health. The National Research Council (1998) recognized three categories of chemical contaminants that are present in TSE: (1) inorganic chemicals and natural organic matter that are naturally present in the water supply, (2) chemicals used or created by industrial, commercial, and other human activities in the wastewater service area, and (3) chemicals added or generated during water and wastewater treatment and distribution processes.

An important challenge associated with ASR using TSE is striking a balance between (1) level of treatment and associated costs, (2) potential impacts to public health and the environment, and (3) potential uses of the reclaimed water. The balance must address technical, economic, and sociocultural issues as well as compliance with the existing regulatory framework. One solution to the pathogenic and emerging contaminant issue for reclaimed water ASR projects is to use aquifers and locations in which indirect potable reuse is unlikely. Indirect potable reuse would not be expected to occur in aquifers that contain brackish water that is not suitable for direct use for potable water supply. ASR systems could also be geographically separated from potable water supply wells in order to provide long travel times. Coastal barrier islands may have freshwater aquifers whose capacity and quality is inadequate for use as potable water supplies, but may be used for local irrigation. These aquifers are potential candidates for TSE or storm water ASR systems. It has also been recognized that the storage of water in aquifers can actually result in an improvement in quality. Operational and experimental results indicate that the concentrations of some contaminants (e.g. disinfection byproducts), nutrients, and pathogenic microorganisms are decreased during storage in aquifers by natural inorganic and microbiological processes [4,9,11–14]. This attenuation process has been referred to as soil aquifer treatment (SAT) [15]. Water could be stored in an ASR system with the intended purpose of using SAT to improve water quality.

Egypt is a hyper-arid country, which has limited water resources, and less than 3% of the country area is cultivated. Water resources in Egypt are limited to the Nile River water which is fixed at 55.5 billion m^3/year by agreement with Sudan in 1959, groundwater from both renewable and nonrenewable aquifer systems, which is about 6.20 billion m^3/year, and the reuse of both treated wastewater and agriculture drainage water, which is about 5.50 billion m^3/year as shown in Fig. 2 [16]. Other non-conventional water resources, such as desalination of seawater and brackish groundwater, have been given a low priority as sources of water for economic reasons. The cost of desalinating either brackish groundwater or seawater is still high compared with other conventional water sources. Use of these sources is therefore limited to water supply for some resorts and tourist areas. Egypt is now fully utilizing its share of the Nile River flow and shallow groundwater, and is effectively reusing drainage water and treated wastewater. Continued population and economic growth will exert further pressure on the existing water resources. Major water quality problems are still limited to a number of hot spots, but proper attention will have to be given to the effects of expected socio-economic developments on water quality. The threat of the available water resources being insufficient to meet the demands from all socio-economic sectors requires an adequate and integrated water resources management [17]. The present situation, with limited possibilities for extension of conventional water supplies and growing demands, provides new challenges for non-conventional water resources and new planning. Within the framework of the Environmental Management of Groundwater Resources project, Egypt launched a program to examine the feasibility of aquifer storage and recovery using surface water and treated wastewater for the augmentation of groundwater supplies [18].

Groundwater is a major source for both rural and agriculture water supplies in many areas in Egypt, especially in the desert regions. Over recent years, increasing abstraction to meet rising demand for domestic supplies and expansion of reclamation of desert fringes has raised concerns over the sustainability of groundwater resources and the livelihoods it supports. To address these concerns, considerable emphasis is being given to the augmentation of natural recharge by both traditional and modern techniques. Some of these techniques have been employed for centuries ranging from simple check bunds in gullies to complex diversion and infiltration structures, as well as injection wells [15]. Recently there have been considerable effort and investment to maintain and restore such traditional facilities as well as investigat-

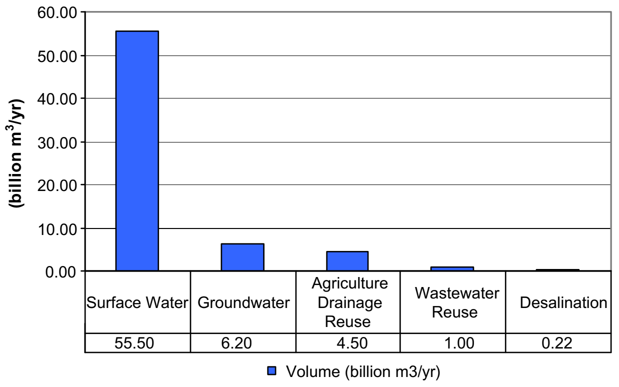


Fig. 2. Water resources in Egypt.

ing new technologies for aquifer storage and recovery. However there has been little systematic assessment of the technical and socio-economic effectiveness of these schemes.

2. Wastewater in Egypt

2.1. Production

In Egypt, historical reuse of sewage in agriculture, after primary treatment, has been in practice since 1911 (Gabal Al Asfar farm: 1,260 ha). Yet, experience of large scale, planned and regulated reuse projects is still limited. At present, there are some large-scale pilot reuse projects (70,140 ha) in East Cairo, Abu Rawash, Sadat City, Luxor, and Ismailia. Currently, most of the sewage water directed to agricultural drains is actually reused in one way or another. The total treated wastewater production from the main cities is about 3.93 billion m^3/y in 2009 as shown in Table 1.

2.2. Wastewater quality

In Egypt, the domestic wastewater in the rural areas is concentrated with a COD as high as 1,100 mg/l, which is almost twice that in the urban areas [19]. El-sherbiney et al. [20] determined the maximum aerobic biodegradability of Egyptian domestic wastewater and found that the minimum aerobic effluent COD concentration in rural areas was similar to the Egyptian effluent standards for COD, whilst in urban areas it was significantly lower than that of the Egyptian effluent standards for COD. Ibrahim [21] evaluated the different technologies used for domestic wastewater treatment in rural areas of Egypt and found that the effluent from these systems did not comply with Egyptian effluent standards for COD.

Using treated wastewater for groundwater aquifer recharge can play an important role in managing these resources and enhancing the groundwater quality and quantity. However, recharging groundwater aquifers with treated wastewater is restricted by the regulation of the Egyptian Environmental EEAA, Authority of Tourism, and irrigation laws. Use of aquifer recharge for wastewater treatment can be an answer to the various problems that have arises due to wastewater sanitation in the small new communities, if it is environmentally safe. The project will provide Ministry of Water Resources and Irrigation with a set of guidelines in applying the obtained results of the controlled artificial recharge technique.

3. Artificial recharge technologies

The increasing demand for water has increased awareness opportunities for the use of artificial recharge for augmentation of groundwater supplies all over the world. Stated simply, artificial recharge is a process by which excess surface water is directed into the ground to replenish an aquifer either by spreading on the surface in basins, by using recharge wells, or by altering natural conditions to increase infiltration [23]. It refers to the movement of water through man-made systems from the ground surface to underground water-bearing strata where it may be stored for future use. Artificial recharge (sometimes called planned recharge) is a way to store water underground in times of water surplus to meet demand in times of shortage.

Artificial recharge of groundwater by land applications is achieved by putting surface water in basins, furrows, ditches, or other facilities where it infiltrates into the soil and moves downward to recharge aquifers. Artificial recharge is increasingly used for short- or long-term underground storage, where it has several advantages over surface storage, and in water reuse [2]. Open basins are fairly inexpensive to construct and simple to operate. However, they can be used to recharge only aquifers that have a direct hydraulic connection with ground surface (phereatic aquifers). Artifi-

Table 1
Wastewater production at major cities

City	Treated wastewater production (billion m^3/y)		
	2000	2009	2017
Cairo	1.40	1.50	1.70
Alexandria	0.60	0.63	0.75
Other areas	1.60	1.80	2.6
Total	3.60	3.93	5.05

cial recharge using surface basins requires permeable surface soils. Where these are not available, trenches or shafts in the unsaturated zone can be used, or water can be directly injected into aquifers through wells. The design of land application requires data on the infiltration rates of the soil, the hydraulic properties of the unsaturated zone and underlaying aquifer, and the location of any soil or groundwater contamination that may be mobilized by the recharge [24]. The aquifer should be sufficiently transmissive to avoid excessive buildup of groundwater mounds.

Water-quality issues must be evaluated, especially with respect to formation of clogging layers on basin bottoms or other infiltration surfaces, and to geochemical reactions in the aquifer [25]. Clogging layers are managed by desilting or other pretreatment of the water and by remedial techniques in the infiltration system, such as drying, scraping, disking, ripping, or other tillage. Recharge wells should be pumped periodically to backwash clogging layers. Table 2 summarizes the major characteristics for various technologies used for artificial recharge.

Infiltration basins are still the most common method of recharge and provide excellent versatility for water resources planning. However, the high cost of land in some urban areas has provided the motivation for the development of vadose zone injection wells. The problem of vadose zone injection wells is that once they are clogged, they are very difficult to redevelop. A variety of low-level technologies can be used to accomplish groundwater recharge with reclaimed water or other poor quality water sources.

Artificial recharge of groundwater can be expected to increase worldwide due to rise in population and increased demand for water, additional freshwater become no longer available, and sites for surface storage are increasingly difficult to find. Dams can have significant evaporation losses, particularly in arid lands. Seasonal or long-term underground storage (water banking), where possible, is often preferred. Artificial recharge also plays an important role in water reuse because it results in water quality improvements (soil-aquifer treatment) and provides storage opportunities to balance temporal variations in supply and demand for reclaimed sewage effluent [26].

Where sewage effluent is to be used for potable purposes, recharge and recovery breaks the toilet-to-tap connection of water reuse and enables blending, and hence dilution, with natural groundwater. Combined with soil-aquifer treatment, artificial recharge may enhance the esthetics and public acceptance of potable water reuse. Water reuse and storage of surplus water for use in times of water shortage also must be increasingly relied upon to cope with uncertainties in future climates and their effect on surface and groundwater supplies. Design and management of artificial recharge systems involves geological, geochemical, hydrological, and engineering aspects. Since soils and underground formations are inherently heterogeneous, planning, design and construction of groundwater recharge schemes must be staged, first testing for fatal flaws and general feasibility, and then proceeding with pilot and small scale systems until the complete system can be designed and constructed. Beneficiaries are water resources planners and managers, consultants, municipalities, government agencies, environmentalists, and the public at large.

4. Selection criteria and preliminary investigation

In order to delineate suitable areas for applying the artificial recharge technique over Egypt, a regional study of the factors affecting the feasibility of artificial recharge has been carried out. The analysis was carried out for the whole of Egypt using a Geological Information System (GIS) and extensive field data. A GIS based method is found to be very useful in suitability analysis for artificial recharge sites [27]. For such analysis the first task was to identify the factors affecting the feasibility of artificial recharge in Egypt, which have been classified as shown in Fig. 3. Based

Table 2
Major characteristics of aquifer recharge methodologies

Parameter	Recharge basin	Vadose zone injection wells	Direct injection wells
Aquifer type	Unconfined	Unconfined	Confined/unconfined
Pre-treatment requirements	Low technology	Removal of solids	High technology
Capacity	1,000–20,000 m^3/ha/day	1,000–3,000 m^3/well/day	2000–6,000 m^3/well/day
Maintenance requirements	Drying and scraping	Drying and disinfection	Disinfection and flow recovery
Soil-aquifer treatment	Vadose zone and saturated zone	Vadose zone and saturated zone	Saturated zone

on the availability of water resources in terms of quantity and quality, physical and hydrogeological settings and a preliminary cost analysis, a set of criteria were been designed to demarcate the most suitable sites for artificial recharge. The thematic information layers used in this suitability analysis and weighted indexed overlay model are: (1) geomorphology, (2) aquifer system and extent, (3) soil classification, (4) land use, (5) depth to groundwater table, (6) hydraulic properties of the aquifer system and (7) underground storage capacity.

Weighted overlay analysis is a simple and straightforward method for a combined analysis of multi-class maps. The efficacy of this method is that human judgment can be incorporated in the analysis. A weight represents the relative importance of a parameter. The weighted index overlay method takes into consideration the relative importance of the parameters and the classes belonging to each parameter. There is no standard scale for a simple weighted overlay method. For this purpose, criteria for the analysis should be defined and each parameter should be assigned importance [28]. Determination of weighting of each class is the most crucial component in integrated analysis, as the output is largely dependent on the assignment of appropriate weighting. Consideration of relative importance leads to a better representation of the actual ground situation [29]. In the weighted index overlay, the individual thematic layers and also their classes are given a specified weight as shown in Table 3 on the basis of their relative effect on the aquifer storage and recovery.

Using these weighting factors, two sites have been selected for investigating their potential for aquifer storage and recovery [30,31]. Fig. 3 shows the schematic diagram for the selection process for the pilot areas. The first is at Abu Rawash to the northwest of Cairo City using treated wastewater and the second site is at El Bustan in the western Nile Delta using the surface.

5. Abu Rawash case study

In Egypt, the raw wastewater from greater Cairo is collected to Abu Rawash wastewater treatment plant at the desert fringes northwest of Cairo. The treated wastewater is disposed into a lined canal then to Al Rahawy Drain. To investigate and quantify the aquifer recharge by treated wastewater under different hydraulic load conditions using a recharge basin or an injection well, a square basin with length of about 50 m was constructed.

5.1. Physical and hydrogeological settings

The recharge site is located 30 km northwest of Cairo City and east of the Cairo-Alexandria desert road as shown in Fig. 4. The surface is almost flat and the ground elevation is about 15.0 m (amsl). Detailed hydrogeological investigation of the site has been carried out including topographical surveying, soil classification, geo-electrical resistivity survey and the native groundwater levels and quality. The investigation results indicated that there is one layer aquifer system which consists of coarse sand with fine gravel and intercalations of thin silt and clay layers which promised to be a good prospect for the groundwater recharge. The depth to groundwater ranges from 4 to 7 m below the ground surface. The pumping test data analysis indicating that the saturated hydraulic conductivity for the study area ranges from 15 to 30 m/day. The average effective porosity ranges from 15 to 25%.

5.2. Design of recharge basin

The wastewater is pumped from the lined canal to a lined basin where fine suspended solids are allowed to settle and also for aeration using air jets. This pretreatment process decreases the chemical and biological load. The BOD and suspended solids (SS) were measured before and after the pretreatment process to assess its efficiency as shown in Table 4. The efficiency of suspended solid removal is about 41% and the bacteriological load decreases by about 25%. The pretreated wastewater is then pumped to a square recharge basin with a length of about 50 m and a depth of about 1.25 m from the ground surface. An injection well with a depth of 25 m was drilled also in the center of the basin. A monitoring system was installed to monitor the effect of the recharge process on the groundwater in terms of quantity and quality. Fig. 5 shows the general layout for the recharge basin in Abu Rawash.

5.3. Recharging process and results

The basin was operated under a variable hydraulic load as well as constant hydraulic head. Variable hydraulic load involves filling the basin to certain depth and stop adding wastewater to the basin until the total volume of wastewater in the basin is fully infiltrated. The time needed for this process is called a round. The basin was operated under constant hydraulic head by keeping the water level in the basin

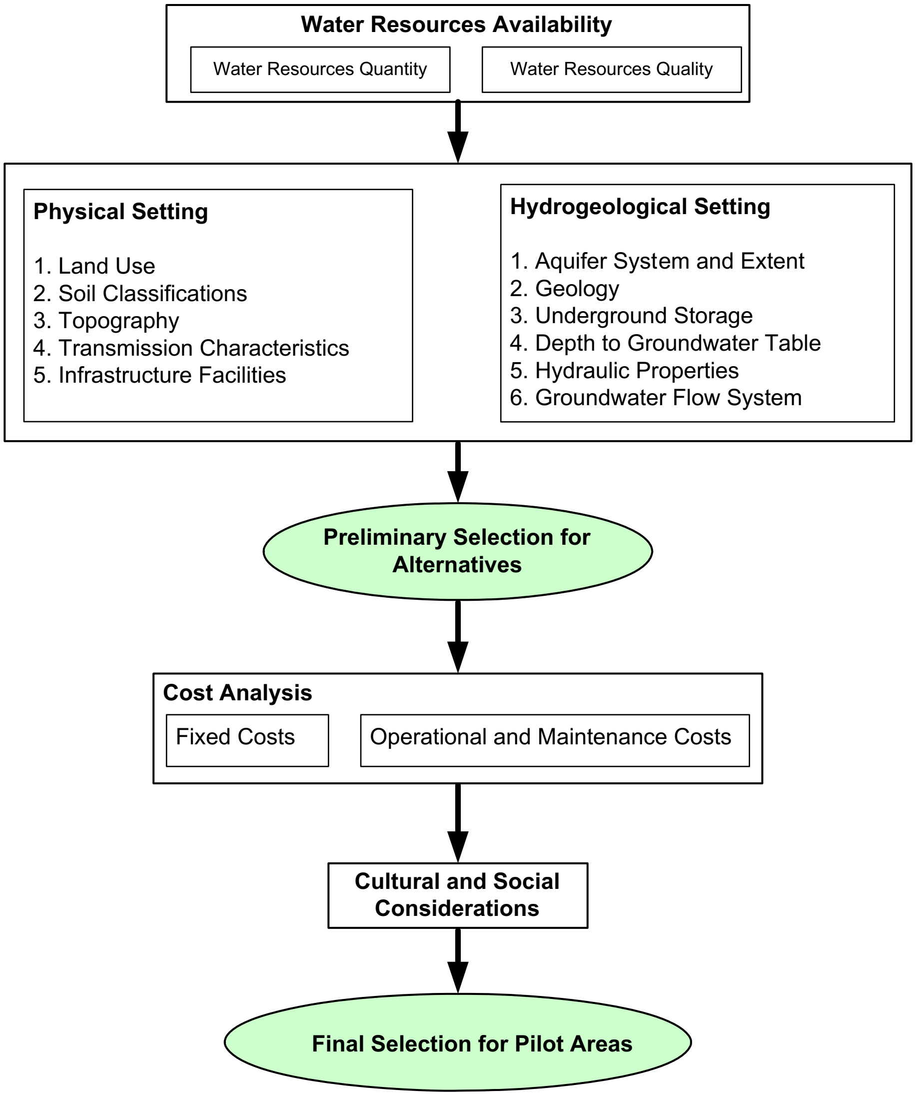


Fig. 3. Schematic diagram of the selection process.

constant at a head of 0.65 m above the basin floor. Table 5 summarizes the operation scenarios for recharging process. During the recharging process the effect of basin hydraulic head on the recharge rate as an indicator for basin clogging rate was evaluated. It was concluded that increasing the basin hydraulic head resulted in significant increase in the infiltration rate. The estimated recharge rate during the operation of the basin with constant hydraulic head ranges from 0.15 to 0.25 m/day.

The observed height of groundwater mound at the center of the basin was 0.60 m after four recharge rounds with variable hydraulic head. After the fifth recharge round with constant hydraulic head the height of the mound at the center of the basin was 1.40 m [32,33].

5.4. Identification of optimum recharge cycle

To identify the optimum recharge cycle, the Accumulative Average Recharge Cycle (AARC) method was used. The method is used to calculate for each periodic measurement of recharge rate, a value representing the average total recharged volume over the entire to date recharge cycle including a required drying period using the following equation:

$$V_t = \sum_{n=1}^{t} \left[\frac{Q_n x \Delta t}{t + d} \right] \tag{1}$$

where V_t represents the total average daily recharge at the start of drying cycle (m^3/h) at time t (h), Q_n is the periodic measured recharge rate (m^3/h), Δt is the

Table 3
Weighting of different parameters for the selection of artificial recharge sites

No.	Criteria	Classes	Weights
1	Water	Water is available	1
		Water is not available	0
2	Aquifer Geology	Alluvial deposits (sand, gravel)	3
		Alluvial deposits (shale, clay)	1
		Sandstone	1
		Limestone	0
		Hard rock	0
3	Geomorphology	Lower alluvial plain	3
		Flood plains and alluvial fill	3
		Upper undulating alluvial plain	3
		Gently to moderately sloping land interspersed with mounds and valleys	2
		Moderate to strongly sloping land interspersed with isolated hills	1
		Rock outcrops	1
4	Top soil	Gravel	4
		Sand	3
		Silt	2
		Clay	1
5	Depth to groundwater	0–5 m	1
		5–10 m	2
		10–20 m	3
		>20 m	4
6	Recharge	25–35 mm/day	3
		25–15 mm/day	2
		0–15 mm/day	1

duration of measurement period and d is the length of drying period (h). The optimum drying point occurs at maximum V_t [34]. Fig. 6 shows the plot of infiltration rate and AARC with time. From this graphs it is concluded that the optimal operating cycle for enhancing the daily recharge rate and restoring the infiltration rate after drying period is 7 days wet and 7 days dry.

5.5. Groundwater quality evaluation

Recharging of wastewater into an aquifer may induce geochemical reactions such as mineral precipitation, dissolution, cation exchange and redox reactions. These reactions have the potential to affect the adsorption or attenuation of metal or inorganic contaminants. Aquifer recharge using wastewater with a high BOD could change groundwater chemistry, with the potential to cause acidification and the release of heavy metals from aquifer sediments. To evaluate the effect of using pretreated wastewater for recharging the aquifer on the groundwater quality, the chemical and bacteriological constituents of the wastewater and groundwater were tested. Total Nitrogen, Phosphorus, BOD and Fecal Coliform were tested as indicators for soil aquifer treatment efficiency.

Operating the recharge basin with wet/dry cycles is critical to demonstrate hydraulic loading rates and to create cyclic aerobic/anoxic conditions for simulation of nitrogen removal [35–39]. Wilson [40] has studied water quality changes and the fate disinfection by-products at Tucson Sweetwater Recharge site. This Study demonstrated that nitrogen removal occurred in the deep vadose zone with approximately 50% removal and that disinfection by-products were efficiently removed. In Abu Rawash pilot project, the removal efficiency of total nitrogen at the depth of 1 m in the unsaturated zone was about 10% and it was

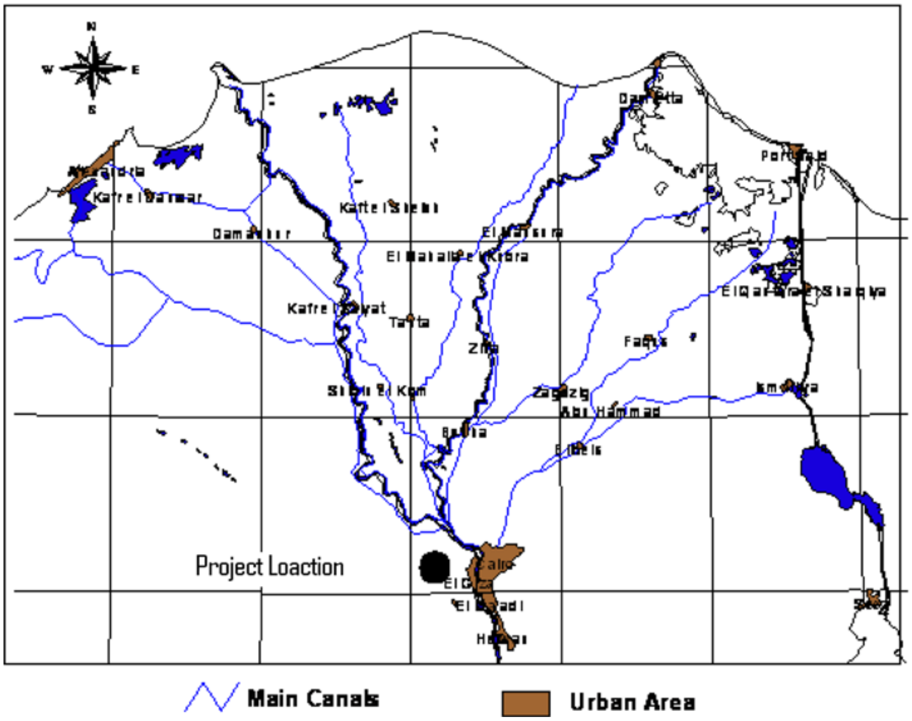


Fig. 4. Pilot project location map.

about 35% at the base of unsaturated zone. The increase of in total Nitrogen removal rate with depth and time is mainly due to the high concentration of Oxygen in the unsaturated zone. The average removal rate for phosphorus within the experimental project was about 5% from the initial concentration of recharged wastewater. Also, at a depth of 2 m in the unsaturated zone the average bacterial removal rate was about 65% [41].

During soil aquifer treatment, cyclic flooding/drying of the basins is necessary for improvement of infiltration rates and to control aerobic/anoxic conditions in the soil. Recharge basins function under wet and dry cycles, alternately. A clogging layer develops at the soil surface during flooding due to the combined effects of algal growth, suspended solids deposition, and bacterial growth in soil pore spaces and slows down the infiltration rate. However, infiltration rates are restored during the drying cycles by allowing the soil surface to dry and develop cracks. Wet-dry cycle operations consist of filling the pond to a certain depth, stopping the inflow (loading) and allowing the water to infiltrate into the ground. After all the water has infiltrated into the soil, the pond is left to dry for a period so that natural aeration can take place. During the drying period, water percolates and the infiltration potential for the next application period increases. When clogging occurs, the recharge basin can be cleaned and possibly restored to their original capacity by draining, drying and scraping. Another method of wet-dry cycle operation is to maintain a full pond, i.e., the influent water is maintained at a rate equal to the recharge rate. When the recharge rate reaches an unacceptable value, the operation is stopped so that the clogging layer can be removed [42,43]. Table 6 summarizes the results of the quantitative assessment of groundwater quality for the recharging process with pretreated wastewater during the wet-dray cycles.

Table 4
Measured BOD and SS for wastewater before and after the pretreatment process

Parameter	Average concentration (mg/l)	
	Raw wastewater	Pretreated wastewater
SS	2,800–2000	1,500–1,300
BOD	400–300	300–200

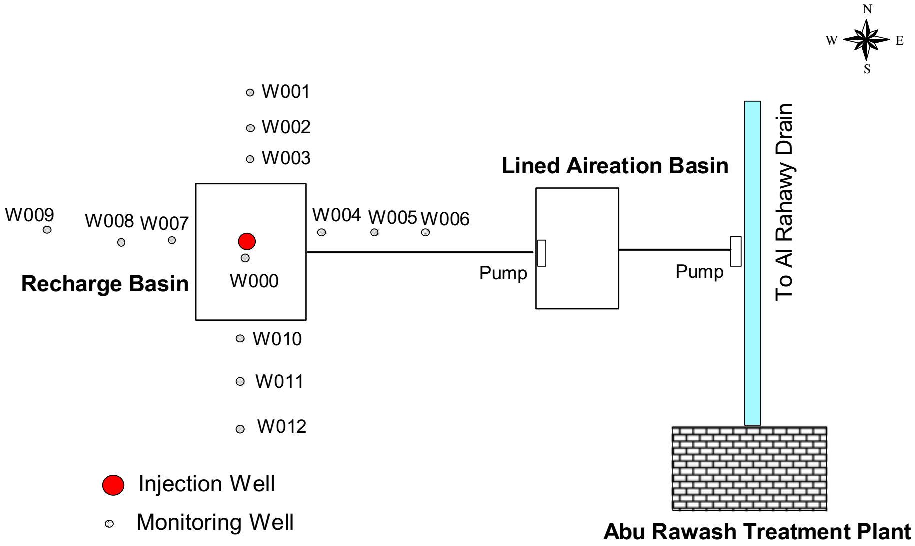


Fig. 5. General layout for artificial recharge basin in Abu Rawash.

Table 5
Operation scenarios for the recharging of treated wastewater in Abu Rawash

Round	Scenario	No. rounds	Duration (days)	
			Wet	Dry
1	Recharging the aquifer with raw wastewater under variable hydraulic head (from 0.75 to 0 m)	2	5	7
2	Recharging the aquifer with treated wastewater under variable hydraulic load (from 0.60 to 0 m)	2	2.7	7
3	Recharging the aquifer with treated wastewater under variable hydraulic load (from 0.75 to 0 m)	5	8.7	9
4	Recharging the aquifer with treated wastewater under variable hydraulic load (from 0.75 to 0 m)	5	7.3	9
5	Recharging the aquifer with treated wastewater under constant hydraulic load (head = 0.65 m)	1	13.5	The end

The analysis results of collected samples from the groundwater monitoring network indicated that SAT systems within the site can handle high BOD-loadings, and BOD levels are generally reduced to essentially 5 mg/l after percolation through soil at the well located at the center of the recharge basin as shown in Fig. 7. However, the final product water from SAT systems still contains some organic carbon. This is probably mostly due to humic and fulvic acids but also to synthetic organic compounds in the sewage effluent that do not break down in the underground environment.

The initial COD of raw sewage was about 350 mg/l, and the first treatment is by anaerobic stabilization pond (recharge basin). The result of the analyzed sample collected from the basin was 205 mg/l. The results of the analyzed samples collected from the groundwater monitoring network indicated COD levels are generally reduced to essentially 10 mg/l after percolation through soil at the well located at the center of the recharge basin as shown in Fig. 8.

6. Summary and conclusions

Increasing demand for water in Egypt, particularly in the areas suffering from shortage of surface water, has shown that the groundwater reservoirs provided by aquifers are invaluable for water supply and storage. Natural replenishment of this vast supply of groundwater is very slow. Artificial recharge as a mean to boost the natural supply of groundwater aquifers is becoming increasingly important in groundwater management particularly for non-potable water reuse.

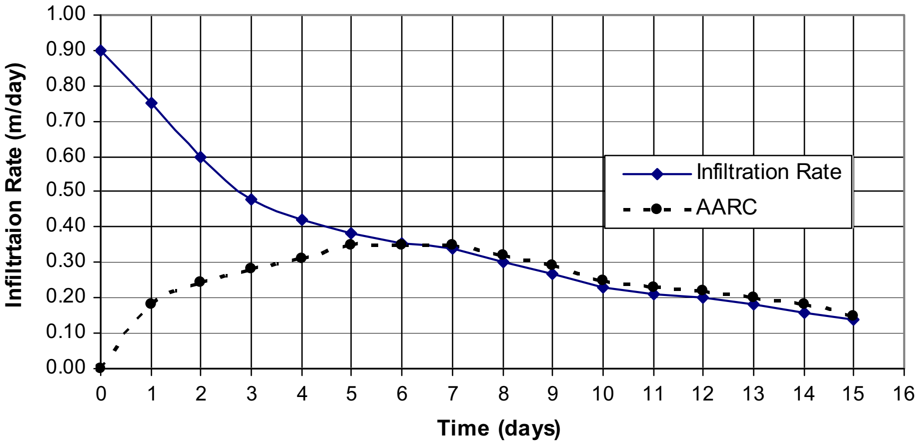


Fig. 6. Calculated infiltration rate and AARC for one round.

Table 6
Change in groundwater quality during the recharge process

Round		Total nitrogen (mg/l)	PO_4-P (mg/l)	Fecal coliform (FUM/100 mm)
Initial condition		1.5	3.9	0
1	Wet	2.5	3.7	2,000
	Dry	1.8	4.5	1,500
2	Wet	2.7	3.7	1,600
	Dry	2.3	4.2	2,350
3	Wet	3.5	3.1	2,100
	Dry	1.7	3.9	2,500
4	Wet	3.0	2.9	2,000
	Dry	1.8	3.5	2,400
5	Wet	1.7	3.0	2,500
	Dry	1.6	3.4	2,300

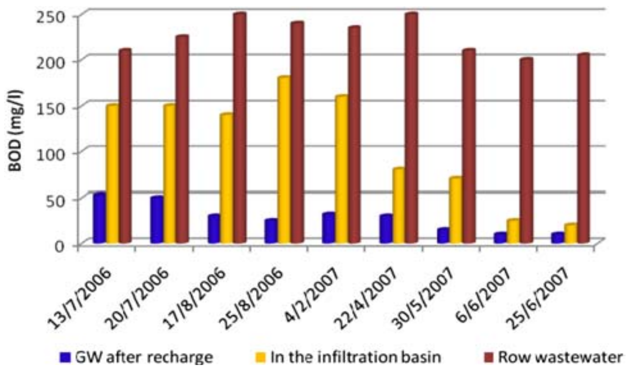


Fig. 7. BOD values (mg/l) for row wastewater, in the basin and after recharge.

The objective of this study was to evaluate the hydrogeological suitability of artificial recharge with pretreated wastewater in Egypt for augmentation of groundwater supply and mitigation the negative environmental impact of direct illegal reuse of raw wastewater. Results indicated that artificial recharge of groundwater with treated wastewater is a promising method for groundwater aquifer replenishment in Egypt, that needs more detailed study, especially in the area of remediation of clogging problems under intermittent as well as continuous recharge. The results indicated that the main factors affecting the success of recharge process are, water availability in terms of quantity and quality, method of aquifer recharge (mainly basins and injection wells), clogging, aquifer extent and boundaries, aquifer hydraulic parameters,

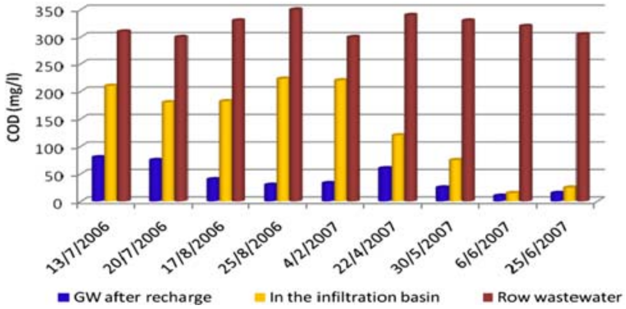


Fig. 8. COD values (mg/l) for row wastewater, in the basin and after recharge.

hydraulic recharge load, groundwater quality maintenance and economical, social and health issues.

Recharging the aquifer with constant hydraulic load increased the recharge rate by about 40%. When using pretreated wastewater, the efficiency of the soil in removing the pollutants decreases over time due to the changes in its chemical balance and physical properties. Therefore, it is recommended that detailed studies to be carried out on the effect of leaching the soil by fresh water and the possibility of adding some chemicals in the recharging basin to activate pollutants removal.

The retrieval of the stored groundwater should be considered as important as the storage of water. A well-designed active recovery system for the recharged pretreated wastewater can be considered as a protection system that prevents the contaminants from migration in the native groundwater body. Also a well designed monitoring system is a vital to evaluate the effects of recharge on the groundwater body in terms of both quantity and quality.

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References

[1] A.J. Horne, C.R. Goldman, Limnology, McGraw-Hill, New York, NY, 1994, p. 133.

[2] R.D.G. Pyne, Groundwater Recharge and Wells: A Guide to Aquifer Storage and Recovery, Lewis Publishers, Boca Raton, FL, 1995.

[3] R.G. Maliva, W. Guo, T.M. Missimer, Aquifer storage and recovery: Recent hydrogeological advances and system performance, Water Environ. Res. 78 (2006) 2428–2435.

[4] R.G. Maliva, T.M. Missimer, ASR, useful storage, and the myth of residual pressure, Ground Water 46 (2008) 171.

[5] R. Dillon, S. Toze, P. Pavelic, J. Vanderzalm, K. Barry, G.-L. Ying, R. Kookana, J. Skjemstad, B. Nicholson, R. Miller, R. Correll, H. Prommer, J. Greskowiak, P. Stuyfzand, Water quality improvements during aquifer storage and recovery at ten sites, in: Recharge Systems for Protecting and Enhancing Groundwater Resources, Proceedings of the 5th International Symposium on Management of Aquifer Recharge, Berlin, Germany, 11–16 June 2005, UNESCO, Paris, 2006, pp. 85–94.

[6] M.E. Pescod, Wastewater treatment and use in agriculture. FAO Irrigation and Drainage Paper 47. Food and Agriculture Organization of the United Nations, Rome, 1992.

[7] S. Toze, Reuse of effluent water—benefits and risks. In New Directions for a Diverse Planet, in: Proceedings of the 4th International Crop Science Congress, 26 Sep–Oct, 2004, Brisbane, Australia, 2004, p. 11.

[8] S. Toze, Pathogen survival in groundwater: a review of the literature, in: P. Dillon, S. Toze (eds.), Water quality improvements during aquifer storage and recovery. Volume 1: Water Quality Improvement Processes, AWWA Research Foundation Report 91056F, 2005, pp. 123–140.

[9] Y. Harpaz, Artificial ground-water recharge by means of wells in Israel: American Society of Civil Engineers, J. Hydraulics Division 97 (1971) 1947–1964.

[10] R.D.G. Pyne, Aquifer storage recovery wells: the path ahead, Florida Water Resour. J. February (2002) 19–27.

[11] J.P. McQuarrie, K. Carlson, Secondary benefits of aquifer storage and recovery: Disinfection by-product control, J. Environ. Eng. 129 (2003) 412–418.

[12] P. Pavelic, B.C. Nicholson, P.J. Dillon, K.E. Barry, Fate of disinfection by-products in groundwater aquifer storage and recovery with reclaimed water, J. Contaminant Hydrol. 77 (2005) 351–373.

[13] P. Pavelic, P. Dillon, B. Nicholson, Analysis of the fate of DBPs at eight ASR sites, in: P. Dillon, S. Toze, (eds.), Water quality improvements during aquifer storage and recovery. Volume 1: Water Quality Improvement Processes, AWWA Research Foundation Report 91056F, 2005, pp. 39–64.

[14] J. Mansell, J. Drewes, T. Rauch, Removal mechanisms of endocrine disrupting compounds (steroids) during soil aquifer treatment, Water Sci. Technol. 50(2) (2004) 229–237.

[15] A.R. Allam, Artificial groundwater recharge in Egypt, Ph.D. Thesis, Irrigation and Hydraulic Department, Faculty of Engineering, Cairo University, Egypt, 1998.

[16] M. Abu Zeid, Irrigation in Egypt—present and future, in: Paper Presented to Eighth Seminar of the Regional Commission on Land and Water Use in Cyprus, FAO, Rome, 1985.

[17] RIGW (Research Institute for Groundwater), Environmental management of groundwater resources in Egypt, Final Report, 2002.

[18] T.A. Elmitwalli, A. Al-Sarawey, M.F. El-Sherbiny, G. Zeeman, G. Lettinga, Anaerobic biodegradability and treatment of Egyptian domestic sewage, in: Proceeding of 5th IWA (International Water Association) Conference in ”Small Water and Wastewater Treatment Systems” Turkey, Selected to be published in Journal of Environmental Science and Health: Part A, 2002.

[19] M.F. El-Sherbiny, A. Al -Sarawey, T. Elmitwalli, Aerobic Biodegradability of Egyptian Domestic Sewage, 2001.

[20] G.E.A. Ibrahim, Comparative study to evaluate different technologies for sewage treatment in rural areas in Egypt, Ph.D. thesis, High Institute of Public Health, Alexandria University, Alexandira, Egypt, 1995.

[21] T. Asano, Artificial Recharge of Groundwater, Butterworth Publishers, Boston, 1985, p. 767.

[22] E.T. Oaksford, Artificial recharge: Methods, hydraulics, and monitoring, In: T. Asamo (Ed), Artificial Recharge of Groundwater, Butterworth Publishers, Boston, 1985, pp. 69–127.

[23] A.I. Johnson, D. Finlayson, Artificial Recharge of Groundwater, American Society of Civil Engineers, New York, NY, 1990.

[24] H. Nightingale, Artificial recharge of urban storm water runoff, Artificial Recharge of Groundwater, American Society of Civil Engineers, New York, NY, 1990.

[25] A.K. Saraf, P.R. Choudhury, Integrated remote sensing and GIS for groundwater exploration and identification of artificial recharge sites, Int. J. Remote Sensing 19(10) (1998) 1825–1841.

[26] A.K. Saraf, P.R. Choudhury, Integrated application of remote sensing and GIS groundwater exploration in hard rock terrain, in: Proceedings of International Symposium on Emerging Trends in Hydrology, Department of Hydrology, Roorkee, September 25–27, vol. I, 1997, pp. 435–442.

[27] P.R. Choudhury, Integrated remote sensing and GIS techniques for groundwater studies in part of Betwa basin, Ph.D. Thesis, Department of Earth Sciences, University of Roorkee, India, 1999.

[28] F.A. Attia, M. Moustafa, T. Olsthoorn, E. Smidt, The role of artificial recharge in integrated water management in Egypt, in: Proceedings of the Third International Symposium on Artificial Recharge, September 21–25, 1998.

[29] A. Fadlelmawla, M. Abdel-Halem, M. Vissers, Preliminary plans for artificial recharge with reclaimed wastewater in Egypt, in: 9th Biennial Symposium on the Artificial Recharge of Groundwater, Tempe, AZ, UAE, 1999.

[30] M.A. El Shewy, Artificial recharge with pretreated wastewater in Egypt, Ph.D. Thesis, Institute for Environmental Research and Studies, Ain Shams University, Egypt, 2002.

[31] RIGW/IWACO, 1999. Artificial recharge pilot projects at El-Bustan area, Egypt, Final report.

[32] Y.S. Saharawat, R.S. Malik, B.S. Jhorar, T. Streck, N. Chaudhary, M.L. Jat, Changes in the recoverable fractions during successive cycles of aquifer storage and recovery system in North-West India, Curr. Sci. 97(9) (2009) 1369–1374.

[33] H. Bouwer, Renovation of wastewater with rapid infiltration land treatment system, in: Artificial Recharge of Groundwater, Butterworth Publishers, Boston, MA, 1985.

[34] H. Bouwer, Soil-aquifer treatment of sewage, Paper prepared for the Land and Water Development Division, FAO, Rome, 1987.

[35] H. Bouwer, Issues in artificial recharge, Water Sci. Technol. 33(10–11) (1996) 381–390.

[36] H. Bouwer, Artificial recharge of groundwater: hydrogeology and engineering, Hydrogeol. J. 10 (2002) 121–142.

[37] H. Bouwer, R.C. Rice, J.C. Lance, R.G. Gilbert, Rapid-infiltration research: The flushing Meadow project, Arizona, J. Water Pollut. Control Federation 52(10) (1980) 2457–2470.

[38] L.G. Wilson, Water quality during soil aquifer treatment of tertiary effluents, Water Environ. Res. 67 (1995) 371–376.

[39] M.A. Dawoud, Numerical simulation for reactive multi-chemical components in groundwater, Ph.D. Thesis, Irrigation and Hydraulic Department, Faculty of Engineering, Ain Shams University, Egypt, 2001.

[40] S.K. Sharma, M. Hussen, G. Amy, Soil Aquifer Treatment Using Advanced Primary Effluent, in: Proceedings of the ISMAR 7 Conference (9–13 October 2010), Abu-Dhabi, UAE, 2010.

[41] S.K. Sharma, R.O.A. al-Sakkaf, G. Amy, Effect of (SAT) pre-treatment of wastewater effluent on performance of MF/UF/NF membranes, in: Proceedings of the IWA REUSE 09 Conference (20–25 September 2009), Brisbane, Australia, 2009.