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Improvement of urban water cycle and mitigation of groundwater table rise through advanced membrane desalination of shallow urban brackish groundwater of Jeddah basin

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ABSTRACT

Jeddah city depends entirely on desalinated seawater for its fresh water supply which exceeds 1.2 Mm^3/d. Around 40% of the water used in the urban area infiltrates into the underlying shallow groundwater from cesspits and wastewater networks. This process resulted in groundwater table rise in many parts of the city and the occurrence of a polluted brackish groundwater (BGW) which is a mix of fresh water, domestic sewage, seawater intrusion, and urban runoff. Membrane technologies such as hybrid membrane systems and membrane bioreactors coupled with reverse osmosis membrane systems have been well established as cost-effective, feasible, and efficient solutions for desalination of contaminated water sources. This study emphasizes on the potential of BGW in Jeddah urban water cycle as one of its main components and the key principles of integrated urban water cycle management applied to Jeddah context. The study assessed the favorable conditions, driving factors, and the feasibility of integrating BGW source of Jeddah basin into the water cycle of the city through the introduction of various options of integrated membrane systems for on-site desalination and treatment. Physiochemical and microbiological analysis of BGW samples taken from selected districts in the basin has been conducted and showed low levels of biological contaminants, as a result of soil aquifer treatment, compared to effluents of wastewater treatment plants. A comparison of costs of current practices of water supply and BGW desalination option for specific on-site uses has been provided as well.

Keyword: Urban water cycle; Brackish groundwater; Groundwater table rise; Desalination; Cost of desalination; Jeddah

1. Introduction

Demand for fresh water in Saudi Arabia is rising at accelerated rates. The rapid economic development coupled with high rates of population growth, which per capita water use ranked third in the world, and depletion of fossil groundwater resources puts the country in front of a major challenge of securing adequate fresh water supplies to meet its demands.

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Currently, water use in Saudi Arabia approaches 20 BMC and will likely double in the next two decades [1]. The share of non-renewable groundwater resources in water supply balance equals about 73% of the total water consumption [2].

For long time, seawater desalination was regarded as a preferred option for augmentations of vanished water resources. The country developed the largest desalination industry in the world with a total capacity of around 3 Mm^3/d which represents 25% of world desalination capacity. Yet, Saudi Arabia plans to increase its overall desalination capacity to 5.2 Mm^3/d by 2015 [3]. Approximately 78% of the desalinated water in Saudi Arabia is produced from seawater and the remaining part from brackish groundwater (BGW) in the inland regions [4]. Other sources of impaired waters that can be used for augmentation of fresh water supplies through desalination have been ignored. In large municipal areas, such as Jeddah basin, other potential sources of impaired water are available for treatment and reuse of treated wastewater and shallow BGW. The shallow BGW in Jeddah basin builds up with the growth of the city because of continuous recharge from septic-percolating pits (cesspits) which accounts for 60% of city sewer drainage [5]. Municipal wastewater is the main origin of this source in addition to the natural recharge due to urban and upper catchment runoff. Saudi Arabia has already adopted large-scale programs to recover and reuse treated municipal and industrial wastewaters and desalinate brackish and marginal water sources to substantially reduce both groundwater and desalinated water withdrawals, while simultaneously minimizing energy use in groundwater withdrawal and in the production and transportation of desalinated water [1]. The National Water Company (NWC) is to invest $23 billion into Saudi Arabia's sewage collection and treatment infrastructure over the next two decades and aims to increase wastewater network coverage to 100%. Saudi Arabia is anticipated to become the third-largest water reuse market in the world after the United States and China [1].

The urban BGW in Jeddah can be used to produce high-quality water that can meet the criteria for many uses, such as restricted and unrestricted irrigation and industrial uses. The advantage of this source is its easy access to any point in basin at very low depths. The major concern hindering the use of this source is its susceptibility to pollutants due to its anthropogenic origin. In fact, the sewerage network connections are available for 35–40% of the population, while the rest of the population uses cesspits for domestic wastewater disposal. A cesspit is a covered dug well that works as an underground storage of wastewater. In this process of storage, some treatment of the wastewater in the form of settling and partial oxidation takes place [6]. A newly dug well in an alluvial formation will allow infiltration of wastewater into the underlying shallow aquifer. The infiltrated wastewater through the unsaturated soil formations undergoes further treatment similar to soil aquifer treatment (SAT) system. Filtration characteristics of the sandy formations in this coastal basin are likely to prevent most of the microbial and colloidal pollutants present in sewage wastewater to reach the groundwater. It has been proven that the SAT system is very effective in removal of micro-organisms and suspended materials from wastewater and reduction of the chemical oxygen demand (COD) and biological oxygen demand (BOD) as well as the removal of potentially toxic inorganic constituents, such as heavy metals and trace oxyanions [7–11]. Up to 50–70% of the COD is removed at operational SAT sites in Mesa and Tucson, Arizona, USA [12]. Other field studies indicated that the removal of dissolved and particulate organic carbon from the effluent was found to be 70–90% [13]. SAT system is capable of inactivation of many micro-organisms of concern found in treated wastewater. The log10 removal times of pathogenic micro-organisms in groundwater of the Middle East are in the range from days to perhaps several weeks, and complete removal would be expected within a year [14]. It has been advised to adopt SAT systems as an integrated urban water management approach involving a semi-closed urban water cycle [15]. The major pollutants in shallow groundwater systems of Southeast Asian megacities were nitrate (NO_3), nitrite (NO_2), and ammonium (NH_4) [16]. Chemical analysis of wastewater stream flowing along the lower part of Wadi Uranah, West Saudi Arabia, and well groundwater in the same area showed that the values of nitrates (NO_3), bacteria count, BOD, and COD are much lower in the case of ground water as compared to the wastewater stream [17].

2. Methodology

Both primary and secondary data were used in this study. The primary data include water quality parameters of BGW samples collected from few districts between June and December 2013. The secondary data were obtained from relevant institutions which include Jeddah Stormwater Drainage Program (JSDP) and NWC as well as a number of unpublished reports together with the published literature. A conceptual model depicting Jeddah urban water cycle was prepared based on the principles of water balance models pertaining to urban catchments. The main components of the Jeddah urban water cycle were quantified based on the data from various research reports and studies addressing water resources management in Jeddah. However, the major source of data being used was the data assessment and analysis report series of the Jeddah environmental assessment study [5,6] which contains comprehensive and up-to-date reports on groundwater and wastewater, and two reports on groundwater modeling and hydrological modeling prepared by AECOM for JSDP [18,19].

3. Jeddah urban water cycle

The urban water cycle is a conceptual model used to study the water balance and conduct water inventories of urban areas. This model represents the hydrological water cycle applied within the city basin boundaries, and hence, it allows to study the interactions between the urban water resources and the human activities represented by the urban settings, population density and distribution, economic and industrial activities, actions of water utilities, or management institutions that include water supply, wastewater collection and treatment, surface runoff, groundwater extraction or recharge, and water reuse [20]. These interactions modify the hydrological cycle and render it to become more complex.

A simplified representation of Jeddah urban water cycle with inputs and outputs of water streams is shown in Fig. 1. The significant water inputs consist of desalinated water, storm runoff, treated wastewater reuse, and groundwater abstractions within the basin boundaries. All other water inputs such as rainfall and base flow from the upper catchment are marginal. The desalinated water is supplied from desalination plants located on the Red Sea coast and distributed through water networks or by water trucks to Jeddah districts. Water outputs consist of treated and untreated wastewater discharges into the sea, leakages from water and wastewater networks, groundwater recharge through cesspits, and storm runoff.

Table 1 contains a brief description of water inflows and outflows impacting Jeddah urban water cycle. The desalinated water accounts for more than 97% of water supply in urban Jeddah, while the remaining quantity (3% of water supply) is groundwater abstraction from wells located in wadis outside the basin, namely Wadi Khulays and Wadi Fatima [5]. This water supply is used mainly for non-consumptive domestic and industrial purposes and eventually is converted into wastewater. The generated wastewater, assumed to be not less than 85% of the water supply, is disposed through three main streams: wastewater network (40%), wastewater tanker trucks (12%), and infiltration into the underlying aquifer through cesspits. In addition to the groundwater recharge through cesspits, the other main sources include water network losses, estimated at 60 Mm^3/y, and wastewater network leakages, estimated at 33 Mm^3/y [6]. By adding natural recharge components, the total estimated recharge into the shallow urban aquifer will be around 294 Mm^3, amounting to 60% of the water inflows into the basin.

Significant fraction of the infiltrated water is accumulated into the shallow aquifer storage, and

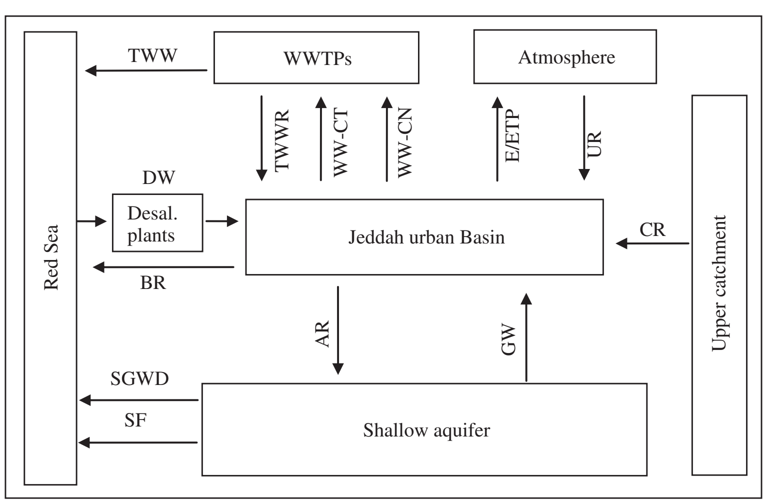

Fig. 1. A simplified Jeddah urban water cycle model.

Table 1
Description of water inflows and outflows impacting Jeddah urban water cycle

Water cycle component	Description	Annual estimated quantity (Mm^3)
Inflows		
DW: Desalinated water supply	Desalinated seawater accounts for 97% of potable water supply, and it is provided from two main desalination plants located on the Red Sea coast [5]	401
TWWR: Treated wastewater reuse	A small fraction (18%) of treated effluents is reused for green areas and parks irrigation [6]	34
UR: Urban area runoff	The average annual rainfall over Jeddah urban area (400 km^2) is 60 mm, but most rainfall events do not generate significant storm runoff. However, cases of intense rainfall events of relatively short duration typical to dry region climate may occur and generate significant storm runoff (estimated based on [18])	15
GW: Groundwater withdrawals	Groundwater withdrawals in the urban area are negligible due to high salinity and pollution. Minor quantity (3%) of water supply is sourced from wells located in Wadi Khulays and Wadi Fatima [5]	12
CR: Catchment runoff	The runoff inflow from the upper catchment (1,400 km^2) is characterized by large variations from year to year (estimated based on [19])	26
Total		488
Outflows		
WW-CN: Wastewater collected via wastewater network	The total generated wastewater was estimated as 85% of water supply. About 40% of wastewater generated is collected to wastewater treatment plants through wastewater network [6]	116
WW-CT: Wastewater collected via tanker truck	Domestic wastewater pumped from cesspits and hauled by tanker trucks to wastewater treatment plants [6]	53
BR: Basin runoff	Storm runoff directly drains to the sea through storm runoff canals estimated at 40% of catchment and urban area runoff	25
E/ETP: Evaporation and Evapotranspiration	Evaporation occurred from bare soil and wetlands and evapotranspiration from green areas and trees (estimated based on [5,18,19])	174
SGWD: Surface drainage	This includes the natural drainage of shallow groundwater through ditches and storm runoff canals to the sea and the drainage through constructed networks of subsurface horizontal drainage pipes which collects groundwater and directs the flow toward storm runoff canals. Also, it includes illegal direct discharges of untreated wastewater (estimated based on [5,18,19])	82
SF: Subsurface flow into Red Sea	Natural subsurface flow of groundwater from the basin aquifer toward the sea [19]	1.2
AR: Aquifer recharge	Infiltrated water into the underlying aquifer through localized and areal infiltration process. This component represents the difference between total inflows and collected wastewater and basin runoff	294
ΔS: Annual change in aquifer storage	The recharge consists basically from wastewater infiltrated into the underlying aquifer through cesspits, wastewater network leakages, water network leakages, and infiltrated runoff	36.8

consequently resulted in an unbalanced recharge of the shallow aquifer and rising of the shallow groundwater level. Although shallow groundwater table rise is observed all over the basin, the field measurements indicated that its magnitude varies in wide range from district to districts. While the water table maintains a constant at some locations, it was increased by 3 m in a period of 2 years in other locations [5]. The rise in groundwater table levels is a clear indicator of the increase in groundwater storage due to recharge process. However, an accurate estimation of the change in aquifer storage is complicated by the variations in population density, availability of water and wastewater networks, aquifer characteristics, and physiographic characteristics coupled with the lack of adequate data, and hence, the result is subject to large uncertainties and errors. The water-budget method can be used to give an approximate estimation of the change in aquifer storage. The method is essentially a book-keeping procedure which estimates the balance between the inflow and outflow components of water in the whole basin. It is assumed that all of the components in the water-budget equation are measured, except for the residual term which represents the change in aquifer storage, ΔS. Obviously, the accuracy of the estimate depends on the accuracy with which the other components in the water-budget equation can be measured or estimated [21]. The following simple form of water-budget equation was used to estimate the annual change in aquifer storage:

$$\Delta S = I - Q \tag{1}$$

where ΔS—annual change in aquifer storage due to recharge, Mm^3; I—total annual water inflows into the basin including annual urban and catchment runoff, Mm^3; and Q—total annual water outflows outside the basin boundaries including annual evaporation, evapotranspiration, shallow groundwater drainage, and basin runoff, Mm^3.

The shallow groundwater storage is discharged mostly through evaporation/evapotranspiration process, natural subsurface flow toward the Red Sea, and subsurface drainage into constructed subsurface horizontal network of perforated pipes that has been installed or is proposed in parts of the city [5]. Evaporation occurs from bare soils in unpaved areas when groundwater table is less than 3 m, as the groundwater will rise by capillary action and eventually evaporates [18]. The deep-rooted trees extract their water requirements directly from the shallow groundwater; hence, it may be assumed that water supply to the evapotranspiration process is not limited, and the process can be treated at its potential rate. Evapotranspiration contributes to the depletion of considerable amount of shallow groundwater estimated at between 0.5 and 1 Mm^3/y, assuming that 50% of the total length of streets and roads (830 km) has a tree density of 40 trees per km, and the potential evapotranspiration ranges between 80 and 200 l/d per tree in arid climate [22].

4. Enabling factors for promotion of urban BWRO desalination

The favorable conditions for the promotion of on-site BWRO desalination in Jeddah urban area can be cited as follows:

4.1. Groundwater table rise problem

Due to hydrogeological properties of Jeddah basin underlying aquifer and limitations of the wastewater drainage system, groundwater table rise is an inherent problem of Jeddah urban area. The annual desalinated water supply in Jeddah Municipality area exceeds 400 Mm^3. Almost half of this huge quantity of water used infiltrates into the underlying shallow groundwater storage through localized and areal infiltration process. Water infiltration occurs due to leakages from water supply network, unlined cesspits, wastewater network, and parks irrigation, in addition to the natural infiltration due to rainfall and storm runoff events. This process results in unbalanced recharge of the shallow aquifer and rising of the shallow groundwater level. In some coastal-close areas in around the city center and the northern part of the city, the depth of water level is less than 2.5 m [23]. The area affected by groundwater rise problem is expanding at high rates. It covers about 61% of the total area of the municipality in 2002, while it was about 56% in 1998 [24]. Various types of leakages during the period from 1996 to 2002 caused groundwater level rise on the average at about ±0.12 m annually in addition to seasonal fluctuations [25]. To overcome this problem, Jeddah Municipality is installing subsurface drainage networks in affected districts to maintain safe water table levels. The drainage network disposes the collected water to storm water network ending in the sea [26].

4.2. Promotion of decentralization and privatization of water supply and treatment in Jeddah Governorate

In 2009, the Jeddah Municipality has approved "Jeddah Strategic Plan" which draws a number of objectives for the development and improvement of the water sector in the city. The Plan states that decentralization will help to increase the flexibility and robustness of the water network. Throughout 2008, Saudi Arabia has embarked privatization process of the water sector, beginning with major cities, including Jeddah. A new NWC was formed that brings together the treatment and supply of potable water and the collection and treatment of wastewater. The NWC is responsible for the privatization process of desalination and wastewater treatment plants. The privatization plan of the water sector will create opportunities for establishment of small and medium firms for the treatment and supply of potable water and the collection and treatment of wastewater. Innovative water treatment technologies have prospective for emerging firms. Smaller decentralized water desalination plants could be less expensive, strategically safer, and less disruptive as compared to mega plants which are usually built at locations remote from urban areas because of additional costs of transporting, storing, and distributing water as the case with mega plants offset higher investment cost per unit production as the case of small plants [27].

4.3. Promotion of integrated urban water cycle management approaches

The methodology of integrated urban water cycle management (IUWCM) provides a useful tool to improve water supply to meet the increased water demand in urban area. The key principles of IUWCM were formulated with an aim to achieve integrated management of various urban water sources present within the basin so that water is used optimally within the urban basin [20]. A few policy guidelines can be deduced based on the key principles of IUWCM applied to Jeddah basin case which are as follows:

(1) *Adopt a policy of different water qualities and quantities for different uses of water*: a large portion of desalinated water supplies which are basically of drinking water quality is being used for uses that can be met with non-drinking water quality. The most potential applications of reclaimed BGW would be in irrigation of green areas and public parks, car washing, firefighting, toilet flushing, street washing, and some industrial uses. To promote the use of non-drinking water quality for toilet flushing, decentralized reclamation systems could be installed for big residential buildings and compounds of buildings, big mosques, large institutional facilities such as schools and universities. BGW could be a competitive source for irrigation of green areas and public parks due to its easy accessibility. Although Jeddah Municipality already uses tertiary-treated wastewater for landscape irrigation, the reclaimed BGW would be of superior quality compared to reclaimed wastewater. The cost of BWRO desalination will offset reverse osmosis (RO) desalination cost of the tertiary-treated wastewater plus transportation cost from WWTP to the location of use. Owing to the areal distribution of shallow aquifer, reclamation of shallow BGW could be conducted on a small-scale basis utilizing on-site treatment and reuse systems.

(2) *Promote decentralized wastewater treatment and water recycling*: home-scale gray water treatment units are already available in the market. This type of water technology could be promoted for internal reuse of gray water. Similarly, mature and efficient small-scale water treatment technologies for domestic wastewater are available. Local authorities may provide incentives to stimulate water users to install such new water treatment technologies. Water reuse will be improved substantially by introducing the dual plumbing networks in public buildings, large housing compounds, and houses where one of the networks will be designated for the potable water and other for non-potable water uses such as irrigation, toilet flushing, car washing, etc. Membrane desalination technologies were introduced for purifying BGW, and valuable water supplies can be generated. The BWRO desalination could be the best option for water reuse in Jeddah owing to the fact that almost 40% of wastewater is disposed into the underlying shallow aquifer. A set of policy interventions would be needed to promote this type of reuse (Fig. 2).

(3) *Reutilize effluent of WWTP*: water reuse schemes become a usual business in many water utilities around the world and reclaimed water with desired levels of quality for safe use is easily attainable. The essential elements of these schemes include identifying purpose of reuse, selection of water quality criteria for such specific reuse confirming with the valid regulations and guidelines, selection of water treatment technology which is capable to provide reclaimed water with the required quality, and evaluating the overall economic feasibility and sustainability. A large-scale project for landscape irrigation, forestation, and aquifer recharge could be implemented to utilize effluents of WWTPs.

(4) *Promote SAT in all districts affected by groundwater table rise problem*: Jeddah basin is located in hyper-arid region and its aquifer has no fossil fresh water reserves. The native groundwater, mostly saline, has no potential uses. Hence, it could be considered that domestic wastewater cesspits are not a threat to the aquifer. The cesspits option could be a cost-effective solution for domestic wastewater disposal if the risks of cesspits overflow and groundwater

level rise are avoided. The main reason of cesspits overflow is clogging of pores and subsequently the reduction in the filtration capacity of the cesspit. The cesspits infiltration capacity is also affected by the rising of groundwater table. When the groundwater table raised up to the levels of cesspits, the effectiveness of the cesspit as a sink or even as storage of wastewater is diminished. Spill-over of cesspits occurs mainly due to this condition. A new design code for cesspits can be developed so that its performance as an efficient wastewater disposal structure is improved. Considering that the construction cost of subsurface groundwater drainage network in more than 40 districts is enormous, the alternative option could be to promote the construction of privately developed septic tanks which incorporates the principles of SAT. The subsequent rise in groundwater table could be dealt with small BWRO desalination units to continuously withdraw groundwater for reuse.

5. Cost evaluation of BGW desalination

The economic benefits of BGW desalination were assessed by comparing the cost of desalinated water with few other options of supplying water for specific uses. The cost of BGW desalination varies in wide range depending on many factors such as characteristics of feed water source, salinity level of feed water, type of contaminants of concern, type and configuration of pretreatment and desalination system, cost of energy and materials, labor cost, and scale of production. Well-defined methodologies were used for estimating desalinated water costs, but it could be observed that for similar desalination systems, plant capacity and feed water conditions, the costs vary considerably either due to the use of different accounting and taxation criteria for cost analysis or due to varied prices of different inputs such as energy and materials which differ from country to country [28,29]. A detailed cost analysis of each desalination option was not undertaken under this study, but an approximation of the cost was given to each option on the basis of the available data in the literature. The on-site BGW desalination (Option 1) was compared with the following few options of desalinated water supply:

(a) Option 2: desalinated seawater supplied by water network
(b) Option 3: desalinated seawater supplied by water trucks
(c) Option 4: treated wastewater for reuse supplied by water trucks

The cost of on-site BGW desalination was compared with the cost of the other options considering the following cases and assumptions:

(1) Water users are connected to the water network, and their water use exceeds the maximum limit of subsidized water range. The unit water price of 1.6 USD/m^3 is charged, when the user consumption exceeds 301 m^3 per month [30]. Below this level of consumption, the water tariff system is heavily subsidized where users pay less than 5% of water production cost [31].
(2) Water users are not connected to the water network (or connected but water supply is not meeting their needs), and water is supplied by truck tankers. The desalinated seawater trucks' price is on average 1.6 USD/m^3 [30]. Some of the new residential districts in Jeddah depend on truck tankers for water supply. Also, water users in districts connected to water networks rely on truck tankers to meet their daily demands, especially during the summer time where the water supply network cannot meet daily demands.
(3) The cost of tertiary-treated wastewater for reuse was taken at 1.06 USD/m^3, which is the price charged by the NWC for recent contracts with big users of treated wastewater. It could be noticed that the price of the tertiary-treated wastewater is not much lower than the price of desalinated water, which reflects the actual costs of wastewater treatment. The cost of RO desalination of tertiary-treated wastewater must be added and may be considered half of the cost of SWRO desalination [32].
(4) The transportation cost depends on the hauling distance from the distribution location to user location.

The on-site BWRO desalination was expressed in terms of the direct costs per m^3 incurred in the desalination process for a given scale of production, feed water, and desalinated water quality. The direct costs include costs of feed water intake, desalination process, brine disposal, and transportation of the desalinated water to users. The cost function has been formulated as follows:

$$C = C_d(p, s, q) + C_f(p) + C_h(d) + C_b(p) \quad (2)$$

where $C_d(p, s, q)$—cost of desalination process as a function of scale of production, p; feed water salinity, s; and product water salinity, q; $C_f(p)$—cost of feed water intake system as a function of p; $C_h(d)$—cost of hauling desalinated water by water trucks to water users up to distance, d; and $C_b(p)$—cost of brine disposal as function of p.

The on-site BGW desalination was assumed to be practiced at small production capacities; hence, only small-size desalination units will be evaluated. The unit capacity will be selected on the basis of the daily use of the user (Table 2). Small-size desalination units are quite costly in either capital expenses or operation and maintenance daily cost [33]. The production cost of small desalination units could be twice or even higher than for larger SWRO desalination. Based on published data [34], the following cost function was used to relate desalinated seawater cost, CD (US $/m^3$), with desalination unit capacity, p, m^3/d:

$$CD(p) = 9.812p^{-0.22} \quad (3)$$

On the other hand, the cost of BGW desalination depends on the salinity levels of feed water and was found to increase linearly with the increase in salinity. As a rule of thumb, for similar scale of production, the cost of brackish water desalination can be assumed almost one half of the seawater desalination cost.

In this analysis, the cost of BGW desalination was taken as 50% of the seawater desalination cost of similar production capacity. Using Eq. (3), the estimated cost was 2.07, 1.25, and 1.07 US$/m^3$ for unit capacities of 50, 500, and 1,000 m^3/d, respectively (Fig. 3). The estimated costs are similar to the reported values in the literature, where the cost for small BWRO units of less than 1,200 m^3/d capacity was varied between 0.9 and 1.3 USD/m^3 [35]. It is obvious from Fig. 2 that the cost of desalinated water produced by small BWRO desalination units of capacity less than 150 m^3/d will be higher than the purchase of desalinated seawater provided by truck tankers. Since the water needs of most of the prospective users of BWRO desalinated water are lower than this level, it will be advised to encourage private investors to establish small BWRO desalinations units of higher capacity at district level

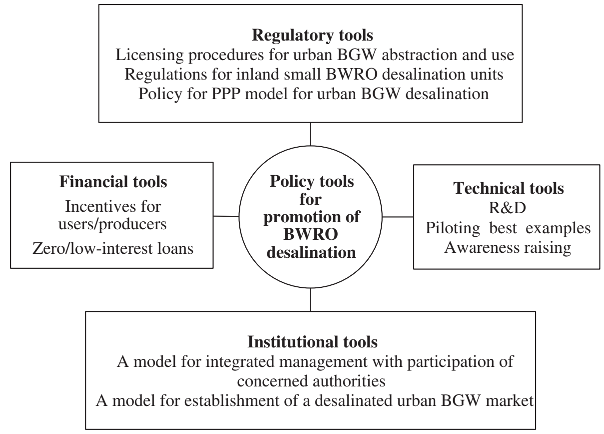

Fig. 2. Needed policy interventions promoting urban BWRO desalination.

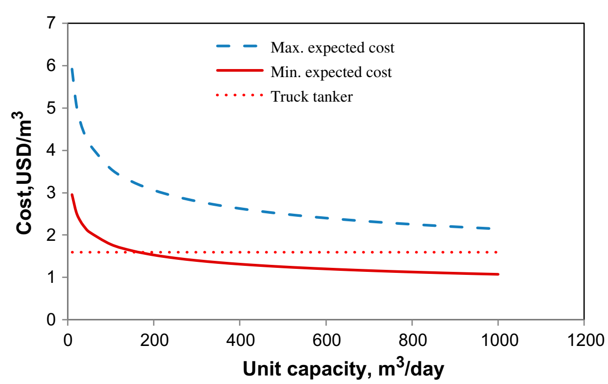

Fig. 3. Cost profile comparison of BWRO desalination option with other alternatives.

Table 2
Potential users of desalinated BGW in urban Jeddah

Water user	Purpose of use	Water needs (m^3/d)
Public park with an area of 5 ha (assuming evapotranspiration value of 6 mm/d)	Irrigation	300
Housing complex (2000 inhabitants, assuming 25–30% of domestic water use is used for toilet flushing)	Toilet flushing	150
Big mosques (2000 persons use toilet per day, water use for toilet flushing 12 l/person)	Toilet flushing	24

for production and sale of BWRO desalinated water for non-potable uses.

The costs of auxiliary facilities such as tube well drilling, pumping system, and brine disposal were considered, while estimating the cost of BGW desalination. Brine disposal of small BWRO is one of the challenges that will be faced by small BWRO units. Probably, the most suitable option is to discharge the brine into the urban storm water network which disposes the flowing stream into the sea. Underground brine injection into the lower saline aquifer formation through injection wells could be another option which is practiced for inland desalination.

Some benefits of BWRO desalination could be easily quantified, but some other benefits have quality and environmental impacts which may have measureable economic values. The BWRO desalination will boost the water supply reliability for users by meeting some of non-potable water uses and conserving considerable amount of drinking water which otherwise would be used for non-potable uses. Users will have a new source of water under their own control, and can expand their economic activities due to improved water availability and gain additional economic benefits. Water utilities will gain economic benefits since for a given quantity of water provided by BWRO units, a similar quantity of desalinated seawater is conserved which, in monetary terms, means conserving financial and energy resources. The network water losses that would be occurred due to distribution of the desalinated seawater are also conserved. Very shallow water table (within 1.5 m below the ground surface) causes health, engineering, and environmental problems and may forms ponds in some places. Problems associated with groundwater table rise such as damage of asphalt streets and basements of buildings will be vanished in the areas affected by this problem, due to expected lowering of water table as a result of groundwater withdrawals.

6. Urban shallow groundwater quality considerations

Numerous studies have been carried out to evaluate the groundwater quality within the Jeddah urban area mostly as a part of exploration studies for construction projects [5,18,23,24,36,37]. These studies reported high salinity levels and pollutions with contaminants of anthropogenic sources. In this study, some water quality parameters were evaluated for samples taken from manholes of the subsurface drainage network of shallow groundwater in four locations in south and east south Jeddah (Table 3). The parameters include pH, turbidity, total coliform bacteria, and concentrations of TDS, nitrate, TOC, COD, and major cations and anions. These parameters have an impact on water purification process using membrane systems since they affect tendency of membranes to fouling and scaling. Although the origin of water is the domestic wastewater, which original TDS values are below 400 mg/l, wide variations in TDS values from location to location were found which are attributed to the accumulation of salts in the top soil profile due to continued evaporation of water, when the groundwater table is very close to ground surface and/or due to dissolution of carbonate minerals in the infiltrated water. Salinity values in these locations, which are similar to salinity levels in many other districts except low lands near the coast, indicate that BGW has low-to-moderate salinity. Moderate salinity values noted in Alsanabel district cannot be attributed to seawater intrusion, because the ground elevation of this area is 31 m above sea level (a.s.l) and it is located at 9 km distance from the sea coast. Previous study reported TDS concentrations ranged from 1,280 to 78,760 mg/l [38]. Another study found TDS ranged between 3,300 and 114,400 ppm [36]. The hyper salinity values were observed in the low lands near the coast due to seawater intrusion and evaporation from the soil surface, while the low salinity are mostly reported in the eastern areas of the basin.

The nitrates concentration of water samples varies between 4 and 135 mg/l. These values are expected as the origin of groundwater is domestic wastewater. Even higher nitrate concentrations of 330 mg/l were reported in groundwater samples collected from wells located around the city center districts affected by groundwater rise problem [23]. A recent study found that total nitrogen concentrations in boreholes located in southern Jeddah districts varied from 2.4 to 61 mg/l with more than 85% of samples had total nitrogen concentrations exceeding 5 mg/l [18], while Subyani and Al-Modayan [37] found nitrates concentration in the port area at approximately 100 mg/l.

The positive effects of soil profile filtration process on the quality parameters of the infiltrated wastewater are manifested by lowering the turbidity values and microbiological contamination of water samples. Turbidity of only 4.6 NTU was observed, and the highest value was 29 NTU, but these values are comparable with typical values observed in most BGW wells. Similarly, the total coliform bacteria count ranged between 61 and 1,600 colonies/100 ml which was much lower than effluents of wastewater treatment plants. The capacity of soil to eliminate pathogens from infiltrated contaminated water is widely recognized, and it has been found that over percolation depths of 2–5 m, the effect of vadose zone attenuation is comparable with

Table 3
Analysis of water samples collected from subsurface drainage network of shallow groundwater in few districts in Jeddah

Parameter	Districts			
	Alsanabel	Kilo 14	Almusaed	Obeid
Topographic data				
Distance from sea coast (km)	9	15	11	13
Ground elevation above msl (m)	31	82	57	64
Manhole depth below ground level (m)	2.2	3.6	2.8	2.5
Analysis results				
pH	7.25	7.02	7.13	7.2
TDS (mg/l)	6,097	1,787	955	706
Turbidity (NTU)	29	10.6	14.2	4.5
TOC (mg/l)	8.0	13.6	12.5	8.2
COD (mg/l)	51.60	57	33.5	46.3
Nitrite (NO_2^-) (mg/l)	0.58	5.37	0.73	1.39
Nitrate (NO_3^-) (mg/l)	135.29		3.99	10.49
Phosphate (PO_4^-) (mg/l)			3.21	2
Sulfate (SO_4^-) (mg/l)	1,910	332	211	109
Fluoride (F^-) (mg/l)	1.07	0.87	0.74	1.06
Chloride (Cl^-) (mg/l)	3,234	757	290	195
Bromide (Br^-) (mg/l)	6.88	2.2	0.77	0.51
Sodium (Na^+) (mg/l)	2,097	612	311	267
Potassium (K^+) (mg/l)	23.13	11.1	6.85	4.87
Magnesium (Mg^{2+})	149	26.5	12.92	4.4
Calcium (Ca^{2+}) (mg/l)	398	102	46.95	27.99
Total coliform bacteria (MPN/100 ml)	61	920	1,600	350

Table 4
Maximum allowable levels of quality parameters for WWTP effluents as proposed in the draft Implementing Regulations: Treating Wastewater and its Reuse Law (PME, Saudi Arabia)

Quality parameter	Secondary treatment	Tertiary treatment	Quality parameter	Secondary treatment	Tertiary treatment
TSS (mg/l)	40	10	Cr (chromium)	0.1	0.1
pH	6–8.4	6–8.4	Co (cobalt)	0.05	0.05
TDS (mg/l)	2,500	2,500	Cu (copper)	0.4	0.4
BOD_5 (mg/l)	40	10	F (fluoride)	1	1
Turbidity (NTU)	5	5	Fe (iron)	5	5
Number of CF colonies (colonies/100 ml)	1,000	1.2	Pb (lead)	0.1	0.1
Helminthes eggs (live egg/l)	1	1	Mo (molybdenum)	0.01	0.01
NO_3^--N (nitrate-N)	10	5	Ni (nickel)	0.2	0.2
NH_3^--N (ammonia-N)	10	5	Se (selenium)	0.02	0.02
Al (aluminum)	5	5	V (vanadium)	0.1	0.1
As (arsenic)	0.1	0.1	Zn (zinc)	4	4
Be (beryllium)	0.1	0.1	Li (lithium)	2.5	2.5
B (boron)	0.75	0.75	Mn (manganese)	0.2	0.2
Cd (cadmium)	0.01	0.01	Hg (mercury)	0.001	0.001
Cl_2 (free chlorine)	>0.5	>0.5	–	–	–

Note: Adapted from [14].

tertiary-level wastewater treatment [39]. In some areas of the city, the low contamination levels of groundwater which meets the national standards for specific reuse applications suggest that this water source can be utilized directly without any pretreatment. In other locations where BGW parameters fall short to meet the quality standards for reuse, a proper purification process shall be advised which assures the minimum water quality levels for water reuse at reduced expenses.

Table 4 shows typical water quality parameters proposed by the Presidency of Meteorology and Environment (PME) in Saudi Arabia for water reuse applications in agriculture and industry which involve direct or indirect human contact [15]. The quality parameters for water reuse are basically developed for treated wastewater effluents, since these effluents are of concern for public health of environment protection. Logically, these parameters can be used to assess the suitability of the contaminated urban brackish shallow groundwater for reuse of specific application with or without additional purification steps.

7. Conclusions

(1) Shallow groundwater occurrence is observed all over the urbanized areas of Jeddah mainly due to infiltration of wastewater from cesspits and network leakages. In general, salinity values are related to the elevation and distance from the sea coast. Low-to-moderate salinity was observed in the eastern urban districts compared to low lands near the coast.

(2) Shallow groundwater could be integrated into the urban water cycle of the city and considered as a potential new source for water reuse. In some areas of the city, salinity and contamination levels of groundwater are as low to meet the national standards for specific reuse applications; while in other locations, the quality parameters fall short to meet the quality standards for reuse. A proper purification process shall be advised which assures the minimum water quality levels for water reuse at reduced expenses.

(3) The production cost of BWRO unit with a capacity less than 150 m^3/d is higher than the purchase option of desalinated seawater supplied by truck tankers; hence, it is advised to encourage private investors to establish small BWRO desalinations units of higher capacity at district level for production and sale of BWRO desalinated water.

(4) The BWRO desalination would bring about economic and environmental benefits to water users and municipality as it will boost the water supply reliability by meeting some of non-potable water uses and conserving considerable amount of drinking water. Also the health, engineering, and environmental problems caused by shallow groundwater table rise would be mitigated.

(5) The measured quality parameters of shallow groundwater in terms of turbidity, TOC, COD, and microbiological contamination are very much better than the quality parameters of domestic wastewater indicating positive effects of soil profile filtration process.

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References

[1] A. Kajenthira, A. Siddiqi, L.D. Anadon, A new case for promoting wastewater reuse in Saudi Arabia: Bringing energy into the water equation, J. Environ. Manage. 102 (2012) 184–192.

[2] M. Al-Saud, G. Teutsch, C. Schüth, R. Rausch, Challenges for an integrated groundwater management in the Kingdom of Saudi Arabia, Int. J. Water Resour. Arid Environ. 1(1) (2011) 65–70.

[3] Ministry of Water & Electricity, Nomination of Ministry of Water & Electricity, Kingdom of Saudi Arabia, Supporting Documents for King Hassan II Great World Water Prize 2012, 2012. Available from: <http://www.worldwatercouncil.org/fileadmin/wwc/Prizes/Hassan_II/Candidates_2011/16.Ministry_SA.pdf>. Accessed 20 January 2013.

[4] ESCWA, Water Resources Issues in the ESCWA Region: Country Fact Sheets, United Nations Economic and Social Commission for Human Rights, Beirut, Lebanon, 2009.

[5] Ramboll, Jeddah Environmental Assessment (JEA) Data Assessment and Analysis Report: Groundwater, Document number: 071-124109002-ENV-REP, Governorate of Jeddah, 2013.

[6] Ramboll, Jeddah Environmental Assessment (JEA) Data Assessment and Analysis Report: Wastewater,

Document number: 082-124109002-ENV-REP, Governorate of Jeddah, 2013.
[7] G. Amy, J.E. Drewes, Soil aquifer treatment (SAT) as a natural and sustainable wastewater reclamation/reuse technology: Fate of wastewater effluent organic matter (EfOM) and trace organic compounds, Environ. Monit. Assess. 129 (2007) 19–26.
[8] J.E. Drewes, Ground water replenishment with recycled water—Water quality improvements during managed aquifer recharge, Ground Water 47(4) (2009) 502–505.
[9] M.A. Ashraf, M.A. Rehman, Y. Alias, I. Yusoff, Removal of Cd(II) onto Raphanus sativus peels biomass: Equilibrium, kinetics, and thermodynamics. Desalin. Water Treat. 51 (22–24) (2013) 4402–4412.
[10] M.A. Ashraf, A.M. Khan, M. Ahmad, S. Akib, K.S. Balkhair, N.K. Abu Bakar, Release, deposition and elimination of radiocesium (Cs-137) in the terrestrial environment. Crit. Rev. Env. Sci. Technol., 44(15) (2014) 1740–1793.
[11] N.H. Hussin, I. Yusoff, Y. Alias, S. Mohamad, N.Y. Rahim, M.A. Ashraf, Ionic liquid as a medium to remove iron and other metal ions: A case study of the North Kelantan Aquifer, Malaysia, Environ. Earth Sci., Online first, 2013, doi: 007/s12665-013-2615-5.
[12] P. Fox, K. Narayanaswamy, A. Genz, J.E. Drewes, Water quality transformations during soil aquifer treatment at the Mesa Northwest Reclamation Plant, USA. Water Sci. Technol. 43 (2001) 343–350.
[13] C. Lin, G. Eshel, I. Negev, A. Banin, Long-term accumulation and material balance of organic matter in the soil of an effluent infiltration basin, Geoderma 148 (2008) 35–42.
[14] D.E. John, J.B. Rose, Review of factors affecting microbial survival in groundwater, Environ. Sci. Technol. 39 (2005) 7345–7356.
[15] KAUST, Promoting Wastewater Reclamation and Reuse in the Kingdom of Saudi Arabia: Technology Trends, Innovation Needs, and Business Opportunities, The KICP Annual Strategic Study, KAUST Industry Collaboration Program (KICP), King Abdullah University of Science and Technology (KAUST), Thuwal, 2011.
[16] Y. Umezawa, T. Hosono, S. Onodera, F. Siringan, S. Buapeng, R. Delinom, C. Yoshimizu, I. Tayasu, T. Nagata, M. Taniguchi, Sources of nitrate and ammonium contamination in groundwater under developing Asian megacities, Sci. Total Environ. 404 (2008) 361–376.
[17] A.A. Al-Harthi, Preliminary environmental assessment of the pollution of soil and water at Wadi Uranah, Makkah Al-Mukarramah, Saudi Arabia, JKAU, Earth Sci. 13 (2001) 123–150.
[18] AECOM, WER 10—Task 2—Groundwater Modelling, Jeddah Storm Water Drainage Program, 2012.
[19] AECOM, JSDP—Large Scale Hydrological Modelling, Jeddah Storm Water Drainage Program, Jeddah, 2012.
[20] J. Marsalek, B. Jiménez-Cisneros, M. Karamouz, P. Malmquist, J. Goldenfum, B. Chocat, Urban Water Cycle Processes and Interactions, Urban Water Series, vol. 2, The United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris; Taylor & Francis The Netherlands, Leiden, The Netherlands, 2008.
[21] D.N. Lerner, Identifying and quantifying urban recharge: A review, Hydrol. J. 10 (2002) 143–152.
[22] R.C. Beeson, in: G. Gerosa, Evapotranspiration from Measurements to Agricultural Environmental Applications, InTech, Rijeka, Croatia, 2011, pp. 347–370.
[23] O. Abu-Rizaiza, H. Sarikaya, M. Khan, Urban groundwater rise control: Case study, J. Irrig. Drain Eng. 115 (4) (1989) 588–607.
[24] S.A. Al-Sefry, Z. Şen, Groundwater rise problem and risk evaluation in major cities of arid lands—Jedddah case in Kingdom of Saudi Arabia, Water Resour. Manage 20(1) (2006) 91–108.
[25] A. Basamad, Hydrochemical Study and Bacteriological Effect on Groundwater in the Northern Part of Jeddah District, M.S. Thesis, Faculty of Earth Sciences, King Abdul Aziz University, Jeddah, Saudi Arabia, 2002.
[26] Jeddah Municipality, Jeddah Strategic Plan, Section 8: Infrastructure, Jeddah, 2009. Available from: <www.jeddah.gov.sa/strategy/English/JSP/JSPFiles/JSP-Eng-08-Infrastructure.pdf>, Accessed 7 July 2013.
[27] A.A. Bushnak, Desalination. in: M. El-Ashry, N. Saab, B. Zeitoon (Eds.), Arab Environment: Water – Sustainable Management of a Scarce Resource, Arab Forum for Environment and Development (AFED), Beirut, 2010, pp. 125–136.
[28] M.H.I. Dore, R.G. Singh, G. Achari, A. Khaleghi-Moghadam, Cost scenarios for small drinking water treatment technologies, Desalin. Water Treat. 51(16–18) (2013) 3628–3638.
[29] I.C. Karagiannis, P.G. Soldatos, Water desalination cost literature: Review and assessment, Desalination 223 (2008) 448–456.
[30] O.K.M. Ouda, Review of Saudi Arabia municipal water tariff, World Environ. 3(2) (2013) 66–70.
[31] O.K.M. Ouda, Towards assessment of Saudi Arabia public awareness of water shortage problem, Resour. Environ. 3(1) (2013) 10–13.
[32] P. Côté, S. Siverns, S. Monti, Comparison of membrane-based solutions for water reclamation and desalination, Desalination 182 (2005) 251–257.
[33] D. Akgul, M. Çakmakcı, N. Kayaalp, I. Koyuncu, Cost analysis of seawater desalination with reverse osmosis in Turkey, Desalination 220 (2008) 123–131.
[34] A. Hafez, S. El-Manharawy, Economics of seawater RO desalination in the Red Sea region, Egypt. Part 1. A case study, Desalination 153 (2002) 335–347.
[35] I.S. Jaber, M.R. Ahmed, Technical and economic evaluation of brackish groundwater desalination by reverse osmosis (RO) process, Desalination 165 (2004) 209–213.
[36] M.B. Alquhtani, W.M. Shehata, Vulnerability Map of the Groundwater Rise in Jeddah, Saudi Arabia, 12th Asian Regional Conference of Soil Mechanics and Geotechnical Engineering, 4–8 August 2003, Singapore, pp. 357–363.
[37] A.M. Subyani, A.A. Al-Modayan, Groundwater vulnerability risk maps using GIS and DRASTIC Index Method for Jeddah City, Western Saudi Arabia, J. King Abdulaziz Univ., Faculty Earth Sci. 23(2) (2012) 71–156.
[38] T.H. Bayumi, M.S. Alyamani, Use of factor analysis to identify sources controlling groundwater chemistry in shallow coastal plain aquifer, Western Saudi Arabia, J. King Abdulaziz Univ., Faculty Earth Sci. 214 (2003) 91–112.
[39] S.S.D. Foster, P.J. Chilton, Downstream of downtown: Urban wastewater as groundwater recharge, Hydrol. J. 12 (2004) 115–120.