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Management options for a multipurpose coastal aquifer in Oman

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Abstract Using MODFLOW 2005, this study numerically evaluated the effects of managed aquifer recharge (MAR) using treated wastewater (TWW) in managing the Al-Khawd coastal aquifer northeast of Oman. Our primary objective is to increase the urban water supply and to sustain the aquifer service with the lowest possible damage to the aquifer. A number of managerial scenarios were simulated and progressively developed to reduce seawater intrusion and outflow of the groundwater to the sea. An economic analysis was conducted to characterize the trade-off between the benefits of MAR and seawater inflow to the aquifer under increased abstraction for domestic supply. The results show that by managing irrigation wells and relocating public wells in conjunction with MAR practices, the abstracted volume for drinking purposes could be doubled. Even though injection of TWW is more expensive (due to the injection cost), it was observed to result in greater benefits. The results indicate that managing the aquifer would produce a net benefit ranging from $8.22 million (scenario 7) to $15.21 million (scenario 4) compared to $1.57 million with the current practice. In conclusion, MAR using TWW is a feasible solution to develop water resources in arid regions, and the best scenario depends on the decision maker's preference when weighing the benefits of MAR and the level of damage to the aquifer. MAR could help manage stressed aquifer systems in arid zones to maximize the benefit of using the water for domestic purposes while minimizing the damage to the aquifer.

Keywords Arid zone · Managed aquifer recharge · Reuse of treated wastewater · Seawater intrusion · Groundwater simulation

Introduction

Arid countries are facing challenges from water shortages that threaten economic development and social stability (Schneier-Madanes and Courel 2010; Kelley et al. 2015). Efforts to augment the water supply are common practice in most countries (Bouwer 2002; Seiler and Gat 2007; NRC 2008; MRMWR 2012). The majority of practices include the construction of recharge dams to capture runoff from flash floods and the introduction of modern irrigation technology and seawater desalination to reduce the pressure on groundwater resources (Kresic 2009; Healy 2010).

Tremendous effort in Oman has been devoted to augmenting conventional and non-conventional water resources (desalination and treated wastewater (TWW)). However, water supply augmentation by desalination is not an efficient solution; it is very costly and exerts pressure on the financial resources of the country (Zekri et al. 2014a). The high cost of desalinated water limits its use to domestic purposes and high economical value activities.

The reuse of TWW has been considered as an alternative to water supply augmentation (Aertgeerts and Angelakis 2003; Kamizoulis et al. 2003; Asano and Cotruvo 2004; EPA 2005;

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Voudouris 2006, 2011). In suitable hydrological and hydrogeological settings, aquifers can store TWW via managed aquifer recharge (MAR) until the water is most needed and can provide additional purification using porous soil and rock as filters and adsorbents of any potentially remaining contaminants. Furthermore, aquifer storage and recovery (ASR) is often less expensive and causes fewer environmental impacts than traditional surface reservoirs.

MAR using TWW faces several challenges and risks, both technical and economical (Hayder Consulting 2006). The technical challenges include understanding the development of the groundwater mound (Tóth 2009), the dynamics of its development and dissipation, the storage period of the injected water and the water recovery rate and distance from the injection site. This can be achieved by improved aquifer characterization and modelling groundwater mounds generated by MAR practices.

The city of Muscat (Oman) has an aquifer allocated for emergency uses. The aquifer is protected and used mainly for urban purposes and is replenished through subsurface flows and during infrequent flash flood events. Groundwater level variations are caused by different stresses, such as periodic recharge, abstraction patterns and discharge to the sea. Natural recharge is uncontrolled, variable and uncertain. Discharge to the sea occurs if the hydraulic gradient gets stronger in the seaward direction and can be reasonably controlled through proper use of the aquifer. Pumping is controllable and adjustable to a certain degree. This study addresses management scenarios for the Al-Khawd costal aquifer for daily and for emergency purposes and builds on the work of Zekri et al. (2015a). This study compares several scenarios, including (1) stopping agricultural pumping by providing TWW to farmers instead, (2) direct injection of TWW while assuring that injected TWW does not mix with native groundwater and reach the capture zone of domestic water supply wells and minimizing seepage to the sea and (3) a combination of the first two scenarios. In all the scenarios, the objective is to maximize the economic returns from the aquifer, reduce the losses through seepage and sustain the aquifer services. The main goal is to increase the abstracted volume for urban uses via managing irrigation wells and relocating a number of public wells in conjunction with MAR practices. The constraints under which MAR simulations are designed are (1) injected TWW should not reach the capture zone of native water by public wells and (2) water outflow through the costal boundary should be minimized.

Different managerial scenarios were evaluated numerically using MODFLOW 2005 (Harbaugh 2005) with Model Muse as a graphical interface (Winston 2009). A particle tracking model, MODPATH (Pollock 2012), was used to track the travel path of imaginary injected particles via advection using the output file of the velocity fields generated by MODFLOW 2005. Therefore, we were able to track the plume of the injected TWW and explore its possible interference with the native urban water supply wells.

Overview of MAR in arid countries

Groundwater dynamics in recharge areas are controlled by the geological nature and hydraulic properties of the aquifer and soil. Natural heterogeneity and anisotropy of the subsurface make groundwater flow patterns difficult to predict accurately. Studying the groundwater flow patterns under MAR at a specific site can be achieved via numerical modelling (Shammas 2008; Dillon 2009; Baawain 2010; Walther et al. 2012; Kacimov et al. 2015; Walther et al. 2014). The feasibility and efficiency of MAR have been studied numerically using MODFLOW and MT3DMS in the United Arab Emirates (Sherif 2014). The developed model serves as a predictive tool to estimate the recovery rate. Baawain (2010) studied the impact of TWW recharge on the water quality of the Salalah coastal aquifer in Oman. Shammas (2008) numerically assessed the impact of MAR using TWW to combat seawater intrusion in Salalah. The developed model predicted wedges of saline intrusion in 2019 of up to 2.7 and 3.4 km from the shoreline with and without the injection respectively, under constant underflow. The results indicated that the MAR scheme can effectively induce a recession of the saline waterfront by 700 m, and if integrated with irrigation water management practices, the saline interface can recede even greater distances. For the latter, MAR involves the design and management of artificial recharge systems that involve geological, geochemical, hydrological, biological and engineering aspects. Therefore, planning, design and construction of MAR systems must start with feasibility studies. Kacimov et al. (2015) explored groundwater mound and dynamics using both analytical and numerical models of unmanaged aquifer recharge using TWW in the Al-Ansab wetlands in Oman. Understanding the fate of recharged water and its impact (e.g. water table rise) is important to avoid unpleasant consequences (e.g. geotechnical problems) and to better manage water resources.

The hydrogeochemistry of TWW is also important to consider in the context of MAR efficiency because TWW may have one or more dissolved constituents (depending on the treatment level and technology) that could lead to clogging, fouling and incrustation at the pond bottom, the well screen/gravel pack and the well pipes (Voudouris 2011). Ensuing alterations of the aquifer, soil and the well itself may ultimately reduce MAR efficiency. Even though the hydrochemistry is very important, it was not considered in this study.

Oman has one of the highest water scarcity indices in the world, which hinders the development of several economic activities. Oman is moving towards recycling tertiary TWW to augment its existing water resources for different uses. The

Al-Khawd aquifer in the Samail lower catchment (SLC) is one of the important aquifer systems that is used to supply urban water to the city of Muscat in Oman, which has a population of approximately 1,210,480 (NCSI 2015). At present, the aquifer is accessed via 68 public wells at a minimum rate of approximately 6.83 Mm^3 annually because the city receives a supply of desalinated water (Zekri et al. 2014b). An additional 1.3 Mm^3 is abstracted for farming activities. The high cost of seawater desalination and its high energy demand along with its environmental impacts requires a reconsideration of the way the aquifer is managed (Zekri et al. 2014b, 2015a). At the same time, stressing the aquifer to supply the volume demanded by Muscat city will result in seawater intrusion and deteriorate groundwater quality, as the aquifer is only replenished by sporadic and erratic patterns of rainfall. MAR using TWW is expected to allow the additional abstraction of pristine water for urban supply with minimum damage to the aquifer.

In the city of Muscat, the Oman Wastewater Services Company "HAYA Water" is in charge of collecting, treating and disposing of wastewater. The treated effluent is estimated to have reached 150,000 m^3/day in Muscat by the end of 2015 (Zekri et al. 2015b). The HAYA Water Company expects that a surplus of up to 100,000 m^3/day will become available during the winter months after meeting the demand for irrigating roadside ornamental plantations, parks and other municipal uses. The HAYA Water Company uses membrane bio-reactors to treat the wastewater. Therefore, this source of water for MAR is considered to be TWW (almost at the level of potable water quality), which may not need additional water treatment.

Materials and methods

Study area

Several papers (e.g. Al-Lawati 1997; Kacimov et al. 2010; Abdalla and Al-Abri 2011; Ebrahim 2013; Zekri et al. 2014b, 2015a) have presented detailed discussions concerning the geological catchment and the hydrogeological properties of the study area; therefore, only a brief discussion is provided below.

The study area comprises the coastal plain of the Wadi Samail catchment and covers an area of approximately 59 km^2 (Fig. 1). The study area is enclosed by the Gulf of Oman to the north, the Wadi Samail catchment to the south, the Wadi Taww to the west and the Wadi Rusayl to the east. In addition to irrigation water, the area has been an important source of potable water supply to a large part of the capital of Muscat throughout the last three decades. Currently, the aquifer is considered a strategic reserve.

To augment water resources through natural recharge during major rainfall events, the Al Khawd recharge dam was constructed between December 1983 and March 1985 in the SLC approximately 7 km from the Gulf of Oman (Fig. 1) (Kacimov et al. 2010; Abdalla and Al-Abri 2011). Both increasing demand and the prevailing arid climate have made the recharge dam inadequate to replenish or control the overexploited aquifers. Therefore, MAR using TWW as an alternative source of aquifer recharge has become increasingly important.

Geology and hydrology of the study area

The SLC mainly consists of Quaternary alluvial deposits, which form extensive terraces and alluvial fans. The catchment deposits are divided into recent and ancient alluvium units. The former makes up approximately 70 % of the total alluvial deposits and thickens towards the coast. The main difference between the recent and ancient alluvium is that the former is better sorted and shows less calcretization and cementation than the latter (Al-Lawati 1997; Ebrahim et al. 2015). Hydrologically, the aquifer is modelled as two primary units.

The aquifer thickness gradually increases from the upstream to the coast of the Gulf of Oman. Due to limited data availability, the thickness of the aquifer in the upstream areas is assumed to be 100 m and to linearly increase towards the coast where it reaches a maximum value of 350 m. This assumption is based on the maximum drilled depths observed in geologic logs within the study area (MWR 1993; Al-Lawati 1997).

Considering the entire Samail catchment, the orographic effect is clearly evident in the distribution of rainfall in the Wadi Samail catchment (MWR 1997). This is clear from the rainfall variation between the upper and lower catchments. The average annual rainfall is 140 mm/year in the upper catchment, while it is approximately 100 mm/year in the lower reaches of the catchment. The aquifer receives approximately 1 million m^3 of water as a direct recharge from rainfall (20 % of the average annual rainfall volume) as illustrated by the calibrated model for the same aquifer (Ebrahim et al. 2015). However, the majority of the recharge is due to surface runoff and subsurface flow from the upper part of the catchment (Abdalla and Al-Rawahi 2013). Inputs to the recharge package in MODFLOW took into consideration the different recharge processes (Ebrahim et al. 2015). Estimating the recharge to aquifers is always a difficult challenge in arid regions (Sen 2008).

Model setup

The conceptual model of the study area is presented in Fig. 2 along with information concerning the observation

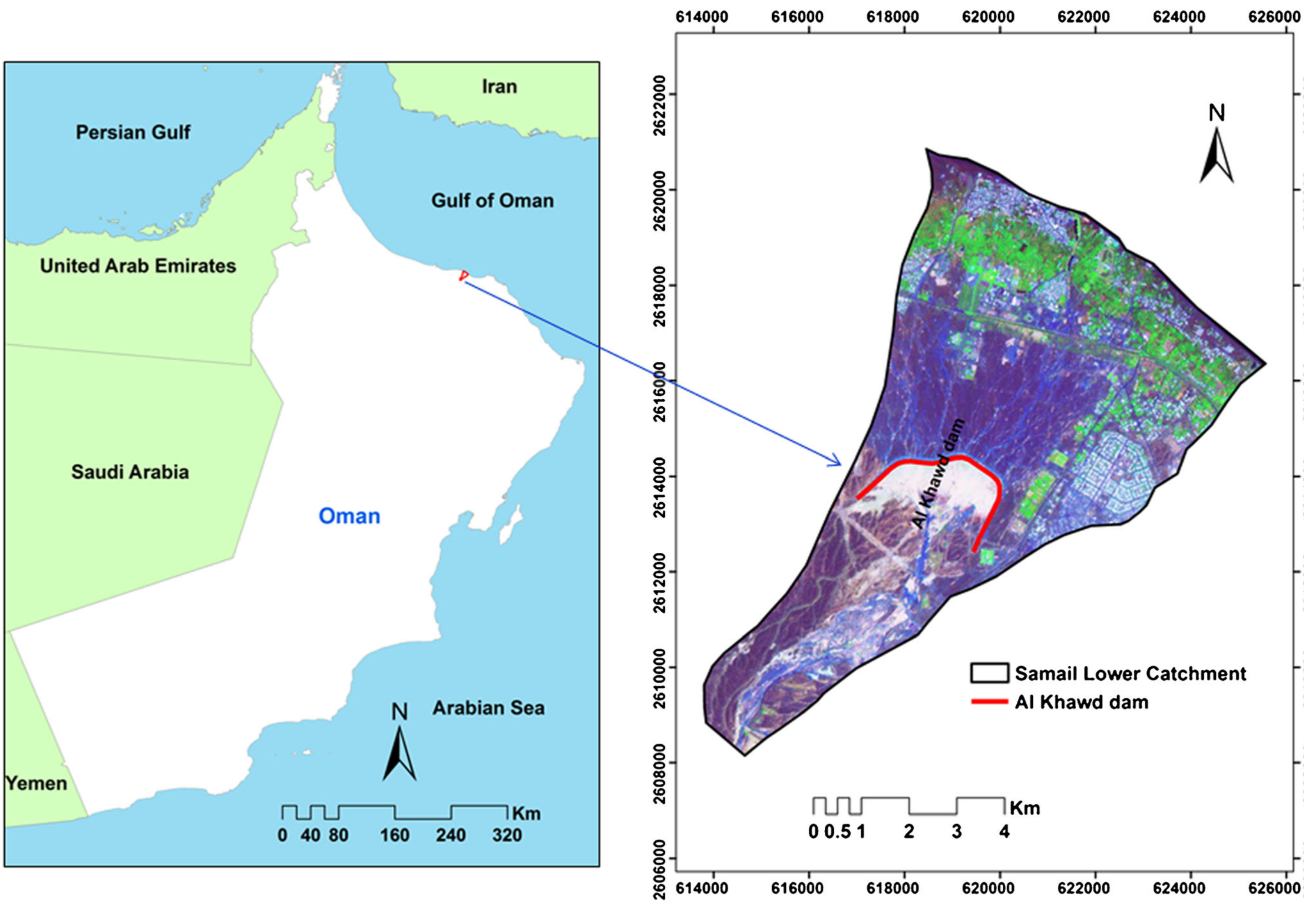

Fig. 1 Location of the Samail lower catchment area

wells, public and irrigation wells, recharge zones, hydraulic conductivity (K) zones and different boundary conditions. The SLC unconfined aquifer is modelled as a single hydrogeological unit (with two-distinct zones, upstream and downstream, with different permeability) that is further divided into four layers for the positioning of injection well screens. For each layer, the horizontal grid block dimensions are 30 m and the modelling domain has 692 rows and 687 columns resulting in a total of 2,322,880 active cells. The simulation time is chosen to be 12 years with 144 stress periods of 30 days long. The analysis (both hydrological and economical) is performed in yearly basis to explore the aquifer response under different scenarios over relatively short period of time (the 12 years).

A calibrated model developed by Ebrahim et al. (2015), with a mean absolute error (MAE) between the observed and simulated groundwater head values of 0.65 m and a root mean square error (RMSE) of 0.70 m, was used.

The different scenarios presented here were simulated with transient conditions using the hydraulic properties from the calibrated steady state model. The data regarding hydraulic heads and historical pumping rates were not sufficient to allow calibration of the transient model parameters. When data becomes available, the model should be calibrated under transient state which will improve the reliability of the model; however, the calibrated steady state model is qualified for the presented work in this paper. Table 1 presents the model parameters of the calibrated steady state model. Details of other parameters and the boundary conditions are presented in Ebrahim (2013) and Ebrahim et al. (2015).

Simulated scenarios

The management scenarios were designed under the constraint that the injected TWW in the SLC aquifer does not mix with the native water used for urban supplies. Because the existing legislation does not allow a mixing of TWW with drinking water, MAR practices are

Fig. 2 Maps of the study area that illustrate **a** the boundary conditions, locations of public and irrigation wells and zones of different hydraulic conductivities as well as **b** the location of observation wells (*upper panel*) and recharge zones (*lower panel*) ▶

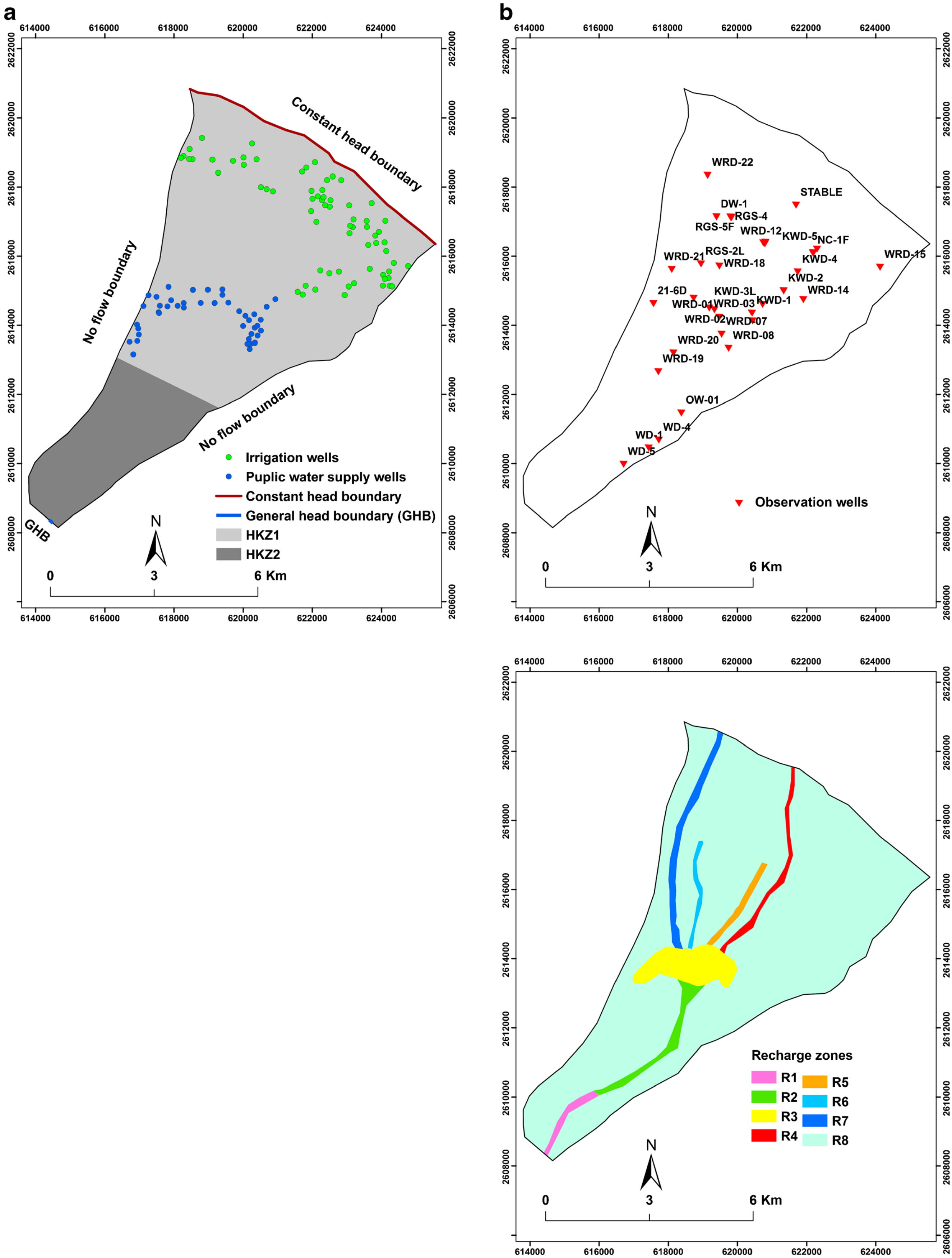
a
Constant head boundary
No flow boundary
No flow boundary
GHB
Irrigation wells
Puplic water supply wells
Constant head boundary
General head boundary (GHB)
HKZ1
HKZ2
N
0 3 6 Km
b
WRD-22
STABLE
DW-1
RGS-4
RGS-5F
WRD-12
KWD-5
NC-1F
WRD-21
RGS-2L
KWD-4
WRD-15
WRD-18
KWD-2
21-6D
KWD-3L
WRD-14
WRD-01
WRD-03
KWD-1
WRD-02
WRD-07
WRD-20
WRD-08
WRD-19
OW-01
WD-4
WD-1
WD-5
Observation wells
N
0 3 6 Km
Recharge zones
R1
R2
R3
R4
R5
R6
R7
R8
N
0 3 6 Km

Table 1 Model parameters used for the simulation of SLC (Ebrahim et al. 2015)

Parameter	Value	Unit	Description
HKZ1	0.79	m/day	Hydraulic conductivity of zone 1
HKZ2	7.76		Hydraulic conductivity of zone 2
R1	3.29×10^{-4}	m/day	Recharge from Wadi far upstream of the dam
R2	1.59×10^{-2}		Recharge from Wadi upstream of the dam
R3	1×10^{-5}		Recharge from the dam itself
R4	3.92×10^{-3}		Recharge from the downstream Wadi (east)
R5	5.28×10^{-3}		Recharge from the downstream Wadi
R6	8.25×10^{-5}		Recharge from the downstream Wadi
R7	9.88×10^{-5}		Recharge from the downstream Wadi (west)
R8	3.64×10^{-6}		Recharge from precipitation
VZ1	10	m/day	Vertical anisotropy for zone 1
VZ2	1		Vertical anisotropy for zone 2
EVT	5	mm/day	Evapotranspiration rate (ET)
GHB_C	1	m^2/day	Conductance for the general head boundary
S_y	0.2	–	Specific yield

constrained. However, MAR could help induce a hydraulic barrier to seawater intrusion and reduce the stress to the aquifer caused by abstraction for both urban and farming uses, allowing more water to be pumped out for urban water purposes. Therefore, the supply of desalinated water could be reduced, and considerable cost cuts could be achieved given the high cost of seawater desalination economically and environmentally. However, the TWW volumes disposed of to the sea should be minimized (Zekri et al. 2015b). Table 2 describes the different scenarios considered. The assigned volume of the injected TWW was chosen based on the current abstracted volume from the irrigation wells and the constraints mentioned above. The main focus of this study was to explore MAR's effect on enhancing the urban supply with the lowest possible damage to the aquifer with minimal cost. Ideally, optimization techniques would have been used to come up with the optimum values of injected volume and number of injection wells coupled with minimizing loss to the sea and preventing the injected TWW from reaching the capture zone of public wells. This was not attempted in this study and is a subject of future work. Only a limited number of scenarios were evaluated in this study. Eight scenarios were proposed and progressively developed after each simulation to look for improvements to reduce seawater inflow or to reduce the groundwater outflow to the sea. Scenario 1 considers a threefold increase as a sharp steps function in the abstraction from the public wells compared to the base case scenario based on the results obtained by Zekri et al. (2015a). Scenario 2 adds

Table 2 Description of the simulated scenarios

Scenario	Description
Base case (BCS)	This case represents the current condition.
S1	This scenario illustrates the case when the abstraction rate from the public wells is increased as recommended by (Zekri et al. 2015a) with no MAR.
S2	This scenario is similar to S1 with MAR injecting TWW for farmer's use.
S3	In this scenario, a volume of 3536 m^3/day of TWW is provided free of charge to farmers through direct pipelines in exchange for shutting down their agricultural wells.
S4	This scenario is similar to S2 except that the injection wells are located near the coast (pattern 2—Fig. 3) using 38 injection wells with an injection rate of 121 m^3/day per well.
S5	This scenario is similar to S4 with reduced pumping from public wells.
S6	This scenario is similar to S5 with relocated public wells.
S7	This scenario is similar to S6 with a 25 % reduced abstracted volume.
S8	This scenario is similar to S7 but without injection of TWW.

injection of TWW to scenario 1 to reduce seawater intrusion. In all scenarios that consider injection of TWW, the annual volumes injected are constant since they are a small portion of the currently disposed of to the sea volumes. Scenario 3 adds to scenario 1 the free distribution of TWW to farmers in return for shutting down their wells. Scenario 4 relocates the injection wells in scenario 2 closer to the sea to test their effect on seawater inflow. Scenario 5 reduces the pumping from public wells compared to scenario 4 to reduce inflow from the sea and the decline in the groundwater level. Scenario 6 reproduces scenario 5 with a more widespread distribution of public wells. Scenario 7 considers a 25 % decrease in pumping from public wells compared to scenario 6 to reduce the inflow from the sea. Finally, scenario 8 eliminates the injection of TWW considered in scenario 7 to reduce the outflow to the sea and to evaluate the impact of MAR using TWW induced under S7.

It is well known that recharge will result in mounding of the water table causing a steeper hydraulic gradient in the vicinity of the injection zone. This affects the dynamics of the injected water and its residence time. Injecting water close to the sea or any discharging boundary will shorten the residence time and accelerate the outflow of the injected water. Therefore, the site of injection wells should be selected based on aquifer properties, distance from the sea and distance from public wells along with land use availability (private property). Figure 3 presents the location of the injection wells and the head distribution in the aquifer after 12 years of simulation in the base case (BCS). Two patterns of injection wells distribution were used. In pattern 1, 10 injection wells were modelled with an injection rate of 459.6 m^3/day per well, and in pattern 2, 38 injection wells were modelled with an injection rate of 121 m^3/day per well and the injection wells were relocated in the seaward direction. In pattern 1, injection wells were located at an average distance of 2.3 km from the coastal line and approximately 2 km from the public wells, while there was an average distance of 0.8 and 4 km respectively, for pattern 2.

The spacing between the injection wells was kept between 100 and 300 m as recommended by Pyne (1995) to avoid over-mounding due to fusion of adjacent mounds of different

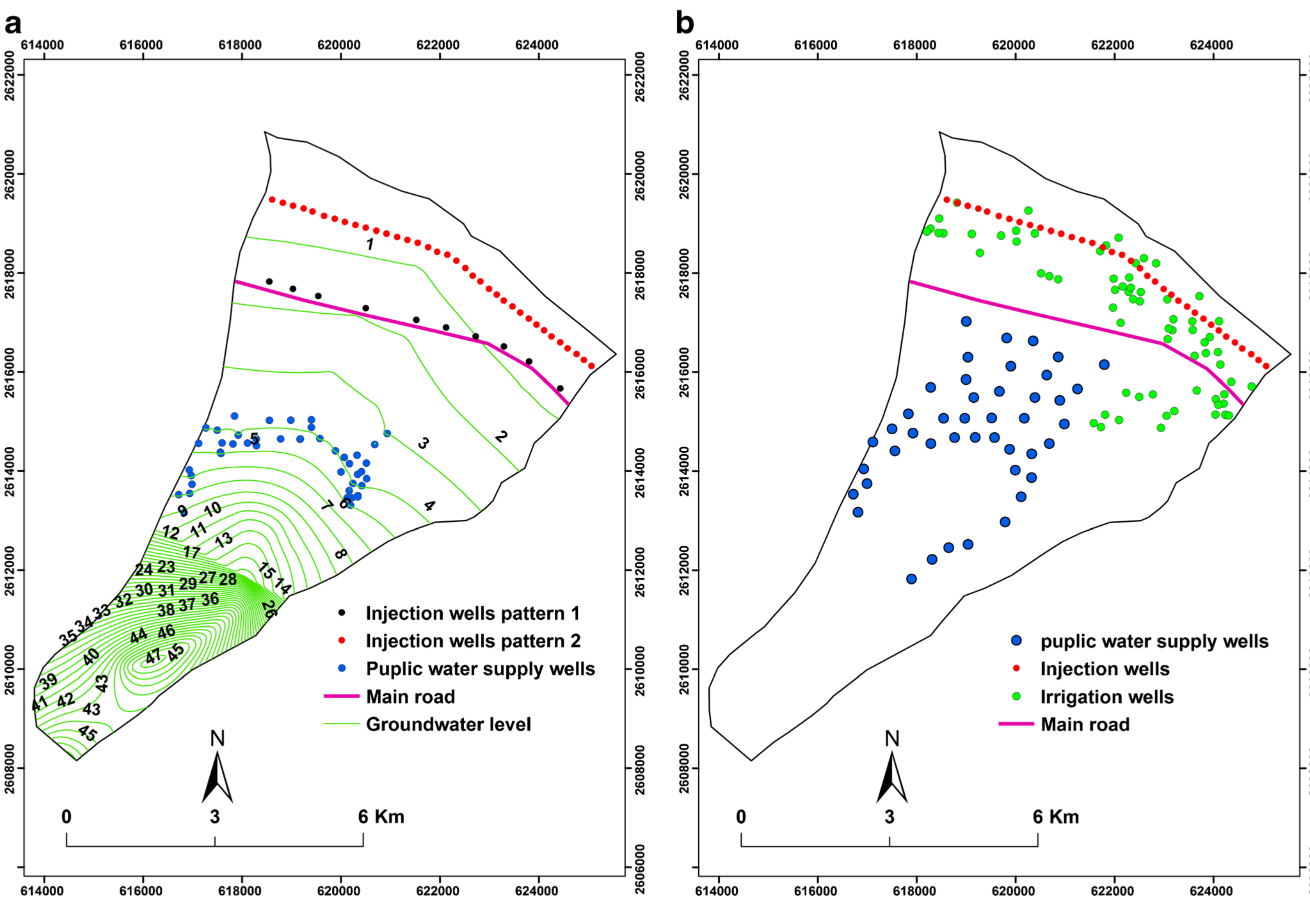

Fig. 3 **a** Simulated groundwater head at the end of stress period 144 (end of year 12) along with the locations of proposed injection wells (patterns 1 and 2). **b** Locations of the redistributed public wells (*blue*)

injection wells, which is impractical and may cause geotechnical and environmental problems.

Results and discussion

Water balance and simulated groundwater levels

The results of the simulated scenarios are discussed based on the inflows (indicating seawater intrusion) and outflows of groundwater to the sea, the evapotranspiration of water, the average decline in the groundwater table and the head distribution. Seawater intrusion is controlled by the hydraulic gradient in the vicinity of the coastal boundary. Therefore, the hydraulic gradient over the first 500 m from the coastal boundary is compared for the various scenarios.

An analysis of the results shows that currently, a large volume of groundwater discharges to the sea (12,837 m^3/day) along with 9067 m^3/day lost via evapotranspiration. As suggested by Zekri et al. (2015a), there is a need to extract an additional groundwater volume of 33,693 m^3/day to reduce the dependence on seawater desalination. Considering the base case scenario as a reference, the increase in abstraction from public wells in S1 will result in a further drop in the hydraulic head by 3.5 m on average over the modelled area, which will consequently increase the seawater intrusion by 22 times (9515 m^3/day compared to 418 m^3/day for the BCS). Without proper management, the aquifer sustainability will be threatened. MAR using TWW is an option to augment the aquifer storage and to act as a hydraulic barrier against seawater intrusion. S2 considers an injection amount of 4596 m^3/day under the constraint of minimizing the loss of injected TWW to the sea and preventing mixing of the TWW with native water pumped from the public wells. The results of S2 indicate that MAR reduced the seawater intrusion by 38 % (considering injection well—pattern 1; see Fig. 3). Similar results were obtained when using injection well—pattern 2 (S4) and when TWW was directly supplied to the farmers (S3). Obviously, reducing the abstraction rate would decrease the seawater intrusion and allow for the recovery of the aquifer storage (S5 results). By decreasing abstraction from public wells by nearly 12 % (from 51,488 m^3/day—as in S4—to 45,604 m^3/day), inflow from the sea decreased by 38 % and the average decline in the water table decreased by nearly 20 % (Table 3). When the public wells are redistributed (Fig. 3b), the groundwater level rose by 8 % compared to S5. However, the aquifer received a higher inflow of seawater (4174 m^3/day). This could be due to the stress exerted by the translocation of the public wells in the seaward direction. The redistribution of wells was undertaken under the constraints of land availability and the existing infrastructure of the urbanized area. Contouring of the equipotential lines shows that the

Table 3 Water balance and the average groundwater level for the simulated scenarios

Scenario	Abstraction from public wells (m^3/day)	Abstraction from agric. wells	Injection rate	Inflow from the sea	Outflow to the sea	Evapotranspiration	Average groundwater level (m)	Average of GW level 500 m from the sea
Base case (BCS)	17,808	3536	0	418	12,837	9067	8.95	0.318
S1	51,488	3536	0	9515	220	5995	5.45	−0.13
S2	51,488	3536	4596	5930	647	6172	5.85	−0.029
S3	51,488	0	0	6636	555	6086	5.75	−0.046
S4	51,488	3536	4596	5884	863	6147	5.75	−0.002
S5	45,604	3536	4596	3627	2494	6536	6.35	0.077
S6[a]	45,604	3536	4596	4174	1750	6551	6.55	0.017
S7[a]	34,180	3536	4596	1582	6896	7507	7.65	0.184
S8[a]	34,180	3536	0	2325	3465	7237	7.4	0.058

[a] In these scenarios, the public wells are redistributed

middle zone of the coastal area is more stressed compared to the areas towards the sides (Fig. 4a–d).

Further decreasing the volume of extracted water from the public wells by 25 % (in S7) from that of S6 causes an average decline in the groundwater level by 1.3 m from the base case regardless of the increase in the abstraction from public wells by 90 % compared to the BCS. The outflow to the sea was reduced by 86 %, and seawater intrusion increased by 2.8 times. MAR using TWW helped maintain a higher hydraulic gradient towards the sea (0.00036 on average over 500 m from the coastal boundary compared to the results of S8, 0.000116, when injection was not practised). However, a significant amount of water still discharges to the sea in S7. There is a trade-off between the damage to the aquifer (the average decline in the water table and seawater intrusion) and maximizing the benefits of groundwater for urban supply instead of using costly desalinated water.

It can be concluded that MAR could help manage stressed aquifer systems in arid zones to maximize the benefit of using pristine water for domestic purposes while minimizing the damage to the aquifer. An optimization study is planned to efficiently develop the Samail aquifer under MAR using TWW and the stated constraints in the introduction. Optimization was not attempted in this study and will be a subject of future work.

Particle tracking of the injected water

As per the constrains of applying MAR using TWW in a multipurpose aquifer system, as highlighted in the introduction, particle path lines were tracked to see if the injected TWW reached the public wells. Figure 5 illustrates the particle tracking path lines of the injected water for the results from S6 using MODPATH. The forward particle tracking for the injection wells (Fig. 5a) and the backward particle tracking for the public wells (Fig. 5b) suggest that the slowly injected TWW primarily flowed in the seaward direction (Fig. 5a) and the public wells received only pristine water from the aquifer (Fig. 5b). This result was observed for all scenarios. The variation of the flow lines marked by the tracked particles indicates the travel during the simulation time (end of each year). As the injection rate is small and performed in the vicinity of active irrigation wells, the produced water table mound is low. Thus, the injected water does not travel longer distance as clearly illustrated by Fig. 5.

Economic analysis of the management scenarios

Table 4 summarizes the criteria involved in the problem. The estimation of the benefits is based on the marginal benefit of the domestic water and the marginal benefit of the agricultural water. The marginal benefit of domestic water is estimated to be \$0.82/m^3, and the marginal benefit for agricultural uses is \$0.06/m^3 based on Zekri et al. (2015a). The costs are related to the cost of injection, estimated at \$0.014/m^3, plus the groundwater lost to the sea through seepage, which was assumed to be equal to the marginal benefit of the domestic water because the aquifer is primarily used for urban purposes. The cost of injection includes the in situ operational and capital costs. The marginal value of TWW injected into the aquifer is assumed to be zero because a large volume is discharged to the sea due to excess supply from HAYA Water, the wastewater treatment company. The net benefit of each scenario is therefore equal to the sum of the marginal benefits minus the sum of the marginal costs per year.

The comparison of the eight scenarios from an economic point of view could be based on the benefits of extracting higher volumes of groundwater and the cost of injecting the TWW. However, in this problem, three additional non-monetary criteria are involved. These are the inflow from the sea, the average decline in the groundwater level and the average groundwater level near the sea. This is therefore a multiple criteria problem. The selection of the best scenario will depend on the decision maker's preferences and on the weights attributed to the different objectives.

A first analysis of the results presented in Table 4 clearly shows that scenario 3 is dominated, in the Pareto sense, by scenario 2. In fact, scenario 2 performs better than scenario 3 in all criteria. That is, S2 has a higher benefit with a lower inflow from the sea, a lower decline in the water table and a better GW level near the sea boundary than S3. Therefore, scenario 3 should be discarded from the list of scenarios to present to the decision maker. The fact that scenario 2 dominates scenario 3 means that it is better to inject TWW in the aquifer at a rate 30 % higher than what the farmers will pump than to directly supply TWW through pipes to the farmers (see Table 3). Even though this is more expensive to undertake, due to the injection cost, it results in higher benefits because farmers will use TWW directly in S3. TWW's opportunity cost is zero. Consequently, scenario 3 is not represented in Fig. 6, which illustrates only the Pareto optimal solutions.

Figure 6 shows the trade-off between the net benefit and the seawater inflow to the aquifer as indicated by the numbers in red. The slope between S7 and S8 is equal to 7.69 meaning that for every Mm^3 the decision maker is willing to accept as deterioration in terms of inflow from the sea, the benefit will go up by \$7.69 million/year. Moving from S8 to S5 will generate a benefit of \$5.58 million/year for a deterioration of 1 Mm^3 of inflow from the sea. The slope between S5 and S6 is equal to 1.12, much lower than the previous slope. Finally, the slope between S4–S2 and S2–S1 is almost horizontal meaning that the benefit obtained is low compared to the inflow

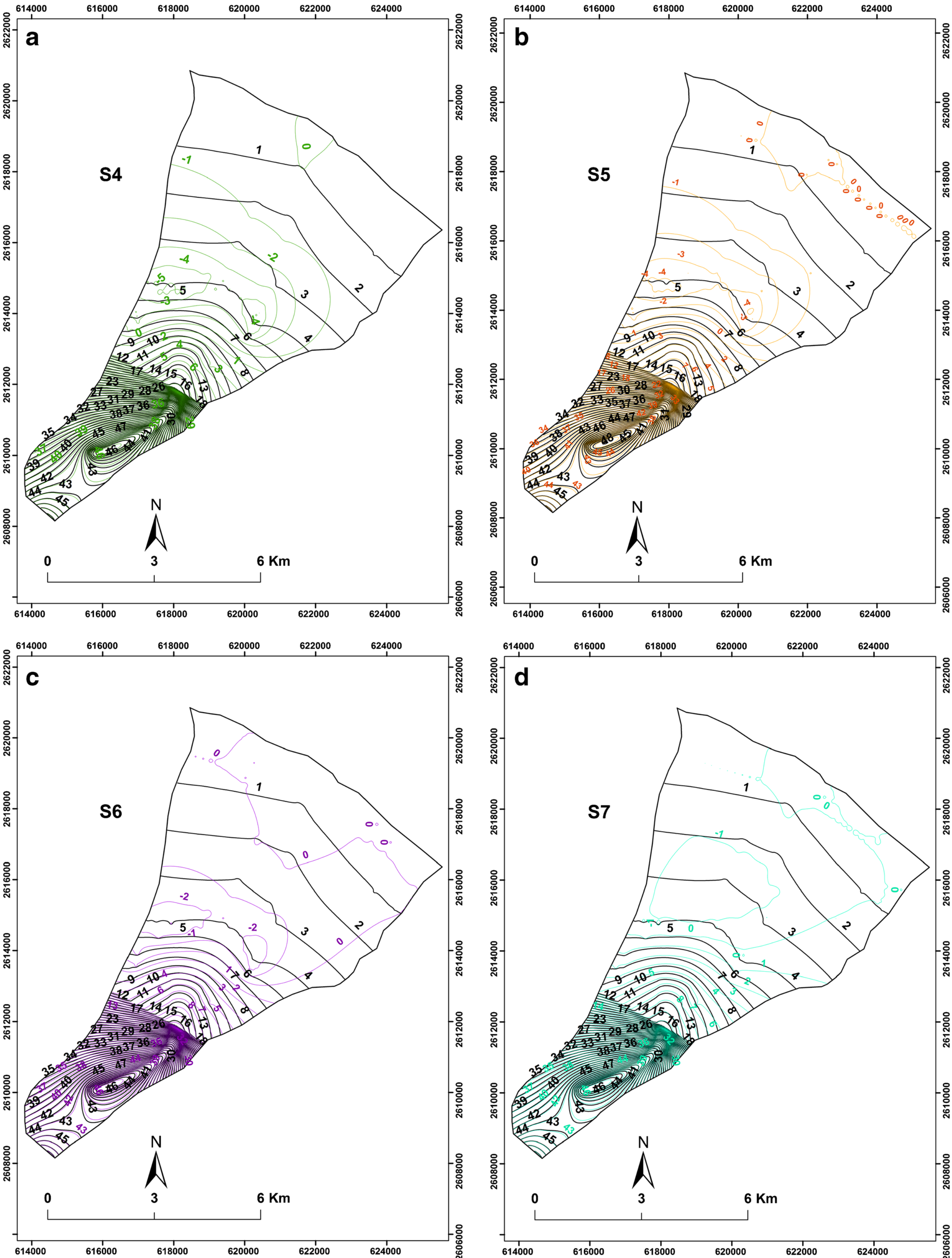

Fig. 4 Equipotential lines for selected scenarios. The *solid black line* represents the base case (BCS)

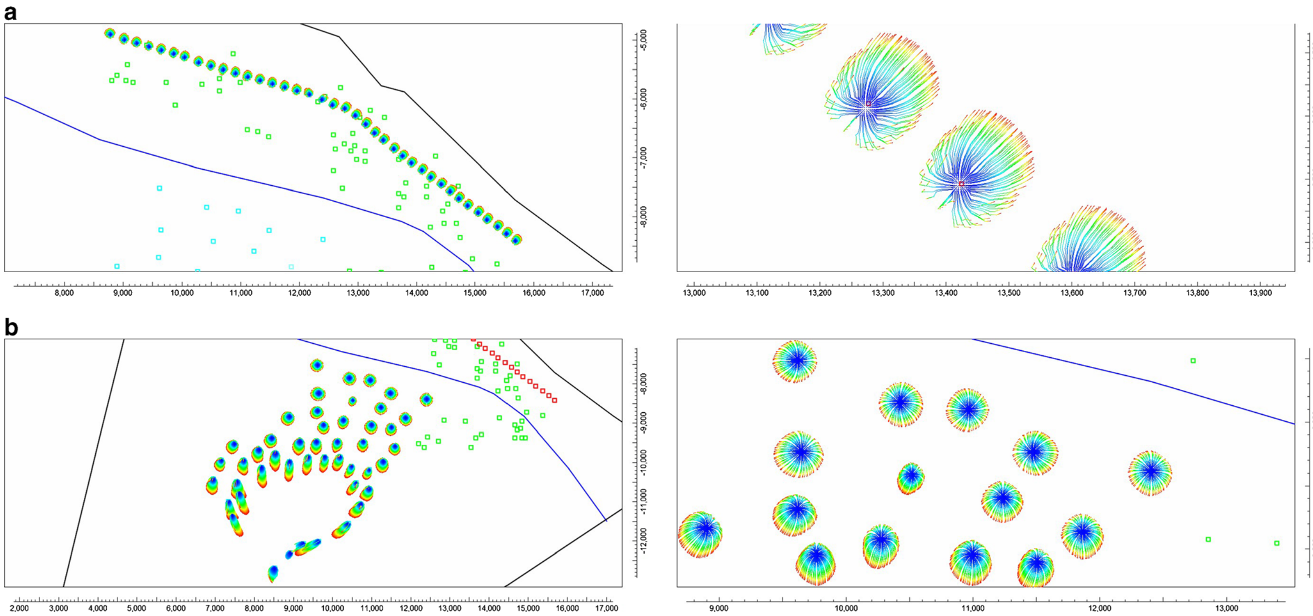

Fig. 5 **a** Forward particle tracking for the injection wells and **b** backward particle tracking for the public wells using the results of S6. The gradual change in the path line colour indicates the travel during the stress periods

from the sea. Consequently, it would be wise not to go beyond S4 (Fig. 6), in this case, as the trade-off is very low. A close look at Table 4 shows that for criteria 4 (GW level in the sea boundary), the value is equal to zero for S4 while it is negative for S1 and S2, meaning a gradient towards the aquifer. Therefore, it is much safer to have a value for criteria 4 equal to or greater than zero. This would allow us to decrease the number of scenarios to present to the decision maker by eliminating S1 and S2.

In all of the remaining scenarios (that is S4 to S8), the results show that the optimal management of the aquifer would produce a net benefit ranging from $8.22 million (S7) to $15.21 million (S4) compared to only $1.57 million for the base case scenario. In other words, managing the aquifer would result in a net benefit to the society regardless of the option considered. Accepting higher benefits also entails accepting higher volumes of seawater inflow. The decision could be made easier if criteria 3 and criteria 4 were combined into one index reflecting the risk of resiliency of the aquifer over the long term. This should be the objective of future work. Finally, the decision maker should prioritize the relative importance of each criteria mentioned above to decide on a proper ranking of the scenarios S4

Table 4 Scenarios and the criteria for selection

	Criteria 1 Net benefit $ million/year	Criteria 2 Inflow from the sea Mm^3/year	Criteria 3 Decline in water Table M	Criteria 4 GW level in sea boundary m
Base case (BCS)	1.57	0.15	–	0.32
S1	15.42	3.47	3.50	−0.13
S2	15.27	2.16	3.10	−0.03
S3	15.24	2.42	3.20	−0.05
S4	15.21	2.15	3.20	0.00
S5	12.96	1.32	2.60	0.08
S6	13.18	1.52	2.40	0.02
S7	8.22	0.58	1.30	0.18
S8	10	0.85	2	0.058

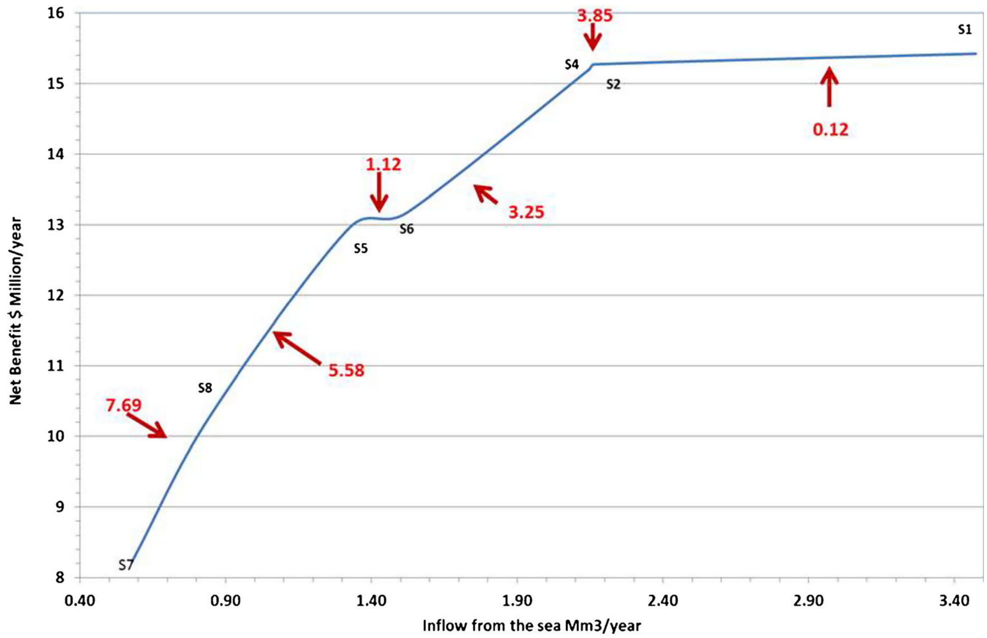

Fig. 6 Trade-off between the net benefit from MAR and the inflow from the sea

to S8. A ranking of the scenarios can then be undertaken using a discrete multicriteria method such as Electre proposed by Vincke (1992).

Conclusions

The effect of MAR using TWW in managing the Al-Khawd coastal aquifer northeast of Oman was studied numerically using MODFLOW 2005. How much water could be abstracted from the aquifer for domestic uses with the lowest possible damage to the aquifer was simulated under different MAR practices. Increasing the urban water supply from the Al-Khawd aquifer is the ultimate goal while ensuring the sustainability of the aquifer service. The scenarios developed progressively to reduce seawater intrusion and outflow of the groundwater to the sea while preventing the injected TWW from interfering with the capture zone of the public wells. An economic analysis using a multicriteria approach was conducted to gain insight into the trade-offs between the benefits of MAR and seawater inflow to the aquifer under the increased abstraction of groundwater for urban use. These criteria include the inflow from the sea, the average decline in groundwater level and the average groundwater level near the sea, as well as the net benefit of the MAR process. The results show that by managing irrigation wells and relocating public wells in conjunction with MAR practices, the abstracted volume for drinking purposes can be increased by two times. With the help of MAR, the hydraulic gradient was maintained in the seaward direction (1.2E−4) regardless of the increased stress on the aquifer (for the base case, the gradient is 6.4E−4). Using the MODPATH code, both forward and backward particle tracking of the injection wells indicate that the injected TWW primarily flows in the seaward direction and that the public wells receive only indigenous groundwater.

Even though the cost of TWW injection is high, it is found to result in large benefits. The results show that managing the aquifer would produce a net benefit ranging from \$8.22 million (scenario 7) to \$15.21 million (scenario 4) compared to the current practice. Opting for higher benefits entails accepting higher volumes of seawater inflow. This necessitates exploring the associated risk to the aquifer over the long term.

MAR using TWW is a feasible solution to develop water resources in arid regions and the best scenario depends on the decision maker's preference when weighing the benefits from MAR and the level of damage to the aquifer. MAR was found to help manage stressed aquifer systems in arid zones to maximize the benefits of using the groundwater for urban supply (instead of costly desalinated water) with minimal damage to the aquifer. The limitation of the model is the historical pumping rates, which are not sufficient to allow run of the transient model. Future work should include upgrading the model to the transient state along with the hydrochemistry of the aquifer to address the aquifer water quality improvements and/or deterioration.

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