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Aquifer storage and recovery, and managed aquifer recharge of reclaimed water for management of coastal aquifers

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ABSTRACT

The hydrological and economic feasibility of aquifer storage and recovery (ASR) of excess desalinated water and managed aquifer recharge (MAR) using tertiary treated wastewater (TTWW) to manage stressed coastal aquifers in Oman has been studied numerically using the code, MODFLOW 2005 and the different transport packages MT3DMS, and MODPATH. The current ASR study aims to assess the feasibility of saving and recovering water for the purpose of supply to the city of MUSCAT during high demand periods by banking excess-desalted water during winter and recover it during the rest of the year. The second objective of the study is to explore the feasibility of MAR using TTWW to mitigate salinity in two costal aquifers in North of Oman exploited for different purposes: domestic water supply (Al-Khod aquifer), and for irrigation purposes (Jamma aquifer). ASR in the Al-Khod Aquifer was explored using Simulation Optimization multi-objective modeling using evolutionary algorithm NSGA-II (namely, the Non-dominated Sorting Genetic Algorithm-II), to generate the set of Pareto optimal solutions according to recharging scenarios. The results show that the potential net benefit of storage and recovery might reach as high as $17.80 million/year. The maximum profitable volume that can be recharged into the aquifer, given the limited number of wells and their locations, is estimated at 8.4 Mm^3/year, which is lower than the current excess estimated of 10 Mm^3/year. For MAR using TTWW, different managerial scenarios were simulated and analysis of the results reveals that the Jamma aquifer will further deteriorate in the next 20 years if it remains poorly managed. The groundwater level will decline further to exceed 3 m on average, and the iso-concentric salinity line of 1,500 mg/L will advance 2.7 km inland that will severely affect farming activities in the area. However, MAR using TTWW when integrated with the management of groundwater abstraction (e.g., smart water meter, higher irrigation efficiency to reduce the abstraction rate) becomes hydrologically feasible to augment the aquifer storage and controlling seawater intrusion, and hence sustains farming activities. The economic analyses of such situation recommend: (1) injecting TTWW in the vicinity of irrigation wells; (2) investing in smart water meters and online control of pumping from the wells to reduce the abstraction rate by 25%; and (3) a combination of both are feasible scenarios with positive net present values. Recharge in upstream areas is found not economically feasible because of high investment cost of the installation of pipes to transport the TTWW over a distance of 12.5 km. Because the financial resources for investments are limited, scenario (2) shows a Net Benefit Investment Ratio of 4.41 (i.e., investment of a $1 yields $4.41). Although option (3) shows the lowest Net Benefit Investment, it is very attractive from a social perspective because it entails an integrated demand and supply management of groundwater. Farmers are requested to reduce pumping, and the government will invest in injecting TTWW to improve groundwater quality in the vicinity of irrigation wells and to form a hydrological barrier to control seawater intrusion in the long run. The primary objective of MAR for the Al-Khod aquifer is to increase the urban water supply and to sustain the aquifer service with the lowest possible damages from seawater intrusion. 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

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the trade-off between the benefits of MAR and seawater inflow to the aquifer under increased abstraction for domestic supply. The results show that the abstracted volume for domestic supply can be doubled under MAR practices if irrigation wells are properly managed and public wells are better located. Even though injection of TTWW is more expensive (due to the injection cost), will result in higher benefits. The results indicate that managing the aquifer would produce a net benefit ranging from $8.22 million to $15.21 million compared with $1.57 million with the current practice. MAR using TTWW is feasible 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, as a smart water governance technology, mitigates stresses on aquifer systems in arid zones, maximizes the benefit of using groundwater for both agricultural and domestic purposes while minimizing the adverse socio-hydrological and agricultural consequences of mismanagement of commingled groundwater-TTWW resources at all scales (national, catchment, metropolitan area, village, farm).

Keywords: Managed aquifer recharge; Aquifer storage and recovery; Salinity; Coastal aquifer; Oman

1. Introduction

In arid regions, such as Oman, water resources are inadequate, and therefore, the development of different sectors (e.g., agriculture, industry, tourism, and municipal) is threatened. Groundwater is overexploited in densely populated/developed coastal areas, which depletes aquifer storage and causes seawater intrusion that degrades agricultural land and hence adversely affects the socioeconomic aspects of the farming community (MRMWR, 2005). Along with the proper management of water resources, additional water sources are needed to augment stressed coastal aquifers. In drought seasons, groundwater abstraction exceeds the safe yield, intensifying the deterioration of aquifer water. Abdalla and Al-Rawahi (2013) reported that since the 1970s, aggravated development of coastal groundwater has resulted in the progressive advancement of seawater and deterioration of water quality (Bajjali 2003; Al Barwani and Helmi 2006). The construction of recharge dams, control/rationing of the development of groundwater abstraction and desalination of seawater are standard measures to manage and augment water resources in arid areas. However, rainfall is irregular, unpredictable and low (annual average rainfall is approximately 100 mm in Oman). Thus, the role of recharge dams is tightly linked to weather conditions, which are characterized by long dry spells and low frequency rainfall (Sen 2008). Desalinated water is expensive (approximately 1$/m^3$ – as estimated by Zekri et al., 2013) and has negative environmental impacts. Recently, managed aquifer recharge (MAR) using TWW as a non-conventional water resource has been viewed as a feasible option (Asano and Cotruvo 2004; Khan et al. 2008; Al-Assa'd and Abdulla 2010, Missimer et al. 2012; Ebrahim et al. 2015). MAR is defined as the intentional recharge of water into an aquifer either by injection or infiltration and recovery by planned extraction (Hayder Consulting, 2006). MAR has been identified as a potential major water management practice to support groundwater storage in arid and semiarid areas (Ebrahim et al. 2015). MAR has been widely practiced. Li et al. (2006) numerically investigated the impact of MAR on Perth Basin, Western Australia. The developed model helped to create flexibility to manage groundwater levels and improve its quality, particularly along the coast and river margins. MAR storage and recovery were found to be feasible water management tools for reducing the impact of droughts in Australia (Khan et al. 2008). Shammas (2008) and Baawain (2010) have assessed the effectiveness of areal injection of tertiary treated wastewater (TTWW) in combating seawater intrusion in the Salalah coastal aquifer (Oman) numerically. Ebrahim et al. (2015) and Al-Maktoumi et al. (2016), by using both simulation and optimization codes, found that MAR using TTWW is a feasible solution to manage coastal aquifers in Oman. The response of the Mujib aquifer in Jordan to different MAR scenarios has been studied by Al-Assa'd and Abdulla (2010). MAR further improved the groundwater quality and augmented the storage of an alluvial Wadi aquifer in Saudi Arabia (Missimer et al., 2012). Moreover, injected TTWW acted as a hydraulic barrier to decelerate seawater intrusion in the Damour and Jieh regions in Lebanon (Masciopinto 2013). Economically, MAR often provides the cheapest form of new water supply (Dillon 2005; Zekri et al. 2013). Khan et al. (2008) suggested that underground storage is much cheaper than surface storage facilities, with less environmental consequences or evaporation losses. Zekri et al. (2013) proposed the reuse of TTWW to farmers through injection/recovery systems via aquifers. The injection of TTWW in aquifers for later use in irrigation will further result in natural treatment and quality improvement. Zekri et al. (2013) estimated the current TTWW cost in Oman for reuse to be $0.55 per m^3, while the cost of injection and recovery of TTWW in an aquifer is approximately $0.026 per m^3. Along with the MAR advantages mentioned above, MAR has some disadvantages. In most cases, only a part of the recharged water is recovered. The quality of water used for aquifer recharge could alter the physical and chemical characteristics of the porous medium. To reduce the associated risks, the injected TTWW must undergo treatment processes that can satisfy drinking water standards (Hayder Consulting 2006; Dillon et al. 2009). In Oman, Haya Water Company (http://www.haya.com.om), the main entity responsible for the collection and treatment of sewage water, produces TTWW. The hydrochemistry of MAR practices is beyond the scope of this paper and will be considered in future studies. According to Zekri et al. (2013), the TTWW volume in Muscat is 100,000 m^3/d. The volume of

TTWW is expected to reach 274,000 m^3/d by 2030 in Muscat, the capital city of Oman (Zekri et al. 2016).

2. Aims of the study

- Assess numerically (using MODFLOW 2005 and MT3-DMS) the feasibility of saving and recovering water for the purpose of supply to the city of MUSCAT during high demand periods by banking excess-desalted water during winter and recover it during the rest of the year.
- Explore the numerical feasibility of MAR using TTWW to mitigate salinity in two costal aquifers in North of Oman exploited for different purposes: domestic water supply (Al-Khod aquifer), and irrigation purposes (Jamma aquifer).

2.1. Description of the study areas

Two aquifer systems were used in the study. Al-Khod aquifer which is used for both aims of the work presented in this paper and Jamma aquifer which is located in the Al-Batinah area of northern Oman (Fig. 1). For detailed description of both aquifers geological settings and in depth hydrological and hydrogeological descriptions readers are referred to Ebrahim et al., 2015, Al-Maktoumi et al. (2016), El-Rawy et al. (2018). However, highlights of both aquifers are presented below:

2.1.1. Al-Khod aquifer

Several papers presented detailed discussions concerning the geological and hydrogeological properties of the Al-Khod aquifer, therefore, only a brief discussion is provided below (Abdalla and Al-Abri 2011; Abdalla and Al-Rawahi 2013, Ebrahim 2013; Zekri et al. 2014a, 2015a). The study area consists of the coastal plain of the Wadi Samail catchment and covers an area of approximately 59 km^2 (Fig. 1). From the North, the study area is bounded by the Oman Sea and by Wadi Samail catchment from the South, Wadi Taww from the west and the Wadi Rusayl from the east. In addition to irrigation water, the aquifer has been an important source of potable water supply to major cities in Muscat Governorate throughout the last three decades. Currently, the aquifer is considered a strategic reserve. Al Khod recharge dam was constructed in March 1985 approximately 7 km from the coastal line (Fig. 1) (Abdalla and Al-Abri 2011; Al-Maktoumi et al., 2016). Over years and because of reduction of abstraction for domestic supply (as government shifted to desalination as the main source for domestic water supply in the area) and dam functionality, the aquifer storage recovered and the hydraulic gradient maintained seaward direction, hence mitigating seawater intrusion observed during the stressful period the aquifer experienced. Hydrologically, the aquifer is modeled as two primary units. Details of modeling conceptualization, setup, and calibration are presented in Al-Maktoumi et al. (2016).

2.1.2. Jamma aquifer

Jamma being a coastal unconfined alluvium aquifer (located in the Al-Batinah area of northern Oman) is mainly used for irrigation purposes (Figs. 1e–h). The Al-Batinah area represents approximately 50% of the total agricultural land in Oman (Oman Salinity Strategy 2012). Over-pumping during the last few decades has resulted in a significant decline in the groundwater level (up to 5 m), which has consequently caused seawater intrusion (>3 km and in adjacent aquifers the saline interface encroached up to 10 km) and hence salinization of agricultural land (MRMWR 2005; Al Barwani and Helmi 2006; Zekri 2008). As a result, suitable agricultural lands in the Al-Batinah plain were reduced by 7% in the period of 2000–2005, which has had socioeconomic consequences (Al Barwani and Helmi 2006; Zekri 2009; Oman Salinity Strategy 2012). It turns to be of paramount importance to manage the aquifer. That is why in this study, to what extent MAR using TTWW can help to mitigate the deteriorated condition of the aquifer and improve farming practices is the core research question. The injection of TTWW will form a hydraulic barrier against seawater intrusion, expected to improve water quality within the vicinity of the injection and furnish additional water for irrigation. In the current study, we will assess numerically the feasibility of MAR in controlling the seawater intrusion and augmenting the depleted storage in the coastal aquifer of Jamma under different scenarios that include the management of irrigation wells. In this study, the geochemistry interactions that may cause clogging effect during the recharge as mentioned by Voudouris 2011 is not considered.

The study area is characterized by a warm winter with low humidity and a very hot and humid summer. The rainfall is low, sporadic and erratic and ranges between 60 mm in the coastal area and 140 mm in the upstream part of the catchment, mountains (Weyhenmeyer et al. 2002).

The aquifer is exploited by about 1,037 unmonitored irrigation shallow dug wells concentrated along a narrow coastal strip (5 km width; Fig. 1e). The total abstracted volume is about 89 Mm^3/year (Mott MacDonald 2013) with an average abstraction rate for each well of 235 m^3/d. The cropped land in the study area is about 1,090 hectares, of which 80% is irrigated by flood irrigation system whereas the remaining 20% adapted modern irrigation systems. A simplified geological map of the Jamma study area is constructed based on the study by Lakey et al. (1995) and presented in Figs. 1–f. For more detailed descriptions, readers are referred to (El-Rawy et al. 2018).

2.2. Approach

MODFLOW-2005 code (Harbaugh 2005) with ModelMuse (Winston 2009) as a graphical user interface (GUI) was used to simulate groundwater flow. The solute transport for seawater intrusion was simulated using the MT3DM model (Zheng and Wang 1999) which is based on a constant density approach. Detailed modeling setup and parameters were presented in Ebrahim et al. 2015, Al-Maktoumi et al. 2016, El-Rawy et al. 2018.

2.3. Simulated scenarios for Al-Khod aquifer, discussion and results

2.3.1. ASR of excess desalinated water

Muscat city depends mainly on desalinated water (approximately 94% [Zekri et al. 2014b]) by a number of desalination

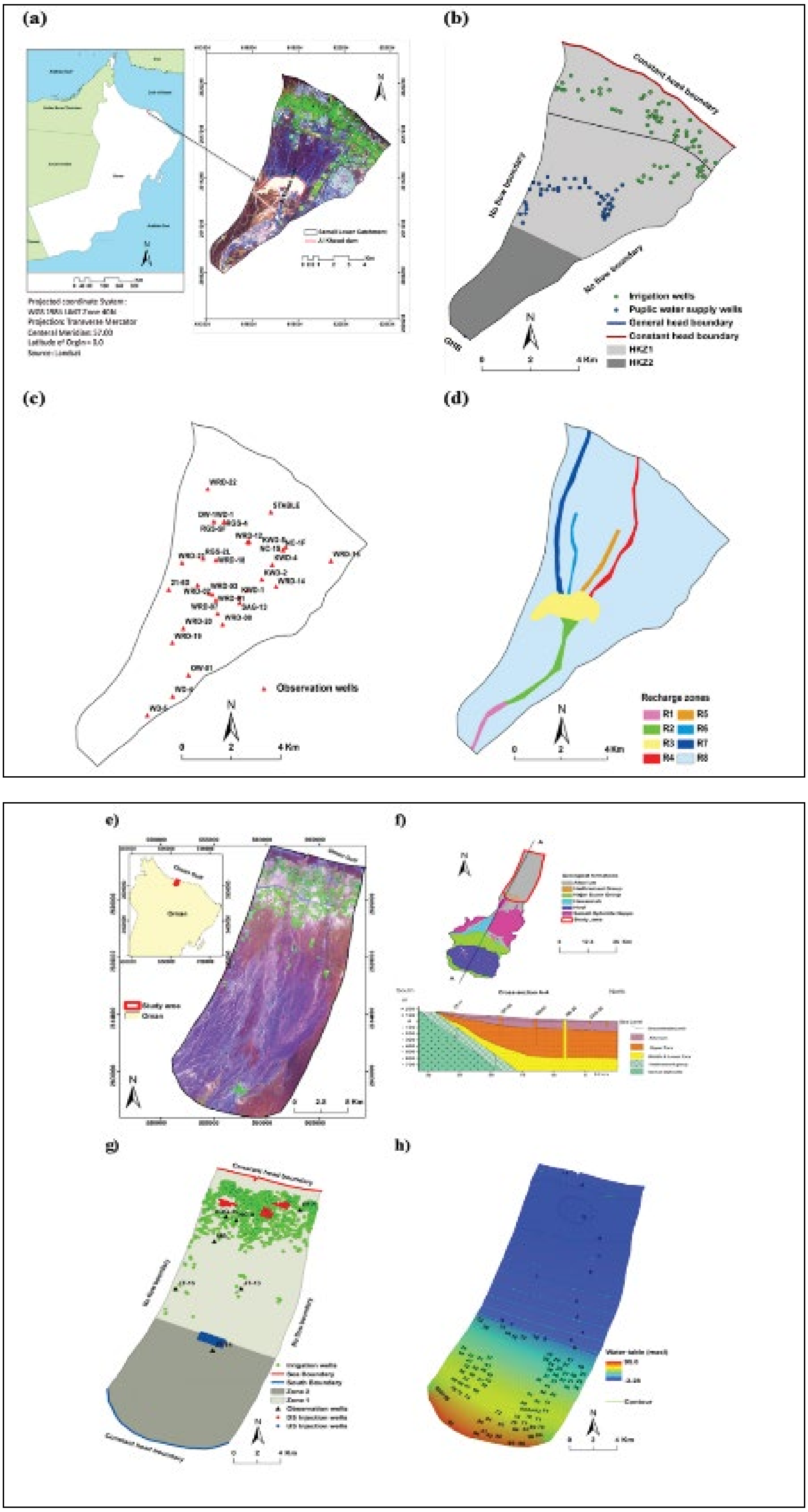

Fig. 1. (a) Location and characteristics of the Al-Khod aquifer, (b) the boundary conditions, locations of public and irrigation wells and zones of different hydraulic conductivities and (c) the location of observation wells (upper panel) and (d) recharge zones (adapted from Al-Maktoumi et al., 2016), (e–h) study area and characteristics of the Jamma aquifer site (El-Rawy et al., 2018).

plants that are connected to the urban network of the city. The desalination plants' capacity is designed for the high demand period corresponding to the summer months (Zekri et al. 2016). As that, an excess of produced desalinated water (more than the demand) is observed during the period of low demand, 4 months (November through February). ASR could be implemented to store the surplus amount and then recovered during the 8 months of high demand period. Two types of desalination plants are operational in Muscat, multi-stage flash (MSF) desalination plant and the reverse osmosis (RO) plants. The MSF plant's production capacity cannot be adjusted, and it produces a constant volume of water throughout the year. However, the RO plants are flexible, and the volume produced can be adjusted daily. The excess volume is thus produced by the MSF plant. The MSF plant, a private operation, sells to the Public Authority for Electricity and Water (PAEW) a fixed daily volume according to the contract that was established prior to start of the construction of the plant. It is the exclusive responsibility of the PAEW to distribute the water produced and manage the excess water. Currently the PAEW reduces the volume of desalinated water produced from the RO plants to balance the total supply, but there is still some excess water produced by the MSF plants which ends up being sent to the sea. The current excess desalinated water in Oman is estimated at approximately 10 Mm^3 (PAEW 2017, personnel interview). At present, groundwater is abstracted daily year round from a number of wellfields in Muscat including the Al-Khod aquifer which is tapped by 45 public utility wells (shown in Fig. 1) with lower abstraction rates in the low demand season. The abstracted groundwater is delivered to the city through the urban network mixed with desalinated water. The work considers banking the excess desalinated water in the unconfined Al-Khod aquifer via injection to make use of the scarce water resource during high demand and emergency periods instead of losing it to the sea. The constraints on the volume to be injected into the aquifer are related to the capacity of the existing pumps installed in the wells and on the hydrogeological characteristics of the aquifer (Zekri et al. 2016).

The results of the numerical simulations illustrated the possibility of recharging the periodic excess desalinated water in the Al-Khod aquifer. Out of the 10 Mm^3/year of excess desalinated water that is discharged to the sea, 8.4 Mm^3/year can be banked in the aquifer. By storing the excess water, a net benefit estimated at $17.80 million/year will be generated. The water authorities in the country must work together to better use this scarce water resource. The existing wells and their locations do not allow the injection of all the excess volume. Furthermore, the current practice of RO plants reducing their production during the low demand winter period is a very costly solution. In fact, the PAEW still must pay up to 85% of the cost, despite the reduction in the desalinated water volume. Further research is thus required to determine the optimal locations of new injection/recovery wells and the optimal volume of excess water to be produced by the desalination plants in conjunction with the storage capacity of the aquifers (Zekri et al. 2016).

2.3.2. MAR using TTWW in Al-Khod aquifer

The management scenarios were designed under the constraint that the injected TTWW in the Al-Khod aquifer does not mix with the native water used for urban supplies. Because the existing legislation does not allow a mixing of TTWW with drinking water, MAR practices are constrained. However, MAR be practiced to generate a hydraulic barrier to seawater intrusion and hence reduce the stress to the aquifer caused by abstraction for both urban and farming uses. Thus, allowing more water to be abstracted for urban water uses. Therefore, the supply of desalinated water could be reduced and considerable cost cuts could be achieved given the high cost of seawater desalination both financially and environmentally. However, the TTWW volumes disposed of in the sea should be minimized (Zekri et al. 2015b). Table 1 summaries the different scenarios considered. The assigned volume of the injected TTWW was chosen based on the current abstracted volume from the irrigation wells and the constraints mentioned above. The main focus of this part of the study was to explore MAR's effect on enhancing the urban supply with the lowest possible damage to the aquifer at low 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

Table 1
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 TTWW for farmer's use.
S3	In this scenario, a volume of 3,536 m^3/d of TTWW 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. 2) using 38 injection wells with an injection rate of 121 m^3/d 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 TTWW.

the sea and preventing the injected TTWW 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 simulated as presented in Table 1.

As obvious, the water table mounds under recharge causing a steeper hydraulic gradient in the vicinity of the injection zone. As a result, dynamics of the injected water and its residence time are affected. Fig. 2 presents the location of the injection wells and the head distribution in the aquifer after 12 years of simulation. In this study, two patterns of injection well distribution were used. In Pattern 1, 10 injection wells were modeled with an injection rate of 459.6 m^3/d per well, and in Pattern 2, 38 injection wells were modeled with an injection rate of 121 m^3/d per well and the injection wells were relocated 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 overlapping of developing mounds by each injection well as fusion of adjacent mounds may result in higher mound which may cause geotechnical and environmental problems.

3. Results and discussion of the simulated scenarios for Jamma aquifer

Eight scenarios (divided into three main clusters: A, B and C) were simulated and are presented in Table 2. The simulation time is set to 20 years, with 244 stress periods and time steps of 30 d. Scenario A considers the case “Business as Usual”, which simulates the current situation assuming that no changes (in terms of management and climatic conditions) will take place for the next 20 years, and hence considered “a base case scenario”, with which the results of the other scenarios are compared. Suggestion of injection well locations, considering the land availability as the area is densely urbanized and the lands are of private ownership (Scenarios A1 and A2 in Table 2). The locations of wells are given subscripts of 1 (for upstream) and 2 (for downstream location, vicinity of farms), as shown in Fig. 1g. The injected volume is based on the availability of excess TTWW, as reported by the Haya Water Company (Zekri et al. 2013). Scenarios B and C are based on policies recommended by the Ministry of Agriculture and Fisheries (Oman Salinity Strategy 2012) and by the MRMWR in Oman (Abdel-Rahman and Abdel-Magid 1993), Table 2.

The injection of 60,000 m^3/d of TTWW in the upstream location (Scenario A1) causes a decrease in the inflow from the sea and southern boundaries by 12,012 and 601 m^3/d, respectively, compared with the base case (scenario A). The groundwater level rises by 0.85 m on average with respect to the base case (A). Implementing MAR in the farming area (scenario A2), the inflows from both the sea and the southern boundaries into the aquifer decreased by 11,608 and 44 m^3/d, respectively, with respect to the base flow (scenario A). It is nearly similar to scenario A1 because of the effect of the active irrigation wells as the injected TTWW is recovered simultaneously and hence slow gain in storage. The groundwater level rises by 0.2 m on average (Table 3) with respect to the base case.

The impact of reducing the abstraction rate of groundwater (Scenario B) is much higher than that induced by MAR in scenarios A1 and A2. However, when Scenario B is complemented with MAR (with 60,000 m^3/d) at the locations described by scenarios B1 and B2, the inflows from both the sea and southern boundaries decreased by 48,344 and 1,554 m^3/d, respectively, for scenario B1 and the groundwater level rises by 1.66 m on average (Table 3). For scenario B2, the volumetric rate of intruded seawater is reduced by 33.5%. MAR increased the average water table rise by 100% for B1 and by 23% for B2 with respect to the case of no MAR (B). This emphasizes the role of active irrigation wells on the recovery of the injected TTWW, providing less opportunity for the water table mound to develop and hence the aquifer storage to recover (Table 3).

A further drop in the volumetric abstraction rate by 50% (Scenario C), even in the absence of MAR, will decrease the seawater intrusion rate by 63% with respect to scenario A. This results in augmentation of the aquifer storage, which

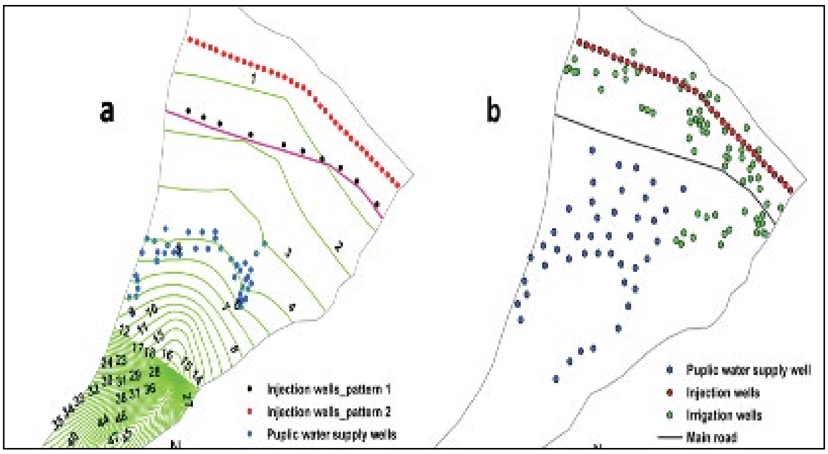

Fig. 2. (a) Simulated groundwater head at the end of stress period 144 (end of year 12) along with the locations of proposed injection wells (Patterns 1 & 2). (b) Locations of the redistributed public wells (blue) [adapted from Al-Maktoumi et al. (2018)].

Table 2
Simulated scenarios for MAR using TTWW in Jamma aquifer (adapted from El-Rawy et al. (2018))

Scenario	Location of the injection	Description	Injection rate and number of wells	Period of injection	Total abstraction rate
A base case	No injection	Represents the current situation	None	None	243,695 m^3/d
A1	Injection was performed 16.5 km upstream of the coastal line (approximately 12.5 km from the highway (water supply line). The blue dots in Fig. 1e represent the proposed injection wells.	This scenario tested the feasibility of upstream injection on augmentation of aquifer storage.	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing, as recommended by Pyne (1995).	4 months followed by 8 months of recovery without injection (WMAR).	243,695 m^3/d
A2	Downstream, in the vicinity of the farming area. Approximately 2.7 km from the highway (water supply line). Red dots represent the injection wells in Fig. 1e.	Aim of this scenario is to test the feasibility of MAR to form a hydraulic barrier against seawater intrusion.	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing.	4 months followed by 8 months of recovery without injection (WMAR).	243,695 m^3/d
B	No injection	This scenario suggests that improvement in irrigation water use efficiency will take place by regulating the abstraction rate. This is expected to reduce the abstraction volume by 25%.	None	None	194,956 m^3/d (dropped by 25% from that for scenario A - base case).
B1	Injection was performed 16.5 km upstream of the coastal line (approximately 12.5 km from the highway (water supply line). The blue dots represent the proposed injection wells in Fig. 1e.	Reduction of the abstraction volume by 25% (same as for Scenario B).	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing.	4 months followed by 8 months of recovery without injection (WMAR).	194,956 m^3/d (dropped by 25% from that for scenario A - base case).
B2	Downstream, in the vicinity of the farming area. Approximately 2.7 km from the highway (water supply line). Red dots represent the injection wells in Fig. 1e.	Reduction of the abstraction volume by 25% (same as for Scenario B).	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing.	4 months followed by 8 months of recovery without injection (WMAR).	194,956 m^3/d (dropped by 25% from that for scenario A - base case).
C	No injection	Adaptation of modern irrigation systems will reduce the abstracted irrigation water by 50% to increase irrigation efficiency (Abdel-Rahman and Abdel-Magid 1993). Approximately 80% of the agricultural area in the study area is irrigated by flood irrigation.	None	None	128,888 m^3/d (dropped by 50% from that for scenario A – base case).
C1	Injection was performed at 16.5 km upstream the coastal line (approximately 12.5 km from the highway (water supply line). The blue dots represent the proposed injection wells in Fig. 1e.	Reduction in the abstraction rate by 50% (as in Scenario C)	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing	4 months followed by 8 months of recovery without injection (WMAR).	128,888 m^3/d (dropped by 50% from that for scenario A – base case).
C2	Downstream, in the vicinity of the farming area. Approximately 2.7 km from the highway (water supply line). Red dots represent the injection wells in Fig. 1e.	Reduction in the abstraction rate by 50% (as in Scenario C).	40 wells with injection rates of 1,500 m^3/d, with 240 m spacing	4 months followed by 8 months of recovery without injection (WMAR).	128,888 m^3/d (dropped by 50% from that for scenario A – base case).

Table 3
Abstraction and injection rates as well as changes in inflow from the sea boundary, discharge through evapotranspiration, and change in the average groundwater level of all scenarios with respect to the base case (El-Rawy et al. 2018)

Scenario	Abstraction from agric. Wells	Injection rate	Change in inflow from the sea boundary	Change in evapotranspiration	Average change in groundwater level
			(m^3/d)		(m)
A (base case)	243,695	0	–	–	–
A1	243,695	60,000	12,012	351	0.85
A2	243,695	60,000	11,608	318	0.2
B	194,956	0	46,235	1,560	0.82
B1	194,956	60,000	58,344	2,106	1.66
B2	194,956	60,000	57,628	2,029	1.01
C	128,888	0	107,881	4,701	1.91
C1	128,888	60,000	119,704	5,608	2.75
C2	128,888	60,000	118,901	5,438	2.1

is reflected in the increase of the average groundwater level by 1.91 m (Table 3).

Similar to the finding of the B1 and B2 scenarios, the injection of TTWW will further enhance the hydrological condition of the aquifer. The inflow of saline water decreases by 70% and the average groundwater level rises by 2.72 m (Table 3) for C1 and C2 scenarios.

The results suggest that MAR will be more effective in restoring the stressed coastal aquifer when integrated with the management of abstraction from irrigation wells. It is obvious that injecting more TTWW will augment more than the aquifer storage, but the availability of TTWW is a limitation. Moreover, the cost-benefit aspect must be considered when the optimization of MAR and irrigation practices are considered, which is not discussed in this paper.

The 1,500 mg/L iso-concentration salinity line for the base case and management scenarios (A1, A2, B1, B2, C1 and C2) has been compared to assess the impact of MAR on the aquifer water quality (Fig. 3). The salinity line receded seaward direction by nearly 1 km at the end of 20 years for scenario A2 and by approximately 1.3 km for B2. The results show that MAR becomes more effective in both restoring the head distribution in the depressed zone and

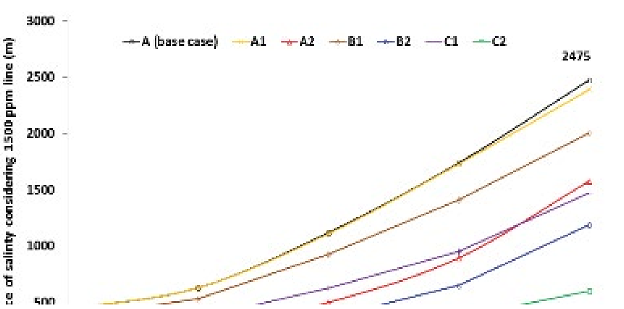

Fig. 3. Intruded distance of the 1,500 mg/L iso-concentration salinity line for selected scenarios.

augmenting the groundwater quality when MAR is practiced in the downstream area and integrated with a 50% reduction in abstracted irrigation water (scenario C2). Comparisons of the results of the different simulated scenarios are presented in Table 3 and Fig. 3 (for their effects on seawater intrusion).

Table 4 presents the salinized water volume and its changes considering the 1,500 mg/L iso-concentration salinity line for the base case and simulated scenarios at the end of the simulation time. In scenario C2, 79% of the salinized water is cleaned to a salinity level lower than 1,500 mg/L and hence becomes suitable for farming activities (for the types of crops and trees cultivated in the study area, i.e., date palm trees, lime trees and fodder crops). Values of the other simulated scenarios are presented in Table 4.

3.1. Economic analysis of the different management scenarios

The economic feasibility of MAR using TTWW in Jamma aquifer is based on a cost-benefit analysis. The net present value (NPV) is used as an indicator of profitability (if NPV is positive, the project is feasible). All simulated scenarios are compared with the base case scenario, A. The benefit of each scenario is the incremental benefit with respect to scenario A. A life span of 20 years and a discount rate of 5% are considered for the calculations of the NPV which is based on the investment costs and operation and maintenance costs on a yearly basis, as well as the indicator of feasibility, the NPV. For the calculations of the benefit cost analysis, the following assumptions are used: the pipes cover a maximum distance of 16.5 km (for the upstream injection location) with a cost of US$31.2 per linear meter. The operating cost for the injection is estimated at US$0.104/$m^3$ with variable amounts. The cost of the bubbler/drip irrigation system is estimated at US$4,875/ha replaced every 7 years. The smart meters will last for the whole duration of the project and their cost is assumed to be US$1,500 each considering 1,037 wells. The annual operating cost of the meters is estimated at US$62.5. The results show that only

Table 4
Salinized water volume for different simulated scenarios and its comparison with the base case considering the 1,500 mg/L iso-concentration salinity line at the end of simulation period (at the end of stress period 244)

Scenario	Salinized water volume
	Million m^3
A (Base case)	2,561
A1	2,488
A2	1,443
B	2,123
B1	2,030
B2	1,067
C	1,400
C1	1,300
C2	537

Scenarios A2, B and B2 are economically feasible since they present positive NPVs. Practicing MAR far from the STPs found to be not economically feasible. This is because of the very high investment cost ($20,592,000) needed to cover the associated cost for constructing pipes to transport water from the STPs to the recharge wells at a distance of 16.5 km. adding to that, the cost of operation and maintenance of the pipes is also high, $748,800/year. A2 represents the scenario in which recharge in the downstream area is considered and has the highest NPV of all the feasible scenarios. Although both A1 and A2 are recharging scenarios, A2 is much more affordable in terms of the investment cost ($1,248,000), as well as the operation and maintenance costs ($374,400/year), making it a feasible option compared with non-feasible option A1. As in scenario B, no MAR involved rather than only water demand management, legislating with proper metering and monitoring abstraction for irrigation water based on predetermined quota will control the over-irrigation. The expected result is that farmers will be more careful about water usage and hence about 25% of water savings. The investment cost in this scenario is related to the cost of installation of smart groundwater meters in each of the 1,037 wells and online monitoring of the pumping (Zekri et al. 2017). The NPV is estimated to be $7,585,026. Scenario B2 is a combination of scenarios A2 and B. It assumes that the injection of TTWW will take place in the downstream area, which will increase the recharge of the aquifer, and at the same time, pumping will be controlled as in scenario B above. Consequently, the cost of investment is the sum of the investments of the A2 and B scenarios for a total of $2,803,500. The resulting NPV of $11,442,837 is quite comparable with that of scenario A2 NPV, which is $11,973,877. In fact, this scenario has a higher chance of sustainability compared with A2, where only a supply increase is proposed. The major issue in groundwater management is the common pool resource and consequent absence of incentives for farmers to use water efficiently. The implication is that when farmers find more free water in the aquifer, they will pump it, and there will be no improvement in the aquifer's storage and quality of the water. Finally, given that financial resources for investments are scarce, the decision

Table 5
Economic feasibility of MAR using TTWW in Jamma aquifer based on a cost-benefit analysis (El-Rawy et al. 2018)

Scenario		Investment cost in $	Operation and maintenance cost in $/year	Net present value $	Net benefit investment ratio
A1	Investment in pipelines to transfer water from the wastewater treatment plant up to the recharging wells upstream at a distance of 16.5 km from source	20,592,000	748,800	–12,122,585	0.57
A2	Investment in pipelines to transfer water from the wastewater treatment plant up to the recharging wells downstream at a distance of 1 km from source	1,248,000	374,400	11,973,877	3.18
B	Investment in smart water meters & online control of pumping from the wells	1,555,500	64,709	7,585,026	4.41
B1	Investment in A1 + investment in smart water meters to control pumping	22,147,500	813,509	–19,489,484	0.36
B2	Investment in A2 + investment in smart water meters to control pumping	2,803,500	439,109	11,442,837	2.48
C	Investment in drip and sprinkler irrigation systems renewable every 7 years	12,653,125	–	–8,344,547	0.68
C1	Investment in A1 + investment in drip and sprinkler irrigation systems	33,245,125	748,800	–36,263,495	0.34
C2	Investment in A2 + investment in drip and sprinkler irrigation systems	13,901,125	374,400	–12,519,153	0.61

criteria on the best scenario should rely on the net benefit investment ratio, which is the ratio of the present value of benefits to the present value of costs presented in the last column of Table 5. The highest ratio corresponds to scenario B, with 4.41, which means that every invested dollar will produce $4.41. The second-best option is scenario A2, with a ratio of 3.38. Scenario B2 is the least best option from a profitability point of view. However, option B2 will be very attractive from a social perspective because it involves two measures at a time. As that, farmers are requested to reduce abstraction and the government will invest in recharge to improve the quality of the groundwater and to protect the aquifer against seawater intrusion in the long run. The joint effort of the water authority and farmers will increase the chance of success compared to when action and responsibility is a responsibility of a single side only.

4. Concluding remarks

The paper presents feasibility of ASR and MAR in managing coastal aquifers in Oman. The following concluding remarks were concluded:

- Banking the excess desalinated water in Al-Khod urban aquifer is a feasible practice. About 85% of the excess desalinated water in Muscat city (that was discharged to the sea) can be stored in the aquifer. This will provide a net benefit estimated at $17.80 million/year. However, the location of injection and recovery wells, and injected volume need to be optimized.
- MAR using TTWW can help to double the abstracted volume for drinking purpose when in parallel manage the pumping from agricultural wells along with better relocating existing domestic supply wells.
- MAR using TWW when integrated with the management of groundwater abstraction (e.g., using modern irrigation systems to reduce the abstraction rate) becomes hydrologically feasible to augment the aquifer storage and controlling seawater intrusion, and hence improve farming activities.
- 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.

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