*8th International Conference on Water Resources and Arid Environments (ICWRAE 8): 609-618*
22-24 January 2019, *Riyadh, Saudi Arabia*

# Optimal Storage and Recovery of Surplus Desalinated Water

*[1]Slim Zekri, [2,3]Chefi Triki, [4]Ali Al-Maktoumi and [5]Mohammad Reza Bazargan-Lari*

[1]Department of Natural Resource Economics, Sultan Qaboos University, 123 Al-Khoud, Oman
[2]Department of Mechanical and Industrial Engineering, Sultan Qaboos University, 123 Al-Khoud, Oman.
[3]Department of Engineering for Innovation, University of Salento, Via per Monteroni, 73100 Lecce, Italy
[4]Department of Soil &Water And Agriculture Engineering, Sultan Qaboos University, 123 Al-Khoud, Oman
[5]Department of Civil Engineering, Islamic Azad University, East Tehran Branch, Tehran, Iran

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**Abstract:** Gulf Cooperation Countries depend mainly on desalinated water for urban purposes. In Muscat, the capital city of Oman, desalinatedwater supplies 94% of the urban water. However, given the nature of take-or-pay contract between the desalinating company and the public water authority a seasonal surplus of desalinated water is produced during thelow demand winter period. The take-or-pay contract is the most common type of contract in the desalination business worldwide. A numerical groundwater flow simulation model is coupled to a dynamic multi-objective optimization model to optimize storage and recovery of the excess desalinated water in a protected coastal aquifer in Oman. Maximizing the net benefit of storage and recovery of the excess desalinated water is undertaken while minimizing the seawater intrusion.. 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.

**Key words:** Aquifer Storage and Recovery (ASR) · Multiple criteria decision making · Coastal aquifer · Conjunctive use management

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## INTRODUCTION

In several coastal arid regions, increased waterdemand caused by economic development and unsustainable agricultural practices leads to groundwater over-abstraction and the consequent salinization of aquifers [1]. Over abstraction can also result in aquifer compaction and loss of its storage capacity. To overcome the imbalance between fresh water supply and demand, seawaterdesalinationplantshave been built to provide a reliable source ofsupply in high income, water stressed countries. Currently almost half of the world's population lives on a coastline [2, 3] and many metropolitan areas have a high dependency on desalinated seawater for urban uses (Shahabi *et al.*, 2015). The availability of low cost sources of fossil energy encouraged Middle Eastern countries to depend almost exclusively on seawater desalination for urban purposes [4]. Similarly, in the USA and Mexico desalinationis part of the solution for the western border areas to meet the increased demand and dwindling supplies [5]. Australia and Spain are other examples of countries that use desalinated water to face cyclical and structural drought problems [6, 7].

Given the role urban water plays in social andeconomic activity, a very high level of supply reliability is required. Supply reliability is the major reason for incurring the use of desalinated water. Choosing the desalination plants' capacity depends onpopulation and economic growth rates and on the probability of drought whenever surface or groundwater is conjunctively used. This usually leadsto deliberatelyoversized desalination plants, at least temporarily and seasonally, when desalinated water capacity is higher than the demand. The planning and construction of desalination plants usually take up to five years, which explains, in part, the excess of supply in the medium term. The other reason for excess supply is the seasonal variations of the urban water demand. Demand is often higher during hot seasons. Most of the desalination water production around the globe involves the private sector and is under the type of build, operate and transfer or build, operate and own. Accordingly, the

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**Corresponding Author:** Slim Zekri, Department of Natural Resource Economics, Sultan Qaboos University, 123 Al-Khoud, Oman. Email: Slim@squ.edu.om.

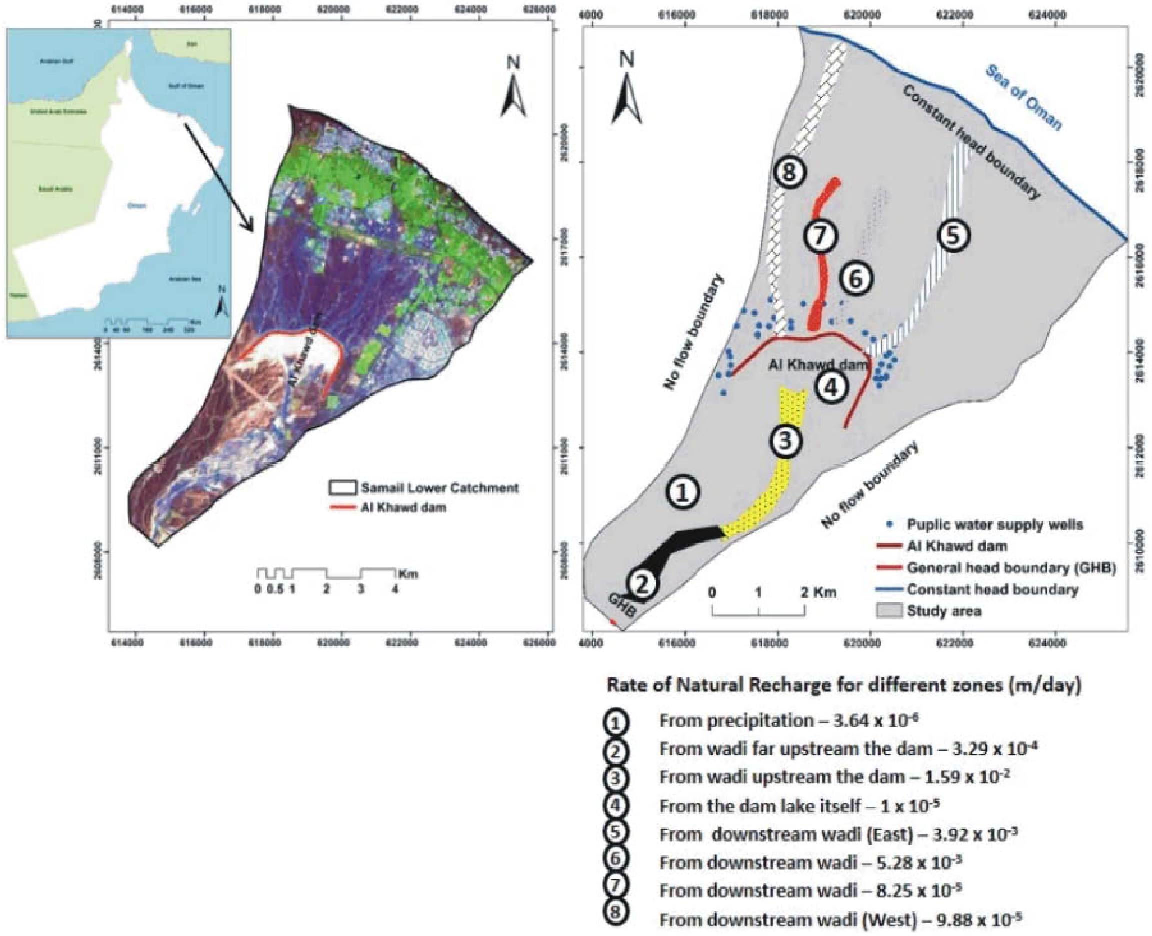
government or water utility buys a fixed volume of water from the desalination company. Most often the contract between the two parties is in the form of take-or-pay a given volume of water agreed upon before the beginning of the construction of the desalination plant to guarantee the long term funding of the plant and avoid the demand risk. This is the most common type of contract in the Gulf countries, in the USA, Israel, Singapore and Australia [8-11].

The aim of this paper is to estimate the potential benefits of recharging the Al-Khoud coastal aquifer using the seasonal surplus desalinated water in Muscat. The optimal injection and abstraction ratesare determined using a multi-objective dynamic programmingmodel coupled with a MODFLOW simulation model. The recharge techniques and quality of recovered water have been widely studied considering different sources of recharging water: fresh; desalinated; treated wastewater; and storm water [3, 12-16] undertook a cost-benefit analysis of Aquifer Storage and Recovery (ASR) using surface water and treated wastewater considering two recharge techniques. The cost estimates are based on MODFLOW simulations. To our knowledge, this is the first time an optimization of an aquifer's spare capacity in conjunction with the supply of desalinated plant has been addressed. The paper is organized as follows. The next section describes the problem. Section 3 briefly presents the study area. Section 4 presents the methodology, whileSection 5 presents the results and discussion. The conclusions are presented in the last section.

**Problem Statement:** Twenty percent of urban water in Oman issupplied from wells, while the majorpart (80%) issupplied by desalination plants [17]. The dependency on desalinated water in the Governorate of Muscat, the capital city is much higher and is approximately 94% [18]. Several desalination plants are operated to serve the Muscat urban network. The desalination plants' capacity is designed for the high demand period corresponding to the summer months. During the period of low demand an excess supply of desalinated water is thus observed. The seasonal excess of supply, during the winter, could be stored in an aquifer and used during the high water demand period. The low demand period is when the water demand in the city is less than the desalinated water supply and corresponds to the months of November through February. Two types of desalination plants are operational in Muscat, multi-stageflash desalination plant (MSF) and the reverse osmosis plants (RO). 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. The PAEW is a governmental water service provider responsible for supplying urban water to all the homes and businesses in Oman. 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.The current excess desalinated water in Oman is estimated at approximately 10 $Mm^3$ [19] personnel communication). The loss of desalinated water to the sea is due to the fragmentation of responsibilities for water resources between several governmental institutions. Natural water is under the umbrella of the Ministry of Regional Municipalities and Water Resources, while the production of desalinated water is under the control of the PAEW.At present, groundwater is abstracted daily yearround from a number of wellfields in Muscat including the Al-Khoud aquifer which is tapped by 45 public utility wells (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 authors of this research consider banking the excess desalinated water in the unconfinedAl Khoud 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.

**Study Area:** The coastal unconfined aquifer that is the object of this research is used as a source of domestic water for the Muscat metropolitan area as well as for emergency purposes. This aquifer is naturally recharged by a dam constructed 7km south of the seashore using controlled infiltration of captured flash floods after intermittent rainfall events. Calculations of the options for the use of the Al-Khoud aquifer have been performed by different investigators for different purposes. Afull description of the aquifer characteristics can be found in (Ebrahim, 2013). The aquifer is protected and the public



**Rate of Natural Recharge for different zones (m/day)**

① From precipitation – $3.64 \times 10^{-6}$
② From wadi far upstream the dam – $3.29 \times 10^{-4}$
③ From wadi upstream the dam – $1.59 \times 10^{-2}$
④ From the dam lake itself – $1 \times 10^{-5}$
⑤ From downstream wadi (East) – $3.92 \times 10^{-3}$
⑥ From downstream wadi – $5.28 \times 10^{-3}$
⑦ From downstream wadi – $8.25 \times 10^{-5}$
⑧ From downstream wadi (West) – $9.88 \times 10^{-5}$

Fig. 1: Study area and recharge zones (adopted from Al-Maktoumi *et al*. 2016 and Zekri et al. 2015)

utility wells are used to abstract groundwater for urban purposes (Fig. 1). The public utility wells are connected to the urban water distribution network. These same wells are used in this study as dual wells (abstraction and injection) to recharge the surplus desalinated water during the excess supply period. The aquifer is located in an urban area, with the dam serving for flood protection and recharge at the same time.

**Research Methodology:** This paper is based on an integration of a groundwater simulation model with a dynamic multi-objective optimization model. A detailed description of the main parts of the methodology is given in the following subsections.

**Groundwater Model:** The impacts of abstraction and/or recharge on an aquifer are determined using a groundwater flow simulation model. The governingflow equation in a saturated porous media is a function of the hydraulic head in space and time, the hydraulic conductivity, the specific storage of the aquifer, sink and source terms as well as the boundary and initial conditions. Several codes have been developed for solving the mentioned governing flow equation. The Modular Finite-Difference Ground-Water Flow Model, MODFLOW 2005 [20], is a widely used three-dimensional mathematical model developed to solve the governing equations using a block-centred finite-difference method. A systematic search for the optimal solutions has been enabled by coupling the groundwater simulation model (MODFLOW 2005) with an optimization model. In this research, the verified and calibrated MODFLOW model used by [21] is utilized for estimating groundwater table fluctuations and the flow across the sea boundary (which is considered to be water lost to the sea). The model area is discretized with 475,404 cells, each having a plan size 30m x 30m.The simulation time is 12 years with daily time steps. Details of the model can be found in the [22].

**Optimization Model:** A multi-objective model is used in this paper. The multi-objective evolutionary algorithms (MOEA) are tools used to optimize several objective functions simultaneously. Several MOEA have been employed to solve nonlinear real world complex problems. Multi-objective problems do not have a single best solution; MOEAs are developed based on the non-dominated principle and their complexity depends on the techniques used to determine the non-dominated set of solutions [23]. In particular, the Non-dominated Sorting Genetic Algorithm (NSGA) is one of the well-known MOEAs. The second generation of NSGAs, namely, NSGA-II proposed by [24] uses an elitist approach in the selection operator, the crowded comparison operator and in the non-dominated sorting for fitness assignment.NSGA-II has been successfully employed in different fields of groundwater resources management [25-34]. In this research, the NSGA-II is used in combination with the constraint and weighting methods Romero and Rahman, 2003.

In this paper, the main variables to determine are the optimal uniform constant daily abstraction rate (CDAR) for the eight hot months (March to October – the high demand period) and the uniform constant daily injection rate (CDIR) for the four months (November to February –the low demand period). Currently excess desalinated water is lost to the sea. The aim is to use the natural spare capacity of the aquifer for an optimal conjunctive use of desalinated water and groundwater. The four objectives considered in this paper are: (1) maximizing the total volume of desalinated water recharged to the aquifer; (2) minimizing the groundwater losses to the sea; (3) minimizing the seawater intrusion, which is done through a surrogate objective consisting of minimizing the maximum seasonal mean drawdown (MSMD); and (4) maximizing the total benefit from the recharge and recovery of the desalinated water.

The normal length of the aquifer's wet-dry natural recharge cycle is 12 years in the study area [21]. Therefore, the model is run over a period of 12 years to match the variability and uncertainty patterns in the natural recharge of the aquifer. The objectives and constraints are fully described in the following subsections:

**Objective 1: Maximize the Recharge to the Aquifer:** The maximization of the recharge using desalinated water gives an estimate to the decision maker of the maximum volume that can be stored in the aquifer. This maximum depends on the existing infrastructure (number of wells and pumps) as well as on the aquifer characteristics.

**Objective 2: Minimizing the Groundwater Losses to the Sea:** The general flow path of groundwater in the study area is towards the sea and thus part of the groundwater is naturally lost to the sea through the seepage face at the coastline. Minimizing the total amount of groundwater losses to the sea is the second objective of this research.

**Objective 3: Minimize Seawater Intrusion:** To reduce the adverse effects of seawater intrusion, the third objective consists of minimizing the maximum seasonal mean drawdown (MSMD) which is defined in Equation (3). The minimization of the *MSMD* is undertaken on a narrow 1 km wide strip of land parallel to the sea shore.

**Objective 4: Maximize the Total Benefit from the Storage and Recovery of Desalinated Water:** The benefit of artificial recharge using excess desalinated water is equal to the value of the water recovered during the peak demand minus the cost of transporting the desalinated water up to the aquifer and minus the cost of injection and recovery. Observe that filtering is the only treatment required after recovery given the fact that the aquifer is a protected and currently used for urban purposes. This objective function uses the weighting method since these three objectives are combined into one single objective using weight. The weights correspond to the value/cost of the water. The excess desalinated water ends up being sent to the sea, so far, hence the opportunity cost of such desalinated water is zero.

Based on the data reported by the PAEW (2015) the total cost of water (including the cost of desalination, transportation and loss) is estimated at US$ 3.18 per cubic metre. The losses (leakages and non-revenue water) represent $\$0.82/m^3$ and desalination cost is around $\$1.04/m^3$(PAEW, 2015). Therefore, the cost of transportation and delivery of water is approximately $\$1.32/m^3$. The cost of injecting the water into the aquifer and recovering it is estimated at $\$0.084/m^3$ [35]. The total cost of recharge and recovery corresponds to the cost of transporting the water from the desalination plant to the aquifer, plus the cost of injectionplus the cost of abstraction. This cost is estimated at $\$1.40/m^3$. Observe that the value of the desalinated water used for injection is considered to be zero as it is currently lost to the sea. On the other hand, the value of water in Muscat is estimated at $\$2.36/m^3$. The natural groundwater lost to the

Table 1: Constraint threshold values

| Parameter | Values for Scenario 1 | Values for Scenario 2 |
|---|---|---|
| $c_1$ (m$^3$/d) | 778 | 1145 |
| $c_2$ (m) | 0.697 | 0.894 |
| $c_3$ (m) | 0.398 | 0.596 |

Source: Zekri *et al.* (2015)

sea corresponds to the value of the water in situ and is estimated at \$1.04/m$^3$. Consequently, the net benefit from recharge is defined in Objective Function 4, Equation (4).

**Constraints:** In Equation (5) $D_{cr}$ is the critical depth to the water table. The wells are 200 m apart. $D_{cr}$ is defined for controlling the local interference effects of the developed hydraulic mounds of the nearby wells. Since the water table rise may cause geotechnical problems (Alawaji, 2008), Equation (5) ensures that the water injection would not lead to a considerable water table rise by imposing a maximum water table elevation of 7 m below the ground. This constraint prevents the potential adverse effects of the water table rising within the urban area where the recharge is taking place. Additionally, the water mound dimensions should not extend to the vicinity of the recharge dam structure to avoid threats to dam stability and safety.

Equation (6) represents the maximum physical capacity of the current abstraction facilities, or pumps. The maximum water injection rate is a function of the hydraulic properties of the aquifer in the vicinity of the wells and depends on the ultimate flow rate capacity of the water distribution network connected to the wells, which is equal to the injection rate capacity of the installed pumps (Equation 7).

For the management of the aquifer, two different scenarios were set up and called Scenario 1 (Sc.1) and Scenario 2 (Sc.2). The only differences between these scenarios are the considered threshold values given for $c_1$,$c_2$ and $c_3$ which are summarized in Table 1.

$$\text{Max} \sum_{t=1}^{nt} GAV_t \tag{1}$$

$$\text{Min } TAWLS = \sum_{t=1}^{nt} AWLS_t \tag{2}$$

$$\text{Min } MSMD = \underset{s=1}{\overset{ns}{Max}} \left( \frac{\sum_{i=1}^{nc} \left| H_i^s - H_i^0 \right|}{nc} \right) \tag{3}$$

$$MAx \;\; Benefit = 2.36TGAV - 1.40TDIV - 1.04TAWLS$$

*or*

$$Max \;\; 2.36\sum_{t=1}^{nt} GAV_t - 1.40\sum_{t=1}^{nt} DIV_t - 1.04\sum_{t=1}^{nt} AWLS_t \tag{4}$$

Subject to:

$$D_{cr} > 7m \tag{5}$$

$$CDAR < CDAR_u \tag{6}$$

$$CDIR < CDIR_u \tag{7}$$

$$CDAR > c_1 \tag{8}$$

$$MAMD = \underset{y=1}{\overset{ny}{Max}} \left( \frac{\sum_{i=1}^{nc} \left| H_i^{y-1} - H_i^y \right|}{nc} \right) < c_2 \tag{9}$$

$$MSMD < c_3 \tag{10}$$

where:

$GAV_t$ = The groundwater abstraction volume from the public utility wells at time step *t*

$DIV_t$ = The desalinated water injection volume to the public utility wells at time step *t*

$TGAV$ = The total groundwater abstraction volume

$TDIV$ = The total desalinated water injection volume

$nt$ = The total number of simulation time steps

$TAWLS$ = The total amount of groundwater lost to the sea during the planning horizon

$AWLS_t$ = The amount of groundwater lost to the sea during time step *t*

$CDAR$ = The constant daily abstraction rate

$MAMD$ = The maximum annual mean drawdown over *ny* years

$H_i^y$ = The hydraulic head in cell *i* at the end of year *y*

$ny$ = The number of simulation years

$MSMD$ = The maximum seasonal mean drawdown near the sea (in a narrow strip of land 1km in width parallel to the sea shore) over the simulation seasons

$ns$ = The number of simulation seasons

$nc$ = The number of cells located on the narrow strip of land 1km in width parallel to the sea shore

$H_i^s$ = The hydraulic head in cell *i* at the end of season *s*

$H_i^0$ = The initial hydraulic head in cell *i*

$c_1,c_2,c_3$ = The constraint threshold values as summarized in Table 1.

$CDAR_u$ = The ultimate achievable constant daily abstraction rate

$CDIR$ = The constant daily injection rate

$CDIR_u$ = The ultimate possible constant daily injection rate

## RESULTS AND DISCUSSION

Two separate models are solved in this paper. The first model is solved uses the non-dominated sorting genetic algorithm II (NSGAII). The second model is solved using a combination of the multi-objective weighting method and the constraint method. Both models are coupled to the MODFLOW simulation model.

The first model optimizes three objective functions at the same time. These are objectivesone to three, which are only subject to the set of constraints (5) to (7). All these objectives are expressed in physical terms and do not account for the value of the water. The pay-off matrix (Table 2) shows that the volume of abstracted water can vary between a minimum of 11.78 $Mm^3$/year and a maximum of 21.69 $Mm^3$/year. In other words, the maximum volume of desalinated water that can be injected in the aquifer is 21.69 $Mm^3$/year. This maximum is limited by the number of injection wells/pumps, their locations and the four months recharge period, November to February. The aquifer can receive more desalinated water if these constraints are relaxed, for instance by adding more injection wells and spreading their locations. This is evidenced by the level of the water table, which is at 14.90 m below the ground, far from the 7 m limit imposed in constraint (5).

The pay-off matrix also shows that the maximization of the abstraction volume and the minimization of the total water loss to the sea are not conflicting. In fact, the higher the volume abstracted, the lower is the volume lost from the aquifer to the sea via seepage. The volume of water lost to the sea varies between 1.31 and 4.28 $Mm^3$/year. The maximum seasonal mean drawdown (MSMD), whichmeasures the drawdown of the water table, varies between 0.02 m to 0.38 m. Observe that the maximum loss to the sea is achieved when the MSMD reaches its lowest value. This means that protecting the fall of the water table and thus minimizing the seawater intrusion, comes at a cost. This cost is the loss of 4.28 $Mm^3$/year of fresh water.

NSGA-II is used to generate the set of Pareto optimal solutions that are shown in Table 3. The first 12 columns show the volumes of water, either injected (indicated by a negative sign) or abstracted (indicated by a positive sign) daily per well. The annual amount of recharge of desalinated water or injected volume (AIV) is shown in column 14. The last three columns show the Pareto optimal values determined by each of the three objectives. The solutions are sorted in an increasing order with respect tothe objective of maximizing the groundwater abstraction volume. The information given is in physical terms which show how the aquifer will behave for a specific injection volume of desalinated water and an abstraction volume of groundwater. Overall, the drawdown of the aquifer is limited to a maximum of 0.38 m as also shown in the pay-off Matrix.

Model 2 combines the use of the multi-objective weighting method and constraint method to generate the Pareto optimal solutions. The model optimizes objective function 4,subject to constraints (5)-(10). In model 2 objective function 4 is based on the weighting method where the weights reflect the cost of injection and the values of the water abstracted and that lost to the sea. Furthermore, two of the objective functions are considered to be constraints. These correspond to the minimization of the maximum annual mean drawdown (MAMD) and minimization of the maximum seasonal mean drawdown, (MSMD) which are limited to the optimal values shown in Table 1. Therefore, Equations (8) and (9) are objectives turned into constraints whose right-hand side is parameterized.

Table 2: Pay-off matrix for the problem.

| Objectives | Abstraction Volume ($Mm^3$/year) | Water Loss to the sea ($Mm^3$/year) | Max Seasonal Mean Drawdown (m) |
|---|---|---|---|
| Max: Annual GAV | 21.690 | 1.319 | 0.37 |
| Min: Annual AWLS | 20.6453 | 1.2968 | 0.38 |
| Min: MSMD | 11.781 | 4.285 | 0.02 |

Table 3: The obtained set of Pareto optimal solutions.

| Pareto | Constant daily abstraction(+ve)/injection(-ve) rate at different months (m3/d) | | | | | | | | | | | | AIV | Objective values | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Solution number | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | (MCM/yr) | AAV (MCM/yr) | MSMD (m) | AWLS (MCM/yr) |
| 1 | -64.8 | -820.8 | 712.8 | 1080 | 1037 | 108 | 1318 | 928.8 | 302.4 | 2657 | -1274 | -2592 | 6.4152 | 10.99 | 0.02 | 4.2694 |
| 2 | -64.8 | -777.6 | 410.4 | 496.8 | 734.4 | 1469 | 2527 | 259.2 | 129.6 | 2700 | -2592 | -1944 | 7.2608 | 11.78 | 0.02 | 4.2851 |
| 3 | -237.6 | -777.6 | 64.8 | 1080 | 734.4 | 1490 | 2527 | 972 | 302.4 | 2225 | -2592 | -1901 | 7.4358 | 12.68 | 0.04 | 4.0334 |
| 4 | -410.4 | -1123 | 756 | 734.4 | 1188 | 86.4 | 2527 | 885.6 | 993.6 | 2657 | -2700 | -1944 | 8.3398 | 13.27 | 0.03 | 4.1641 |
| 5 | -583.2 | -345.6 | 2484 | 2117 | 388.8 | 432 | 1058 | 950.4 | 993.6 | 1620 | -2268 | -2635 | 7.8732 | 13.56 | 0.06 | 3.8059 |
| 6 | -237.6 | -691.2 | 1102 | 1080 | 43.2 | 1814 | 2527 | 1015 | 993.6 | 1620 | -2592 | -2635 | 8.3106 | 13.76 | 0.05 | 3.9213 |
| 7 | -151.2 | -1123 | 756 | 1037 | 1080 | 259.2 | 2743 | 864 | 993.6 | 2657 | -2700 | -1944 | 7.9898 | 14.03 | 0.07 | 3.7678 |
| 8 | -237.6 | -475.2 | 1447 | 734.4 | 1188 | 0.001 | 2614 | 864 | 1339 | 2311 | -1966 | -2592 | 7.1150 | 14.17 | 0.10 | 3.3962 |
| 9 | -151.2 | -1037 | 712.8 | 1080 | 1145 | 1490 | 2614 | 799.2 | 129.6 | 2722 | -583.2 | -2678 | 6.0070 | 14.43 | 0.14 | 2.9911 |
| 10 | -324 | -734.4 | 756 | 1080 | 842.4 | 1836 | 2441 | 928.8 | 302.4 | 2657 | -2635 | -1685 | 7.2608 | 14.64 | 0.11 | 3.3083 |
| 11 | -928.8 | -777.6 | 1447 | 1080 | 734.4 | 1663 | 2527 | 950.4 | 302.4 | 2225 | -2592 | -1901 | 8.3689 | 14.75 | 0.08 | 3.6350 |
| 12 | -151.2 | -691.2 | 734.4 | 1166 | 734.4 | 1490 | 2225 | 1318 | 1253 | 2182 | -2592 | -1901 | 7.2025 | 14.99 | 0.12 | 3.1714 |
| 13 | -583.2 | -1123 | 1404 | 1037 | 1080 | 1490 | 2592 | 756 | 1253 | 1598 | -1037 | -1901 | 6.2694 | 15.13 | 0.15 | 2.8639 |
| 14 | -237.6 | -1080 | 43.2 | 2419 | 1102 | 1663 | 2441 | 280.8 | 1598 | 2484 | -950.4 | -2678 | 6.6776 | 16.24 | 0.18 | 2.6436 |
| 15 | -583.2 | -43.2 | 388.8 | 2549 | 1102 | 1534 | 2484 | 1318 | 907.2 | 1966 | -950.4 | -2678 | 5.7445 | 16.53 | 0.22 | 2.2545 |
| 16 | -669.6 | -1080 | 1447 | 2074 | 1123 | 108 | 1944 | 756 | 2376 | 2657 | -1231 | -2635 | 7.5816 | 16.85 | 0.17 | 2.7366 |
| 17 | -237.6 | -799.2 | 756 | 2419 | 1102 | 1534 | 2592 | 777.6 | 1339 | 2225 | -1339 | -1901 | 5.7737 | 17.20 | 0.24 | 2.0954 |
| 18 | -64.8 | -1037 | 2138 | 86.4 | 2484 | 1642 | 2635 | 1512 | 1339 | 1166 | -734.4 | -1555 | 4.5781 | 17.55 | 0.29 | 1.7233 |
| 19 | -496.8 | -1037 | 2484 | 2549 | 388.8 | 1814 | 2527 | 324 | 993.6 | 1966 | -1382 | -2635 | 7.4941 | 17.61 | 0.20 | 2.4222 |
| 20 | -64.8 | -1123 | 1447 | 2635 | 2549 | 1469 | 2527 | 237.6 | 993.6 | 1966 | -259.2 | -2635 | 5.5112 | 18.66 | 0.29 | 1.6549 |
| 21 | -669.6 | -43.2 | 756 | 2117 | 1123 | 453.6 | 2592 | 2290 | 2376 | 2657 | -2657 | -2290 | 7.6399 | 19.39 | 0.25 | 2.0036 |
| 22 | -324 | -0.001 | 2117 | 2074 | 1123 | 108 | 1901 | 2138 | 2376 | 2657 | -1274 | -2592 | 5.6570 | 19.57 | 0.32 | 1.5187 |
| 23 | -1879 | -691.2 | 712.8 | 2678 | 2117 | 2182 | 799.2 | 2311 | 1339 | 2376 | -2074 | -1901 | 8.8355 | 19.60 | 0.21 | 2.3079 |
| 24 | -324 | -799.2 | 2117 | 2419 | 1166 | 151.2 | 1901 | 2160 | 2722 | 2311 | -1253 | -1922 | 5.8028 | 20.18 | 0.33 | 1.4632 |
| 25 | -583.2 | -432 | 561.6 | 2225 | 1361 | 1750 | 2614 | 2268 | 2030 | 2484 | -993.6 | -1642 | 4.9280 | 20.65 | 0.38 | 1.2968 |
| 26 | -324 | -1123 | 2311 | 2074 | 1102 | 1469 | 2592 | 2074 | 1339 | 2398 | -1253 | -2592 | 7.1442 | 20.73 | 0.31 | 1.5809 |
| 27 | -1534 | -1058 | 2376 | 2117 | 1166 | 108 | 2614 | 1620 | 2722 | 2657 | -1339 | -2246 | 8.3398 | 20.76 | 0.27 | 1.8815 |
| 28 | -410.4 | -1145 | 712.8 | 2635 | 2527 | 2527 | 2657 | 669.6 | 1253 | 2700 | -648 | -2722 | 6.6485 | 21.17 | 0.34 | 1.4300 |
| 29 | -324 | -1145 | 1404 | 2462 | 2225 | 1814 | 2570 | 2398 | 216 | 2700 | -2722 | -2722 | 9.3312 | 21.32 | 0.26 | 1.8974 |
| 30 | -410.4 | -1145 | 928.8 | 2290 | 2419 | 2182 | 2592 | 540 | 2722 | 2398 | -518.4 | -2592 | 6.2986 | 21.70 | 0.37 | 1.3189 |

MSMD:Maximum Seasonal Mean Drawdown  
AWLS:Annual amount of groundwater losses to the sea  
AAV:Annual amount of abstraction volume  
AIV:Annual amount of Injection volume

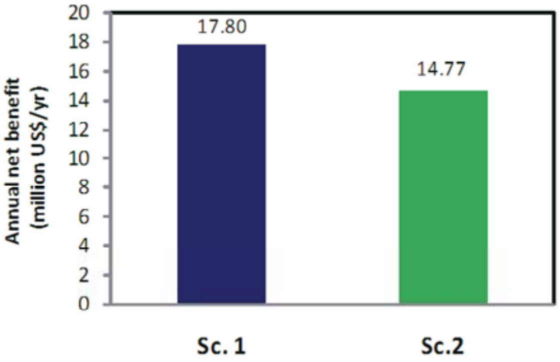


Fig. 2.Annual net benefit.

Two Pareto optimal solutions are obtained and are called Scenario 1 (Sc1) and Scenario 2 (Sc2). The results are shown in the following figures. It is to be noted that groundwater abstraction from the aquifer for urban uses has been the practice for decades, without the injection of desalinated water that is considered in this paper. Consequently, to estimate the net benefit due to the recharge of desalinated water, only the incremental benefit should be considered. The incremental benefit is estimated as the value of objective function 4 minus the benefit "without injection" which are estimated at $10.5 million and $15.4 million/year for Sc1 and Sc2, respectively.

Thus, Fig. 2 shows the incremental benefit compared to the current situation "without injection". In other words, the annual net benefit shown in Fig. 1 is the difference between the benefit from the aquifer "with injection" minus the benefit from the aquifer "without injection". The average annual net benefit due to the injection of desalinated water in the aquifer varies between $14.77 and $17.80 million.

Fig. 3 shows the optimal values for the decision variables CDIR and CDAR, for Scenarios 1 and 2 in $m^3$/day/well. The daily volumes injected vary between1,123 and 1,555 $m^3$/day/well for a period of four months each year from November to February. The abstraction rate from the aquifer will reach volumes of between 2,290 and 2,614 $m^3$/day/well, during the eight month period each year, compared to 778 and 1,145 $m^3$/day/well in the "without injection" condition (Table 1). Note that water security is further improved as the volumes that could be extracted during emergency periods are much higher than those of the case of the aquifer not being recharged with desalinated water. The benefit of improved response to emergency situations is not accounted for in this paper.

Fig. 4 shows the total volume injected versus the total net incremental volume abstracted compared to the situation "without injection" for Sc1 and Sc2.Observe that the total net incrementalvolume abstracted is higher than the desalinated volume injected. In fact, the volume lost to the sea is negative, which means that the total loss to the sea has been reduced in the situation of "with injection" compared to the "without injection"situation. Said in other words, part of the water that was lost to the

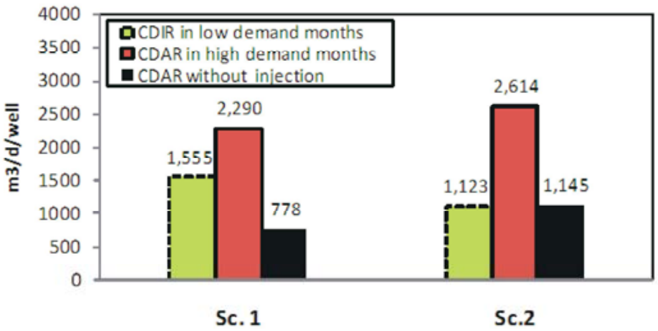


Fig. 3: The output of optimization for wet and dry months.

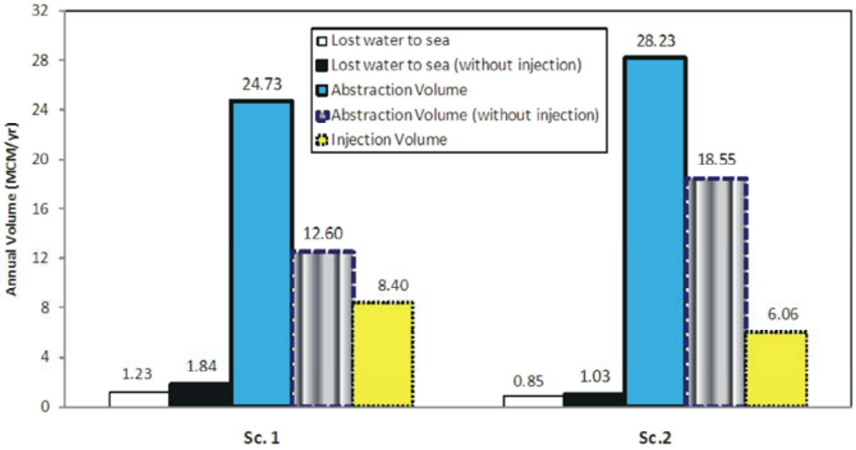


Fig. 4: Net annual volume of lost water to sea, abstraction and injection.

sea is now abstracted for urban usessince injection of desalinated water improved the level of the water table in the aquifer allowing higher abstraction rates. [4] estimated that the average annual water demand per household, residing in villas, is approximately 480 m$^3$/year. Thus, the incremental abstraction volume will suffice to provide water for an additional 20,000 to 25,000 households.

## CONCLUSIONS

The paper has shown the possibility of storing seasonal excess desalinated water inan urban aquifer. Out of the 10 Mm$^3$/year of excess desalinated water that is eventually sentto the sea, 8.4 Mm$^3$/year can be stored inan aquifer. This will provide a net benefit estimated at \$17.80 million/year. Both the Ministry of Regional Municipalities and Water Resources and the PAEW will have to work together to better use this scarce water resource. The current number of wells and their locations does not allow the injection of all the excess desalinated water produced in the low demand period. 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 investigation 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.

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