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Storing Treated Wastewater Underground in Arid Countries: A Case Study From Oman

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ABSTRACT

Most of the water stressed countries such as the Sultanate of Oman are vulnerable to the potential adverse impacts of climate change, the most significant of which are increased average temperatures, less and more erratic precipitation, sea level rise (SLR) and desertification. The combined effect of existing adverse conditions and likely impacts of future climate change will make water management even more difficult than what it is today. Managed Aquifer Recharge (MAR) is practiced widely to store water during periods of surpluses and withdraw during deficits from an aquifer. With reasonable care the water is protected from pollution. It uses minimum land area and causes no environmental damage. Recharged water is distributed across the aquifer due to natural gradients. When practiced along coastal aquifers, MAR mitigates seawater intrusion. It is less expensive, and easier to operate and maintain compared to surface dams, and it is always available on demand. On the other hand, MAR has some disadvantages. In most cases, only a part of the recharged water is recovered. Quality of recharging water could lead to changes in physical and chemical characteristics of the soil and aquifer. Some impurities, such as microbes, heavy metals or trace elements, if present in recharging water will contaminate the aquifer, and will be very expensive to contain and clean. To avoid these problems, the injected water usually undergo treatment processes that can satisfy drinking water standards. In Muscat, there will be a surplus of 100,000 m3/day of treated effluent (TE) during winter months by 2015. The aquifer along the northern coast of Oman (Lower Samail Catchment) is conducive for MAR. Data show that TE volumes will increase from 7.6 Mm3 in 2003 to 70.9 Mm3 in 2035. HYDRUS 3D simulations show that, areas with sandy loam soils are suited for infiltration ponds. Numerical simulations with MODFLOW (in combination with PEST and GWM) show that injection wells can be used for recharge without causing undue water ponding. Numerical simulations show that when groundwater level is limited to 10 m below the ground surface, no feasible solution that satisfies the optimization problem was found (with 4 month recharge and no abstraction), but when the head constraint is relaxed to 5 m below the ground, a feasible solution was found. Therefore, in order to maximize the amount of water injected into aquifer, MAR was subjected to the following constraints: limit groundwater mound below 5 meters, maximum allowable injection rate is 1000 m3/day and decision variables are injection rate and location of the wells. Results show that 66 injection wells with a total injection rate of 64,620 m3/d was found to be a feasible option, there will be a discharge of maximum 7,500 m3/day towards the sea and the injection rate of each wells ranges from 200 -1000 m3/d. Preliminary financial analysis has shown that the cost USD 0.353/m3 will be incurred for further Reverse Osmosis (RO) membrane treatment and injection. Issues such as ownership of the water, quality requirements of recharged water, uses of such waters, health and safety considerations and cost recovery need concrete government decisions after discussions with all stakeholders and on the basis of proper environmental and technical analysis.

Keywords: Managed Aquifer Recharge, Oman, Climate Change, Treated Effluent, MODFLOW

INTRODUCTION

Managed aquifer recharge (MAR) is practiced widely to store water during periods of surpluses and withdraw during deficits from an aquifer. MAR implies aquifer recharge is accelerated by altering natural soil surface conditions to increase infiltration or water is injected directly via recharge wells. With reasonable care the water is protected from pollution. It uses minimum land area and causes no environmental damage. Recharged water is distributed across the aquifer due to natural gradients. When practiced along coastal aquifers, MAR mitigates seawater intrusion. It is less expensive, and easier to operate and maintain compared to surface dams, and it is always available on demand. On the other hand, MAR has some disadvantages. In most cases, only a part of the recharged water is recovered. Quality of recharging water could lead to changes in physical and chemical characteristics of the soil and aquifer. Some impurities, such as microbes, heavy metals or trace elements, if present in recharging water will contaminate the aquifer, and will be very expensive to contain and clean. To avoid these problems, the injected water usually undergo treatment processes that can satisfy drinking water standards.

In the Muscat region of Oman, the Oman Wastewater Services Company (OWSC) is mandated to collect,

treat and dispose domestic wastewater. OWSC anticipates the percentage of households in the sewer network to increase to 80% in the near future. By then, it also anticipates a surplus up to 100,000 m3 of treated (using most advanced MBR technology) wastewater per day during winter months, after meeting the demand to irrigate city parks, roadside plants and trees.
The objectives of the present study were: to evaluate soil and hydrogeological conditions in the vicinity of OWSC's STPs to select areas for MAR and to conduct financial analyses of a MAR project with treated wastewater for a period of 30 years.

RESEARCH METHODOLOGY

Our first task was to identify an area which is likely to be suitable for MAR. Our main focus here was to identify areas with good infiltration and transmission capacity. We also concentrated on sites near Treated Effluent (TE) pipelines to ensure TE pipelines constructed to supply irrigation water are used to transport recharge water during winter. The analysis of the geology, hydraulic properties, availability of agricultural lands together with proximity to the wastewater pipe lines has suggested lower Samail catchment area as the potential area for MAR. Samail Catchment which covers an area of about 1635 km2 and consists of three main tributaries: Wadi AlRusail, Wadi AlKhod and Wadi Semail. The average hydraulic conductivity estimated by pumping tests varies between 14 and 34 m/day decreasing with depth and coastal proximity [1]. Water table contour lines are closely spaced in the upstream side of the dam yielding an average hydraulic gradient of 0.01, whereas contour lines are widely spaced in the coastal plain giving rise to an average 0.002 gradient [2]. Depth to the groundwater varies between 5 m and 10 m below the ground surface (bgs) in the coastal plain areas and >55 m bgs in the upstream part. In the area located close to the AlKhod Dam it reaches about 25 m below the ground surface. Hydraulic heads at the coast proximity tend to zero and exceed 30 m in the upstream side.

Model studies

In order to understand the physical process of aquifer recharge and identify locations as well as behavior of the aquifers after recharge, two models were used. HYDRUS-3D [3] is a software package for simulating the two-dimensional movement of water, heat, and multiple solutes in variably-saturated media. This model was used to understand whether soil physical properties may limit infiltration and recharge of TE. The other model used was MODFLOW which was used for simulating MAR using injection and recovery wells. The calibration was performed using the automated parameter estimation code PEST [4]. Details of the model set up, calibration and scenario analysis are available in this web address.
http://www.google.co.za/url?sa=t&rct=j&q=&esrc=s&source=web&cd=7&ved=0CEAQFjAG&url=http%3A%2F%2Frepository.tudelft.nl%2Fassets%2Fuuid%3A1b2cb509-9e79-4ad6-b6ab-7a21a8e63f7a%2FUNESCO-IHE_PHD_EBRAHIM_THESIS.pdf&ei=jLsfVMDmN43OaK2vgMgP&usg=AFQjCNEwHG9eMIUm7hgQbgD_aCiSj5RayQ&sig2=owzKYJkssJFx4TwOIKB3kw
Economic analysis An economic analysis was done to see the cost of MAR on the basis 30 yr period with 5% interest rate. The cost model WaTER was used.

RESULTS AND CONCLUIONS

The OWSC expects TE volumes to increase as they increase the extent of the sewerage network. The expected volumes are summarized in Figure 1 with the highest volume available in 2035 of 70.9 Mm3. The quality of the TE is also given in Table 1 along with permissible limits for agriculture.

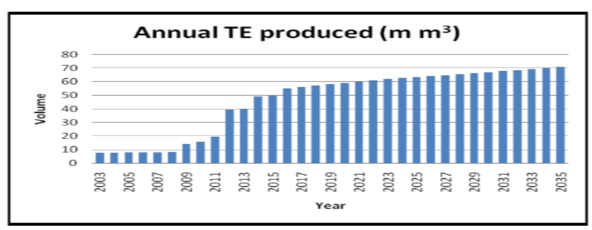

Figure 1 Annual TE produced in million m3

Table 1Expected treated effluent (TE) quality from OWSC plants

Parameters	Units	Effluent from Al Ansab Plant	Class A (Agricultural irrigation permissible limits)
BOD	mg/l	5	15
TSS	mg/l	5	15
Total N as N	mg/l	8	21.3
NH3 an N	mg/l	1	5
Organic N as N	mg/l	0	5
NO3 as N	mg/l	7	11.3
Total P as P	mg/l	-	30
pH	-	-	6.9
Fats, Oil & Greases	mg/l	-	0.5
TotalDissolvedSolids (TDS)	mg/l	<1000	1500
Total alkalinity (as CaCO3)	mg/l	150	-
Faecal Coliforms Bacteria	MPN/100l	<2.2	200
Visible Helminth ova	Number/l	0	<1
Turbidity	NTU	0.5	-
Residual Chlorine	mg/l	0.3<X<1	-

Simulation of surface ponding MAR with HYDRUS-3D

HYDRUS-3D is a package to simulate movement of water, contaminants, and heat through the unsaturated zone. 10X20-m grid was used to simulate 3-m water recharge pond for 24 hours. Boundary conditions used were: top: constant head, bottom: free drainage, sides: no flow. Two materials were considered: loamy sand and sandy loam with dry initial condition. 24-h simulation showed that depth of saturated column reach a depth of about 19 m. A total of 17.2 m3/10 m2 infiltrated in 24 h, of which 0.37 m3/10 m2 left the profile reaching the water-table. It indicates of high infiltration capacity of the soil which will result in relatively small sized recharge ponds. But there are advantages in recharging through injection wells such as no standing water in a hot country like Oman.

Scenario analysis for MAR with injection wells

Three scenarios were considered: Four months of injection without recovery; Four months of injection and eight months of recovery; and Four months of injection and continuous (12 months) recovery. The groundwater management software package GWM [5] that couples MODFLOW with mathematical optimization routines were used to solve the three groundwater management problems described above.

Groundwater management scenario 1: Four months of injection without recovery

The objective of this management problem is to maximizes the total quantity of water injected into the aquifer for transient condition while satisfying head constraint that prevent excessive groundwater mounding. The constraints are (1) groundwater level should be at least 5 m below the ground surface; (2) the lower and upper bound of the injection rate respectively should be zero and 1000 m3/d. The decision variables are the rate and location of injection wells. The model results show that 66 optimal injection wells were selected from 109 potential injection wells and the total optimal injection rate is computed to be 6.4622E+04 m3/d. The total volume of injected water in the four month period is about 7.76 E+06 m3.

Groundwater management scenario 2: Four months of injection and 8 months of recovery

The objective of this management problem is to maximize the total quantity of water that can be recovered without violating head gradient from the aquifer to the sea. The constraints are: (1) the head gradient at the control point along the sea coast should be greater than head gradient of the transient simulation (pre-injection); 2) at least 60 days of residence time between the injection and recovery wells; 3) the lower and upper bound of the injection rate respectively should be zero and 1500 m3/d. The decision variables are the rate and location of recovery wells. In this case optimal injection rate from scenario-1 was used and the optimal rate and locations of recovery wells were optimized. 13 optimal recovery wells were selected from 30 potential injection wells. The total optimal recovery rate is computed to be 1.27E+04 m3/d. The total volume of recovered water in the eight month period is about 3.11 E+06 m3 . Recovery efficiency computed for the whole period is about 40%.

Groundwater management scenario 3: Four month of injection and 12 months of recovery

This management problem is similar to management problem 2. The objective of this management problem is to maximize the amount of injected and recovered water. The constraints of both case 1 and case 2 applies. 88 optimal injection wells were selected from 109 potential injection wells. 12 optimal recovery wells were selected from 30 potential recovery wells. The total optimal injection rate is computed to be 7.36E+04 m3/d. The total optimal recovery rate is computed to be 1.12E+04 m3/d. The total volume of injected water in the four month period is about 8.83 E+06 m3 . The total volume of recovered water in the 12 month period is about 4.1 E+06 m3. Recovery efficiency computed for the whole period is about 46%. Placement of recovery wells relative to the injection or recharge facilities depends on the recovery objectives, legal and regulatory constraints and hydrogeologic constraints. Since our interest was to recover the same water that was used for recharge, we located the recovery wells down gradient from the injection wells. If recovering the same water is not important, it is possible to increase the recovery efficiency by placing additional recovery wells upstream of the injection facility.

Economic analysis

An economic analysis was done to see the cost of MAR on the basis of the following assumptions: for advanced treatment before injection a 85,000 m3/day single pass RO system with feed pressure of 13.6 bar to be used. The analysis is based on a 30 yr period with 5% interest rate (assuming that the project will be undertaken by the Government of Oman). The recovery efficiency of 85%, no pre-treatment and electricity cost of 0.046 and 0.064 USD/Kwh were used. The cost model WaTER was used. The table 2 shows the output from the cost model [6].

Table 2 MAR cost at 5% interest rate, lifespan of 30 years, 2 electricity costs and 85% recovery rate

		Capital Cost (US$ million)	O&M Cost (US$ million)	Capital cost (US$/m3/yr)	O&M cost (US$/m3/day)	Total cost (US$/m3)
Scenario 1	C1	51.569	6.851	606.692	0.221	0.276
Electricity cost=	C2	2.9132	0.332	34.2729	0.0107	0.0138
$0.046/KWh	C3	2.0854	0.2385	28.8641	0.009	0.0117
Total cost scenario 1		56.45	7.421	669.829	0.282	0.353
Scenario 2	C1	51.569	7.158	606.692	0.231	0.286
Electricity cost=	C2	2.9132	0.4343	34.2729	0.014	0.0171
$0.064/KWh	C3	2.0854	0.311	28.8641	0.0118	0.0144
Total cost scenario 2		56.45	7.903	669.829	0.300	0.371

C1= Cost of RO treatment, C2 = Cost of recharge, C3 = Cost of extraction

The cost in both cases is lower than the more typical desalination costs using RO technology. The reason being the low salinity of input water and low feed pressure. Another reason being the government's borrowing power at low interest rate, availability of government land. Even with such low cost of MAR it would be unwise to use this water for low return sectors like agriculture. Use of injected water for drinking or industrial use must be allowed to make the whole MAR process economically attractive. From cost consideration the project may not look very attractive but in making a decision the other benefits should also be considered. Benefits for the community and society are very important and could be summarized as follow: job creation and reduction of any environmental burden resulting from disposing the water in the sea. Given the high impacts on community, OWSC can easily justify the need for subsidy from government to install and maintain a fully functioning MAR system.

An advanced treatment of the excess effluent and subsequent recharging of aquifers is a technically feasible project. The Samail lower catchment is suitable as location for MAR. However, the financial analysis results have shown that the project will cost a further USD 0.353/m3 under best case scenario for further treatment by RO membrane technology and injection into the aquifer. In order to be implemented. Issues such as ownership of the water, quality requirements of recharged water, uses of such waters, health and safety considerations and cost recovery need to be considered before a final decision is made.

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