ELSEVIER

Desalination 133 (2001) 135–147

DESALINATION

www.elsevier.com/locate/desal

Brine disposal from reverse osmosis desalination plants in Oman and the United Arab Emirates

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Received 29 May 2000; accepted 2 October 2000

Abstract

Reverse osmosis (RO) desalination plants are used for supplying potable water to small communities in inland areas of Oman as well as small to large communities in the United Arab Emirates (UAE). Most of these desalination plants use brackish groundwater as feedwater. The production of brine (also known as concentrate or wastewater) is an integral part of the operation of desalination plants. Ten small-scale desalination plants in the interior parts of Oman and eight RO plants in the coastal areas of the UAE were investigated with regard to their brine disposal methods. The capacity of the Omani plants varied from 50 m^3/d to a maximum of 1000 m^3/d. The salinity level of wastewater varied from 9.8 to 61.2 dS/m (1 dS/m = 640 mg/L). Various disposal methods were observed. These included lined evaporation ponds, ocean/beach disposal, and unlined small bores. The depth to the water table in the areas of the investigated desalination plants varies from 40 to 80 m, while the average distance between feedwater intake and disposal areas was approximately 200 m. In the UAE, the capacities of the investigated plants varied between 950 to 15,000 m^3/d. All the UAE plants dispose of their brine in the sea, although some of the plants dispose of their brine in nearby creeks that are linked to the sea. The chemical characteristics of the brine, feedwater, product water, and water from evaporation ponds (or bores) were determined. The presence of other chemicals including iron, copper, zinc, and cleaning agents (such as hydrochloric acid, sodium hexametaphosphate, and anti-scalants) is likely to pollute the groundwater, if the brine were to reach the underlying aquifers. Under certain conditions, brine from the desalination plants can have useful applications. Potentials for such applications are addressed in this paper.

Keywords: Oman; UAE; Desalination; Wastewater; Evaporation ponds; Concentrate disposal; Brine; Reverse osmosis

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PII: S0011-9164(01)00092-3

1. Introduction

The Sultanate of Oman occupies the southeastern corner of the Arabian Peninsula and is located between latitudes 16°40′ and 26°20′ north and longitudes 51°50′ and 59°40′ east. The country has a coastal line that extends more than 1600 km along the southeastern coast of the Arabian Peninsula. Oman is bordered on the north by the Gulf of Oman, on the east and south by the Arabian Sea, on the southwest by the Republic of Yemen, on the west by the Rub' al Khali (the Empty Quarter) of Saudi Arabia, and on the northwest by the United Arab Emirates. The country's territory also includes the northern tip of Musandam that juts between the Persian Gulf and the Gulf of Oman. This portion is separated from the rest of the country by the territory of the United Arab Emirates. The climate of Oman is generally hot and arid. However, the humidity along the coast is high. The average annual temperature is about 28.3°C. The average annual rainfall is generally less than 102 mm. On the other hand, the UAE is a federation of seven states lying along the east central coast of the Arabian Peninsula. The states include Abu Dhabi, Ajman, Dubai, Al Fujairah, Ra's al Khaymah, Sharjah, and Umm Al-Qwain. UAE is bounded on the north by Qatar and the Persian Gulf, on the east by the Gulf of Oman and Oman, and on the south and west by Saudi Arabia. Most of the inhabitants of the UAE live in either coastal towns or inland oases. The rest of the UAE is sandy and unproductive. The climate is extremely hot and humid in summer, with average maximum temperatures exceeding 40°C. Winters are mild, and the average rainfall is very low.

Both Oman and the UAE are arid countries with hot dry climates. The per capita demand for fresh water is high, especially for domestic, agriculture, and industrial purposes. This demand increased dramatically along with the improvement and development of living standards [1]. Agriculture uses the lion share of water in Oman (approximately 90% of country's total water use). Groundwater resources have been over-exploited resulting in seawater intrusion in coastal aquifers. To meet the demand for domestic water, the Omani government opted for the establishment of several desalination plants. In the 1980s and 1990s, desalination plants were built in inland rural areas. Most of these were RO plants of small capacities. The development of the desalination industry followed the same pattern in the UAE. Given the high standard of living in the UAE, the per capita consumption of water is also very high. The UAE desalination plants supply the major share of domestic water needs while some other plants even supply water for agricultural use.

Disposal of brine (also referred to as membrane concentrate, reject brine, and wastewater) in RO plants is of much significance both from economic and environmental standpoints. Improper surface disposal has the potential for polluting the groundwater resources that are used as feedwater for many of the RO plants. The groundwater pollution is likely to result from high salinity and the presence of other harmful chemicals in the brine. Khordagui [2] identified the following options for disposal of reject brine from inland RO desalination plants: pumping into specially designed lined evaporation ponds, deep-well injection, disposal into surface water bodies, disposal through pipelines to municipal sewers, concentration into solid salts, and irrigation of plants tolerant to high salinity (halophytes). Mickley et al. [3] identified the factors that influence the selection of a disposal method. These include the volume or quantity of concentrate, quality or constituents of concentrate, physical or geographical location of the discharge point of the concentrate, availability of receiving site, permissibility of the option, public acceptance, capital and operating costs, and ability for the facility to be expanded. They also presented a survey of drinking water plants in the continental US (for drinking water membrane plants having a capacity of 98 m^3/d or more) that included 137 plants where 48% dispose of the concentrate to surface water, 23% dispose to the head-works of wastewater treatment plants, 12% utilize a land application process, 10% dispose via deep well injection, and 6% use evaporation ponds.

According to ESCWA [4], cost plays an important role in the selection of a brine disposal method. This cost ranges from 5% to 33% of the total cost of desalination. The cost of disposal depends on the characteristics of reject brine, the level of treatment before disposal, means of disposal, volume of brine to be disposed of, and the nature of the disposed environment. Glueckstern and Priel [5] found that the disposal costs of inland RO desalination plants are higher than that of plants disposing reject brine in nearby seas or lakes.

Evaporation ponds can be successfully used for disposal of brine, especially in countries such as Oman and the UAE where hot and dry weather conditions prevail with high evaporation rates coupled with the availability of land at low cost. Sealing of evaporation ponds reduce the risk of groundwater contamination. Truesdall et al. [6] observed that evaporation ponds were used in some of the small desalination plants in the US. Evaporation ponds ranging from 13.6 to 34.3 ha are used for disposal purposes in the desalination plants in the central region of Saudi Arabia [7]. Mickley [8] considers evaporation ponds most appropriate for relatively warm and dry climates with high evaporation rates, level terrain, and low land costs. Squire et al. [9] described a method of surface water disposal of RO membrane concentrate by blending the concentrate with backwash water from sand filters. Many small RO plants dispose their reject brine in municipal sewerage systems. This process has the attraction of lowering the BOD of the domestic sewage. However, the increase in TDS may make it impossible to use the treated effluent for irrigation purposes.

The primary objective of this study was to assess the present status of disposal mechanisms of brine from RO desalination plants in Oman and the UAE as well as to explore alternative mechanisms for such disposals.

2. Methodology

Questionnaires were prepared to gather information and data. The questionnaires dealt with basic information and types of chemicals used in the desalination process. The plants targeted in Oman for the gathering of information included RO plants that utilize brackish groundwater as feedwater and have mostly land-based disposal methods to get rid of the brine. However, the plants investigated in the UAE disposed their brine into the sea. Relevant questionnaires were sent to government authorities in Oman and the UAE. The Ministries of Electricity and Water in the Sultanate of Oman and the UAE responded with data and information on several desalination plants.

During field visits to desalination plants in Oman and the UAE, water samples were collected from feedwater, product water, and brine. Some samples were also collected from the standing water in evaporation ponds and disposal pits. Samples were analyzed for various chemicals and heavy metals at the Chemical Laboratory of the Ministry of Water Resources in Oman. Data on the use of chemicals in some of these plants were also collected. Most of the plants were government owned and used for domestic water supply. The method of disposal of brine in the visited 18 plants ranged from using evaporation ponds to the disposal in boreholes, shoreline, wadi beds, and ocean.

3. Results and discussion

The information presented in this paper was mostly gathered through field visits of 10 desalination plants in the Sultanate of Oman and the eight plants in the UAE, in addition to gathered information through a questionnaire survey. The following provides brief descriptions of the visited 18 desalination plants in Oman and the UAE as well as the cost of disposal of brine through evaporation ponds and the perceived challenges and opportunities of brine disposal methods.

3.1. Visited Omani plants

Adam desalination plant: This plant started operation in 1997. It supplies water for domestic uses and has a capacity of 1000 m^3/d. It is an RO plant with brackish groundwater as feedwater. The average recovery rate is 75%. The average quality of feedwater and concentration are 3.5 and 9.65 dS/m, respectively. The disposal method is evaporation ponds having the dimensions of 320 by 180 m. The evaporation ponds are 1368 m from the intake well. Polyethylene sheeting was used as liner in the pond. No salt build-up was observed in the ponds, which may be due to leakage.

Haima desalination plant: This plant started operation in 1996. The plant supplies water for domestic purposes with a capacity of 100 m^3/d. It is also an RO plant that uses brackish groundwater as feedwater. The average recovery rate is 38%. The average feedwater salinity is very high (approximately 28.0 dS/m). Consequently, the salinity level of the concentrate is also very high (approximately 43.0 dS/m). Evaporation ponds, each with the dimensions of 89 by 169 m, are used for disposal purposes. Polyethylene liners are used in the ponds. The feedwater well is nearly 200 m from the ponds. The observed lack of salt build-up in the ponds may be indicative of leakage.

Esherjah desalination plant: This plant started operation in 1996. It is also an RO plant supplying water for domestic purposes with a capacity of 100 m^3/d. The average recovery rate is 42%. The average quality of feedwater is 42.5 dS/m and that of concentrate is 67.0 dS/m. Evaporation ponds with polyethylene liners are also used. Each of the ponds had the dimensions of 80 by 165 m. Some holes were observed in the liner and no salt build-up was noticed in the pond. The intake well is 290 m from the pond.

Sowqrah desalination plant: This plant is located near the beach and started its operation recently. It is an RO plant with a capacity of 100 m^3/d. The actual production has been less than the installed capacity of the plant due to the lack of demand. The feedwater is seawater and the concentrate is discharged into the sea. No environmental impacts were noticed.

Hitam desalination plant: This plant was commissioned in 1985. It is an RO plant supplying water for domestic purposes with a capacity of 100 m^3/d. It uses brackish groundwater as feedwater. The recovery rate is 25% while the average quality of feedwater is 20 dS/m and that of concentrate is 31 dS/m. The concentrate is disposed in a small bore, approximately 200 m from the intake well. The average groundwater depth is 40 m. It is highly likely that the disposed concentrate reaches the groundwater rather quickly.

Madrakah desalination plant: This RO plant is also located near the beach. The intake of feedwater is done through beach wells. It produces 100 m^3/d of water for domestic purposes and 420 m^3/d of concentrate. The quality of feedwater is approximately 53 dS/m and that of the concentrate is nearly 70 dS/m. The concentrate is disposed on the beach, approximately 500 m from the intake wells.

Zahar desalination plant: This RO plant started operation in 1985. It has a capacity of 50 m^3/d and a recovery rate of 63%. The average quality of feedwater and concentrate are 5 and 14 dS/m, respectively. The concentrate is dumped in an unlined bore at a distance of 180 m from the intake. The groundwater table is located at 90 m from the surface. Because of the disposal practice, it is likely that the groundwater is being polluted.

Assadanat desalination plant: This plant also started functioning in 1985. It is a RO plant with a capacity of 50 m^3/d. It uses brackish groundwater as feedwater with a recovery rate of 60%. The average quality of feedwater and that of concentrate are 10.2 and 20 dS/m, respectively. The concentrate is dumped in an unlined bore at a distance of 200 m from the intake well. There exists risk of groundwater contamination. The plant operators stated that the groundwater table rises quickly after rainfall, possibly indicating that concentrate dumped in the bore is ultimately finding its way to the groundwater system.

Abu-Mudhaibi desalination plant: This RO plant was established in 1985 for supplying water for domestic purposes. It has a capacity of 50 m^3/d and uses brackish groundwater with a recovery rate of 64%. The salinity of feedwater and concentrate are 8.4 and 23 dS/m, respectively. The groundwater is extracted from a depth of 40 m while the concentrate is disposed in a bore, 200 m from the intake well. The pit did not indicate any salt build-up. It appeared that most of the salt enters the groundwater system.

Safah desalination plant: This RO plant is operated by the Occidental Petroleum Co. in Oman. The plant is located in Safah, 130 km from Ibri. It was constructed in 1983 with a capacity of 100 m^3/d. The water is used for both domestic (major) and agricultural (minor) purposes. The groundwater is used as feedwater with a recovery rate of 50%. The depth to groundwater table is approximately 100 m. The average quality of feedwater is between 14 and 20 dS/m. An evaporation pond of the dimensions 10×20 m is used for concentrate disposal. The pond, lined with a PVC sheet, is located 100 m from the intake well. Salt is removed manually from the pond. The plant operators stated that environmental assessments were carried out and no adverse impacts were anticipated.

3.2. Visited UAE plants

Qidfa I plant: The Qidfa I plant is located in Qidfa, the Fujairah Emirate. This RO plant began its operation in 1990 to supply water for domestic use. The capacity of the plant is 4550 m^3/d. In 1997, 1.72×10^6 m^3 of water were supplied. Open seawater is used as feedwater and the average recovery rate is 40%. The average quality of feedwater and concentrate are 58 and 66 dS/m, respectively. The concentrate is disposed directly on the shoreline.

Qidfa II RO plant: The Qidfa II plant is also located in Qidfa. This RO plant began its operation in 1991. It supplies water for domestic use and has a capacity of 9100 m^3/d. In 1997, 2.58×10^6 m^3 of water were supplied from the plant. Beach wells are used for supplying feedwater and the plant average recovery rate is 35%. On average, about 17,000 m^3 of concentrate are produced every day. In 1997, 6.2×10^6 m^3 of concentrate were produced. The average quality of feedwater and concentrate is 56 and 66 dS/m, respectively. The concentrate is disposed directly on the shoreline.

Kalba plant: The Kalba RO plant is located in Kalba, the Emirate of Sharjah. The water is used for domestic purposes. The plant started operation in January 1995 and has a capacity of 14,550 m^3/d. Sixty-five brackish water wells are used for supplying feedwater to the plant. The wells are scattered around the plant at distances of 2.5 to 10 km. The plant is comprised of nine units. The average recovery rates of these units vary between 65 and 70%. On average, the volume of concentrate produced on a daily basis is more than 4550 m^3/d. The average quality of feedwater and concentrate are 6 and 18 dS/m, respectively. The concentrate is dumped back into the sea given its proximity to the plant.

Umm Al-Qwain water desalination plant: This RO plant is located in the Emirate of Umm Al-Qwain. The plant started operation in 1985 and provides 10,500 m^3/d of desalinated water. After blending with brackish water, the plant can supply up to 15,000 m^3/d. Sand filtration is done before the start of desalination. In 1997, the total volume of water supplied was 3.686×10^6 m^3. Groundwater from Sirrah well field, located 14 km from the plant, is used as feedwater. The average recovery rate is 75% and the average volume of daily concentrate produced is 3480 m^3/d. The average quality of feedwater and concentrate are 4.6 and 14.6 dS/m, respectively. The concentrate is first dumped in the Umm Al-Qwain creek by gravity pipes. Ultimately the concentrate reaches the ocean. The depth to the underlying groundwater table in the aquifer is about 30 m.

Jabal Al-Dhana plant: This RO plant is located in Jabal Al-Dhana of Abu Dhabi. The plant started operation in June 1991. Desalinated water from the plant is intended mostly for agricultural and domestic purposes. The capacity of the plant is 9100 m^3/d. Open seawater is used as feedwater and the recovery rate is approximately 30%. The average salinity of feedwater is around 65 dS/m while the salinity of concentrate is 80 dS/m. The latter is directly dumped into the sea.

Hamriyah desalination plant: This RO plant is located in the Emirate of Sharjah. The plant started operation in 1995, with additional units being added in 1997. The produced water is used for domestic purposes. The capacity of the plant is 2900 m^3/d. Brackish groundwater is used as feedwater and the supply wells are located 12 km from the plant. The average recovery rate is approximately 70%. The average volume of concentrate produced is 870 m^3/d. The average salinity of feedwater and concentrate are 3.2 and 10.5 dS/m, respectively. The concentrate is dumped in a nearby creek. Since the aquifer is away from this creek, no harmful effects are anticipated.

Al-Aryam plant: This RO plant is located in the western part of Abu Dhabi. The plant started its operation in 1991. The water supplied from this plant is used for agricultural and domestic purposes. The capacity of the plant is 950 m^3/d. Seawater is used as feedwater and the recovery rate is approximately 30%. The salinity level of concentrate is approximately 80 dS/m, which is being dumped directly into the sea.

Al-Rafeek plant: This RO desalination plant is located in the western part of Abu Dhabi. Water from the plant is used for agricultural purposes. The recovery rate of the plant is 30% (design), although the actual recovery rate is less than 22%. The capacity of the plant is 950 m^3/d. The plant treats seawater and the concentrate with a salinity level of 90 dS/m is being dumped back into the sea.

4. Chemical analysis

Tables 1 and 2 contain brine characteristics data of some selected small-scale desalination plants in Oman and the UAE. These data were obtained from a single sampling of water and brine from various RO desalination plants during field visits. As such, the data may not reflect the average characteristics of brine. Table 3 provides a summary of observed brine disposal methods in the plants visited. Table 4 shows the ratios of major ions of feedwater and brine of some Omani plants. The concentration of major ions in the brine appears to be proportional to those measured in the feedwater. This indicates that the process of desalination does not lead to the enrichment of reject brine with any particular ion.

Table 1
Chemical and heavy metal characteristics of brine from desalination plants in Oman

Parameter	Name of the plant									
	Adam	Haima	Esherjah	Sowqrah	Hitam	Madrakah	Zahar	Assadanat	Abu-Mudhaibi	Safah
Chemical characteristics:										
Calcium (mg/L)	417	1020	841	625	665	611	612	923	962	463
Magnesium (mg/L)	280	406	1900	1830	448	1980	315	413	448	260
Sodium (mg/L)	1670	5250	14,800	14,600	4250	15,300	1980	2780	4630	4889
Potassium (mg/L)	43.1	174.0	631.0	668.0	145.0	685.0	95.4	81.5	101	—
Strontium (mg/L)	13.1	23.9	18.3	12.4	15.3	11.4	16.3	28.2	26.9	—
pH	5.56	3.07	6.94	7.94	7.66	7.07	7.32	7.21	6.03	8.1
Carbonate (mg/L)	—	—	—	—	—	—	—	—	—	7.0
Bicarbonate (mg/L)	37	—	221.0	—	173	125	859	464	205	300
Chloride (mg/L)	1964	9090	24,062	—	8118	24,802	4367	4532	77,335	5520
Sulphate (mg/L)	4336	3881	6139	4824	2466	3846	1143	1552	3296	4625
Nitrate as NO_3 (mg/L)	5.2	—	5.50	—	46.7	6.1	24.2	7.2	56.4	—
Fluoride (mg/L)	—	—	—	—	—	—	—	—	—	—
E.C (mS/cm)	9870	28000	61,100	60,500	21,400	61,220	12,230	16,800	23,400	24,400
S.A.R (me/L)	15.51	—	64.65	—	30.5	67.68	16.21	19.12	30.92	—
S.E.R (me/L)	61.77	—	75.01	—	70.99	75.93	59.39	59.55	69.72	—
Langelier Index (me/L)	—1.86	—	0.63	—	1.14	0.32	1.47	1.24	−0.33	—
Ryzner Index (me/L)	9.27	—	5.68	—	5.37	6.43	4.38	4.73	6.68	—
TDS (mg/L)	8747	—	48,510	—	16,142	47,305	8990	10,553	16,960	16,200
Total ions (mg/L)	8765	—	48,618	—	16,227	47,367	9412	10,781	17,061	—
Total alkalinity (mg/L)	30	—	181	203	142	102	704	380	168	—
Total hardness (mg/L)	2211	—	9951	—	3526	9698	2846	4041	4281	2225
Heavy metal characteristics:										
Iron (mg/L)	0.06	0.14	0.43	0.41	0.10	0.43	< 0.05	0.06	0.12	0.03
Manganese (mg/L)	0.07	< 0.05	0.05	0.05	0.05	0.05	< 0.05	< 0.05	< 0.05	—
Copper (mg/L)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	—
Zinc (mg/L)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	—
Chromium (mg/L)	< 0.05	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	—

Table 2
Chemical and heavy metal characteristics of feed-water and brine of desalination plants, the UAE

Parameter	Qidfa I		Qidfa II		Kalba		Jabal al-Dhana		Hamriyah		Umm Al-Qwain	
	Feed	Brine	Feed	Brine	Feed	Brine	Feed	Brine	Brine	Feed	Brine	Feed
Chemical characteristics:												
Calcium (mg/L)	464	617	533	730	446	1180	636	760	173	48	202	49
Magnesium (mg/L)	1640	2150	1620	2240	245	644	2140	2660	311	85	510	110
Sodium (mg/L)	11,900	15,100	12,200	15,800	536	1170	14,200	17,700	1930	498	3190	775
Potassium (mg/L)	574.0	767.0	581.0	805.0	11.0	34.1	661.0	950.0	50.7	13.2	84.5	19.4
Strontium (mg/L)	4.56	7.19	7.29	11.50	5.05	10.70	10.00	10.40	14.20	3.73	21.10	4.96
Silicon as SiO_2	1.07	1.07	15.04	19.94	32.30	82.79	1.07	1.07	133.71	41.82	164.09	37.01
Silicon (mg/L)	<0.5	<0.5	7.03	9.32	15.10	38.70	<0.50	<0.50	62.50	19.50	76.70	17.30
$\sum$ of cations (me/L)	690.44	884.18	705.47	928.65	66.02	163.65	842.45	1051.07	119.48	31.39	192.98	45.71
pH	7.87	6.76	7.06	6.97	7.48	7.59	7.83	6.38	7.66	7.31	7.54	7.80
Bicarbonate (mg/L)	136	117	100	125	133	347	138	117	753	216	656	275
Chloride (mg/L)	23149	30,540	23,484	32,004	2103	5413	27,098	34,839	2933	779	4108	1182
Sulphate (mg/L)	2787	3931	3181	4500	265	756	3121	4602	1537	407	2444	562
Nitrate as N (mg/L)	<0.5	0.7	0.5	0.7	4.7	10.7	0.6	0.8	3.6	1.1	6.2	1.8
Nitrate as NO_3 (mg/L)	<2.2	3.0	3.3	3.1	20.5	47.2	2.5	3.4	15.9	4.8	27.4	7.7
Fluoride (mg/L)	1.5	2.1	0.6	0.9	<0.1	<0.1	1.8	2.3	1.3	0.2	1.6	0.4
$\sum$ of anions (me/L)	713.40	945.46	730.43	998.67	67.36	174.90	831.81	1080.73	127.41	34.08	178.05	49.70
E.C (mS/cm)	55,700	73,300	56,130	78,000	6190	15,100	65,900	81,100	10,850	3300	14,960	4680
Ion balance (me/L)	−1.64	−3.35	−1.74	−3.63	−1.01	−3.32	0.64	−1.39	−3.21	−4.12	4.02	−4.18
SAR (me/L)	58.22	64.45	59.35	65.42	5.06	6.80	60.59	67.95	20.30	10.00	27.20	14.06
SER (me/L)	74.97	74.29	75.23	74.01	35.32	31.10	73.32	73.25	70.27	69.02	71.91	73.76
Langelier Index (me/L)	1.10	0.01	0.15	0.30	0.62	1.56	1.20	−0.28	1.26	−0.19	1.04	0.40
Ryzner Index (me/L)	5.67	6.73	6.76	6.37	6.29	4.47	5.43	6.93	5.14	7.69	5.46	7.00
TDS (mg/L)	40,592	53,177	41,661	56,158	3700	9432	47,941	61,587	7350	1949	10,923	2851
Total ions (mg/L)	40,658	53,235	41,710	56,220	3765	9602	48,009	61,645	7719	2055	11,245	2986
Total alkalinity (mg/L)	111	96	82	102	109	285	113	96	617	177	538	226
Total hardness (mg/L)	7922	10,409	8015	11,067	2130	5615	10,418	12,871	1730	474	2630	581
Heavy metal characteristics:												
Iron (mg/L)	0.22	0.33	0.22	0.35	< 0.05	0.08	0.27	0.37	0.05	< 0.05	0.08	< 0.05
Manganese (mg/L)	< 0.05	0.06	0.06	0.07	< 0.05	< 0.05	0.05	0.07	< 0.05	< 0.05	< 0.05	< 0.05
Copper (mg/L)	< 0.5	< 0.5	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Zinc (mg/L)	< 0.5	< 0.5	< 0.0.5	< 0.05	< 0.05	0.07	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Chromium (mg/L)	< 0.5	< 0.5	< 0.5	< 0.05	< 0.05	0.06	< 0.05	< 0.05	< 0.05	0.23	0.12	0.26

Table 3
Summary of observed brine disposal from plants in Oman and UAE

Plant	Disposal method	Comments
Adam, Oman	Evaporation pond	Leakage from the pond is suspected
Haima, Oman	Evaporation pond	Leakage from the pond is suspected
Esherjah, Oman	Evaporation pond	Holes were noticed in the liner
Sowqrah, Oman	Ocean disposal	
Hitam, Oman	Disposal to a bore	Potential for groundwater contamination
Madrakah, Oman	Disposal to the beach	
Zahar, Oman	Disposal to unlined bore	Potential for rapid groundwater contamination
Assadanat, Oman	Disposal to unlined bore	Potential for groundwater contamination
Abu-Mudhaibi, Oman	Disposal to unlined bore	Likelihood of groundwater contamination
Safah, Oman	Disposal to lined evaporation ponds	Well-managed disposal system
Qidfa I, UAE	Shoreline disposal	No adverse impact on the shoreline was noticed other than the growth of green algae
Qidfa II, UAE	Shoreline disposal	No adverse impact on the shoreline was noticed other than the growth of green
Kalba, UAE	Ocean disposal	
Umm Al-Qwain, UAE	Dumped in the nearby creek that ultimately reaches the ocean	
Jabal Al-Dhana, UAE	Ocean disposal	
Hamriayah, UAE	Dumped in the creek far away from the feed-water source	
Al-Aryam, UAE	Ocean disposal	
Al-Rafeek, UAE	Ocean disposal	

Table 5 contains a list of chemicals used in RO desalination plants in Oman. The capacities of the 10 plants in Oman varied from 50 m^3/d to a maximum of $1000 m^3/d$. The salinity level of reject brine varied from 9.8 to 61.2 dS/m. Groundwater tables were at depths between 40 to 80 m from the surface. Heavy metals (Mn, Cu, Zn, and Cr) were found at trace levels in the concentrates. Various types of chemicals such as chlorine, sulphuric acid, sodium meta-bisulphite, lime powder, and citric acid are used in the RO plants in Oman. In the UAE, the plant capacities varied from 950 to $15,000 m^3/d$. Both groundwater and seawater are used as feedwater, depending on the location of the desalination plant. The salinity level in the brine of the UAE plants varied from 10.8 to 81.1 dS/m, while the sodium absorption ratio (SAR) varied from 6.8 to 68.0.

The newer plants in Oman have well-designed lined evaporation ponds whereas the older ones have unlined disposal pits. It appears that the lined evaporation ponds and disposal pits are not very effective. Lined-evaporation ponds prevent leakage resulting in increased concentration of salts and other chemicals in comparison to the wastewater that is dumped in the pond. Water samples collected from the evaporation pond in

Table 4
Ratio of major ions of feed-water and brine of some Omani plants

Location	Chemical parameter	Feed-water	Brine	Ratio (brine/feed)
Adam	Ca (mg/L)	103	417	4.05
	Mg (mg/L)	70	280	4.00
	Na (mg/L)	410	1,670	4.07
	Cl (mg/L)	506	1,964	3.88
	SO_4 (mg/L)	773	4,336	5.61
	EC (dS/m)	2.89	9.87	3.42
Haima	Ca (mg/L)	652	1,020	1.56
	Mg (mg/L)	267	406	1.52
	Na (mg/L)	3,340	5,250	1.57
	Cl (mg/L)	1,697	9,090	5.36
	SO_4 (mg/L)	2,037	3,881	1.91
	EC (dS/m)	19.2	28.0	1.46
Esherjah	Ca (mg/L)	490	841	1.72
	Mg (mg/L)	1,100	1,900	1.73
	Na (mg/L)	8,630	14,800	1.72
	Cl (mg/L)	15,868	24,062	1.52
	SO_4 (mg/L)	4,104	6,139	1.50
	EC (dS/m)	41.9	61.1	1.46
Hitam	Ca (mg/L)	563	665	1.18
	Mg (mg/L)	382	448	1.17
	Na (mg/L)	3,400	4,250	1.25
	Cl (mg/L)	7,483	8,118	1.08
	SO_4 (mg/L)	2,366	2,466	1.04
	EC (dS/m)	18.75	21.40	1.14
Zahar	Ca (mg/L)	179	612	3.42
	Mg (mg/L)	95	315	3.32
	Na (mg/L)	746	1,980	2.65
	Cl (mg/L)	1,408	4,367	3.10
	SO_4 (mg/L)	—	1,143	—
	EC (dS/m)	4.57	12.23	2.68
Assadanat	Ca (mg/L)	367	923	2.51
	Mg (mg/L)	174	413	2.37
	Na (mg/L)	1,290	2,780	2.15
	Cl (mg/L)	2,160	4,532	2.10
	SO_4 (mg/L)	—	1,552	—
	EC (dS/m)	8.69	16.8	1.93
Abu-Mudhaibi	Ca (mg/L)	294	962	3.27
	Mg (mg/L)	137	4,48	3.27
	Na (mg/L)	1,360	4,630	3.40
	Cl (mg/L)	2,151	7,335	3.41
	SO_4 (mg/L)	515	3,296	6.40
	EC (dS/m)	7.8	23.4	3.00

Haima and the disposal pits in Assadanat and Abu-Mudhaibi showed little or no increase in the concentrations of salts (Table 6).

It was also observed during the field visits that some of the recently constructed evaporation ponds had leaks. There were some clear indications that leakage from some of the ponds and pits existed since no salt build-up was noticed in these structures and the volumes of standing water were very small. Further in-depth investigations through water balance studies and the monitoring of the underlying groundwater aquifers should enable the detection of any significant leakages from such structures.

5. Construction cost

Very little information is available on the cost of disposal from the plants visited. The Ministry of Electricity and Water in Oman provided data on construction costs of five recently built evaporation ponds (Table 7). From the table, it is clear that the unit cost of construction is reduced as the pond size increases. However, there are several other factors involved. Such factors include the remoteness of the plant location, distance to nearby towns, availability of local construction materials, and labor.

6. Challenges and opportunities of brine disposal methods

Various options exist for the disposal of reject brine from inland desalination plants. These include waste minimization, discharge to surface water, discharge to wastewater treatment plants, deep wells, land application, evaporation ponds, and wastewater evaporators. Waste minimization is an approach in which the objective is to produce less concentrate (generally by membrane-process recovery-enhancement techniques) or to reduce the concentrators prior to ultimate

Table 5
Chemicals used in RO desalination plants in Oman

Plant name	Treatment of feed-water	Treatment of produced water	Chemicals used in cleaning	Post-cleaning treatment	Others
Adam	Sulphuric acid, chlorine, Flocon-100, sodium meta bisulphite	Chlorine, lime powder	Citric acid, EDTA, trisodium phosphate, sodium tripoly phosphate		
Haima	Sulphuric acid, sodium meta bisulphite, Flocon-100, chlorine	Chlorine, lime powder	EDTA, citric acid, ammonia, sodium hydroxide	PT-A, PT-B	
Esherjah	Flocon-100, sodium meta bisulphite	Chlorine, lime powder	EDTA, citric acid, sodium hydroxide, ammonia	PT-A, PT-B	
Sowqrah	Chlorine, Flocon-100, sodium meta bisulphite	Chlorine, lime powder			
Hitam	Chlorine, Flocon-100, sodium meta bisulphite	Chlorine, limestone	EDTA, sodium hydroxide, citric acid		
Madrakah	Sulphuric acid	Chlorine, limestone	Formaline		
Zahar	Sodium meta bisulphite, Flocon-100	Chlorine, limestone	EDTA, citric acid, sodium hydroxide		
Assadanat	Sodium meta bisulphite, Flocon-100	Chlorine, limestone	Citric acid, sodium hydroxide, Sodium dodecyle sulphate		
Abu Mudhaibi	Sulphuric acid, sodium meta bisulphite	Chlorine, limestone	EDTA, citric acid, sodium hydroxide		
Khumkham	Sulphuric acid, Flocon-100, polyelectrolyte, sodium meta bisulphite	Chlorine, lime powder	EDTA, citric acid, ammonia	PT-A, PT-B	Perma clean sodium hexameta phosphate

disposal [3]. This particular approach is not usually very economical since the increase in cost is substantial, given the need for an extensive pretreatment and the increased membrane area. Although the volume is reduced, the concentration of various minerals and chemicals increases. Such high concentrations can create special problems with disposal since many disposal regulations are based on concentrations, not volume.

Under certain conditions, brine from desalination plants can have useful applications. Production of salt and other minerals (Mg) are the most obvious. Al-Mutaz and Wagialla [10] reported that caustic soda can be produced from desalination brines at a cost of about 149 $US/t.

Table 6
Ratio of water quality parameters (disposal pond water vs. wastewater)

Location	Parameter	Wastewater	Pond water	Ratio
Haima	Ca (mg/L)	1020	1100	1.08
	Mg (mg/L)	406	438	1.08
	Na (mg/L)	5250	5870	1.12
	Cl (mg/L)	9090	9661	1.06
	SO_4 (mg/L)	3881	3881	1.00
	Fe (mg/L)	0.14	0.18	1.29
	EC (dS/m)	28.0	30.2	1.08
Assadanat	Ca (mg/L)	923	871	0.94
	Mg (mg/L)	413	413	1.00
	Na (mg/L)	2780	2790	1.00
	Cl (mg/L)	4532	4717	1.04
	SO_4 (mg/L)	1552	1578	1.02
	Fe (mg/L)	0.06	0.07	1.17
	EC (dS/m)	16.8	16.9	1.00
Abu-Mudhaibi	Ca (mg/L)	962	929	0.97
	Mg (mg/L)	448	438	0.98
	Na (mg/L)	4630	4430	0.96
	Cl (mg/L)	7335	9006	1.23
	SO_4 (mg/L)	3296	3059	0.93
	Fe (mg/L)	0.12	0.12	1.00
	EC (dS/m)	23.4	23.15	0.99

Table 7
Cost of disposal (evaporation pond construction in Oman)

Plant	Capacity (m^3/d)	Recovery rate (%)	Design reject brine production (m^3/d)	Cost of construction ($US)	Pond size (m^2)	Unit cost ($US/$m^2$)	Unit cost per m^3/d of reject brine ($US/$m^3$/d)
Adam	1000	75	333	384,157	57,600	6.7	1154
Haima	100	38	163	121,360	15,041	8.1	745
Esherjah	100	42	138	184,766	13,200	15.0	339
Al-Haj	100	40	150	153,423	13,200	11.6	1023
Khum-kham	100	45	122	65,629	1,200	54.7	538

The use of evaporation ponds for brine shrimp cultivation has been attempted in Australia. Evaporation ponds are ideal places for brine-shrimp production since no food competitors or predators survive at high salinity, resulting in a mono-culture under natural conditions. Irrigation of salt-tolerant plants by reject brine will also be possible provided that soil salinization is maintained at acceptable levels by controlling leaching and minimizing the risk of groundwater contamination. Soil solutions composed of high solute concentrations (salinity), or dominated by calcium and magnesium salts, are conducive to good soil physical properties. Conversely, low salt concentrations and relatively high proportions of sodium salts adversely affect permeability and tilth [11].

The salinity of brine from desalination plants in Oman and the UAE is very high and so is the SAR. However, the amount of brine in Oman is relatively small. Considering that the rate of evaporation in Oman and the UAE is extremely high, it is unlikely that any large-scale use of brine (from desalination plants) for irrigation will be feasible. Other uses of brine are unlikely for the following reasons: the volume of brine produced is relatively small in many plants, most of the desalination plants are located in the desert far from big towns, and the environmental concerns related to any product produced or extracted from brine are high.

7. Conclusions

The small-scale RO desalination plants in Oman use mostly lined evaporation ponds and unlined pits for the disposal of brine. Considering the high salt concentrations and the presence of other chemicals, it is imperative that safe methods of disposal be used for the protection of groundwater resources. Evaporation ponds (lined) and disposal pits did not show any noticeable increase in the concentration of various salts and EC levels. This is an indication that brine could be reaching the groundwater. In the UAE, the RO plants investigated dispose their brine in the sea. Due to technical, environmental, and economic constraints, it is unlikely that the brine reject from desalination plants can be used for any meaningful purposes in Oman and the UAE. As such, well designed and well constructed evaporation ponds under proper management will be the most appropriate disposal mechanism for inland desalination plants in Oman, while disposal to the sea will likely continue for foreseeable future in the UAE.

Acknowledgements

This study was made possible partially through funding from the Middle East Desalination Research Center under contract number 98-R-004. The authors would also like to acknowledge the valuable assistance provided by the Omani Ministry of Water Resources, the Omani Ministry of Electricity and Water, Oman National Electricity Company, and the UAE Ministry of Water and Electricity.

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