Desalination and Water Treatment
www.deswater.com
1944-3994 / 1944-3986
doi: 10.5004/dwt.2011.1965

25 (2011) 276–285
January

Environmental assessment of brine discharge and wastewater in the Arabian Gulf

Raed Bashitialshaaer[a]*, Lena Flyborg[a], Kenneth M. Persson[a,b]

[a]*Department of Water Resources Engineering, Lund University, PO Box 118, SE-221 00 Lund, Sweden*
Tel. +46 (46) 222-4367, -8729; Fax +46 (46) 222-4435; email: Raed.Alshaaer@tvrl.lth.se
[b]*Sydvatten AB, R&D, Skeppsgatan 19, SE 211 19 Malmö, Sweden*

Received 19 April 2010; Accepted in revised form 6 July 2010

ABSTRACT

This study assesses the environmental effects of brine discharge into the Arabian/Persian Gulf and the option of mixing with wastewater to reduce the salt content in the discharge. The Arabian Gulf region occupies about 3.3% of the world area and has 1.0, 2.0 and 2.2% of the total world population in the years 1950, 2008 and 2050 (prognosis) respectively. The study area desalination capacities were obtained as 50, 40 and 45% of total world capacity at the end of 1996, 2008 and 2050 (prognosis) respectively. The trend towards increased recovery ratio in the desalination plants was considered as one important environmental factor. This will significantly increase the brine salt concentration from 1.5 to more than 2 times the seawater. The allocation of wastewater and brine is important for the Arabian Gulf. Straightforward water and salt mass balances were used to calculate residual flow, exchange flow and exchange time in the Arabian Gulf. For example, at zero wastewater discharge from 1996 to 2008, the net volume in the Arabian Gulf decreased by 7.4 million m^3/d, the exchange volume increased by 69 million m^3/d, and the mixing time decreased by 22.5 d. Discharging a mix of brine and wastewater in the Arabian Gulf reduces the water and salt exchange between the Gulf and the Indian Ocean. Nutrients in wastewater may cause problems such as eutrophication in the Gulf if the exchange of water is low or if wastewater is discharged to the Gulf with insufficient treatment.

Keywords: Arabian Gulf; Desalination; Wastewater; Population; Water–salt balance; Environmental impacts; Salinity

1. Introduction

1.1. General

Desalination is an important source of potable water in arid areas. Six percent of all desalination plants are located in the Asia-Pacific region, 7% in the Americas, 10% in Europe, and 77% in the Middle East and North Africa [10,11]. The largest number of desalination plants can be found in the Arabian Gulf with a total seawater desalination capacity of approximately 11 million m^3/d, which means a little less than half (45%) of the worldwide daily production. The main producers in the Gulf region are the United Arab Emirates (26% of the worldwide seawater desalination capacity), Saudi Arabia (23%, of which 9% can be attributed to the Gulf region and 13% to the Red Sea), and Kuwait (<7%) [11,28]. The water sources are 58% seawater, 22% brackish water and 5% tertiary treated wastewater. The mineral content of brine is usually found to be double or close to double that of natural seawater

* Corresponding author.

[12]. The total dissolved solids (TDS) in the three main regions are higher, 38.6, 45 and 41 g/l for the Mediterranean, the Arabian Gulf, and the Red Sea respectively, compared to typical seawater of about 34.5 g/l [9].

Usually a country is considered to face a water shortage if renewable fresh water resources are below 1000 m^3/cap/y [1]. This is the case for all Middle East countries. To solve this problem, more desalination plants are being built all over the world. However, the increasing number of desalination plants along the coast lines as well as the higher capacity recovery ratio, from 30 up to 50% in some countries, increases the brine discharge concentration from 1.5 to 2 times of the intake concentration. A higher brine concentration results in weaker mixing, stronger stratification, and a longer traveling time that affects and may harm the coastal area.

In this paper, a comparison between the world and the Arabian Gulf region was made for: 1) Average annual population growth rate (PGR) in three periods (1950, 2008 and 2050), 2) Average annual desalination growth ratio (DGR) during two periods (at the end of 1996 and 2007–08), 3) Coverage area ratio, and 4) Desalination recovery ratio related to freshwater production (Q_F), brine discharge (Q_{Brine}), and seawater intake (Q_{Intake}).

The Arabian Gulf (AG) area has a very high evaporation rate, between 1200–2000 mm annually, and a very low annual precipitation, between 90–150 mm. The AG is semi-enclosed and the arid climate characterized by a higher salt content due to the high rate of evaporation [2]. Although the existing amount of water resources on our planet is substantial, it is generally saline and unevenly distributed [3]. For instance, only five great rivers capture about 27% of the global renewable fresh water resources (Amazon, Ganges-Brahmaputra, Congo, Yellow and Orinoco) [4,5].

1.2. Dispersion of the concentrated salts

One major environmental problem associated with a desalination plant is disposal of and/or minimization of the brine concentration. A natural and easy way is to discharge the brine to the sea, but an appropriate design is required in order to ensure proper dispersion of the brine. Different alternatives have been suggested in previous studies such as discharge by a long pipe, direct discharge of the brines at the coastline, mixing of the brine via the outlet of power stations' cooling water or wastewater, using the brines for a salt production evaporation pond, and having more than one outlet to the sea.

The forces of buoyancy in wastewater and brine discharge are important in the dilution process of water jets [13]. For saline waters, brine discharges have normally negative buoyancy and wastewater have positive buoyancy. Negatively buoyant brine discharge is also important and requires submerged discharge location in form of jet that ensures a high dilution in order to minimize harmful impacts on the marine environment. The process of brine dilution is a combination of two physical processes: 1) the primary (jet) dilution and 2) the natural dilution process. A co-location of a power station and a desalination plant (joint project) offers many advantages when handling the brine discharge, although most of these are relevant to plants that are based on the various evaporation systems as opposed to reverse osmosis plants [14–18]. A co-location will give a chance of mixing brine water with water from power station and discharge together back to the sea in order to reduce salinity.

The data presented in Table 1 were adopted from International Desalination Association (IDA) yearbooks 2006–07, 2007–08, 2008–09 and 2009–2010. The data are collected to help us to find better and accurate result regarding future calculations. These data were collected from different projects mainly in the Middle East countries. In Table 1, eight co-location projects and available data for recovery ratios of the desalination plants are also presented. The results from the Ashkelon and Hadera desalination plants indicate that the total salinity of the water in the vicinity of the outlet of the discharge pipe would increase by 1–5%. This result was based on the available models for dispersion. The effect of the concentrated brine will disappear at a distance of a few meters from the outlet [19,20].

1.3. Objectives

This study was initiated for assessing the effects of brine discharge into recipients. A large number of desalination plants that have been built around the Arabian Gulf using its water both for intake and as recipient for brines. Population increase and economical growth are also considered as main driving forces in this area. They are directly related to fresh water consumption, brine production and wastewater production and possible reuse. The main objective of this study is to analyze the effects of increasing desalination in the AG area on the AG seawater quality. Therefore, the following studies have been executed:

- The effects of discharge of brines of desalination plants and wastewater to the Arabian Gulf are calculated for 1996 and 2008, and assessed for the year 2050.
- Water and salt mass balances were employed to find residual flow, exchange flow, and exchange time for the Gulf for the same years.
- The allocations of wastewater and brines have been assessed. Mixing brine with wastewater has been calculated on the basis of a recycling percentage of 0, 25, 50, 75 and 100%. Many countries around the Arabian Gulf already reuse wastewater or have plans to do so in the future. With very high evaporation rate in the area, reuse of wastewater will reduce the flow of low-salinity waters to the Gulf.

Table 1
Data from different desalination plants including eight power plant projects, desalinated water output and recovery ratio

Project name IDA year book (2006–2007)	Date	Total capacity (m^3/d)	Intake TDS (mg/l)	Production recovery ratio (%)	Output TDS (mg/l)	Within project (MW)	Technology type
Ashkelon SWRO, Israel	2005	326144	40679	40.7	300		RO
Carboneras SWRO, Spain	2002	120000	39000	45	<500		RO
Fujairah, UAE*	2003	454000	40000	NA	<180	500	MSF
Shuweihat, UAE*	2004	454000	44000	NA	<250	1500	MSF
IDA year book (2007-2008)							
Dhekelia, Cyprus	1997	40000	40570	50	<500		RO
Larnaca, Cyprus	2001	54000	40300	50	<500		RO
Perth, Australia	2007	143700	36500	42.6	30		RO
Wadi Ma'in, Jordan	2006	128767	2000	85–90	250		RO
IDA year book (2008–2009)							
Hidd (IWPP), Bahrain*	07–08	408780	44000	45	<50	910	MED
Taweelah B: Extension, UAE*	2008	315000	44000	40	<25	1000	MSF
Ras Laffan B (IWPP), Qatar*	2008	272520	42000	40	<25	1025	MSF
Hamma (SWRO) , Algeria	2008	200000	39000	42	<500		RO
Palmachim SWRO, Israel	2007	110000	40233	45	<300		RO
IDA year book (2009–2010)							
Barcelona-Liobregat, Spain	2009	200000	44800	44	400		
Marafiq IWPP-Jubail, KSA*	2009	800000	42000	45	<25	2745	MED
Barka 2 IWPP, Oman*	2009	123000	39300	39	45	678	RO
Alicant 1 and 2, Spain	03-08	130000	40000	42	400		RO
Rabigh IWSPP, KSA *	2007	218000	39600	35	<10	360	RO

IDA — International Desalination Association Yearbook; SWRO — seawawter revers osmosis; WEB — Water Energiebedrijf; APP — atomic power project; IWPP — independent water power project; IWSPP — integrated water steam and power project; KSA — Kingdom of Saudi Arabia; UAE — United Arab Emirates; MSF — multistage flash; MED — multi-effect distillation.
* indicates a co-location plant

- In all studies above, the increase in population and population growth rate was considered.

2. Study area: background and characteristics

2.1. General

The countries bordering the Arabian Gulf are: Iran, Iraq, Kuwait, Saudi Arabia, Qatar, Bahrain, and the United Arab Emirates (as shown in Fig. 1). The Arabian Gulf is a shallow semi-enclosed marginal sea, with maximum depth less than 100 m over its entire extent and a mean depth of only 35 m [21]. It covers an area of about 240,000 km^2, with 1000 km in length and widths ranging from 185 km to 370 km, with a mean of 240 km. The total water volume in the Gulf is approximately 8,400 km^3. There are freshwater inflows from the Tigris, the Euphrates, and the Karun at the delta of the Shatt al Arab, estimated at 0.2 m/y over the gulf cross-sectional area, in which fresh water and river inflow equals 48 km^3/y (131.5×10^6 m^3/d) [21,22]. The mean annual evaporation rate is estimated at approximately 1.5 m/y [23]. Most brines are discharged to the AG directly, with exception for Iraq. The total brine discharge from Iraqi desalination plants is about 715,000 m^3/d. Of this amount 5% is estimated to be discharged to the Arabian Gulf and the rest to be discharged to other places such as rivers or lakes upstream. The same percentage is also used for Iraqi wastewater. The total discharge Q_T to the Gulf is estimated as the sum of brine discharge Q_B and wastewater discharge Q_W. The values presented for Q_T includes the discharge of 100% wastewater, which will be mixed with brine water (Fig. 1).

The shallowness and humidity lead to the formation of saline, dense water, with maximum salinities as high as 57 g/l in the AG [24]. Ahmad and Sultan (1991) employed the Knudsen relations to estimate the annual mean Gulf water outflow transport at 14.7×10^9 m^3/d [25] and compared it with the observation from an Acoustic Doppler Current Profiler (ADCP) moored in the Strait of Hormuz,

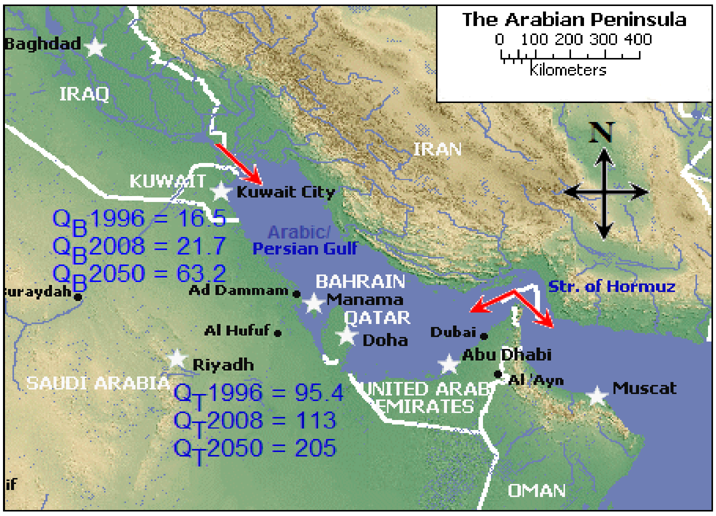

Fig. 1. Results of water discharged to the Arabian Gulf in (10^6 m^3/d) in 1996, 2008 and 2050 (Map from Google).

which indicated no strong seasonal variation outflow transport and an annual mean of (17.3–21.6)×10^9 m^3/d [26]. Bidokhti and Ezam estimated a typical mass transport of the outflow from the Arabian Gulf at about 34.5×10^9 m^3/d, which was larger than previously reported [27].

2.2. Population and area

A comparison of population, area, and population growth rate for the world and the study area is presented in Table 2 for a span of 100 years. The total population in the study area is approximately 1.0 and 2.0% of the world's population in the years 1950 and 2008 and prognoses to increase to 2.2% by the year 2050 [29]. The area around the Arabian Gulf occupies approximately 3.3% of the world area. Population growth ratio is high in the AG area. The annual population growth rate in the world and study area in the 100 year period from 1950 to 2050 was found to be 1.30 and 2.07 respectively.

The growth rates were calculated using the formula: $R(t) = \ln [P_{t+1} / P_t]$, in which t = year; P_{t+1} = population at mid-year $t+1$, P_t = population at mid-year t, and ln = natural log [29]. The growth rate is normally calculated from mid-year to mid-year.

3. Long-term data

3.1. Desalination capacities distribution

An estimate of desalination capacity and capacity per capita up to 2050 was made with available and calculated data. Fig. 2 is a typical diagram of a seawater desalination plant including pre and post treatment, where S_{Intake} and Q_{Intake} are salinity and volume of seawater intake, S_{Brine} and

Table 2
Comparison of area and population growth rate in the world and study area in 1996, 2008 and 2050 [29]

Country or area	Population			Area (km^2)	Population growth rate (PGR)
	1950	2008	2050		
World	2,555,948,654	6,677,602,292	9,392,797,012	130,772,667	1.30
Bahrain	114,840	718,306	973,412	665	2.14
Iran	16,357,000	65,875,223	81,490,039	1,636,000	1.61
Iraq	5,163,443	28,221,181	56,360,779	432,162	2,39
Kuwait	144,774	2,596,799	6,374,800	17,820	3.78
Qatar	25,101	928,635	1,239,216	11,437	3.90
KSA	3,859,801	28,161,417	49,706,851	2,149,690	2.56
UAE	71,520	4,621,399	8,018,904	83,600	4.72
Total	25,736,479	131,122,960	204,164,001	4,331,374	2.07
Percentage	1.0	2.0	2.2	3.3	0.77

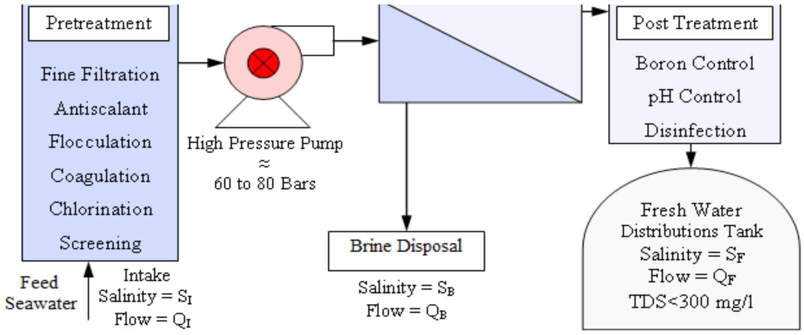

Fig. 2. A typical reverse osmosis seawater desalination plant scheme showing input/output and different stages of treatment. Note that boron control involves a second RO stage (BWRO), which also produces brine with a low TDS (< 3000 mg/l).

Q_{Brine} salinity and volume of brine discharge, and S_F and Q_F salinity and volume of fresh water produced by the desalination plant. $S_{Brine} = S_{Intake}/(1 - r)$ and $Q_{Brine} = (1 - r) Q_{Intake}$, where r is the recovery ratio between 35–45% of the intake and $S_F \approx 0$ and $Q_F = rQ_{Intake}$. The high concentration brine is discharged back to the open sea through pipes and in some cases in an open channel. The cooling water flows in MSF and MED are disregarded, since they do not affect salinity.

Over the last ten years of desalination development, the recovery ratio r has been significantly increased in reverse osmosis plants. For example, Raed et al. demonstrated that seawater intake salinity, S_{Intake}, is equal to 41.7 ppt, and the brine directly in front of the output pipeline is equal to 74 ppt. The recovery ratio will be $S_{Brine} = S_{Intake}/(1 - r)$, or $r = 44\%$ recovery ratio [30]. Table 3 presents desalination capacities in 1,000 m^3/d globally as well as for the studied area at the end of 1996 and 2008, and estimated values for 2050. The operation temperature in a multistage flash desalination plant (MSF) can reach up to 120°C. In multi-effect distillation plants (MED), the plants operate at temperatures below 70°C. Brines from thermal desalination plants can be mixed with cooling water to decrease the temperature or mixed with wastewater to dilute the brine salinity. This may give the effluents a positive buoyant. If not mixed with cooling water or wastewater, the brines can also have negative or neutral buoyant, depending on salinity and temperature. More and recent examples for recovery ratio can be found in Table 1. These data contain the major desalination technologies RO membrane and thermal desalination.

Three types of water in the typical desalination plant

Table 3
Comparison between the world and study area for desalination capacity at the end of 1996, 2008, and predictions for the year 2050 [4,10,11,15–18,28]

Country	Desalination capacity in 1,000 m^3/d								
	1996			2008			2050		
	Q_F	Q_B	Q_I	Q_F	Q_B	Q_I	Q_F	Q_B	Q_I
World	20000	46667	66667	47709	71564	119273	192211	192211	384422
Bahrain	283.0	660	943	825.2	1238	2063	3022	3022	6044
Iran	423.4	988	1411	547.8	822	1370	3138	3138	6276
Iraq	324.5	757	1082	476.6	715	1192	2519.3	2519	5039
Kuwait	1284.3	2997	4281	2308.7	3463	5772	10822	10822	21644
Qatar	560.8	1308	1869	1026.3	1539	2566	4762	4762	9524
KSA	5006.2	11681	16687	7750.8	11626	19377	39669	39669	79339
UAE	2134.2	4980	7114	6094.7	9142	15237	22533	22533	45065
Total	10016	23372	33388	19030	28545	47575	86465	86465	172931
Percentage	50.1	50.1	50.1	39.9	39.9	39.9	45.0	45.0	45.0
Total*	7078	16515	23592	14480	21720	36201	63179	63179	126359

Q_F = freshwater production; Q_B = brine discharge; Q_I = seawater and brackish water intake
*Total for the KSA with 41.3% of the flows reaching the AG

(freshwater production Q_P, brine discharge Q_{Brine}, and seawater intake Q_{Intake}) were defined and compared in the last twelve years between early 1996 and 2008 and estimated for the year 2050 for the total desalination capacity in the world and the study area. Calculations made by Lattemann and Höpner and the IDA year books (2006–07; 2007–08 and 2008–09) show that Saudi Arabia (KSA) has approximately 41.3% of its desalination capacity along the shores of the Arabian Gulf and 58.7% along the Red Sea [8,11,17,31]. In this study, just 41.3% of the total daily brine discharge of Saudi Arabia will be considered and the same will apply to the wastewater calculations. The results describe the relation between the three water types in three different time periods.

3.2. Wastewater collection

In recent decades, the water demand in the Gulf Cooperation Council (GCC) countries has more than doubled compared to the increase in population, due to more water supply, higher living standards, expansion of agriculture, and green land irrigation [32]. The water consumption around the millennium was over 700 l/person/d (255 m^3/cap/y) in the UAE and in Kuwait and Qatar over 400 l/person/d (145 m^3/cap/y) [32]. In Europe, the corresponding figure for 2005 was 920 m^3/cap/y [33]. The USA has the largest consumption of 1720 m^3/cap/y and Denmark the lowest with 130 m^3/cap/y [33]. These figures include also agricultural demand. An increase in water consumption in the AG — area caused by an expansion of agriculture has not been considered in this study because this sector uses groundwater as the main source [32].

With the increase in population and associated increase in water consumption, the amount of wastewater that has to be treated increases as well. More wastewater treatment plants must be built to protect the environment. The amount of wastewater that will be recycled to agriculture, green land irrigation, and augmentation of aquifers will most probably increase due to the shortage of water [32]. Many countries around the Arabian Gulf already reuse the wastewater or have plans to do so, for example Kuwait, where treated wastewater is used for irrigation and landscaping [34], while the UAE has initiated a nation-wide program for reuse of treated wastewater in landscaping [35].

4. Methodology and modeling

4.1. Wastewater calculation

In order to estimate the amount of wastewater generated in 2050, the following assumptions were made:

- Population increase calculated on the basis of the increase between 1996 and 2050.
- Water produced by desalination is only distributed for domestic and industrial use. Therefore all the produced freshwater will end as potential wastewater.
- Leaks in pipes transporting potable water and wastewater are assumed to be equal to other potable water sources.

Due to the general water stress situation in the AG-area, the amount of treated wastewater that will be reused will probably be high. An analysis of mixing brine with wastewater was also made, assuming four different scenarios:

- All wastewater is reused; 0% of produced desalinated water is discharged with brine
- 25% of produced desalinated water is discharged with brine
- 75% of produced desalinated water is discharged with brine, or
- 100% of produced desalinated water is discharged with brine

4.2. Water and salt mass balances

A generalized diagram summarizing water and salt budgets for coastal ecosystems is presented in Fig. 3. The Arabian Gulf is considered to be a one-layer system (non-stratified) to easily modify and describe such a budget in terms of a simple mass balance equation. In accordance with LOICZ biogeochemical modeling, it is important to estimate the mixing volume Q_{EX} (exchange volume between system body and ocean) across the open boundary of the system. Q_{EX} is estimated from the water and salt budgets [36].

In Fig. 3, the total water received from rivers and springs is denoted Q_{RI}, average rainfall Q_P, average annual evaporation Q_E, the amount of wastewater that will be added to the system and can be mixed with brine water Q_W, and the residual volume (net volume) transport associated with freshwater discharge Q_N. Q_{Brine} is brine discharge to the sea surface from a desalination plant with a high salt concentration and Q_{Intake} the amount of water intake to the desalination plant from the open sea or wells located about 20–30 m away from the coastline. S_{sys} is the system salinity, S_{ocn} the adjacent ocean salinity, and all other terms have salinity values except precipitation and evaporation, which were approximated to zero. The units for all output and input are usually in m^3/s and all concentrations will be assumed to be g/l.

5. Results and recommendations

5.1. Study area characteristics

The water mixing across the open boundary of the water system is governed by the dispersion process [37]. The following criteria are used to decide how the system will be treated in shape, shear, and mixing. A system is considered to be "narrow and deep" if $L_C/B > 2$ and B/H

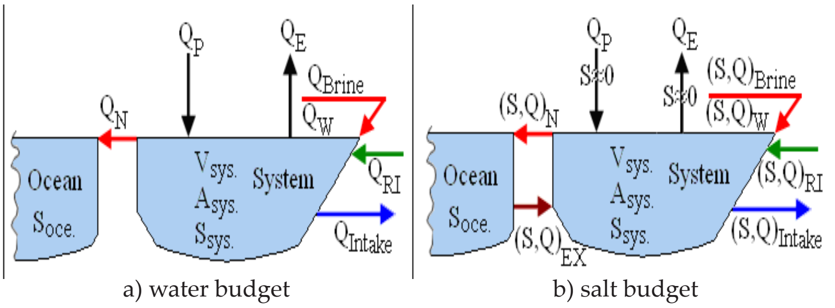

Fig. 3. Generalized diagram summarizing water and salt budgets for coastal ecosystems.

< 500 (vertical shear dominant). A system is considered "wide and shallow" if $L_C/B < 2$ and $B/H > 500$ (horizontal shear dominant) as defined by Taylor [38]. L_C (m) is the distance from the center of the system to its mouth, H (m) the average depth of the system, and B (m) the width of the system.

The typical and calculated parameters related to the Arabian Gulf are presented in Table 4. From Table 4 it can be concluded that the Arabian Gulf system should be considered "wide and shallow" and dominated by horizontal shear. This result will help us to understand the circulation and mixing in the system.

5.2. Results from desalination and wastewater discharge

The result of net volume, exchange volume, exchange time, calculation of brine and wastewater discharge to the Arabian Gulf in late 1996 and 2008, and a prediction for the year 2050 are presented in Table 5. The amount of wastewater is added stepwise to the brine discharge from 0 to 100% in order to find differences in exchange time and the mixing behavior in the whole system. These percentages are also derived from the wastewater used per capita per year in the countries in the study area, where zero percent in the table means that all wastewater is treated and used for different purposes on land, while 100% implies that all wastewater is mixed with the brine and discharged to the Arabian Gulf.

The differences from zero to 100% were calculated for net volume, exchange volume, and exchange time for the entire Arabian Gulf in order to separately evaluate and understand the conditions in each period and changes between the three periods. The net volume increased by 79 million m^3/d in 1996 when changing the wastewater discharge to the Gulf from zero to 100%, decreasing the exchange volume by about 524 million m^3/d and increasing the mixing time by about 203 d.

Correspondingly, the net volume increased by 92 million m^3/d in 2008, decreasing the exchange volume by 608 million m^3/d and increasing the mixing time in the system by about 233 d. In the forecast for 2050 after desalination and wastewater capacity calculations, the difference in net volume increased to 143 million m^3/d, the exchange volume decreased to 947 million m^3/d, resulting in an increase in the mixing time of about 328 d.

The different years presented in Table 5 can first be compared without wastewater discharge. From 1996 to 2008, the net volume decreased by 7.4 million m^3/d, the exchange volume increased by 69 million m^3/d, and the mixing time decreased by 22.5 d. For the next 42 years from 2008 until 2050, the calculation shows a decrease in net volume of 48.7 million m^3/d, an exchange volume increase of 424 million m^3/d, and a mixing time decrease of about 126 d. And within the 54 years from 1996 to 2050, the net volume decreased by 56 million m^3/d, the exchange volume increased by 493 million m^3/d, and the mixing time decreased by 149 d. Obviously, the more desalinated water that is collected from the Gulf, the higher is the remaining salinity. With higher salinity in the Gulf,

Table 4
The typical and calculated parameters for the Arabian Gulf [36–39]

Categories	Arabian Gulf
Parameters	
L_{ave} (×10^3 m)	1,000
L_C (×10^3 m)	450
B (×10^3 m)	240
H (m)	35
A (×10^6 m^2)	240,000
V (×10^9 m^3)	8,400
Input/output, 10^6 m^3/d	
Average ppt., P_{ave}	65.8
Evaporation rate, E	986.3
River discharge, Q_{RI}	131.5
Average outflow, Q_O	25,918
Classifications	
L_C/B ratio	1.9< 2
B/H ratio	6857>500
Shape	Wide and shallow
Shear	Horizontal shear dominant

Table 5
Results of brine and wastewater discharge to the Arabian Gulf in 1996 and 2008 and the prediction for 2050

Parameters	Brine and wastewater discharges (10^6 m^3/d)					Difference (0 compared with 100% wastewater)
Wastewater discharge in %	0	25	50	75	100	
Total discharge in 1996	16.5	36.2	55.9	75.7	95.4	
Q_N (10^6 m^3/d)	–796	–776.4	–756.7	–737.0	–717.3	79
Q_{EX} (10^6 m^3/d)	4507	4376	4245	4114	3 983	–524
τ (time in y)	4.34	4.46	4.60	4.74	4.89	0.56
τ (time in d)	1584	1630	1679	1732	1787	203
Total discharge in 2008	21.7	44.6	67.5	90.4	113.3	
Q_N (10^6 m^3/d)	–804	–780.6	–758	–734.9	–712	92
Q_{EX} (10^6 m^3/d)	4576	4 424	4272	4120	3968	–608
τ (time in y)	4.28	4.42	4.57	4.74	4.91	0.64
τ (time in d)	1561	1614	1670	1730	1795	233
Total discharge in 2050	63.2	98.8	134.4	170.1	205.7	
Q_N (10^6 m^3/d)	–852	–816.6	–781.0	–745.3	–709.7	143
Q_{EX} (10^6 m^3/d)	5000	4763	4527	4290	4 053	–947
τ (time in y)	3.93	4.12	4.33	4.57	4.83	0.90
τ (time in d)	1435	1505	1583	1668	1764	328

the exchange with the Indian Ocean will increase (S_{Ex} and Q_{Ex} in Fig. 3).

The various years can also be compared by means of 100% wastewater discharge mixed with brine. From 1996 to 2008, the net volume increased by 5.3 million m^3/d, the exchange volume decreased by 15 million m^3/d and the mixing time increased by 7.8 d. For the next 42 years from 2008 until 2050, the calculation shows a net volume increase of 2.3 million m^3/d, the exchange volume increased by 85 million m^3/d, and the mixing time decreased by 31 d. Within the next 54 years from 1996 to 2050, the net volume increased by 7.6 million m^3/d, the exchange volume increased by 70 million m^3/d, and the mixing time decreased by 23.5 d. Mixing brine with wastewater reduces the water and salt exchange between the Gulf and the Indian Ocean.

Overall, the result from 1996 to 2008 revealed that the net volume amounted to 13 million m^3/d, the exchange volume decreased by 84 million m^3/d, and the mixing time increased by 30 d. For the next 42 years from 2008 until 2050, the calculation shows an increase in the net volume of 51 million m^3/d, in exchange volume by 339 million m^3/d, and in the mixing time by 95 d.

According to the above comparisons, the higher percentage of wastewater added to the system, i.e. discharged back to the Arabian Gulf, the greater the net volume flow and the lower the exchange volume due to the mixing of high saline brine. Thus, the exchange volume from the ocean will become gradually smaller due to reduced water flow from low to higher saline concentration. On a local scale, the mixing of wastewater with brine will help to reduce the salinity gradients in the coastal areas.

So is it positive or negative to increase the mixing of wastewater with brine? This is a difficult question. The environmental effects depend on all inputs and outputs as defined by water and salt mass balance, population growth and the increase in desalination. Mixing times are attributed to the net and exchange volume. When comparing 1996 with 2050, it is obvious that mixing times will decrease due to increasing desalination. Salinity will increase even more if the wastewater discharge goes down, reducing the exchange volume.

Exchange time or mixing time calculations for these different water concentrations demonstrate that the higher the amount of wastewater mixed with brine discharge, the longer the mixing time. However, if untreated, the wastewater will contribute to an increasing eutrophication of the Gulf. The management of the Arabian Gulf needs to be studied thoroughly. Other conditions contribute to the system performance. For instance, the amount of natural evaporation is huge when compared to the total amount extracted from the Arabian Gulf. However, while the water is locally extracted, the evaporation occurs all over the surface area of the Gulf and thus has less impact than local extraction.

6. Conclusion

Desalination and wastewater treatment plants are needed in all countries of the study area due to the scarcity of fresh water. The mixing of wastewater and brine discharge is an important method for minimizing the salinity increase in the coastal waters of the Arabian Gulf. Therefore, it will be possible to minimize the impact and reduce the salt concentration in the future when adding wastewater to the brine discharge. This method will, however, also minimize the water that comes from the ocean to the Gulf. It will be very difficult to decide whether to use the wastewater for mixing with brine or reuse for other purposes after treatment.

Some points must be taken into account in the future, such as:

- The building of wastewater treatment plants to take care of increased wastewater production in urban areas.
- The extra cost of advanced treatment compared with the costs of the extra production of desalinated water, damaged groundwater aquifers, and potential environmental problems will probably promote water recycling.
- In some cases there might be no appropriate space close enough to irrigate with treated wastewater, which therefore may be discharged with brine.
- The content of nutrients in wastewater is positive for irrigation, but with only secondary treatment, problems such as eutrophication in the Gulf may increase if the exchange of water is low.
- Considering the concentration of dissolved solids in the Gulf water, simultaneous discharge of wastewater with brine conserves the salt (reduces the salt concentration of the brine when discharged back to the sea). This may actually be one argument for not recycling the wastewater on land.

The higher the percentage of wastewater added to the system, the greater the net volume flow and the smaller the exchange volume due to the mixing of high saline brine and low saline wastewater. Thus, the exchange volume from the ocean will be progressively minimized due to a reduced flow from low saline to high saline concentration waters. On a local scale, the mixing of wastewater with brine will help to reduce the salinity gradients in the coastal areas. It will be possible to minimize the impact and reduce the salt concentration in the future by adding wastewater to the brine discharge.

Abbreviations and symbols

ADCP — Acoustic doppler current profiler
APP — Atomic power project
BWRO — Brackish water reverse osmosis
DGR — Desalination growth ratio
GCC — Gulf Cooperation Council
IWPP — Independent water power project
IWSPP — Integrated water steam and power project
MED — Multi-effects distillation
MSF — Multistage flash distillation
PGR — Population growth rate
RO — Reverse osmosis
TDS — Total dissolved solids
WEB — Water Energiebedrijf
Q_{Brine} — Brine discharge
Q_{EX} — Exchange volume
Q_F — Freshwater production
Q_{Intake} — Intake seawater or brackish water
Q_N — Residual volume (net volume)
Q_{RI} — River flow
Q_T — Total discharge (brine + wastewater)
Q_W — Wastewater discharge
S_{Brine} — Salinity of brine
S_F — Salinity of produced fresh water
S_{Intake} — Intake salinity
S_{ocn} — Adjacent ocean salinity
S_{sys} — System salinity
τ — Mixing time

References

[1] D.M.A. Al-Gobaisi, Sustainable augmentation of fresh water resources through appropriate energy and desalination technology. IDA World Congress on Desalination and Water Reuse Madrid, Spain, 1997.
[2] A. Purnama, H.H. Al-Barwani and S. Ronald, Calculating the environmental cost of seawater desalination in the Arabian marginal seas, Desalination, 185 (2005) 79–86.
[3] I. Shiklomanov, World Water Resources: Modern Assessment and Outlook for 21st century. Hydrological Institute, Saint Petersburg, 1999.
[4] M. Ruiz-Mateo Antequera and J. Gonzalez, Discharges to the sea from desalination plants. MEDCOAST-07, Alexandria, Egypt, 13–17 November 2007.
[5] A. Valero, J. Uche and L. Serra, Desalination as an Alternative to Spanish National Hydrology Plan. Technical Report, CIRCE and University of Zagaroza, 2001.
[6] A.A. Akkad, Conservation in the Arabian Gulf countries: Management and operations, J. AWWA, May (1990) 40–50.
[7] O.K. Buros, The ABCs of Desalting, 2nd ed., 1998.
[8] IDA — International Desalination Association Yearbook, 2007–2008.
[9] Magazine Water Condition and Purification, January, 2005, http://www.lenntech.com/WHO-EU-water-standards.htm.
[10] IDA Worldwide Desalting Plant Inventory in MS Excel format, Media Analytics Ltd., Oxford, UK, 2006, No. 19.
[11] S. Lattemann and T. Höpner, Environmental impact and impact assessment of seawater desalination, Desalination, 220 (2008) 1–15.
[12] C. Vanhems, Critical Review of Desalination Concentrate Disposal to Surface Water, USA, 1992 (after UNEP, 2001).
[13] UNEP, Assessment of the State of Pollution of the Mediterranean Sea by Zinc, Copper and their Compounds. Document UNEP (OCA)/MED WGer it&., 1995, pp. 121.
[14] S. Barak, Water &Watering, 4 (2000) 406–411 [in Hebrew].
[15] M. Perla, The Israel Electric Corporation Ltd, 2000 [in Hebrew].
[16] Worldwater: http://www.worldwater.org/data.html. Last update January 2009.
[17] IDA — International Desalination Association Yearbook, 2006–2007.
[18] S. Ghabayen, M. McKee and M. Kemblowski, Characterization of uncertainties in the operation and economics of the proposed seawater desalination plant in the Gaza Strip, Desalination, 161 (2004) 191–201.
[19] A. Glazer and M. Dadon, The Israel Electric Corporation Ltd, 2000 [in Hebrew].

[20] M. Sladkevich, E. Kit and M. Glozman, Numerical simulation of cooling water recirculation for the Rutenberg power station. Prepared for the Israel Electric Corporation Ltd., Technion, Haifa, PN 371194, 1994.

[21] R.M. Reynolds, Physical oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman — Results from the Mt Mitchell expedition. Mar. Pollut. Bull., 27 (1993) 35–59.

[22] J.R. Hunter, The physical oceanography of the Arabian Gulf: A review and theoretical interpretation of previous observations. In: Marine Environment and Pollution, Proc. 1st Gulf Conference on Environment and Pollution, KISR, Kuwait, 7–9 February 1982, pp. 1–23.

[23] P.G. Brewer and D. Dryssen, Chemical oceanography of the Persian Gulf. Progr. Oceanography, 14 (1985) 41–55.

[24] V.C. John, S.L. Coles and A.I. Abozed, Seasonal cycle of temperature, salinity and water masses of the Western Arabian Gulf, Oceanol. Acta, 13 (1990) 273–281.

[25] E. Ahmad and S.A. Sultan, Annual mean surface heat fluxes in the Arabian Gulf and the net heat transport through the Strait of Hormuz, Atmos. Ocean., 29(1) (1991) 45–61.

[26] A.S. Bower, H.D. Hunt and J.F. Price, Character and dynamics of the Red Sea and Persian Gulf outflows, J. Geophys. Res., 105(C3) (2000) 6387–6414.

[27] A.A. Bidokhti and M. Ezam, The structure of the Persian Gulf outflow subjected to density variations, Ocean Sci. Discuss., 5 (2008) 135–161.

[28] R. Wiseman, Editor's corner, Desal. Water Reuse, 16(3) (2006) 10–17.

[29] US Census Bureau International: Data Base; World Bank, 2004. Data updated 01-05-2009, http://www.census.gov/ipc/www/idb/idbprint.html

[30] A.I.B. Raed, M.P. Kenneth, L. Magnus and E. Mustafa, Impact of brine disposal from EMU desalination plant on seawater composition, IDA World Congress, Maspalomas, Gran Canaria, Spain, October 2007, pp. 21–26.

[31] IDA — International Desalination Association Yearbook, 2008–2009.

[32] F. Al-Rashed Muhammad and M.S. Mohsen, Water resources in the GCC countries: An overview, Wat. Resources Manage., 14 (2000) 59–75.

[33] OECD Factbook, 2005, ISBN 92-64-01869-7.

[34] M.A. Jasem, S.B. Haider and T.H. Abdullah, Wastewater reuse practices in Kuwait, Environmentalist, 23 (2003) 117–126.

[35] UAE, United Arab Emirates Yearbook 2008: http://viewer.zmags.co.uk/showmag.php?mid=stfrs&preview=1&_x=1#/page158/.

[36] D.C. Gordon, Jr., P.R. Boudreau, K.H. Mann, J.-E. Ong, W.L. Silvert, S.V. Smith, G. Wattayakorn, F. Wulff and T. Yanagi, LOICZ Biogeochemical Modelling Guidelines. LOICZ Reports & Studies, 5 (1996) 1–96.

[37] T. Yanagi, Coastal Oceanography. Kluwer., Dortrecht, 2000, 162 p.

[38] G.I. Taylor, Dispersion of soluble matter in solvent slowly flowing through a tube. Proc. Royal Soc. London, A219 (1953) 186–203.

[39] M. Masahiro, Managing Water for Peace in the Middle East: Alternative Strategies, United Nations University Press, Tokyo – New York – Paris, The United Nations University, 1995, 319 p.