

# ESTIMATED FUTURE SALINITY IN THE ARABIAN GULF, THE MEDITERRANEAN SEA AND THE RED SEA CONSEQUENCES OF BRINE DISCHARGE FROM DESALINATION

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## ABSTRACT

Seawater desalination constitutes an important source for water supply to the population bordering the Arabian Gulf, the Mediterranean Sea, and the Red Sea. The three regions represent about 11.8% of the world land area and the countries hosted approximately 9% of the world population in 1950 and 2008 and are projected to do so again in 2050. Population statistics for a 100-year period has been used including a prognosis from 2010 to 2050. Data on desalination plant capacity covering 12 years from 1996 to 2008 has been summarized and a prognosis of the increase in desalination for the three regions until 2050 developed. The results obtained for desalination capacity in the study area were 62%, 58%, and 60% of the world capacity for 1996, 2008, and 2050, respectively.

The increase in the recovery ratio is considered an important factor in this study. In 1996 this ratio was about 30 to 35%, and in 2008 it was 40 to 45%, although in some plants it reached up to 50%. Brine discharge will increase the salinities of the Arabian Gulf, Mediterranean Sea, and Red Sea, by some extra 2.24, 0.81 and 1.16 g/l in the year 2050.

**Key words:** Arabian Gulf; Mediterranean Sea; Red Sea; Desalination; Water-Salt balance; 1D-advection-diffusion; Salinity

## 1. INTRODUCTION

### 1.1. An overview

Water and salt mass balances were both employed to calculate residual flow, exchange flow, and exchange time in each of the receiving water systems in order to understand system dynamics, water movement, and mixing times. The effects of desalination plant and brine discharge in the Arabian Gulf, the Mediterranean Sea and the Red Sea were mathematically modeled and evaluated for the years 1996, 2008 and 2050. The calculations presented here focus on salinity changes in three receiving water systems due to brine from seawater desalination plants. The three regions, the Arabian Gulf (AG), the Mediterranean Sea (MS) and the Red Sea (RS) have very high evaporation rates, from 1.2 to 2 m annually, and very low annual precipitations, from 90 to 150 mm. The salinity in the recipients may increase in the long term if larger and larger amounts of desalinated water are removed from the water bodies. Due to their semi-enclosed nature and arid climate, AG, MS, and RS waters are naturally characterized by a higher salt content due to the accelerated rate of evaporation (Anton et al., 2005).

Desalination is considered an important source of fresh water that should proportionally follow the increase in populations. Any country with water resources of less than 1000 m<sup>3</sup>/capita/yr is considered in trouble (Al-Gobaisi, 1997). Thus, increasing water resources mainly from desalination through improving the recovery ratio from 30 to 50 percent in some countries will increase the brine salt concentration. The existing amount of water resources on our planet is enormous compared with the population increments (Shiklomanov, 1999). Almost 95% is in oceans and seas that contain a high degree of salinity, thus it is impossible to directly use the water resources for any purpose (e.g. agriculture, industry or domestic) unless they have been previously treated (Ruiz et al., 2007). Six countries receive nearly 50% of the total freshwater resources (Brazil, Canada, Russia, United States, China and India) and five great rivers transport 27% of the renewable resources (Amazon, Ganges-Brahmaputra, Congo, Yellow and Orinoco) (Ruiz et al., 2007; Valero et al., 2001).

The amount of desalinated water in the Arabian Gulf accounts for over 60% of the world's total production (Akkad, 1990). The installation capacity was counted at the end of 1999 as follows: 60% in the Middle East, 16% in the United States; 10% in the European Union, 6% in the Arabian Mediterranean countries, and 8% in the rest of the world (Ruiz et al., 2007). The desalination capacities in 1998 were distributed as 60% in West Asia and the Middle east, 11% in the United States; 7% in the European Union, 7% in North Africa, 4% in South and Central America, and 11% in the rest of the world (Magazine, 2005). About 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 (IDA, 2006; Lattemann & Höpner, 2008).

The total daily capacity of installed desalination plants worldwide was 22.7 million cubic meters (MCM), an increase of about 70% from that previously reported in the Desalting ABCs in 1990 (Buros, 1998; IDA, 2006-07). The energy demand for reverse-osmosis seawater desalination has decreased, leading to a reduction of production cost from about 2.5 to 0.5 US \$/m<sup>3</sup> in some places, partly depending on the intake raw water quality. The cost of desalination plants may also depend on their location as well as on the local unit costs and operations, in which

prices have decreased from roughly \$1.5/m<sup>3</sup> in the early 1990s to around \$0.50/m<sup>3</sup> in 2003 (Pankratz, 2004), for example, according to Crisp, the Perth desalination plant consumes only 3.7 kWh/m<sup>3</sup> of fresh water (Gary, 2006).

### 1.2. Brine discharge and dispersion of salt

All desalination brines, the concentration of which is higher than that of natural seawater, are normally returned to the sea. The salt concentrations of the brines are usually found to be double or close to double that of natural seawater (Vanheems, 2001). In the reverse osmosis desalination plants (RODP), the total water is taken from the sea and the brine is discharged back to the same medium, where salinity will increase by 70% (Ruiz et al., 2007). Constructions close to the coastline give opportunities for one or more outfalls to the sea and can thus minimize or reduce the environmental impact of brine discharge (Raed et al., 2007).

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 34.5g/l (Magazine, 2005). These values help us to understand each region separately in terms of the intake water and how the brine water will act on the recipient. The recovery ratio is also related to these values as well as the quality of fresh water production and the desalination cost.

### 1.3. Objectives

This study was initiated to estimate the effects of brine discharge into recipients such as changing in salinity. A large number of desalination plants that have been built around the three regions mainly Arabian Gulf and using same water for both for intake and for brine. Population increase and economical growth are also considered as main driving forces in these areas. They are directly related to fresh water consumption and amount of brine discharge. The main objective of this study is to analyze the effects of future increasing in desalination capacity. Therefore, the following studies have been executed:

- The effects of brines discharge from desalination plants in the three regions for 1996 and 2008, and prognosis 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.
- Future salinity and changes from the past, today and for year 2050.

## 2. STUDY AREA: BACKGROUND AND CHARACTERISTICS

The water scarcity in the Middle East regions (MENA), especially the Arabian Gulf countries, has reached unprecedented crisis levels. Desalination is the most important source in these countries and the largest capacity is also located in these regions. The results of brine water  $Q_{\text{Brine}}$  (10<sup>6</sup> m<sup>3</sup>/d) from the three regions, the Arabian Gulf (AG), Mediterranean Sea (MS) and Red Sea (RS), in late 1996, 2008 and 2050 are presented in (Figure 1). The red arrows indicate the location of the exchange water, e.g. river inflow, inflow through the Dardanelle Strait from the Black Sea, and exchange flow from the Gibraltar Strait etc, all related to the three systems.

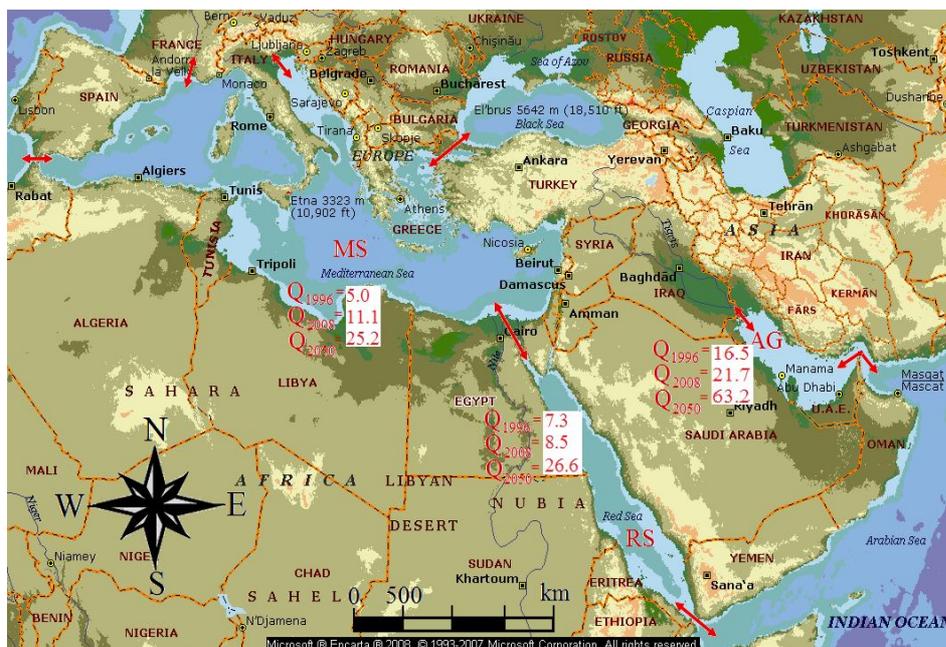
The countries bordering the Arabian Gulf are: Iran, Iraq, Kuwait, Saudi Arabia, Qatar, Bahrain, the United Arab Emirates and Oman. The countries bordering the Mediterranean Sea are: Spain, France, Monaco, Italy, Malta, Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Albania, Greece, Turkey, Cyprus, Syria, Lebanon, Palestine, Israel, Egypt, Libya, Tunisia, Algeria and Morocco. The countries bordering the Red Sea are: Egypt, Israel, Jordan, Sudan, Eritrea, Saudi Arabia, Yemen and Djibouti.

### 2.1. Arabian Gulf (AG)

The Arabian Gulf is a shallow semi-enclosed marginal sea, with less than 100 m in depth over its entire extent and with a mean of only 35 m (Reynolds R.M., 1993). It covers an area of about 240,000 km<sup>2</sup>, with 1000 km in length and widths ranging from 185 km to 370 km, with a mean of 240 km. The volume is approximately 8,400 km<sup>3</sup>. 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/yr, in which fresh water and river inflow equals 48 km<sup>3</sup>/yr (Reynolds, 1993; Hunter, 1986). The mean annual evaporation rate is estimated at approximately 1.5 m/yr (Brewer & Dryssen, 1985).

The shallowness of the Arabian Gulf water leads to the formation of a very high saline and dense water, with maximum salinities as high as 57 g/l along the southern coast (John et al., 1990). Typical mass transport by the outflow from the Arabian Gulf has been estimated to be about 34.5 x10<sup>9</sup> m<sup>3</sup>/day, which is larger than that reported by other studies (Bidokhti & Ezam, 2008). Ahmad and Sultan (1991) employed the Knudsen relations and estimated that the annual mean Gulf water outflow transport was about 14.7 x10<sup>9</sup> m<sup>3</sup>/day, compared to the observation of an annual mean of (17.3-21.6) x10<sup>9</sup> m<sup>3</sup>/day from an Acoustic Doppler Current Profiler (ADCP) in the Strait of Hormuz (Bower et al., 2000).

The largest number of desalination plants can be found along the shores of the Arabian Gulf with a total seawater desalination capacity of approximately (45%) of the worldwide daily production. The main producers in the Gulf region are the United Arab Emirates, Saudi Arabia (9% from the Gulf region and 13% from the Red Sea), Qatar and Kuwait (Lattemann & Höpner, 2008; Wiseman, 2006). There are about 1,500 desalination units operating in the Arabian Gulf countries, which account for 58% of the world desalination production (Al-Mutaz et al, 1989). The brine percentage discharged to the Arabian Gulf from the Iraq desalination plant is not clear to me but I estimate it to be about 5%.



**Fig.1.** Brine water  $Q_B$  results in  $10^6 \text{ m}^3/\text{d}$  for the Arabian Gulf (AG), Mediterranean Sea (MS), and Red Sea (RS) in 1996, 2008, and 2050 (map from: Google Earth)

## 2.2. Mediterranean Sea (MS)

The Mediterranean Sea in (Figure 1), including the Sea of Marmara, occupies an area of approximately 2,960,000 km<sup>2</sup>. The Mediterranean is connected to the Atlantic Ocean by the narrow and shallow channel of the Strait of Gibraltar and to the Black Sea through the Dardanelles (Britannica http, 2009). The typical values for the Mediterranean Sea comprise a mean width of about 800 km, a mean depth of approximately 1500 m, an extreme length of about 3,860 km, an average length of approximately 2700 km and an evaporation rate of approximately 1.3 m/yr (Moncef & Bernard, 2000; Rahmstorf, 1998).

Along the North African coast from Gabis in Tunisia to Egypt, precipitation of more than 250 mm per year is rare, whereas on the Dalmatian coast of Croatia there are places that receive 2,500 mm. Maximum precipitation is found in mountainous coastal areas (Mediterranean Sea, 2008). Precipitation on the coastal plain near Tel Aviv (on the MS coast) is 200 mm near Beersheba and less than 50 mm at Eilat in the south (on the RS coast) (Gisser & Pohoryles, 1977). Large volumes of sewerage are dumped directly into the Mediterranean Sea (<http://en.wikipedia>, 2009). Several important desalination plants are located along the Mediterranean coast. Ashkelon desalination plant is an example with a maximum production of 110 MCM/yr, with an intake salinity of 40,679 ppm TDS and brine concentration of <80 ppm TDS (Sauvet, 2007). The construction of the Hadera desalination plant was expected to begin during late 2007 and it has a planned production capacity of up to 100 MCM/year (Gustavo, 2007). In the Mediterranean, the total daily production from seawater is about 17% of the world total desalination capacity. Spain is the largest desalination producer in Europe with 7% of the worldwide capacity. The main process in Spain is reverse osmosis (RO) comprising 95% of all desalination plants (IDA, 2006; Lattemann & Höpner, 2008).

## 2.3. Red sea (RS)

The maximum width of the Red Sea is about 225 km, its greatest depth 3,040 m, and its area approximately 450,000 km<sup>2</sup>. The typical values for the Red Sea are a mean width of about 225 km, a mean depth of around 500 m, a gross length of about 2000 km, and an evaporation rate of approximately 2 m/yr (Anton et al., 2005). In the Red Sea region, the third highest daily production of desalinated water can be found, with a combined capacity of 14% of the world total desalination capacity (IDA, 2006; Lattemann & Höpner, 2008). The exchange of water between the Red Sea and the Gulf of Aden occurs at the strait of Bab el Mandab. There is virtually no surface water runoff because no river enters the Red Sea (Shahin, 1989; Morcos, 1970).

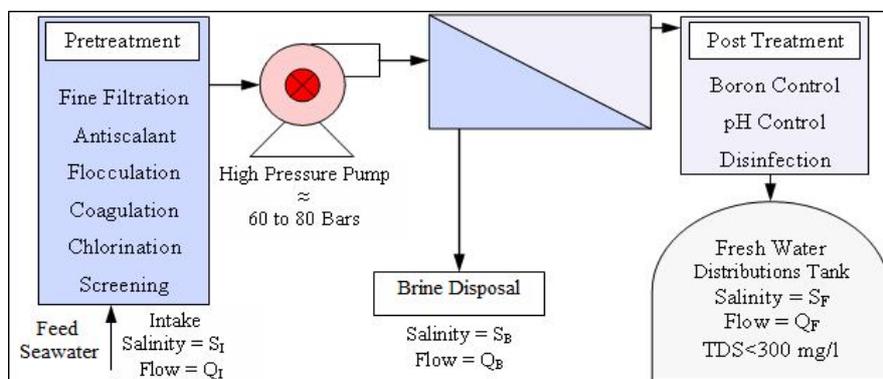
The winter (November–May) exchange value is about 0.5 MCM/sec, which occurs at the surface and bottom layers, whereas in summer (June–October) this figure is about 0.16 MCM/sec (Thompson, 1939; Murray & Johns, 1997). Murray and Johns (1997) also estimated that the annual mean Red Sea outflow transport is about 0.37 MCM/sec, which roughly agrees with Siedler's (1969) estimated amount of 0.33 MCM/sec, based on the Knudsen relation. The rainfall over the Red Sea and its coasts is extremely low, averaging 60–100 mm/y with an average volume of about 233,000 km<sup>3</sup>. The renewal of water in the Red Sea is estimated to take 20 years (Red Sea, 2008).

## 3. LONG TERM DATA COLLECTION AND CALCULATION

### 3.1. Desalination parameters

Desalination plant capacity, annual population growth rate, and recovery ratio for the years 1996 to 2008 have been summarized in this study in order to compare world and study area data. From the available calculated data, desalination capacity and capacity per capita up to the year 2050 have been extrapolated. (Figure 2) is the

typical diagram for a seawater desalination plant including details of pre and post treatment.  $S_{Intake}$  and  $Q_{Intake}$  are the salinity and volume of seawater intake,  $S_{Brine}$  and  $Q_{Brine}$  are the salinity and volume of brine discharge, and  $S_F$  and  $Q_F$  are the salinity and volume of fresh water produced by desalination plants. Moreover,  $S_{Brine} = S_{Intake}/(1-r)$  and  $Q_{Brine} = (1-r)Q_{Intake}$ , where  $r$  is the recovery ratio, generally between 35 and 45% of the intake,  $S_F \approx 0$  and  $Q_F = rQ_{Intake}$ . The cooling water flows in MSF and MED are disregarded, since they do not affect salinity. Brine is discharged back to the open sea through pipes and in some cases in open channels. During the past ten years of desalination development, the recovery ratio  $r$  has been significantly increased in reverse osmosis plants. For example, Raed et al. (2007) stated that seawater intake salinity,  $S_{Intake}$ , is equal to 41.7 ppt and the brine outlet is 74 ppt. According to the relation  $S_{Brine} = S_{Intake}/(1-r)$ , the recovery ratio  $r = 44\%$ . If the recovery ratio increases, the brine concentration also increases.



**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 (<3000mg/l)

**3.2. Population growth rate**

In total, 25 countries (approximately 90% of the countries) in the three regions were studied in respect of area and population. There are about 35 countries in the regions but some of them e.g. Oman and Iraq are not directly connected to the coasts of these three regions. Comparisons for the population, area, and population growth rate for the world and the study area are used in this study for 100 years. Data was collected for the period 1950-2008 and calculated for the period 2009-2050. The growth rate from the mid year of the whole period is the most common way of expressing population growth as a rate. The growth rates for the 24 countries were calculated using the formula:  $R(t) = \ln [ P_{t+1} / P_t ]$ , in which  $t = \text{year}$ ;  $R(t) = \text{growth rate from mid year } t \text{ to mid year } t+1$ ;  $P(t) = \text{population at mid year } t$  and  $\ln = \text{natural log}$  (from: U.S. Census Bureau, 2008). The total population in the study area is approximately 9.4% of the world population during the 100 years and the land area occupies approximately 11.8% of the world total land area. The population growth rates over 100 years from 1950 to 2050 were found to be 1.30 and 1.35 in the world and the study area respectively.

**3.3. Desalination production**

Desalination capacities expressed as 1,000 m<sup>3</sup>/day in the world and study area for the year 1996 and the estimated values for the year 2050 are listed and compared in (Table 1). The three types of water in the typical desalination plant (freshwater production  $Q_F$ , brine discharge  $Q_{Brine}$ , and seawater intake  $Q_{Intake}$ ) were compared for 1996 and 2008 and calculated for 2050 for both the world and study area desalination capacity. These results describe the relation between three water types in three different time steps for each country as well as the whole study area. They were also compared with the world capacities. It was important to estimate the fresh water in 2050 in order to calculate the increase in desalination in the studied area compared with the increase in world capacity.

The final result suggests that in 1996, 2008 and 2050, the study area represents about 62%, 58%, and 60% of the overall world capacity. (Table 1) also presents the results in terms of desalination capacity in cubic meters per capita per year in 1996, 2008 and 2050. For example, in this calculation, Bahrain's capacity per capita in 1996 was 164 m<sup>3</sup>, increasing to 409 m<sup>3</sup> in 2008 and reaching 718 m<sup>3</sup> in 2050.

**Table 1.** Comparisons between the world and study area desalination capacity and amount in cubic meters per capita per year at the end of 1996, 2008 and 2050 (Magazine, 2005; IDA, 2006; Lattemann & Höpner, 2008; IDA, 2007-08; IDA, 2008-09; Worldwater, 2009; IDA, 2006-07; Ghabayen et al., 2004)

Country or area	Brine location	Desalination capacity in 1,000 m <sup>3</sup> /day						Desalination capacity in m <sup>3</sup> /capita/year		
		1996		2008		2050		1996	2008	2050
		Q <sub>F</sub>	Q <sub>B</sub>	Q <sub>F</sub>	Q <sub>B</sub>	Q <sub>F</sub>	Q <sub>B</sub>	Q <sub>F</sub>	Q <sub>F</sub>	Q <sub>F</sub>
<b>WORLD</b>		<b>20000</b>	<b>46667</b>	<b>47709</b>	<b>71564</b>	<b>192211</b>	<b>192211</b>	<b>1.19</b>	<b>2.54</b>	<b>4.74</b>
<b>Algeria</b>	MS	190.8	445	1055.9	1584	3044.1	3044	2.30	11.13	16
<b>Bahrain</b>	AG	283.0	660	825.2	1238	3022.0	3022	164	409.0	718
<b>Cyprus</b>	MS	6.275	15	183	275	399.0	399	3.01	82.3	110
<b>Egypt</b>	MS,RS	102.1	238	491.1	737	1479.6	1480	0.51	2.14	2.68

France	MS	29.1	68	230.3	345	603.7	604	0.17	1.28	2.00
Greece	MS	36.0	84	50.0	75	273.7	274	1.26	1.66	6.31
Iran	AG	423.4	988	547.8	822	3138.2	3138	2.63	2.96	8.91
Iraq	AG!	324.5	757	476.6	715	2519.3	2519	4.76	6.01	10.3
Israel	MS,RS	90.4	211	630.1	945	1703.6	1704	5.27	31.54	36.4
Italy	MS	483.7	1129	824.3	1237	3984.7	3985	3.06	5.05	18.3
Jordan	RS	7.0	16	173.0	260	382.1	382	0.48	9.94	7.51
Kuwait	AG	1284.3	2997	2308.7	3463	10822	10822	210	316.5	393
Lebanon	MS	17.0	40	27.0	41	136.1	136	1.72	2.42	6.34
Libya	MS	638.4	1490	940.0	1410	4961.1	4961	43.1	54.2	106
Malta	MS	145.0	338	248.4	373	1197.3	1197	133.2	219	700
Morocco	MS	20.0	47	36.0	54	168.6	169	0.24	0.37	0.76
Palestine	MS	9.0	21	10.0	15	63.4	63	0.89	0.86	1.50
Qatar	AG	560.8	1308	1026.3	1539	4761.9	4762	258	393	889
KSA	AG,RS	5006	11681	7750.8	11626	39669	39669	74.4	98.0	184.7
Spain	MS	492.8	1150	3420.7	5131	9258.7	9259	4.58	30.1	60.2
Sudan	MS,RS	1.0	2	23.0	35	51.1	51	0.01	0.20	0.13
Tunisia	MS	47.4	111	98.8	148	426.7	427	1.83	3.39	7.89
Turkey	MS	6.0	14	39.0	59	107.4	107	0.03	0.19	0.29
UAE	AG	2134	4980	6094.7	9142	22532	22533	198	469.5	650
Yemen	RS	37.0	86	47.0	71	272.5	272	0.66	0.73	0.88
<b>Total</b>		<b>12375</b>	<b>28876</b>	<b>27558</b>	<b>41337</b>	<b>114979</b>	<b>114979</b>	<b>7.86</b>	<b>15.61</b>	<b>29.54</b>
<b>Percentage</b>		<b>62</b>	<b>58</b>		<b>60</b>					

Where,  $Q_F$  = Freshwater production from desalination and  $Q_{Brine}$ =Brine Discharge.

#### 4. METHODOLOGY AND MODELING

##### 4.1. Water and salt mass balances

A generalized diagram summarizing water and salt budgets for coastal ecosystems is described in (Figure 3). This diagram assumes a one-layer system for the Arabian Gulf, Mediterranean Sea, and the Red Sea. From this, budgets for water mass and salt mass can be calculated through a simple mass balance equation. The general definitions of the input/output in the system are presented in (Figure 3). The total water received from rivers and springs is denoted ( $Q_{RI}$ ), average rainfall ( $Q_P$ ), average annual evaporation ( $Q_E$ ), the mixing volume (exchange volume between system body and ocean) across the open boundary of the system ( $Q_{EX}$ ), and the residual volume transport associated with freshwater discharge ( $Q_N$ ).  $Q_{Brine}$  is the brine discharge to the sea and  $Q_{Intake}$  the amount of feed water intake to the desalination plant from the open sea or from wells located about 20 to 30 meters 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 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).

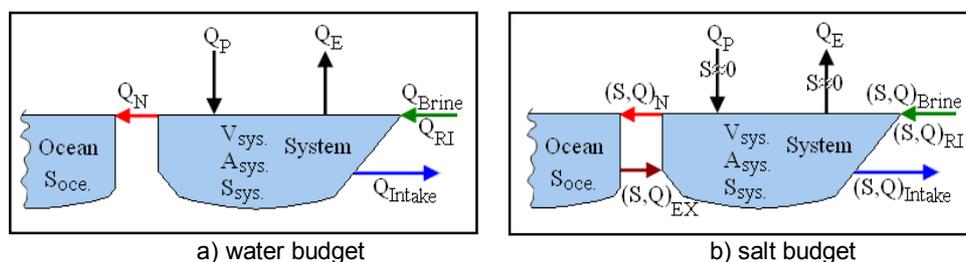


Fig. 3. Generalized diagram summarizing water and salt budgets for coastal ecosystems

According to 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 (Gordon et al., 1996).

#### 5. RESULTS AND DISCUSSIONS

It is necessary to calculate desalination capacity in the three different periods in order to estimate it in cubic meters per capita per year in each country and the whole region to determine the amount of fresh water collected from desalination. The aim here is to determine the total brine water in each region for the past and future as accurately as possible in order to avoid or minimize some of the impacts. The calculated desalination capacities in the world and the three regions for fresh water  $Q_F$ , brine water  $Q_{Brine}$ , intake water  $Q_{Intake}$ , and percentages from world production at the end of the years 1996, 2008 and 2050. Corresponding desalination capacities of about 35.4, 10.7 and 15.7% have been found in the Arabian Gulf, Mediterranean Sea and Red Sea respectively at the end of 1996.

##### 5.1. Results for recipients

Comparison between the world and the study area (AG, MMS and RS) for: 1) Average annual population growth rate (PGR) in three periods (1950, 2008 and 2050), 2) Average annual desalination growth rate (PGR) in two periods (late 1996 to 2008), 3) Coverage area ratio, 4) Desalination recovery ratio related to: Freshwater production ( $Q_F$ ), Brine discharge ( $Q_{Brine}$ ), Seawater intake ( $Q_{Intake}$ ), and 5) Desalination capacity estimation,  $m^3/capita$  in 2008 and 2050.

The mixing of different inputs across the open boundary of the recipient is governed by the dispersion process (Yanagi, 2000b). The following criteria are used to decide how to classify the water body. The recipient is considered to be "narrow and deep" if  $L_c/B > 2$  and  $B/H < 500$  (vertical shear dominant). The recipient is considered "wide and shallow" if  $L_c/B < 2$  and  $B/H > 500$  (horizontal shear dominant) (Taylor, 1953). Where  $L_c$  is the distance in meters from the center of the water system to its mouth,  $H$  (m) is the system average depth and  $B$  (m) the width of the system.

The typical and calculated parameters are related to the Arabian Gulf, the Mediterranean Sea and the Red Sea water systems. (Table 2) presents the summary results of water and salt mass balances and salinity results for the Arabian Gulf, the Mediterranean Sea, and the Red Sea based on desalination data from 1996. The result also contains the net volume, the exchange volume, and the exchange time in late 1996 and 2008 and predictions for 2050. The exchange time calculation in the three water systems was found to have insignificant changes over 54 years but significant differences between the three systems that are proportional to the system area and the total amount of desalination capacities.

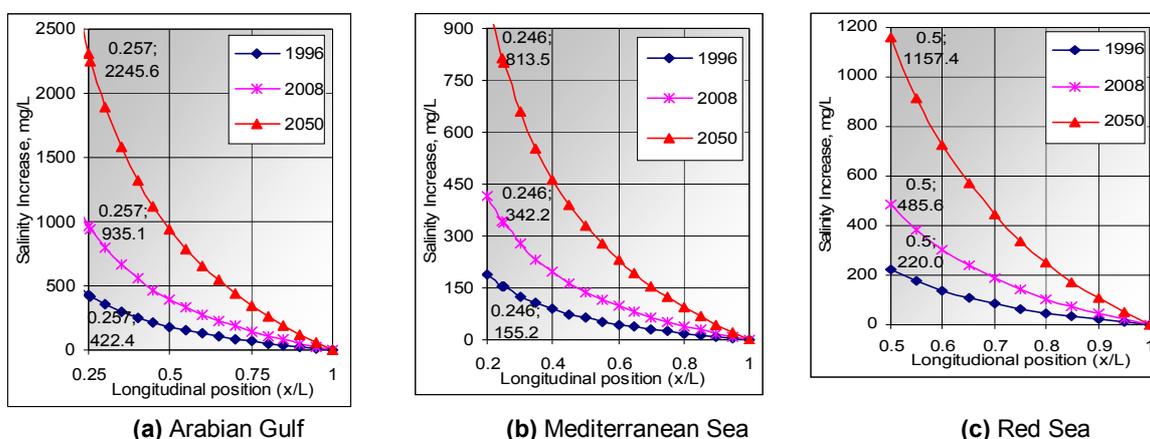
**Table 2.** Water and salt mass balances and salinity results for the three regions  
(<sup>a</sup>Masahiro, 1995; <sup>b</sup>Rajar et al., 2007)

Parameters	Region								
	Arabian Gulf			Mediterranean Sea			Red Sea		
<b>Input/Output at the end of year 1996 (MCM/day)</b>									
Average Ppt., $P_{ave}$	65.8 <sup>b</sup>			1,825			100		
Evaporation Rate, $E$	986.3			10,543			2,466		
River Discharge, $Q_{Rl}$	(48km <sup>3</sup> /yr) = 131.5			(347km <sup>3</sup> /yr) = 950.4 <sup>a</sup>			-----		
Average Outflow, $Q_o$	25,918			3198 <sup>a</sup>			34,560		
Brine Discharge, $Q_B$	16.5			5.0			7.3		
Seawater Intake, $Q_i$	23.6			7.2			10.5		
<b>Results:</b>	<b>1996</b>	<b>2008</b>	<b>2050</b>	<b>1996</b>	<b>2008</b>	<b>2050</b>	<b>1996</b>	<b>2008</b>	<b>2050</b>
$Q_N$ (x10 <sup>6</sup> m <sup>3</sup> /day)	-796	-804	-852	-7770	-7775	-7793	-2369	-2372	-2393
$Q_{EX}$ (x10 <sup>6</sup> m <sup>3</sup> /day)	4507	4576	5000	479963	480267	481695	31154	31208	31564
$\tau$ (days)	1584	1561	1435	8919	8913	8887	6712	6700	6626
$\tau$ (years)	4.34	4.28	3.93	24.42	24.40	24.33	18.4	18.3	18.1
Salinity, g/L, ppt	0.42	0.93	2.24	0.16	0.34	0.81	0.22	0.49	1.16

**5.2. Salinities modeling**

The results in (Figure 4) for cases (a) and (b) are the logarithm and peak logarithm of relative salinity due to seawater desalination in the Arabian Gulf and the Mediterranean Sea respectively. This is due to the fact that seawater desalination activities in the two regions were calculated for 1996, 2008 and 2050. The Arabian Gulf and Mediterranean Sea were both defined as wide and shallow and thus horizontal shear dominant, which means that the logarithm of relative salinity with  $Q_B$  = brine discharge from desalination production 10 years before 1996 and  $Q_B$  = brine discharge in 1996, 2008 and 2050. Anton Purnama et al. (2005) found that the peak salinity in the Arabian Gulf occurs at  $(X_{max}/L) \approx (X^*/L) (1-q)^{(2/3)}$ , where  $(X^*/L)$  is the brine discharge location.

Thus, the effect of the desalination plant in the Arabian Gulf with  $Q_B$  = brine discharge in 1996 is equivalent to the peak salinity increased by 0.42 ppt, in 2008 increased by 0.93 ppt, and in 2050 by 2.24 ppt. The result for the Mediterranean Sea with  $Q_B$  = brine discharge in 1996 is also equivalent to the peak salinity increased by 0.16 ppt, in 2008 increased by 0.34 ppt, and in 2050 by 0.81 ppt. Case (c) in (Figure 4) presents the result of applying the logarithms of relative salinity and salinity increase in the Red Sea due to a desalination plant located at  $a/L = 0.5$ , in 1996, 2008 and 2050. Thus, the effect of the desalination plant in the Red Sea with  $Q_B$  = brine discharge in 1996 is equivalent to the peak salinity increased by 0.22 ppt, in 2008 increased by 0.49 ppt and in 2050 by 1.16 ppt.



**Fig. 4.** Results from (a) and (b) are the logarithm and peak logarithm of relative salinity due to seawater desalination in the Arabian Gulf and the Mediterranean Sea, and (c) is the logarithm of relative salinity and salinity increase in the Red Sea due to a desalination plant located at  $a/L = 0.5$  in 1996, 2008 and 2050

The results by Anton Purnama et al. (2005) are that the effect of brine discharge in the Arabian Gulf is equivalent to the peak increased by 0.06 ppt and by 0.23 and 0.47 ppt for 5 and 10 times the amount of present brine discharge. In the Red Sea, the effect of brine discharge is equivalent to the peak increased by 0.14 and 0.28 ppt corresponding to 10 and 50 times of present brine discharge. The amount of natural evaporation in the three regions is huge compared to the total amount of water that is extracted by desalination. Evaporation takes place all over the surface area of the three regions but the amount extracted by desalination is local and has a greater effect than evaporation.

## 6. CONCLUSION

Population and desalination growth were considered as two equally important parts of this research in terms of the result. Estimated desalinated production from seawater and population prognoses also help us to take care of the impact from salinity increments, desalination activities, and amount of brine discharge on coastal receiving water. Desalination capacity in cubic meters per capita per year for each country was also calculated for comparison with the world standards and to understand the shortage of fresh water.

The purpose of this study was to evaluate how the coasts of the Arabian Gulf, the Mediterranean Sea and the Red Sea are and will be affected by seawater desalination brine discharge. For example, the results reveal significant volumes of brine discharge to the sea. In 1996 about 14 million m<sup>3</sup>/day was discharged into the Arabian Gulf, 4.6 million m<sup>3</sup>/day into the Mediterranean Sea, and 6.4 million m<sup>3</sup>/day into the Red Sea. In 2008, these figures had increased to 18.4, 9.8, and 6.8 million m<sup>3</sup>/day respectively. Thus, the increase in brine discharge significantly raises the salt concentration in the recipients as shown in this study. This increase must be observed from an environmental point of view, as well as technically and economically. As seawater salinity increases, the recovery ratio decreases, which raises the cost of desalinated water. This can already be partly observed in the Arabian Gulf area.

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