Estimated Future Production of Desalinated Seawater in the MENA Countries and Consequences for the Recipients

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Estimated Future Production of Desalinated Seawater in the MENA Countries and Consequences for the Recipients

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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. Desalination has advantages and disadvantages which may depend on the region, location, technology, impact and amount of fresh water production. Desalination may also have other impacts. For example, chemicals added in the pre-treatment stages could harm the fish production as well as the marine life in general.

The total land area in the three regions represents about 11.8% of the world land area and the countries host approximately 9% of the world population in the three years 1950, 2008 and 2050. Population statistics for a 100-year period has been used inclusive 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. This study also included estimates of the desalination capacity in cubic meter per capita of fresh water in the years 1996, 2008, and 2050: this capacity is about 1.2, 2.5, and 4.7 m^3/capita/yr in the world compared to 7.7, 15.6, and 30 m^3/capita/yr in the study area.

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

I. 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 effect 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 are directed towards salinity changes in three receiving water system due to brine from seawater desalination plant. The three regions, the Arabian Gulf (AG), the Mediterranean Sea (MS) and the Red Sea (RS) have very high evaporation rates, between 1.2 to 2 m annually, and very low annual precipitations, between 90 to 150 mm. The salinity in the recipients may increases in the long run if larger and larger amounts of desalinated water are removed from the water bodies. Due to its semi-enclosed nature and arid climate (AG), (MS) and (RS) waters are naturally characterized by a higher salt content due to the accelerated high rate of evaporation [1].

Desalination is considered as an important source of fresh water to proportionally follow the increasing in populations. Any country of water resources less than 1000 m^3/capita/yr is considered in trouble [2]. Thus, increasing of water resources which is mainly from desalination through developing recovery ratio from 30 to 50 percent in some country will increase the brine salt concentration. The existing amount of water resources in our planet is enormous compared the population increments [3]. Almost 95% is in oceans and seas that contains high amount of salinity, thus it is impossible to use the water resources directly for any purpose (e.g. agriculture, industry and domestic) unless it's treated previously [4]. Six countries receive nearly 50% of the total freshwater resources (Brazil, Canada, Russia, United State, China and India) and five great rivers transport 27% of the renewable resources (Amazon, Ganghes-Brahmputra, Congo, Yellow and Orinoco) [4,5].

The amount of desalinated water in the Arabian Gulf accounts for over 60% of the world's total production [6]. The installation capacity was counted at the end of 1999 as follow, 60% in the Middle East; 16% in the United State; 10% in the European Union; 6% in the Arabian Mediterranean countries; and 8% rest of the world [4]. The desalination capacities at 1998 were distributed as 60% in the West Asia and Meddle east; 11% in the United State; 7% in the European Union; 7% in North Africa; 4% South and Central America; and 11% rest of the world [7]. 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 [8,9].

The total daily capacity of installed desalination plants worldwide was 22.7 million cubic meters (MCM), an increase of about 70% from that previously was reported in the Desalting ABC's in 1990 [10,11]. Desalination from seawater accounts for about 58% of this gross capacity, brackish water treatment for 22% and wastewater reuse 5% [8,9]. 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^3 in some places, partly depending on the intake raw water quality. Although the cost of desalination plants may also depend on where they are located, as well as the local unit costs and operations, in which the prices has decreased from roughly \$1.5/m^3 in the early 1990s to around \$0.50/m^3 in 2003[12]. For example Perth desalination plant that consumes only 3.7 kWh/m^3 of fresh water, according to Crisp [13].

1.2. Brine Discharge and Dispersion of Salt

In all desalination brines, the concentration of which is higher than that of the 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 [14]. 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, salinity will increase by 70% [4]. Constructions nearby coastline give opportunities of choosing one or more outfall (building a series of outfalls) to the sea; it can minimize or reduce the environmental impact of brine discharge [15].

In (Table 1) the major compositions of three different regions Mediterranean, Arabic Gulf and Red Sea are compared to typical seawater [7]. These values help us to understand each region separately in the intake water and how the brine water would act on the recipient. The recovery ratio is related to these values and the quality of fresh water production and desalination cost. The major environmental problem associated with a desalination plant is the brine discharge.

Elements name	**Typical Seawater**	**Eastern Mediterranean**	**Arabian Gulf at Kuwait**	**Red Sea at Jeddah**
Chloride (Cl^-)	18,980	21,200	23,000	22,219
Sodium (Na^+)	10,556	11,800	15,850	14,255
Sulfate (SO_4^{2-})	2,649	2,950	3,200	3,078
Magnesium (Mg^{2+})	1,262	1,403	1,765	742
Calcium (Ca^{2+})	400	423	500	225
Potassium (K^+)	380	463	460	210
Bicarbonate(HCO_3^-)	140	-	142	146
Strontium (Sr^{2+})	13	-	-	-
Bromide (Br^-)	65	155	80	72
Borate (BO_3^{3-})	26	72	-	-
Fluoride (F^-)	1	-	-	-
Silicate (SiO_3^{2-})	1	-	1.5	-
Iodide (I^-)	<1	2	-	-
Others	-	-	-	-
Total dissolved solids , TDS	**34,483**	**38,600**	**45,000**	**41,000**

Table 1: Main ion composition of three different regions compared to typical seawater (mg/L) [7]

II. STUDY AREA: BACKGROUND & 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 sources in these countries and the largest capacity is also located at the same region. The results of brine water Q_{Brine} (10^6 m^3/d) for the three regions Arabian Gulf (AG), Mediterranean Sea (MS) and Read Sea (RS) at the end of 1996, 2008 and 2050 are shown in (Figure 1). The red arrows are describing the location of the exchange water e.g. rivers inflow; inflow through Dardanelle Strait from the Black Sea and exchange flow from the Gibraltar Strait etc, all related to the three systems.

Arabian Gulf bordering countries are: Iran, Iraq, Kuwait, Saudi Arabia, Qatar, Bahrain, United Arab Emirates and Oman. Mediterranean Sea bordering countries 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. Red Sea bordering countries are: Egypt, Israel, Jordan, Sudan, Eritrea, Saudi Arabia, Yemen and Djibouti.

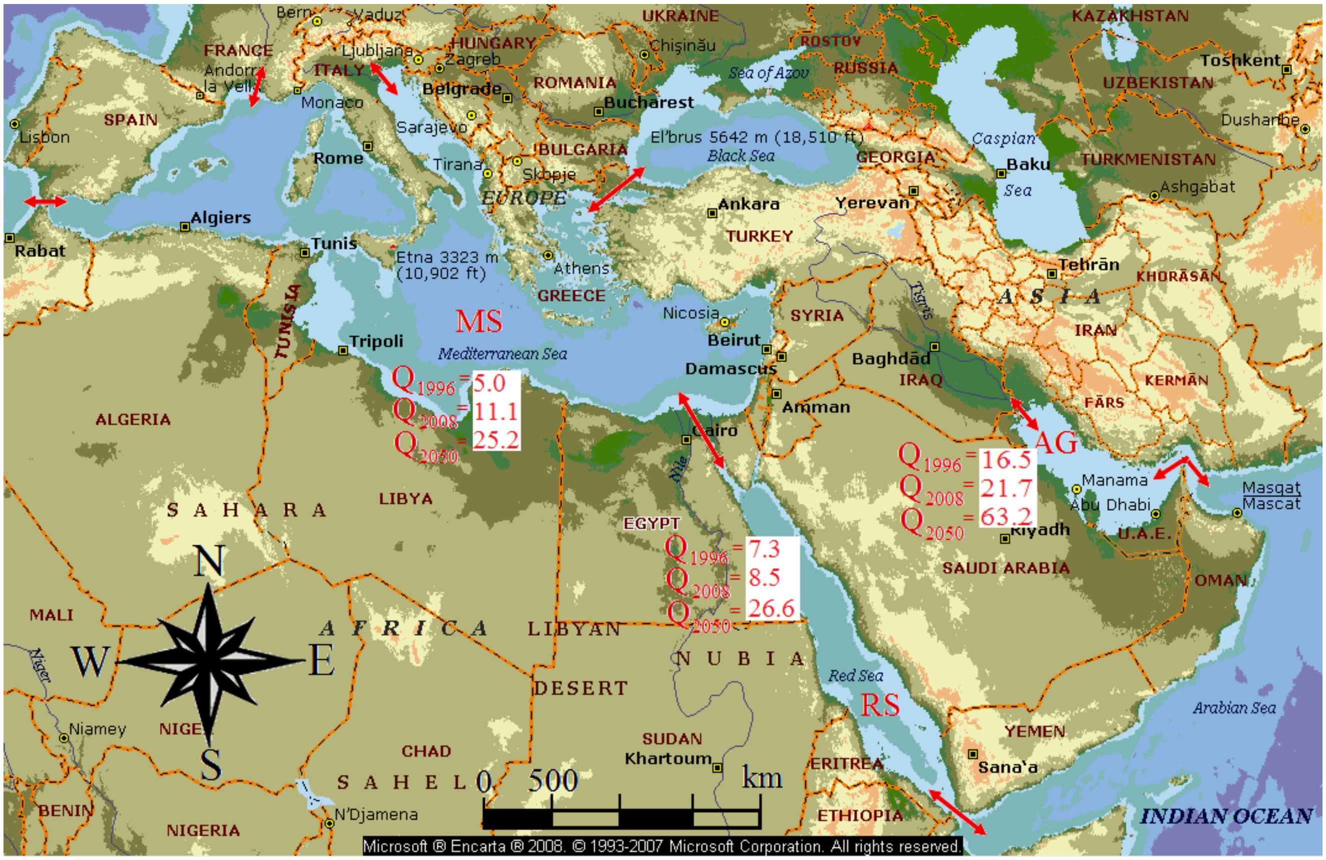


Fig. 1. Brine water Q_B results in 10^6 m^3/d for Arabian Gulf (AG), Mediterranean Sea (MS) and Read Sea (RS) in 1996, 2008 and 2050 (map after: Google Earth)

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 its mean only 35 m [16]. 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 volume 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/yr, in which fresh water and river inflow equals to 48 km^3/yr [16,17]. The mean annual evaporation rate is estimated at approximately 1.5 m/yr [18].

The shallowness of the Arabic Gulf water leads to the formation of a very high saline and dense water, having maximum salinities as high as 57 g/l along the southern coast [19]. Typical mass transport has been estimated by the outflow from Arabian Gulf to be about 34.5 x10^9 m^3/day, which is larger than those reported by other studies [20]. Ahmad and Sultan 1991 [21] employed the Knudsen relations and estimated that the annual mean Gulf water outflow transport was about 14.7 x10^9 m^3/day, compared to the observation of annual mean of (17.3-21.6) x10^9 m^3/day from an Acoustic Doppler Current Profiler (ADCP) in the Strait of Hormuz [22].

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 [9,23]. There are about 1,500 desalination units operating in the Arabian Gulf countries, which account for 58% of the world desalination production [24]. For Iraq desalination plant, the brine percentage discharged to the Arabian Gulf is not clear to me but my guess is about 5%.

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^2. The Mediterranean is connected with the Atlantic Ocean by the narrow and shallow channel of the Strait of Gibraltar and is connected with the Black Sea through the Dardanelles [25]. The typical values for the Mediterranean Sea is a mean width of about 800 km, a mean depth of about 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 [26,27].

Along the North African coast from Gabis in Tunisia to Egypt, precipitation more than 250 mm per year is rare, whereas on the Dalmatian coast of Croatia there are places that receive 2,500 mm. Maximum precipitations is found in mountainous coastal areas [28]. 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) [29]. Large volumes of sewerage is dumped directly into the Mediterranean Sea [30]. Several important desalination plants are located along the Mediterranean coast. Ashkelon desalination plant is an example with maximum production of 110 MCM/yr having an intake salinity of 40,679 ppm TDS and brine concentration of <80 ppm TDS [31]. Hadera desalination plant project was expected to begin construction during late 2007 and has a designed production capacity of up to 100 MCM/year [32]. 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) with 95% of all desalination plants [8,9].

2.3. Red sea (RS)

The Red Sea maximum width is about 225 km, its greatest depth 3,040 m, and its area approximately 450,000 km^2. The typical values for the Red Sea is a mean width of about 225 km, a mean depth of about 500 m, a gross length of about 2000 km, and an evaporation rate of approximately 2 m/yr [1]. 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 [8,9]. The exchange water between 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 [33,34].

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) the exchange amount is about 0.16 MCM/sec [35,36]. Murray and johns 1997 [36] also estimated that the annual mean Red Sea outflow transport is about 0.37 MCM/sec, which roughly agrees with Siedler's 1969 [37] 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 per year and an average volume of about 233,000 km^3. The renewal of water in the Red Sea is estimated to take 20 years [38].

III. LONG TERM DATA COLLECTION AND CALCULATION

3.1. Desalination Parameters

Desalination plants capacity, annual population growth ratio 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 and calculated data, desalination capacity and capacity per capita up to year 2050 has been extrapolated. (Figure 2) is the general typical diagram for seawater desalination plant including details for 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 plant. Further on $S_{Brine} = S_{Intake}/(1-r)$ and $Q_{Brine} = (1-r)Q_{Intake}$, where, r is the recovery ratio, generally between 35 to 45% of the intake, $S_F \approx 0$ and $Q_F = rQ_{Intake}$. The cooling water flows in MSF and MED are omitted since these do not affect the salinity.

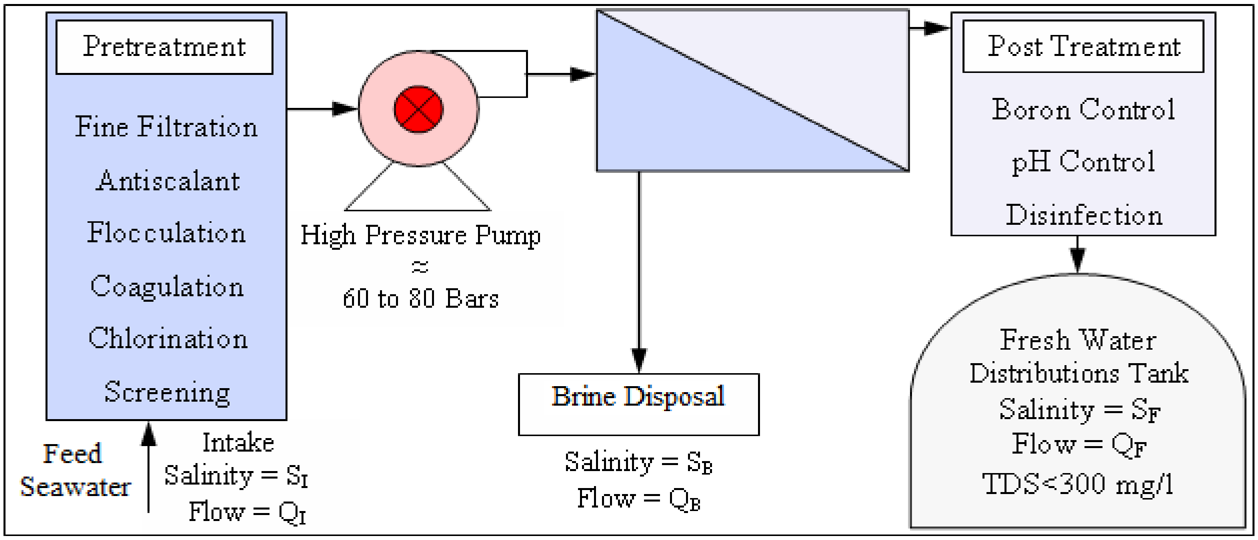


Fig. 2. Reveres osmosis seawater desalination plant typical scheme showing input/output and different stages of treatment

Brine is discharged back to the open sea through pipes and in the some cases in open channels. During the last ten years of desalination development, the recovery ratio r has been increased in reverse osmosis plants significantly. For example from Al Shaaer et al., 2007 [15] seawater intake salinity, S_{Intake} is equal to 41.7 ppt, and the brine outlet is 74 ppt. From the relation $S_{Brine} = S_{Intake}/(1-r)$ the recovery ratio r = 44%. If the recovery ratio increases, the brine concentration increases as well.

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 three regions. Comparison for population, area and population growth ratio for world and study area are presented in (Table 2) for 100 years. Data were collected for the period 1950-2008 and calculated for the period 2009-2050. The growth rate from midyear of the whole period is the most common way to express 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 = year; R(t) = growth rate from midyear t to midyear t+1; P(t) = population at midyear t and Ln = natural log (after: U.S. Census Bureau, 2008) [39].

The total population in the study area is approximately 9.4% of the world population during all the 100 years and the land area occupies approximately 11.8% of the world total land area. Population growth rate in 100 years from 1950 to 2050 is found to be 1.30 and 1.35 in the world and study area respectively.

Country or area	Population			Area	Population growth rate
	1950	2008	2050	Km^2	PGR
WORLD	**2,555,948,654**	**6,677,602,292**	**9,392,797,012**	**130,772,667**	**1.30**
Algeria	8,892,718	33,769,669	44,163,403	2,381,740	1.60
Bahrain	114,840	718,306	973,412	665	2.14
Cyprus	494,000	792,604	841,102	9,240	0.53
Egypt	21,197,691	81,713,517	127,563,256	995,450	1.79
France	42,517,690	64,057,790	69,768,223	640,053	0.50
Greece	7,566,028	10,722,816	10,035,935	130,800	0.28
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
Israel	1,286,131	7,112,359	10,828,462	20,330	2.13
Italy	47,105,000	58,145,321	50,389,841	294,020	0.07
Jordan	561,254	6,198,677	11,772,789	91,971	3.04
Kuwait	144,774	2,596,799	6,374,800	17,820	3.78
Lebanon	1,364,030	3,971,941	4,964,025	10,230	1.29
Libya	961,305	6,173,579	10,817,176	1,759,540	2.42
Malta	311,973	403,532	395,639	316	0.24
Morocco	9,343,384	34,343,219	51,083,745	446,300	1.70
Palestine	1,016,540	4,149,173	9,789,347	6,000	2.26
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
Spain	28,062,963	40,491,051	35,564,293	499,542	0.25
Sudan	8,051,151	40,218,455	88,227,761	2,376,000	2.39
Tunisia	3,517,210	10,383,577	12,512,323	155,360	1.27
Turkey	21,121,639	71,892,807	86,473,786	770,760	1.41
UAE	71,520	4,621,399	8,018,904	83,600	4.72
Yemen	4,777,089	23,013,376	71,278,172	527,970	2.70
Total	**233,884,275**	**628,676,423**	**900,633,279**	**15,446,996**	**1.35**
Percentage	**9.2**	**9.4**	**9.6**	**11.8**	**0.05**

Table 2: Comparisons for area and population growth rate for worldwide and study area in 1996, 2008 and 2050 [39]

3.3. Desalination Production

Desalination capacities expressed as 1,000 m^3/day, in the world and study area for the years 1996 and the estimated values for the year 2050 are listed and compared in (Table 3). 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 the years 1996 and 2008 and calculated for the year 2050 for both the world desalination capacity and study area desalination capacity. These results describe the relation between three water types in three different time steps for each country and as well as the whole study area.

Further on, they are also compared with the world capacities. It was important to find and estimate the fresh water in the year 2050 to be able to calculate the growing in desalination in the studied area compared to the world growing.

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

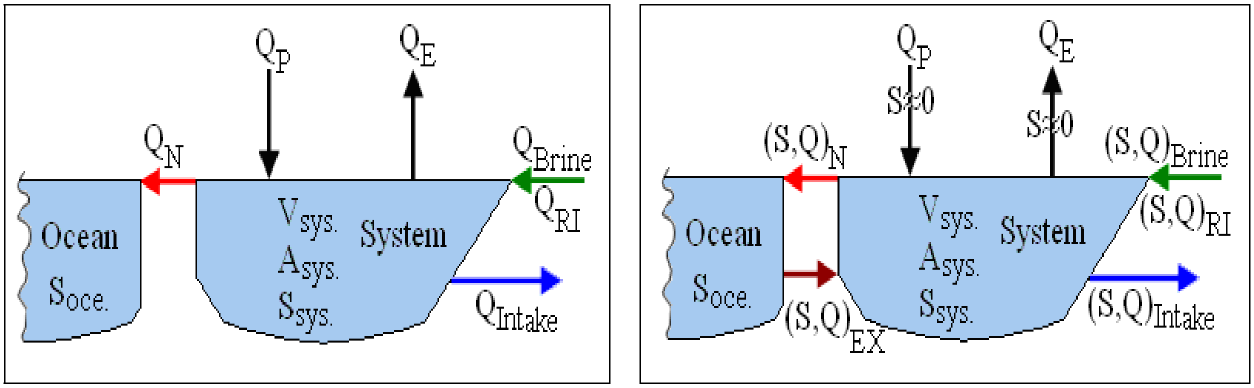
Country or area	**Brine location**	**Desalination capacity in 1,000 m^3/day**						**Desalination capacity in m^3/capita/year**		
		1996		**2008**		**2050**		**1996**	**2008**	**2050**
		Q_F	**Q_B**	**Q_F**	**Q_B**	**Q_F**	**Q_B**	**Q_F**	**Q_F**	**Q_F**
WORLD		**20000**	**46667**	**47709**	**71564**	**192211**	**192211**	**1.19**	**2.54**	**4.74**
Algeria	MS	190.8	445	1055.9	1584	3044.1	3044	2.30	11.13	16
Bahrain	AG	283.0	660	825.2	1238	3022.0	3022	164	409.0	718
Cyprus	MS	6.275	15	183	275	399.0	399	3.01	82.3	110
Egypt	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
Total		**12375**	**28876**	**27558**	**41337**	**114979**	**114979**	**7.86**	**15.61**	**29.54**
Percentage		**62**		**58**		**60**				

Table 3: Comparisons between world and study area for desalination capacity and amount in cubic meters per capita per year at the end of 1996, 2008 and 2050 [after: 7,8,9,11,23,40,41,42,43], in which, Q_F = Freshwater production from desalination and Q_{Brine}=Brine Discharge

IV. METHODOLOGY AND MODELING

4.1. Water and Salt Mass Balances

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 are denoted by (Q_{RI}), average rainfall (Q_P), average annual evaporation (Q_E), (Q_{EX}) is the mixing volume (exchange volume between system body and ocean) across the open boundary of the system and (Q_N) is the residual volume transport associated with freshwater discharge. Q_{Brine} is the brine discharge to sea and Q_{Intake} is the amount of feed water intake to the desalination plant from open sea or from wells located about 20 to 30 meters away from the coastline. S_{sys} is the system salinity, S_{ocn} is 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 common in (m^3/s) and all concentration will be taken as (g/l).



a) water budget

b) salt budget

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

Following the 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 [44]. Q_{EX} is estimated from water and salt budgets.

A. Water mass balance

The amount of waters flows into the system, the same amount of waters must flow out in order to keep the volume constant. In principle, this flow, called the "residual flow, Q_N" or the net residual volume in which can be written as:

$$Q_N = \sum Q_{in} - \sum Q_{out} = (Q_p + Q_{RI} + Q_{Brine}) - (Q_E + Q_{Intake}) \tag{1}$$

B. Salt mass balance

For the salt budget, we assign related salinity to each one of the water inputs and outputs. The inputs and outputs then become each flow multiplied by the appropriate salinities (designated as S's) for most of the terms if they are important. For the terms having small salinity (that has no effect to the system) like evaporation and precipitation it is sufficiently accurate to assume their salinity to be (Zero) and excluding it from calculations.

$$Q_{EX} = [(Q.S)_N + (Q.S)_{RI} + (Q.S)_{Brine} - (Q.S)_{Intake}]/(S_{ocn} - S_{sys}) \tag{2}$$

where, salinity of the exchange volume is the difference between ocean salinity S_{ocn} and system salinity S_{sys}, and the net volume Q_N salinity is equal to the average of ocean and system salinities.

$$\tau = V_{Sys.}/(\ Q_{EX} + |Q_N|) \tag{3}$$

where, τ is exchange time, system volume divided by the sum of Q_{EX} plus the absolute value of Q_N as stated in a single layer, single box system [44].

4.2. Mathematical Model

We here model the Arabian Gulf, the Mediterranean Sea and the Red Sea following Anton Purnama et al., 2005 and balances from (Figures 2 and 3). As they defined and assumed that the water exchange with the open sea at x = L is the main source of water in which A = BH is the cross-sectional area, U the incoming tidally averaged current and U_L is the tidally averaged value of the rate of change of water depth [1]. The equation of mass flux of water is a balance between the incoming current and the freshwater input from rivers Q_{RI}, with continuous depletion by evaporation at the rate E and the seawater intake by a desalination plant located at x = a:

$$\frac{d}{dx}\left(AU - \mathrm{Q}_{\mathrm{RI}}\right) = -EB - rQ_I\delta(x-a) \tag{4}$$

where rQ is the rate of the plant's water production and δ is the Dirac delta function. Seawater of salinity s is removed at the volumetric rate Q_I (intake water), so a one-dimensional advection-diffusion approach can be adopted [45,46]:

$$\frac{d}{dx}(AUs) - \frac{d}{dx}\left(AD\frac{ds}{dx}\right) = Q_I s\delta(x-a) \tag{5}$$

where D is the tidally averaged shear dispersion coefficient that could be estimated numerically from field observations of surface salinity. On integrating, and matching the salinity to s_L at x = L, we obtain the logarithm of relative salinity [1].

$$\ln\left(\frac{s}{s_L}\right) = \left\{\begin{aligned} &\int_x^L \frac{dz}{AD}\left(E\int_0^z B(P)dP - \mathrm{Q}_{\mathrm{RI}}\right) + (1+r)Q_I\int_x^L \frac{dz}{AD}, && 0 = \mathrm{x} < \mathrm{a} \\ &\int_x^L \frac{dz}{AD}\left(E\int_0^z B(P)dP - \mathrm{Q}_{\mathrm{RI}} + (1+r)Q_I\right), && \mathrm{a} = \mathrm{x} < \mathrm{L} \end{aligned}\right\} \tag{6}$$

Thus, the logarithm of relative salinity increase due to seawater desalination can be evaluated from:

$$\ln\left(\frac{s}{s\,*}\right) = \left\{\begin{aligned} &(1+r)Q_I\int_a^L \frac{dz}{AD}, && 0 \le x < a \\ &(1+r)Q_I\int_z^L \frac{dz}{AD}, && a \le x < L \end{aligned}\right\} \tag{7}$$

where s* is the salinity for the case without seawater desalination in which the increase exponentially depends on the seawater intake rate Q_I and the location of the plant x = a. Therefore, it is more severe the further the desalination plant is from the open sea x = L.

V. RESULTS AND DISCUSSIONS

It is necessary to calculate desalination capacity in the three different periods in order to estimate desalination capacity cubic meters per capita per year in each country and whole region to determine the amount of fresh water that are collected from desalination. The aim here is to find the total brine water in each region for the past and future as correct as possible in order to avoid and minimize some of the impacts. (Table 4) is the summary of the calculated desalination capacities in the world and three regions for fresh water Q_F, brine water Q_{Brine} and intake water Q_{Intake} and percentages from world production at the end of year 1996, 2008 and 2050. Desalination capacity comparison has been found in the Arabian Gulf, Mediterranean Sea and Red Sea at the end of year 1996 of about 35.4, 10.7 and 15.7% respectively.

Year		**World**	**Arabian Gulf**			**Mediterranean Sea**			**Red Sea**		
		10^6 m^3/d	**10^6 m^3/d**	**km^3/yr**	**%**	**10^6 m^3/d**	**km^3/yr**	**%**	**10^6 m^3/d**	**km^3/yr**	**%**
1996:	**Q_F**	20.0	7.1	2.6	35.4	2.1	0.8	10.7	3.1	1.1	15.7
	Q_B	**46.7**	**16.5**	**6.0**	**35.4**	**5.0**	**1.8**	**10.7**	**7.3**	**2.7**	**15.7**
	Q_I	66.7	23.6	8.6	35.4	7.2	2.6	10.7	10.5	3.8	15.7
2008:	**Q_F**	47.7	14.5	5.3	30.4	7.4	2.7	15.5	5.7	2.1	11.9
	Q_B	**71.6**	**21.7**	**7.9**	**30.4**	**11.1**	**4.1**	**15.5**	**8.5**	**3.1**	**11.9**
	Q_I	119.3	36.2	13.2	30.4	18.5	6.8	15.5	14.2	5.2	11.9
2050:	**Q_F**	192.2	63.2	23.1	32.9	25.2	9.2	13.1	26.6	9.7	13.8
	Q_B	**192.2**	**63.2**	**23.1**	**32.9**	**25.2**	**9.2**	**13.1**	**26.6**	**9.7**	**13.8**
	Q_I	384.4	126.4	46.2	32.9	50.5	18.4	13.1	53.1	19.4	13.8

Table 4: Summary of world and the three regions desalination capacities in 1996, 2008 and 2050

5.1. Results in Recipients

Comparison between world and study area (AG), (MS) and (RS) made 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 (at the end of year 1996 to years 2008), 3) Coverage area ratio, 4) Desalination recovery ratio related to: Freshwater production (Q_F) Brine discharge (Q_{Brine}) and, Seawater intake (Q_{Intake}) and 5) Desalination capacity estimation, m^3/capita in years 2008 and 2050.

The mixing of different input across the open boundary of the recipient is governed by the dispersion process [47]. The following criteria are used to decide how the water body will be classified. 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) [48]. 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) is the width of the system.

The typical and calculated parameters related to the three water systems Arabian Gulf, the Mediterranean Sea and the Red Sea. The result of net volume, exchange volume and exchange time for 1996, 2008 and 2050 are presented in (Table 5). These calculations also helped us to classify the three systems as follow: a wide and shallow (Arabian Gulf and Mediterranean Sea) are both having horizontal shear dominant and a narrow and deep (Red Sea) will be in a vertical shear dominant. **(**Table 6) is the summary results of water and salt mass balances and salinity results for the Arabian Gulf, the Mediterranean Sea and the Red Sea with desalination data of year 1996.

The result also contains the net volume, the exchange volume and the exchange time at the end of 1996 and 2008 and prediction of year 2050. The exchange time calculation in the three water systems have shown insignificant changes over 54 years and significantly differences between three systems as proportional to the system area and total amount of desalination capacities.

Categories	**Region**		
	Arabian Gulf	**Mediterranean Sea**	**Red Sea**
Parameters:			
L_{ave} ($x10^3m$)	1,000	2,700	2,000
L_C ($x10^3m$)	450	1,000	1,000
B ($x10^3m$)	240	800	225
H (m)	35	1,500	500
A ($x10^6m^2$)	240,000	2,960,000	450,000
V ($x10^9m^3$)	8,400	4,350,000	225,000
Classifications:			
(L_C/B) ratio	$1.9< 2$	$1.25< 2$	$4.4> 2$
(B/H) ratio	$6857>500$	$533>500$	$450<500$
Shape	Wide and Shallow	Wide and Shallow	Narrow and Deep
Shear	Horizontal shear dominant	Horizontal shear dominant	Vertical shear dominant

Table 5: Typical and calculated related parameters for the Arabian Gulf, the Mediterranean Sea and the Red Sea [44,47,48]

Parameters	**Region**								
	Arabian Gulf			**Mediterranean Sea**			**Red Sea**		
Input/Output at the end of year 1996 (MCM/day)									
Average Ppt., P_{ave}	65.8[b]			1,825			100		
Evaporation Rate, E	986.3			10,543			2,466		
River Discharge, Q_{RI}	($48km^3/yr$) = 131.5			($347km^3/yr$) = 950.4[a]			-----		
Average Outflow, Q_O	25,918			3198[a]			34,560		
Brine Discharge, Q_B	16.5			5.0			7.3		
Seawater Intake, Q_I	23.6			7.2			10.5		
Results:	**1996**	**2008**	**2050**	**1996**	**2008**	**2050**	**1996**	**2008**	**2050**
Q_N ($x10^6m^3/day$)	-796	-804	-852	-7770	-7775	-7793	-2369	-2372	-2393
Q_{EX} ($x10^6m^3/day$)	4507	4576	5000	479963	480267	481695	31154	31208	31564
τ (days)	1584	1561	1435	8919	8913	8887	6712	6700	6626
τ (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

Table 6: Water and salt mass balances and salinity results for the three regions [[a]49,[b]50]

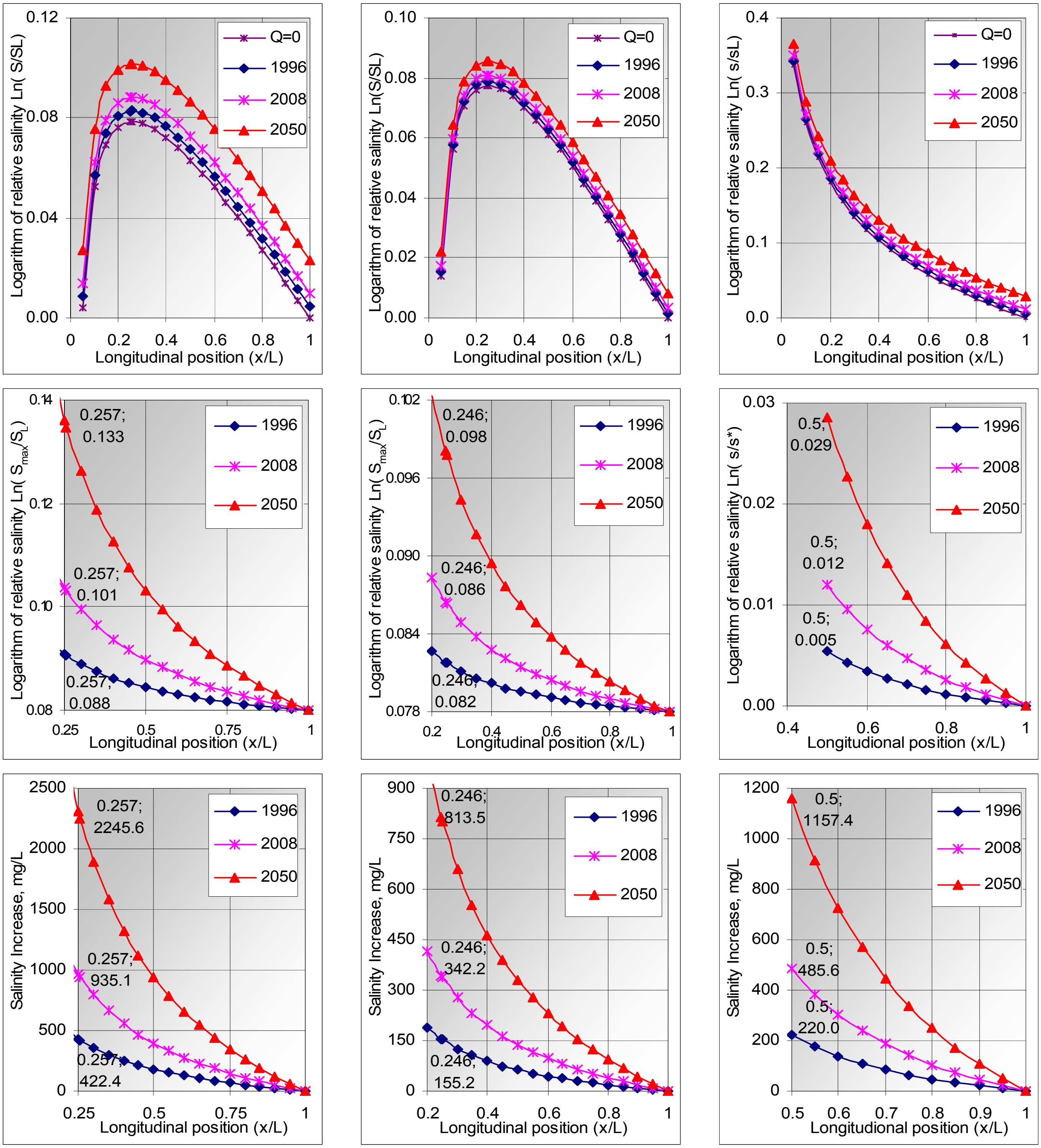
5.2. Salinities Modeling

The results in (Figure 4) for cases (a) and (b) are the logarithm of relative salinity and peak logarithm of relative salinity due to seawater desalination in the Arabian Gulf and the Mediterranean Sea respectively. This is due to seawater desalination activities in the two regions were calculated at years 1996, 2008 and 2050. Arabian Gulf and Mediterranean Sea both were defined as wide and shallow and horizontal shear dominant then the logarithm of relative salinity with Q_B = brine discharge 10 years before 1996 of desalination production and Q_B = brine discharge at years 1996, 2008 and 2050. After

Anton Purnama et al., 2005 they 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 [1].

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

The results found by Anton Purnama et al., 2005 and according to their calculation the effect of brine discharge in the Arabian Gulf is equivalent to the peak increased of 0.06 ppt and the peak increased by 0.23 and 0.47 ppt for 5 and 10 times of present brine discharge amount. 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 extracted by desalination. Evaporation extracted from all over surface area of three regions but the amount extracted by desalination is locally and have greater effect than evaporated amount.



(a) Arabian Gulf **(b)** Mediterranean Sea **(c)** Red Sea

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

VI. CONCLUSION

Population and desalination growth were considered as the two parts of this research in which gives the same level of importance to the result. Estimated desalinated production from seawater and population prognosis also helps us to take care about coastal receiving water impact from salinity increments, desalination activities and amount of brine discharge. 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 the fresh water.

The importance of this study was to evaluate how the three coasts of the Arabian Gulf, Mediterranean Sea and the Red Sea are affected and will be affected from seawater desalination brine discharge. For example, the results show significant volumes of brine discharge to the sea. In 1996 about 14 millions m^3/day were discharged to the Arabian Gulf, 4.6 millions m^3/day to the Mediterranean Sea and 6.4 millions m^3/day to the Red Sea. In 2008, the figures had increased to 18.4, 9.8 and 6.8 millions m^3/day in the three regions respectively. Thus, the increase in brine discharge significantly rises the salt concentration in the recipients as shown in this study. This increase has to observed, from an environmental point of view. But also technically and economically. As seawater salinity increases, the recovery ratio decreases, which increases the cost of desalinated water. This can partly be observed already in the Arabian Gulf area.

VII. REFERENCES

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