Desalination and Water Treatment
www.deswater.com

18 (2010) 80–85
June

doi: 10.5004/dwt.2010.1341

A model study of desalination and hypersalinity of the Arabian Gulf

Anton Purnama*, H.H. Al-Barwani

Department of Mathematics and Statistics, College of Science
Sultan Qaboos University, PO Box 36, Al-Khod PC123, Muscat, Sultanate of Oman
Tel.: +968 24141428; Fax: +968 24141490; e-mail: antonp@squ.edu.om

Received 30 April 2009; Accepted 10 February 2010

ABSTRACT

Desalinated seawater is indispensably required at all costs in the hot and arid climate of the Arabian Gulf countries of Kuwait, Saudi Arabia, Bahrain, Qatar and the United Arab Emirates to sustain and allow the continuing long-term socio-economic development. Building more seawater desalination plants and increasing water production rates appear to be the answer to satisfy the projected future water demands. On the other hand, the Arabian Gulf itself is a shallow semi-enclosed marginal sea and environmentally very fragile. Its water is naturally characterized by higher salinity due to an extremely high evaporation rate as a consequence of solar heating, and therefore any further loss of water by desalination plants operated along its coast would make the Arabian Gulf hypersaline. However, many scientists believe and state that the environmental impact of seawater desalination on the Arabian Gulf as a whole is negligible because natural evaporation is magnitudes higher. Using a simple mathematical model for a semi-enclosed sea of simple geometry, the role of natural evaporation and seawater desalination in the Arabian Gulf is formulated.

Keywords: Arabian Gulf; Evaporation; Hypersaline; Mathematical model; Seawater desalination; Semi-enclosed sea

1. Introduction

In the arid Arabian Gulf countries of Kuwait, Saudi Arabia, Bahrain, Qatar and the United Arab Emirates (UAE), the water produced by seawater desalination has been commonly used to alleviate water shortages due to their rapid industrial development and population growth [1,2,3]. To avert the real threat to resource sustainability, the Arabian Gulf countries are steeping up efforts to boost availability by building seawater desalination plants (mostly MSF), and therefore a rapid increase of the number of coastal seawater desalination plants built along the coast of the Gulf is also expected. As shown in Table 1, the daily total production capacity of all desalination plants in the Arabian Gulf countries was estimated to be 12.77 million m^3. Since the desalination technology can achieve a recovery of up to 50% of product water from the plant's feedwater, the desalination process also produces brine, wastewater containing a highly concentrated salt solution, and the continuous discharge of brine waste stream into the Arabian Gulf is the practical method for disposal [1].

The Arabian Gulf is a shallow semi-enclosed sea situated in the northern-eastern Arabian Sea, with an average depth of 35 m [4,5]. It covers an area of approximately 230 000 km^2, and is about 1000 km long with widths ranging from 200 km to 345 km. The Arabian Gulf is connected to the Gulf of Oman via the narrow Strait of Hormuz, with a deep channel off the coast of Iran, and shallow areas off the coasts of Kuwait, Saudi Arabia, Qatar and the UAE.

*Corresponding author.

Table 1
Seawater desalination in the Arabian Gulf.

Country	Daily plants capacity (million m^3)	Annual water produced (km^3)
Kuwait	1.93	0.704
Saudi Arabia	3.14	1.146
Bahrain	0.85	0.310
Qatar	1.01	0.368
United Arab Emirates [a]	5.67	2.069
Iran	0.17	0.062
Total	12.77	4.659

[a]Fujairah desalination plant is not included.

At the head of the Arabian Gulf, there are freshwater inflows from the Tigris, Euphrates and Karun rivers at the delta of the Shatt al Arab. The annual mean discharge was estimated at 46 km^3/year by Reynolds [5], being equivalent to 0.2 m/year when evenly distributed over the surface of the Arabian Gulf. In the volume of water budget calculations, the total river discharge of 37 km^3/year or 0.16 m/year was quoted by Brewer and Dyrssen [4]. For the numerical studies of circulation in the Arabian Gulf, Chao *et al*. [6] used a value of 43.8 km^3/year or 0.19 m/year, and Kampf and Sadrinasab [7] used a much lower value of 15.8 km^3/year or 0.07 m/year.

The water in the Arabian Gulf is naturally characterized by higher salinity due to an extremely high evaporation rate as a consequence of solar heating. Privett [8] was the first to report an estimated mean evaporation rate of 1.44 m/year. The higher rate at 2.0 m/year was later reported by Meshal and Hassan [9]. Based on the measurement at the Strait of Hormuz, Johns *et al*. [10] estimated the annual surface fresh water loss to be 1.69±0.39 m. Surface salinity values exceeding 43 ppt (parts per thousands) were recorded, especially in the shallow waters around the island of Bahrain and the coasts of Kuwait, Qatar and the UAE [1,4,5,11]. In general, the progressive increase in salinity is observed towards the head of the Gulf, where the water column is almost mixed.

The Arabian Gulf is environmentally very fragile, and any further loss of freshwater, such as the extraction of water by desalination plants located along its coast, would deteriously change the salinity. A mathematical model using a simple channel geometry representation of the semi-enclosed sea makes it possible to derive an analytical description of the dispersion of salinity in the Arabian Gulf [12]. Thus, the role of natural evaporation and seawater desalination is formulated, and will be used to provide answers to questions such as, how much of an evaporation rate is needed to raise the salinity by 1 ppt, and what is the critical rate before the contribution from the plants' water production becomes significant?

2. Mathematical model

Presently, due to lack of data and other physical properties, the scale of variability and many aspects of the current in the Arabian Gulf are still poorly understood [6,7,11,13]. Exchanges through the Strait of Hormuz, considered to be the main source of the water for the Arabian Gulf, are not well measured [10,14]. Thus, if we are to use simple mathematical modeling [12,15], it is then necessary to make many simplifying assumptions.

Along the Arabian Gulf, the channel depth and breadth vary markedly; therefore, as shown in Fig. 1, we first model the Arabian Gulf as the channel geometry of a parabolic depth profile with square root increasing width $B = \left(3B_L/2\right)\sqrt{x/L}$ and constant depth $H = 2H_L$. Other previous models of channel geometry have been reported in Smith et al. [12] and Purnama et al. [15].

The equation mass flux of water is a balance between the incoming current U from the mouth of the semi-enclosed sea $x = L$ through a cross-sectional area $A = BH$ and freshwater inflow F from the head of the semi-enclosed sea $x = 0$, with continuous depletion by evaporation at the rate μ, and the rate of water production r_jQ_j by a seawater desalination plant (for a seawater intake rate Q_j) located at $x = aj$:

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(AU - F\right) = -\mu\, B - \sum_{j=1}^{n} r_j\, Q_j \delta\left(x - a_j\right), \qquad (1)$$

where δ is the Dirac delta function. The plant's recovery rate r_j varies typically from 10–30% for MSF seawater desalination plants to 30–50% for RO plants.

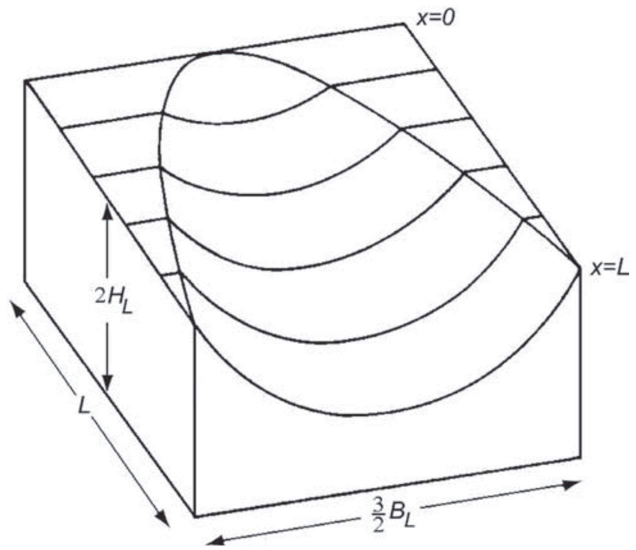

Fig. 1. Channel geometry of a semi-enclosed sea.

Assuming that the mechanisms by which salinity are mixed and dispersed in the semi-enclosed sea are related to the incoming currents driven by tidal motion from the mouth of the semi-enclosed sea, the advection-diffusion equation of salinity s is given by

$$\frac{\mathrm{d}}{\mathrm{d}x}(AUs) - \frac{\mathrm{d}}{\mathrm{d}x}\left(AD\frac{\mathrm{d}s}{\mathrm{d}x}\right) = \sum_{j=1}^{n} Q_j\, s\, \delta\left(x - a_j\right), \qquad (2)$$

where D is the shear-dispersion coefficient. If seawater of salinity s is abstracted by the desalination plant at the volumetric rate Q_j, then $(1 - r_j)Q_j$ is the rate of brine waste stream discharges from the plant with salt concentration $s/(1 - r_j)$.

Next, we assume that D is proportional to $\frac{B^2U}{H}$, and as formulated in Smith *et al.* [12], $D = \frac{\alpha B}{H^2}\int_0^x B(z)\,\mathrm{d}z$. The corrected factor α will be chosen so that, for the case when there is no seawater desalination in the semi-enclosed sea, the model prediction agrees with the observed surface salinity in the Arabian Gulf. Using the reference values $B_L = 230$ km, $H_L = 25$ m, $L = 1000$ km, $\mu = 2$ m/year, $F = 35$ km^3/year or 0.15 m/year, and the observed surface salinity maximum value of 45 ppt and 38 ppt at the Strait of Hormuz, we obtain $\alpha = 0.0055$ m/year.

3. Hypersalinity of a semi-enclosed sea of simple geometry

Setting $Q_j = 0$, and on integrating Eqs. (1) and (2), we obtain by solving $\mathrm{d}s/\mathrm{d}x = 0$, for the case when there is no seawater desalination, the salinity maximum occurs at x^* given by

$$\int_0^{x_*} \mu(p)B(p)\,\mathrm{d}p = F. \qquad (3)$$

Using the annual mean evaporation rate, the position of salinity maximum in the chosen model channel with simple geometry is given by $x^*/L = \Gamma^{2/3}$, where the model parameter $\Gamma = F/\mu B_L L$ represents the ratio of freshwater discharge (over surface area $B_L L$) to evaporation. Due to lack of data, Fig. 2 shows the uncertainty in the model parameter Γ for some reported values of μ and the annual mean freshwater inflow $F/B_L L$ from the rivers Tigris, Euphrates and Karun. The larger values of Γ are most likely due to stronger river discharges that compensate smaller evaporation rates. Thus, Γ in the range of 0.05–0.15 are suitable for the case of a moderate river inflow.

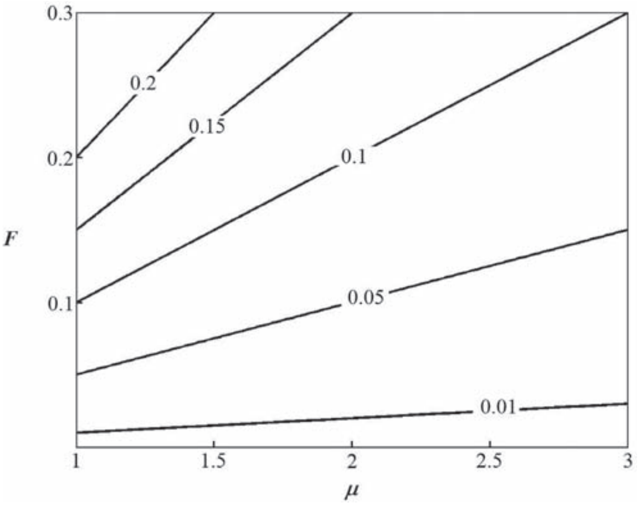

Fig. 2. The model parameter Γ.

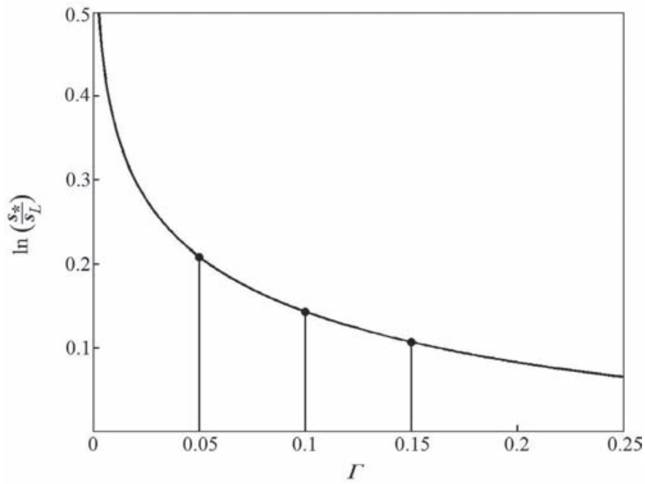

Fig. 3. Logarithm of relative salinity maximum.

Next, by matching salinity to s_L at $x = L$, the logarithm of relative salinity maximum s^* at $x = x^*$ is formulated by

$$\ln\left(\frac{s_*}{s_L}\right) = \int_{x_*}^{L} \frac{\mathrm{d}z}{A(z)D(z)}\left(\int_{x_*}^{z} \mu(p)B(p)\,\mathrm{d}p\right). \qquad (4)$$

In the chosen model of channel with simple geometry, the salinity maximum is simplified to

$$\ln\left(\frac{s_*}{s_L}\right) = 0.1019\,(\Gamma - 1 - \ln\Gamma).$$

As shown in Fig. 3, the salinity maximum value decreases as the parameter Γ becomes larger, i.e. as the river discharges become stronger, or equivalent, the evaporation rate becomes weaker. Due to a higher annual mean evaporation rate chosen as a reference in the model, if the value of Γ increases from 0.05 to 0.1, then the salinity maximum value s^* is reduced by 7%, and similarly, if Γ increases from 0.05 to 0.15, then s^* is reduced by 11%.

4. Seawater desalination in a semi-enclosed sea of simple geometry

The model applications for a single desalination plant in a semi-enclosed sea of simple geometry have been reported in Purnama et al. [15] and Smith et al. [12]. For the case when there are many desalination plants operated in a semi-enclosed sea, the position of salinity maximum will shift to a new position x_1^* as specified by

$$\int_0^{x_{1*}} \mu(p)B(p)\,\mathrm{d}p = F - (1+r_1)Q_1. \tag{5}$$

In the chosen model of the channel with simple geometry, we obtain

$$x_{1*}/L = \Gamma^{2/3}\left[1-\left(\frac{1+r_1}{r_1}\right)q_1\right]^{2/3},$$

where $q_1 = r_1Q_1/F$ is the ratio of the water production rate by the first (closest to the head of the semi-enclosed sea) desalination plant at $x = a_1$ to freshwater inflow at the head of the semi-enclosed sea. Note that the new position x_1^* depends only on the first desalination plant, and if $q_1^* = r_1/(1 + r_1)$ then $x_1^* = 0$, that is, the new position of the salinity maximum is precisely at the head of the semi-enclosed sea. As might be anticipated from physical considerations, seawater desalination has the exact opposite effect on salinity to that of freshwater inflow from the head of the semi-enclosed sea. As shown in Fig. 4, depending on the recovery rate r_1, this severely critical situation corresponds to the plants' water production rate $q_1^* < 0.4$. For example, using the reference value for the annual mean river discharge $F = 35$ km^3/year, the critical water production rate would be $r_1Q_1^* = 3.18$ km^3/year for a lower recovery rate of 10%, and $r_1Q_1^* = 5.83$ km^3/year for a recovery rate of 20%.

Fig. 5 shows the position of salinity maximum x_1^*/L for two values 0.05 and 0.15 of the parameter Γ. The position of salinity maximum approaches the head of the semi-enclosed sea faster at a recovery rate of 10% than that of 50% as the water production rate increases.

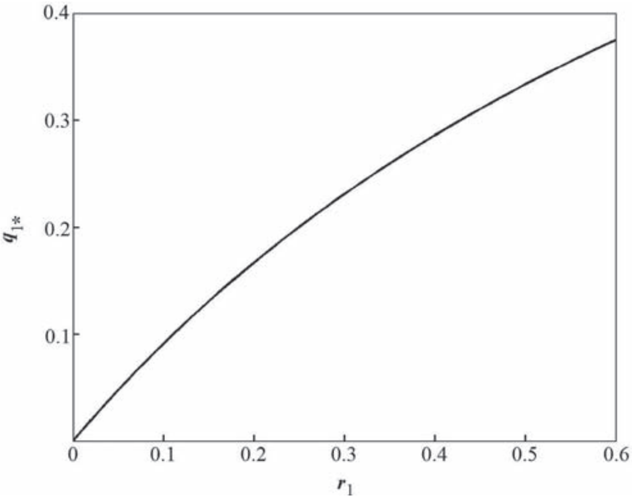

Fig. 4. The critical rate of the water production for the desalination plant at $x = a_1$.

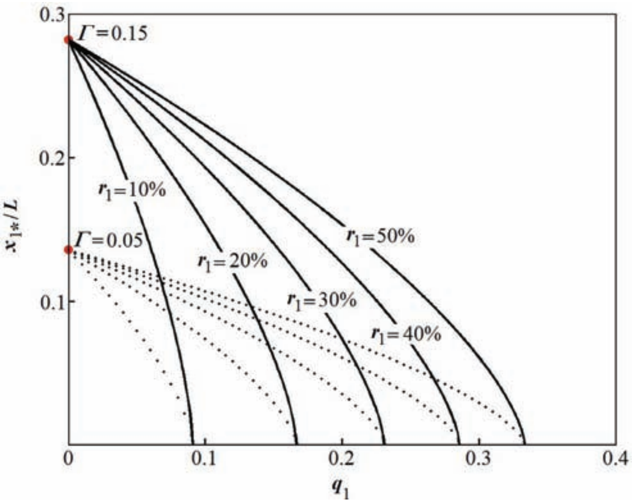

Fig. 5. The location of salinity maximum.

Similarly, for the case when there are many desalination plants operated in a semi-enclosed sea, the logarithm of relative salinity maximum s_n^* at $x = x_1^*$ is formulated as

$$\ln\left(\frac{s_{n*}}{s_L}\right) = \int_{x_{1*}}^{L} \frac{\mathrm{d}z}{A(z)D(z)}\left(\int_{x_{1*}}^{z} \mu(p)B(p)\right. \\ \left. + \sum_{j=2}^{n}\left(\frac{1+r_j}{r_j}\right)q_j\int_{a_j}^{L}\frac{F}{A(z)D(z)}\,\mathrm{d}z, \right. \tag{6}$$

which depends on the ratio of the water production rate of all desalination plants q_j, their recovery rates r_j and locations $x = a_j$. In the chosen model of the channel with simple geometry, it simplifies further to

$$\ln\left(\frac{s_{n*}}{s_*}\right) = -0.1019 \left[\Gamma\left(\frac{1+r_1}{r_1}\right)q_1 + \ln\left\{1-\left(\frac{1+r_1}{r_1}\right)q_1\right\} + \Gamma\sum_{j=2}^{n}\left(\frac{1+r_j}{r_j}\right)q_j\left\{\left(\frac{L}{a_j}\right)^{3/2}-1\right\}\right]$$

To illustrate the effects of seawater desalination in the Arabian Gulf, Fig. 6 shows the logarithm of salinity maximum when there are five plants with recovery rates of 10% and 20% operated within the semi-enclosed sea. The first plant at $a_1/L = 0.1$ with a ratio of water production rate $q_1 = 0.02$ represents seawater desalination in Kuwait. The second plant at $a_2/L = 0.3$ with a ratio of water production rate $q_2 = 0.033$ represents seawater desalination in Saudi Arabia. The third and fourth plants at $a_3/L = 0.45$ and $a_4/L = 0.6$, each with a ratio of water production rate $q_j = 0.01$ represents seawater desalination in Bahrain and Qatar. The last plant at $a_5/L = 0.8$ with a ratio of water production rate $q_5 = 0.06$ represents seawater desalination in the UAE. In comparison with the case when there is no seawater desalination, if the value of Γ increases, then the salinity maximum s^* with a recovery rate of 10% is increased by 4% when $\Gamma = 0.05$ to 6% when $\Gamma = 0.15$. Using the observed surface salinity maximum value $s^* = 45$ ppt, the increase is equivalent to 1.8 ppt to 2.7 ppt respectively.

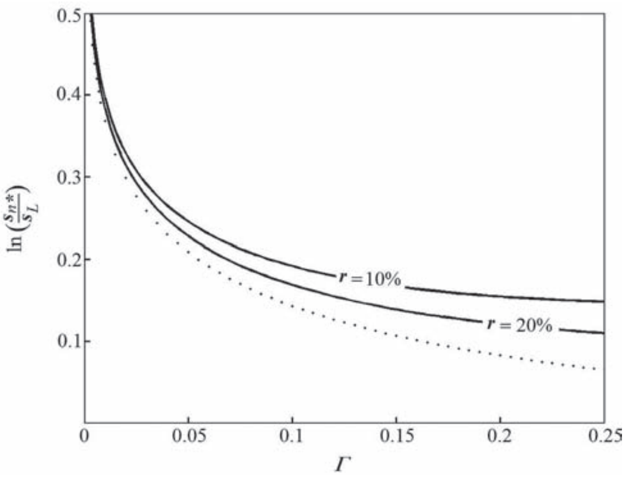

Fig. 6. Logarithm of relative salinity maximum when there are five desalination plants operated. The case when there is no seawater desalination is shown by the dotted line.

Note that the role of water production of the first seawater desalination plant at $x = a_1$ is essential in determining the salinity maximum in a semi-enclosed sea. For the case of the Arabian Gulf, it would be the role of seawater desalination in Kuwait, which is the main source of potable water [2,3,16]. The water demand in Kuwait is doubling every 10 years, and the current daily total water production capacity is estimated at 1.93 million m^3, or equivalent to the annual total water production of 0.704 km^3/year. Therefore, using the reference value for the annual mean river discharge $F = 35$ km^3/year and assuming a lower recovery rate of 10%, the current ratio of water production rate stands at 22% of the critical level.

5. Conclusions

The important physical features of the Arabian Gulf with respect to many adverse impacts of seawater desalination are its semi-enclosed, shallow nature and its arid setting. The Arabian Gulf seawater is naturally characterized by higher salt content due to high evaporation rates. In particular, the occurrence of hypersalinity is commonly associated with the summer conditions of hot and dry, resulting in net evaporation and high salinities [6,13,14], although it may be expected to weaken as the net evaporation reduces during the winter [9,11]. However, in the Arabian Gulf, the hypersaline conditions are persistent throughout the winter [4,5,7], and therefore special attention should be given to the impact of seawater desalination [1].

Many scientists have stated that the environmental impact of seawater desalination on the Arabian Gulf as a whole is negligible because natural evaporation is magnitudes higher. The rate of water loss by desalination is currently estimated at 20 mm/year, which is only about 1% of the net evaporation rate. However, evaporation is the natural response of the Gulf due to the freshwater inflows, and stronger river discharges will reduce the evaporation rates. Therefore, the rate of water loss by desalination should be compared to the freshwater inflows to the Gulf, and this rate has now reached as high as 30% of the freshwater inflows.

Considering the complexity of the Arabian Gulf, more field data are urgently needed in order to quantify the impact of seawater desalination. So far there are no field monitoring programs planned for the Gulf, and the last field measurements (due to the Gulf War) was reported in 2003 [5]. As the sophisticate numerical models will require many input parameters and computer resources to run, simple mathematical models remain useful in providing missing parameters, and especially in deciding whether it is cost effective to run a numerical model.

Acknowledgments

The authors are grateful to Professor Ronald Smith, Loughborough University, UK, for his collaboration on this research.

References

[1] S. Lattemann and T. Hoepner, Seawater Desalination–Impacts of Brine and Chemical Discharges on the Marine Environment, Desalination Publications, L'Aquila, Italy, 2003, 142p.
[2] M.A. Dawoud, The role of desalination in augmentation of water supply in GCC countries, Desalination, 186 (2005) 187–198.
[3] M.A. Darwish, F.M. Al-Awadhi and A.M. Darwish, Energy and water in Kuwait: Part I. A sustainability view point, Desalination, 225 (2008) 341–355.
[4] P.G. Brewer and D. Dryssen, Chemical oceanography of the Persian Gulf, Prog. Oceanog., 14 (1985) 41–55.
[5] R.M. Reynolds, Physical oceanography of the Gulf, Strait of Hormuz, and the Gulf of Oman – Results from the Mt Mitchell expedition, Mar. Poll. Bull., 27 (1993) 35–59.
[6] S-Y. Chao, T.W. Kao and K.R. Al-Hajri, A numerical investigation of circulation in the Arabian Gulf, J. Geophys. Res., 97 (1992) 11219–11236.
[7] J. Kampf and M. Sandrinasab, The circulation of the Persian Gulf: a numerical study, Ocean Sci., 2 (2006) 27–41.
[8] D.W. Privett, Monthly charts of evaporation from the Indian Ocean (including the Red Sea and the Persian Gulf), Q. J. R. Meteorol. Soc., 85 (1959) 424–428.
[9] A.M. Meshal and H.M. Hassan, Evaporation from the coastal waters of the central part of the Gulf, Arab Gulf J. Sci. Res., 4 (1986) 649–655.
[10] W.E. Johns, F. Yao, D.B. Olsen, S.A. Josey, J.P. Grist and D.A. Smeed, Observations of seasonal exchange through the Straits of Hormuz and the inferred freshwater budgets of the Persian Gulf, J. Geophys. Res., (2003) 3391.
[11] S.A.R. Sultan and N.M. Elghribi, Temperature inversion in the Arabian Gulf and the Gulf of Oman, Continental Shelf Res., 16 (1996) 1521–1544.
[12] R. Smith, A. Purnama and H.H. Al-Barwani, Sensitivity of hypersaline Arabian Gulf to seawater desalination plants, Appl. Math. Modell., 31 (2008) 2347–2354.
[13] M.H. Azam, W. Elshorbagy, T. Ichikawa, T. Terasawa and K. Taguchi, 3D model application to study residual flow in the Arabian Gulf, J. Waterw., Port, Coastal, Ocean Eng., 132 (2006) 388–400.
[14] S.A. Swift and A.S. Bower, Formation and circulation of dense water in the Persian/Arabian Gulf, J. Geophys. Res, 108 (2003) 3004.
[15] A. Purnama, H.H. Al-Barwani and R. Smith, Calculating the environmental cost of seawater desalination in the Arabian Gulf, Desalination, 185 (2005) 79–86.
[16] M.A. Darwish and N. Al-Najem, The water problem in Kuwait. Desalination, 177 (2005) 167–177.