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Calculating the environmental cost of seawater desalination in the Arabian marginal seas

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Abstract

Seawater desalination in the Arabian Gulf and the Red Sea is the reliable source of water supply to the population of Kuwait, Saudi Arabia, Bahrain, Qatar, and the United Arab Emirates. If desalination plants were to operate along the coasts of these arid climate semi-enclosed Arabian marginal seas, then the additional loss of water and returned brine waste due to the plant's water production would increase the salinity. A mathematical model is presented to calculate the impact of desalination plants on the salinity within a semi-enclosed sea of simple geometry. Due to the exponential sensitivity to the plant's location and its water production capacity, the effect of seawater desalination at the northern Arabian Gulf or Red Sea is found to be more severe.

Keywords: Arabian Gulf; Mathematical model; Red Sea; Seawater desalination

1. Introduction

The water scarcity in the arid climate of the Arabian Gulf states has reached unprecedented crisis levels. Almost all the existing underground water resources have been developed and are being exploited at an unsustainable rate [1,2]. The groundwater level has been reported to be falling at a rate of 1 m every year and saltwater is contaminating coastal aquifers. Therefore demands are partially met, but at the expense of the groundwater resources. To avert the real threat to resource sustainability, the Arabian Gulf countries are steeping up efforts to boost availability by building seawater desalination plants.

There is no doubt that the desalination of seawater will be the ultimately reliable water

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resource. The consumption of desalinated water in the Arabian Gulf countries accounts for over 60% of the world's total production [1]. Desalinated water already accounts for all water supplies in Kuwait, Bahrain and Qatar, and for at least half of the supplies in Saudi Arabia and the United Arab Emirates. Desalination of seawater is likely to be required to make up deficiencies in supplies of water as drought conditions worsen and water demands increase due to rapid industrial development and population growth. Once a desalination plant is built, its daily water production capacity will subsequently be increased in line with the projected demands.

The unwanted by-product of seawater desalination processes is brine, highly concentrated salt water (up to factors of 2.5). The continuous discharge into the sea is the best cost-effective option available to dispose of brine waste from a desalination plant. The semi-enclosed Arabian marginal seas of the Arabian Gulf and the Red Sea (Fig. 1) are the most saline bodies of water in the world's oceans and environmentally very fragile; therefore any further loss of water by desalination plants and the returned discharge of brine waste would make these marginal seas become hypersaline.

Fig. 1. The map of Arabian peninsula.

To assess the impact of seawater desalination on the salinity, a mathematical model is developed. Using a simple channel geometry representation of the semi-enclosed marginal sea, the model shows that seawater desalination at the northern Arabian Gulf or Red Sea would deteriously change the salinity. Although the current production capacity of desalination plants are safely in the linear regime, special attention should be given in the long-term water planning as the impact depends exponentially on the plant's location and its volumetric rate of seawater extraction.

2. Mathematical model

The scales of variability and many aspects of the currents in the Arabian marginal seas are still poorly understood [3–5]. The exchange of water through the Strait of Hormuz [6,7] or the Strait of Bab el Mandab [8,9] is not yet well measured. Thus, if we are to develop a mathematical model, it is then necessary to make many simplifying assumptions. We model both the Arabian Gulf and the Red Sea as a semi-enclosed sea with simple depth topography, joining to the open sea at $x = L$, where $B(x) = (3B_L/2)\sqrt{x/L}$ and $H(x) = (2H_L)x/L$ [10]. The channel depth profile is specified as the topographic surface $z/H = -x/L + (y/B_L)^2$. As shown in Fig. 2, it is a channel of square-root increasing width of parabolic cross-sections, and its valley bottom is uniformly descending with the slope $2H_L/L$.

Assuming that the water exchange with the open sea at $x = L$ is the main source of water for the semi-enclosed sea, we have $A(x)U(x) = U_L \int_0^x B(z)dz$, where $A = BH$ 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.

The equation of mass flux of water is a balance between the incoming current and the freshwater input F from the head of the semi-enclosed sea, with continuous depletion by

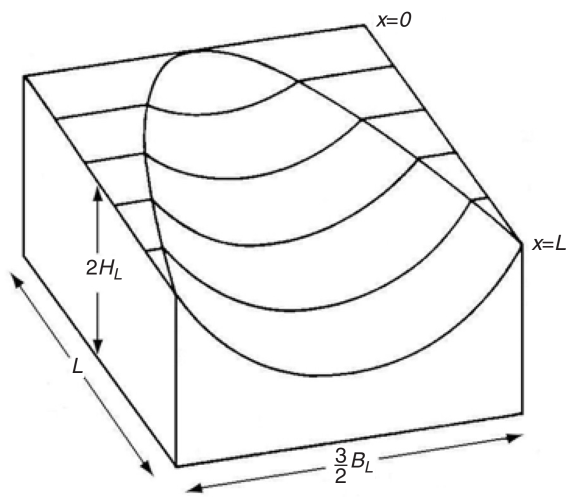

Fig. 2. Geometry with a square-root increasing width and uniformly descending depth of parabolic cross-sections.

evaporation at the rate μ and the seawater intake by a desalination plant located at $x = a$:

$$\frac{d}{dx}(AU - F) = -\mu B - rQ\delta(x - a), \tag{1}$$

where rQ is the rate of the plant's water production and δ is the Dirac delta function. The plant's recovery ratio is typically $r \geq 0.6$. Seawater of salinity s is removed at the volumetric rate Q, and $(1–r)Q$ is the rate of brine waste discharges from the plant with salt concentration $s/(1–r)$.

The surface salinity in the Arabian Gulf increases roughly with distance from the Strait of Hormuz [11,12]. Similarly, the salinities increase in the Red Sea roughly with distance from the Strait Bab el Mandab [5,13]. So a one-dimensional advection-diffusion approach can be adopted [14,15]:

$$\frac{d}{dx}(AUs) - \frac{d}{dx}\left(AD\frac{ds}{dx}\right) = Qs\delta(x - a), \tag{2}$$

where D is the tidally averaged shear-dispersion coefficient. On integrating, and matching the salinity to s_L at $x = L$, we obtain the logarithm of relative salinity

$$\ln\left(\frac{s}{s_L}\right) = \int_x^L \frac{dz}{AD}\left(\mu\int_0^z B(p)dp - F\right) + (1+r)Q\int_a^L \frac{dz}{AD}, \quad 0 \leq x < a, \tag{3}$$

and

$$\ln\left(\frac{s}{s_L}\right) = \int_x^L \frac{dz}{AD}\left(\mu\int_0^z B(p)dp - F + (1+r)Q\right),$$

$$a \leq x < L, \tag{4}$$

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

$$\ln\left(\frac{s}{s^*}\right) = \begin{cases} (1+r)Q\int_a^L \frac{dz}{AD}, \ 0 \leq x < a, \\ (1+r)Q\int_z^L \frac{dz}{AD}, \ a \leq x < L, \end{cases} \tag{5}$$

where s^* is the salinity for the case without seawater desalination. The increase exponentially depends on the seawater intake rate Q and the location of the plant $x = a$. Therefore, it is more severe the further the desalination plant is from the open sea $x = L$. As it might be explained from the physical considerations, a plant with intake rate Q at the head of the semi-enclosed sea $x = 0$ has a salinity increase equivalent to a $(1 + r)Q$ reduction in freshwater inflow F from the rivers. If $F \neq 0$ and by differentiating, the maximum salinity occurs at

$\mu \int_0^{x_{\max}} B(z)dz = F - (1+r)Q$. The peak logarithm of relative salinity can be obtained for $x^* \leq a < L$ from (3) by replacing x^* in place of x in the limit of the integration, where $\mu \int_0^{x^*} B(z)dz = F$, and similarly by replacing $x_{\max}$ in place of x in the limit of the integration for $0 \leq a < x_{\max}$ from (4).

Next, to illustrate how a seawater desalination plant operated along its coast would change the salinity distribution within the semi-enclosed sea, we need to model the longitudinal dispersion coefficient D. Geometrical constraints imposed upon the flow make it possible to derive an analytical description of the dispersion of salinity. Thus, D could be estimated numerically from field observations of surface salinity.

3. The impact on the salinity in the Red Sea

The Red Sea is a part of the World Rift system separating the African continent from Arabia [13]. Its area is about 450,000 km^2, and it has a distinct feature like a deep long narrow channel almost in a straight line, a distance of 2000 km, with widths ranging from 145 km to 306 km (Fig. 1). The deepest part of more than 2000 m has been recorded at the central Red Sea, but the average depth of the Red Sea is only 490 m.

The exchange of water between the Red Sea and the Gulf of Aden occurs at the Strait of Bab el Mandab. There is no surface water run off because no rivers enter the Red Sea [2,13]. The rainfall over the Red Sea and its coasts is extremely small. Solar heating across the air–sea interface is enhanced by the extremely arid nature of the bordering lands. The annual mean evaporation is estimated at 2 m/yr [13], thus generating high salinity with the increase of surface salinity observed from south to north [5,13] and, in particular, surface salinity of more than 40 ppt observed at its northern end.

Saudi Arabia is the main producer of the desalinated Red Sea water, and by 2006 the daily water production capacity of seawater desalination plants along the coasts of the Red Sea is estimated to 5.65 million m^3. Assuming a 60% recovery rate, brine waste in excess of 1.7 million m^3 per day is discharged into the Red Sea. The largest plants are Shuaiba with a capacity of 1.1 million m^3 of water per day and Jeddah with 0.4 million m^3 for supplying water to the western region's two most populated cities of Jeddah and Makkah.

To illustrate how a seawater desalination plant operated along its coast would change the salinity in the Red Sea, we assume that the vertical shear dispersion dominates [3,16], and D is proportional to HU [17], i.e. $D(x) = \alpha_{\rm H} U_{\rm L} \int_0^x B(z)dz / B(x)$. The typical values relevant to the Red Sea are $B_{\rm L} = 225$ km, $H_{\rm L} = 500$ m, $L = 2000$ km and the evaporation rate $\mu = 2$ m/yr. The other parameters related to the seawater desalination plant are $r = 0.6$ and the Shuaiba and Jeddah plants' total annual water production rate $rQ^* \approx 0.55$ km^3/yr. Hence, $q^* = (1 + r)Q^*/\mu L B_{\rm L} \approx 0.001$. The model parameter $\alpha_H U_{\rm L}$ is "scaled" so that in the case with no seawater desalination, the model agrees with the observed surface salinity in the Red Sea. Using $s^* = 40$ ppt as the value of salinity at the central Red Sea $x/L = 0.5$ (approximating the location of the Shuaiba and Jeddah plants) and the salinity at the Strait Bab el Mandab $s_{\rm L} = 37$ ppt, gives $\mu L/\alpha_H U_{\rm L} H_{\rm L} \approx 0.225$.

Thus, since $F = 0$ and for a desalination plant with $q = (1 + r)Q/\mu L B_{\rm L}$ located at $x = a$, the logarithm of the relative salinity (3) and (4) reduces to

$$\ln\left(\frac{s}{s_{\rm L}}\right) \approx 0.1125 \ln\left(\frac{\rm L}{x}\right) + 0.075 q \left\{ \left(\frac{\rm L}{a}\right)^{3/2} - 1 \right\}, \quad 0 \leq \frac{x}{\rm L} < \frac{a}{\rm L}, \tag{6}$$

and

$$\ln\left(\frac{s}{s_L}\right) \approx 0.1125\ln\left(\frac{L}{x}\right) + 0.075q\left\{\left(\frac{L}{x}\right)^{3/2} - 1\right\}, \quad \frac{a}{L} \le \frac{x}{L} < 1. \tag{7}$$

Fig. 3 plots the logarithm of relative salinity with $q = 50q^*$ at 2 locations of $a/L = 0.3$ and 0.5. For comparison, the hypersaline condition without seawater desalination is also shown by the dashed curve, and for a plant at the head of the Red Sea $a = 0$ by the dotted curve.

The logarithm of relative salinity increase (5) due to a desalination plant at $a/L = 0.5$ is shown in Fig. 4. The effect of a plant with $q = 25q^*$ is corresponding to the salinity increase by 0.14 ppt, and with $q = 50q^*$ the increase by 0.28 ppt.

4. The impact on the salinity in the Arabian Gulf

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 [12]. It covers an area of about 240,000 km^2, with 1000 km in length and widths ranging from 185 km to 370 km. The Arabian Gulf is connected to the Gulf of Oman via the narrow Strait of Hormuz. 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 [12,18].

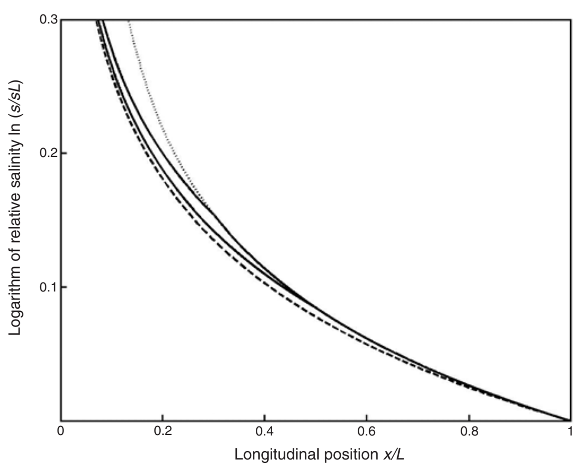

Fig. 3. Logarithm of relative salinity in the Red Sea due to a desalination plant with $q = 50q^*$ at $a/L = 0.3$ and 0.5.

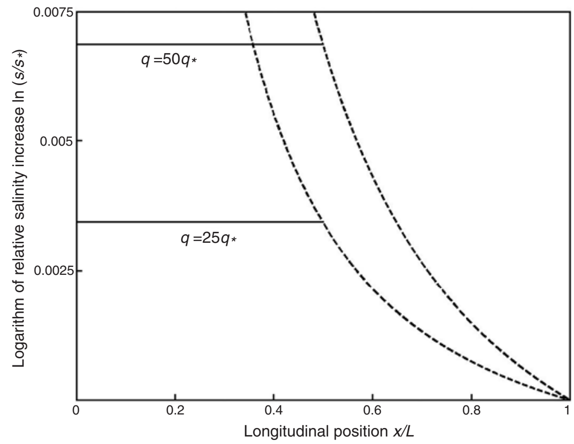

Fig. 4. Logarithm of relative salinity increase due to seawater desalination at $a/L = 0.5$.

The mean annual evaporation rate is estimated at approximately 1.5 m/yr [11]. The Gulf acts as an inverted estuary, where the surface salinity values exceeding 40 ppt were recorded especially in the shallow waters around the island of Bahrain, the coasts of Qatar and the United Arab Emirates [12]. In general, the progressive increase in salinity is observed towards the head of the Gulf, where the water column is almost mixed.

The total daily water production capacity of desalination plants in the Arabian Gulf countries was estimated at 8.22 million m^3. The world's largest seawater desalination plant with the daily production capacity of more than 2 million m^3 of water is Al Jubail on the coast of Saudi Arabia. All together the plants are discharging their brine waste in excess of 5.48 million m^3 per day into the Gulf.

For illustrations, we assume that the transverse shear dispersion dominates [18], so that D is proportional to B^2U/H [19], i.e. $D(x) = \alpha_T U_L B(x) \int_0^x B(z)dz/H^2(x)$. The typical values relevant to the Arabian Gulf are $B_L = 240$ km, $H_L = 35$ m, $L = 1000$ km, the evaporation rate $\mu = 1.5$ m/yr and the river inflow $F = 48$ km^3/yr. The other parameters related to the seawater desalination plant are $r = 0.6$ and Al Jubail's plant total annual water production rate $rQ^* \approx 0.75$ km^3/yr. Hence, $q^* = (1 + r)Q^*/F = 0.025$. The model parameter $\alpha_T U_L$ is "scaled" by matching the model peak salinity with the observed peak surface salinity in the Arabian Gulf. It is straightforward to calculate $x^*/L \approx 0.261$. Using the peak salinity in the Gulf $s^* = 40$ ppt and the salinity at the Strait of Hormuz $s_L = 37$ ppt, we find $\alpha_I U_L \approx 0.005$ m/yr.

Thus, for a desalination plant with $q = (1 + r)Q/F$ located at $x = a$, the logarithm of relative salinity (3) and (4) reduces to

$$\ln\left(\frac{s}{s_L}\right) \approx 0.162\left(1-\frac{x}{L}\right) + 0.0432\left(1-\sqrt{\frac{L}{x}}\right) + 0.0432q\left(\sqrt{\frac{L}{a}}-1\right), \quad 0 \le \frac{a}{L} < \frac{x}{L}, \tag{8}$$

and

$$\ln\left(\frac{s}{s_L}\right) \approx 0.162\left(1-\frac{x}{L}\right) + 0.0432(1-q)\left(1-\sqrt{\frac{L}{x}}\right) \quad \frac{a}{L} \le \frac{x}{L} < 1, \tag{9}$$

The logarithm of relative salinity with $q = 10q^*$ located at $a/L = 0.4$ (approximating the location of Al Jubail plant) is shown in Fig. 5. The dashed curve represents the hypersaline condition without seawater desalination, and the dotted curve shows the case for a plant located at the head of the Arabian Gulf $a = 0$.

The peak salinity in the Arabian Gulf occurs at $x_{\max}/L \approx 0.261(1-q)^{2/3}$. The peak logarithm of relative salinity due to a seawater desalination plant with $q = q^*$ as typified by Al Jubail plant is shown in Fig. 6. The effect of a plant with $q = q^*$ located near the head of the Gulf is equivalent to the peak salinity increased by 0.06 ppt. If $q = 5q^*$, the peak is increased by 0.23 ppt, and similarly for $q = 10q^*$, the peak increased by 0.47 ppt.

5. Concluding remarks

The protection of the new Arabian Gulf countries non-conventional precious water resource is vital to sustain and to allow the continuing long-term socio-economic development. So far the main concern is focus to the oil pollution from

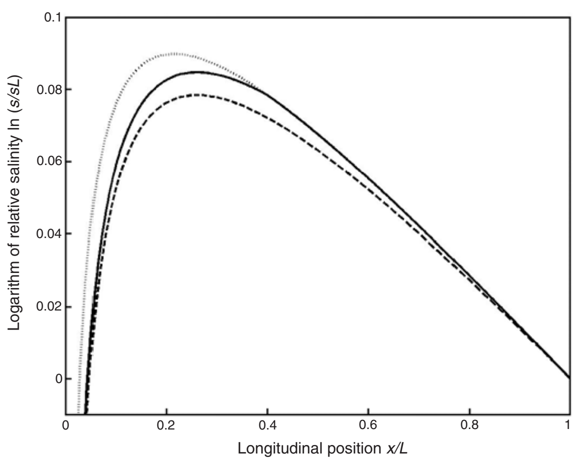

Fig. 5. Logarithm of relative salinity in the Arabian Gulf due to seawater desalination with $q = 10q^*$ at $a/L = 0.4$.

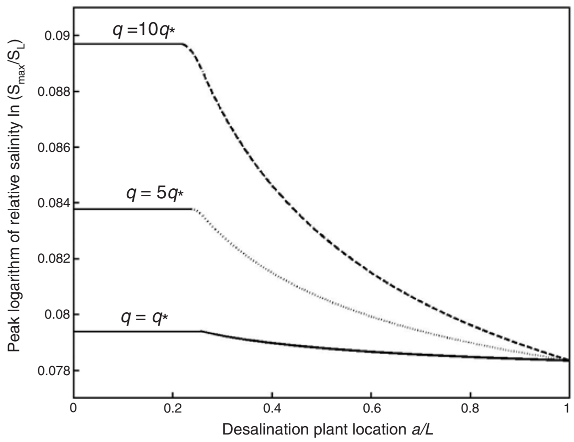

Fig. 6. Peak logarithm of relative salinity due to seawater desalination.

the illegal dumping of oil sludge by the oil tankers in the Arabian Gulf. Special attention should also be given to the impact of seawater desalination on the hypersaline Arabian Gulf or Red Sea. Higher seawater salinity will reduce the desalination plant's recovery ratio, and hence increase the cost of desalinated water. For example, AdDur seawater desalination plant in Bahrain was originally designed to produce 38,000 m^3 of water per day, but the operated plant's production has a reduced daily capacity of 11,500 m^3 due to deteriorating seawater quality.

Due to its semi-enclosed nature and arid climate, the Arabian Gulf and the Red Sea waters are naturally characterized by a higher salt content due to the accelerated high rate of evaporation. Lessons from the exploitation of the groundwater resources should have been learned so that meeting the water demands should not be at the expense of the Arabian Gulf or the Red Sea's fragile environment.

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References

[1] A.A. Akkad, Conservation in the Arabian Gulf countries. Management and Operations, Journal of the American Water Works Association, May (1990) 40–50.
[2] M. Shahin, Review and assessment of water resources in the Arab region. Water Int., 14 (1989) 206–219.
[3] W.E. Johns, G.A. Jacobs, J.C. Kindle, S.P. Murray and M. Carron, Arabian Marginal Seas and Gulfs, Florida, USA. (the reference is a technical report, which is published by the University of Miami. The report is also available online from the website http://www.rsmas.miami. edu/ personal/zantopp/AMSG-report.html.) Technical Report 2000–01, RSMAS, University of Miami, 2000, 41pp.
[4] 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.
[5] M. Clifford, C. Horton, J. Schmitz and L.H. Kantha, An oceanographic nowcast/forecast system for the Red Sea. J. Geophys. Res., 102 (1997) 25101–25122.
[6] K. Banse, Irregular flow of Persian (Arabian) Gulf water to the Arabian sea. J. Mar. Res., 55 (1997) 1049–1067.
[7] F. Ahmad and S.A.R. Sultan, Annual mean surface heat fluxes in the Arabian Gulf and the net heat transport through the Strait of Hormuz. Atmosphere-Ocean, 29 (1991) 54–61.
[8] S.P. Murray and W.E. Johns, Direct observations of seasonal exchange through the Bab al Mandab Strait. Geophys. Res. Lett., 24 (1997) 2557–2560.
[9] D. Smeed, Seasonal variation of the flow in the Strait of Bab al Mandab. Oceanologica Acta, 20 (1997) 773–781.
[10] R. Smith, Long-term dispersion of contaminants in small estuaries. J. Fluid Mech., 82 (1977) 129–146.
[11] P.G. Brewer and D. Dryssen, Chemical oceanography of the Persian Gulf. Progress in Oceanography, 14 (1985) 41–55.
[12] 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.

[13] S.A. Morcos, Physical and chemical oceanography of the Red Sea. Oceanography Marine Biology Annual Review, 8 (1970) 73–202.
[14] J.L. Largier, C.J. Hearn and D.B. Chadwick, Density structures in low inflow estuaries. Coastal and Estuaries Studies, 53 (1996) 227–241.
[15] J.L. Largier, J.T. Hollibaugh and S.V. Smith, Seasonally hypersaline estuaries in Mediterranean-climate regions. Estuarine, Coastal and Shelf Science, 45 (1997) 789–797.
[16] E. Tragou and C. Garrett, The shallow thermohaline circulation of the Red Sea. Deep-Sea Res., 44 (1997) 1355–1376.
[17] J. Elder, The dispersion of marked fluid in turbulent shear flow. J. Fluid Mech., 5 (1959) 544–560.
[18] J.R. Hunter, The physical oceanography of the Arabian Gulf: A review and theoretical interpretation of previous observations. In: Halwagy, Clayton, and Bebehabi, eds., Proceedings of the 1st Gulf Conference on Environment and Pollution, KISR, Kuwait. (KISR is the Kuwait Institute for Scientific Research), 1986, pp. 1–23.
[19] H.B. Fischer, The mechanics of dispersion in natural streams. J. Hydraulics Division, Proc. ASCE, 93 (1967) 187–216.