ABSTRACT
Desalinated water is becoming a valuable commercial resource in sustaining growth and to allow further development in the arid climate countries. The standard disposal method for a large-scale seawater desalination plant is to continuously discharge brine waste stream into the sea via an outfall. When two or more sea brine outfalls are discharging into shallow coastal waters, the potential adverse impacts are strongly inter-dependent. Modeling studies of the interaction of two brine discharged plumes are presented. The results are found to be influenced by the outfall lengths, distance between the two outfalls, and the concentration factor at the discharge point. The model application to the combined power generation and seawater desalination plant is illustrated.

Keywords: brine discharge, seawater desalination, two outfalls, tidal flow

INTRODUCTION
Due to the scarcity of rainfall, population growth, agricultural and industrial initiatives, water shortages are becoming a critical problem in the Arabian Gulf, Middle East and North Africa countries. To overcome the soaring need for water, large coastal cities have no other choice but to depend solely on desalination technologies to process seawater to provide continuous supplies of clean water. Thus, more than half of the world's desalination plants are operated along the coasts of the Arabian Gulf, Gulf of Oman and Red Sea [1]. As the need for desalinated seawater is steadily increasing, not only are the number of new large scale desalination plants constructed along the sea growing, the existing plants are also gradually increasing their water production capacities.

Like any large scale industrial process, seawater desalination unfortunately has its potential environmental impacts. Since desalination technology can manufacture up to 60% of desalinated water, it also produces brine, a high salinity concentration waste stream. The unwanted brine product is primarily seawater but at a more concentrated level, with the concentration factor being as high as 2.5. Owing to the highly variable nature of the sea, we do not yet have a full understanding or description of the mixing processes of brine discharges from coastal desalination plants [2,3,4]. However, the steady discharges brine plume is observed to be drifted away with the longshore currents, and due to relatively shallow water depth, this elongated plume is spreading towards the shoreline and may cause an increase in salinity in the coastal waters [4,5,6].
Considering the growth in desalination plants and their capacity, there is an urgent need to reliably evaluate and minimize the long-term potential environmental impacts of the brine effluent discharges. The merging of two or more brine plumes adds further complexity: such situations are not uncommon along the coasts of the Arabian Gulf, Gulf of Oman and Red Sea, where the large scale desalination plants often tend to be tightly clustered together. Therefore, if a new large scale seawater desalination plant is to be built on a coastline where an existing plant is operated that complies with the imposed regulatory environmental guidelines, how can one calculate the compounded impacts? In particular, will a possible scenario ever arise in which the existing plant is no longer meeting the regulatory requirements?

In an attempt to answer these questions, an extension of a previously developed mathematical model [5,6] for continuous brine discharges from two coastal seawater desalination plants is presented. The solution is best illustrated graphically to study the interaction of two brine plumes, and the result agrees with the standard practice of building a longer outfall in order to minimize the potential environmental impact of brine discharges. Finally, since most seawater desalination plants in the Arabian Gulf countries are operated jointly with a power generation plant, the role of the cooling water outfall from a combined power generation and seawater desalination plant in diluting brine discharges will also be discussed.

![Two sea outfalls](image)

**Figure 1. Two sea outfalls.**

**TWO OUTFALLS MODEL EQUATION AND SOLUTION**

Since we are only concerned with the effect of longshore currents on the long time (far field) brine plume, following [7,8,9,10] a highly simplified vertical beach profile is considered, where the shoreline is straight and of a constant water depth. The coastal current is assumed to be uniform over water depth and remains in the x-direction parallel to the beach. The dispersion
processes are represented by the longitudinal diffusivity $D_x$ and lateral diffusivity $D_y$. For simplicity, the other complexities, such as density and temperature, are ignored.

As illustrated in Figure 1, we consider the concentrated brine stream to be steadily discharged, starting from the initial time $t_i$, from two large scale desalination plants at $L$ distance apart at a rate $Q_2$ from the first (old) sea outfall at a distance $\beta > 0$ from the beach, and the second (new) outfall at a distance $\alpha > 0$ from the beach at a different rate $Q_1$. As the discharge is made via diffusers and utilizing the best available technology to promote rapid initial dilution, we also assume that the outfall’s brine plume is vertically well-mixed over the water depth [11]. Note also that, for shallow coastal waters, the dispersion in the vertical direction occurs much faster than in the lateral direction [3].

Following [5,6] and by applying a linear superposition, the two-dimensional advection-diffusion equation for the far field brine plume concentration $c$ from the two outfalls is given by

$$\frac{\partial c}{\partial t} + u(t)\frac{\partial c}{\partial x} - D_x \frac{\partial^2 c}{\partial x^2} - D_y \frac{\partial^2 c}{\partial y^2} = Q_1 \delta(t - t_i) \delta(x)[\delta(y - \alpha) + \delta(y + \alpha)] + Q_2 \delta(t - t_i) \delta(x - L)[\delta(y - \beta) + \delta(y + \beta)],$$  \hspace{1cm} (1)

where $u(t)$ is the tidally oscillating flow and $\delta$ the Dirac delta function. It is noted that each outfall is represented as a point source; for example, the new outfall is at $(x = 0, y = \alpha)$, and in order to satisfy the boundary condition at the beach $y = 0$, an imaginary source is added at $(x = 0, y = -\alpha)$.

The coastal current is modeled to consist of a steady (residual) drift and a periodic component with amplitude $U_0$ that can be represented by [7,8,9,10]: $u(t) = v + U_0 \sin \omega t$. The subsequent movement of discharged brine plumes is given by $x_i(t) = \int_{t_i}^{t} u(t_0) \, dt_0$, and on integrating, we obtain in its dimensionless form, $X_i(T) = VT_i - \cos T + \cos(T - T_i)$, where $X_i = \omega x_i / U_0$, $\omega = k \Omega^0$, $T = \omega t$ and $T_i = T - \omega t_i$. Although the discharged brine plume is observed to be drifting back and forth, the net transport depends on $V$ the ratio of the drift current to tidal amplitude [6,8]. Using numerical values of the mean tidal amplitude $U_0 = 0.4$ m/s [5,6] and the period $2\pi / \omega = 4.5 \times 10^4$ s, we define a length scale $U_0 / \omega$ of the order of 2.8 km.

In terms of the dimensionless variables, the solution of equation (1) is given by
\[
C = \int_0^{T_i} \frac{dT_0}{T_0} q_s \exp \left[ -\frac{\lambda}{T_0} \left( X - X_0(T) \right)^2 \right] \left\{ \exp \left[ -\frac{\lambda \eta (Y - \Lambda)^2}{T_0} \right] + \exp \left[ -\frac{\lambda \eta (Y + \Lambda)^2}{T_0} \right] \right\} \\
+ \exp \left[ -\frac{\lambda}{T_0} \left( Y - L - X_0(T) \right)^2 \right] \left\{ \exp \left[ -\frac{\lambda \eta (Y - B)^2}{T_0} \right] + \exp \left[ -\frac{\lambda \eta (Y + B)^2}{T_0} \right] \right\}, \tag{2}
\]

where \( C = 4\pi c \sqrt{D_x D_y / Q_2} \), \( T_0 = T - \omega \tau_0 \), \( \lambda = U_0^2 / 4 \omega t_x \), \( \eta = D_x / D_y \), \( Y = \omega y / U_0 \), \( \Lambda = \alpha \omega / U_0 \), \( q_s = Q_1 / Q_2 \) and \( B = \beta \omega / U_0 \). Note that the model parameters \( V \), the ratio of the drift current to tidal amplitude, \( \lambda \), the distances by which the plume is transported and spread over by advection to that by longitudinal diffusion, and \( \eta \), the ratio of longitudinal to lateral diffusivities, which characterize the brine discharged plume, have been further discussed in [6].

Figure 2. Brine plumes when the distance between the two outfalls: a) \( L = 4 \) and b) \( L = 16 \).
The effect of the coastal current on the mixing and dispersal of brine discharges from two desalination plants is illustrated graphically by plotting the results of numerical integrations of (2). Due to the unpredictable sea conditions, very little information is available on these parameters [6], and for the model applications, the values of $V = 0.3$, $\lambda = 15$ and $\eta = 25$ will be used in all plots. The interaction of two discharged brine plumes is also governed by $L$ the distance between the two outfalls, the outfall lengths $A$ and $B$, and the concentration factor $q_*$ of the second (new) outfall.

Finally, an appropriate measure for assessing the impact of brine stream discharges into the sea would be the concentration values at the beach [4,5,6]. On substituting $Y = 0$ into (2), the concentration at the beach is given by

$$C_0 = 2q* \int_0^{T_1} \frac{dT_0}{T_0} \exp \left[ -\frac{\lambda}{T_0} \left( X - X_0(T) \right)^2 \right] \exp \left[ -\frac{\lambda \eta A^2}{T_0} \right]$$

$$+ 2 \int_0^{T_1} \frac{dT_0}{T_0} \exp \left[ -\frac{\lambda}{T_0} \left( X - L - X_0(T) \right)^2 \right] \exp \left[ -\frac{\lambda \eta B^2}{T_0} \right].$$

(3)

Note also that due to the second exponential term in the integrand, the concentration levels at the beach can be reduced by building a longer outfall [2,5,10].

![Figure 3. Concentration at the beach for various values of $L$. Dashed line for $L = 10$.](image)

**PRACTICAL APPLICATION**

In order to study the long-term interaction of brine plumes from two sea outfalls, we consider the following scenario where the first (old) outfall of an existing desalination plant is located at a distance $B = 0.4$. As $U_0/\omega$ is about 2.8 km, this value corresponds to a sea outfall length of 1120 m. The new desalination plant is also built on a coastline at a distance $L$ from the first plant and its (second) outfall is located at a distance $A$ and it discharges brine with the concentration...
factor $q_\ast$. The results obtained by varying these parameters are discussed below. Note that since
the flow periodicity enables us to restrict our observation time, the value of $T = \pi/2$ in a single
representative tidal cycle will be used in all plots.

![Diagram](image)

Figure 4. The interaction of two brine plumes: a) $\Lambda = 0.6$ and b) $\Lambda = 0.2$.

A. Distance Between the Two Outfalls
To investigate the effects of the distance between the two outfalls $L$, we set the second outfall
length $\Lambda = 0.4$ with the concentration factor $q_\ast = 1$. That is, the two outfalls are at the same
length and are discharging at the same rates. As shown in Figure 2, for a small distance $L = 4$ or
equivalent to 11 km, the brine plumes are completely merging and they appears to be similar to a
single plume steadily discharged from one outfall. Note that the actual plumes are very elongated
in the $x$-direction by a factor of 100. The peakiness of the plume reflects the physical feature of
flow oscillations. However, when the value of $L$ is greater than 10 or equivalent to 28 km, the
two brine plumes are clearly separated.

The corresponding concentration at the beach is shown in Figure 3. The single (due to complete
merging) plume appearance is evident from the shape of the concentration distribution. As a
result, concentration levels higher than 0.3 are maintained and spread downstream of the outfall over long distances of the order 90 km. In contrast, the hump features when the distance between the two outfalls \( L = 16 \) or equivalent to 45 km is clearly due to a superposition of the two brine plumes, the second plume combined with the first one.

![Graph](image)

**Figure 5.** Concentration at the beach for various values of \( \Lambda \). Dashed line for \( \Lambda = 0.4 \).

**B. Outfall Lengths**

In this scenario, we choose a moderate distance between the two outfalls \( L = 8 \) and again, each outfall is discharging with the same rate, i.e. \( q^* = 1 \). The contour plots in Figure 4 clearly show the interaction between two brine plumes when the outfalls are at different lengths. The longer the second outfall lengths \( \Lambda = 0.6 \) or equivalent to 1680 m, the more efficient the brine dispersal, and hence the concentration levels at the beach are reduced (Figure 5).

However, the shorter the second outfall lengths \( \Lambda = 0.2 \) or equivalent to 560 m, the brine discharges plume from the first (old) outfall appears to be turning directly towards the beach. Again, as shown in Figure 5, the build-up of the concentration at the beach is really the worst, as it occurs practically from the position of the second (new) outfall.

**C. Combined Power Generation and Seawater Desalination Plant**

Similarly, we choose a shorter distance between the two outfalls \( L = 4 \) or equivalent to 11 km, and use the two different second outfall lengths \( \Lambda = 0.2 \) and \( \Lambda = 0.6 \), and also for each scenario we choose two values for concentration factor at the second outfall, i.e. \( q^* = 0.5 \) and \( q^* = 1.5 \). In particular, the scenario with \( q^* = 0.5 \) is a representative of the combined power generation and seawater desalination plant, where the second outfall might be considered as the cooling water outfalls.

As shown in Figure 6, even for a shorter cooling outfall length compared to the first brine outfall, the concentration level at the beach is still less than both outfalls that are discharging brine at the rate. However, a longer cooling outfall length is by far the best option. Therefore, the result
agrees with the standard disposal practice of diluting brine waste which can be achieved by combining discharges with the cooling water used in the power generation plant.

![Concentration at the beach for various values of $q^*$: a) $A = 0.6$ and b) $A = 0.2$. Dashed line for $q^* = 1$.](image)

**CONCLUSION**

The mixing and dispersion of brine discharges from two seawater desalination plants are governed by $L$ the distance between the two outfalls, the outfall lengths $A$ and $B$, and the concentration factor $q^*$ of the second (new) outfall. Therefore, if a new large scale seawater desalination plant is to be built on a coastline where an existing plant is operated, then the compounded impacts should be included in the imposed regulatory environmental guidelines.

Most large seawater desalination plants in the Arabian Gulf countries are operated jointly with a power generation plant. The cooling water outfall dilutes the brine discharges from the desalination plant, and thus minimizes the long-term potential environment impacts.
REFERENCES