Modeling Brine Discharges from Multiple Marine Outfalls

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Abstract
When many marine outfalls are discharging brine to shallow coastal waters, the adverse long-term mutual impacts are strongly inter-dependent and of a capacity limit of the receiving waters. A mathematical model using a two-dimensional advection-diffusion equation based on a flat seabed is developed, and incorporates the effect of a coastal tidal current. The solutions are illustrated graphically to study the interaction of multiple brine plumes, and then an asymptotic approximation will be made to the shoreline's concentration to evaluate the long-term salinity build-up in the coastal waters. An extension for calculating the compounded concentration following discharges from a modern marine outfall with a multiport diffuser is also considered.

Keywords
Brine discharge; far field model; long term impact assessment; multiport; tidal flow; two sea outfalls

INTRODUCTION

As desalinated water is indispensably required at all costs in hot and arid climate countries, there are intense seawater desalination activities in certain coastlines of the Arabian Gulf, Red Sea, Mediterranean Sea, and the Gulf of Oman. In particular, more than half of the world's desalination plants are constructed along the coasts of the Arabian Gulf (a total capacity of 12 million m^3/day), Gulf of Oman (1.1 million m^3/day) and Red Sea (3.4 million m^3/day) [1,2,3]. Thus, along such coastal areas, many seawater desalination plants are commonly found to be operated closely together. Furthermore, as the needs for desalinated seawater is steadily increasing, not only are the number of new large scale desalination plants growing, the existing plants are also gradually increasing their water production capacities. Like any large scale industrial process, seawater desalination unfortunately also has its potential environmental impacts [3,4,5]. Desalination plants generate two products, pure water and unwanted brine, a reject concentrate stream. Current technology limits the efficiency of producing desalinated water, and up to 60% is lost via concentrate stream that is more than double the typical seawater salinity. One issue for the plant operator to overcome in order to implement desalination technologies as a long-term water supply is the disposal of the concentrate produced.

Most large scale coastal desalination plants dispose of their concentrate via long pipes that stretch far into the ocean [2,3,6], and as concentrate stream enters the receiving water, it creates a high salinity plume. An engineering solution is required where a diffuser would be installed at the pipe-end to rapidly dilute the concentrate. Without proper dilution, the plume may extend for hundreds of meters beyond the mixing zone, harming the ecosystem along the way. Most at risk are the benthic marine organisms living at the sea bottom. If the area is highly populated, coastline disposal may be a problem, because of the interference of the mixing zone with the recreation area on the beach. This is especially noticeable on days when the sea is calm and little to no natural dilution occurs.

Considering the growth in desalination plants and their capacity [1,2], there is an urgent need to reliably evaluate and minimize the long-term potential localized impacts of the continuous brine effluent discharges from the individual plant, and the cumulative strategic impacts compounded from the neighbouring plants. At present, a standard environmental impact assessment procedure for evaluating and minimizing the impacts of desalination projects is not available [1,6]. The merging process of multiple brine plumes adds further complexity: such situations are commonly encountered 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 [1,2]. Figure 1 shows two marine outfall systems used for discharging brines from the (up to 4 co-location) Barka power generation and seawater desalination plants in the Gulf of Oman [7]. Each outfall system is designed for a maximum capacity of 122,100 m^3/h to discharge the cooling water from the power generation plants and mix it with brine reject (and other effluents) from seawater desalination plants. The old outfall pipe length is about 650 m, while the new outfall pipe length is about 1200 m, and the distance between the two discharge points is 1000 m.

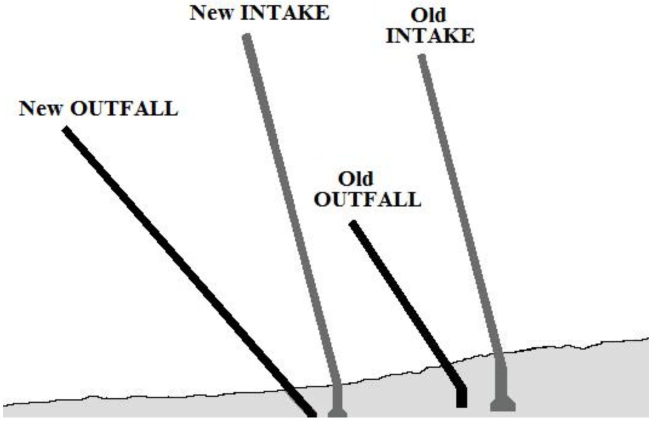

Figure 1. Two marine outfall systems of Barka plants, Oman

MODEL FORMULATION

Immediately after release from the diffuser, vigorous and rapid dilution of concentrate brine is governed by the effluents buoyancy, momentum of the discharge and its interaction with the sea currents [2,6,8]. At the end of this mixing zone stage, the established steady discharges brine plume then continues to drift away with the currents. However, due to relatively shallow water depth, it is observed that the elongated brine plumes are spreading towards the shoreline and may cause an increase in salinity in the coastal waters [2,11].

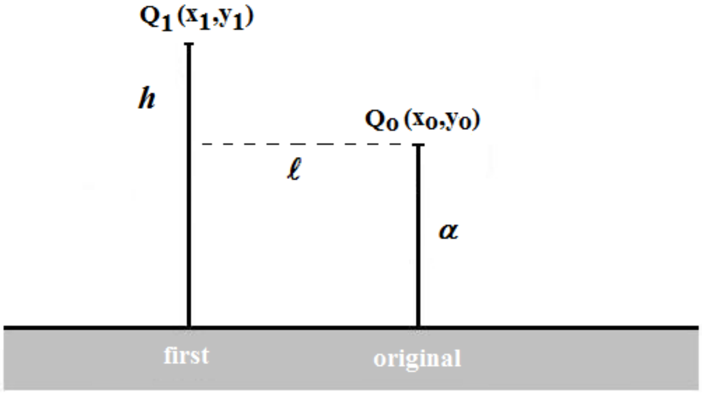

Figure 2. Schematic diagram of two long sea outfalls

A simple model of a longshore current that consists of a steady (residual) drift and a periodic component with amplitude U_0 can be represented by [11,12,13]: $u(t)=v+U_0\sin\omega t$. The oscillatory 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 $X_i = \omega x_i / U_0$, $V = v/U_0$, $T = \omega t$ 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 [11,12]. Using typical numerical values of the mean tidal amplitude $U_0 = 0.1$ m/s [2,7,11] relevant to the Gulf of Oman and the period $2\pi/\omega = 4.5 \times 10^4$ s, we define a length scale U_0/ω of the order of 0.7 km.

As we are only concerned with the effect of longshore currents on the long-term (far field) brine plume, following [2,11,12,15] a highly simplified semi-infinite flat seabed 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 2, we consider the concentrated brine stream to be steadily discharged, starting from the initial time t_i , at a rate Q_0 from the original (reference) outfall at the position $(x_0 = 0, y_0 = \alpha)$, and at a different rate Q_1 from the first outfall at the position $(x_1 = -\ell, y_1 = \alpha + h)$. As the discharge is made via diffusers and utilizes the best available technology to promote rapid initial dilution [8], we also assume that the outfall's brine plume is vertically well mixed over the water depth. Note also that, for shallow coastal waters, the dispersion in the vertical direction occurs much faster than in the lateral direction.

Following [2,11] and by applying a linear superposition, the two-dimensional advection-diffusion equation for the far field plume concentration c from the n individual outfalls discharge is given by

$$\frac{\partial c}{\partial t} + u(t)\frac{\partial c}{\partial x} - D_x \frac{\partial^2 c}{\partial x^2} - D_y \frac{\partial^2 c}{\partial y^2} = \delta(t - t_i) \sum_{k=0}^{n} Q_k \; \delta(x - x_k)\,[\delta(y - y_k) + \delta(y + y_k)], \qquad (1)$$

where δ is the Dirac delta function, and each outfall is represented as a point source $(x_k = -k\ell, y_k = \alpha + kh)$; and in order to satisfy the boundary condition at $y = 0$, an imaginary source is added at $(x_k, -y_k)$.

In terms of the dimensionless variables, the solution of equation (1) is given by

$$C = \int_0^{T_i} \frac{dT_0}{T_0} \sum_{k=0}^{n} q_{k*} \exp\left[-\frac{\lambda}{T_0}\{X + kL - X_0(T)\}^2\right] \left\{\exp\left[-\frac{\lambda\eta(Y - \Lambda - kH)^2}{T_0}\right] + \exp\left[-\frac{\lambda\eta(Y + \Lambda + kH)^2}{T_0}\right]\right\}$$

, (2)

where $C = 4\pi c\sqrt{D_x D_y}/Q_0$, $T_0 = T - \omega t_0$, $q_{k*} = Q_k/Q_0$, $\lambda = U_0{}^2/4\omega D_x$, $L = \omega\ell/U_0$, $X_0(T) = VT_0 - \cos T + \cos(T - T_0)$, $\eta = D_x/D_y$, $Y_k = \omega y_k/U_0 = \Lambda + kH$, $\Lambda = \omega\alpha/U_0$ and

$H=\omega h/U_0$. The merging process of multiple plumes [11,12] behaviour is controlled by the interplay of the model parameters; V, the ratio of the drift current to tidal amplitude; λ, the distances by which the plume is transported and spread over by advection to that by longitudinal diffusion [13]; and η, the ratio of longitudinal to lateral diffusivities.

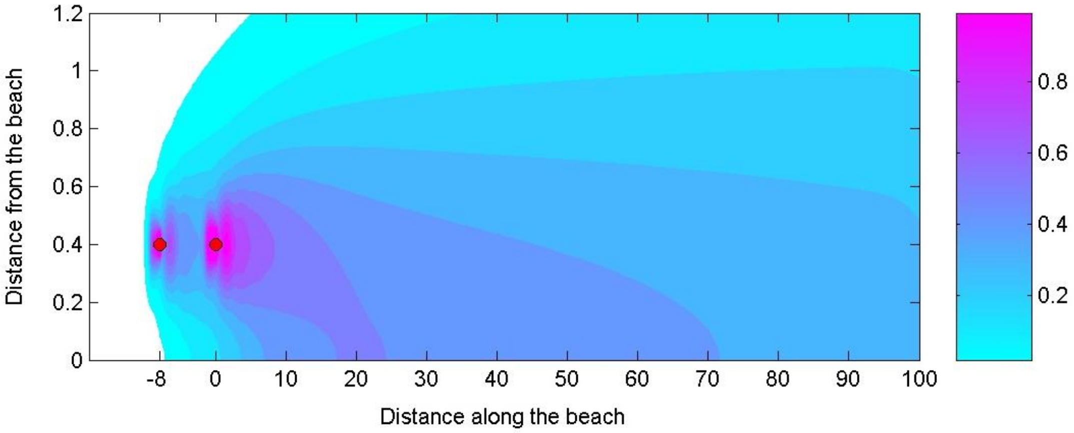

Figure 3. Simulated plume merging from two outfalls

Due to the unpredictable sea conditions, very little information is available on these parameters [9,10], and for the model applications, the values of $V=0.3$, $\lambda=10$, $\eta=25$ will be used in all plots. The interaction process of two discharged plumes is also governed by the outfall lengths $Y_0=\Lambda$ and $Y_1=\Lambda+H$, L, the separation distance (along the shore) between them, and the concentration factor q_{1*} of the first outfall. 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 equation (2). Figure 3 shows a dynamically equivalent representation of the merging of two plumes drifting along the coast at $T=2\pi$ when both outfall lengths are equal, i.e. $\Lambda=0.4$ and the separation distance (offshore) $H=0$, $q_{1*}=1$ and along the shore separation distance $L=8$. Note that the actual plumes are very elongated in the x-direction, and the peakiness of the plume reflects the physical feature of flow oscillations. As a result, concentration levels higher than 0.5 are maintained and spread downstream of the original outfall over long distances of the order 80 km.

SHORELINE'S CONCENTRATION FROM TWO SEA OUTFALLS

An appropriate measure for assessing the impact of brine stream discharges into the sea would be the shoreline's concentration values [2,11]. On substituting $y=0$ into equation (2), we obtain

$$C_*=2\int_0^{T_i}\frac{dT_0}{T_0}\sum_{k=0}^{n}q_{k*}\exp\left[-\frac{\lambda}{T_0}\left(\{X+kL-X_0(T)\}^2+\eta\{\Lambda+kH\}^2\right)\right]. \tag{3}$$

If we are only interested in the long-term impact, i.e. in the limit as $T_i\rightarrow\infty$, then the term $\cos(T-T_0)$ may be neglected from equation (3) as it has little contribution to the integral [12].

From the integral formula $\int_0^\infty \frac{dx}{x}\exp\left(-\frac{A}{x}-Bx\right)=2K_0\left(2\sqrt{AB}\right)$, where K_0 is a modified Bessel function of the second kind [16], the resulting closed form of equation (3) simplifies to

$$C_{*\infty}=4\sum_{k=0}^{n}q_{k*}\exp\left(2\lambda V\{X+kL+\cos T\}\right)K_0\left(2\lambda V\sqrt{\{X+kL+\cos T\}^2+\eta\{\Lambda+kH\}^2}\right). \tag{4}$$

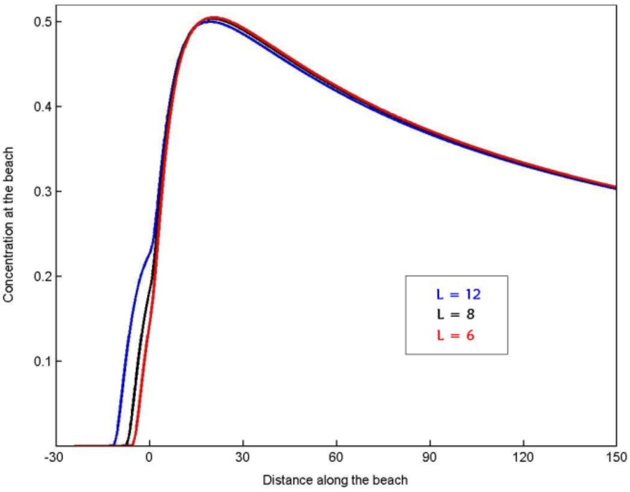

Figure 4. Shoreline's concentration from two outfalls

Next, using the asymptotic representation $K_0(x)\approx\sqrt{\pi/2x}\,\exp(-x)$, we can approximate further

$$C_{*\infty}\approx\sum_{k=0}^{n}q_{k*}\sqrt{\frac{4\pi}{\lambda V(X+kL+\cos T)}}\exp\left(-\frac{\lambda V\eta\{\Lambda+kH\}^2}{X+kL+\cos T}\right). \tag{5}$$

The long-term compounded shoreline's concentration from two plumes is shown in Figure 4 when both outfall lengths are equal with $\Lambda=0.4$ and $H=0$, and $q_{1*}=1$. The merging of two plumes is evident due to the shorter along the shore separation distance L between two outfalls. It also has one maximum concentration value occurring downstream of the original outfall, and it can thus be used as the numerical upper limit for a regulatory quality standard measure in the long-term impact of brine discharge.

By differentiating the second term of equation (5) with respect to X, the maximum shoreline's concentration occurs at $X_{\max}=2\lambda V\eta\Lambda^2-\cos T$ with the value given by

$$C_{*\max}=C_{*0}\left[1+\sum_{k=1}^{n}q_{k*}\sqrt{\frac{2e\Lambda^2}{2\Lambda^2+kL/\lambda V\eta}}\exp\left(-\frac{\{\Lambda+kH\}^2}{2\Lambda^2+kL/\lambda V\eta}\right)\right], \tag{6}$$

where $C_{*0} = \frac{1}{\lambda V \Lambda}\sqrt{\frac{2\pi}{\eta e}}$ is the maximum shoreline's concentration from the original outfall [2,11]. Figure 5 shows the concentration from two outfalls as a function of along the shore separation distance between them when the original outfall length $\Lambda = 0.4$ and $q_{1*} = 1$. The longer both the separation distances (L and H) between two outfalls, the smaller the contribution of the first outfall.

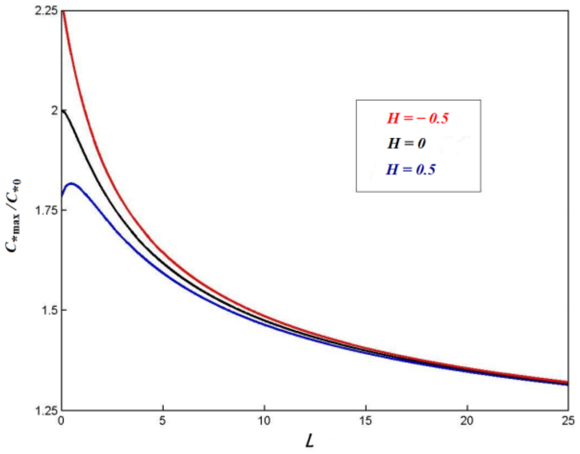

Figure 5. Maximum shoreline's concentration from two outfalls

For a much shorter along the shore separation distance between the outfalls $kL \le 2\lambda V \eta \Lambda^2$, we can approximate equation (6) further

$$C_{*\max} \approx C_{*0}\left[1 + \sum_{k=1}^{n} q_{k*} \exp\left(-\frac{kH}{2\Lambda}\left\{2 + \frac{kH}{\Lambda}\right\}\right)\right]. \tag{7}$$

A situation describes a series of outfalls, equally spaced by the offshore separation distance *H*, which is similar to an engineering design of a multiport diffuser. For the case of discharges from two outfalls, and as shown in Figure 6, by extending the first outfall length, the maximum shoreline's concentration can be minimized. For example, when $H = \Lambda$ and $q_{1*} = 1$, the maximum concentration will increase by about 22%.

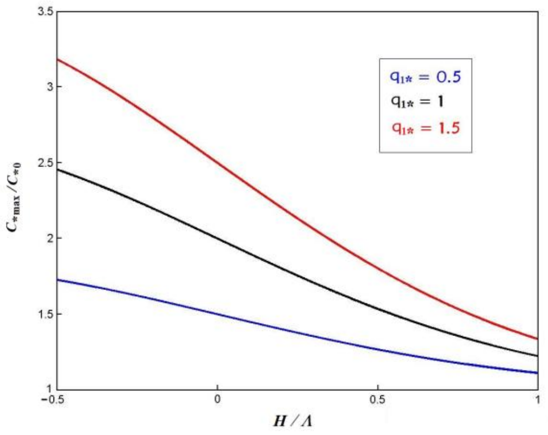

Figure 6. Maximum shoreline's concentration from two outfalls

CONCLUSIONS

A key concern of desalination plants are the concentrate and chemical discharges to the marine environment, which may impair coastal water quality and affect marine life. Most organisms can adapt to minor deviations from optimal salinity and temperature conditions, and might even tolerate extreme situations temporarily, but not a continuous exposure to unfavourable conditions. The continuous discharge of brine streams with high salinity can thus be fatal for marine life, and can cause a lasting change in species composition and abundance in the discharge site.

There are several approaches to mitigate the environmental effects of the brine discharges. To avoid impacts from high salinity, the desalination plant brine stream can be pre-diluted with other waste streams where applicable, such as power plant cooling water [7]. Finally, a multiport diffuser is commonly installed when a single outfall discharge no longer suffices to obtain the desired degree of plume dilution [8]. The diffuser is designed in the form of a linear structure consisting of many closely space ports or nozzles which inject a series of effluent plumes into the receiving water. The mathematical model can be extended to replicate and capture the process of overlapping discharge plumes from such a diffuser.

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