Chapter

# Desalination Brine Management: Effect on Outfall Design

*Ishita Shrivastava and Edward Eric Adams*


## Abstract

Recently proposed options for desalination brine management involve blending of brine with a lighter effluent or concentrating the brine prior to discharge, either of which can significantly alter the discharge concentrations of contaminants. We evaluate the effect of these brine management strategies on the design of submerged outfalls used to discharge brine. Optimization of outfall design is considered such that adequate mixing can be provided with minimum cost. Designs with submerged and surfacing plume are considered for outfalls located in shallow coastal regions with small currents (quiescent receiving water is assumed). Pre-dilution with treated wastewater is shown to reduce the outfall cost, whereas pre-dilution with seawater or pre-concentration are shown to result in higher costs than the discharge of brine alone. The effect of bottom slope is also explored and the results suggest that multiport diffusers are better suited than single jets at locations with a mild bottom slope.


**Keywords:** brine disposal, desalination, outfall, optimization, brine management, multiport diffuser

## 1. Introduction

Reject brine from desalination plants can have twice as high salinity as seawater [1] as well as high concentrations of other contaminants such as anti-fouling agents, anti-scalants, products of corrosion, etc., which can be harmful to benthic organisms. Thus, brine is usually discharged as a dense submerged jet which provides rapid mixing with ambient water. However, at locations that are characterized by shallow water depth and mild tidal currents, such as the north-western Arabian Gulf [2], diffusers with multiple jets are preferred as they can generate the required amount of mixing in smaller water depths.

Various options have been proposed for better management of reject brine from seawater reverse osmosis (SWRO) desalination plants [3, 4]. Processes such as pressure retarded osmosis (PRO) [3, 5] and reverse electrodialysis (RED) [6, 7] utilize the salinity difference between brine and treated wastewater effluent (TWE) to recover energy. On the other hand, processes such as electrodialysis (ED) [8] and ion-concentration polarization (ICP) [9] concentrate brine further to increase freshwater recovery [4] or lead to a zero discharge scenario. These options for brine management (pre-dilution with TWE or concentration) affect the discharge concentrations of contaminants present in brine, and can affect the design of outfall used to discharge brine.

Coastal desalination plants are often co-located with power plants which provide them with low-grade heat, used in the distillation of seawater (for multistage flash desalination plants) [10], or electricity (for reverse osmosis plants). Brine is often blended with condenser cooling water (CW) from the power plant before being discharged. TWE can also be used for pre-dilution (mixing with brine before discharge) if a treatment plant is nearby. Pre-dilution helps in reducing concentrations of salt and other contaminants present in brine as well as contaminants in the prediluting stream (e.g., condenser cooling water or treated wastewater effluent). It also results in increased discharge flow rate (due to blending of the two streams) and reduced discharge salinity which, in turn, reduces the density of the blended effluent. This leads to progression towards shallow or vertically mixed conditions [11].

If treated wastewater effluent from a treatment plant or condenser cooling water from a coastal power plant are not utilized for pre-dilution, they are usually discharged separately and need an outfall. Thus, in addition to the reduction in discharge concentrations of contaminants, pre-dilution also leads to a reduction in total outfall cost by eliminating the need for two separate outfalls which would cost more than one outfall for the blended stream. Thus, blending of brine with cooling water or wastewater is often recommended [12].

While concentration of brine prior to discharge using submerged outfalls (which result in dilution) is not environmentally desirable in its own right, brine can be concentrated to increase freshwater recovery or harvest salts. In order to increase freshwater recovery, brine can be desalinated in two steps involving ICP and reverse osmosis (RO) [4]. ICP is used to separate brine into two streams: 1) a lighter stream with salinity of about 35 ppt, which is then desalinated using RO; and 2) a concentrated brine stream, which is either used to harvest salts or discharged using an outfall. The concentrations of contaminants present in brine increase due to concentration. Due to the high concentrations of contaminants in concentrated brine, the near-field mixing required to dilute contaminants to desirable levels is also high.

From an environmental standpoint, one is interested in reducing concentrations of contaminants in receiving water beyond a certain mixing zone. Environmental regulations usually specify the size of a mixing zone and require outfall designs that ensure that contaminant concentrations at the edge of the mixing zone are lower than specified threshold concentrations. To dilute a contaminant to a desired concentration, the outfall needs a certain water depth. At a location with offshore sloping bottom, this means going offshore to a certain distance which has an associated capital cost. Also, the cost for pumping the effluent constitutes an operating cost. The design parameters can be optimized to achieve the right balance of these two costs and design an outfall which provides desired dilutions at the end of the mixing zone with minimum cost.

We look at the effects of four brine management strategies – pre-dilution with seawater, power plant cooling water, treated wastewater effluent and preconcentration on the design of submerged single and multiport outfalls. Outfall design variables (discharge velocity, number of ports, receiving water depth, etc.) are optimized for four different designs such that contaminants can be diluted to satisfy environmental objectives. Effect of brine management strategies on outfall cost is investigated and discussed using examples. Recommendations regarding the cost-effectiveness of different brine management options are presented.

## 2. Review of near-field mixing concepts for dense discharges

High velocity submerged jets are often used for the discharge of brine from desalination plants as they induce rapid mixing with ambient water and lead to reduction of contaminant concentrations. Inclined jets located near the sea floor are commonly used to discharge dense effluents as they increase the jet trajectory (and, in turn, dilution). Such jets rise to a maximum (terminal rise) height equal to $y_T$ before the negative buoyancy causes the jets to return to the seafloor at the impact point. For a jet (with diameter $D_0$) discharging an effluent of density $\rho_0$ with a velocity of $u_0$ in an ambient of density $\rho_a$ and uniform depth $H$, one of three regimes – deep, shallow or vertically mixed can be identified depending on the value of the shallowness parameter $D_0F_0/H$ [11, 13]. Here, $F_0 = u_0/\sqrt{g_0{}'D_0}$ is the densimetric Froude number of the jet, $g_0{}' = (\Delta\rho/\rho_a)g = \{(\rho_0 - \rho_a)/\rho_a\}g$ is the reduced gravity and $g$ is the acceleration due to gravity.

The receiving water is considered "deep" if its depth is sufficiently large and the dense effluent does not interact with the surface. "Shallow" conditions occur if the effluent interacts with the surface but it forms a bottom layer in the vicinity of the discharge. If the depth is small enough, the effluent can be mixed over the entire water column for large distances. Such a situation is categorized as being "vertically mixed". Increase in the value of $D_0F_0/H$ leads to a progression towards vertically mixed conditions. For a jet inclined at 30°, the transition between deep and shallow conditions is observed at $D_0F_0/H = 0.72$ and that between shallow and vertically mixed conditions is observed at $D_0F_0/H = 7.36$ [11].

### 2.1 Negatively buoyant submerged jet

In deep water, the impact point dilution, which is the minimum dilution along the seafloor, of an inclined submerged jet is proportional to $F_0$ [14–16]. In shallow water and vertically mixed conditions, the dilution is independent of $F_0$ and is proportional to $H/D_0$ [11, 17]. The constants of proportionality depend on the discharge angle ($\theta_0$). In deep receiving water, an inclination of 60° provides the highest dilution (for fixed value of $F_0$). However, smaller angles are preferred in shallow conditions [13, 17]. An inclination of 30° is chosen for further analysis which is suitable for shallow regions. For this choice of $\theta_0$, the impact point dilutions in deep and shallow (and vertically mixed) conditions are given by Eqs. (1) and (2), respectively [11, 13].

$$S_{i,deep} = 1.2F_0 \tag{1}$$

$$S_{i,shallow} = 0.86H/D_0 \tag{2}$$

### 2.2 Unidirectional diffuser

A unidirectional (or tee) diffuser is an outfall which consists of an array of submerged jets (number of jets $= N$) arranged in parallel with all jets pointing in one direction perpendicular to the manifold. Use of a unidirectional diffuser is suitable in locations with mild bi-directional currents [18]. Individual jets of a unidirectional diffuser interact with each other in shallow water and lead to mixing that is different from a mere superposition of individual jets [19].

In deep water ($D_0F_0/H < 0.72$) and with adequate port spacing, there is no interaction among individual jets of a unidirectional diffuser [20] and the dilution is the same as that of a single jet (given by Eq. (1) for $\theta_0 = 30°$).

In shallow water ($D_0F_0/H$ between 0.72 and 7.36), there is more interaction among individual jets and the impact point dilution of a unidirectional diffuser with port spacing equal to water depth ($l = H$) is given by:

$$S_{i,shallow,ud} = 0.82F_0{}^{-0.15}(H/D_0)^{1.15} \tag{3}$$

In vertically mixed conditions ($D_0F_0/H > 7.36$), the dilution is independent of the discharge buoyancy (or $F_0$). The impact point dilution of a unidirectional diffuser with port spacing equal to water depth ($l = H$) in vertically mixed conditions is:

$$S_{i,mixed,ud} = 0.61H/D_0 \tag{4}$$

For a unidirectional diffuser discharging in quiescent shallow or vertically mixed conditions, proximity to shoreline can result in a reduction in dilution [21]. However, the reduction in dilution is less than 15% if the separation between the diffuser and the shoreline (in constant water depth) is more than 60% of the diffuser length. At a location with uniformly sloping bottom, this is roughly equivalent to an offshore distance equal to 1.2 times the diffuser length [21]. In the presence of moderate to high crossflow, Shrivastava and Adams [22] observed no significant reduction in dilution if the separation between the diffuser and the shoreline is at least 15% of the diffuser length for a diffuser discharging in uniform water depth. This corresponds to a shoreline separation of 30% or more of the diffuser length at a location with uniformly sloping bottom.

## 3. Previous studies

Several studies have examined outfall optimization for brine disposal. Jiang and Law [23] provided semi-analytical solutions for the combination of port diameter ($D_0$) and number of ports ($N$) required to meet design objectives (dilution greater than a specified value and rise height of plume lower than a fraction of the water depth) for non-interfering multiport diffusers. They investigated $D_0 - N$ combinations for full submergence and surface contact scenarios (analogous to deep and shallow conditions, respectively) for a given range of brine flow rate. They did not consider a cost function but asserted that the capital cost increases with the number of ports, and thus the optimum design is the one that satisfies design objectives with minimum number of ports. They assumed jets to be non-interfering, and thus did not account for the interaction between jets in shallow water depths.

Maalouf et al. [24] provided a simulation-optimization framework to optimize SWRO outfall design. They used a regression model, calibrated using results from an initial mixing model (CORMIX), to quantify the effects of various parameters on dilution. Using this regression model for dilution, they optimized the design variables to minimize the total cost. The total cost was assumed to be a linear function of outfall pipe length ($X$), internal port diameter ($D_0$) and number of ports ($N$). Their analysis was based on a similar analysis done by Chang et al. [25] to evaluate optimal strategies for the expansion of a wastewater treatment plant in South Taiwan. Uncertainties in ambient parameters (e.g., ambient current speed) were also considered.

The above studies only considered linear cost functions and have not been compared to cost functions in the real world.

## 4. Brine management strategies

Recently proposed brine management options [3, 4] include pre-dilution with a lighter effluent and pre-concentration, and can cause significant changes to contaminant concentrations and, in turn, the required dilution. Contaminants of concern for the discharge of pre-diluted brine can be categorized into three categories

[26]. First, there are contaminants similar to salt which are present in ambient water but get concentrated due to the desalination process. Thus, the discharge concentrations are higher than ambient concentrations and these contaminants need to be diluted. Examples include salts and metals. Second, there are contaminants that are introduced by the desalination process, such as anti-scalants and cleaning chemicals [27]. Third, there are contaminants that are present in the pre-dilution stream. Examples include biochemical oxygen demand (BOD), nutrients etc. present in TWE and excess temperature from CW. While some of the contaminants of concern degrade with time (e.g., ammonia), most of them are conservative and require mixing with ambient water to reduce their concentrations below harmful levels.

For the case of pre-dilution, reject brine from a typical reverse osmosis (RO) plant (having double the salinity as ambient seawater and with flow rate $= Q_b$, reduced gravity $= g_b'$ and excess salinity above ambient water $= \Delta s_b$) is considered to be blended with a pre-dilution stream (flow rate $= (R_B - 1)Q_b$, reduced gravity $= g_p'$, excess salinity $= \Delta s_p$ and excess temperature $= \Delta T_p$), making a total flow rate of $Q_0 = R_B Q_b$. The blending ratio ($R_B$) is, thus, the ratio of the blended effluent flow rate ($Q_0$) to the brine flow rate ($Q_b$). The blended effluent has a reduced gravity of $g_0' \cong \left\{g_b' + (R_B - 1)g_p'\right\}/R_B$ and excess salinity of $\Delta s_0 = \left\{\Delta s_b + (R_B - 1)\Delta s_p\right\}/R_B$. In addition to the use of TWE and CW as the pre-diluting stream, pre-dilution with ambient seawater (SW) is also considered. **Table 1** gives the properties of brine, seawater, TWE and CW used in this analysis.

Pre-dilution with TWE leads to a rapid reduction in discharge salinity as the salinity deficit of TWE (with respect to ambient water) cancels out some of the salinity excess of brine. Similarly, the reduced gravity of the effluent when brine is blended with TWE decreases rapidly. On the other hand, SW and CW do not have any salinity excess or deficit (with respect to ambient water), and thus the reduction in discharge salinity (and, in turn, reduced gravity) is less than that for the case of pre-dilution with TWE. As CW is positively buoyant with respect to ambient water, the decrease in $g_0'$ as a function of $R_B$ is faster for the case of blending with CW than for the case of blending with SW.

For the case of pre-concentration, it is assumed that brine (with initial flow rate $= Q_b$) is concentrated by removing fresh water (salinity = 0 or excess salinity $= -\Delta s_b$) such that a more concentrated discharge stream is produced with flow rate of $Q_0 = Q_b/R_C$ (with $R_C > 1$). Thus, the discharge salinity is equal to $\Delta s_0 = (2R_C - 1)\Delta s_b$, where $R_C$ is the concentration ratio defined as the ratio of the brine flow rate ($Q_b$) to the discharge flow rate ($Q_0$).

Since the salinity of brine is double the salinity of seawater and the salinity of TWE is assumed to be zero, the blended effluent has the same salinity as ambient seawater when the flows (of brine and TWE) are blended in a 1:1 ratio ($R_B = 2$). The pre-dilution of excess salinity ($= \Delta s_b/\Delta s_0$) in this case is infinite. For high values of $R_B$, the blended effluent may become positively buoyant ($R_B > 2$ for pre-dilution with TWE and $R_B > 8.7$ for pre-dilution with CW) in which case there is no

| | Reject Brine | TWE | CW | SW |
|---|---|---|---|---|
| Salinity | 72 ppt | 0 | 36 ppt | 36 ppt |
| Temperature | 27°C | 27°C | 37°C | 27°C |
| Reduced gravity | $0.27\ m/s^2$ | $-0.26\ m/s^2$ | $-0.035\ m/s^2$ | 0 |

**Table 1.**
*Properties of brine and various pre-dilution streams.*

impact point. But the dilution equations for negatively buoyant effluent are used for this case too. These results are only meant to provide qualitative predictions.

## 5. Optimization parameters

Optimization of the design of outfalls discharging pre-diluted or pre-concentrated brine is considered here such that regulatory requirements on contaminant concentrations can be met at the end of the mixing zone with minimum cost. The end of the mixing zone is assumed to be at the impact point of the jets. Thus, the expressions for impact point dilution of a single port outfall and a multiport (unidirectional) diffuser can be used to calculate the "physical" dilution induced by the outfall.

The location of an outfall depends on many factors, such as the availability of deep water, absence of natural submerged sills, spits, and manmade jetties, and knowledge of the offshore bathymetry; hydrodynamic modeling is often utilized to test a proposed design before it is adopted. In addition, detailed analysis of the forces exerted on the outfall due to oceanographic conditions is also carried out to ensure its stability. These factors are site-specific and beyond the scope of this chapter. Here, we are considering generic outfall designs and calculating values of design variables, such as receiving water depth, discharge velocity, number of ports, etc., that result in minimum cost. For this calculation, the outfall is considered to be located at a place with uniformly sloping bottom in the offshore direction.

Optimization of outfall design requires identification of outfall cost, desired dilution and design alternatives, which are discussed below.

### 5.1 Costs

One of the major components of outfall cost is the cost of the conveyance system to carry brine to the offshore discharge location. Depending on the oceanographic conditions and the discharge location, this can be done by running a pipe through a tunnel or a trench, or laying a pipe on the seabed secured using ballast weights [28]. Here, we have assumed that high density polyethylene (HDPE) pipes are used.

The capital cost is considered to be composed of four major components. The first is the cost of laying the HDPE pipe to the required offshore distance. The cost per unit length of HDPE pipes was found to be proportional to the pipe diameter ($D_p$) [29, 30]. Thus, the cost of the pipe is proportional to the pipe diameter ($D_p$) times the length of the pipe ($X$).

The most common way to secure HDPE pipes to the sea bed is to attach concrete ballast weights [28]. The cost of concrete weights per unit length of the pipe was found to increase with pipe diameter [29] and a linear fit was used. Thus, the total cost of anchor blocks was proportional to the product of pipe diameter and length. Combining the cost of the HDPE pipe and the concrete anchor blocks, the cost of laying the outfall pipe is:

$$CC_1 = AD_pX \tag{5}$$

At a location with uniformly sloping bottom (with slope $= \Gamma$), the length of the pipe is related to the ambient depth required ($X = H/\Gamma$). The pipe diameter depends on many factors including the size of the plant, construction material, water depth, available hydraulic head etc. [28]. Assuming the size of the pipe to be a function of the flow rate only, an analysis of the available data for outfalls around the world (from [31, 32], shown in **Figure 1**) shows the following dependence of pipe size (in m) on flow rate (in $m^3/s$):

$$D_p = 0.98{Q_0}^{0.36} \tag{6}$$

The cost of the outfall pipe is then given by:

$$CC_1 = a{Q_0}^{0.36}H/\Gamma \tag{7}$$

where $a = 0.98A$.

The second component is the cost of the diffuser manifold. Assuming that the diffuser manifold has the same diameter as the outfall pipe ($D_m = D_p$) and that the spacing between adjacent nozzles is equal to the water depth ($l = H$), the capital cost of the manifold becomes:

$$CC_2 = a{Q_0}^{0.36}NH \tag{8}$$

This component of cost is only considered for a multiport diffuser, i.e., $CC_2 = a{Q_0}^{0.36}H$ for a single port discharge is neglected in comparison to other costs.

The third component is the cost of nozzles. A linear fit to the cost per nozzle data, reported in [29, 30], was used to estimate the total cost of nozzles as:

$$CC_3 = N(B + CD_0) \tag{9}$$

The fourth component is the cost of pumps required to pump the effluent to the offshore location of the outfall. The cost of pumps increases with the flow rate and the total head loss in the outfall. Based on the cost of pumps for pumping product water reported by [29], this cost was found to be proportional to the product of effluent density, flow rate and total head loss ($H_L$). Thus:

$$CC_4 = E\rho_0 Q_0 H_L \tag{10}$$

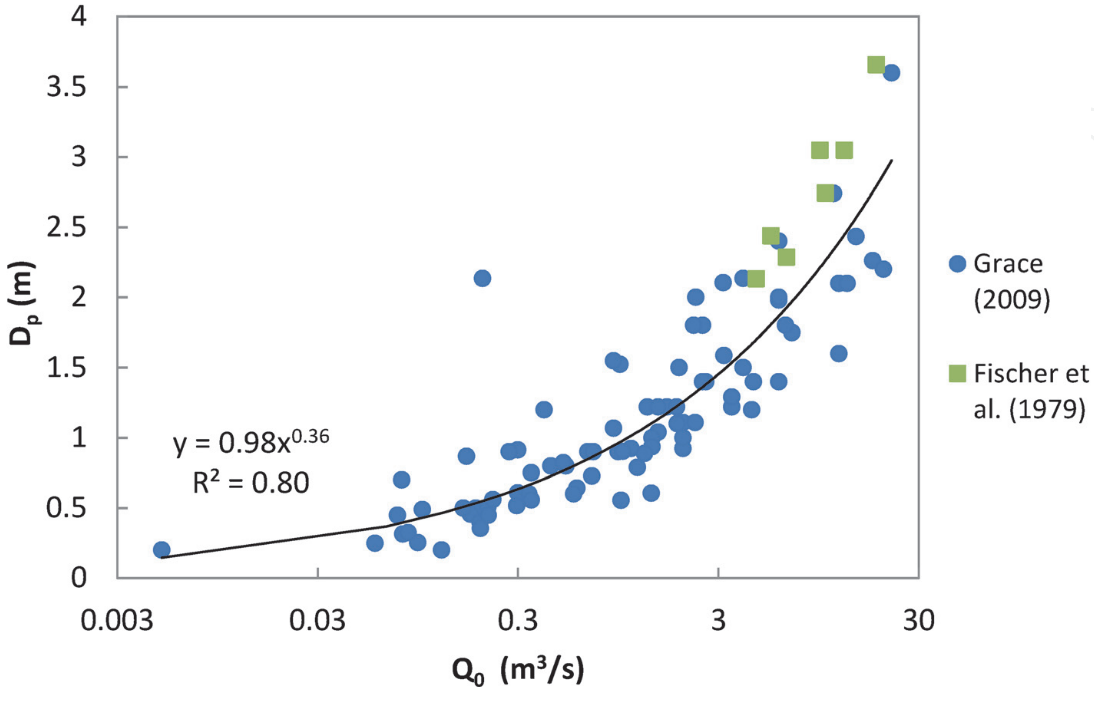


**Figure 1.**
*Correlation between outfall pipe diameter and flow rate.*

The first three cost components ($CC_1, CC_2$ and $CC_3$) only include material costs. The installation cost is assumed to be 1.2 times the material cost (based on cost estimates from [30]) so that the total cost is 2.2 times the material costs. For the cost of pumps ($CC_4$), the installation cost is already included in Eq. (10).

The total cost of the outfall also includes an operating cost which mainly consists of the cost of electricity for pumping the effluent, and operation and maintenance cost. It is assumed that the available pressure and elevation head before discharge are negligible and thus pumping is required to discharge the effluent with high velocity. The pumping cost is proportional to the product of effluent density, flow rate and total head loss. Thus, the pumping cost over the life of the plant is:

$$OC_1 = F\rho_0 Q_0 H_L \tag{11}$$

where $F$ depends on the cost of electricity, discount rate and outfall lifetime.

Malcolm Pirnie [29] reported values of operation and maintenance cost for different scenarios which suggest that it is independent of design variables. Therefore, a constant value was used for the operation and maintenance cost.

**Table 2** provides a summary of the cost functions and typical values of cost coefficients (for costs in USD, as per May 2016 ENR index).

An estimation of head loss is required to calculate the total cost. Head loss is estimated by considering the components listed in **Table 3**. Here, $V_p$ is the velocity inside the outfall pipe. The head loss incurred in conveying the effluent to the shoreline is not included as it is the same for all designs and does not affect the optimization analysis. Thus, the outfall costs calculated here represent the cost above the cost of the simplest (shoreline) discharge.

### 5.2 Desired dilution

Environmental regulations usually specify threshold concentrations for various contaminants. These are maximum acceptable concentrations in the water body that are considered to be safe for aquatic organisms. Thus, outfalls are required to reduce contaminant concentrations to threshold levels within a regulatory mixing zone. Here, the impact point of the jets is assumed to be the end of the mixing zone.

Threshold concentrations can be different at different locations as they are based on the toxicological adaptability of the marine species thriving in that location. Also, regulatory requirements vary from country to country, with international guidelines also referring to local regulations [34, 35]. In addition, source stream concentrations vary depending on the quality of feed water, desalination process etc.,

| Costs | Expression | Cost coefficients |
|---|---|---|
| Cost of outfall pipe | $CC_1 = 2.2aQ_0{}^{0.36}H/\Gamma$ | $a = 1.47 \times 10^3$ |
| Cost of diffuser manifold | $CC_2 = 2.2AD_mNH$ | $A = 1.5 \times 10^3$ |
| Cost of nozzles | $CC_3 = 2.2N(B + CD_0)$ | $B = 2.1 \times 10^3, C = 3.3 \times 10^4$ |
| Cost of pumps | $CC_4 = E\rho_0 Q_0 H_L$ | $E = 35$ |
| Pumping cost[a,b] | $OC_1 = F\rho_0 Q_0 H_L$ | $F = 73$ |
| Operation and maintenance cost[b] | $OC_2 = G$ | $G = 1.4 \times 10^6$ |

[a]*Assuming cost of electricity = 0.10 USD/kWh.*
[b]*Assuming discount rate of 10% and plant lifetime of 20 years.*

**Table 2.**
*Break-down of total outfall cost.*

| Component | Description | Expression | Coefficient value |
|---|---|---|---|
| Conveyance to offshore location of the outfall | Friction loss in a pipe of length $X$ and diameter $D_p$ | $f(X/D_p)(V_p^2/2g)$ | $f = 0.015$ |
| A T-junction[a] | | $K_T(V_p^2/2g)$ | $K_T = 1$[d] |
| Diffuser manifold | Friction loss in a pipe of length $L = NH$ and diameter $D_p$ | $f(NH/D_p)\left\{(V_p/2)^2/2g\right\}$ | |
| Entry loss[a] | Loss incurred while entry into the riser[c] | $K_{en}(u_0^2/2g)$ | $K_{en} \approx 0.3$[e] |
| Sudden contraction[b] | Contraction from pipe diameter to nozzle diameter | $K_c(u_0^2/2g)$ | $K_c$[f] |
| A 30° elbow | For the nozzles pointing at 30° | $K_{el}(u_0^2/2g)$ | $K_{el} = 0.3$[d] |
| Exit loss | | $u_0^2/2g$ | |

[a]*Only for the design with a unidirectional diffuser.*
[b]*Only for a single port design.*
[c]*Assuming riser diameter equal to the nozzle diameter.*
[d]*From Davis [33].*
[e]$K_{en} \approx 0.2 + (V_d/V_r)^2$ *from Fischer et al. [31].* $V_d$ *is the velocity inside the manifold and* $V_r$ *is the velocity in the riser. With the constraint on* $u_0$ *for uniform flow (discussed later),* $K_{en}$ *has a maximum value of 0.3 which is used here.*
[f]*Assumed to vary linearly with the ratio of cross-sectional areas of the two pipes from 0.45 to 0.16 for area ratio (ratio of smaller cross-sectional area to larger cross-sectional area) from 0.04 to 0.64.*

**Table 3.**
*Components of total head loss.*

resulting in a range of values of the desired dilution. For simplicity, salinity is assumed to be the most constraining contaminant. The threshold concentration of salt is assumed to be 2 ppt in excess of ambient salinity [36] and outfall designs which dilute salinity to an excess of 2 ppt at impact point are discussed.

Effective dilution for a contaminant is defined as the ratio of its excess concentration in the source stream (e.g., brine for salinity) to its excess concentration at a given location. Thus, if the excess salinity of the diluted effluent at the impact point is equal to 4 ppt (in excess of ambient salinity), then the effective dilution of salinity at impact point is equal to $36/4 = 9$, where 36 ppt is the excess salinity of reject brine (**Table 1**). Similarly, the desired effective dilution for any contaminant is the ratio of its concentration in the source stream to the threshold concentration (both in excess of ambient concentration). Thus, the desired effective dilution of salinity is equal to 18.

Unlike the desired effective dilution, the desired physical dilution at the impact point also depends on the amount of pre-dilution or pre-concentration (the value of $R_B$ or $R_C$), in addition to the source streams and threshold concentrations. For example, if brine is pre-diluted with TWE with $R_B = 1.5$, then the discharge excess salinity is 12 ppt and the desired physical dilution is equal to $12/2 = 6$, which is different than the desired effective dilution which is equal to 18. The outfall design in this case needs to provide an impact point dilution of 6.

### 5.3 Design alternatives

Brine can be discharged through an outfall in two ways – the discharge can be such that the plume stays below the water surface or it can be allowed to hit the surface. The former design would be implemented if the regulations require the plume to not be visible at the surface. However, the latter design usually costs less and should be preferred when there are no restrictions on plume visibility.

For a jet inclined at 30°, the depth below which the impact point dilution is affected by the water surface is more than the depth at which the jet hits the water surface [11]. Thus, for a submerged plume (which is not allowed to hit the surface), the maximum dilution (with minimum total cost) is achieved when the terminal rise height of the jet is just high enough that the ambient depth affects the dilution, i.e., at the transition point between deep and shallow conditions ($D_0F_0/H = 0.72$). To dilute a contaminant to a threshold concentration, the design variables for this design can be determined by ensuring that the physical dilution is just enough to get the desired concentration and the discharge plume rises to just below the water surface ($D_0F_0/H = 0.72$ for an inclination of 30°). The design variables for this design are denoted using the subscript 'd', for deep.

These design parameters do not minimize the total cost as they require a large capital cost. Specifically, in locations with very small bottom slope, such as the Arabian Gulf [2], the capital cost can be several orders of magnitude larger than the pumping cost and the total cost can be very high. To reduce the capital cost, it is beneficial to achieve the desired dilution with smaller ambient depth by reducing the port diameter or to employ a multi-port diffuser. Using a single, smaller diameter port will result in an increase in discharge velocity, and thus the pumping cost.

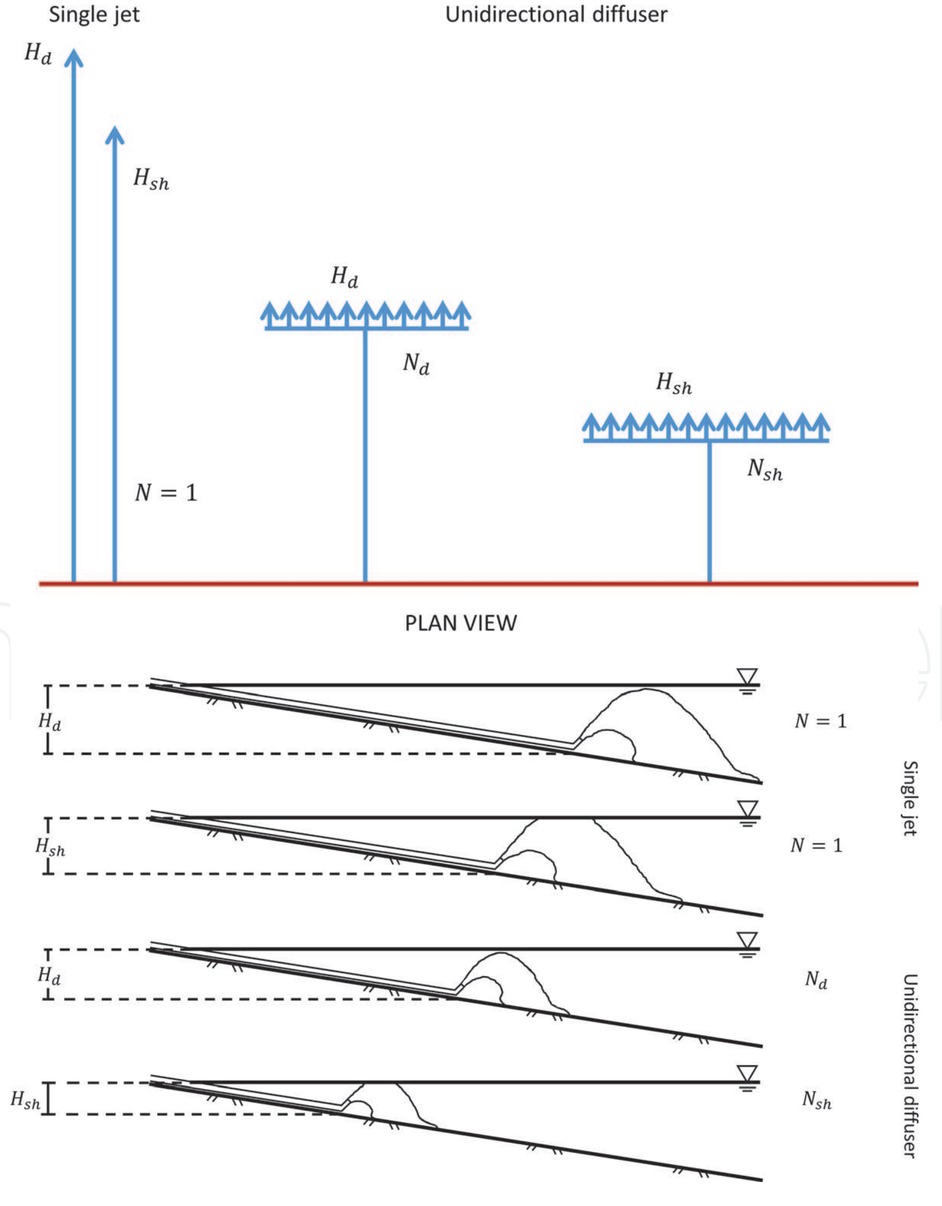


**Figure 2.**
*Schematic showing the plan view (top) and elevation view (bottom) of the four designs considered.*

The optimum design will be the one that minimizes the total cost (capital cost + pumping cost). The design variables for this design are denoted using the subscript 'sh', for shallow. Similarly, for a multiport diffuser, optimum design variables can be computed for the two designs, one with the diffuser plume submerged and the other with surfacing plume. A schematic of the four designs is shown in **Figure 2**.

## 6. Design optimization

### 6.1 Discharge through a single jet creating a submerged plume

The optimum values of water depth, diameter and discharge velocity needed to dilute a contaminant with excess concentration of $\Delta c_0$ to a desired excess concentration of $\Delta c_{th}$, with the additional constraint that the plume remains submerged, are given by Eqs. (12)–(15), respectively. $H_d$ depends on the mass loading of the contaminant (in excess of ambient concentration, $\dot{m} = Q_0 \Delta c_0$), buoyancy flux of the effluent ($B_0 = Q_0 g_0{}'$) and desired concentration ($\Delta c_{th}$), but is independent of the flow rate ($Q_0$) as shown in Eq. (13). Therefore, the required water depth for salinity as the contaminant of concern and seawater as the pre-diluting stream is independent of $R_B$ (as $\dot{m}$ and $B_0$ are independent of $R_B$ in that case).

$$H_d = 1.38 \frac{Q_0{}^{2/5}}{g_0{}'^{1/5}} \left( \frac{\Delta c_0}{\Delta c_{th}} \right)^{3/5} \tag{12}$$

$$\text{or } H_d = \frac{1.38}{B_0{}^{1/5}} \left( \frac{\dot{m}}{\Delta c_{th}} \right)^{3/5} \tag{13}$$

$$(D_0)_d = 1.18 \frac{Q_0{}^{2/5}}{g_0{}'^{1/5}} \left( \frac{\Delta c_{th}}{\Delta c_0} \right)^{2/5} \tag{14}$$

$$(u_0)_d = 0.91 Q_0{}^{1/5} g_0{}'^{2/5} \left( \frac{\Delta c_0}{\Delta c_{th}} \right)^{4/5} \tag{15}$$

**Figure 3** shows the variation of $H_d$, $(D_0)_d$ and $(u_0)_d$ as functions of $R_B$ (for different pre-dilution streams) and $R_C$. The variables are scaled so that they can be plotted on the same plot. The scaling is the same for all the pre-dilution cases (indicated in the legend for SW blending plot) but is different for the pre-concentration case (indicated in the legend for pre-concentration plot) because of the different range of values.

When brine is pre-diluted, the desired physical dilution reduces with an increase in $R_B$ (except for $R_B > 2$ for blending with TWE), and thus the discharge velocity also reduces. For the case of brine concentration, the desired physical dilution increases rapidly as $R_C$ increases and the effluent needs to be discharged with very high velocity to achieve better mixing. For example, the desired physical dilution is equal to 54 for $R_C = 2$ and $(u_0)_d$ is equal to 17.7 m/s which is not realistic. $(u_0)_d$ is even higher for higher values of $R_C$ which suggests that a single jet should not be used to discharge concentrated brine at a location with restriction on plume visibility.

### 6.2 Discharge through a single jet creating a surfacing plume

This section explores the optimum design with no restriction on plume visibility, i.e., the design which minimizes total cost without any constraint. For most cases, this design results in a plume which hits the surface. But for some cases, the design

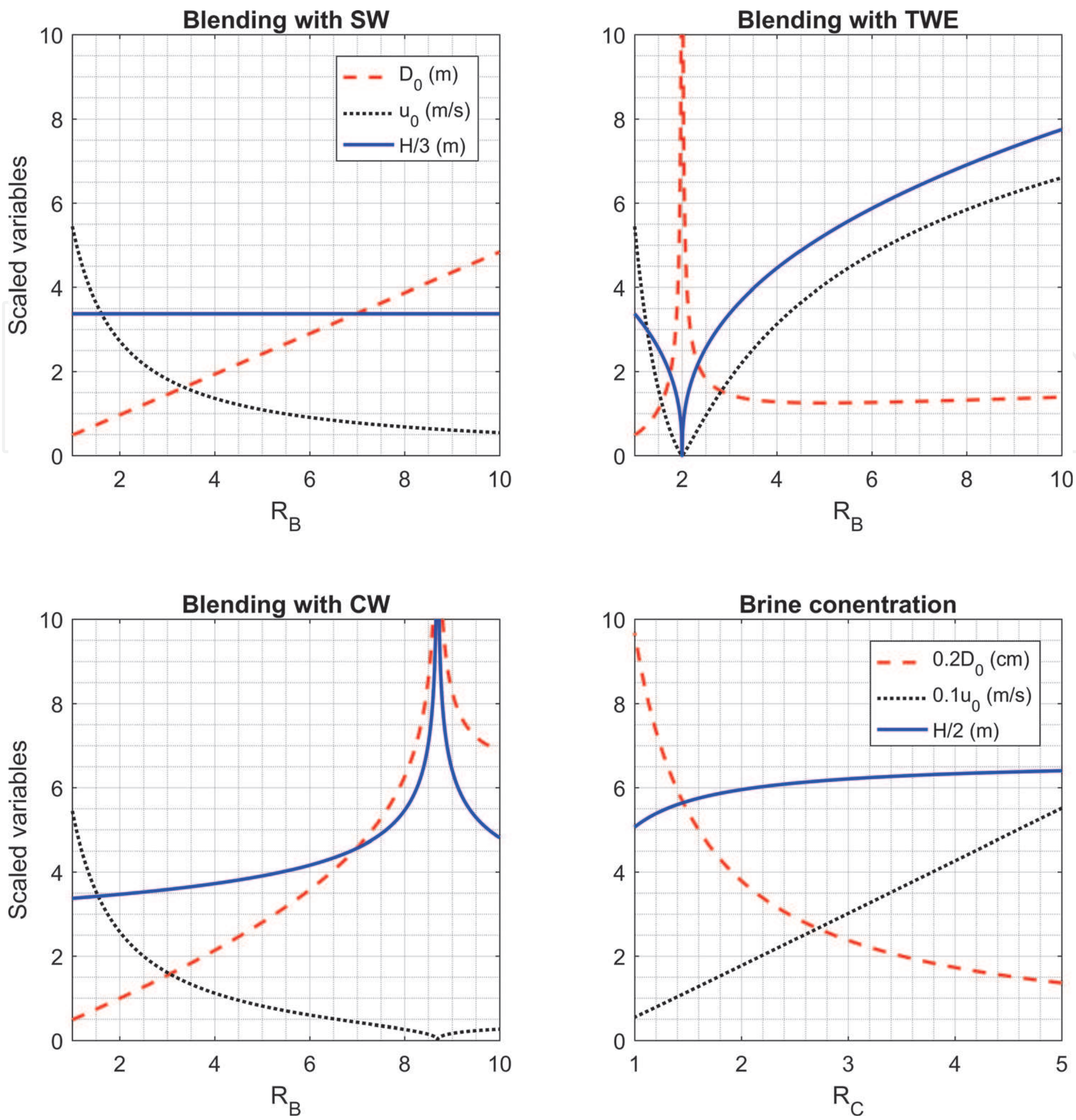


**Figure 3.**
*Variation of H, $D_0$ and $u_0$ with $R_B$ and $R_C$ for discharge using a single jet with submerged plume for $Q_b = 1\ m^3/s$, $\Gamma = 0.01$ and a desired excess salinity of 2 ppt. (variables are scaled differently for the pre-dilution and pre-concentration cases as indicated in the legend).*

with a submerged plume is also the one which minimizes the total cost and should be adopted. This design optimization results in non-linear equations which are solved using the 'fsolve' function in MATLAB.

**Figure 4** shows the variation of $H_{sh}$, $(D_0)_{sh}$ and $(u_0)_{sh}$ as functions of $R_B$ and $R_C$. Unlike the design with a submerged plume where the required water depth is either constant or increases with $R_B$ (for pre-dilution with SW and CW), the required water depth for the surfacing plume design reduces with $R_B$ as the desired physical dilution reduces. For pre-dilution with TWE, the required water depth follows the same trend as the desired physical dilution. Thus, it reduces with $R_B$ for $R_B < 2$ and increases with $R_B$ for $R_B > 2$. When brine is concentrated, the design with a submerged plume is the optimum design for $R_C > 1.4$ because the smaller flow rate and higher density difference (as compared to brine which is not concentrated) are less likely to lead to shallow conditions. Thus, even when there are no restrictions on plume visibility, the design of a single jet to discharge concentrated brine results in unrealistically high values of $u_0$. For all cases (except pre-concentration with $R_C > 1.4$), the design with a surfacing plume has a higher discharge velocity and lower water depth than the corresponding values for the design with submerged

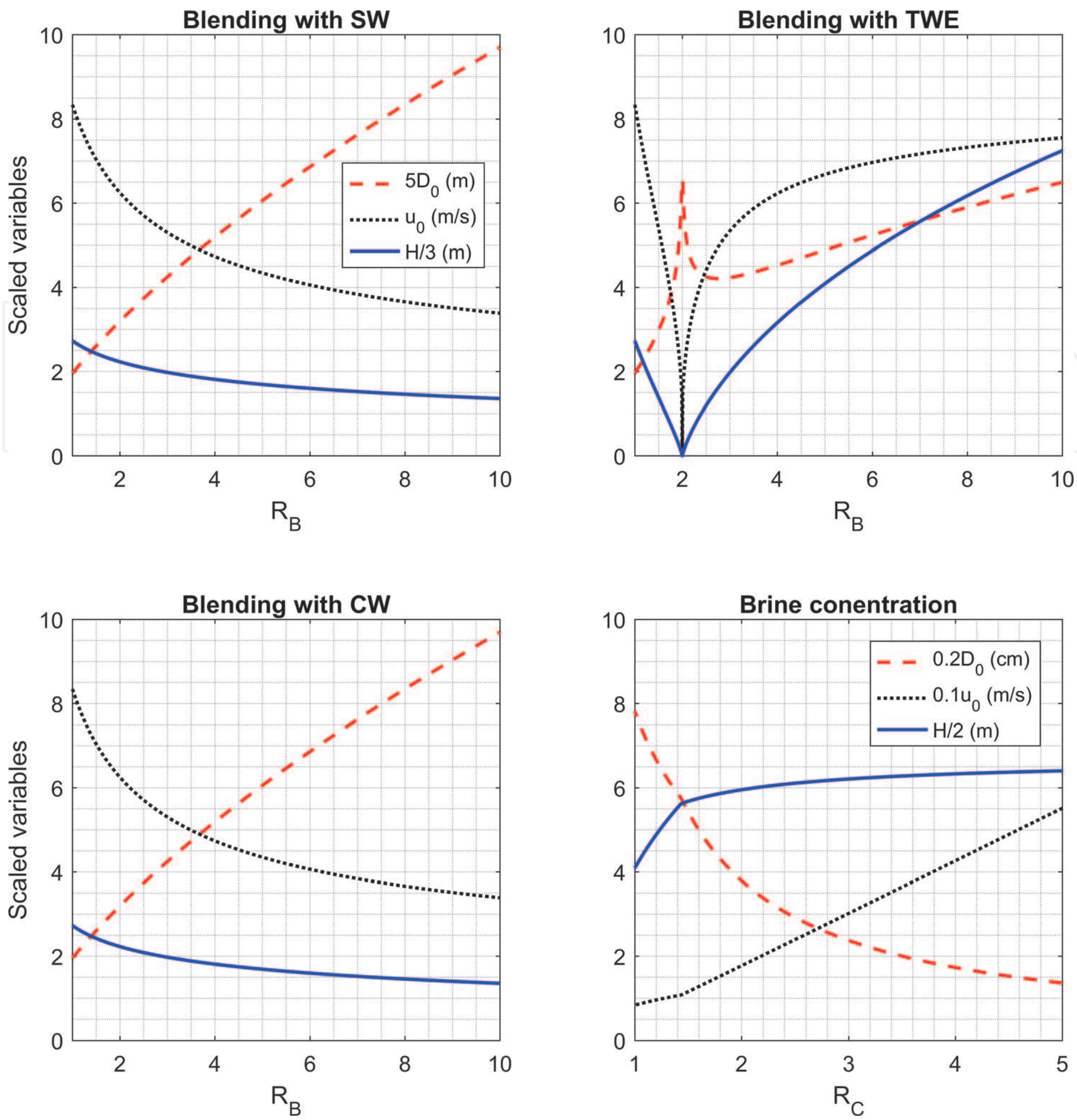


**Figure 4.**
*Variation of H, $D_0$ and $u_0$ with $R_B$ and $R_C$ for discharge using a single jet with surfacing plume for $Q_b = 1\ m^3/s$, $\Gamma = 0.01$ and a desired excess salinity of 2 ppt. (variables are scaled differently for the pre-dilution and pre-concentration cases as indicated in the legend).*

plume. The higher velocity helps in generating the same amount of mixing as the submerged plume case but in smaller water depth.

### 6.3 Discharge through a unidirectional diffuser

The design optimization for a unidirectional diffuser also results in non-linear equations which are solved using the 'fsolve' function in MATLAB. Optimum design variables are calculated which achieve desired dilution and minimize total cost. However, in some cases the optimized design variables need to be adjusted. For example, to ensure uniform flow through all the ports, the aggregate cross-sectional area of the nozzles should be less than two-thirds of the cross-sectional area of the diffuser manifold [31]. Since the manifold diameter is assumed to be related to the discharge flow rate (Eq. (6)), this requires the discharge velocity to be at least equal to $2{Q_0}^{0.28}$. Thus, if the optimum value of $u_0$ is less than $2{Q_0}^{0.28}$, $u_0$ is fixed to be equal to $2{Q_0}^{0.28}$ and other design variables are re-evaluated to minimize total cost.

For certain cases, the design with a single port is the one which minimizes cost, i.e., any design with multiple ports will have higher total cost than the design with one port. This is observed for cases which require a submerged plume and for which the desired physical dilution is small. The optimum discharge velocity (not adjusted for uniform flow) for such cases is small and adjustment for uniform flow results in a design with total cost higher than the cost of the single jet design. For these cases, the single port design is accepted as the optimum design.

Once the optimum design variables are calculated (which satisfy all constraints), $N$ is rounded to the nearest integer and $D_0$ is adjusted such that $Q_0 = (\pi/4) N u_0 {D_0}^2$.

*6.3.1 Discharge through a unidirectional diffuser creating a submerged plume*

**Figure 5** shows the variation of $H_d$, $(D_0)_d$, $(u_0)_d$ and $N_d$ as functions of $R_B$ and $R_C$. The design with a single jet is the optimum design for $R_B > 2.1$ for blending with SW and CW, and for $R_B$ between 1.4 and 3.8 for blending with TWE. The discharge velocity is fixed to be equal to $2{Q_0}^{0.28}$ (to ensure uniform flow through nozzles) for

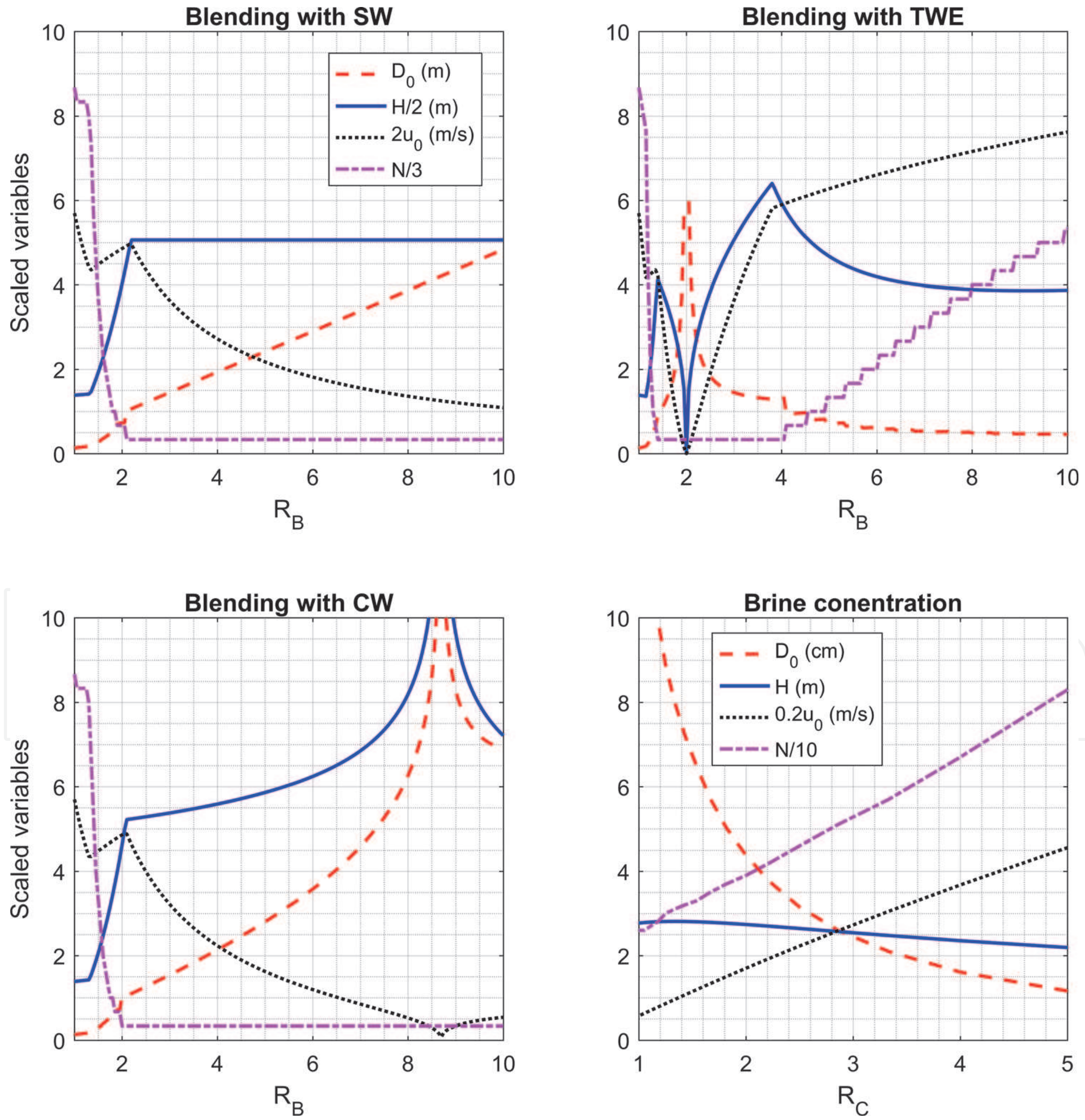


**Figure 5.**
*Variation of H, N, D₀ and u₀ with $R_B$ and $R_C$ for discharge using a unidirectional diffuser with submerged plume for $Q_b = 1\ m^3/s$, $\Gamma = 0.01$ and a desired excess salinity of 2 ppt. (variables are scaled differently for the pre-dilution and pre-concentration cases as indicated in the legend).*

$R_B$ between 1.3 and 2.1 (for pre-dilution with SW and CW), and for $R_B$ between 1.2 and 1.4 and greater than 3.8 (for pre-dilution with TWE).

### *6.3.2 Discharge through a unidirectional diffuser creating a surfacing plume*

An optimum design with multiple ports (which has lower cost than a single port design) can be found for all cases when the effluent plume is allowed to hit the surface. **Figure 6** shows the variation of $H_{sh}$, $(D_0)_{sh}$, $(u_0)_{sh}$ and $N_{sh}$ as functions of $R_B$ and $R_C$. The discharge velocity needs to be adjusted to ensure uniform flow for $R_B > 4.2$ when brine is blended with SW and CW and for $R_B > 9.6$ when brine is blended with TWE. For other cases, all variables can be adjusted to minimize cost. The required water depth can be seen to reduce as $R_B$ increases for pre-dilution with SW and CW. This is similar to the case of a single jet with surfacing plume.

For the multiport diffuser designs calculated here, the ratio of offshore distance of the diffuser ($X$) to its length ($L$) is more than 3 for the pre-dilution cases and more than 1.2 for the pre-concentration cases. For these values of $X/L$, the presence

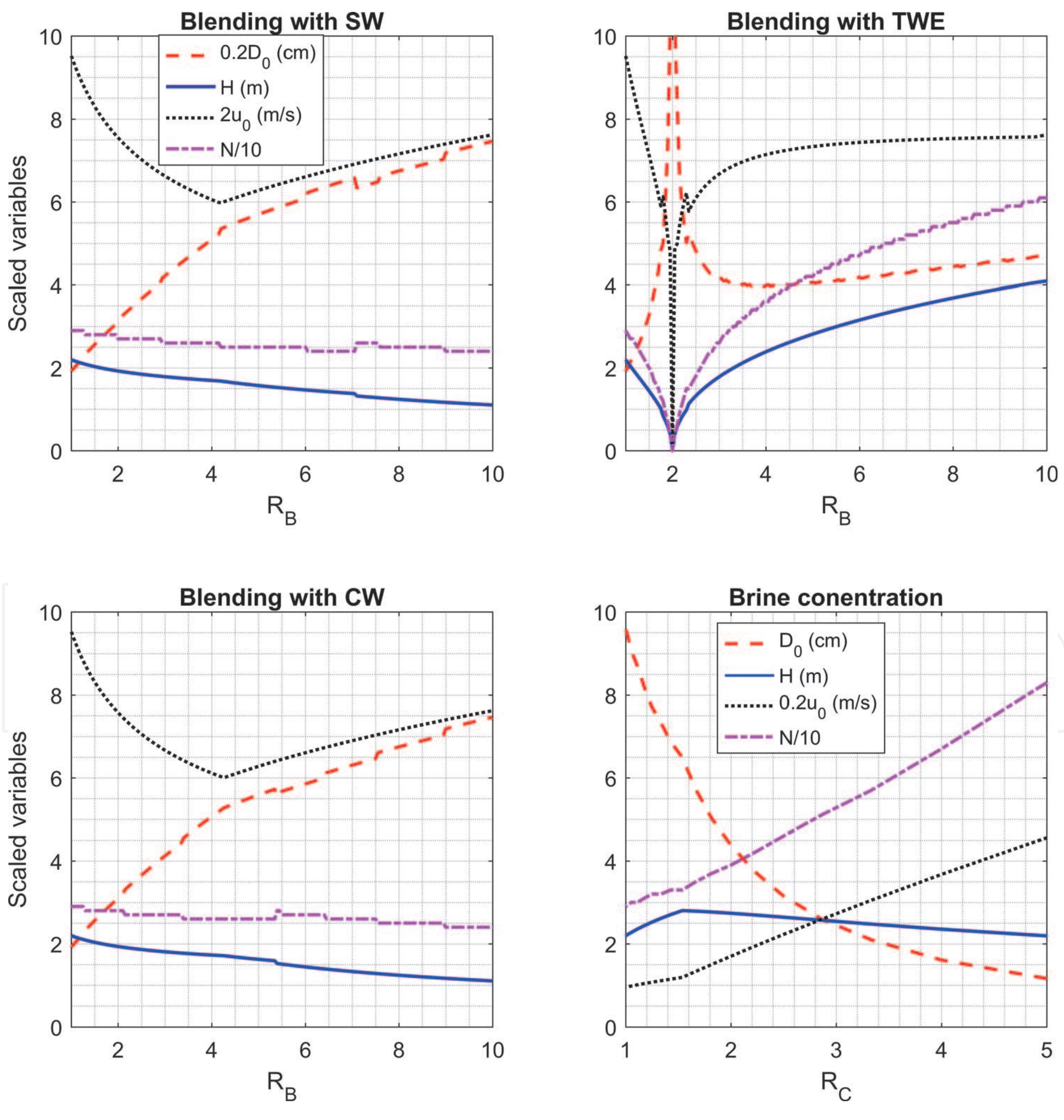


**Figure 6.**
*Variation of H, N, $D_0$ and $u_0$ with $R_B$ and $R_C$ for discharge using a unidirectional diffuser with surfacing plume for $Q_b = 1\ m^3/s$, $\Gamma = 0.01$ and a desired excess salinity of 2 ppt. (variables are scaled differently for the pre-dilution and pre-concentration cases as indicated in the legend).*

of the shoreline is not expected to have a significant effect on outfall dilution (dilution reduction of less than 15% in stagnant receiving water) [21, 22].

## 7. Results and discussion

### 7.1 Cost of outfalls

**Figure 7** shows the comparison of total costs for the four designs (single jet and unidirectional diffuser with submerged and surfacing plume) with $Q_b = 1\ m^3/s$, $\Gamma = 0.01$ and desired excess salinity of 2 ppt. It can be seen that for pre-dilution with SW and CW, the costs of all four designs increase with increase in $R_B$ in spite of the fact that the desired physical dilution decreases with increase in $R_B$. The increase in total cost is caused due to the increase in discharge flow rate. For the case of blending with TWE, however, the costs of all four designs decrease with increasing $R_B$ for $R_B < 2$ due to the rapid reduction of desired physical dilution in that case. (The desired physical dilution goes down from 18 for $R_B = 1$ to 6 for $R_B = 1.5$.) The blended effluent is positively buoyant for $R_B > 2$ and $R_B > 8.7$ when brine is blended with TWE and CW, respectively, and the trends shown are

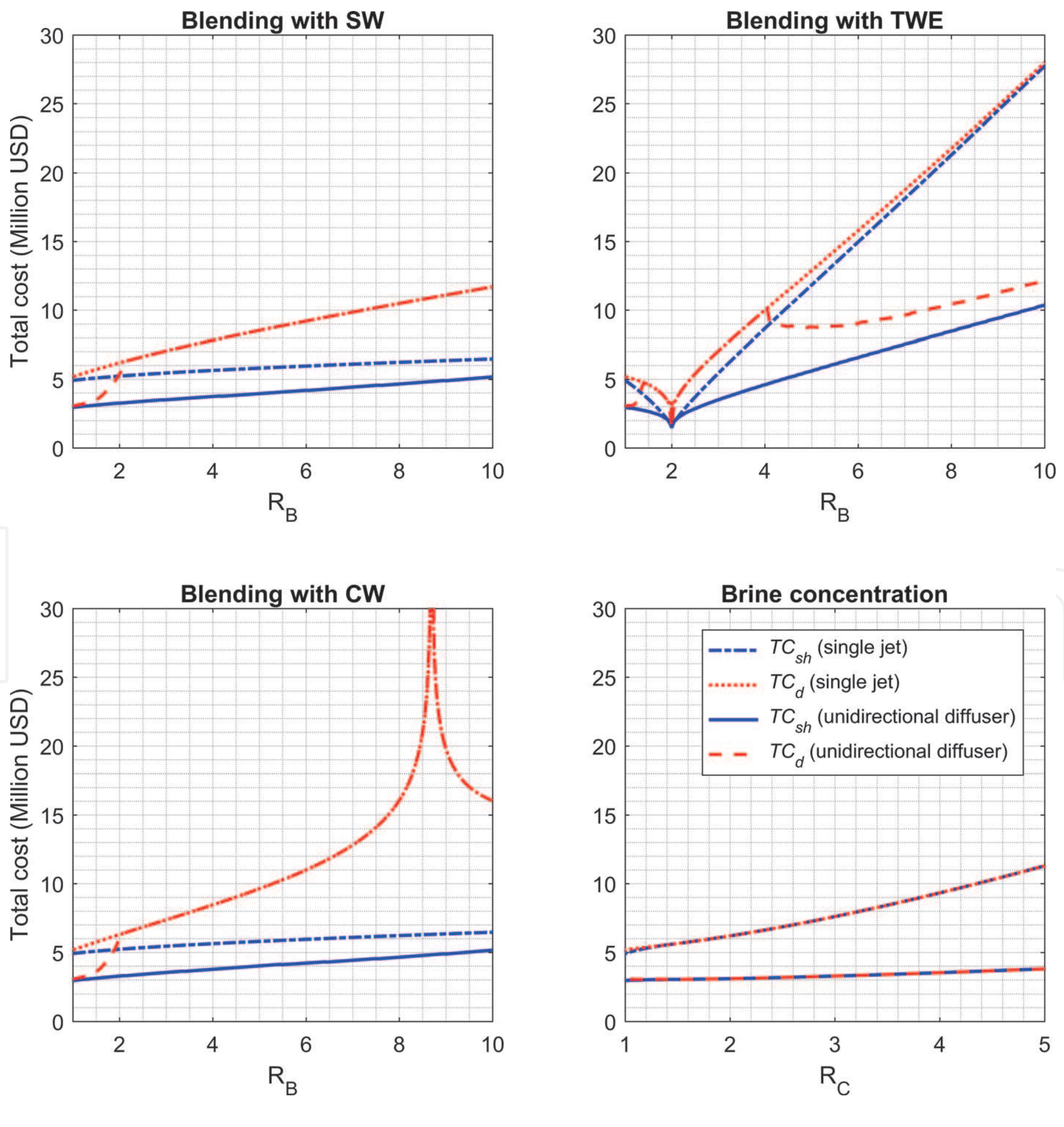


**Figure 7.**
*Total costs of the four design alternatives to achieve desired excess salinity of 2 ppt at the impact point with* $Q_b = 1\ m^3/s$ *and* $\Gamma = 0.01$.

different for $R_B$ in this range. For the case of pre-concentration, the desired physical dilution increases rapidly with $R_C$ leading to the increase in total cost.

**Figure 7** shows that for most of the pre-dilution cases, the design with a single jet is the optimum design when the regulations require the plume to be submerged. Thus, for these cases, the '$TC_d$ (single jet)' and '$TC_d$ (unidirectional diffuser)' curves overlap. For pre-dilution cases, the total cost can be significantly lower for the surfacing plume design as compared to the submerged plume design. For blending with SW ($R_B = 2$), TWE ($R_B = 1.5$) and CW ($R_B = 5$), the ratio of the total cost for surfacing plume design to that for the submerged plume design with a single jet is 0.84, 0.77 and 0.60, respectively. Using a unidirectional diffuser, this ratio is 0.60, 0.58 and 0.42 for blending with SW ($R_B = 2$), TWE ($R_B = 1.5$) and CW ($R_B = 5$), respectively.

For the discharge of brine without pre-dilution or pre-concentration, the total costs (in million USD) of the four designs are $TC_d = 5.2$ and $TC_{sh} = 4.9$ (for a single jet discharge), and $TC_d = 3.1$ and $TC_{sh} = 3.0$ (for a unidirectional diffuser). Thus, compared to the cost of a single jet design with submerged plume, the cost can be reduced by 40% if a multiport diffuser is used (with submerged plume), by 6% if the plume is allowed to hit the surface (but still using a single jet), and 42% if a multiport design with a surfacing plume is adopted.

When brine is concentrated, the desired physical dilution increases rapidly with increase in $R_C$. Hence, discharge of concentrated brine is not preferable from an environmental standpoint. If brine is concentrated, it needs to be discharged with high (perhaps unrealistic) discharge velocity and/or using a large number of ports to generate adequate mixing. **Table 4** shows an example of the design variables calculated for $R_C = 2$. (Only designs with submerged plume are included because they are also the designs which minimize cost).

Pre-concentration of brine increases the concentrations of contaminants present in brine. Thus, the total cost of discharging concentrated brine increases with $R_C$ as shown in **Figure 7**. The processes used to concentrate brine also have some cost. Thus, whether brine should be concentrated prior to discharge depends on the value of the extra fresh water produced compared to the cost of pre-concentration and the additional cost of the outfall. At locations with regulatory restrictions on discharge concentrations, pre-concentration might not be possible. Pre-concentration could be beneficial if brine is concentrated to the extent that salts can be crystallized as there would be no cost of discharge.

The costs in **Figure 7** are calculated for salinity as the contaminant of concern. However, the relative importance of different types of contaminants (present in brine, TWE or CW) depends on the blending ratio (for pre-dilution with TWE and CW). At low blending ratio, the contaminants present in brine require higher dilution and are likely to be the constraining contaminants whereas contaminants present in TWE or CW require higher dilution at high blending ratio. Thus, the designs and the associated costs calculated above need to be adjusted at high blending ratio.

| Design | $N$ | $H$ (m) | $u_0$ (m/s) | Capital cost (million USD) | Operating cost (million USD) | Total cost (million USD) |
|---|---|---|---|---|---|---|
| Single jet with submerged plume | 1 | 11.9 | 17.7 | 3.6 | 2.6 | 6.2 |
| Unidirectional diffuser with submerged plume | 39 | 2.7 | 8.5 | 1.4 | 1.7 | 3.1 |

**Table 4.**
*Example showing calculated design variables for the discharge of concentrated brine ($R_C = 2$) with $\Gamma = 0.01$.*

### 7.2 Effect of threshold concentrations on outfall design

Since the outfall design depends on desired physical dilution, which in turn, depends on the threshold concentrations, it is important to analyze the effect of threshold concentrations on the optimum design. This is illustrated through an example in **Figure 8** in which the threshold concentration of salinity ($\Delta s_{th}$) varies between 0.5 and 5 ppt (above ambient). The variation in required depths and total costs with the threshold salinity is shown for discharge of brine without pre-dilution or pre-concentration.

The required depths and total costs (for designs with submerged and surfacing plume) decrease with increase in threshold concentrations (for discharge through a single jet) because the additional mixing required to achieve those concentrations is less. For a design with multiple ports which requires the plume to be submerged and has the discharge velocity fixed to ensure uniform flow, the required depth is proportional to the inverse of desired dilution, i.e., the depth is proportional to $\Delta s_{th}$. This can be seen for $\Delta s_{th} > 3.3$ ppt. When the discharge velocity is not fixed (for $\Delta s_{th} < 3.3$ ppt), the required depths and total costs reduce with increase in $\Delta s_{th}$ similar to the case of a single jet discharge.

### 7.3 Effect of bottom slope

The optimum design at a location with a mild bottom slope, such as the Arabian Gulf which has bottom slopes as little as about $4 \times 10^{-4}$ [2], can be quite different as compared to the design at a location with a steep slope. With a mild bottom slope, the offshore distance to locate the outfall in sufficient depth of water can be long which also increases the total cost significantly. In that case, it costs less to achieve the desired dilution in small water depth by increasing the discharge velocity and/or the number of ports. This is illustrated by considering outfall designs at two locations with $\Gamma = 0.01$ and 0.001. For discharge using a single jet in deep water (submerged plume), the design variables are independent of $\Gamma$ (Eqs. (12)–(14)) but the total cost is higher for a location with smaller bottom slope because of the increased offshore distance. For discharge using a single jet with a surfacing plume and discharge through a unidirectional diffuser, the design variables can be adjusted to reduce the total cost. But, the total costs are still significantly higher for smaller $\Gamma$. **Figure 9** shows the effect of $\Gamma$ on the total cost to discharge brine pre-diluted with SW using a single jet and a multiport diffuser. The total cost for a submerged plume

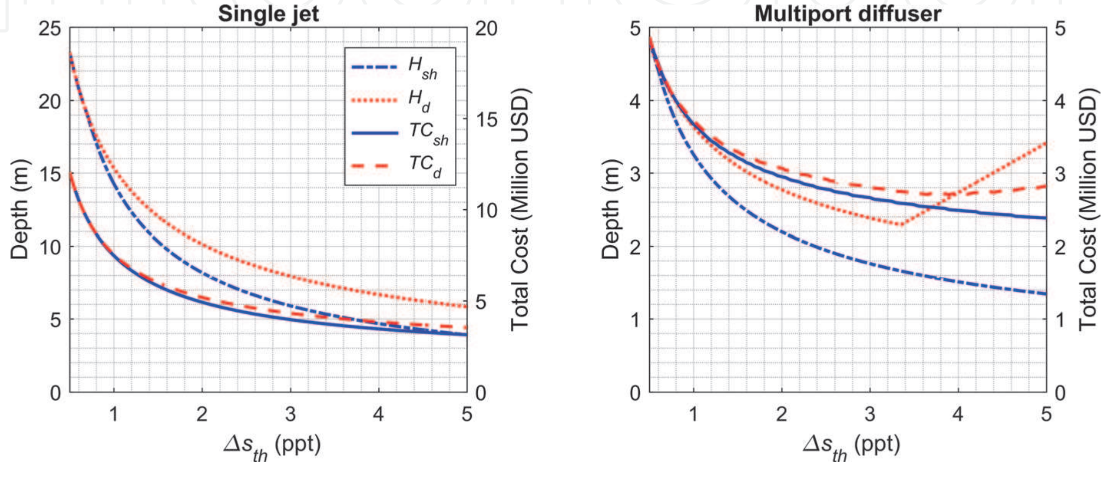


**Figure 8.**
*Variation of $H_d$, $H_{sh}$, $TC_d$ and $TC_{sh}$ with threshold salinity for discharge of brine through a single jet and a tee diffuser with $Q_b = 1\ m^3/s$ and $\Gamma = 0.01$.*

design with $\Gamma = 0.001$ is approximately 10 times the corresponding cost for $\Gamma = 0.01$.

A comparison of optimum design variables at locations with different bottom slopes is shown in **Table 5** for discharge of brine without pre-dilution or pre-concentration. For this example, two bottom slopes ($\Gamma = 0.01$ and $\Gamma = 0.001$) are considered. The design of a single jet with surfacing plume for $\Gamma = 0.001$ has a discharge velocity of 20.8 m/s which is not realistic. The designs with multiple ports are preferable with reasonable velocities. It can be seen from **Table 5** that the cost of the unidirectional diffuser design is about 60% of the cost of a single jet design for $\Gamma = 0.01$ but only 25% of the single jet cost for $\Gamma = 0.001$ which suggests that a multiport design is more realistic at locations with small $\Gamma$.

For the unidirectional diffuser designs in **Table 5**, the required water depths are 1.4 m and 0.8 m (for $\Gamma = 0.001$). Thus, the lengths of outfall pipe to outfall location are 1.4 km and 0.8 km, which are quite long. For such locations, a staged diffuser [37] can also be used which has ports along the length of the outfall pipe. For the same diffuser length, water depth, flow rate and discharge velocity, the dilution of a staged diffuser in quiescent conditions is less than the dilution of a unidirectional diffuser [18]. But considering that the length of the outfall pipe is much longer as compared to the diffuser length for a unidirectional diffuser design, the staged diffuser design will get much higher dilution than the unidirectional diffuser. In fact, if a staged diffuser is designed to achieve the desired physical dilution, its offshore distance would be less that the 1.4 km (or 0.8 km) distance for the unidirectional diffuser design.

### 7.4 Comparison with the cost of discharging brine without pre-dilution or pre-concentration

As shown in **Figure 7**, the cost of discharging brine blended with TWE is less than the cost of discharging brine without pre-dilution for $R_B < 2$. However, the total costs (for all four designs) for other pre-dilution cases increase as $R_B$ increases (except when brine is blended with CW with $R_B > 8.7$), which means that the cost of discharging pre-diluted brine is higher than the cost of discharging brine without pre-dilution. However, these costs should be compared to the cost of two outfalls for discharging brine and the pre-dilution stream separately (for blending with

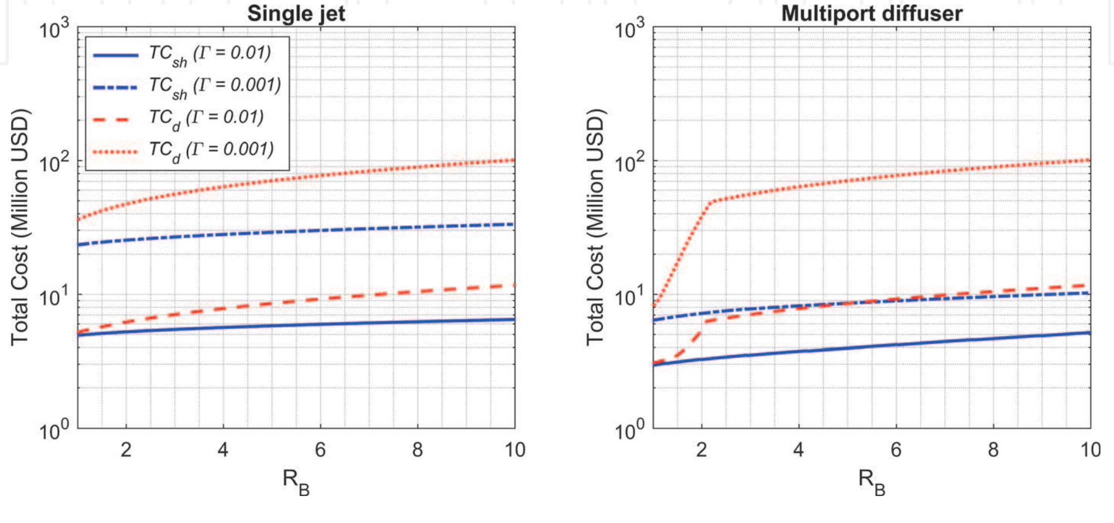


**Figure 9.**
*Comparison of total costs at locations with $\Gamma = 0.01$ and $\Gamma = 0.001$ for the discharge of brine pre-diluted with SW using a single jet and a tee diffuser with $Q_b = 1\ m^3/s$ and $\Delta s_{th} = 2\ ppt$.*

| Design | Variables | $\Gamma = 0.01$ | $\Gamma = 0.001$ |
|---|---|---|---|
| Single jet with submerged plume | $H$ (m) | 10.1 | 10.1 |
| | $u_0$ (m/s) | 5.4 | 5.4 |
| | TC (Million USD) | 5.2 | 35.9 |
| Single jet with surfacing plume | $H$ (m) | 8.2 | 5.2 |
| | $u_0$ (m/s) | 8.3 | 20.8 |
| | TC (Million USD) | 4.9 | 23.3 |
| Unidirectional diffuser with submerged plume | $H$ (m) | 2.8 | 1.4 |
| | $u_0$ (m/s) | 2.8 | 2.0 |
| | $N$ | 26 | 150 |
| | TC (Million USD) | 3.1 | 8.2 |
| Unidirectional diffuser with surfacing plume | $H$ (m) | 2.2 | 0.8 |
| | $u_0$ (m/s) | 4.8 | 8.2 |
| | $N$ | 29 | 174 |
| | TC (Million USD) | 3.0 | 6.4 |

**Table 5.**
*Example showing calculated design variables for discharge of brine (without pre-dilution or pre-concentration) at two locations with* $\Gamma = 0.01$ *and* $\Gamma = 0.001$.

TWE and CW; since these effluents have to be discharged anyway), which will likely be more than the cost of discharging the blended effluent.

Unlike TWE and CW, SW does not need a separate outfall. In fact, intake of seawater for pre-dilution adds an extra cost. Also, as shown in **Figure 7**, the total cost increases with increase in $R_B$ for the case of pre-dilution with SW. Thus, pre-diluting brine with SW is not economical. But it might be needed if there are regulatory restrictions on discharge concentrations themselves which are not met without pre-dilution.

For the calculations in this paper, a wide range of $R_B$ (1 to 10) is considered. The flow rate of condenser cooling water from power plants is usually quite high as compared to the flow rate of brine. Therefore, a high value of $R_B$ is possible for CW. However, the availability of TWE for blending with brine can be limited as it can be re-used or used for other purposes (e.g., irrigation).

## 8. Conclusions

Brine management strategies cause changes to the discharge flow rate, discharge concentrations of contaminants and the density difference between the effluent and seawater, and thus require changes to the outfall design. It is shown that pre-dilution with seawater is less economical than the discharge of brine without any pre-dilution. Thus, seawater should only be used for pre-dilution if there are restrictions on discharge concentrations of contaminants and other effluents (TWE or CW) are not available for pre-dilution. Concentration of brine is also not viable from an environmental standpoint. On the other hand, pre-dilution with TWE or CW is likely to be economically beneficial.

For the design of a new outfall for a desalination plant with known amount of pre-dilution or pre-concentration, design variables are calculated for both a single port and a multiport outfall. Depending on the environmental regulations which might have restrictions on plume visibility, design parameters are evaluated for a submerged plume or a surfacing plume. It is shown that when the plume is allowed to hit the water surface (no restrictions on plume visibility), the required water depth and total cost of the outfall can be significantly reduced. For such cases, the required water depth and the offshore distance decrease as the blending ratio increases. At locations which require the plume to be submerged, the design with a single jet is found to have lower cost than a design with multiple ports (for most values of the blending ratio). However, for locations with no restrictions on plume visibility, use of a multiport diffuser is recommended as it can result in much lower cost than a single jet.

The effect of bottom slope and threshold concentrations on outfall design is also explored. Locations with mild bottom slope encourage the use of outfalls with multiple ports which can reduce the required water depth and, in turn, the offshore distance of the outfall from the shoreline. An increase in threshold concentrations usually leads to a reduction in outfall cost as the outfall needs to achieve a smaller dilution. Similarly, more stringent regulations (smaller threshold concentrations) can lead to a rapid increase in outfall cost.

## Acknowledgements

This work was supported by Kuwait-MIT Center for Natural Resources and the Environment (CNRE), which was funded by Kuwait Foundation for the Advancement of Sciences (KFAS).

## Conflict of interest

The authors declare no conflict of interest.



## Author details

Ishita Shrivastava* and Edward Eric Adams
Massachusetts Institute of Technology, Cambridge, MA, USA

*Address all correspondence to: ishita@mit.edu

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