

DESIGN OF SEAWATER DESALINATION BRINE DIFFUSERS

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ABSTRACT

Reverse Osmosis (RO), the most common seawater desalination process, generates brine waste whose salinity is about twice that of the intake seawater. This level of salinity would be toxic to many marine organisms, so it must be quickly diluted to safe levels. Until recently, the California Ocean Plan did not specifically address desalination discharges. This changed in a 2015 amendment in which new regulations were adopted. These include the definition of a brine mixing zone (BMZ) and assessment of mortality of marine organisms due to the shear and turbulence resulting from the discharge. Predicting the entrainment of marine organisms into the diffuser jets and the effect of turbulence on them is difficult. To unify the process, the California State Water Resources Control Board (SWRCB) commissioned two studies for diffuser design and prediction of entrainment mortality. In addition to this hydrodynamic effect, recent field studies in Sydney, Australia, suggest that the dynamics of the dense bottom spreading layer can also result in environmental impacts. In this paper we review and summarize the changes in the Ocean Plan. We give example applications to diffuser design and show the implications of designing to meet salinity requirement either at the jet impact point or at the end of the near field for the size of the BMZ and shear mortality using the recommended California design procedures. The velocity of the bottom spreading layer can be considerable and may need to be considered in design. We discuss the implications of hydrodynamic impacts on diffuser design.

Keywords: Seawater desalination; Diffusers; Brine disposal; Dilution; Mixing zones

1 INTRODUCTION

Diffusers for brine disposal resulting from seawater desalination are typically designed to meet a salinity limit within a certain distance from the diffuser. Some typical international standards are summarized in SCCWRP (2012). For example, Perth, Australia requires a salinity increment less than 1.2 ppt within 50 m and 0.8 ppt within 1,000 m from the diffuser. The recent requirements for brine disposal from desalination facilities of the Water Quality Control Plan for Ocean Waters of California (SWRCB, 2016), hereafter The Ocean Plan, contains limitations on salinity that must be met at the edge of a designated Brine Mixing Zone (BMZ).

New environmental issues related to discharge hydrodynamics are also being raised. The Ocean Plan requires estimation and minimization of mortality due to turbulence of organisms that are entrained into the diffuser jets. Field tests on an operating brine diffuser (Clark et al. 2018) showed impacts due to higher near-bed flow away from the diffuser that can "scour" the seabed.

Two recent reports were commissioned by the State of California (Roberts, 2018a, 2018b) to present procedures used to evaluate brine diffusers and estimate shear mortality and the BMZ. These reports are summarized in this paper. We address the issues related to diffuser hydrodynamics and how the Ocean Plan affects diffuser design. Brine diffuser designs for typical multiport diffuser designs are presented along with methods to predict dilutions and the extent of the BMZ. A suggested method is then presented to predict the volume of water that is entrained into the jets that may be subject to damaging turbulence. Finally, an example of how to apply these methods to predict dilution and entrainment for a typical diffuser is presented.

2 BACKGROUND

Brine concentrate is more dense than seawater and is often discharged from a diffuser as high velocity upwardly-inclined jets. The high exit velocity causes shear that entrains, or engulfs, ambient seawater, which then mixes with and dilutes the jets, resulting in rapid salinity reduction.

A laboratory image and definition sketch of the major characteristics of an inclined dense jet are shown in Figure 1. Figure 1a shows a laser-induced fluorescence (LIF) image with relative salinity levels shown in false

color, ranging from red (high levels) through orange, yellow, and green to blue (low levels). Figure 1b defines the main properties of a dense jet inclined at an angle Θ to the horizontal.

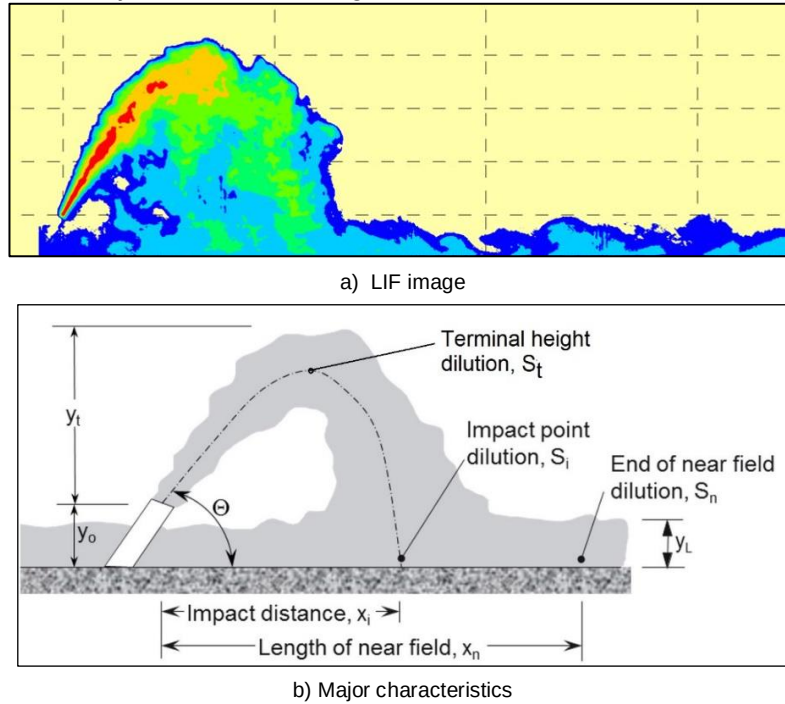


Figure 1. a) LIF image and b) definition of major characteristics of an inclined dense jet. After Roberts et al. (1997).

The dominant hydrodynamic processes change along the flow trajectory. Initially, the discharge behaves like a jet that entrains ambient water that dilutes it. The jet reaches a terminal rise height y_t where the centerline dilution is S_t . It then descends as a plume with continuing entrainment and dilution. The centerline of the descending plume, where it impacts the bed, is called the impact point, and the dilution there is the impact dilution, S_i . The distance from the nozzle to the impact point is x_i . After impacting the bed, the flow becomes horizontal and proceeds as a turbulent density current that continues to entrain and dilute. Eventually, the turbulence collapses under the influence of its self-induced density stratification, and active mixing essentially ceases. This collapse signifies the end of the near field. It occurs at a distance x_n (the length of the near field), where the dilution is the near field dilution, S_n . The increase in dilution from the impact point to the end of the near field can be substantial.

The near field therefore encompasses the ascending jet and the descending plume and extends beyond the seabed impact point to include the horizontal flow up to the point of turbulence collapse. For typical brine diffusers, the near field will extend a few tens of meters from the diffuser where near field dilutions will range from about 15:1 to 40:1. Beyond the near field, mixing is primarily due to ambient (oceanic) turbulence. This is the far field, where mixing is much slower than in the near field.

Many experiments have been performed over the years to predict the main flow characteristics of a single dense jet (Figure 1b). The optimum and usual angle for jets from brine diffusers is 60° . For typical brine discharge conditions, the dilutions and geometrical properties for 60° jets can be estimated from (Roberts et al. 1997):

$$\frac{S_i}{F} = 1.6 \quad \text{and} \quad \frac{S_n}{F} = 2.6 \quad \text{and} \quad \frac{S_t}{F} = 0.6 \quad (1abc)$$

$$\frac{y_t}{Fd} = 2.2 \quad \text{and} \quad \frac{x_i}{Fd} = 2.4 \quad \text{and} \quad \frac{x_n}{Fd} = 9.0 \quad \text{and} \quad \frac{y_L}{Fd} = 0.7 \quad (2abcd)$$

where F is the densimetric jet Froude number (also referred to simply as the Froude number) defined by:

$$F = \frac{u}{\sqrt{g'_o d}} \quad (3)$$

where d is the port diameter, u the jet exit velocity, $g'_o = g(\rho_o - \rho_a)/\rho_a$, is the modified acceleration due to gravity, g the acceleration due to gravity, ρ_a the ambient density, and ρ_o the effluent density ($\rho_o > \rho_a$). The

geometrical properties y_i , x_i , and x_n scale with Fd . Eqs. 1 and 2 can be used to estimate the main characteristics of 60° jets. Other nozzle angles have been reported by Abessi and Roberts (2015) and others.

3 CALIFORNIA OCEAN PLAN

The Ocean Plan (SWRCB, 2016) contains requirements to address desalination facilities. The most relevant here relate to salinity and shear mortality to aquatic organisms. The Plan states that “Discharges shall not exceed a daily maximum of 2.0 parts per thousand (ppt) above natural background salinity measured no further than 100 meters (328 ft) horizontally for each discharge point. There is no vertical limit to this zone.”

In addition, the Ocean Plan defines the BMZ as: “...the area where salinity may exceed 2.0 parts per thousand above natural background salinity...The standard brine mixing zone shall not exceed 100 meters (328 feet) laterally from the points of discharge and throughout the water column...The brine mixing zone is an allocated impact zone where there may be toxic effects on marine life due to elevated salinity.” And “Multiport diffusers shall be engineered to maximize dilution, minimize the size of the brine mixing zone, minimize the suspension of benthic sediments, and minimize mortality of all forms of marine life.”

The interpretation of the brine mixing zone (BMZ) is that it is the area within which the salinity may exceed 2 ppt over natural background with a maximum allowable extent of 100 m from the diffuser. The BMZ for a linear diffuser is therefore interpreted as in Figure 2, where L is the diffuser length (end port to end port) and r the distance to the 2 ppt salinity isocontour.

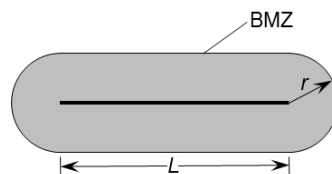


Figure 2. BMZ area definition

4 SHEAR MORTALITY

4.1 Turbulence and Shear Mortality

It has been suggested that planktonic organisms entrained into the high velocity turbulent jets could be subject to injury, possibly fatal, because of turbulence and shear.

Foster et al. (2013) reviewed the biological literature on the effects of turbulence and shear stress on aquatic organisms. The experimental evidence suggests that the main turbulence effect on planktonic organisms is caused by small-scale eddies, known as the Kolmogorov scales, and that most damage occurs when their size is comparable to or smaller than the size of the organisms. These small eddies subject the organism to high strain rates and viscous shear stress that can cause injury or death, whereas larger eddies mainly translate the organisms without causing significant shear. Studies on the effects of flow and turbulence on marine and freshwater organisms are summarized in Roberts (2018a), Appendix A.

Rehmann et al. (2003a) performed laboratory experiments in which zebra mussel veligers were subjected to controlled turbulence in beakers. They found that mortality depended on the ratio $d^* = d/\eta$, where η is the Kolmogorov size and d is the body length. Mortality increased from about 35% for $d^* < 0.9$ to about 62% for $d^* > 0.9$. That is, the mortality changed significantly when the size of the larvae was about 90% of the Kolmogorov scale. Note that, in their experiments, the mortality rate was about 35% in essentially quiescent water so the incremental mortality for $d^* > 0.9$ is less than 65%. The smallest Kolmogorov scales in these experiments corresponded to $d^* \approx 1.1$. Jessopp (2007) measured survival rates in a highly turbulent tidal channel with $0.06 < \eta < 0.25$ mm. Survival rates varied with species; thin-shelled veligers showed significant mortality of 45% to 64%, but some taxa showed no mortality. Zhang et al. (2017) further confirmed the importance of the Kolmogorov scale relative to organism size as the most important parameter in determining veliger mortality. Their study extended the range of d^* studied by Rehmann et al. from 1.1 to 3.4. Zhang's experiments were conducted in the context of enhancing mortality of golden mussel veligers by artificially generated turbulence in pipes. They performed experiments in pipelines fitted with turbulence-generating devices and measured mortality of veligers and velocity and turbulence intensity with an acoustic Doppler velocimeter. The mortality rate increased with d^* , i.e. it increases as the Kolmogorov scale becomes smaller relative to the body size. The criterion for steady killing is $d^* > 1$. Although their data showed considerable scatter, the fraction killed increased from about 10% for $d^* = 0.4$ to 25% at $d^* = 3.4$. Mortality increased in the first five minutes or so and then remained relatively constant.

4.2 Entrainment and Turbulence Scales in Jets

The results of the previous section are difficult to translate to diffuser-induced turbulence. In the beaker experiments, the organisms were subject to homogeneous turbulence for up to 24 hours whereas in the diffuser jets, the organisms are subject to turbulence for a few seconds. Kolmogorov scales are shortest near the nozzle and increase along the trajectory; they are shortest on the centerline and increase towards the jet edges. In the field and pipeline experiments, the turbulence levels and transit times through the most turbulent regions varied. These issues are discussed below. For more details, see Roberts (2018a).

The ascending and descending portions of dense jets, Figure 1, have different dynamics. The ascending portion is driven by the source momentum flux, which is proportional to $u^2 d^2$ where u is the jet velocity as it exits the port and d the port diameter or equivalent port diameter for a check valve. A flow driven by momentum flux only is called a jet (Fischer et al. 1979). Jets have high turbulent energy dissipation rates, therefore small Kolmogorov scales and potentially high shearing-related mortality. Density differences, or buoyancy effects, drive the descending portion. A flow driven by buoyancy flux only is called a plume. Energy dissipation rates are much smaller in this region and are not expected to be high enough to cause mortality. The difference between the two regions can be seen in this video: <http://www.youtube.com/watch?v=TCZV2gVkpfg>.

Most of the shearing-related mortality is therefore expected to occur in the ascending jet region, whose turbulence properties are well known. The size of the Kolmogorov eddies η_c on the jet centerline is given by:

$$\frac{\eta_c}{x} = 0.24 \text{Re}^{-3/4} \quad (4)$$

where x is distance measured along the centerline and $\text{Re} = ud/\nu$ is the jet Reynolds number. The Kolmogorov scales therefore increase linearly with distance along the jet trajectory. The ratio of the Kolmogorov scale on the centerline to that at the jet edge is:

$$\frac{\eta_c}{\eta_e} = \left\{ \frac{(\ell_c/\ell_e)}{(\tilde{u}_c/\tilde{u}_e)^3} \right\}^{1/4} \approx 0.2 \quad (5)$$

where the subscripts c and e refer to the jet centerline and edge, respectively. Eq. 5 indicates that the Kolmogorov scales at the jet edge are about five times larger than on the centerline.

Travel times along the jet trajectory of entrained larvae will vary with their distance from the centerline. On the centerline, the time for a particle to traverse a distance χ from the nozzle is given approximately by:

$$t = \int_0^\chi \frac{dx}{u_m} = \int_0^\chi \frac{x}{6.2ud} dx = \frac{\chi^2}{12.4ud} \quad (6)$$

The volume flow rate in a jet Q is directly related to dilution and is given by (Fischer et al. 1979):

$$Q = S_a Q_j = 1.4 S_m Q_j \quad (7)$$

where Q_j is the jet discharge rate, S_a the average dilution, and S_m the minimum (centerline) dilution. The average and minimum dilutions are related by $S_a = 1.4 S_m$.

4.3 Estimation of Potentially Harmful Entrained Flow into Brine Diffuser Jets: Mortality Due to Jet Turbulence

Only planktonic organisms that cannot swim away from the jets are likely to be entrained so they are the main emphasis here. The biological evidence suggests that the main effect of turbulence on these organisms is mortality due to shear stresses resulting from eddies whose smallest scales (the Kolmogorov eddies) are less than or comparable to their body size. Some natural mortality due to turbulent shear will occur in the ocean so we are only interested in the incremental mortality due to the jets. This incremental mortality will occur where energy dissipation rates are greater than naturally occurring, i.e. where the Kolmogorov scales are smaller than ambient oceanic values.

There are few measurements of Kolmogorov scales in the ocean. Walter et al. (2014) reported values in Monterey Bay, California, to be about one mm. The Kolmogorov scale is insensitive to changes in the energy dissipation rate and should not vary greatly in California coastal waters. Therefore, the region in the jets where entrained organisms may be exposed to harmful turbulence is presumed to be where the Kolmogorov scale is less than one mm.

4.4 Diffuser Design Implications

It is possible to design brine diffusers to meet the Ocean Plan's salinity requirement either at the impact point or at the end of the near field (Figure 1). If it is met at the impact point, the required dilution is S_i and Eq. 1a applies; if it is met at the near field, the required dilution is S_n and Eq. 1b applies.

If the receiving water limit for salinity is met at the impact point, the potentially harmful entrained flow is greater because more of the required dilution occurs in the rising jet region. If it is met at the end of the near field, the volume of entrained flow exposed to lethal turbulence is less because some of the required dilution occurs in the horizontal density current that is not subject to high shear rates. Meeting the salinity requirement at the impact point results in a much smaller BMZ than if met at the near field, but meeting at the impact point requires a higher jet velocity and therefore higher head loss in the outfall. These issues are illustrated in the example calculation below.

4.5 Recommended Procedure for Entrainment Calculations

To estimate the entrained flow for arbitrary jet angles, Roberts (2018a) recommends use of the EPA mathematical model UM3. UM3 was originally developed by the US EPA and has been widely used around the world. It is part of the modeling suite Visual Plumes and is freely available for download from the State Water Board at:

https://www.waterboards.ca.gov/water_issues/programs/ocean/
or <https://ftp.waterboards.ca.gov/>

A user's manual is available on the FTP site, and it is described in other publications such as Baumgartner et al. (1994), Frick (2004), Frick et al. (2010), and Frick and Roberts (2016).

UM3 is an entrainment model for jet and plume calculations typical of wastewater discharges from diffusers. It computes the three-dimensional trajectories of individual and merging jets and plumes in stationary and flowing currents and stratified and unstratified environments. It has the advantage that its emphasis is on average properties and it predicts the entrained volume flux directly. It is simple to use and is robust. For reasons discussed below, however, we do not recommend it to be used for impact or near field dilutions, but it can be used to estimate jet properties up to the terminal rise height, which is the region where shear mortality is expected to occur.

UM3 was run for a variety of typical conditions and the predictions were expressed in dimensionless form to compare with the previous experimental results. A typical jet trajectory and plume width are shown in Figure 3 for a 60° jet with Froude number $F = 24$. The height to the top of the jet at its terminal rise height y_t (Figure 1b) was computed as the centerline height at the terminal rise plus half the plume diameter. The results are summarized in Roberts (2018a).

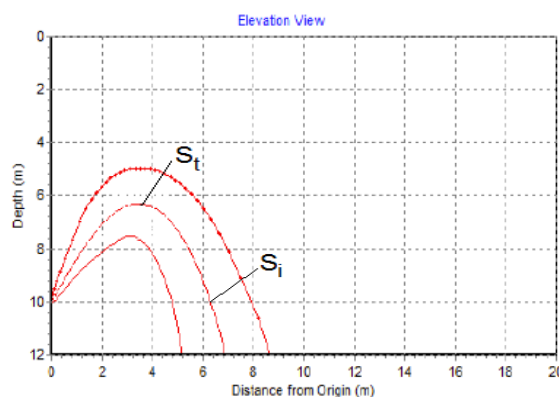


Figure 3. Typical UM3 graphical output for a 60° dense jet.

For 60° jets, the UM3 predicted dimensionless dilutions at the terminal rise height that agree well with the experimental value $S_t/F = 0.6$ (Eq. 1c). For nozzle angles ranging from 15 to 85° UM3 underestimates the normalized rise height y_t/Fd and impact distance x_i/Fd by 16 to 27%. UM3 significantly underestimates the impact dilution.

The significant underestimation of impact dilution of dense jets by UM3 (and other entrainment models) has been previously reported by Palomar et al. (2012). Some reasons for this are that the entrainment models assume the flow to be everywhere radially symmetric whereas experimental observations show the flow to become increasingly asymmetric as the terminal rise height is approached. This asymmetry is caused by "gravitational instabilities" (heavier fluid over lighter fluid) that cause considerable internal mixing that is not

accounted for in the models. In addition, the length of the jet trajectory is underestimated, providing less opportunity for entrainment along its length.

Where the flow is more jet-like and round, however, i.e. where it is dominated by source momentum during its upward trajectory, UM3 gives good dilution predictions. This was also observed in comparisons of UM3 predictions with experimentally based empirical equations for the desalination outfall in Monterey, CA (Roberts 2016), which has horizontal jets and whose dilution is momentum-dominated.

Note that, in UM3, the default predicted dilution that is labeled *Dilutn* is actually an average, or flux-average, value. The centerline dilution, denoted by *CL-diln*, is not outputted by default and must be added. For a round jet, UM3 assumes the centerline dilution is one-half of the average dilution.

Note also that UM3 does not predict near field dilution; it only applies in the free jet or plume region and not after the transition to horizontal flow or the subsequent turbulent collapse. This does not affect its ability to evaluate or predict shear mortality in the ascending jet region.

It is recommended to apply UM3 to predict entrainment at the terminal rise height. This is obtained at the level designated in UM3 as “local maximum rise or fall.” Denoting the UM3 average dilution at this point by S_{ta} , the potentially harmful entrained volume flux Q_e is then computed from:

$$Q_e = nQ_j(S_{ta} - 1) \quad (8)$$

where n is the total number of ports and Q_j is the volume flux per port. This calculation assumes no interference or merging of the jets in the ascending region. For multiport diffusers, this is assured if $s_p/Fd > 2$ (Abessi and Roberts, 2014).

The Kolmogorov scales up to the terminal rise height should be estimated from Eq. 6 where x is replaced by χ , the distance along the curved jet centerline from the nozzle to the terminal rise height. This can be obtained from the UM3 output, which provides horizontal and vertical coordinates of the jet trajectory. If the Kolmogorov length at the terminal rise height is greater than one mm, the entrained volume flux should be computed up to the point where it is equal to one mm. This point can be calculated from Eq. 4. For typical desalination diffusers, however, the Kolmogorov scale will be less than one mm at the terminal rise height so this calculation will not be necessary.

5 EXAMPLE DIFFUSER DESIGN

5.1 Introduction

This section presents an example calculation for a diffuser design as stated in the Ocean Plan and application of the recommended method for estimating the volume of entrained water that may be subject to harmful turbulent shear.

Design of a brine diffuser involves many variables: The outfall length (and therefore discharge depth), number of ports and their orientation and diameter, port spacing (and therefore diffuser length), and diffuser configuration (whether the ports are in one or more multiport rosettes or arranged linearly on one or both sides of the diffuser). A full discussion of design involving all of these variables is beyond the scope of the present paper and the final project will include other considerations such as local conditions, constructability and cost. Some general observations can be made, however.

If possible, the nozzles should be oriented at 60° to minimize shear entrainment and jet velocity. This is the case for the following example, where the discharge depth is assumed to be prescribed and the optimum number of ports and the diffuser length are determined. If the discharge depth and diffuser length are both variables, however, there is no optimum hydraulic design - discharge into shallower water will require a longer diffuser - and other factors will come into play. If the receiving water depth is predetermined and shallow and the diffuser length constrained, such as with a single rosette riser, it may be necessary to orient the nozzles at less than 60° to prevent plume surfacing. An example of the procedure for this case is given in Roberts (2018b), Section 3.2.

For a linear diffuser the ports can discharge to one or both sides. Discharge to one side results in a net horizontal momentum flux that can aid in moving the mixed wastefield offshore. The diffuser length and size of the BMZ are larger. Discharge to both sides results in no net horizontal momentum flux; the diffuser is shorter and the size of the BMZ is smaller. In the following example, we assume discharge is to one side. An example of a linear diffuser with discharge to both sides is given in Roberts (2018b), Section 3.3.

5.2 Design Procedure

For this example, we assume a seawater desalination plant that produces 2.63 m³/s (60 mgd) of brine. The ambient ocean salinity is 34 ppt and the discharge salinity is doubled to 68 ppt. Assuming temperatures of 20°C,

the ambient density $\rho_a = 1024.0 \text{ kg/m}^3$ and the effluent density $\rho_o = 1050.2 \text{ kg/m}^3$. The depth of the ports is assumed to be 9.1 m (30 ft). We assume a linear diffuser array with the ports arranged on one side.

The primary environmental design requirements are initial dilution and plume submergence. A salinity increment of 2 ppt requires a dilution:

$$S = \frac{68 - 34}{2} = 17 \quad (9)$$

The diffuser can be designed to achieve this dilution either at the impact point or at the end of the near field; both calculations are presented here. Abessi and Roberts (2015) suggest that the rise height y_t can be up to 90% of the water depth with no effect of the free surface on dilution. Therefore, we take the maximum rise height y_t as 90% of the port depth, i.e. 8.2 m (27 ft). The following calculation is to compute the minimum number of ports required (and therefore minimum diffuser length) to achieve $y_t \leq 8.2 \text{ m}$ and salinity after initial dilution less than 2 ppt. Increasing the number of ports above this minimum number results in lower jet velocity and rise height but does not significantly affect the entrained volume. It increases the diffuser length and possibly the size of the BMZ.

The following steps assume the dilution $S = 17$ (Eq. 9) needed to meet the salinity requirement occurs at the impact point. To computing the diffuser configuration:

1. Calculate the required Froude number from Eq. 1a.

$$F = \frac{S}{1.6} = \frac{17}{1.6} = 10.6$$

2. Calculate the nozzle diameter from Eq. 2a:

$$d = \frac{y_t}{2.2F} = \frac{8.2}{2.2 \times 10.6} = 0.35 \text{ m}$$

3. Calculate the jet exit velocity from Eq. 3:

$$u = F \sqrt{g \frac{\rho_o - \rho_a}{\rho_a} d} = 10.6 \sqrt{9.81 \times \left(\frac{1050.2 - 1024.0}{1024.0} \right) \times 0.35} = 3.1 \text{ m/s}$$

4. Calculate the flow from this port (velocity times port area):

$$Q_j = u \frac{\pi}{4} d^2 = 3.1 \times \frac{\pi}{4} \times 0.35^2 = 0.30 \text{ m}^3/\text{s} = 7.11 \text{ mgd}$$

5. Calculate the required number of ports n from:

$$n = \frac{Q_T}{Q_j} = \frac{2.63}{0.30} = 8.8$$

6. Because a diffuser must have an integral number of ports, we round up to the nearest whole number, so $n = 9$.

7. Recompute the flow per port from:

$$Q_j = \frac{Q_T}{n} = \frac{2.63}{9} = 0.29 \text{ m}^3/\text{s} = 6.6 \text{ mgd}$$

Then:

- a. Recompute the port diameter d to achieve the impact dilution $S_i = 17$ ($F = 10.6$). This is done by rearranging Eq. 3 given the jet flow rate Q_j , and jet velocity $u = 4Q_j / \pi d^2$:

$$\begin{aligned} d &= \left(\frac{4Q_j}{F\pi} \right)^{2/5} \left(g \frac{\rho_o - \rho_a}{\rho_o} \right)^{-1/5} \\ &= \left(\frac{4 \times 0.29}{10.6 \times \pi} \right)^{2/5} \left(9.81 \times \frac{1050.2 - 1024.0}{1024.0} \right)^{-1/5} \\ &= 0.34 \text{ m} \end{aligned}$$

- b. Compute the near field dilution from Eq. 1b.

$$S_n = 2.6 \times 10.6 = 28$$

- c. Compute the rise height, impact distance, and the near field length from Eq. 2abc.

$$y_t = 2.2Fd = 2.2 \times 10.6 \times 0.34 = 7.9 \text{ m}$$

$$x_i = 2.4Fd = 2.4 \times 10.6 \times 0.34 = 8.7 \text{ m}$$

$$x_n = 9.0Fd = 9.0 \times 10.6 \times 0.34 = 32.4 \text{ m}$$

8. Compute the minimum port spacing s_p to avoid jet interference from:

$$s_p = 2Fd = 2 \times 10.6 \times 0.34 = 7.2 \text{ m}$$

9. Compute the diffuser length (assuming the ports are on one side of the diffuser) from:

$$L = (n-1)s_p = (9-1) \times 7.2 = 58 \text{ m}$$

The calculations were then repeated assuming that the dilution was met at the end of the near field using Eq. 1b. Table 1 summarizes the results (for a 60° nozzle angle).

Table 1. Summary of Diffuser Designs for Trial Case

Parameter	If salinity requirement are met at:	
	Impact point	End of near field
Number of ports, n	9	5
Port diameter, d	0.34 m	0.53 m
Jet velocity, u	3.1 m/s	2.4 m/s
Froude number, F	10.6	6.6
Rise height, y_t	8.0 m	7.6 m
Impact dilution, S_i	17	10
Near field dilution, S_n	28	17
Impact distance, x_i	8.8 m	8.3 m
Near field length, x_n	33 m	31 m
Port spacing, s	7.3 m	7.3 m
Diffuser length, L	59 m	29 m

5.3 Entrainment, Turbulence, and BMZ Calculations

UM3 was then run for the two diffuser designs in Table 1. The dilutions S_{ta} at the terminal rise height were 6.71 and 4.22 respectively. The steps to compute entrainment are:

1. Compute the jet Reynolds number from:

$$Re = \frac{ud}{\nu} = \frac{3.1 \times 0.34}{1.12 \times 10^{-6}} = 9.4 \times 10^5$$

2. Compute the jet path length from nozzle to the terminal rise height from the UM3 trajectory output:

$$\chi = \sum_{i=1}^j \sqrt{(\Delta x)^2 + (\Delta y)^2}$$

where Δx and Δy are the horizontal and vertical displacements of the jet centerline between computational steps i and $i+1$ up to the local maximum rise. These displacements are obtained from the columns labeled *Depth* (for the vertical y -displacements) and *x-posn* (for the horizontal x -displacements). The computed lengths are 5.8 m and 5.0 m respectively.

3. Compute the centerline Kolmogorov scale at the terminal rise height from Eq. 4:

$$\begin{aligned}\eta_c &= 0.24\chi \text{Re}^{-3/4} \\ &= 0.24 \times 5.8 \times (9.2 \times 10^5)^{-3/4} = 4.7 \times 10^{-5} \text{ m} = 0.047 \text{ mm}\end{aligned}$$

4. Compute entrained flow from Eq. 8:

$$\begin{aligned}Q_e &= nQ_j (S_{ta} - 1) \\ &= 9 \times 0.29 (6.71 - 1) = 14.9 \text{ m}^3/\text{s} = 340 \text{ mgd}\end{aligned}$$

5. Compute the area of the BMZ (see Figure 2):

$$\begin{aligned}A_{BMZ} &= 2rL + \pi r^2 \\ &= 2 \times 28.8 \times 192 + \pi \times 28.8^2 \\ &= 13,660 \text{ ft}^2 = 0.31 \text{ acre}\end{aligned}$$

(For a diffuser with discharge from one side only, this equation underestimates the BMZ somewhat. For a single rosette diffuser, L would be zero and the radius r would be the radial distance from the riser center to the port openings plus the impact distance.)

Table 2 summarizes the results.

Table 2. Summary of Entrainment, Kolmogorov Scales, and BMZ Areas for Trial Case

Parameter	If salinity requirement met at:	
	Impact point	End of near field
Reynolds number, Re	9.2×10^5	1.1×10^6
Trajectory length to top, χ	5.8 m	5.0 m
UM3 dilution at top, S_{ta}	6.71	4.22
Entrained volume to top, Q_e	15.0 m ³ /s (342 mgd)	8.5 m ³ /s (193 mgd)
Centerline Kolmogorov scale at top, η_c (Eq. 4)	0.047 mm	0.035 mm
Area of BMZ	1270 m ² = 0.31 acre	4856 m ² = 1.20 acre

Meeting the salinity requirement at the end of the near field results in fewer ports, a shorter diffuser, lower jet velocity, lower entrainment, but a much larger BMZ. Deciding between the designs will be a policy decision, that will involve project and site-specific factors.

The Kolmogorov scales at the jet top are much less than one mm. This is expected to be the usual case for a brine diffuser, but if it is less than one mm at the top, the entrainment calculation can be terminated where the Kolmogorov scale falls to one mm.

6 DISCUSSION

The velocity of the bottom spreading layer u_L at the end of the near field can be estimated by continuity assuming two-dimensional flow from:

$$u_L = \frac{1.4S_n Q_T}{Ly_L} \quad (10)$$

where the factor 1.4 is the conversion from minimum ("centerline") dilution to average dilution. Q_T is the total discharge rate and y_L is the spreading layer thickness (Figure 1b).

Using the values in Table 1 for impact point and end of near field calculations, we obtain layer thicknesses from Eq. 2d of 2.6 m and 2.4 m and layer velocities are then 0.70 and 0.88 m/s respectively. The higher velocity for the near field calculations are because of the shorter diffuser. It is clear that spreading layer velocities can be considerable.

7 CONCLUSIONS

The procedure for designing a brine diffuser to meet the requirements of the California Ocean Plan are illustrated. The Ocean Plan requires estimation of the area of the Brine Mixing Zone (BMZ) and the volume of water entrained into the diffuser jets that may result in mortality to organisms carried with the entrained flow.

Diffusers are often designed to meet the salinity requirement at the point where the jet centerline impacts the seabed. It is shown, however, that it may also be designed to meet the requirements at the end of the near field. In this case, use is made of the considerable additional mixing that occurs in the bottom spreading layer. Meeting the salinity requirement at the end of the near field results in fewer ports, a shorter diffuser, lower jet velocity, lower entrainment, but a much larger BMZ. Deciding between the designs will be a policy decision that will involve project and site-specific factors. Often, designing for near field dilution will be best as this configuration reduces the entrained flow exposed to lethal turbulence, resulting in lower mortality of marine organisms due to the shear and turbulence resulting from the discharge. Estimates of the speed of the bottom spreading layer show that it can be quite high. Although there are as yet no regulatory requirements for this speed, it should also be considered in design.

Finally, it should be noted that the design to meet the salinity criteria is quite conservative. The salinity increment must be less than 2 ppt. This level is only reached at the seabed, however, and in a very limited spatial area. The salinity increment decreases rapidly with height above the bed to near zero at the top of the spreading layer (y_L in Figure 1b) which in the example given is of order three meters high.

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