Appendix 14A

Modeling of Linear Diffusers for Brine Disposal

Modeling Linear Diffusers for Brine Disposal from the West Basin Ocean Water Desalination Plant

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ESA | Environmental Science Associates
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CONTENTS

EXECUTIVE SUMMARY

Dilution simulations are presented for possible linear diffuser configurations to dispose of brine concentrate from the proposed West Basin desalination plant at El Segundo, California.

Concentrate disposal may be through an existing tunnel to a vertical structure in water about 28 feet deep. A pipe will be threaded through the tunnel and extend out onto the seabed where it will terminate in a linear diffuser. The diffuser nozzles will discharge the effluent at an upward angle at high velocity that results in high dilution and rapid reduction of salinity down to regulated levels allowed for brine discharges in the California Ocean Plan.

Two projects are considered, a local plan that will generate 20 mgd of potable water, and a regional plan that will generate 60 mgd of potable water. Each project has two flow variations that depend on the amount of backwash water discharged.

The diffusers must meet the assumed environmental criteria. These are: The salinity increment must be less than 2 ppt within the maximum allowable Brine Mixing Zone (BMZ) of 100 m (328 ft) as specified in the Ocean Plan, and the jets must be fully submerged and not impact the water surface. In addition, it is required to minimize the extent of the BMZ and to minimize the jet exit velocity in order to minimize mortality of organisms that may be entrained into the jets due to turbulence and shear.

The calculation procedures recommended in Roberts (2018a) were followed. The port depth was 24 ft. A nozzle angle of 60° was assumed and the dilution requirement was met at the end of the near field in order to minimize the jet exit velocity and harmful entrainment.

A diffuser design was sought that would meet the environmental constraints for all flow scenarios. This was found to be not possible due to the wide flow variations. A diffuser design was found that had a common port spacing and number of ports, and therefore diffuser length. One port diameter is needed for the regional projects and a different diameter for the local projects. Therefore, only the port diameters need be changed when transitioning from the local to regional projects. The designs, extents of the BMZ and entrainment are summarized in Table 4.

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1. INTRODUCTION

The Ocean Water Desalination Project proposed by the West Basin Municipal Water District (West Basin) is a desalination facility that would produce 20 mgd (million gallons per day) of potable water supply (the "Local Project"), with potential expansion of the facility to supply up to 60 mgd (the "Regional Project"). It is proposed to build the desalination facility at the existing El Segundo Generating Station (ESGS) in El Segundo, California. The facility will include pretreatment, reverse osmosis (RO), energy recovery, post-treatment, and residuals handling and disposal.

RO concentrate (brine) that results from the desalination process, and possibly treated wastewater from process washing operations, would be disposed into Santa Monica Bay. Disposal could be through an existing ESGS discharge tunnel. The concentrate has a salinity approximately twice that of the ambient ocean water and must be rapidly diluted after entering the ocean in order to achieve receiving water quality criteria specified in the California Ocean Plan (SWRCB, 2015).

In a previous report, Roberts (2018b), a rosette-type diffuser design with ports added to the existing riser structure was considered. Because of the shallow water and jet merging, this required ports oriented at less than the optimum angle of 60°, resulting in somewhat increased shear mortality. Subsequently, the State Water Resources Control Board (SWRCB) requested an alternative design for a linear diffuser where the ports are arrayed along a linear axis. The nozzles would be oriented at 60°, which minimizes shear entrainment and mortality of organisms due to shear and turbulence in the jets.

In this report, we consider the design of linear diffuser systems. The specific tasks addressed are:

- Perform analyses to evaluate the feasibility of discharge from linear diffusers;
- Design diffusers that meet the environmental constraints with minimal modifications for different discharge scenarios;
- Evaluate dilutions and extents of the brine mixing zone;
- Estimate the volume of water that could cause organism mortality due to shear and turbulence in the jets.

2. DIFFUSER ANALYSIS

2.1 Introduction

The concentrate may be discharged through the existing, but now disused, tunnel that was used for cooling water discharge from generating Units 3 and 4. The tunnel consist of a 12-foot inside diameter concrete pipe perpendicular to shore. The tunnel is parallel to and approximately 23 feet south of a similar existing tunnel that was previously used for the cooling water intake. The discharge tunnel extends on a downward slope 2,078 feet from the existing onshore gate structure and terminates in a vertical concrete offshore discharge structure. The water depth at the discharge structure varies with the tide from 28 to 34 feet and the top of the structure is about 8 feet above the seafloor. Figure 1 shows the existing discharge structure. The diffuser pipe would extend from the riser to the adjacent seabed.

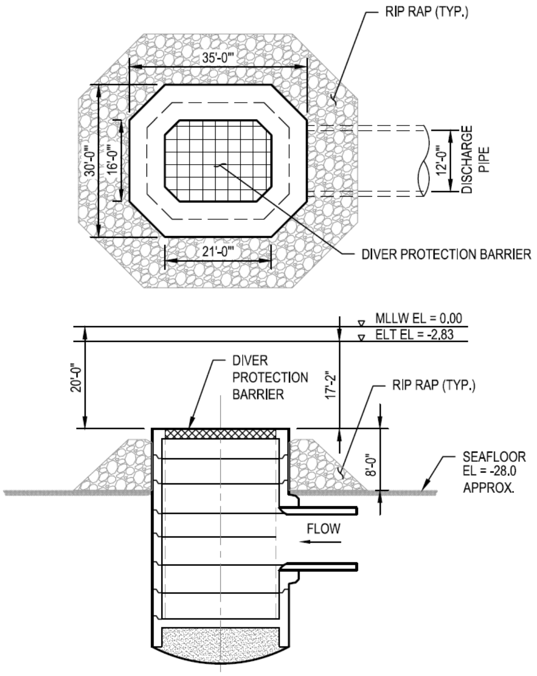

Figure 1. Existing cooling water discharge structure

2.2 Analytical Approach

Concentrate diffusers consist of upwardly inclined dense jets. For relatively large discharges, it is usual to employ multiple ports to reduce the required jet exit velocity and avoid impacting the water surface in shallow water. The ports may be arranged in a linear array or in multiport "rosette" risers. A multiport rosette deign was considered in Roberts (2018b).

The environmental design criteria for the diffuser are to maintain a submerged plume that does not impact nor appear on the water surface and that results in a salinity increment of less than 2 ppt over background within the Brine Mixing Zone (BMZ). The brine discharge regulations in the California Ocean Plan (SWRCB 2015) allow the BMZ to extend a maximum distance of 100 m from the diffuser. In addition, the extent of the BMZ should be minimized, and the jet velocity should be minimized in order to lessen shear and turbulence-induced mortality of organisms that may be entrained into the diffuser jets.

Below is a general discussion of the dynamics of discharges from single jets and multiport diffusers and a presentation and explanation of the analytical technique that will be employed.

2.3 Brine Diffuser Discharge Dynamics

2.3.1 Single Jets

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 reduction of salinity to near background levels. Figure 2 shows a laser-induced fluorescence (LIF) image of a typical inclined dense jet. Relative salinity levels are shown in false color, ranging from red (high levels) through orange, yellow, and green to blue (low levels).

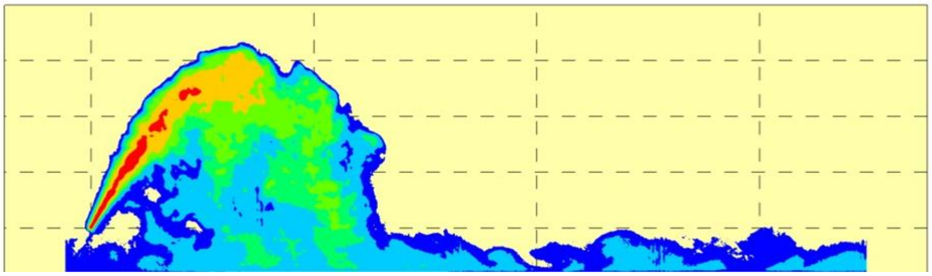

Figure 2. LIF image of an inclined dense jet (after Roberts et al. 1997)

Figure 2 illustrates the most important and relevant features of dense jet mixing. As it ascends, the jet entrains ambient water that dilutes it. Because the jet is more dense than the receiving water it reaches a terminal rise height and then falls back to the bed. Entrainment, mixing and dilution continue in the descending plume phase. After impacting the bed, the flow becomes horizontal and proceeds as a turbulent density current that continues to entrain and dilute. At some distance from the diffuser, this turbulence collapses under the influence of its own induced density stratification and active mixing essentially ceases. The region that encompasses the ascending jet and the descending plume, the seabed impact and horizontal flow up to the point of turbulence collapse is called the near field. Beyond the near field, mixing is primarily due to ambient (oceanic) turbulence. This region is called the far field, in which mixing is much slower than in the near field. For further discussion of the definition of the near field, especially as it applies to dense jets, see Roberts et al. (1997), and Doneker and Jirka (1999).

These main properties for a dense jet inclined at an angle Θ to the horizontal are shown and defined in Figure 3. The terminal rise height to the jet top is y_t. The centerline of the jet 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. Turbulence collapse, which signifies the end of the near field, occurs at x_n (the length of the near field). The dilution at this location is the near field dilution, S_n. For a single jet, the increase in dilution from the impact point to the end of the near field is about 60% (Roberts et al. 1997).

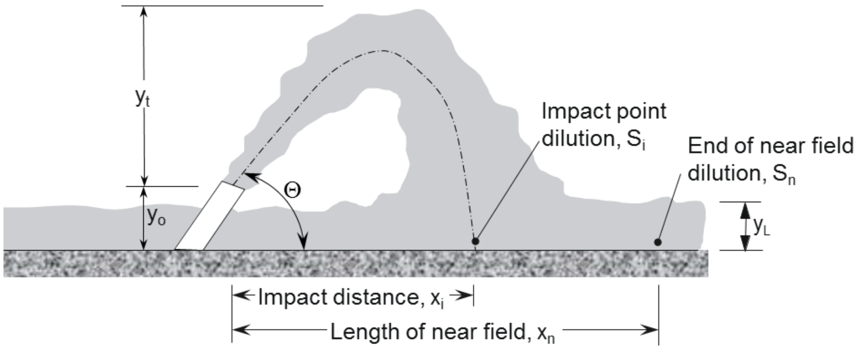

Figure 3. Characteristics of an inclined dense jet (after Roberts et al. 1997)

Many experiments have been performed over the years to predict the main flow characteristics shown in Figure 3. For typical brine discharge conditions, the impact and near field dilutions are given by:

$$\frac{S_i}{F} = f(\Theta) \text{ and } \frac{S_n}{F} = f(\Theta) \tag{1}$$

where F is the densimetric jet Froude number defined by:

$$F = \frac{u}{\sqrt{g_o' d}} \tag{2}$$

where d is the port diameter, u the jet exit velocity, $g_o' = g(\rho_a - \rho_o)/\rho_o$, is the modified acceleration due to gravity, g the acceleration due to gravity, ρ_a is the ambient density and ρ_o the effluent density ($\rho_o > \rho_a$). The geometrical properties scale with dF and are given by:

$$\frac{y_t}{dF} = f(\Theta) \text{ and } \frac{y_L}{dF} = f(\Theta) \text{ and } \frac{x_i}{dF} = f(\Theta) \text{ and } \frac{x_n}{dF} = f(\Theta) \tag{3}$$

Dilution is maximum for an angle of about 60°, and this is the generally accepted value used for diffuser designs. The increase in dilution from the impact point to the end of the near field ranges from about 30 to 60%, depending on the nozzle angle.

2.3.2 Multiport Linear Diffusers

Multiport linear diffusers where the nozzles are arrayed along one or both sides of a nominally straight diffuser are often used if the outfall is a pipe laid along the seabed (e.g. Perth, Australia, Marti et al. 2011). Abessi and Roberts (2014, 2017) discuss the dynamics of dense jets from multiple jets and the design of linear multiport diffuser arrays.

For widely spaced ports ($s/dF > 2$) the jets do not merge and the equations for single jets apply. For a nozzle angle of 60° they are (Roberts et al., 1997):

$$\frac{S_n}{F} = 2.6 \qquad \frac{y_t}{dF} = 2.2 \qquad \frac{y_L}{dF} = 0.7 \qquad \frac{x_n}{dF} = 9.0 \tag{4}$$

If the port spacing parameter s/dF is less than two, the dilution, rise height and length of the near field are reduced compared to isolated jets. The equations for this regime are (Abessi and Roberts 2014):

$$\frac{S_n}{F} = 1.1\left(\frac{s}{dF}\right) \qquad \frac{y_t}{dF} = 1.9\left(\frac{s}{dF}\right)^{1/2} \qquad \frac{x_n}{dF} = 6.0\left(\frac{s}{dF}\right)^{1/2} \tag{5}$$

2.3.3 Computation of BMZ

For a diffuser with nozzles discharging on both sides, the BMZ is defined as shown in Figure 4 (Roberts 2018a). The area of the BMZ is computed from:

$$A_{BMZ} = 2rL + \pi r^2 \tag{6}$$

where L is the diffuser length and r the distance from the nozzles to the location where the salinity falls to 2 ppt. In this case, the distance r is the distance to the end of the near field x_n (see Figure 3).

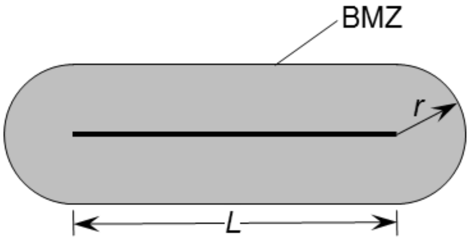

Figure 4. BMZ area definition

2.3.4 Shear Mortality

The volume of water entrained into the jets that may result in mortality to planktonic organisms is calculated according to the recommendations in Roberts (2018a) (R2018). There, it is recommended that the entrained volume of concern includes the volume which is entrained up to the terminal rise height, and that volume be calculated by the mathematical model UM3, which is part of the modeling suite Visual Plumes.

The entrained volume up to the terminal rise height Q_e was calculated from Eq. 36 of R2018:

$$Q_e = n(S_{ta} - 1)Q_j = \left(S_{ta} - 1\right)Q_T \tag{7}$$

where n is the number of ports, S_{ta} is the average dilution computed by UM3 at the terminal rise height (local maximum rise or fall), Q_j is the flow per jet, and Q_T the total flow rate.

3. APPLICATION TO WEST BASIN

3.1 Flow Scenarios

For the 20 mgd Local Project, the normal amount of flow to be discharged from the ocean desalination facility would be approximately 25.4 mgd, which would be composed of 20.9 mgd of RO concentrate (brine) and 4.5 mgd of treated backwash water from the HRGMF and MF processes. If washwater is internally recycled, the normal discharge flow would be reduced to approximately 21 mgd, composed of 20.9 mgd of RO brine and 0.1 mgd from the washwater recycling process.

For the 60 mgd Regional Project, the normal amount of flow to be discharged from the ocean desalination facility would be approximately 76.2 mgd, which would be composed of 62.7 mgd of RO concentrate (brine), and 13.5 mgd of treated backwash water from the HRGMF and MF processes. If the washwater is internally recycled, the normal discharge flow would be reduced to approximately 63 mgd with 62.7 mgd from the RO process and 0.3 mgd from the washwater recycling process.

Table 1 summarizes the discharge scenarios and properties of the effluents assuming a salinity of 68 ppt for RO brine and 34 ppt for treated washwater.

Table 1. Properties of Effluent Constituents for Various Scenarios

Project	Case ID	Brine			Washwater			Combined effluent			
		Flow (mgd)	Temp. (°C)	Salinity (ppt)	Flow (mgd)	Temp. (°C)	Salinity (ppt)	Flow (mgd)	Temp. (°C)	Salinity (ppt)	Density (kg/m³)
Local	L1	20.9	17.6	68.0	4.5	17.6	34.0	25.4	17.6	62.0	1046.2
	L2	20.9	17.6	68.0	0.1	17.6	34.0	21.0	17.6	67.8	1050.8
Regional	R1	62.7	17.6	68.0	13.5	17.6	34.0	76.2	17.6	62.0	1046.2
	R2	62.7	17.6	68.0	0.3	17.6	34.0	63.0	17.6	67.8	1050.8

The assumed oceanic properties, and therefore background conditions, are the average seasonal temperatures and salinities obtained from more than 20 years of local NPDES monitoring. Table 2 summarizes the background oceanic properties.

Table 2. Assumed Oceanic Properties

Temperature (°C)	Salinity (ppt)	Density (kg/m³)
17.6	33.5	1024.2

3.2 Diffuser Designs

Using the methodology outlined in Section 2.3, near field dilution, rise height, near field length, and layer thickness were computed for various diffuser designs for each scenario of Table 1 using Eqs. 4 and 5 as appropriate with the assumed background properties of Table 2. The BMZ area was calculated from Eq. 6 and entrainment from Eq. 7 following application of UM3.

The diffusers must satisfy the environmental criteria. That is, the increment in salinity on the seabed is less than 2 ppt and the top of the jets, y_t, is below the water surface so that the plume remains submerged. The port depth was assumed to be 24 ft to account for the height of the nozzles above the seabed. The computations were done assuming the salinity requirement was met at the end of the near field in order to minimize the shear entrainment and jet exit velocity.

First, diffuser designs that had the same number of ports and spacing were sought for the local and regional projects with washwater discharged with the brine (L1 and R1). The minimum number of ports required for the regional projects was found to be six with a diameter of 23.6 inches. To satisfy the environmental constraints for Project L1 with six ports the port diameter must be reduced to 15.2 inches. The port and flow characteristics are summarized in Table 3.

Next, a diffuser design was sought that would accommodate all scenarios (L1, L2, R1, and R2) with minimal modifications between them. Ideally, the port spacing, diameter, and number of ports would be the same for all local and regional projects. This was found to be not possible, however, and two diffuser configurations were required: one for the local projects and one for the regional projects. Solutions were therefore sought that had the same number of ports and spacing (and therefore diffuser length), but different port diameters for the local and regional projects. To change from the local to regional projects, only the nozzle diameters would need changing.

Because of their higher flows, the regional projects control the number of ports and their spacing. Of these, R2 is controlling because of its higher salinity that requires higher dilution to achieve the salinity requirement. Beginning with two ports, the number of ports was gradually increased for R2 and the port diameter varied until the rise height and salinity requirements were just met. It was found that 14 ports 13.9 inch diameter spaced 15.5 ft apart sufficed. The results are summarized in Table 4.

This diameter was then applied to R1. Some merging of the jets prior the near field resulted, so Eqs. 5 were used to estimate the near field dilution, rise height, and length of near field. The results are summarized in Table 4. The dilution requirement is slightly exceeded with a near field salinity increment of 1.9 ppt.

The same port spacing and number of ports was then applied to the local projects. Of these, L2 is controlling because of the higher discharge salinity that requires higher dilution to achieve the salinity requirement. The port diameter was gradually reduced until the rise height and salinity requirements were just met. The required port diameter is 9.0 inches. This results in the dilution requirement for L1 to be exceeded with a near field salinity increment of 1.2 ppt. The results are shown in Table 4.

Table 3. Linear Diffuser for Local and Regional Projects L1 and R1. Salinity Increment at the end of the Near Field ≤ 2 ppt.
Six Port Design. Port spacing = 21.8 ft. All ports at 60°. Two-sided discharge.

Scenario	Case ID	Diffuser details				Impact point			BMZ[1]			UM3 predictions at top	
		Number of ports	Port diameter (in)	Jet velocity (ft/s)	Diffuser length (ft)	Dilution Si	Length xi (ft)	Salinity increment (ppt)	Layer thickness, y_L (ft)	Distance, x_n (ft)	Area (acres)	Average dilution, S_{ta}	Entrained flow (mgd)
Local project, 20.9 mgd brine plus 4.5 mgd backwash.	L1	6	15.2	5.2	44	8.9	16.9	3.2	4.9	63	0.42	3.6	66.0
Regional project, 62.7 mgd brine plus 13.5 mgd backwash.	R1	6	23.6	6.5	44	8.9	26.2	3.2	7.6	98	0.89	3.6	198.0

[1] The BMZ boundary is at the end of the near field. Flow properties there are the near field properties (Figure 3).

Table 4. Linear Diffusers for Local and Regional Projects. Salinity Increment at the end of the Near Field ≤ 2 ppt.
14 Port Designs. Port spacing = 15.5 ft. All ports at 60°. Two-sided discharge.

Scenario	Case ID	Diffuser details				Impact point			BMZ[1]			UM3 predictions at top	
		Number of ports	Port diameter (in)	Jet velocity (ft/s)	Diffuser length (ft)	Dilution S_i	Length x_i (ft)	Salinity increment (ppt)	Layer thickness, y_L (ft)	Distance, x_n (ft)	Area (acres)	Average dilution, S_{ta}	Entrained flow (mgd)
Local project, 20.9 mgd brine plus 4.5 mgd backwash.	L1	14	9.0	6.4	93	14.1	15.9	2.0	4.6	60	0.51	5.56	116
Local project, 20.9 mgd brine plus 0.1 mgd backwash. Remaining backwash recycled.	L2	14	9.0	5.3	93	10.6	11.9	3.2	3.5	45	0.34	4.24	68
Regional project, 62.7 mgd brine plus 13.5 mgd backwash.	R1	14	13.9	8.0	93	14.3	24.8	2.0	7.2	76	0.74	5.62	352
Regional project, 62.7 mgd brine plus 0.3 mgd backwash. Remaining backwash recycled.	R2	14	13.9	6.6	93	10.7	18.7	3.2	5.4	70	0.65	4.30	208

[1] The BMZ boundary is at the end of the near field. Flow properties there are the near field properties (Figure 3).

3.3 Discussion

The diffusers proposed in Table 4 will meet the requirements of all projects. The port diameters are different for the local and regional projects, however.

The lengths of the BMZ are very short, 45 to 76 ft. These are much less than the maximum allowable length of the BMZ, which is 100 m (328 ft). The areas of the BMZ range from approximately 0.3 to 0.7 acres. Entrained flows up to the top of the terminal rise height range from 68 to 352 mgd.

The thickness of the spreading layer at the end of the near field ranges from about four to seven feet. The salinity increment varies approximately linearly through this layer, from 2 ppt at the seabed to zero near the top.

The additional hydraulic head due to the jets ranges from about 0.4 to 1.0 ft. This corresponds to a pressure of 0.2 to 0.4 psi.

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Appendix 14B

Peer Review of Linear Diffuser Modeling

ESA

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May 13, 2019

Subject **Review of Brine Discharge Calculations for West Basin Ocean Water Desalination Plant**

Mr. Donovan:

I reviewed the report, "Modeling Linear Diffusers for Brine Disposal from the West Basin Ocean Water Desalination Plant" by Dr. Philip Roberts, dated May 10, 2019.

As requested by the State Water Resource Control Board, the methodology of the calculations in the report closely follows that previously developed by Roberts[1]. That methodology was developed for a single constant discharge flow rate and discharge salinity, whereas in the present application the flow rates differ between Local and Regional project capacities and may also vary over time due to recycling of backwash water.

For the design when backwash water is not recycled a two-sided diffuser layout with six (6) ports (three (3) ports on each side) was calculated to be optimal to satisfy the California Ocean Plan (Ocean Plan) dilution and brine mixing zone (BMZ) requirements for both Local and Regional flow rates. This required using different size ports for the different flow rates (i.e., smaller port diameter for Local project and larger port diameter for Regional project). The Regional project also requires larger port spacings than the Local project, but for practical design and construction the larger port spacings were adopted for both the Regional and Local projects. This may result in a slight increase (less than 0.1 acres) of the BMZ area and a slight increase (less than 14 feet) in the diffuser length than would be otherwise be required for the Local project but will enable the diffuser to be readily modified in the future, with minimal environmental disturbance, by simply replacing the smaller ports with larger ports.

For the design when backwash water is recycled the flow rates and brine concentrations for both the Local and Regional projects vary over time. This scenario requires increasing the number of ports from six (6) to fourteen (14) (seven (7) ports on each side) to meet the dilution requirements across the range of operating conditions. This results in a diffuser that is approximately twice as

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[1] Roberts, P.W., 2018. Brine Diffusers and Shear Mortality. Prepared for Eastern Research Group. April 18, 2018.

long as the six-port diffuser, but notably the changes in the BMZ area are small (up to approximately 0.2 acres) and can either increase or decrease depending on the operation scenario.

In summary, the calculations follow the methodology requested by the State Water Resource Control Board, as close as practical given the need to account for different flow rates (i.e., Local versus Regional) and potentially account for flows and salinities varying with time due to recycling of backwash water. Importantly, the analyses, calculations, and results demonstrate the following key aspects:

- The potential for shear mortality in the entrained jet/plume is minimized by using ports with the optimal 60-degree vertical angle,
- The diffuser length (and therefore construction footprint) is minimized by using the largest port diameters possible for the given depth (while still meeting dilution requirements) and using a two-sided diffuser configuration,
- The 2 ppt limit on the incremental salinity at the edge of the BMZ (per Ocean Plan) is achieved for the range of flow rates and operations,
- The BMZ areas are small and extend less than 100 ft from the diffuser, substantially less than the Ocean Plan requirement of 100 m (328 ft).

In closing, it is my professional opinion that these calculations have been carried out appropriately and result in diffuser configurations that are in compliance with the Ocean Plan.

Sincerely,

Al Preston, PhD, PE (CA)
Senior Engineer