Modeling Brine Disposal from the West Basin Ocean Water Desalination Project

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CONTENTS

EXECUTIVE SUMMARY

Dilution simulations are presented for possible 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 that terminates in a vertical structure in water about 28 to 34 feet deep. Calculations are performed for a possible modification to the structure to convert it into a diffuser by adding multiple nozzles in a "rosette" configuration. The 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.

A procedure for predicting dilution due to a riser with an arbitrary number of jets at an arbitrary angle to the horizontal was devised and is described. Because the receiving water is relatively shallow, the diffuser nozzles must be oriented at less than the usually accepted optimum angle of 60°. Generally, increasing the number of ports reduces the jet velocity required and the jet rise height. However, too many ports inhibits entrainment, which reduces dilution. The dynamics of dense jet mixing was discussed and the procedure for calculating the jet properties was presented. The procedure involves calculation of single jet properties at arbitrary orientations with a correction factor to account for the decrease in dilution due to merging.

The procedure was then applied to the proposed projects to 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) 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 due to turbulence and shear of organisms that may be entrained into the jets.

Because the design of the riser is not finalized, two port depths and two dilution criteria were considered. The port depths were 20 or 24 ft, and the dilution meets the salinity requirement either at the jet impact point or at the end of the near field. Tables A1 and A2 show the results for the best port diameter and orientation for varying numbers of ports. All of the options meet the environmental criteria for all projects for both port depths. Meeting the salinity requirement at the impact point results in higher jet velocity and a smaller BMZ. Meeting it at the end of the near field requires a lower velocity but a larger BMZ. The lengths of the BMZ were always much less than the maximum allowed distance of 100 m.

An optimization was performed for the case of a 20 ft port depth with the salinity requirement met at the impact point. This minimizes the BMZ. The optimum configuration is defined as the number of ports and their diameter and orientation that minimizes the jet velocity and therefore the head loss and shear mortality. Table 3 summarizes the results for each flow scenario.

The different flow scenarios have different optimum port configurations. For the local projects, the optimum number of ports is between four and six, and for the regional projects, from six to eight. Because the design is not yet finalized we assumed four ports for the local projects and eight ports for the regional projects. For the local projects, the ports are 12.4 or 15.0 inches diameter oriented at 46°; jet velocities are 8.0 or 9.7 ft/s. For the regional projects, the ports are 11.1 or 13.4 inches diameter at 26°; jet velocities are 15.0 or 18.1 ft/s. The incremental head loss due to the jets ranges from 1.0 to 5.1 feet, corresponding to pressure increments of 0.4 to 2.3 psi. These may be higher depending on the design of the riser chamber.

Entrainment of potentially harmful flows were calculated for the port configurations of Table 3 according to the recommendations of Roberts (2018). The results are shown in Table 4.

Final designs may differ depending on the hydraulic characteristics of the check valves. The dilution predictions are believed to be conservative but are based on limited experimental data. It is recommended that physical model tests be considered during final design in order to confirm and refine the chosen riser configurations.

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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 intake 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 order to accomplish this dilution a multiport diffuser system will be constructed on or near the terminal structure at the ocean end of the tunnel. The diffuser could be inserted directly into the vertical section of the existing terminal structure, thereby eliminating installation of discharge pipelines beneath the seafloor.

In this report, we consider the feasibility and preliminary design of a diffuser system that utilizes the existing discharge structure by adding risers that eject the concentrate at relatively high velocity. The specific tasks addressed are:

- Perform preliminary analyses to evaluate the feasibility of discharge from the existing discharge structure;
- Assess modifications to the existing discharge structure to meet environmental criteria;
- Evaluate dilutions and extents of the brine mixing zone;
- Estimate organism mortality due to shear and turbulence from the jets.

2. Diffuser Analyses

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 is 12-foot inside diameter concrete pipe perpendicular to shore. The pipeline crown is approximately five feet below the seafloor in the offshore area. 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 ranges 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 and conceptual modifications to convert it into a multiport diffuser.

The following narrative discusses diffuser alternatives that utilize this existing discharge structure.

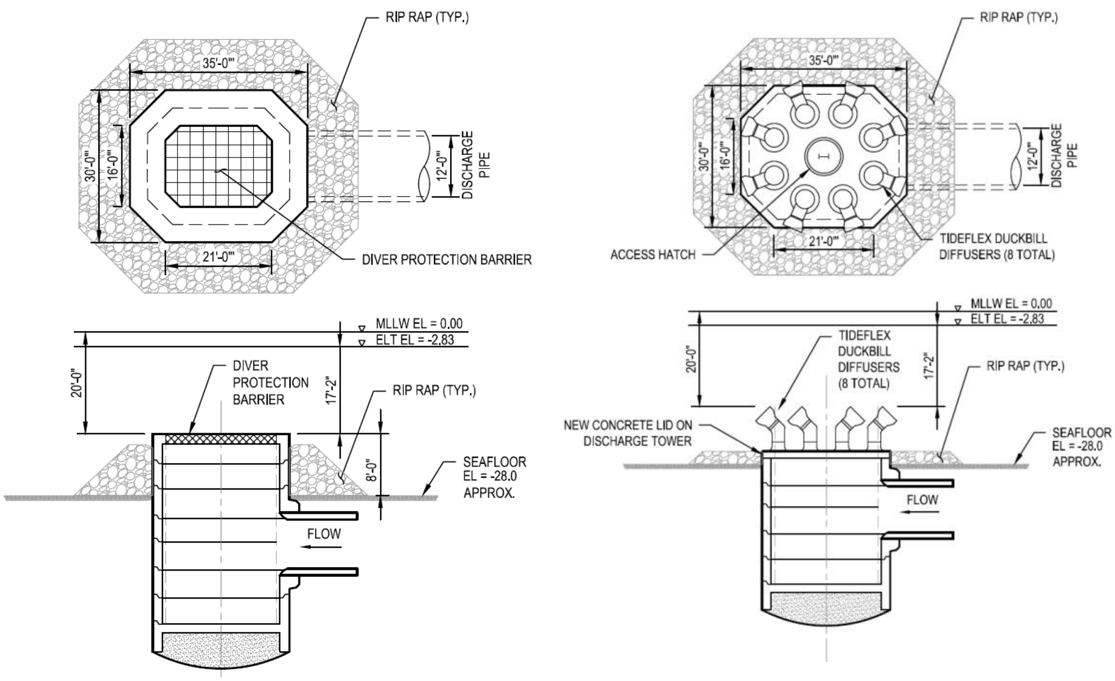


Figure 1. Existing and possible modified cooling water discharge structure

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. The proposed diffuser would be similar to a rosette configuration.

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 a maximum extent of the BMZ 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.

The ports will be arranged in a "rosette" pattern (Abessi et al. 2016). Because the water depth at the structure is relatively shallow, the nozzles may have to be oriented less steeply than normally employed for concentrate diffusers to avoid impacting the water surface.

There are no general analytical techniques or models for predicting the dilution of a multiport rosette diffuser with an arbitrary number of ports discharging at an arbitrary angle to the horizontal. Entrainment models, such as UM3 in the EPA Model Suite Visual Plumes, or CORMIX, underestimate dense jet dilutions (Palomar et al. 2012), cannot handle the complex radial merging that may occur, and do not show the sensitivity of dilution to discharge angle that has been experimentally observed. CFD (Computational Fluid Dynamics) models are not yet proven reliable for diffuser-type flows and very long computational times make them unsuitable for evaluating many alternatives in an engineering analysis. For these reasons, physical model tests (Miller et al. 2007, Tarrade and Miller 2010) are often used for specific rosette diffuser designs, and generic experiments (e.g. Abessi et al. 2016) provide general insight into rosette discharge behavior. Although it would be expected that adding more ports would increase dilution, these experiments showed that increasing the number of ports in a rosette above about six results in jet merging and inhibition of entrainment that reduces dilution. Similar effects on multiport rosettes were reported in model studies on the Boston outfall (Roberts and Snyder, 1993) which resulted in reducing the number of ports per riser from 12 to 8.

Given these known effects and the limitations of mathematical models, the analytical approach we will adopt is to use experimental studies of the effect of nozzle angle on dilution for single jets with corrections that account for the reduction in dilution due to merging as the number of ports is increased. The correction factors are based on experimental studies of multiport rosettes.

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).

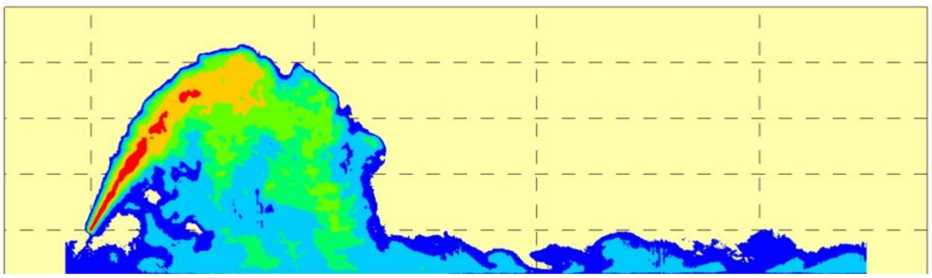


Figure 2. LIF image of an inclined dense jet (after Roberts et al. 1997)

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).

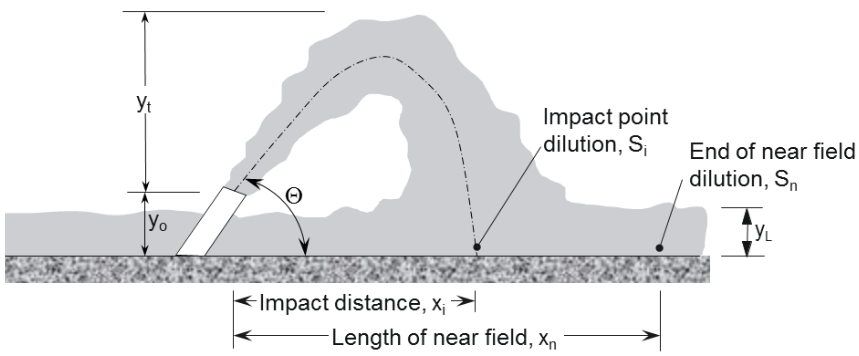


Figure 3. Characteristics of an inclined dense jet (after Roberts et al. 1997)

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 the ambient density and ρ_o the effluent density ($\rho_o > \rho_a$). The geometrical properties scale with dF and are given by:

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

Abessi and Roberts (2015) have recently investigated the effects of nozzle angle on dense jets. Figure 4 shows central-plane tracer concentrations obtained by laser-induced fluorescence for dense jets with angles Θ ranging from 15° to 85°. For very shallow angles, e.g. 15°, the jet impacts the bed quickly, reducing dilution. For steep angles, e.g. 85°, the trajectory is also truncated and the jet falls back on itself, which also reduces dilution.

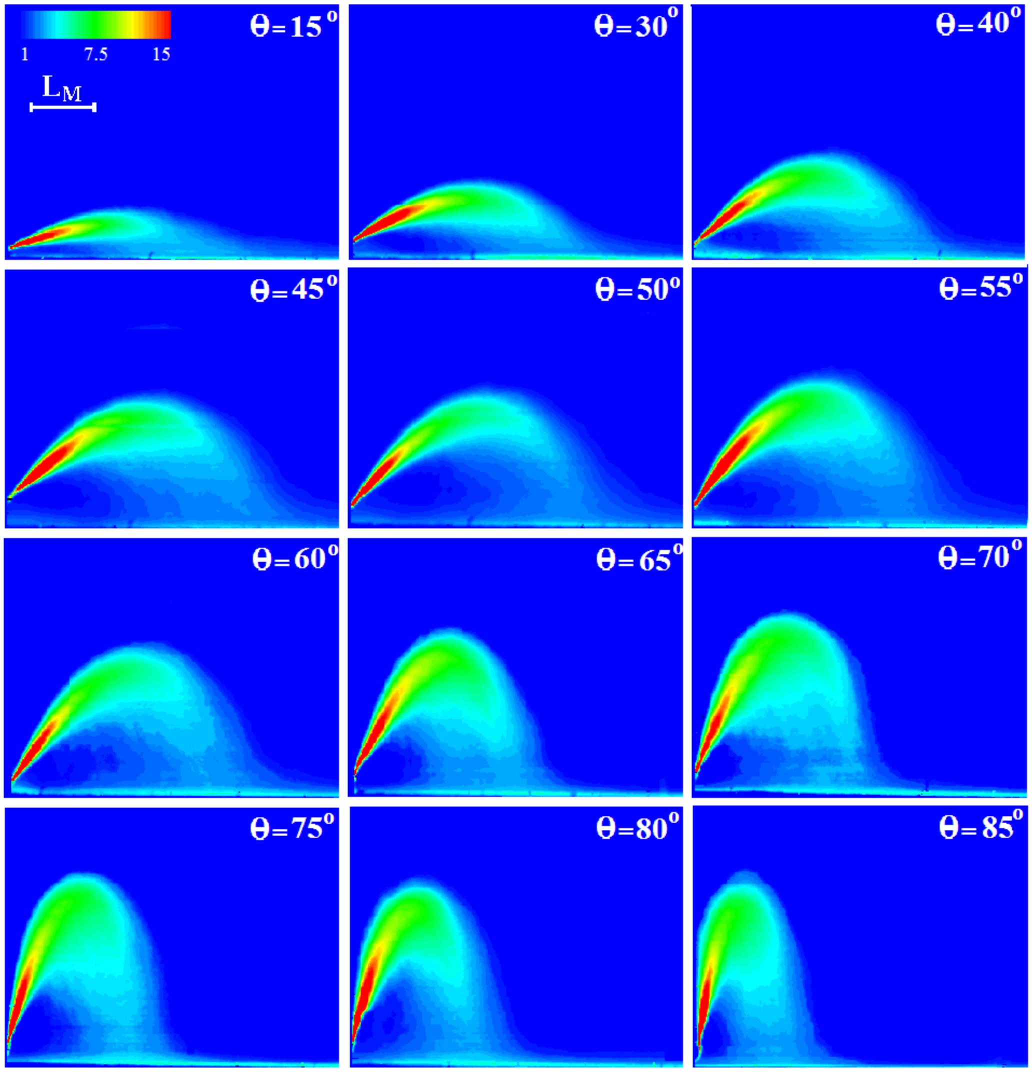


Figure 4. Center-plane tracer concentrations for single dense jets at various nozzle angles from 15° to 85°. After Abessi and Roberts (2015).

Dilution is maximum for an angle of about 60°, and this is the generally accepted value used for diffuser designs. This is illustrated by Figure 5, which shows the variation with nozzle angle of normalized impact dilution (S_i/F) and near field dilution (S_n/F) for single jets. 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.

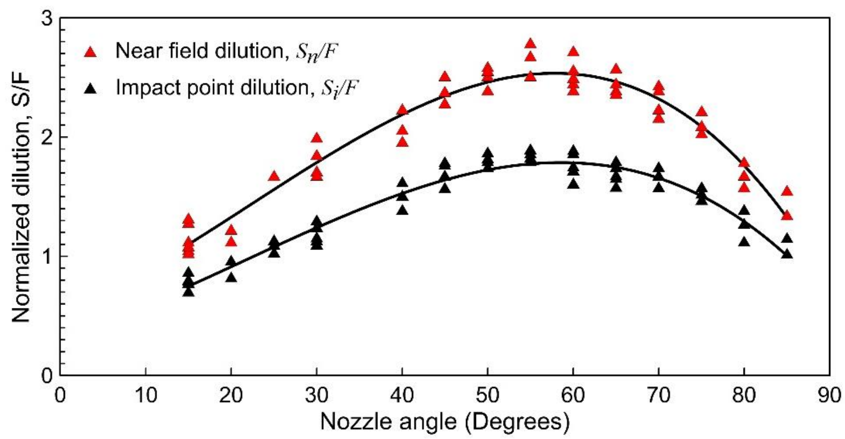


Figure 5. Effect of nozzle angle on normalized impact and near field dilutions of single dense jets. After Abessi and Roberts (2015).

The geometrical properties normalized according to Eq. 3 are shown in Figures 6 and 7. The rise height, location of impact point, and length of the near field depend on the nozzle angle. The maximum distance of the impact point and the near field length occur at an angle of about 40°. The rise height increases with nozzle angle up to about 75° beyond which it decreases slightly due to reentrainment of the ascending plume.

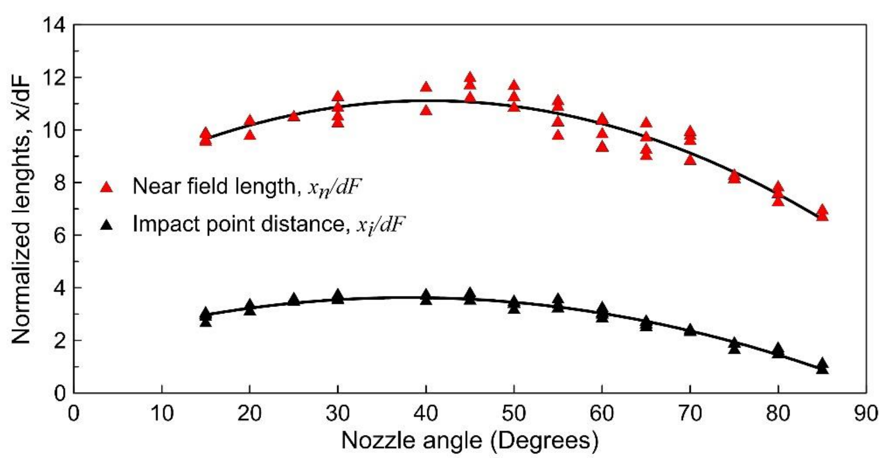


Figure 6. Effect of nozzle angle on normalized lengths of impact point, x_i/dF, and near field, x_n/dF, for single dense jets (After Abessi and Roberts, 2015)

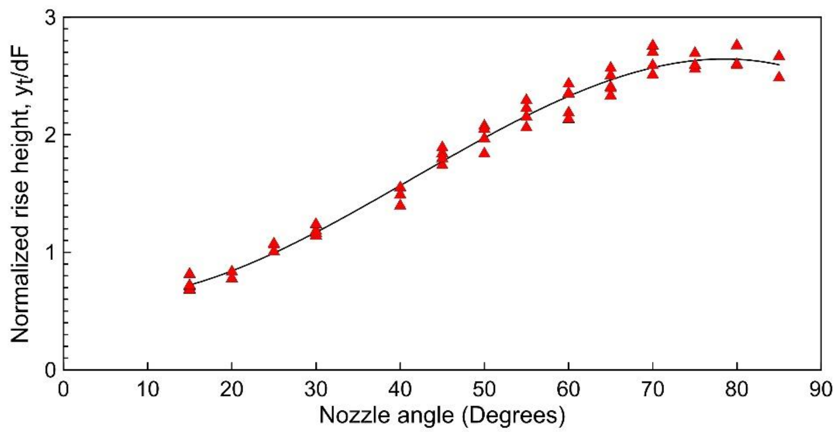


Figure 7. Effect of nozzle angle on normalized rise height y_t/dF for single dense jets (After Abessi and Roberts, 2015).

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.

2.3.3 Multiport Rosettes

Multiport "rosette" diffusers, where more than two nozzles are clustered on top of a riser, are often used if the outfall is tunneled in order to minimize the number of risers and therefore the construction cost. Several desalination plants in Australia employ rosette-type diffusers, e.g. Melbourne and Sydney.

A possible configuration for the present discharge is to utilize the existing discharge structure as, in effect, a single riser with multiple ports in a rosette configuration (see Figure 1). There are no general theories to predict dilution from a rosette diffuser with arbitrary number of ports and discharge angle, so we use a semi-empirical approach based on existing theories, experiments, and physical model studies. The procedure is presented below.

For a multiport rosette diffuser, Eq. 1 becomes:

$$\frac{S_i}{F} = f\left(\Theta, n\right) \text{ and } \frac{S_n}{F} = f\left(\Theta, n\right) \tag{4}$$

where n is the number of ports on the riser. Estimates of the form of Eq. 4 are discussed below.

Abessi et al. (2016) reported extensive generic experiments on four-port rosettes. Figure 8 shows images of a rosette discharge into stationary water. The results implied that the jets from four ports are similar to single jets, although merging in the spreading layer (visible in Figure 8) reduced the near field dilution by about 27% compared to that of single jets. Physical model tests with 9 and 12 port risers were reported by Tarrade and Miller (2010). For 12-port risers, they reported that impact and near field dilutions were both reduced by about 50%.

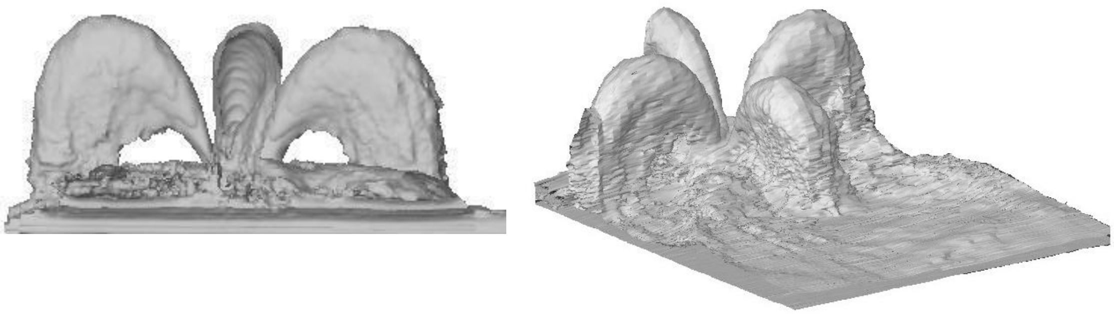


Figure 8. Images of four-port riser jets. From Abessi et al. (2016).

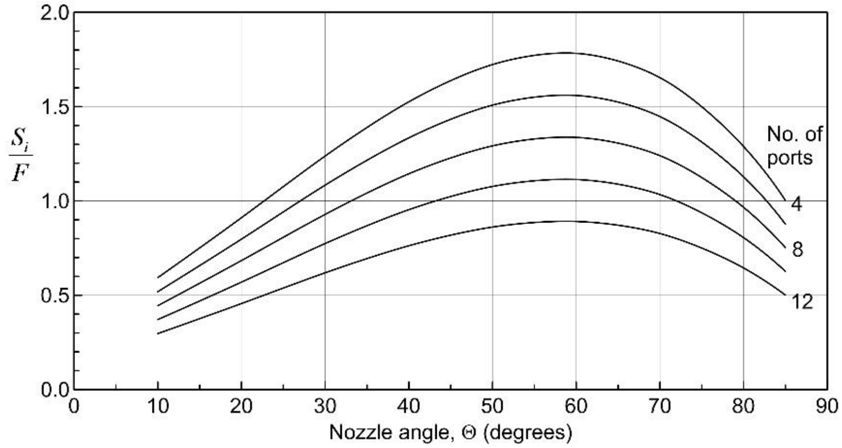
Based on these observations, simple linear equations were assumed for the reduction in dilution due to increasing number of ports:

$$C_i = 1 - \left(\frac{n-4}{16}\right) \text{ and } C_n = 0.73 - 0.23\left(\frac{n-4}{8}\right) \tag{5}$$

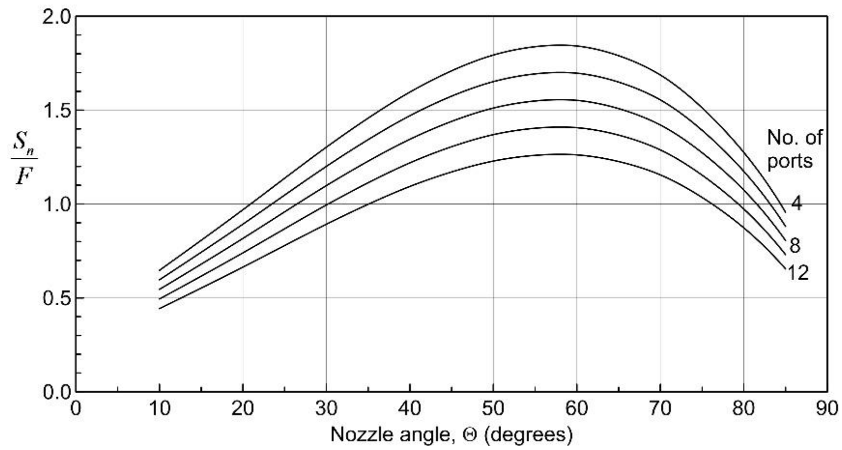
where the corrected impact and near field dilutions accounting for the number of ports are given by:

$$S_{ic} = C_i S_i \text{ and } S_{nc} = C_n S_n \tag{6}$$

where S_i and S_n are the dilutions for a single jet obtained from Figure 5. Combining this figure with the correction factors from Eq. 5 we arrive at the generalized curves for impact and near field dilutions that account for the number of ports and their inclination that are shown in Figure 9.



a) Impact dilution



b) Near field dilution

Figure 9. General curves for impact and near field dilutions of a single multiport rosette diffuser as functions of number of ports and nozzle angle.

There are no detailed measurements of the impact point location, near field length, or spreading layer thickness for rosette diffusers with arbitrarily angled nozzles. Therefore, we use the results for single jets shown in Figures 6 and 7. This is a conservative assumption, as the model tests of Tarrade and Miller and the experiments of Abessi and Roberts show that these distances are generally reduced for multiport diffusers compared to single jets. Abessi and Roberts (2016) measured spreading layer thicknesses for four-port risers at 60° and found that Eq. 3 became:

$$\frac{y_L}{dF} = 0.7 \tag{7}$$

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, comprised of 20.9 mgd of Reverse Osmosis (RO) concentrate (brine), and 4.5 mgd of treated backwash water. If the washwater is internally recycled, the normal discharge flow would be approximately 21.0 mgd, comprised of 20.9 mgd of RO brine and 0.1 mgd from the washwater recycling process.

For the regional project, the normal concentrate flow would be approximately 76.2 mgd, comprised of 62.7 mgd of concentrate and 13.5 mgd of washwater. With internal recycling, the flow is 63.0 mgd, comprising 62.7 mgd of concentrate and 0.3 mgd of washwater.

Table 1 summarizes the discharge scenarios, 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/m^3)
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/m^3)
17.6	33.5	1024.2

3.2 Diffuser Design

Using the methodology outlined in Section 2.3.3, dilutions, rise heights, and lengths of impact distance and near field were computed for each scenario of Table 1 with the assumed background properties of Table 2. The following procedure was used.

For a fixed number of ports and port depth the nozzle angle and diameter were varied to find the largest port diameter that satisfies 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. Maximizing the nozzle diameter minimizes the jet exit velocity and therefore the mean shear that may be injurious to marine organisms. The number of ports was varied from four to 12. Because the port depth is not yet finalized, calculations were done for two port depths: 20 and 24 ft, which brackets the range of possible depths. The computations were done assuming the salinity requirement was met at either the impact point or the end of the near field. If met at the impact point, the BMZ is a circle around the diffuser of radius equal to the impact point distance; if met at the near field it is a circle of radius equal to the length of the near field.

The results are shown in Appendix A. Table A1 summarizes the results assuming that the BMZ is at the impact point, and Table A2 summarizes the results assuming it is at the end of the near field.

Tables A1 and A2 show that, with suitable nozzle configurations, it is possible to meet the salinity requirements for all flow scenarios at either the impact point or the near field. For the local projects (L1 and L2), the nozzles can be oriented at nearly the optimum angle of 60°. For the regional projects (R1 and R2), however, the flows are much greater and it is necessary to orient the nozzles at a more shallow angle, around 30°, to avoid disturbing the water surface. This necessitates higher jet velocities than for 60° jets to effect the required dilutions. In all cases, the salinity requirement is met well within the maximum allowable BMZ of 100 m (328 ft).

Applying the salinity criteria at either the impact point or the near field involves tradeoffs. If the impact point dilution is used the jet velocity is higher but the BMZ is smaller. If the near field dilution is used the jet velocity is lower but the BMZ is larger.

The optimum number of ports for a port depth of 20 ft and salinity requirement met at the impact point was then found for each flow scenario from the results in Appendix A. The optimum is the number of ports that minimizes the jet exit velocity, and therefore the head loss and mean shear. Meeting the salinity requirement at the impact point minimizes the BMZ and also ensures that no point on the seabed will exceed 2 ppt excess salinity.

Without jet merging, the optimum number of ports would be 12 as this minimizes the jet velocity and head loss for a fixed dilution target. However, because of the reduction in dilution due to merging resulting from increasing the number of ports on a single riser, discussed in Section 2.3.3, the optimum numbers are less than 12. For the local projects, the optimum number of ports is between four and six, and for the regional projects, from six to eight. Because the design is not yet finalized we assume four ports for the local projects and eight ports for the regional projects. The layer thickness is predicted by Eq. 7. Table 3 summarizes the results.

In each case, the salinity requirement of 2 ppt is met at the impact point. The dilution at the maximum BMZ at 100 m is assumed to be that at the end of the near field, i.e. no further dilution due to far field mixing beyond the end of the near field is assumed. This is a conservative assumption that neglects any further dilution due to far field mixing.

Table 3. Optimum Port Configurations for Each Flow Scenario Assuming Port Depth of 20 ft and Salinity Increment less than 2 ppt at the Jet Impact Point.

Project	Case ID	Effluent			Nozzle conditions						Geometrical		Impact point			Near field		
		Flow (mgd)	Salinity (ppt)	Density (kg/m^3)	No. of ports	Diam. (in)	Angle (deg)	Flow (cfs)	Velocity (ft/s)	Froude no.	Rise height y_t (ft)	Layer thickness y_L (ft)	Dilution, S_i	Length x_i (ft)	Salinity increment (ppt)	Dilution Sn	Length x_n (ft)	Salinity increment (ppt)
Local	L1	25.4	62.0	1046.2	4	15.0	46	9.8	8.0	8.6	19.5	7.5	14.3	38	2.0	14.9	119	1.9
	L2	21.0	67.8	1050.8	4	12.4	46	8.1	9.7	10.4	19.5	7.5	17.3	38	2.0	18.0	119	1.9
Regional	R1	76.2	62.0	1046.2	8	13.4	26	14.7	15.0	17.1	19.6	13.4	14.3	66	2.0	16.9	203	1.7
	R2	63.0	67.8	1050.8	8	11.1	26	12.2	18.1	20.6	19.6	13.3	17.2	66	2.0	20.3	203	1.7

3.3 Shear Mortality

The volume of water entrained into the jets that may be harmful to planktonic organisms was calculated according to the recommendations in Roberts (2018) (R2018). There it is recommended that the harmful volume is that 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 jet Reynolds numbers $\mathrm{Re} = ud/\nu$ were calculated assuming the kinematic viscosity ν = 1.26×10^{-5} ft^2/s. Reynolds numbers are of order 10^6. The jet path length χ up to the terminal rise height was calculated from the UM3 trajectory results. They are of order 20 to 28 ft. The centerline Kolmogorov scales η_c at the top after a trajectory length χ (R2018 Eq. 22):

$$\frac{\eta_c}{\chi} = 0.24\,\mathrm{Re}^{-3/4}$$

are therefore of order 0.05 mm. Travel times in the jet of organisms entrained into it up to the top are of the order of 10 seconds.

Because the Kolmogorov scale at the top is less than one mm, deleterious entrainment is assumed up to this point. This is typical for a brine diffuser. Following the suggested procedure (R2018 Section 4.4.3), UM3 was run for each case of Table 3; the outputs are given in Appendix B.

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

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

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. The percentage of this entrained flow to the total entrained flow up to the impact point is computed from:

$$Q_e\left(\%\right) = \frac{100Q_e}{1.4(S_i - 1)Q_T}$$

where S_i is the impact dilution (Table 3) and the factor 1.4 is to convert the minimum dilutions to average dilutions. The results are shown in Table 4.

Table 4. UM3 Entrainment Calculations for Optimum Port Configurations for Each Flow Scenario Assuming Port Depth of 20 ft and Salinity Increment less than 2 ppt at the Jet Impact Point.

Project	Case ID	Effluent			Nozzle conditions						UM3 predictions at top		
		Flow (mgd)	Salinity (ppt)	Density (kg/m^3)	No.	Diam. (in)	Angle (deg)	Flow (cfs)	Velocity (ft/s)	Froude no.	Average dilution, S_{ta}	Entrained flow Q_e (mgd)	Entrained flow %
Local	L1	25.4	62.0	1046.2	4	15.0	46	9.8	8.0	8.6	5.7	119	25
	L2	21.0	67.8	1050.8	4	12.4	46	8.1	9.7	10.4	7.0	126	26
Regional	R1	76.2	62.0	1046.2	8	13.4	26	14.7	15.0	17.1	9.9	678	52
	R2	63.0	67.8	1050.8	8	11.1	26	12.2	18.1	20.6	12.0	693	49

3.4 Discussion

For the assumed port depth and salinity requirement the local project (four nozzles) jet velocities are 8.0 and 9.7 ft/s with nozzle diameters 12.4 or 15.0 inches. Nozzle angles are around 46°. For the regional project (eight nozzles), jet velocities are 15.0 and 18.1 ft/s with diameters 11.1 or 13.4 inches. The nozzle angles are about 26°. The projects with internal washwater circulation (L2 and R2) require higher jet velocities because of the higher effluent salinity. This has two effects: The required dilution to achieve 2 ppt is higher, and the effluent density is higher which requires more jet momentum flux. The lengths of the BMZ are very short, about 38 ft for the local project and 66 ft for the regional project. These are much less than the maximum allowable length of the BMZ, which is 100 m (328 ft).

The additional hydraulic head due to the jets ranges from about 1.0 to 5.1 ft. This corresponds to a pressure of 0.4 to 2.3 psi. The actual pressure may be up to 50% higher depending on the design of the riser chamber.

The optimum designs of Table 3 are different for each flow scenario. The final designs will depend on the characteristics of the TideFlex check valves. For example, regional project R1 corresponds to a Tideflex 12 inch Wide Bill valve, but this might not work for the other flows. Depending on the valve characteristics, different strategies may be needed for the different projects. For example, simply opening or closing ports may not meet all environmental criteria for all projects, and retrofitting new valves may be needed if and when the regional project is built.

The assumed environmental criteria can be met for both port depths (20 and 24 ft) at both the impact point and the end of the near field. If the port depth is increased from 20 to 24 ft, the required jet velocity is decreased and the lengths of the mixing zones are also decreased.

The fraction of the entrained flow is less for the more steeply angled jets of the local project, more for the flatter jet trajectories of the regional project. These calculations assume that the BMZ dilution is met at the impact point; if met at the end of the near field the entrained volumes would be less.

As the design is refined, the results of Appendix A can be used to assess the effects of port depth and of meeting the salinity requirement at the end of the near field rather than at the impact point.

The dilution predictions are believed to be conservative but are based on limited experimental data. It is recommended that physical model tests be considered during final design in order to confirm and refine the chosen riser configurations.

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APPENDIX A. DILUTION CALCULATIONS FOR VARYING NUMBERS OF PORTS

Table A1. Optimum Port Diameters and Orientations for Two Port Depths to Satisfy Plume Submergence and Salinity Increment at the Impact Point

Case ID	Effluent			Nozzle conditions					Impact point conditions		
	Flow (mgd)	Salinity (ppt)	Density (kg/m3)	Port depth (ft)	No. of ports	Diam. (in)	Angle (deg)	Jet velocity (ft/s)	Dilution, Si	Salinity increment (ppt)	BMZ (ft)
L1	25.4	62.0	1046.2	20.0	4	15.0	46	8.0	14.3	2.0	38
					6	12.3	50	7.9	14.2	2.0	33
					8	10.4	54	8.3	14.2	2.0	31
					10	8.8	52	9.3	14.3	2.0	32
					12	7.4	48	11.0	14.2	2.0	36
				24.0	4	15.4	48	7.6	14.2	2.0	33
					6	12.4	54	7.8	14.3	2.0	31
					8	10.4	54	8.3	14.2	2.0	30
					10	8.8	52	9.3	14.3	2.0	29
					12	7.5	52	10.7	14.2	2.0	34
L2	21.0	67.8	1050.8	20.0	4	12.4	46	9.7	17.3	2.0	38
					6	10.2	52	9.5	17.3	2.0	32
					8	8.6	54	10.1	17.2	2.0	31
					10	7.3	52	11.2	17.1	2.0	32
					12	6.1	48	13.3	17.3	2.0	36
				24.0	4	12.8	56	9.1	17.1	2.0	34
					6	10.3	54	9.4	17.1	2.0	31
					8	8.6	54	10.1	17.2	2.0	31
					10	7.3	52	11.1	17.3	2.0	32
					12	6.2	52	12.9	17.2	2.0	34
R1	76.0	62.0	1046.2	20.0	4	17.2	16	18.3	14.3	2.0	80
					6	15.6	24	14.8	14.3	2.0	69
					8	13.4	26	15.0	14.3	2.0	66
					10	11.4	26	16.6	14.2	2.0	67
					12	8.9	20	22.7	14.5	2.0	76
				24.0	4	20.7	30	12.6	14.3	2.0	71
					6	17.6	36	11.6	14.3	2.0	61
					8	15.0	38	12.0	14.3	2.0	58
					10	12.5	36	13.8	14.4	2.0	61
					12	10.3	32	17.0	14.3	2.0	68
R2	63.0	67.8	1046.2	20.0	4	14.3	16	21.8	17.1	2.0	79
					6	12.9	24	17.9	17.2	2.0	69
					8	11.1	26	18.1	17.2	2.0	66
					10	8.9	22	22.6	17.5	2.0	70
					12	6.9	16	31.3	17.6	1.9	78
				24.0	4	17.5	32	14.6	17.2	2.0	69
					6	14.6	36	14.0	17.2	2.0	61
					8	12.4	38	14.5	17.3	2.0	58
					10	10.4	36	16.5	17.2	2.0	61
					12	8.5	32	20.6	17.4	2.0	68

Table A2. Optimum Port Diameters and Orientations for Two Port Depths to Satisfy Plume Submergence and Salinity Increment at the End of the Near Field

Case ID	Effluent			Nozzle conditions					Near field conditions		
	Flow (mgd)	Salinity (ppt)	Density (kg/m3)	Port depth (ft)	No. of ports	Diam. (in)	Angle (deg)	Jet velocity (ft/s)	Dilution, Sn	Salinity increment (ppt)	BMZ (ft)
L1	25.4	62.0	1046.2	20.0	4	15.4	48	7.6	14.2	2.0	113
					6	12.9	56	7.2	14.2	2.0	95
					8	11.1	56	7.3	14.2	2.0	89
					10	9.7	52	7.7	14.2	2.0	89
					12	8.6	52	8.1	14.3	2.0	89
				24.0	4	15.7	58	7.3	14.2	2.0	104
					6	12.9	58	7.2	14.2	2.0	95
					8	11.1	56	7.3	14.2	2.0	89
					10	9.7	52	7.7	14.2	2.0	89
					12	8.6	52	8.1	14.3	2.0	89
L2	21.0	67.8	1050.8	20.0	4	12.7	48	9.2	17.3	2.0	114
					6	10.6	56	8.8	17.5	2.0	98
					8	9.2	58	8.8	17.1	2.0	87
					10	8.0	58	9.3	17.6	1.9	86
					12	7.2	58	9.6	17.1	2.0	84
				24.0	4	13.0	58	8.8	17.1	2.0	104
					6	10.7	58	8.7	17.1	2.0	93
					8	9.2	58	8.8	17.1	2.0	87
					10	8.0	58	9.3	17.6	1.9	86
					12	7.2	58	9.6	17.1	2.0	85
R1	76.0	62.0	1046.2	20.0	4	18.4	20	16.0	15.0	1.9	242
					6	17.0	28	12.5	14.4	2.0	192
					8	14.9	30	12.2	15.4	1.9	177
					10	13.6	34	11.7	14.4	2.0	165
					12	12.1	34	12.3	14.4	2.0	163
				24.0	4	21.5	32	11.7	14.4	2.0	206
					6	18.9	40	10.1	14.2	2.0	169
					8	16.4	42	10.0	14.7	1.9	156
					10	14.6	44	10.1	14.5	2.0	149
					12	13.1	46	10.5	14.3	2.0	145
R2	63.0	67.8	1046.2	20.0	4	16.0	22	17.5	17.1	2.0	228
					6	14.1	28	15.0	17.2	2.0	191
					8	12.6	32	14.1	17.3	2.0	172
					10	11.3	32	14.0	17.4	2.0	162
					12	10.0	34	14.9	17.5	2.0	164
				24.0	4	17.9	32	13.9	17.1	2.0	204
					6	15.4	38	12.6	17.4	2.0	172
					8	13.6	42	12.1	17.4	2.0	156
					10	12.2	46	12.0	17.4	2.0	146
					12	10.8	46	12.8	17.4	2.0	146

APPENDIX B. UM3 OUTPUTS

Outputs from the mathematical model UM3 for cases in Table 3: L1, L2, R1, R2.

Project "C:\Plumes17\West Basin\WBL1" memo

/ UM3. 2/9/2018 8:52:44 AM
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Ambient Table:

Depth	Amb-cur	Amb-dir	Amb-sal	Amb-tem	Amb-pol	Decay	Far-spd	Far-dir	Disprsn	Density
m	m/s	deg	psu	C	kg/kg	s-1	m/s	deg	m0.67/s2	sigma-T
0.0	0.0	90.00	33.50	17.60	0.0	0.0	-	-	0.0	24.24463
9.754	0.0	90.00	33.50	17.60	0.0	0.0	-	-	0.0	24.24463

Diffuser table:

P-dia	Ver angl	H-Angle	SourceX	SourceY	Ports	Spacing	MZ-dis	Isoplth	P-depth	Ttl-flo	Eff-sal	Temp	Polutnt
(in)	(deg)	(deg)	(m)	(m)	()	(ft)	(m)	(concent)	(ft)	(MGD)	(psu)	(C)	(ppb)
15.000	46.000	0.0	0.0	0.0	4.0000	100.00	100.00	0.0	20.000	25.400	62.000	17.600	1000.0

Simulation:
Froude No: -8.674; Strat No: 0.0000; Spcg No: 80.00; k: 2.44E+5; eff den (sigmaT) 46.41048; eff vel 2.440(m/s);
Current is very small, flow regime may be transient.

Step	Depth	Amb-cur	P-dia	Polutnt	Dilutn	x-posn	y-posn	Iso dia	
	(ft)	(m/s)	(in)	(ppb)	()	(ft)	(ft)	(m)	
0	20.00	1.000E-5	15.00	1000.0	1.000	0.0	0.0	0.3810;	
100	13.00	0.0	74.40	225.7	4.431	8.518	0.0	1.8898;	
181	11.81	0.0	99.83	178.3	5.608	12.57	0.0	2.5357;	begin overlap;
194	11.80	0.0	102.4	174.0	5.746	13.10	0.0	2.6012;	local maximum rise or fall;
200	11.80	0.0	103.5	172.2	5.806	13.34	0.0	2.6280;	
286	12.69	0.0	113.2	149.1	6.705	16.77	0.0	2.8763;	end overlap;
300	13.02	0.0	114.4	144.8	6.904	17.38	0.0	2.9067;	
400	19.50	0.0	126.6	101.6	9.841	23.33	0.0	3.2155;	
444	30.32	0.0	151.0	67.30	14.86	28.15	0.0	3.8357;	bottom hit;

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Lmz(m): 8.5795
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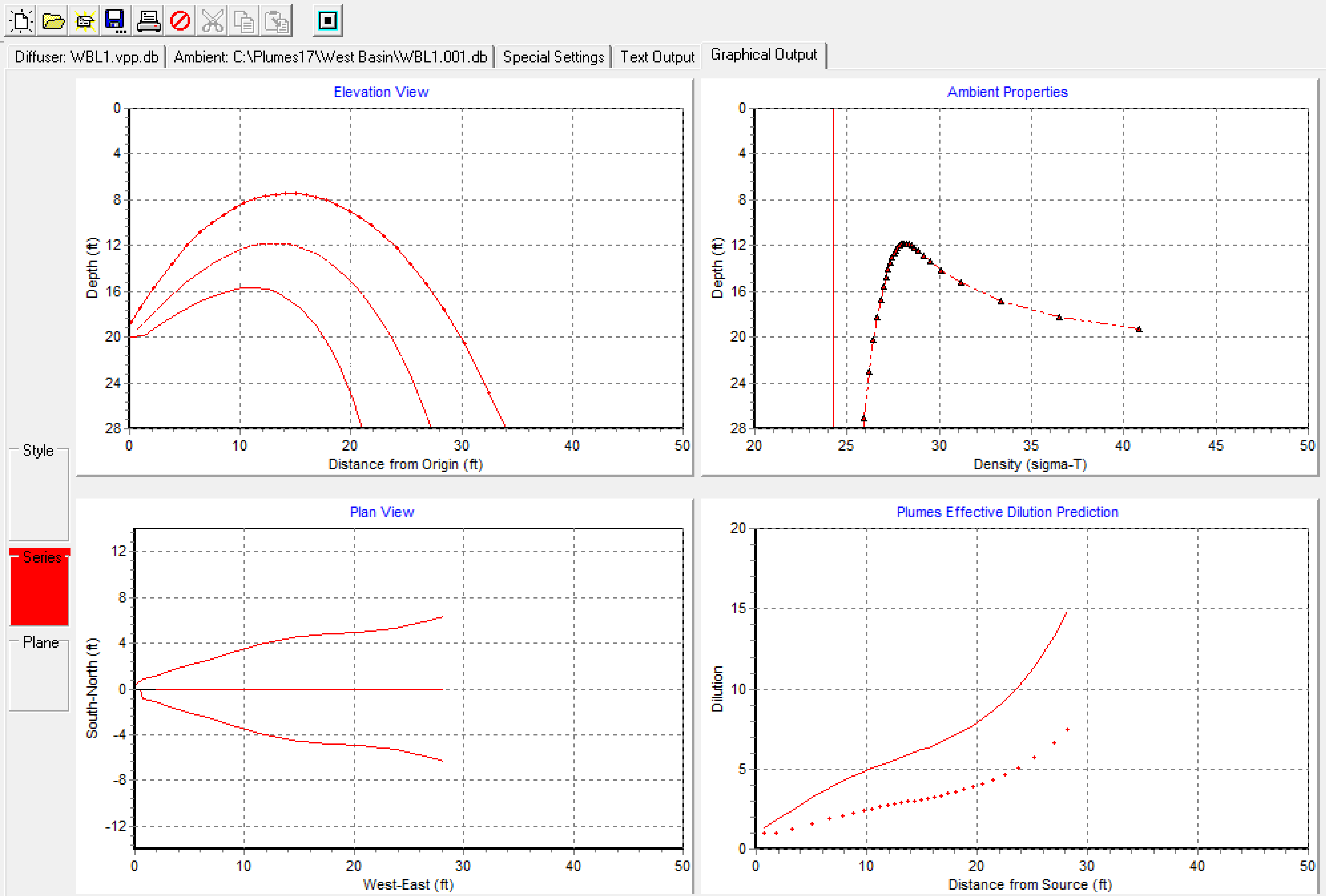
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Density (sigma-T)
Style
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Plane
Plan View
South-North (ft)
West-East (ft)
Plumes Effective Dilution Prediction
Dilution
Distance from Source (ft)

Project "C:\Plumes17\West Basin\WBL2" memo

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Ambient Table:

Depth	Amb-cur	Amb-dir	Amb-sal	Amb-tem	Amb-pol	Decay	Far-spd	Far-dir	Disprsn	Density
m	m/s	deg	psu	C	kg/kg	s-1	m/s	deg	m0.67/s2	sigma-T
0.0	0.0	90.00	33.50	17.60	0.0	0.0	-	-	0.0	24.24463
9.754	0.0	90.00	33.50	17.60	0.0	0.0	-	-	0.0	24.24463

Diffuser table:

P-dia	Ver angl	H-Angle	SourceX	SourceY	Ports	MZ-dis	Isoplth	P-depth	Ttl-flo	Eff-sal	Temp	Polutnt
(in)	(deg)	(deg)	(m)	(m)	()	(m)	(concent)	(ft)	(MGD)	(psu)	(C)	(ppb)
12.400	46.000	0.0	0.0	0.0	4.0000	100.00	0.0	20.000	21.000	67.800	17.600	1000.0

Simulation:
Froude No: -10.52; Strat No: 0.0000; Spcg No: 29.50; k: 2.95E+5; eff den (sigmaT) 51.06172; eff vel 2.952(m/s);
Current is very small, flow regime may be transient.

Step	Depth	Amb-cur	P-dia	Polutnt	Dilutn	x-posn	y-posn	Iso dia	
	(ft)	(m/s)	(in)	(ppb)	()	(ft)	(ft)	(m)	
0	20.00	1.000E-5	12.40	1000.0	1.000	0.0	0.0	0.3150;	
100	12.98	0.0	69.98	195.5	5.114	8.285	0.0	1.7774;	
192	11.46	0.0	100.2	146.6	6.823	13.08	0.0	2.5455;	begin overlap;
200	11.45	0.0	101.8	144.4	6.927	13.41	0.0	2.5865;	
203	11.45	0.0	102.4	143.6	6.965	13.53	0.0	2.6009;	local maximum rise or fall;
294	12.34	0.0	113.3	123.0	8.131	17.18	0.0	2.8785;	end overlap;
300	12.47	0.0	113.9	121.5	8.231	17.44	0.0	2.8921;	
400	18.10	0.0	124.8	87.86	11.38	23.10	0.0	3.1702;	
453	30.28	0.0	152.0	54.94	18.20	28.71	0.0	3.8616;	bottom hit;

Horiz plane projections in effluent direction: radius(m): 0.0; CL(m): 8.7512
Lmz(m): 8.7512
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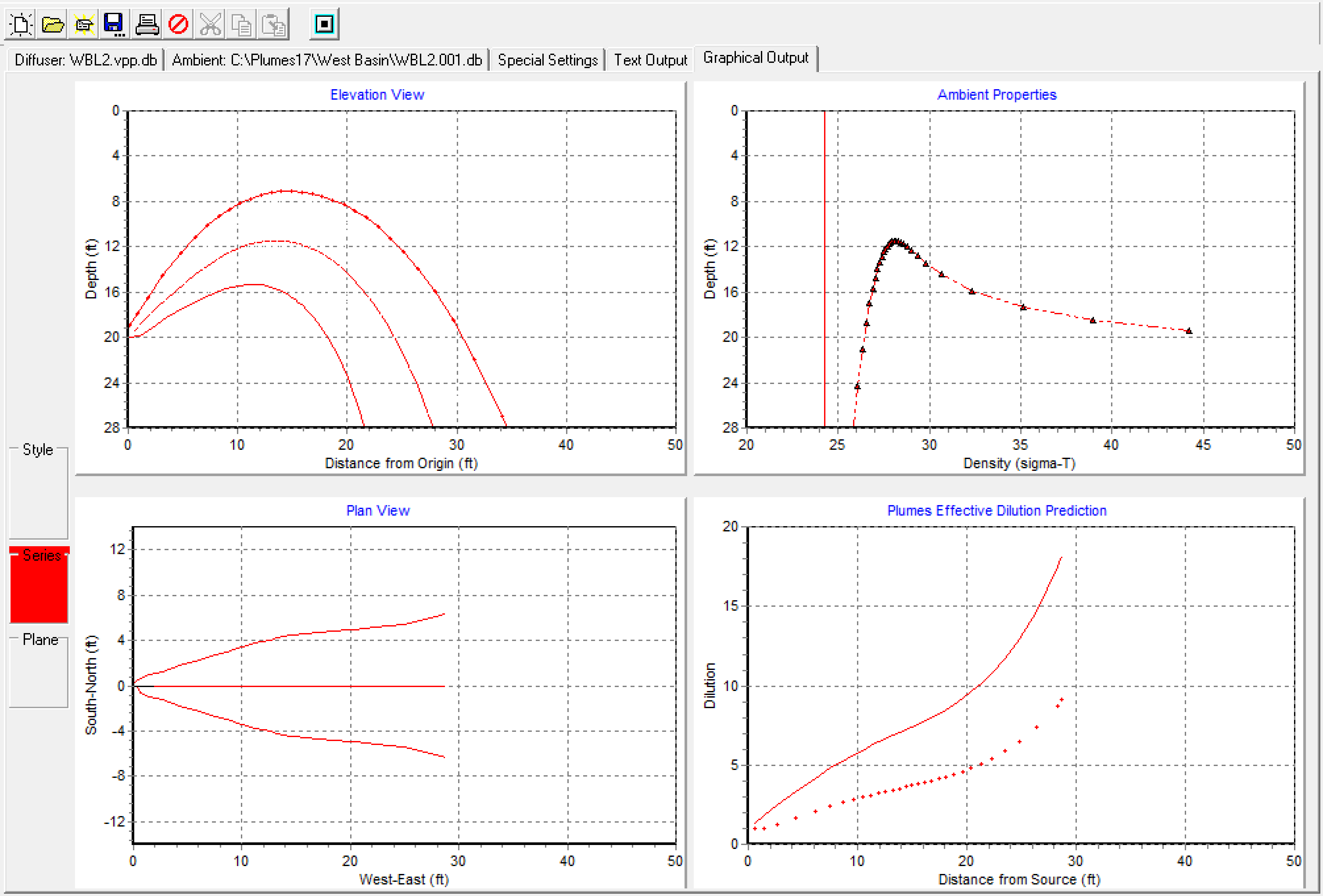
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West-East (ft)
Plumes Effective Dilution Prediction
Dilution
Distance from Source (ft)

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/ UM3. 2/9/2018 9:05:22 AM
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Ambient Table:

Depth	Amb-cur	Amb-dir	Amb-sal	Amb-tem	Amb-pol	Decay	Far-spd	Far-dir	Disprsn	Density
m	m/s	deg	psu	C	kg/kg	s-1	m/s	deg	m0.67/s2	sigma-T
0.0	0.0	90.00	33.50	17.60	0.0	0.0	-	-	0.0	24.24463
9.754	0.0	90.00	33.50	17.60	0.0	0.0	-	-	0.0	24.24463

Diffuser table:

P-dia	Ver angl	H-Angle	SourceX	SourceY	Ports	MZ-dis	Isoplth	P-depth	Ttl-flo	Eff-sal	Temp	Polutnt
(in)	(deg)	(deg)	(m)	(m)	()	(m)	(concent)	(ft)	(MGD)	(psu)	(C)	(ppb)
13.400	26.000	0.0	0.0	0.0	8.0000	100.00	0.0	20.000	76.200	62.000	17.600	1000.0

Simulation:
Froude No: -17.25; Strat No: 0.0000; Spcg No: 27.30; k: 4.59E+5; eff den (sigmaT) 46.41048; eff vel 4.587(m/s);
Current is very small, flow regime may be transient.

Step	Depth	Amb-cur	P-dia	Polutnt	Dilutn	x-posn	y-posn	Iso dia	
	(ft)	(m/s)	(in)	(ppb)	()	(ft)	(ft)	(m)	
0	20.00	1.000E-5	13.40	1000.0	1.000	0.0	0.0	0.3404;	
100	13.97	0.0	93.02	147.0	6.802	14.96	0.0	2.3628;	
153	12.74	0.0	138.2	101.0	9.898	23.78	0.0	3.5110;	local maximum rise or fall;
200	13.47	0.0	165.0	83.51	11.98	29.75	0.0	4.1920;	
300	20.41	0.0	208.5	57.80	17.30	42.22	0.0	5.2968;	
335	26.35	0.0	226.8	48.39	20.67	47.65	0.0	5.7615;	bottom hit;

Horiz plane projections in effluent direction: radius(m): 0.0; CL(m): 14.525
Lmz(m): 14.525
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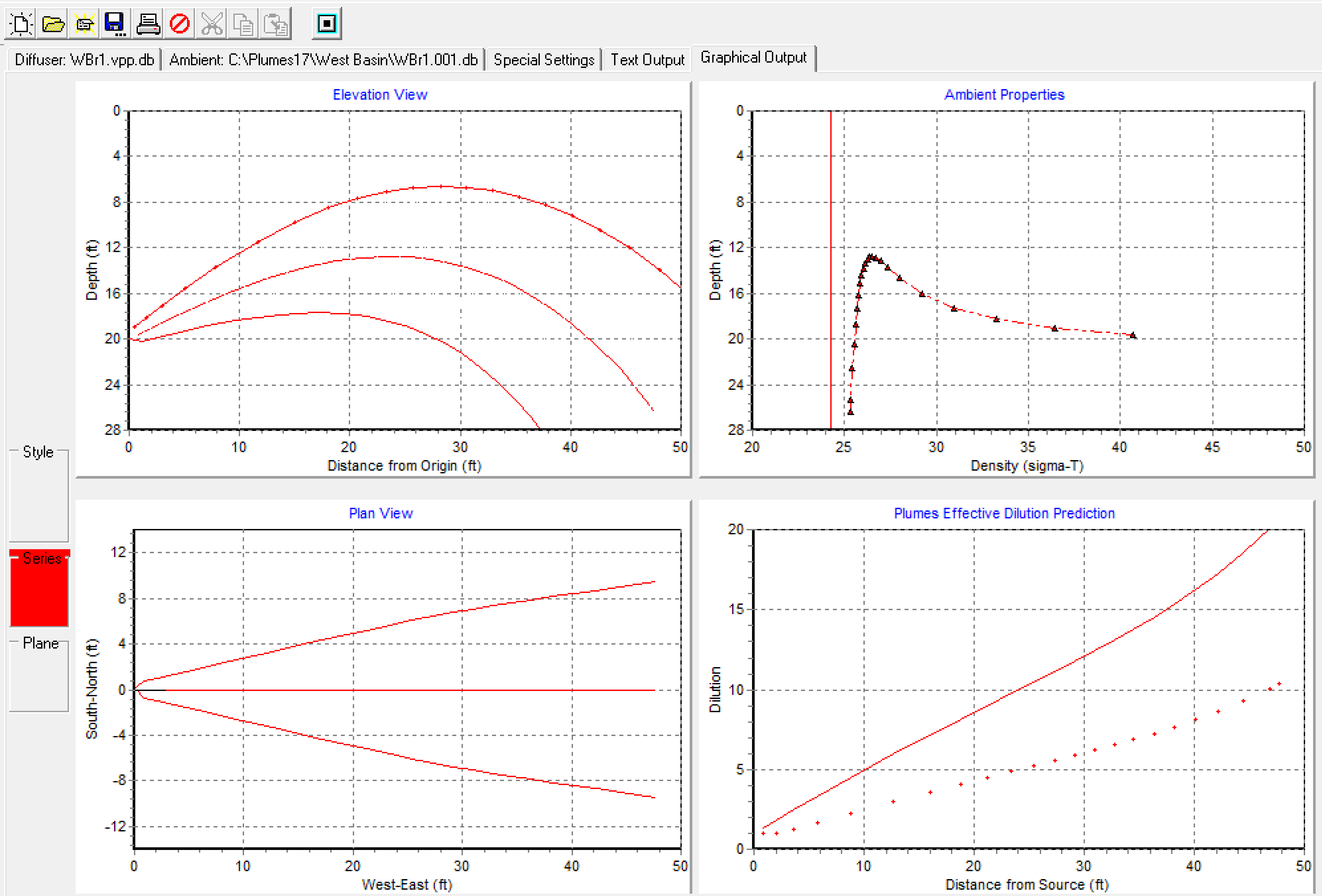
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Depth (ft)
Density (sigma-T)
Style
Series
Plane
Plan View
South-North (ft)
West-East (ft)
Plumes Effective Dilution Prediction
Dilution
Distance from Source (ft)

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/ UM3. 2/9/2018 9:11:41 AM
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Ambient Table:

Depth	Amb-cur	Amb-dir	Amb-sal	Amb-tem	Amb-pol	Decay	Far-spd	Far-dir	Disprsn	Density
m	m/s	deg	psu	C	kg/kg	s-1	m/s	deg	m0.67/s2	sigma-T
0.0	0.0	90.00	33.50	17.60	0.0	0.0	-	-	0.0	24.24463
9.754	0.0	90.00	33.50	17.60	0.0	0.0	-	-	0.0	24.24463

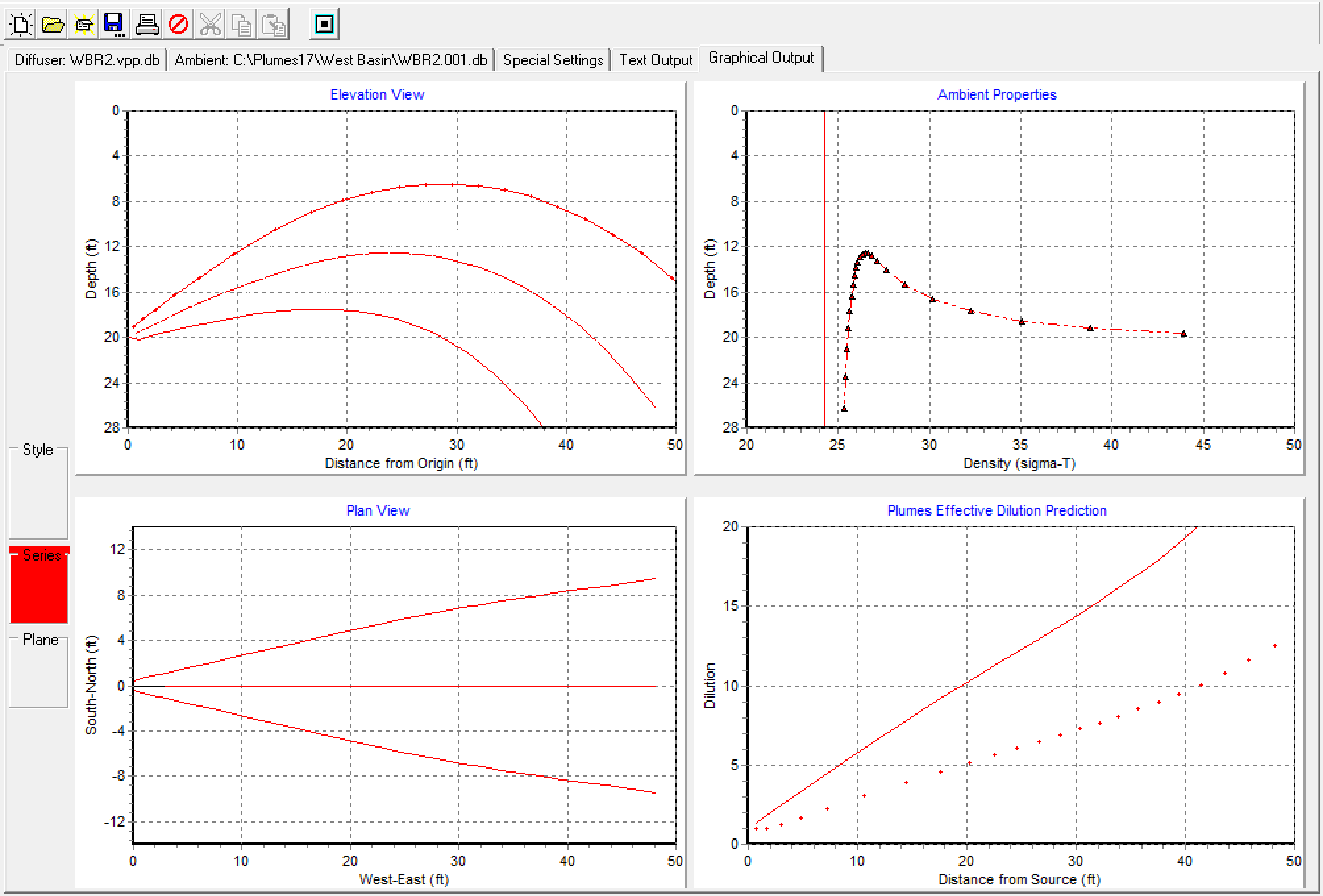
Diffuser table:

P-dia	Ver angl	H-Angle	SourceX	SourceY	Ports	MZ-dis	Isoplth	P-depth	Ttl-flo	Eff-sal	Temp	Polutnt
(in)	(deg)	(deg)	(m)	(m)	()	(m)	(concent)	(ft)	(MGD)	(psu)	(C)	(ppb)
11.100	26.000	0.0	0.0	0.0	8.0000	100.00	0.0	20.000	63.000	67.800	17.600	1000.0

Simulation:
Froude No: -20.81; Strat No: 0.0000; Spcg No: 32.95; k: 5.53E+5; eff den (sigmaT) 51.06172; eff vel 5.526(m/s);
Current is very small, flow regime may be transient.

Step	Depth	Amb-cur	P-dia	Polutnt	Dilutn	x-posn	y-posn	Iso dia	
	(ft)	(m/s)	(in)	(ppb)	()	(ft)	(ft)	(m)	
0	20.00	1.000E-5	11.10	1000.0	1.000	0.0	0.0	0.2819;	
100	14.38	0.0	81.91	136.9	7.307	13.32	0.0	2.0804;	
162	12.56	0.0	138.2	83.51	11.98	24.23	0.0	3.5110;	local maximum rise or fall;
200	13.05	0.0	160.5	71.31	14.02	29.11	0.0	4.0765;	
300	19.17	0.0	204.7	49.60	20.16	41.44	0.0	5.1987;	
344	26.23	0.0	227.0	39.93	25.04	48.14	0.0	5.7666;	bottom hit;

Horiz plane projections in effluent direction: radius(m): 0.0; CL(m): 14.675
Lmz(m): 14.675
forced entrain 1 0.0 -1.898 5.767 0.618
Rate sec-1 0.0 dy-1 0.0 kt: 0.0 Amb Sal 33.5000
;
9:11:41 AM. amb fills: 4



Diffuser: WBR2.vpp.db
Ambient: C:\Plumes17\West Basin\WBR2.001.db
Special Settings
Text Output
Graphical Output
Style
Series
Plane
Elevation View
Depth (ft)
0
4
8
12
16
20
24
28
0
10
20
30
40
50
Distance from Origin (ft)
Ambient Properties
Depth (ft)
0
4
8
12
16
20
24
28
20
25
30
35
40
45
50
Density (sigma-T)
Plan View
South-North (ft)
12
8
4
0
-4
-8
-12
0
10
20
30
40
50
West-East (ft)
Plumes Effective Dilution Prediction
Dilution
20
15
10
5
0
0
10
20
30
40
50
Distance from Source (ft)