



## 6. Ocean Modeling

### 6.1 Introduction

As discussed in Chapter 4, the preferred alternative for RBWWTP effluent disposal is an ocean outfall. To help understand and predict the environmental impacts of this alternative, two numerical ocean circulation and plume dispersion models were developed by GHD and calibrated using published and collected field data. The models estimate the rate at which treated effluent will dilute at the point of discharge (near-field) and the far-field fate of the effluent as it migrates away from the zone of initial mixing and dissipates.

Both the far-field and near-field models were developed to assist in determining the dilution of RBWWTP treated effluent that is expected to occur within the ocean in the vicinity of the proposed ocean outfall. Both models rely on an accurate description of the characteristics of the receiving waters in the area and predict the rate of dilution of the effluent – a key parameter in determining the associated magnitude and extent of potential environmental impacts.

The developed far-field model extends over more than 15,000 square miles (39,000 square kilometers). Far-field modeling incorporates existing oceanographic conditions and relevant coastal processes including water levels, currents, winds and wave action. It also provides a means to assess the potential for and extent of any long term buildup of effluent concentrations, and to address whether there is any risk of the effluent plume migrating back towards the coastline. It should be noted that any such potential should be considered in the context of existing conditions and the rationale for relocating the existing point of discharge.

Near-field modeling provides a different function, involving simulation of the entrainment of a plume into a water body. The near-field zone is where turbulent mixing dominates and is often limited to the point at which the plume reaches the ocean surface.

The modeling report and corresponding results are included in (Appendix J). A brief description of the model and summary of the obtained results is provided in the following sections of this chapter where the modeling report is referred to as the *model report*.

### 6.2 Field Data

#### 6.2.1 Field Data Collection

Data required to calibrate and validate the hydrodynamic model was collected by the Woods Hole Group, Inc. The data collection effort targeted two potential outfall sites referred to as northern and southern outfalls (see Appendix A of model report) and was organized in two long-term field monitoring campaigns and six short-term intensive periods of measurement.

The first campaign was undertaken from September 1 to November 10, 2010. An Acoustic Doppler Current Profiler (ADCP) was deployed on the ocean floor to measure current profiles and wave height at each of the two proposed outfall locations. Additionally, at each location, anchored buoys were deployed with a string of four conductivity / temperature / density (CTD) instruments evenly spaced between the ocean floor and surface, which also collected data continuously during the same period. The northern ADCP and both CTD



meters operated successfully. The ADCP deployed near the proposed southern point of discharge suffered a battery failure and no data was collected at this site.

The second field monitoring campaign was carried out in late summer 2011 (July 6 to September 12, 2011). A summary of the ADCP and CTD data collected at each outfall location is presented in Table 6-1.

**Table 6-1 ADCP and CTD data collected at each outfall location**

Date	Location	Properties Measured	Frequency	Depth Range
9/2/2010 to 11/9/2010	Northern Outfall (38.730 °N, 75.058 °W)	Temperature, Conductivity, Pressure, Salinity,	Every 10 min	10 ft (3.0 m), 20 ft (6.1 m), 47 ft (14.3 m)
		Current Speed and Direction	<i>Battery Failure – No Data</i>	
		Hs, Tp, Dp, Depth, H1/10, Tmean, Dmean, Current Speed and Direction	<i>Battery Failure – No Data</i>	
	Southern Outfall (38.722 °N, 75.060 °W)	Temperature, Conductivity, Pressure, Salinity,	Every 10 min	10 ft (3.0 m), 20 ft (6.1 m), 44 ft (13.4 m)
		Current Speed and Direction	Every 10 min	4.9-37.7 ft (1.5- 11.5 m), at 1.6 ft (0.5 m) increments
		Hs, Tp, Dp, Depth, H1/10, Tmean, Dmean, Current Speed and Direction	Every 1 hour	0-34.4 ft (0-10.5 m), at 1.6 ft (0.5 m) increments
7/6/11 to 9/12/11	Northern Outfall (38.730 °N, 75.058 °W)	Temperature, Conductivity, Pressure, Salinity,	Every 10 min	3 ft (0.9 m), 10 ft (3.0 m), 20 ft (6.1 m), 47 ft (14.3 m)
		Current Speed and Direction	Every 10 min	4.9-39.4 ft (1.5-12 m), at 1.6 ft (0.5 m) increments
	Southern Outfall (38.722 °N, 75.060 °W)	Hs, Tp, Dp, Depth, H1/10, Tmean, Dmean, Current Speed and Direction	Every 1 hour	4.9-36.1 ft (1.5-11 m), at 1.6 ft (0.5 m) increments
		Temperature, Conductivity, Pressure, Salinity,	Every 10 min	3 ft (0.9 m), 20 ft (6.1 m), 44 ft (13.4 m)
		Current Speed and Direction	Every 10 min	4.9-37.7 ft (1.5- 11.5 m), at 1.6 ft (0.5 m) increments



Date	Location	Properties Measured	Frequency	Depth Range
		Hs, Tp, Dp, Depth, H1/10, Tmean, Dmean, Current Speed and Direction	Every 1 hour	4.9-34.4 ft (0-10.5 m), at 1.6 ft (0.5 m) increments

Dissolved oxygen profiles were also collected at each outfall location on November 18, 2010. Surface water samples were collected at each fixed location on November 18, 2010 and June 30, 2011 and sent to a lab for analysis (Appendix K).

Ship based transect surveys (as part of the short-term intensive surveys) were performed about every two months for a period of a year. The transect surveys obtained CTD profiles at approximately 3,200 foot intervals as the ship moved along the transect. The depth intervals were approximately the same as the fixed CTD instruments. The collection schedule is presented in Table 6-2.

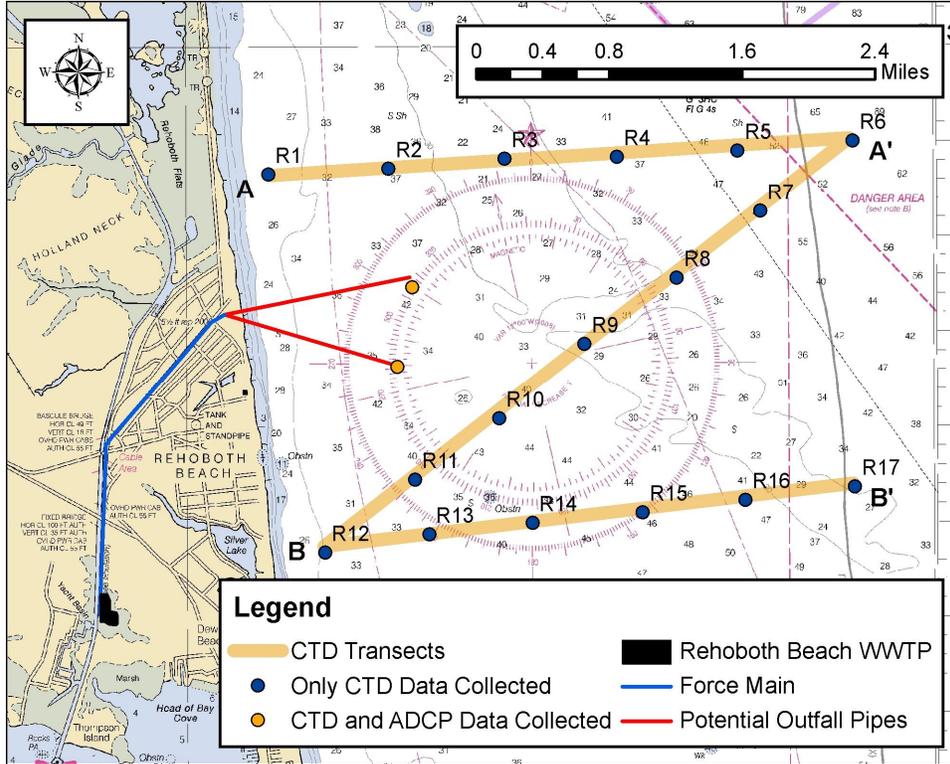
**Table 6-2 CTD Collection Schedule**

CTD Cruise Number	Date
CTD Cruise #1	November 18, 2010
CTD Cruise #2	January 25, 2011
CTD Cruise #3	March 17, 2011
CTD Cruise #4	May 25, 2011
CTD Cruise #5	July 11, 2011
CTD Cruise #6	September 14, 2011

The coordinates of the transect lines are shown in Figure 6-1 and described in Table 6-3. The instruments utilized for data collection are presented in Table 6-4 along with the frequency of calibration. Calibration reports and procedures are included in (Appendix L).



**Figure 6-1 Location of Buoy Deployment and Transect Surveys**



**Table 6-3 Location of Transect Surveys**

Location	Coordinates	
A Transect Nearshore End (A)	75° 4.44' W	38° 44.33' N
A Transect Offshore End (A')	75° 0.56' W	38° 44.51' N
B Transect Nearshore End (B)	75° 4.09' W	38° 42.38' N
B Transect Offshore End (B')	75° 0.54' W	38° 42.70' N

**Table 6-4 Data Collection Instruments**

Data Parameter	Instrument	Calibration Frequency
DO	YSI Sonde	Morning of data collection
ADCP (Moored)	Teledyne RD	Within 24 hours of deployment



<b>Data Parameter</b>	<b>Instrument</b>	<b>Calibration Frequency</b>
CTD (Moored)	Seabird Electronics SBE 37 SMP	Factory calibrated every 5 years
CTD (Transect)	YSI Castaway	Factory calibrated annually

### 6.2.2 Field Data Analysis

Each installation was equipped with a self-recording Teledyne RD Instrument ADCP instrument with WAVES and Seabird Electronics SBE 37 SMP CTD instrument. CTD measurements through the water column were made via in-situ instruments on a chain mooring from a conventional surface buoy configuration.

### 6.3 Modeling Scope

The far-field modeling exercise comprises of six steps including:

1. Review and assimilation of existing data
2. Acquisition of new data where existing data is insufficient
3. Development of an ocean circulation and effluent dispersion modeling system
4. Calibration of the modeling system to field measurements
5. Validation of the system to a second dataset of field measurements, different from the one used in the calibration process
6. Operation of the model for the assessment of circulation patterns and the potential for far-field dispersion of the effluent and plume build up beyond the near-field

Near-field modeling involves the simulation of the plume fate as injected into the water column, with emphasis on buoyancy and the dilution performance of the preferred diffuser configuration. This allows consideration of the degree of dilution that can be achieved in the immediate vicinity of the outfall (assuming the receiving waters are “clean”). Far-field modeling then allows for the build-up of concentrations to a position of equilibrium, whereby the net rate of effluent discharge is matched by the dispersion or decay of that effluent such that the plume becomes effectively indistinguishable from the receiving water.

### 6.4 Modeling Studies

Using the collected field data, modeling was undertaken to understand the trajectory of the effluent plume from the outfall and the concentration of effluent within the plume under various operating conditions. In addition to the field data, the model also utilized web based datasets, including wind speed and direction and wave height, wave period and wave direction provided by the United States Army Corps of Engineers (USACE), surface and bottom salinity and temperature from NOAA’s Northeast Fishery Science Center, and additional data provided by the Delaware Geologic Survey and the NOAA National Geophysical Data Center. The model was compared with previous modeling exercises, including the Lawler, Matusky & Skelly Engineers near-field model (2003) utilized in the 2005 Effluent Disposal Study and the circulation model developed at the University of Delaware (Garvine 2003).



## 6.5 Far-Field Modeling

### 6.5.1 Description of Model

The modeling system adopted for the Rehoboth Beach outfall study is applicable to scales ranging from estuaries to regional ocean domains. In its current application, it simulates two-dimensional, depth-averaged, non-linear, unsteady flow and transport phenomena resulting from the effects of the tide, winds, waves, freshwater inflows, and the effects of the earth's rotation.

The prognostic model variables include the free surface elevation and the two components of transport or velocity. The spatial discretization of the primitive equations is performed using a cell-centered finite-volume method. In two-dimensional mode, the spatial domain is represented on a flexible (unstructured) mesh of non-overlapping triangular or quadrilateral elements.

The hydrodynamic model is an implementation of Mike 21 Flexible Mesh module integrated in the Danish Hydraulic Institute (DHI) suite of models.

Sharing the unstructured mesh of the hydrodynamic model is a fully spectral wind-wave model based on the wave action conservation equation. The wave model has been developed to calculate the growth, decay and transformation of wind-generated waves in the study.

The simulation domain (Figure 6-2) includes the entire Delaware estuary and 233 miles (375 km) of the adjacent continental shelf extending some 65 miles (105 km) offshore to maximum depths of approximately 330 ft (100 m). The included section of continental shelf stretches from the mouth of the Delaware estuary 100 miles (160 km) north past Bamegat Bay reaching Point Pleasant Beach and 135 miles (215 km) to the south ending at Cape Charles at the mouth of Chesapeake Bay.

The model mesh contains 12730 elements and 7247 nodes with highest horizontal resolution encountered near the outfall of the order of 520-655 ft (160-200 m).

A preliminary three-dimensional scenario was also developed for the southern outfall. The scenario accounted for density effects (e.g. includes the effects of space and time varying salinity and temperature) and was designed to inform on the depth-varying physical aspects of the receiving waters that may not have been adequately represented in the depth-averaged, two dimensional modeling frame. The preliminary results of this model and field data collected by the CTD meters indicate that vertical stratification is not expected, and therefore two-dimensional models for each outfall should be sufficient. The results of the 2D far-field and near-field models, as discussed below and in Section 6.6, illustrate that adequate dilution can be achieved, even under periods of seasonal vertical density stratification.



**Figure 6-2 Simulation Domain**



### 6.5.2 Model Operation

The model was operated in a two-dimensional, depth-averaged mode for calibration and validation purposes as well as for long-term (one-year duration) operational runs applied to the investigation of effluent dispersion. The adopted two-dimensional formulation implies that stress terms are applied only at the surface (wind effects) and at the sea bed as bottom friction.

All modeling scenarios involved the three most significant driving forces governing the ocean hydrodynamics of the area - tide, freshwater inflows from the Delaware River and offshore winds. The importance of these forces has been established from a review of the existing scientific literature with some of the reviewed documents dating back to the 1980s.



### **6.5.3 Forcing of the Model**

The primary forcing factors included in the analysis are: tides, winds, waves, and Delaware River discharge. Excluded from the model are heat transfer processes through the water surface, precipitation, evaporation and large-scale shelf circulation.

Tidal elevations are imposed along the offshore boundaries of the model by specifying amplitude and phase for each of the following eight (8) major tidal constituents: Q1, O1, P1, K1, N2, M2, S2 and K2. These are obtained from the DHI global tidal model, which is an integral part of the adopted modeling system.

The wave model is forced by offshore winds applied to the free-surface of the model and offshore open boundary conditions comprising significant wave height, spectral peak wave period, mean wave direction and a directional spreading index.

### **6.5.4 Model Calibration**

Model calibration is a process whereby model predictions are compared to field data consisting of measured water levels and currents in order to assess the predictive capability of the model.

In total, 32 scenarios were investigated for calibration purposes with modeling conditions including:

- ▶ tide only;
- ▶ tide and freshwater river inflow;
- ▶ tide and wind;
- ▶ tide, freshwater river inflow and wind; and
- ▶ tide, freshwater river inflow, wind and wave.

Water elevation, current and wave measurements used for calibration of the modeling system were recorded by the ADCP deployed near the proposed northern outfall location (38.730° N, 75.058° W) for the period September 1, 2010 to November 10, 2010 (refer section 3.2 of the model report in (Appendix J) for details). For the purpose of calibration, the system was operated for a period of three months starting on August 15, 2010, thus including a two-week warm-up period in the simulation.

Since the results of the model are two-dimensional, depth averaged in nature, they were compared against depth-averaged current direction and current magnitude obtained from the ADCP records.

Predictions of tidal elevation for the tidal station at Lewes (based on eight (8) major tidal constituents) were also obtained and used in the process of calibration of the model to tide alone. The tidal constituents for the prediction were obtained from NOAA.

#### **6.5.4.1 Model Calibration to Predicted Tides**

A total of nine three-month simulations starting on August 15, 2010 were initially undertaken, during which Manning's roughness coefficient and tide-only water level offshore boundary conditions were gradually adjusted. The Manning's roughness coefficient  $n$  was varied in the 0.024 to 0.045 range. The offshore boundary conditions consisted of time series of water level forcing constructed from astronomical tidal constituents at the offshore boundary. Only the tidal constituents (tidal amplitude and phase) specified at the



boundary are propagated into the modeling domain from the offshore boundary. As part of the calibration process, tidal amplitude was multiplied by a factor in the 1.1 to 1.2 range.

The root-mean-square-error (RMSE) was used as an objective criterion for the assessment of the performance of the modeling system. The best performance, (i.e., lowest RMSE for water levels achieved in the above simulations) was 0.20 ft (0.06 m) for  $n=0.045$  and a scaling factor for tidal amplitudes of 1.2. A value of  $RMSE \leq 0.3$  ft (0.1 m) indicates that there is excellent agreement between predicted and simulated tidal elevations.

While the calibration to water levels involved a comparison of modeled and predicted entities, the calibration to currents involved the comparison of modeled tidal streams (currents generated by the tide alone) versus measured currents. The latter comparison (in terms of current magnitude) generated a RMSE of 0.30 ft/s (0.089 m/s). In terms of absolute values, modeled peak current magnitudes were of the order of 1.80 ft/s (0.55 m/s) whereas instances of measured peak current magnitudes reaching 2.43 ft/s (0.74 m/s) (e.g. as measured on September 9, 2010) can be observed in the measurements.

The results from the calibration to tide alone were interpreted as an indication that:

- ▶ With respect to tidal elevation and currents (magnitude), the quality of the obtained solution at the outfall site is sufficiently close to the recorded field data ( $RMSE=0.06$  m and 0.089 m/s, respectively)
- ▶ Tidally-induced mixing processes are expected to be adequately represented in plume dispersion solutions
- ▶ Tidal forces, while a dominant factor in the formation of currents, are not sufficient to reproduce the latter to full scale. It is necessary to investigate the additional contributions to the formation of currents by other driving forces (e.g. winds, waves and freshwater inflows)

#### **6.5.4.2 Calibration to Tide, Winds, Waves and Freshwater Inflows**

The process involved operating the system in two-dimensional mode using as input predicted tides, wind, waves and freshwater inflows with the purpose of improving the agreement between modeled and measured currents. The definition of horizontal eddy viscosity followed Smagorinsky's formulation. Manning's roughness coefficient  $n$  was kept at 0.045 with the scaling factor for tidal amplitude at 1.2.

The results of the calibration to tides, winds, waves and freshwater inflows were presented in the form of:

- ▶ Time histories of measured and modeled water levels
- ▶ Time histories of measured and modeled (two-dimensional) current magnitudes
- ▶ Polar plots of measured and modeled currents with the measured currents presented in two ways: (1) as a statistical mean and (2) a 95<sup>th</sup> percentile graph
- ▶ Time histories of measured and modeled significant wave heights  $H_s$  (m)
- ▶ Time histories of measured and modeled peak wave periods  $T_p$  (s)

The findings of the calibration are discussed below.



The inclusion of the additional forces yielded a slight improvement in the RMSE for current magnitude (RMSE = 0.29 ft/s (0.087 m/s) compared to RMSE = 0.30 ft/s (0.089 m/s)). However, in terms of absolute value the observed improvement was more substantial. Modeled instantaneous peak current magnitude reached 2.07 ft/s (0.63 m/s) in comparison to the instantaneous peak current magnitude, 1.80 ft/s (0.55 m/s), modeled in the tide only case.

The RMSE for water elevations reached 0.51 ft (0.15 m). Water elevation residuals calculated as the difference between modeled and measured water levels at the outfall site are observed to vary on average in the 0.66 to 0.98 ft (0.2 to 0.3 m) range reaching occasionally up to  $\pm 1.6$  ft (0.5 m) for the period of the measurements.

Using the polar plots as a mean to assess the direction of currents, the agreement between model and measurements is sufficiently close with the model tidal orbits predominantly showing only one axis oriented towards  $350^\circ$  or  $10^\circ$  W of North and  $170^\circ$  or  $10^\circ$  E of South.

While there are no established standards for the use of the RMSE as an assessment criteria, based on some preliminary qualifications, RMSE < 0.1 is considered an excellent match between model results and measurements whereas a RMSE in the 0.1 to 0.2 range is considered a good match. This is particularly true in the current study especially when the complexity of the area is taken into account: high horizontal variability in the current field, a near shore regime strongly affected by re-circulating flow patterns and the presence of the Hen and Chickens Shoal.

It is important to also note that a comparison of predicted and measured water levels undertaken by NOAA at tidal station Lewes for the months of September, October and November 2010 (Figures C-10 to C-12 of (Appendix J)) estimates the maximum water level residuals for the three months at 1.64 ft, 2.62 ft, 2.30 ft (0.5 m, 0.8 m and 0.7 m), respectively. While Lewes is some distance away from the proposed outfall site, the results highlight further the complexity of the hydrodynamic processes occurring in the study area.

As seen from Figures C-8 and C-9 (Appendix J), model report), the model provides a good match of the observed significant wave height and peak wave period for the period of the measurements. This is evidence that the wind and wave data included in the modeling represent fairly well the wave climate along the coast of Rehoboth Beach. In addition, the agreement between modeled and measured wave heights and peak wave periods is interpreted as evidence that both wind speed and direction, major factors in the formation of local sea wave climate, are adequately represented in the modeling system.

In addition to the above comparison of model results and measurements in the field by means of time histories, a comparison of depth averaged model results to ADCP records has been also undertaken at 8.2 ft (2.5 m) above seabed. The comparison was conducted in terms of probability of exceedance of current magnitude, frequency histogram for current magnitude and frequency histogram for current direction. This has been done in order to assess the performance of the model in a statistical manner (with high relevance to the process of regulatory mixing zone evaluation) rather than on the basis of individual records. Selection of ADCP records at 8.2 ft (2.5 m) above seabed is done for the comparison due to the fact that observed near-bottom currents are lower than those near the surface (refer to section 3.2 of (Appendix J)) and as such will generate worse case assessment scenarios.



As evident from Figure 4-4 in (Appendix J), the agreement between current measurements and model results is satisfactory, implying that near-field analysis (drawing substantially from ADCP data) and model-based far-field analysis (verified against ADCP data) are expected to be highly consistent in terms of the applied forcing to plume formation in the near-field and advection-diffusion in the far-field as well as throughout the assumptions adopted for the analysis. In other words, no discontinuities associated with the applied forcing are anticipated to occur in the solution.

### **6.5.5 Model Validation**

In addition to calibration, the model was subjected to a process of validation which consisted of rerunning the model for the period of late summer 2011 (second field monitoring campaign) and comparing model results to both tidal predictions and field measurements following the already established procedure. The aim of the validation process was to confirm the predictive capability of the model by targeting a different period of time from the one adopted during the calibration process (Autumn 2010).

The results of the validation process are presented starting with Figure C-21 of Appendix C in the model report. Figures C-21 and C-22 show water levels (predicted using NOAA tidal constituents versus modeled) at station Lewes for the month of July 2011. An RMSE value of 0.23 ft (0.07 m) has been achieved over a period of the 63 days indicating that the quality of the prediction is very similar to the one achieved during the calibration process (0.20 ft (0.06 m)).

Figures C-23 and C-24 of the Appendix compare the simulated elevations in the vicinity of the proposed outfall site (site of deployment of ADCP #1) with the NOAA predictions and reveal that there is little difference in the predicted behavior of the tide at the outfall and station Lewes. Similarly to the calibration results shown in Figures C-3 and C-4, a minor phase lag accounts for the distance between the two locations (Lewes and the outfall site).

Validation to tide, winds, waves and freshwater inflows at the site of ADCP #1 deployed in the vicinity of the proposed northern outfall is illustrated in Figures C-25 to C-29 showing:

- ▶ Time histories of measured and modeled water levels and a time history of the corresponding residuals (measured water levels – modeled water levels), Figure C-25;
- ▶ Time histories of measured and modeled (two-dimensional) current magnitude at the site of deployment of the ADCP and a time history of the residual (measured current magnitude – modeled current magnitude), Figure C-26;
- ▶ Polar plots of measured and modeled currents with the measured currents presented in two ways: (1) as a statistical mean and (2) a 95<sup>th</sup> percentile graph (Figure C-27);
- ▶ Time histories of measured and modeled significant wave heights  $H_s$  (m), Figure C-28; and
- ▶ Time histories of measured and modeled peak wave periods  $T_p$  (s), Figure C-29.

For the same period, the above sequence of graphs has been also generated for ADCP #2 deployed in the vicinity of the proposed southern outfall. The corresponding figures in Appendix C (model report) are Figures C-30 to C-34.



Figures C-35 to C-38 illustrate the impact of Hurricane Irene on the data recorded by ADCP #2. As such, the data recorded after August 27, 2011, has been excluded from the analysis.

Finally, Figures C-39 to C-41 (directly comparable to C-10 to C-12 of Appendix C corresponding to the calibration period) present a comparison of predicted and measured water levels undertaken by NOAA at tidal station Lewes for the months of July, August and September 2011 and give estimates of the maximum water level residuals for the three months.

In summary, the results obtained during the process of model validation are found to be qualitatively and quantitatively consistent with the calibration results across all investigated parameters. The predictive capability of the model is adequate for the intended purpose, namely, the prediction of the footprints of the plume transported by advection and dispersion.

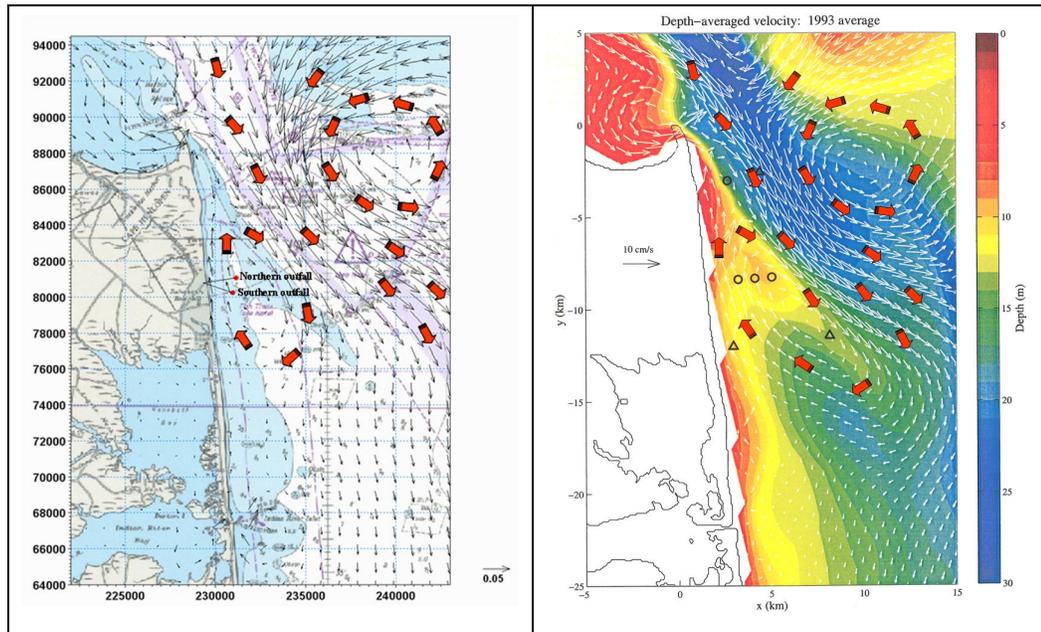
#### **6.5.6 Verification to Previous Work**

Finally, an assessment of the performance of the model can be made by comparing depth-averaged mean flow patterns from the current model for the duration of the Fall 2010 field studies against plots of similar nature as work obtained from Dr. Michael Whitney as reported by Garvine (2003). Despite undertaking the comparison for different periods of time (e.g. Fall 2010 versus whole of 1993), the results from the current simulation are in agreement with previously published work (Figure 6-3). This is true both qualitatively and quantitatively. Eddies in both panels of Figure 6-3 are of similar size and form at the same location. Current magnitudes are also very similar and typically of the order of 2 in/s (5 cm/s).

It should be noted, however, that the flow patterns presented in the left panel of Figure 6-3 are driven by tide, wind, freshwater inflow and waves. Those displayed in the right panel of the figure, generated by the University of Delaware, exclude wave effects. Based on this comparison alone, it is concluded that wave effects only play a limited role in the formation of the currents in the area.



**Figure 6-3** Depth-averaged mean flow velocity for the duration of the Fall 2010 field studies (left) and depth-averaged mean flow velocity for 1993 (right) sourced from the dissertation of Dr. M Whitney (Garvine 2003).



### 6.5.7 Model Conclusions

The following conclusions are made with respect to the model:

- ▶ The current model is well calibrated and accounts for the primary physical forces governing the flow field in the study area as indicated by the similarity of the results obtained from the calibration and validation processes;
- ▶ In terms of water elevation and current magnitude, the quality of the obtained tide-only solution at the outfall site is qualified as good (RMSE=0.2 ft (0.06 m) and 0.29 ft/s (0.087 m/s), respectively). Accordingly, tidally-induced mixing processes are expected to be well represented in the subsequent plume dispersion solutions.
- ▶ The quality of the full (tide, wind, wave and freshwater inflows) solution is also good with RMSE for water elevation of 0.51 ft (0.155 m) and RMSE for current magnitude of 0.29 ft/s (0.087 m/s). Modeled current directions are consistently oriented to 350° North and 170° South match measured directions well.
- ▶ Any differences between modeled and measured water levels and current magnitudes observed during the verification of the model are attributed to:
  - The lack of representation in the model of currents operating at low sub-tidal frequencies (low frequency motions);
  - Variations in density produced by the Delaware River discharge. That is, while the daily varying river discharge is included in the model, the associated density fluctuations due to salinity and



temperature are not. This comment is particularly relevant considering the adoption of a two-dimensional, depth-averaged modeling frame for the base analysis.

- ▶ The model represents the wave climate in the study area well.
- ▶ Long-term transport trends as represented by simulated depth-averaged mean flows are in good qualitative and quantitative agreement with previously published work. The latter finding applies consistently throughout the entire coastal area near the proposed outfall.
- ▶ A 2-D modeling framework is adequate for the project.
- ▶ The statistical agreement between measurements and model results is encouraging, implying that a high level of consistency between near- and far-field analytical results is achievable.

### **6.5.8 Far-Field Modeling Results**

Two long-term far-field scenarios associated with the operation of the proposed northern and southern outfalls under normal working conditions have been investigated in two-dimensional, depth-averaged mode over a period of 11 months with the following common characteristics:

- ▶ The proposed discharge of 3.4 MGD ( $0.1489 \text{ m}^3/\text{s}$ ) was introduced in one model cell (the approximate length of the diffuser is 37 m) and the discharged effluent treated as a hypothetical conservative, non-decaying substance with a concentration of  $1 \text{ kg}/\text{m}^3$ ;
- ▶ The discharge was modeled without interruption for the nominated period starting on February 1, 2010 using flow predictions for the same period provided by the model, which was started a month earlier (January 1, 2010) to overcome any potential influence of model warm-up effects in the dispersion analysis of the discharged effluent; and
- ▶ The hydrodynamic model was operated in two-dimensional mode and driven by tide, time-varying freshwater inflow, winds and waves as described in Sections 4.5 and 4.6 of the model report (Appendix J). The time step for the simulation was 1 second.

Further details of the two scenarios are:

- ▶ Southern outfall ( $38^\circ 43.333' \text{ N}$ ,  $75^\circ 3.631' \text{ W}$ ) scenario: the discharge was allocated to a mesh cell with an area of 2.26 acres ( $9,150 \text{ m}^2$  or equivalent to a square cell with less than 100 m length) and approximate depth of 35.43 ft (10.8 m); and
- ▶ Northern outfall ( $38^\circ 43.787' \text{ N}$ ,  $75^\circ 3.506' \text{ W}$ ) scenario: the discharge was allocated to a mesh cell with an area of 2.97 acre ( $12,000 \text{ m}^2$  or equivalent to a square cell with 110 m length) area and approximate depth of 39.37 ft (12 m);

#### **6.5.8.1 Modeling Assumptions**

The following assumptions apply to the far-field modeling exercise:

- ▶ Well-mixed conditions in the Delaware estuary would appear to justify the adoption of a two-dimensional, depth-averaged frame of analysis for the project. In other words, a two-dimensional, depth-averaged frame of analysis captures reasonably well the physics of the modeled environment as expressed in



terms of tidal elevations, circulation patterns and density variation. This assumption is supported by the field data collected to date, the classification of the Delaware Bay as a vertically homogenous water body (USEPA 1984) and a Richardson number of  $Ri < 0.08$  indicating well-mixed conditions (refer to model report in (Appendix J))

- ▶ Discharged effluent does not decay; it is only subject to dispersion and dilution by ambient currents. This assumption is conservative.
- ▶ The effluent is assumed to mix instantaneously in the water of the receiving cell.
- ▶ The background concentration of effluent in the receiving waters is negligible.

#### **6.5.8.2 Qualifications**

Analysis has been undertaken subject to the following qualifications:

- ▶ Complex biological or physical processes (such as uptake of nutrients or absorption to particles), which can reduce the concentration of the various constituents of the effluent in the water column, have not been modeled. This adds conservatism to the adopted modeling approach as concentrations will remain higher if decay is not allowed for.
- ▶ The analysis is depth-averaged, two-dimensional in the horizontal plane. Buoyancy effects are not represented in two-dimensional model simulations.
- ▶ The impacts of extreme winds, waves and freshwater inflows on plume advection and dispersion have been included indirectly in the analysis by means of the use of measured datasets for the relevant entities. No specific extreme event analysis has been carried out in order to determine extreme conditions for plume dispersion analysis.

#### **6.5.8.3 Presentation of Results**

The results from the analysis are presented in the form of:

- ▶ Time histories of effluent concentration at a selection of representative stations.
- ▶ Snapshots or instantaneous plume footprints generated at five (5) day intervals to illustrate the dynamics of the plume and the correlation that exist between plume shape and wind effects (Figures D-1 to D-2, (Appendix J)).
- ▶ Percentile maps of dilution generated using effluent concentration results extracted at 1-hour interval for a period of 2.5 months. There is one dilution map per scenario with the 95<sup>th</sup> percentile of effluent concentration used to generate the maps.

Only the percentile maps are presented in the current document. Note that in the assessment of percentiles of concentration, the choice of the assessment window can play an important role in determining the quality of the overall results. The main role of the window is to eliminate from consideration the effects of the initial conditions and warm-up stages of the modeling exercise thus setting the focus of the analysis on developed conditions alone. In the current analysis, the assessment window has been set to coincide with the last 2.5 months of the hydrodynamic analysis, that is, plume behavior is assessed after an initial period of 6.5 months of outfall operation.



#### **6.5.8.4 Timeframes**

The timeframes adopted in the analysis are:

- ▶ Hydrodynamic modeling – 12 months
- ▶ Effluent discharge simulation – 11 months
- ▶ 95<sup>th</sup> percentile assessment window - 2.5 months

#### **6.5.8.5 Southern Outfall – Instantaneous Plume Footprints**

It is noted that very low concentrations of the effluent have been plotted in order to illustrate the trajectory of the plume and the ultimate fate of the effluent rather than to indicate the potential for impacts. Also, the concentrations are associated with a hypothetical discharge concentration in the pipe of 1 kg/m<sup>3</sup> (1000 mg/L) rather than any specific water quality parameter. As such, the instantaneous footprints shown could be interpreted as snapshots taken with a very sensitive camera (high detection rate) at regular time intervals during a long-duration dye tracing experiment.

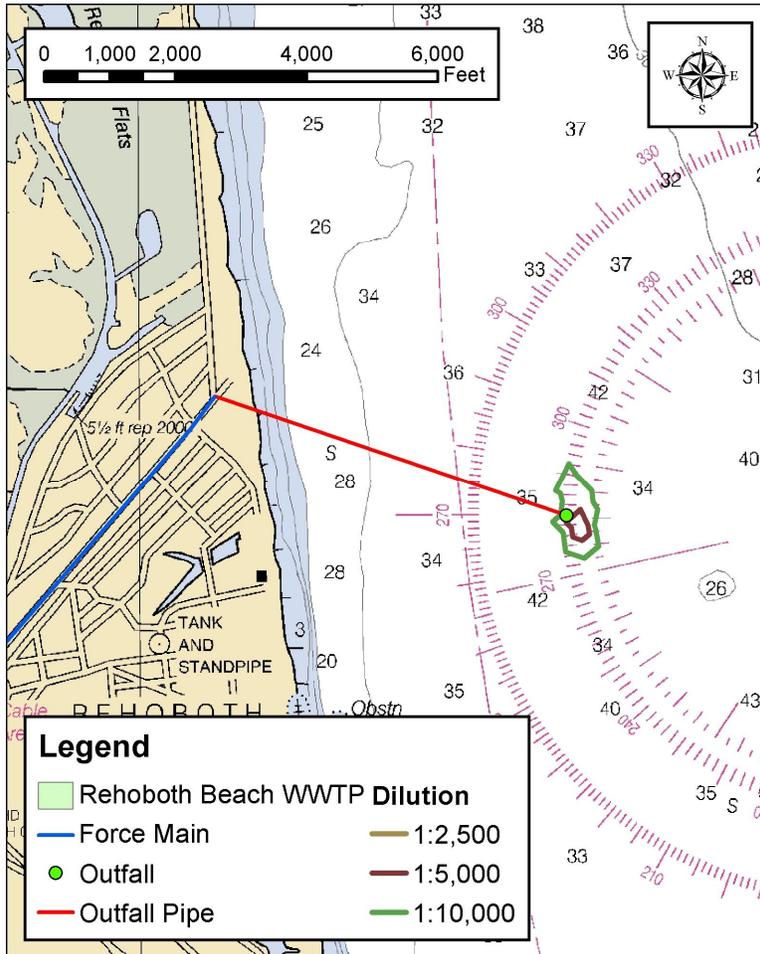
Figures D-1 and D-2 of (Appendix J) capture a sequence of relatively stable states of the plume reaching to the north and south of the proposed outfall.

#### **6.5.8.6 Southern Outfall – Dilution Map**

The dilution map shown in Figure 6-4 is an indirect depiction (based on dilution contours rather than concentration contours) of the potential long term footprint of the plume. The shape of the plume, in this case delimited by the 10,000:1 dilution contour, is elongated with its major axis running parallel to the coast. There is no evidence of plume encroachment on the coast, which indicates that there are no risks for primary contact recreation activities. The use of the 10,000:1 dilution contour to delimit the plume footprint yields a rather conservative representation of the latter. From a regulatory viewpoint, the 200:1 or 500:1 dilution contours would be adequate and should be used for this purpose. Such contours, however, do not appear in the current far-field analysis owing to the combined effects of low discharge volume and the resolution of the far-field model in the outfall area.



**Figure 6-4 Southern Outfall: Contour plot showing the 95th percentile of dilution after 11 month of outfall operation**



Total areas enclosed within the dilution contours are listed in Table 6-5. As shown in the table, the predicted area enclosed by the 5000:1 dilution contour is as low as 2.5 acres (1 ha) suggesting a very low risk of any plume (as measured by a meaningful concentration) reaching the coastline.

**Table 6-5 Total Area within a Given Dilution Contour for the Southern Outfall**

Dilution Contour	95% probability area
10000	15 acres (14 ha)
5000	2.5 acres (1 ha)



#### 6.5.8.7 Northern Outfall

For the Northern outfall and with reference to Table 6-6, the shape and extent of the predicted plume generated at the (potential) northern outfall is similar to the one predicted at the (potential) southern outfall leading to identical findings; that is, there is no evidence of plume encroachment on the coast which indicates that there are no risks for primary contact recreation activities.

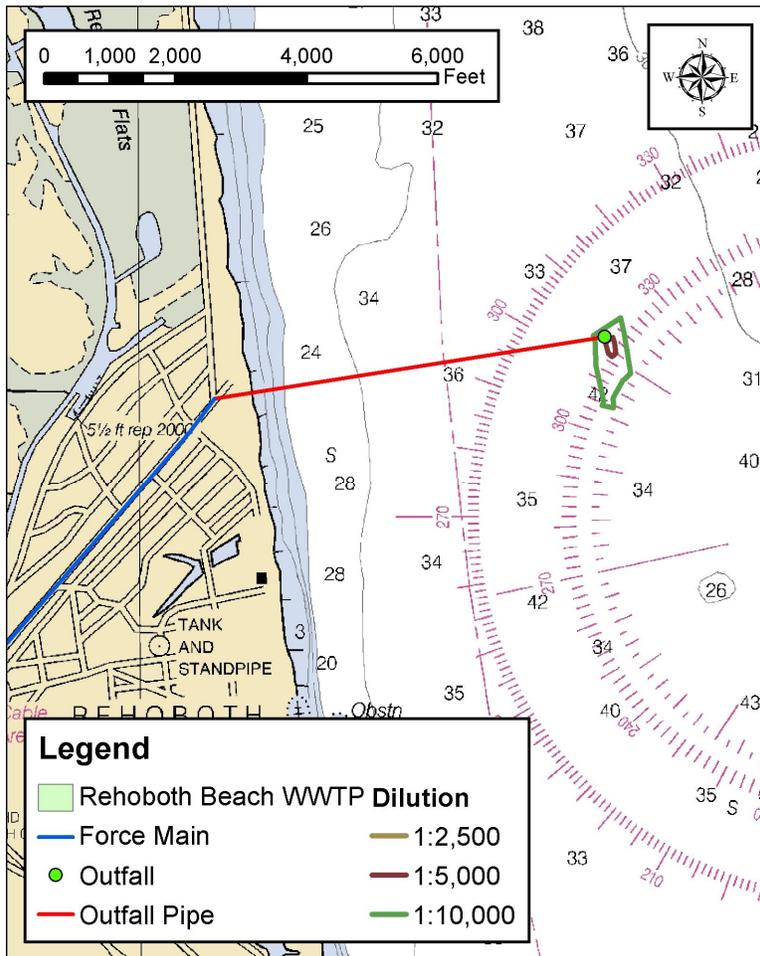
Total areas enclosed within the dilution contours are listed in Figure 6-5. As seen from the table, the area enclosed by the 5000:1 dilution contour is less than 1 ha.

**Table 6-6 Total Area within a Given Dilution Contour for the Northern Outfall**

<b>Dilution Contour</b>	<b>95% probability area</b>
10000	15 acres (14 ha)
5000	2.5 acres (1 ha)



**Figure 6-5 Northern Outfall: Contour plot showing the 95th percentile of dilution after 11 month of outfall operation**



### 6.5.9 Conclusions - Far-Field Modeling

Based on the far-field analysis of effluent plume advection and dispersion for both potential outfall locations (north and south) and subject to the discharge characteristics specified in section 6.5.8, the adopted 2-D modeling frame, year 2010 meteorological conditions and qualifications presented in section 6.5.8.2, it is observed that both plume footprints as identified by the 10,000:1 dilution contour:

- ▶ Form offshore and remain in the vicinity of their respective sources;
- ▶ Assume somewhat elongated shapes with a major axis running parallel to the coast;
- ▶ Are subject to the variation in magnitude of the combined effects of the driving forces (tide, winds, waves and freshwater inflows); and
- ▶ Are not predicted to reach the coast.



For the 11-month simulation period starting February 1, 2010, the maximum predicted (at 1 hour interval) effluent concentration for the proposed southern outfall did not exceed 0.3 mg/L (Note the concentration is the result of the discharge of effluent at a hypothetical concentration of 1000 mg/L in the pipe). This is equivalent to a minimum dilution in excess of 3000:1. Owing to the identified similarities in receiving water conditions and statistical plume footprints at both potential outfall sites, it is expected that the maximum predicted (instantaneous) effluent concentration at the proposed northern outfall will be of similar magnitude. Because of the similarity of the results at the northern and southern outfall locations, the choice of outfall site can be based on factors other than hydrodynamics and dilution.

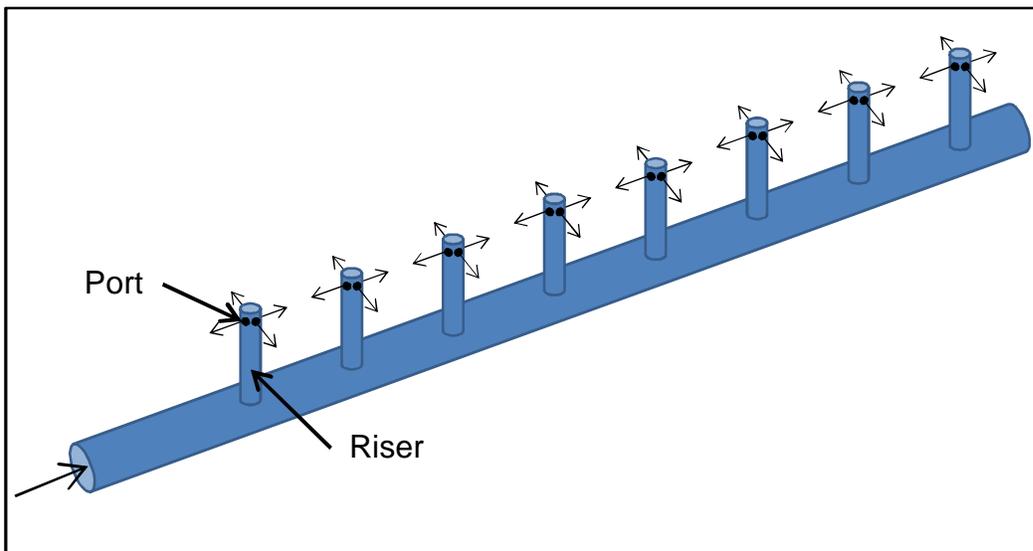
## 6.6 Near-Field Modeling

### 6.6.1 Near-Field Model Set-up

Near-field modeling of the proposed ocean outfall has been undertaken using CORMIX, the software preferred by the USEPA and state regulators. The diffuser configuration previously proposed comprised a Y shape in plan with symmetrical arms, each with 8 vertical risers, as described in Lawler, Matusky & Skelly Engineers (2003) and Stearns & Wheler (2005). Each riser terminated with two nozzles.

However, this Y type configuration (presented in Appendix A of the modeling report) cannot be implemented in CORMIX directly, and hence a projected linear diffuser with a rosette arrangement was adopted (consistent with previous modeling). The linear diffuser with rosette consisting of four ports per riser is shown in Figure 6-6. Details of the diffuser configuration are presented in Table 6-7.

**Figure 6-6 Schematic Diagram of Modeled Diffuser**





**Table 6-7 Diffuser Configuration as Initially Modeled**

<b>Parameter</b>	<b>Value</b>
Diffuser length	120 ft (37 m)
Distance from shore	5,430 ft (1823 m)
Port height from seabed	1.5 ft (0.5 m)
Port diameter	3 inches (0.075 m)
Number of risers	8
Number of ports per riser	4
Total number of openings (ports)	32
Alignment of ports	Horizontal

The CORMIX software has been used on the basis of its preferred status (by USEPA and state regulators). CORMIX offers the following advantages in conducting near-field modeling:

Multiple ports in the form of complex linear diffusers (such as rosettes) can be implemented using the pre-processing tools within CORMIX. The simulation of multi-port diffusers allows the model to assess plume merging and interaction with the ocean floor. It should be noted that for this reason, it is difficult to compare model outcomes with other near-field models which may typically reflect higher dilutions.

CORMIX allows three types of vertical density specifications; (a) linear, (b) two layer system with constant densities and density jump, and (c) constant density surface layer with linear density profile in the bottom layer separated by a density jump. For the present scenarios, the second option has been assessed as this presents the most conservative vertical stratification scenario.

### **6.6.2 Aims**

The preliminary diffuser design was based on "...generally accepted principles..." aimed to provide a balance between dilution and costs (Lawler, Matusky & Skelly Engineers 2003). The first aim of the current near-field modeling exercise is therefore to verify that the dilutions and mixing patterns described in previous modeling reports can be replicated. A second, more general aim becomes possible through the availability of additional and better quality receiving water data, that is, to test the performance of the diffuser for the expected spectrum of ambient conditions.

### **6.6.3 Target Dilution**

A key outcome of near-field modeling is to confirm whether sufficient dilution will be achieved in order to meet environmental protection criteria. The definition of what the target dilution should be therefore becomes an important criterion, with the typical process being to compare discharge concentrations (of pollutants of concern) with nominated receiving water standards.



In the absence of specific values, a target dilution factor of 100 would generally be chosen, though it may be that a lower value (e.g. 50) will meet all environmental protection requirements.

For TSS, the discharge of 5.4 mg/L is already lower than the water quality limits.

#### 6.6.4 Discharge Characteristics

The discharge characteristics utilized in the model are presented in Table 6-8.

**Table 6-8 Rehoboth Beach WWTP Current Effluent Performance Data**

Parameter	Measured Concentration
BOD	2.8 mg/L
TSS	5.4 mg/L
TN	6.2 mg/L
TP	0.3 mg/L
Ammonia	0.769 mg/L
Temperature	64.6 °F (18.1 °C)
Enterococcus	2.7 Colonies / 100 mL

Note:

1. Performance data based on January 2007 – July 2010. Annual average flow for reported period was 1.1 MGD.

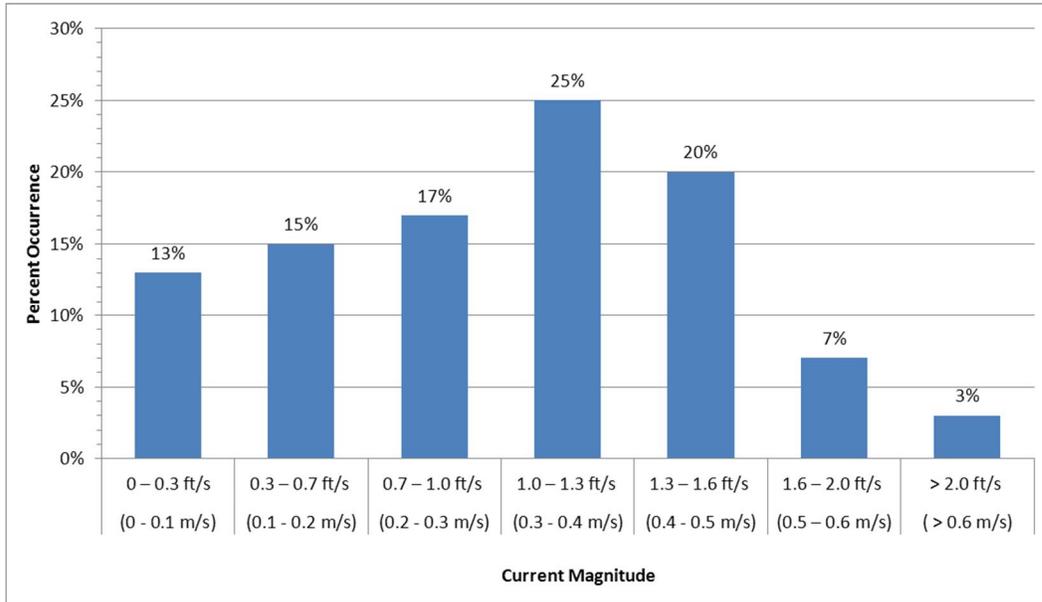
#### 6.6.5 Input Data

The availability of data was addressed in Chapter 3 of the modeling report (Appendix J). Of most relevance to the near-field modeling exercise are field measurements of ambient conditions, comprising salinity, temperature, and the direction and magnitude of currents.

Figure 6-7 provides a summary of the relative occurrence of each of the primary bands of current magnitude. The figure shows that near-zero or very low currents occur for some 13% of the monitoring period, with the median current falling within the 1.0 – 1.3 ft/s (0.3 to 0.4 m/s) band. The maximum current band (> 2.0 ft/s or 0.6m/s) occurred for only 3% of the record.



**Figure 6-7 Measured Current Magnitude at 8.2 ft (2.5 m) above the seafloor (% Occurrence)**



Note: % occurrence is based on the first period of ADCP deployment.

### 6.6.6 Stratification

Stratification, whether arising from temperature or salinity differentials, has the potential to affect the achieved dilution, with the potential existing for plume trapping below the surface. Reference is therefore made to field measurements, conducted at regular intervals from November 2010.

In total, six short-term (one day) intensive surveys were conducted to collect measurements of CTD using instrumentation operated from a vessel.

The finding (to April 2011) is that increased stratification was evident during March 2011 compared to the results obtained in January and November 2010. This is most likely a consequence of seasonal stratification (changing temperatures at different depths) and the impact of freshwater flows from the Delaware Estuary.

For the November 2010 and January 2011 monitoring exercises, the temperature between the surface and the deepest recordings fluctuated (at most) by 1.8 °F (1° C). However, the March field study measured temperature variations of as much as 5.4 °F (3° C).

The resulting change in density was evident as a fluctuation of only 2 kg/m<sup>3</sup> in November 2010 and January 2011, rising to a fluctuation of approximately 9 kg/m<sup>3</sup> in March. Measurements on the March 17, 2011 at Site R17 (see Figure 6-1) show that the variation between surface and bottom densities was approximately 8 kg/m<sup>3</sup> with 1024 kg/m<sup>3</sup> recorded at the bottom. The pycnocline was the top 13 ft (4 m) of water depth. In comparison, Site R13 showed a much smaller vertical gradient from 1022 (surface) to 1023.5 kg/m<sup>3</sup> at the bottom. It should be noted that these density gradients were representative of only one day of measurements and do not necessarily represent the worst gradients that could exist.



Offshore, beyond the 30 feet depth contour, density differentials in the 1 to 3 kg/m<sup>3</sup> range are expected to be common during the spring and autumn period with peaks reaching in the 6 to 9 kg/m<sup>3</sup> range during high river inflow periods that could last for up to two weeks and occur 3-4 times during the same season. These peak ranges (of estimated density differential) are substantially narrower in shallow coastal waters (where the proposed outfall is located) and, based on the collected evidence to date, could reach up to 3-4 kg/m<sup>3</sup>.

Temperature and density data have been utilized in near-field modeling, in order to test the impact on dilution for differing strengths of stratification.

### **6.6.7 Model Scenario Definition**

A total of nine different cases have been modeled. The first of these is a base case, as defined by the previously proposed diffuser configuration, a near zero ambient flow, and no stratification. The base case scenario is consistent with previous findings (Lawler, Matusky & Skelly Engineers 2003) as these had been tested for diffuser performance as well as costs. However, the diffuser design needs to be further tested for newly acquired (i.e. most current) ambient conditions data, and for the influence of stratification. These tests have been completed in Cases 001 to 009, as described below.

The following describes the nine cases that were investigated:

- ▶ Case 000 represents the base condition consistent with the preliminary design (modeled as a linear diffuser) albeit with very low ambient currents around 0.13 ft/s (0.04 m/s). The primary reason for the choice of low ambient current was that it sets the worst mixing performance under a non-stratified receiving environment (In this model setup, CORMIX does not allow specification of currents less than 0.13 ft/s (0.04 m/s) as this creates plume instabilities). This ambient current typically corresponds to a nontidal velocity; however, ADCP measurements in the vicinity of the proposed outfall indicate that velocities between 0 and 0.3 ft/s (0 and 0.1 m/s) occur for more than 13% of the time. Hence the dilutions (possibly worst case) arising from this scenario are likely to have a low probability of incidence. It has also been observed from the CTD data that whenever vertical stratification does not exist, the water column density is typically 1024 kg/m<sup>3</sup>.
- ▶ Cases 001 to 003 investigate the influence of increasing ambient current. The basis of selection of currents can be seen with reference to Figure 6-7. Case 003 represents the most frequently occurring current condition, and is therefore of value when considering the median condition at the study site. A case corresponding to the high ambient current condition around 2 ft/s (0.6 m/s) is not presented, as this simply confirms that significant dilution will occur when ambient currents are strong.
- ▶ Case 004 investigates the impacts on dilutions when moderate stratification is evident in the receiving environment, with a differential of 1.5 kg/m<sup>3</sup>. The latter value is typically associated with low to average inflow periods (e.g. Delaware River discharges in the 10,600 to 18,000 cfs (300 to 500 m<sup>3</sup>/s) range) and has a relatively high probability of occurrence at offshore locations during the spring and autumn seasons. Near the coast however, the value is expected to be encountered and exceeded only during periods of high river inflows lasting for up to two weeks and occurring more than once during the same season.



- ▶ Case 005 involves the consideration of a longer diffuser with twice the length of the base case scenario while halving the number of ports per riser from four to two. While longer, this type of diffuser system can be easier to construct and maintain since there are a reduced number of external connections per riser. A cost analysis has not been undertaken to determine if this diffuser arrangement is less expensive than the preliminary design.
- ▶ Case 006 tests the effect of mixing using a theoretical wind speed of 16.4 ft/s (5 m/s). It is noted that a higher wind speed could have been selected, but that high periods of wind are often directly linked to larger waves, with the combination of the two forces leading to greater mixing. Given the purpose of the nearfield assessment is to consider potential impacts, it is appropriate to select a moderate wind.
- ▶ Case 007 investigates the effect of increasing vertical density stratification for the median current condition. CTD data for the region indicates the presence of seasonal density stratification within the water column and the largest difference observed was eight (8) kg/m<sup>3</sup> between surface (1016 kg/m<sup>3</sup>) and bottom (1024 kg/m<sup>3</sup>). A linear gradient in density has been prescribed in CORMIX. This case is simulates the poorer mixing conditions associated with a stratified environment at the proposed outfall site.
- ▶ Case 008 assesses the combination of large ambient currents around 2 ft/s (0.6 m/s) with the same degree of stratification described in Case 007.

### **6.6.8 Modeling Results**

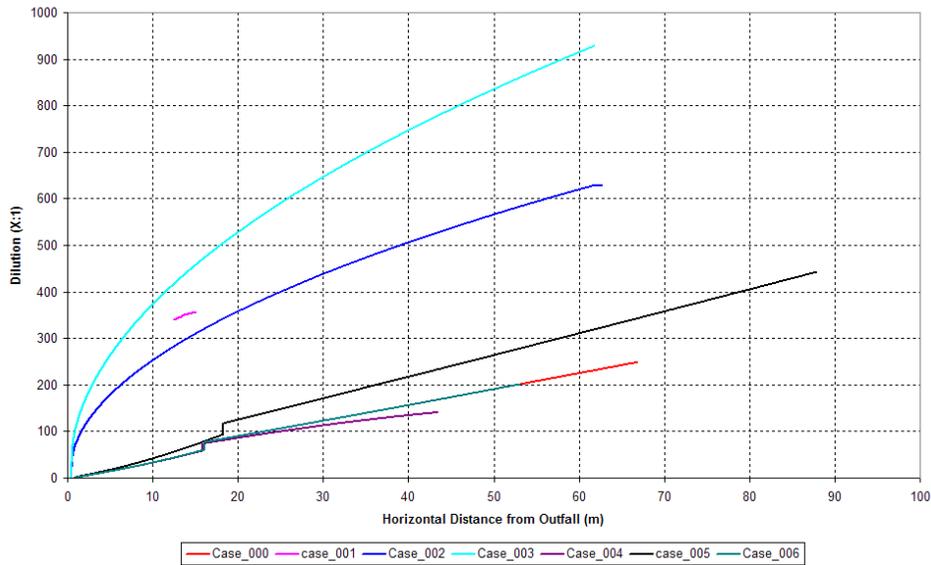
The results of CORMIX modeling are presented in this section.

As previously described, the base case (Case 000) reflects the previously proposed diffuser configuration and typical ambient conditions (without consideration of current magnitudes). All other cases investigate variations in ambient and diffuser parameters.

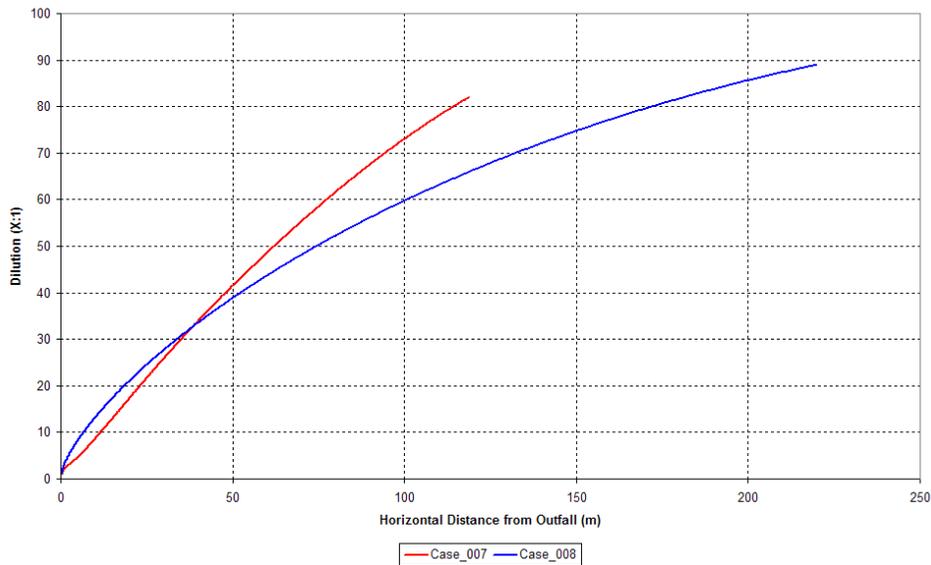
Dilutions from all nine simulations have been plotted in Figure 6-8 (Cases 000 – 006) and Figure 6-9 (Cases 007 – 008). Results are also summarized in Table 6-9.



**Figure 6-8 Near-Field Dilutions for Simulation Cases 000 to 006**



**Figure 6-9 Near-Field Dilutions for Simulation cases 007 and 008**





**Table 6-9 Dilution Summary**

<b>Run Scenario</b>	<b>Distance to end of NFR (m)</b>	<b>Dilution at end of NFR (1:D)</b>	<b>Terminal height of plume above ports (m)</b>
Case 000	217 ft (66 m)	250	Rise to surface
Case 001	Undefined	360 at 33 ft (10 m)	Rise to surface
Case 002	203 ft (62 m)	630	Rise to surface
Case 003	203 ft (62 m)	930	Rise to surface
Case 004	141 ft (43 m)	141	4.39
Case 005	289 ft (88 m)	442	Rise to surface
Case 006	217 ft (66 m)	250	Rise to surface
Case 007	36 ft (11 m)	82	1.69
Case 008	72 ft (22 m)	89	1.27

**Result Interpretation**

In interpreting near-field results, the following factors must be noted:

- ▶ Results should not be considered in isolation from far-field model results.
- ▶ Results exclude the potential for tidal build-up; i.e. the build-up of plume concentration to a point of equilibrium as the tide fluctuates.
- ▶ CORMIX results are typically regarded as conservative (i.e. the program will typically under-estimate dilution).

**Case 000 & Case 001**

- ▶ It can be seen that the near-field region ends for the base case (Case 000) within the first 217 ft (66 m) and an end dilution of 1:250.
- ▶ Low ambient currents (Case 001) produce an unstable near-field region and therefore CORMIX does not predict near-field dilutions but rather present the transition into far-field . Due to the interaction between the discharge fluxes and the entraining properties of ambient magnitudes in the 0.3 ft/s (0.1 m/s) range, there are large instabilities within the discharge plume. For this reason CORMIX does not predict near-field dilution for currents that cause such instabilities (Case 001) but rather present the transitional dilutions into mid field. This is indicated in Figure 6-8 in the form of a small line. It can, therefore, be concluded that the end of the near-field region (NFR) and the corresponding dilutions for Case 001 is 43 ft (13 m) and 1:340.



#### **Case 002 & Case 003 (higher currents)**

- ▶ These cases confirm the relative magnitude of the higher dilutions achieved in association with ambient currents in the range of 0.7 to 1.3 ft/s (0.2 to 0.4 m/s) (i.e. currents most commonly occurring).
- ▶ Case 002 has a NFR of 203 ft (62 m) and end point dilution of 1:630 while Case 003 has a NFR of 203 ft (62 m) but appreciably higher dilution of 1:930.

#### **Case 005 (Longer Diffuse)**

- ▶ Case 005 confirms the benefit to dilution in doubling the length of the diffuser and thereby reducing the total number of ports per riser. The NFR is 289 ft (88 m) with dilution of 1:442. It should be noted that the longer diffuser may be more cost effective than the originally proposed Y-diffuser as it is a simpler construction, while possessing a similar length to the cumulative lengths of the Y-diffuser.

#### **Case 006 (influence of wind)**

- ▶ Surface winds do not impact dilutions in the near-field as demonstrated by Case 006. Results are identical to Case 000.

#### **Cases 004, 007, 008 (Stratification)**

- ▶ Cases (004, 007 and 008) show a decrease in dilutions. This demonstrates that vertical (stable) density stratification inhibits mixing of the discharge plume under the simulated conditions. The plumes from all the three scenarios are vertically trapped at 14.4, 5.5, and 4.2 ft (4.39, 1.69 and 1.27 m) from the seafloor.
- ▶ With large vertical stratification, the dilutions potentially decrease to less than 1:90, irrespective of whether ambient currents are large or small. This scenario therefore imposes the most significant mixing and dilution constraint.

#### **Flow Direction**

All currents modeled were taken to flow perpendicular to the diffuser line (or parallel to the coast) as the ADCP data indicates that this was the direction of prevailing currents.

There are brief instances (i.e. of low incidence) where currents flow perpendicular to the shore, though these will almost always be for short durations only, and dilution in the near-field will still occur.

The results of the far field model were utilized to confirm that the overall dilutions from this arrangement will not vary compared to the dilution seen when currents flow perpendicular to the diffuser arrangement.

### **6.6.9 Conclusions**

Near-field dilution performance has been simulated based on the preliminary linear diffuser design. Nine simulations in total were conducted, with Case 000 reflecting the projected rosette design of the previously proposed Y type diffuser (i.e. base case). The modeled cases investigated the effect of ambient current speed, ambient vertical density stratification and also the effect on dilution by increasing the length of the diffuser. The following conclusions can be derived from this study:

- ▶ Overall, a high level of dilution should be achieved.



- ▶ The linear diffuser achieved a dilution in excess of 1:250 for an unstratified ocean with close to zero ambient current magnitudes. As typically expected, dilutions increased with increasing current magnitudes and the most frequent current of 0.3 m/s results in dilution of 1:930 within 203 ft (62 m) of the discharge.
- ▶ Vertical density stratification provides some limitation to mixing, though this appears unlikely to lead to any impact of consequence. It is indicated that the diffuser should be optimized for worst case ambient stratification. Recognizing the conservatism of CORMIX, a dilution of only 1:82 is achieved at a distance of 390 ft (119 m) when the ambient current speed is close to zero and an ambient density difference of 8 kg/m<sup>3</sup> between surface and bottom water column is included. The mixing outcome does not change significantly with increasing currents.
- ▶ There is potential merit in doubling the length of the diffuser (Case 005) while reducing the number of ports per riser to two as this diffuser offers better dilution compared to the preliminary design. The longer diffuser can potentially help overcome the mixing constraints when the water column is density stratified. A linear diffuser system can also enable better head loss and port exit velocity control, in comparison to a Y-shaped design. This diffuser may also be simpler to construct (one single trench) and maintain (simpler risers and ports).

#### **6.6.10 Qualifications**

Conclusions relate to the modeled cases only. Model input data have been sourced from various reports and measured data as indicated.

All the modeled cases can be interpreted to be linear diffusers, lying perpendicular to the prevailing currents (north-south).



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