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City of Rehoboth Beach

Report on Ocean Outfall Permitting

Assessment of the Performance of the Rehoboth Beach Ocean Outfall

December 2011

INFRASTRUCTURE | MINING & INDUSTRY | DEFENCE | PROPERTY & BUILDINGS | ENVIRONMENT

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Limited Glossary of Selected Terms

A

ADCP	Acoustic Doppler Current Profiler – instrument used to measure currents and wave height, period and direction. An ADCP anchored to the seafloor can measure current speed not just at the bottom, but also at equal intervals all the way up to the surface. The instrument can also be mounted to the bottoms of ships to take constant current measurements as the boats move. In very deep areas, they can be lowered on a cable from the surface.
Astronomical tide	The tidal levels and character which would result from gravitational effects, e.g. of the Earth, Sun and Moon, without any atmospheric influences.

B

Baroclinic flow	Flow conditions in the ocean such that levels of constant pressure are inclined to surfaces of constant density. In this case, density varies with depth and horizontal position.
Barotropic flow	Flow conditions in the ocean such that levels of constant pressure are always parallel to the surfaces of constant density.
Bathymetry	The measurement of water depths in oceans, seas, and lakes; also information derived from such measurements.

C

Coriolis Force	The deflection of moving objects (air and water currents) due to the rotation of the Earth - to the right in the northern hemisphere, and to the left in the southern.
Calibration	Adjustment of a model's numerical and physical parameters such as roughness or dispersion coefficients so that it reproduces observed prototype data to acceptable accuracy.

D

DHI	Danish Hydraulic Institute

F

Far-field	The region of the receiving waters where conditions existing in the ambient environment gain control over the trajectory and dilution of the turbulent plume.
Fetch	The area of sea, along the direction of the wind, over which winds are relatively constant and wave generation occurs.
Fully developed sea	Sea in a quasi-steady state in which the energy gained by waves from the wind is approximately equal to that lost to wave breaking and other mechanisms.

G

Geographic Information System (GIS)	A computer-based system used to capture, create, maintain, display and analyse spatially-related information.

H

Hurricane	A tropical cyclone in the Atlantic, Caribbean Sea, Gulf of Mexico, or eastern Pacific, with a maximum 1-minute sustained surface wind of 64 knots (74 mph) or greater.
Hydrographic survey	The measurement and description of the physical features offshore and adjoining coastal areas with special reference to their use for the purpose of navigation.

K

Knot	A nautical unit of speed defined as 1 international nautical mile per hour. The knot is equal to 1.852 km/h.

M

Magnetic Declination	The observed angular distance between magnetic north on a compass and true north.

N

Nautical mile	Unit of length corresponding approximately to one minute of arc of latitude along any meridian, but is approximately one minute of arc of longitude only at the equator. By international agreement it is exactly 1,852 metres (approximately 6,076 feet).

Near-field	The region of the receiving waters where the initial jet characteristics or discharge conditions and the outfall geometry influence the jet trajectory and mixing.
NOAA	National Oceanic and Atmospheric Association
O	
Onshore wind	A wind blowing landward from the sea in the coastal area.
Offshore wind	A wind blowing seaward from the land in the coastal area.
P	
Primary contract recreation	Any water-based form of recreation, the practice of which has a high probability for total immersion or ingestion of water (examples include but are not limited to swimming and water skiing)
R	
Richardson Number	The primary parameter that can be used to classify the stratification potential of an estuary defined as (Fischer et al., 1979) $Ri = \frac{\Delta\rho}{\rho}\frac{gQ_f}{WU_t^3}$ where $\Delta\rho$ is the difference between freshwater and seawater density, typically 25 kg/m^3; ρ is the reference density, typically 1000 kg/m^3; g is gravity (m/s^2), Q_f is the freshwater inflow (m^3/s); W is the width of the estuary (m); and U_t is the mean tidal velocity (m/s). If Ri is large (>0.8), the estuary is expected to be strongly stratified and dominated by density currents, and if Ri is small (<0.08), the estuary is expected to be well mixed. Transition from a well-mixed to a strongly mixed estuary occurs in the range $0.08 < Ri < 0.8$.
Regulatory mixing zone	A designated, mathematically defined portion of a receiving water body, in close proximity to a discharge, in which the initial dilution, dispersion, and reaction of discharged pollutants occur.
RMSE	Root-Mean-Square-Error - a criteria for the assessment of model performance

S

Shelf	Surrounding nearly all continents is a shallow extension of that landmass known as the continental shelf. This shelf is relatively shallow, tens of meters deep compared to the thousands of meters deep in the open ocean, and extends outward to the continental slope where the deep ocean truly begins (sourced from http://www.onr.navy.mil/focus/ocean/regions/oceanfloor2.htm)
Stratification	The separation of the water column into layers. More specifically, in the context of the Delaware Estuary, stratification is a category used for classifying a water body influenced by tides and freshwater inflows. Three stratification classes of estuaries are: 1. Highly stratified (salt wedge) estuaries that have large river discharges flowing into them. 2. Partially mixed estuaries with medium river discharges. 3. Vertically homogeneous estuaries that have small river discharges.
Secondary contact recreation	A water-based form of recreation, the practice of which has a low probability of for total body immersion or ingestion of water (examples include but are not limited to wading, boating and fishing)

T

Tide	The periodic rising and falling of the water that results from gravitational attraction of the moon and sun and other astronomical bodies acting upon the rotating earth. Although the accompanying horizontal movement of the water resulting from the same cause is also sometimes called the tide, it is preferable to designate the latter as TIDAL CURRENT, reserving the name TIDE for the vertical movement.

U

Upwelling	The vertical motion of water in the ocean by which subsurface water of lower temperature and greater density moves toward the surface of the ocean. Upwelling occurs most commonly among the western coastlines of continents, but may occur anywhere in the ocean. Upwelling results when winds blowing nearly parallel to a continental coastline transport the light surface water away from the coast. Subsurface water of greater density and lower temperature replaces the surface water, and exerts a considerable influence on the weather of coastal regions. Upwelling also results in increased ocean productivity by transporting nutrient-rich waters to the surface layer of the ocean.

V

Validation	Comparison of model results with a set of prototype data that were not used for calibration.

Executive Summary

The City of Rehoboth Beach is considering building an ocean outfall for discharging effluent (wastewater) from its existing advanced secondary treatment plant. This would replace the existing point of discharge which occurs in the Lewes-Rehoboth Canal. At this stage two candidate locations are being considered for the new ocean outfall. These are referred in the text as northern and southern outfalls. Both options are included in the analysis to facilitate the decision-making process.

The purpose of this document is to provide support for the proposed project by (1) describing the hydrodynamics of the receiving waters offshore of Rehoboth Beach and (2) predicting the ultimate fate of the effluent so that potential environmental impacts can be adequately assessed.

To do so, a large-scale finite volume hydrodynamic model of the Delaware Estuary has been established and operated in a series of calibration scenarios involving the three most significant driving forces governing the ocean hydrodynamics of the area - the 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 going back to the 1980s.

The newly established hydrodynamic model uses the flexible (unstructured) mesh concept and has been built as an implementation of the DHI Mike 21 FM modeling system. The model has been calibrated to tides and verified against water elevation and currents by operating the model under the combined action of tides, winds, waves and freshwater discharge from the Delaware River.

Chapter 1 describes the proposed key project activities, expected project outcomes and areas of environmental significance. Chapter 2 lists previous studies of significance, summarizes their findings and makes an analytical assessment based on the Richardson number. Chapter 3 reviews the data used in the study.

Chapter 4 describes model establishment, calibration and validation to independent datasets in addition to verification of the modeling results against previous work. Tidal predictions used in the calibration and validation processes have been sourced from NOAA with the level of agreement between model (tide-only) results and NOAA predictions quantified using the root mean square error (RMSE) of water levels.

Two field data collection campaigns were organised during the course of the project thus supplying the independent datasets needed to support the calibration and validation of the model.

Tidal and wave measurements used in the process of calibration of the model are as recorded by Acoustic Doppler Current Profiler (ADCP) deployed offshore of Rehoboth Beach during the first data collection campaign undertaken in 2010 for a period of 2.5 months. A satisfactory level of model calibration has been achieved based on comparison to water levels, current magnitude and current direction in a highly complex physical environment. Model calibration extended over the entire period of the first field data collection campaign which lasted for approximately 10 weeks.

Tidal and wave measurements used in the process of validation of the model were those obtained during the second field data collection campaign undertaken during the summer and autumn of 2011. This second campaign provided two full months of data which were successfully used in the validation process to demonstrate a similar level of agreement to field measurements as the one observed during the model calibration exercise and thus provide confidence in the predictive capabilities of the model.

Further, a good agreement has been achieved between model results and previous work undertaken by the University of Delaware.

The focus of Chapter 5 is on far-field results with the results of two long-term scenarios simulating plume advection and dispersion reported in the form of 95th percentile maps of dilution. The scenarios correspond to the two potential outfall locations referred to as northern and southern outfalls.

Following from the investigation, it is concluded that, for both the north and south location, 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
- Do not reach the coast.

Chapter 6 describes the findings of nine near-field scenarios using a linear diffuser with 8 risers and a rosette arrangement consisting of four ports per riser. The analysis was carried out with the CORMIX software assuming a two layer configuration of the receiving waters with a constant density associated with each layer and a density jump implemented at the interface of the layers.

The investigation reached the conclusion that overall, a high level of dilution should be achieved with more specific findings as follows:

- The linear diffuser achieved a dilution in excess of 1:250 for an un stratified ocean with close to zero ambient current magnitudes. As typically expected, dilutions increase 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^3 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 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).

As reported in USEPA (1984) the Delaware Bay may be on a decline in terms of its water quality hence the need to protect and maintain the existing water quality standards and assess potential impacts in a rigorous manner. The findings of the current modeling study indicate that, while re-locating the point of discharge from inland to ocean should benefit inland waters, there is no evidence of plume encroachment on the coast and no impacts on ocean waters. There are no risks for primary contact recreation activities.

1. Introduction

1.1 Project Description

The City of Rehoboth Beach Wastewater Treatment Plant (RBWWTP) receives wastewater from the City and surrounding areas of Henlopen Acres and Dewey Beach, discharging the treated effluent to the Lewes-Rehoboth Canal (Appendix A). From there the effluent reaches Inland Bay (Rehoboth Bay and Indian River Bay). Despite several upgrades to the plant spanning over a period of more than 20 years, concerns about the water quality of Inland Bay have led to a revision by Delaware Department of Natural Resources and Environmental Control (DNREC) of the discharge permit of the plant and the need to seek alternative methods of discharging the treated effluent.

After detailed evaluation of various options, building an ocean outfall has emerged as the preferred solution.

1.2 Objectives

The purpose of this document is to provide support for the proposed project by (1) describing the hydrodynamics of the receiving waters offshore of Rehoboth Beach and (2) predicting the ultimate fate of the discharge effluent so that potential environmental impacts can be adequately assessed.

Two forms of modeling have been undertaken: far-field and near-field.

The far-field modeling component of this study has allowed the description of existing oceanographic conditions and relevant coastal processes including water levels, currents and wave action. It also provides a means to assess the potential for and extent of any long term build up of pollutant concentrations, and to address whether there is any significant risk of the pollutant 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 that in which turbulent mixing dominates, and is often limited to the point at which the plume reaches the ocean surface. Near-field modelling is also used to facilitate diffuser design.

1.3 Philosophy of Modeling

Understanding of the physical processes in the marine environment is a fundamental step towards assessing the potential for environmental impacts. Modeling of hydrodynamic, transport and water quality processes plays a key role in this process.

Modeling is of high value when:

- Calibrated to quality datasets;
- Used to predict how planned infrastructure will interact with the coastal environment and whether adverse impacts are likely;
- Results are presented in forms that aid the comprehension (by the public and agencies) of flow patterns and pollutant/plume fate.

1.4 Modeling Scope

The far field modeling exercise comprises five steps including:

1. review and assimilation of existing data,
2. acquisition of new data where existing data is insufficient,
3. development of a hydrodynamic, transport and water quality modeling system,
4. calibration of the modeling system to field measurements,
5. validation of the system to a second, different from the one used in the calibration process, dataset of field measurements, and
6. model operation for the assessment of currents with the outfall in place, and the potential for far field dispersion, 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 pollutant discharge is matched by the dispersion or decay of that pollutant such that the plume becomes effectively indistinguishable from the receiving water.

1.5 Areas of Environmental Sensitivity

The identification of areas of environmental sensitivity is an important step in determining the potential for environmental impact to occur. By determining the extent and strength of the wastewater plume at key locations, and comparing either concentrations or dilutions to target values at these sites, it is then a relatively simple manner to gauge the potential for impacts, or to confirm that impacts are unlikely to occur.

In this case, the primary areas of environmental sensitivity, or the areas with recognised environmental values (EVs) comprise:

- Swimming and surfing waters adjacent to the shoreline; and
- The Chicken Henlopen shoal.

2. Literature Review

2.1 Garvine's Report to Stearns and Wheler, 2003

Garvine describes the waters off the Delaware coast south of Cape Henlopen as having a complicated physical regime with abundant variability in both time and space. In his analysis, Garvine divides the current field in three frequency ranges: **tidal** (one cycle per 12 hours, for example), **sub-tidal** (range of one cycle per 12 hours up to one cycle per month) and **low sub-tidal** (frequencies lower than one cycle per month). Tidal frequency variations are mostly driven by the astronomical tidal forces while sub-tidal frequency variations are driven primarily by wind stress acting on the water surface and water density variations, especially those produced by major fresh water sources such as the Delaware estuary. Near the mouth of major estuaries – states Garvine – a major source of low sub-tidal variability is again tidal forcing acting through a rectifying mechanism associated with tidal currents themselves.

Garvine's work was based on the application of the ECOM3d hydrodynamic model. Features of the model are listed below:

- A sigma coordinate system in the vertical plane, i.e., one in which the bottom boundary and free surface are represented smoothly with the water column divided into the same number of layers independent of the water depth. An advantage of the sigma grid is that the vertical resolution increases automatically in shallow areas.
- A curvilinear horizontal grid with smallest grid cell near the Bay mouth of 750 m and progressively larger (3 km) cells well offshore near the shelf-break;
- Treats both dynamics and thermodynamics, including the Mellor-Yamada level 2.5 turbulence scheme;
- Uses an external or barotropic time step to treat the free surface and an internal or baroclinic time step to handle variations in the density field.

Model runs reported were produced by applying observed forcing by tides offshore, measured winds and the discharge of the Delaware River at Trenton, NJ. Comparison of model results sourced from the dissertation of Michael Whitney (2003) at the University of Delaware and field observations showed that the model had useful predictive skill.

Field observations used in the study included:

- A current meter record for two months in the summer of 1983 off Rehoboth Bay in water depth of 10 m;
- Records obtained at three depths (not specified) from the National Ocean Service of NOAA taken near the then proposed diffuser site; and
- Records obtained at three depths from the 1993 University of Delaware program to study the Delaware Coastal Current.

The study revealed that:

- The spatial variability in the current field, both vertical and horizontal, is high;
- Residual eddies of the order of 5 km in diameter are evident in averaged mean annual flow (year 1993) at the mouth of the estuary with tidal rectification (low frequency motion effects) playing an important role in the structure of the currents. Tidally rectified flow tends to follow isobaths and this

tendency helps create an elongated anti-cyclonic (clockwise) gyre or re-circulating region that strongly affects the near shore regime off Rehoboth that lies onshore of the crest of the Hen and Chicken Shoal.

- Vertical variability is prominent, with mean annual (1993) currents flowing in opposite directions at the surface and near the bottom.

Differences between observations and model results (tide only) are of the order of 7 cm/s for the alongshore current (magnitude of averages about 60 cm/s) and about 5 cm/s for the offshore component which averages about 35 cm/s.

The study confirms that there is little stratification during late autumn and winter at the site of the proposed outfall and finds that no substantial stratification occurred between depths of 2 and 7 m during spring and summer 1993.

The study applies a criteria known as the Richardson number as an indicator of the intensity of the mixing processes during the tidal cycle and finds intermittent mixing for an average duration of 1 hour and weak or no mixing for an average duration of 5.5 hours.

2.2 Sanders, T.M., and R.W. Garvine, Fresh Water Delivery to the Continental Shelf and Subsequent Mixing: An Observational Study, Journal of Geophysical Research, Vol. 106, No. C11, pages 27,087-27,101, November 15, 2001

With the focus of the study on the Delaware Coastal Current - the buoyancy driven current originating in the Delaware estuary, the authors address two questions related to buoyant coastal discharge: (1) What agents control the delivery of estuarine fresh water to the shelf? and (2) How is this fresh water mixed with shelf water?

According to the study, the delivery of freshwater to the shelf at sub-tidal frequencies is controlled by two forcing agents: upland freshwater discharge into the estuary and the component of the wind parallel to the axis of the estuary.

It is reported that the mean current observed in the source region showed a strong decline in speed and large counter-clock wise rotation with increased depth. According to the authors, these variations in the mean current are best explained by thermal wind shear with moored instrument records providing evidence that in the source region mixing events of several hours duration are common at tidal frequencies.

Data from satellite tracked drifters showed a striking difference between the coastal current configuration during down-welling and upwelling events. During down-welling, the flow is down-shelf and weakly onshore with particle trajectories orthogonal to the mean horizontal salinity gradient. In contrast, during upwelling the flow is strongly offshore and somewhat up-shelf with particle trajectories down the mean salinity gradient, implying rapid mixing of plume water with shelf water. Corresponding values for horizontal dispersion of plume water showed modest values for both the along-shelf and across-shelf directions under down-welling but a very large value for the across-shelf dispersion under upwelling. The authors conclude that wind stress, acting through the mediation of the strain field produced by coastal upwelling circulation is the primary means for completing the mixing of fresh water within the plume with shelf water.

2.3 Quantitative Seasonal Aspects of Zooplankton in the Delaware River Estuary, Chesapeake Science, Vol 3, No 2 (June 1962) pp. 63-93

The study reporting on quantitative sampling for net zooplankton at quarterly intervals over a two-year period also includes hydrographic data on salinity, temperature, dissolved oxygen, and surface transparency.

The study indicates that *the Delaware estuary has always showed a gradient salinity from fresh water to about 31 ppt, but strong seasonal pulses responded to changes in runoff of fresh water. For the period of the measurements, temperatures varied from 3°C to 28°C in the river, with greater stability near the sea. Turbid river water cleared appreciably near the ocean, and dissolved oxygen levels were high except where pollution loading was apparent in the river. Both salinity and temperatures showed vertical stratification, especially during periods of maximum flow in winter and spring.*

There is strong tidal action with constantly varying water at any one point. There are broad expanses of shallow water stirred and mixed by tides and wind, and there are deep troughs of lesser turbulence. There is a circulation pattern which may show horizontal, vertical, and lateral striation or may produce a relatively homogeneous mixture. There is a heavy intrusion of fresh water during the spring runoffs and a lesser dilution at other seasons.

Any comprehensive study must be long range to include the effects of seasonal climatic changes as well as those of the rhythmic tidal fluctuations and variable flow.

This is a Coastal Plain estuary with significant tidal influences. The flow of the river into the estuary varies widely with an average at Trenton of 11,770 cubic feet per second, and recorded extremes of 1,240 cfs and 250,000 cfs. Tidal amplitudes are about 4-6 feet and a tidal excursion may transport water about 10 miles. Ketchum (1952) has estimated average flushing time for the estuary to be about 100 days, with a range from 60-120 days. It is clear that this is a highly dynamic system.

Seasonal pulses in the salt content of the lower river and bay are apparent, with maximum up-stream intrusion in summer and fall in response to low river flow and downstream compression in winter and spring. Periods of low flow result in vertical homogeneity, but periods of high flow tend to strengthen vertical stratification. Plotted averages (of salt content) do not reveal the importance of tidal surges (or of the effects of wind), but even these averaged data demonstrate the wide variation which occurs. The oceanic end is relatively stable, but also shows response to run-off.

In terms of temperature, the river end varies widely, from near 0°C to about 25°C. The mouth of the bay is less variable and contributes a stabilizing effect on the lower bay. Temperature distributions often reflect the changing degrees of stratification and indicate possible shifts in the broad patterns of circulation. Deevey (1960) provides complementary data extending offshore.

Data on salinity and temperature yield clues to the circulation patterns at each season. There is strong layering during periods of high flow in winter and spring, moderate layering in the fall, and approximate vertical homogeneity within the estuary during low flow periods. These suggest periodic transition between two of the estuarine circulation types set up by Pritchard (1955). High flows are followed by a two-layered system with net outflow of river water near the surface and net inflow of ocean water near the bottom, with exchange between these layers augmented by tidal action. This is Pritchard's type B estuary. Lowered flows convert the same estuary to his type C with vertical homogeneity and a lateral flow system, with net downstream flow along the right side of the estuary (facing downstream) and upstream flow along the left. Data from the study indicate type B circulation during high flows and type C during low river flow.

2.4 WHITNEY, M. M., AND GARVINE, R. W., Simulating the Delaware Bay Buoyant Outflow: Comparison with Observations, Journal of Physical Oceanography, Vol 36, January 2006

The objective of the document was to *evaluate the performance of a numerical model developed by the authors to simulate the freshwater outflow from the Delaware Bay into the Middle Atlantic Bight against field observations. Simulation efforts focus on spring 1993 and spring 1994 with the simulation forced by river discharge, winds and tides. Only tidal-averaged results are discussed.*

An important reference is made to work undertaken by Sharp (1984) describing:

- *the Delaware estuary constituted by the tidal portions of The Delaware River and the Delaware Bay stretching over 210 km to the mouth of the bay. Maximum width of the bay is 45 km narrowing to 18 km at the mouth between Cape Henlopen and Cape May.*
- *the Delaware River as providing only 58% of the freshwater inflow to the Delaware Bay with the confluence of the Schuylkill River below Philadelphia adding another 14% and other sources collectively accounting for the remaining 28%. Average freshwater inflow is 570 m^3/s and high river discharge conditions occur during the spring. The typical river discharge rate during April is 1100 m^3/s. Even under peak freshwater inflow, the estuary is vertically well mixed by the tides.*

The document also provides a useful description of the buoyant flows exiting the mouth of the estuary and how these flows interact with winds. *Upon exiting the mouth, buoyant waters turn anti-cyclonically [clockwise] under the influence of the earth's rotation. During light winds, the buoyant outflow propagates down-shelf along the Delmarva Peninsula coast in a slender coastal current. Downwelling-favourable winds tend to accelerate down-shelf flow in the coastal current and compress its waters against the coast. Upwelling-favourable winds counter buoyancy-driven down-shelf flow and tend to spread buoyant waters offshore. Remote wind events can generate barotropic shelf waves that propagate down-shelf through the study area (at a rate of 930 km/day) and modulate shelf currents as they pass.*

The numerical model adopted for this study is the same as that described in section 2.1. In addition, it is noted that *bottom friction follows the quadratic drag law. The bottom friction coefficient C_D has been set to $5x10^{-3}$ (2 times the standard value) to best match model results with observed tidal characteristics within the estuary. Bottom roughness was parameterized with a standard height of 0.3 cm.*

2.5 Lawler, Matusky & Skelly Engineers, Regional Effluent Disposal Study for the City of Rehoboth Beach, Delaware – Supplemental Dilution Modeling, 2003.

This document describes modeling undertaken to conclude a preliminary study of the proposed ocean outfall for the City of Rehoboth Beach. Lawler, Matusky & Skelly Engineers (2003) assessed the optimum diffuser design including the extension of the outfall further offshore and a regional scenario for outfall location north of Rehoboth beach off Cape Henlopen State park in Lewes. The model used was the Cornell Mixing Zone Expert System (CORMIX) version 4.1GT.

The preliminary design consisted of a Y type diffuser with symmetrical arms, each with 8 vertical risers and two symmetrically opposing ports per riser. The preliminary designs for both scenarios are described in Table 1.

Table 1 Preliminary Diffuser Designs

Item		Rehoboth	Regional Scenario
Outfall	Material	HDPE[1]	HDPE
	Diameter (in)	24	36
	8-hr Peak Flow (MGD)	6.67	20
Diffuser	Type	Y	Y
	Length (ft)	120	184
	Diameter (in)	18	24
Riser	Number	16	24
	Length (ft)	1.5	1
	Diameter (in)	4	6
Nozzle	Number	32	48
	Length (ft)	1	1
	Diameter (in)	3	4

Diffuser optimisation was carried out by varying the number of ports, diffuser length and port spacing and picking the combination of the three parameters that resulted in the highest dilution. An average current magnitude of approximately 0.33 m/s flowing almost parallel to the shore was used for the proposed diffuser at 6000 feet from the shore. Based on Garvine (2003), densities of 1021 and 1023.6 kg/m^3 between surface and bottom were used. The water depth at the diffuser site was not provided in the report.

Diffuser optimisation results suggested that a 16 port diffuser with port spacing of 8 feet and total diffuser length of 120 feet was the ideal configuration (providing minimum dilution of 1:69 at the shoreline). The following conclusions were derived from this study:

[1] High density polyethylene

- Modification of port spacing or the total number of ports did not significantly improve dilution and since the preliminary diffuser design was based on generally accepted principles balancing dilution and costs, the preliminary design was deemed acceptable for the combination of effluent discharge and ambient conditions at the site;
- An assessment to check the relative benefit of locating the outfall to either 9000 or 12000 feet (compared with the initially proposed 6000 feet) demonstrated that the distance to achieve 1:100 dilution is not improved. While not explicitly indicated in the report, this may be because of the relatively similar current magnitudes at these three locations. It was also concluded that while there was no relative improvements in dilutions, extending the outfall may provide an additional margin of safety by allowing more time for decay. The downside would be that such outfall lengths would increase head losses. [*This uncertainty provides one of the reasons for undertaking far field modeling.*]
- A dilution of 1:100 was expected to be achieved within 500 feet of the diffuser for the Regional scenario and this mixing was considered to be adequate;
- The modeling exercise used average tidal currents compared to subtidal (small) currents used in the preliminary exercise. The use of average currents was considered more appropriate as the currents in the Delaware coast are principally tidal. Dilution of 1:100 was achieved within 500 feet of the outfall for average currents; and finally
- The report noted that Garvine (2003) showed that both the horizontal and vertical variability of the current field are high. Eddies of approximately 5 km in diameter surround the alternative diffuser locations for Rehoboth Beach and the Regional solution. These current fields were not simulated in the CORMIX model but are expected to further disperse the plume and limit its contact with the shoreline.

2.6 State of Delaware Surface Water Quality Standards, DNREC 2004

Delaware's bacterial water quality criterion requires for primary and secondary contact recreational marine waters the following values not to be exceeded

Contact Type	Single-Sample Value (Enterococcus Colonies/100 ml)	Geometric Mean (Enterococcus Colonies/100 ml)
Primary	104	35
Secondary	520	175

The criteria apply to enterococcus bacteria determined by the Department to be of non-wildlife origin based on best scientific judgement using available information.

2.7 Key Findings

Key findings from the literature review are summarised as follows:

- Three frequency ranges (tidal, sub-tidal and low sub-tidal) are present in the current field at the proposed outfall site;
- Comprehensive analysis must be carried out on a long-term basis to include the effects of seasonal climatic changes as well as those of the rhythmic tidal fluctuations and variable inflow of freshwater;
- Major forces driving the formation of currents and the mixing processes along the coast at Rehoboth beach include the tides, winds, freshwater inflows and density variations;
- Using observed (rather than synthetic) tidal elevations at the offshore boundaries of the model (if such data exist) has the potential to yield good agreement between model predictions and observations; and
- The duration of mixing processes during the tidal cycle is expected to be of the order of 1 hour as a minimum.

It should be noted that USEPA (1984) classifies the Delaware Bay as a vertically homogenous water body, that is, non-stratified and subjected to a small river discharge. The well-mixed nature of the Delaware River estuary is attributed to the fact that the estuary is generally shallow with a large tidal amplitude to depth ratio such that mixing can easily penetrate throughout the water column.

A rough estimate of the Richardson number – the primary parameter used to classify the stratification potential of an estuary yields a value of Ri=0.07 which is also an indication of well mixed conditions in the estuary (Ri<0.08).

Richardson number has been estimated with Q_f = 5000 m^3/s, W = 18000 m and U_t = 1 m/s using the following relationship:

$$Ri = \frac{\Delta\rho}{\rho}\frac{gQ_f}{WU_t^3} \ ,$$

where $\Delta\rho$ is the difference between freshwater and seawater density, typically 25 kg/m^3; ρ is the reference density, typically 1000 kg/m^3; g is gravity (m/s^2), Q_f is the freshwater inflow (m^3/s); W is the width of the estuary (m); and U_t is the mean tidal velocity (m/s). If Ri is large (>0.8), the estuary is expected to be strongly stratified and dominated by density currents, and if Ri is small (<0.08), the estuary is expected to be well mixed. Transition from a well-mixed to a strongly mixed estuary occurs in the range $0.08 < Ri < 0.8$.

It is noted that the above estimate of Ri is conservative. Average freshwater inflow of the Delaware River (Whitney and Garvine 2006) is 570 m^3/s and a typical high river discharge occurring during the spring period is of the order of 1100 m^3/s while the Delaware estuary is 18 km wide only at the mouth between Cape Henlopen and Cape May. Accordingly, Ri is expected to be significantly less than 0.07.

As discussed in the subsequent sections of this report, the presence of well-mixed conditions in the Delaware estuary lends support to the primary adoption of a two-dimensional, depth-averaged frame of analysis for the project. Well-mixed conditions also facilitate effluent dilution.

3. Project Data

Data for the modeling component of the project comprises USGS and NOAA hydrographic and meteorological datasets, depth soundings retrieved from the C-MAP bathymetric database integrated into the DHI Mike suite of models, field data from a long-term monitoring campaign and six short-term intensive periods of measurement.

3.1 Short-Term Intensive Surveys

The short-term intensive surveys were one-day measurements of conductivity and temperature using CTD instrumentation operated from a vessel. A CTD is an instrument that is lowered by a cable in the water and measures the conductivity and temperature at a given water depth. A CTD has three probes. One is a ceramic probe that measures the conductivity, a thermistor that measures the temperature, and a pressure gauge that measures the ambient water pressure. The temperature and conductivity are used to compute the water's salinity (Encyclopedia of Marine Science, 2009).

In total, six short-term intensive surveys were undertaken at the locations shown in Figure 3-1. The surveys, undertaken to examine seasonal variation of density in the water column, proceed sequentially along the three transects shown in the figure and include a varying number of individual measurements (17 on average). The vertical profiles of salinity, temperature and density, plotted in Appendix B, reveal that:

- In November 2010 and January 2011, temperature between the surface and the deepest recordings fluctuated (at most) 1 degree Celsius. However, March 2011 data suggests that temperatures may vary by as much as a 3 degrees Celsius. Similarly with salinity, in November profiles fluctuated only about 2 practical salinity units (psu) and in January 1 psu but in the March data salinity fluctuated between approximately 20-21 psu at the surface and 30 psu at the deepest records. This is a variation of 10 psu compared to 1 or 2 previously. With density the increase is also substantial going from a fluctuation of only 2 kg/m^3 in November and January to a fluctuation of 10 kg/m^3 in March.
- The May 2010 observations were similar to the March ones. Maximum temperature difference between the surface and the deepest recordings varied up to 4 degrees Celsius while generally a difference of 1-2 degrees was recorded in depths similar to the ones associated with the proposed outfalls. The maximum salinity and density differences between the surface and the deepest recordings were 10 psu and 10 kg/m^3, however the differences were of the order of 1 psu and less than 1 kg/m^3 in depths similar to the ones associated with the proposed outfalls.
- During the July 2011 short-term survey, the maximum temperature difference (between surface and bottom) in the vicinity of the proposed outfalls reached 3.5 degrees Celsius (stations R2 and R11) but salinity difference did not exceed 1 psu thus the maximum recorded density difference was also low – approximately 1.5 kg/m^3.
- The September 2011 survey produced records were similar to the first two (November 2010 and January 2011) with maximum temperature difference in the vicinity of the proposed outfalls of less than 1.0 degrees Celsius and maximum salinity and maximum density of less than 2 psu and 2.0 kg/m^3 respectively.
- Overall, it appears that there is a relative increase in stratification at the deepest monitoring locations during March, May and July 2011 compared to the results obtained in November 2010, January and

September 2011. This is mainly due to changing temperatures, the warming of surface waters and a freshwater lens impacting the surface waters. However, as observed, these effects are significantly less pronounced in depths shallower than 15 m where the outfall is proposed to be built, hence, on the basis of the short term surveys documented in this section, the assumption of well-mixed conditions holds true.

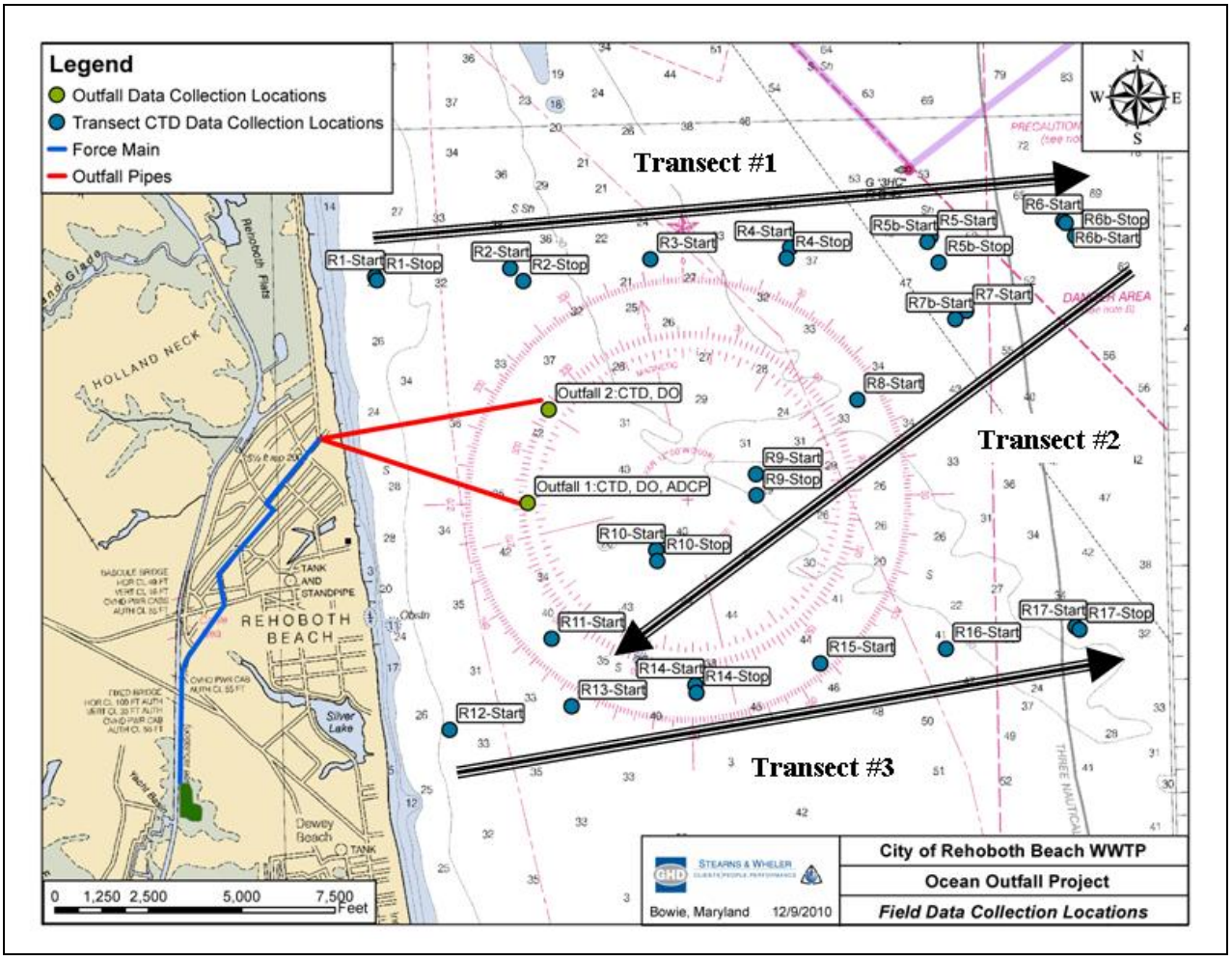

Figure 3-1 Field Data Collection Locations and Survey Transects

3.2 Long-Term Monitoring

Two long-term monitoring campaigns were conducted with the aim of collecting data on currents and wave climate at the site of the proposed outfall. The first campaign, for a two and a half month period, extended from September 1st to November 10th 2010. The second campaign commenced on July 06th 2011 and completed on September 14th 2011 yielding a total of 83 days of observations of which 63 days contained valid, continuous data. Following the passage of Hurricane Irene in the study area during the second campaign, the data collected after August 27th 2011 was found to be unreliable for comparison to model results and therefore excluded from consideration.

During both campaigns, the equipment used to collect the data consisted of two bottom-mounted Acoustic Doppler Current Profilers or ADCPs (Figure 3-2). During the first campaign, the device deployed at site #2 located in the vicinity of the southern outfall malfunctioned thus only the dataset generated by

the ADCP deployed at site #1 (near the proposed northern outfall) was made available for visualisation and analysis. The loss of the data from the second instrument precluded any measurements of the spatial characteristics of the velocity field at the outfall site as well as the possibility of conducting sanity checks on the obtained records.

During the second campaign, both instruments functioned properly thus capturing the spatial distribution of flow in the area of interest and providing concurrent records at both potential outfall sites.

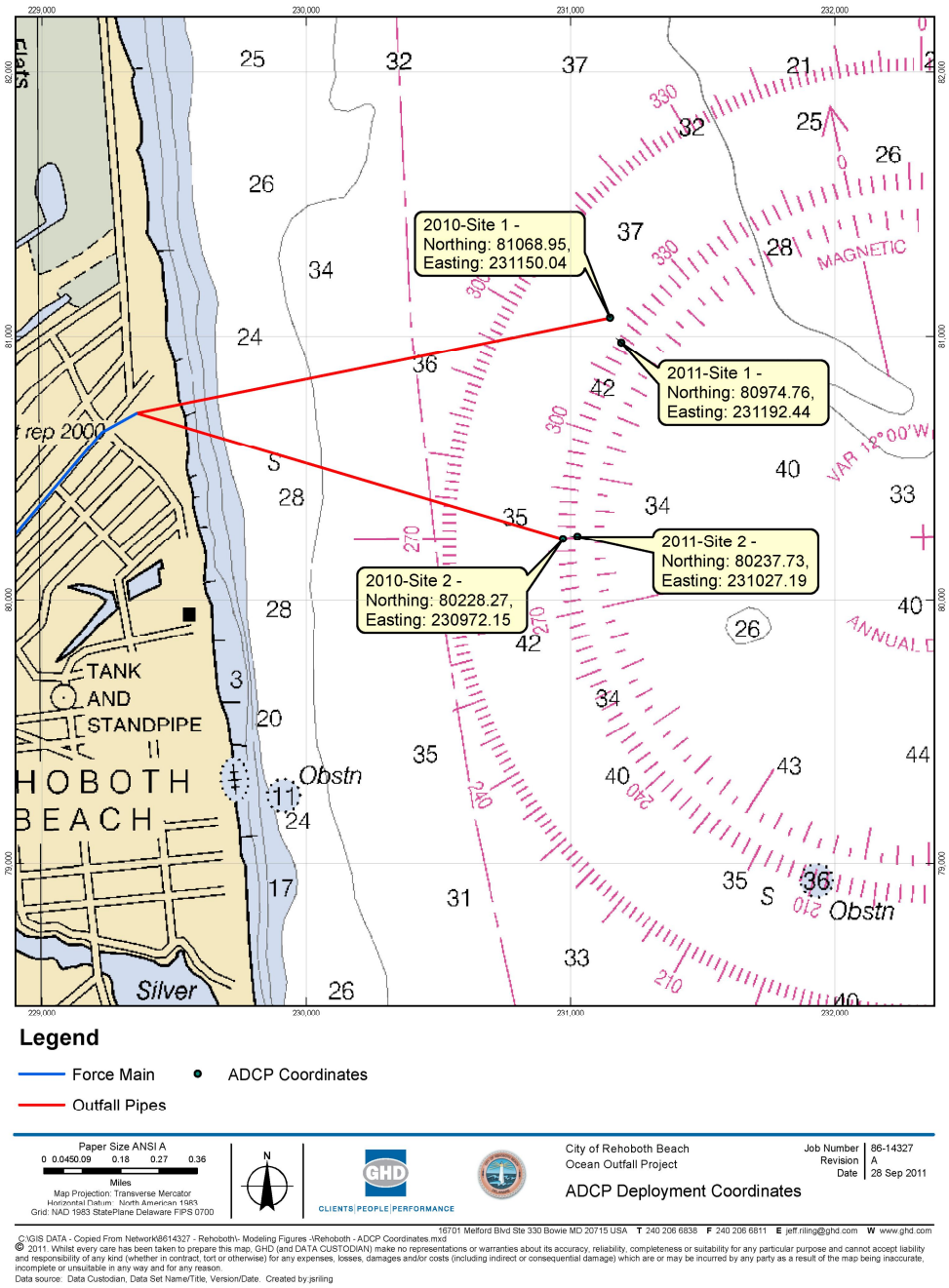

Figure 3-2 ADCP Deployment Locations

ADCPs are designed to measure current velocity and direction at discrete intervals through the water column but can also measure significant wave height, peak wave period and direction when wave enabled. All ADCP instruments deployed in the study area were wave enabled.

It should be noted that the current is measured throughout the water column in a series of depth cells or “bins” which are nominally of equal length and equally spaced. The measured currents are averaged over the range of each bin. The number of bins and the depth of the bins can be chosen by the operator to suit the site conditions and to provide the required degree of vertical resolution.

During the first (2010) campaign, data for site #1 was collected in 21 bins at 0.5 m depth increments with the first and last bins set at 1.5 m and 11.5 m above the bottom, respectively. The average depth at the site was estimated at 11.5 m below MSL.

During the second (2011) campaign, data for both sites was collected at a similar vertical resolution, i.e. 19 bins at site #1 and 20 bins at site #2. The average depth at site #1 was estimated at 12.2 m and the average depth at site #2 was estimated at 12.8 m.

In the remaining of this section, we further review and discuss the ADCP data collected during the first field campaign noting that the ADCP data collected during the second, 2011 campaign exhibit very similar characteristics to those of the data obtained during the first campaign as outlined in section 4.8 on model validation.

Three different techniques have been adopted in the visualisation of the ADCP data (Figure B-2 of Appendix B). The techniques - frequency histograms, tidal orbits and the conventional time-series, substantially complement each other. For instance, frequency histograms make it possible to quantify even minor changes in current magnitude and direction occurring in each bin owing to the adoption of frequency analysis. Alternatively, tidal orbits and time-series tend to provide the best correlation between changes in current magnitude and corresponding shifts in current direction.

As seen from Figure B-2 of Appendix B, the currents in all vertical bins (as defined by the directional frequency histograms) sit mainly in the alongshore direction defined as 360° and 180° True North while the offshore component of the currents is a minor contributor as the 330° and 150° directional bins indicate, never lasting more than 25% of the time in total. It is worth noting that for the period of measurements during the first campaign (01 September to 10 November 2010) alongshore currents headed north for a maximum of 35% of the time with the remaining balance headed south.

A review of the frequency histograms for current magnitude from Figure B-2 indicates that with respect to **alongshore currents**:

- Near the bottom, the most frequently encountered current magnitude (alongshore currents) is in the 0.3 to 0.4 m/s range for 47% of the time;
- In the first, bottom bin current magnitudes (alongshore currents) in the 0.3 m/s range dominate;
- Near the sea surface the distribution of current magnitude gradually shifts towards the 0.5 m/s current magnitude bin with magnitudes of this order observed less than 20% of the time;
- Current magnitudes exceeding 0.55 m/s have been encountered approximately 20% of the time or less.

An indication of the magnitude of the **cross-shore currents** is gained from the polar plots. Cross-shore currents are observed to remain under 0.1 m/s and are mostly uniformly distributed throughout the water depth. Occasional spikes have occurred near the surface that reach 0.15-0.20 m/s.

Figures B-2r and B-2s corresponding to near-surface measurements (10 m and 10.5 m above bottom) have been excluded from consideration owing to suspected fouling of the ADCP records in these depth bins.

Some representative current magnitudes and their corresponding minimum percent of exceedance are summarized in Table 2. These are read from the probability of exceedance curve for the second from the bottom depth bin shown in Figure B-2c of Appendix B and can be used as inputs for near-field modeling of mixing characteristics.

Table 2 Representative Current Magnitudes and Minimum Exceedance for the Period of Measurements

#	Current Magnitude (m/s)	Minimum Exceedance 2.5 m above bottom (% of time)
1	0.6	3
2	0.5	10
3	0.4	30
4	0.3	55
5	0.2	72
6	0.1	87

3.3 Meteorological Data

Winds in the model are represented as time varying, spatially uniform forcing using wind data (magnitude and direction) at 6 minute or 1 hour intervals obtained from three existing weather buoys in the study area. These are (Figure B-3, Appendix B):

- Station LWSD1 - 8557380 - Lewes, DE (6 minute interval, 6 year record starting 2004)
- Station CMAN4 - 8536110 - Cape May, NJ, (6 minute interval, 6 year record starting 2004) and
- Station 44009 (LLNR 168) DELAWARE BAY 26 NM Southeast of Cape May, NJ44009, (1 hour interval, 26 year record starting 1984) considered to represent inner shelf meteorological conditions.

Wind statistics for station 44009 over a period of 5 months (August to December 2010), including the period during which the first long-term monitoring campaign was carried out (September 1st to November 10th 2010), are presented in Table 3 and Table 4 and visualised in Figure 3-3. Monthly wind roses are also provided in Appendix B.

For the nominated period (August to December 2010), the interpretation of the results using Table 4 and each respective wind rose indicates that:

- During the months of August and September, the prevailing winds were blowing from the SSW (180º to 210º);
- A relatively even distribution characterised the month of October. Directions from which the winds

were blowing were spread between the NE (30º to 60º), the SW (210º to 240º) and the NW (300º to 330º);

- During the months of November and December, the prevailing winds were from the NW and NNW (300º to 360º) and NNE (0º to 30º) sectors.

Using Table 3 and Figure 3-3, it is observed that for the nominated period, winds blowing from the SSW (180º to 210º) and NW (300º to 330º) had the highest percentage of occurrence. Winds blowing from the NNE and NE direction were dominant during the month of November. The latter wind directions are of particular interest in this study since the winds blowing from these directions are likely to have an impact on the water quality near the coast.

Wind statistics for station 44009 over a period of 3 months (July, August and September 2011), including the period during which the second long-term monitoring campaign was carried out (July 6th to September 14th 2011) are shown in Figure 3-4. As indicated from the figure, the prevailing winds for this period were blowing from the SSW (180º to 210º). There were no winds from the NW quadrant for the period.

Also summarised in Figure 3-5 for comparative purposes are the wind statistics for the first half of 2011. While the dominance of winds blowing from the SSW (180º to 210º) is still clearly observed, a contribution from winds from the NNW (330º to 360º) sector is also evident for the period.

As noted in the following sections, provisions have been made to represent the seasonal variability of the wind (and hence wave) climate (as illustrated by the above figures) in the effluent plume analysis by conducting the latter over a period of 11 months.

Table 3 Wind Statistics – Wind Speed/Wind Direction at Station 44009 for the Period August 1st to December 31st 2010

Wind Speed (m/s)	Wind Direction True North (degrees)												
	≥0 ~ <30	≥30 ~ <60	≥60 ~ <90	≥90 ~ <120	≥120 ~ <150	≥150 ~ <180	≥180 ~ <210	≥210 ~ <240	≥240 ~ <270	≥270 ~ <300	≥300 ~ <330	≥330 ~ <360	**Total**
≥0 ~ <1	0.08%	0.11%	0.14%	0.03%	0.03%	0.08%	0.16%	0.08%	0.03%	0.08%	0.08%	0.11%	**1.01%**
≥1 ~ <2	0.54%	0.52%	0.33%	0.49%	0.25%	0.49%	0.38%	0.30%	0.35%	0.14%	0.16%	0.33%	**4.28%**
≥2 ~ <3	0.54%	0.44%	0.33%	0.79%	0.74%	0.49%	0.84%	0.82%	0.52%	0.71%	0.44%	0.41%	**7.05%**
≥3 ~ <4	0.65%	0.52%	0.54%	1.03%	0.76%	0.74%	0.63%	0.76%	0.74%	0.71%	0.74%	0.65%	**8.47%**
≥4 ~ <5	1.12%	0.68%	0.87%	0.71%	0.87%	1.06%	1.42%	1.66%	0.65%	0.90%	0.71%	1.12%	**11.76%**
≥5 ~ <6	0.87%	0.82%	0.54%	0.71%	0.60%	0.76%	1.99%	1.03%	0.68%	0.63%	0.57%	1.09%	**10.29%**
≥6 ~ <7	0.65%	0.44%	0.68%	0.60%	0.33%	0.60%	1.36%	0.54%	0.49%	0.87%	0.82%	0.82%	**8.20%**
≥7 ~ <8	1.28%	0.27%	0.38%	0.25%	0.35%	0.22%	1.44%	1.12%	0.63%	0.65%	1.39%	1.42%	**9.40%**
≥8 ~ <9	0.60%	0.71%	0.27%	0.19%	0.33%	0.33%	1.12%	1.31%	0.22%	0.65%	2.12%	1.12%	**8.96%**
≥9 ~ <10	0.71%	0.71%	0.25%	0.16%	0.30%	0.30%	1.25%	0.60%	0.25%	0.65%	1.93%	0.95%	**8.06%**
≥10 ~<11	0.76%	0.76%	0.05%	0.19%	0.38%	0.19%	0.68%	0.35%	0.08%	0.41%	1.61%	0.87%	**6.35%**
≥11 ~<12	0.30%	0.27%	0.00%	0.08%	0.19%	0.22%	0.35%	0.30%	0.08%	0.38%	1.17%	1.31%	**4.66%**
≥12 ~<13	0.05%	0.11%	0.03%	0.00%	0.03%	0.22%	0.14%	0.22%	0.03%	0.65%	1.33%	0.98%	**3.79%**

Wind Speed (m/s)	Wind Direction True North (degrees)												
	≥0 ~ <30	≥30 ~ <60	≥60 ~ <90	≥90 ~ <120	≥120 ~ <150	≥150 ~ <180	≥180 ~ <210	≥210 ~ <240	≥240 ~ <270	≥270 ~ <300	≥300 ~ <330	≥330 ~ <360	**Total**
≥13 ~<14	0.08%	0.16%	0.00%	0.00%	0.05%	0.03%	0.16%	0.08%	0.00%	1.20%	1.69%	0.46%	**3.92%**
≥14 ~<15	0.08%	0.30%	0.00%	0.00%	0.03%	0.11%	0.00%	0.03%	0.00%	0.49%	0.95%	0.46%	**2.45%**
≥15 ~<16	0.05%	0.08%	0.00%	0.00%	0.00%	0.03%	0.00%	0.00%	0.00%	0.03%	0.19%	0.16%	**0.54%**
≥16 ~<17	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.33%	0.14%	**0.46%**
≥17 ~<18	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.16%	0.14%	**0.30%**
≥18 ~<19	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.05%	0.00%	**0.05%**
Total	**8.39%**	**6.89%**	**4.41%**	**5.23%**	**5.23%**	**5.86%**	**11.93%**	**9.20%**	**4.74%**	**9.15%**	**16.45%**	**12.53%**	**100.00%**

Table 4 Wind Statistics – Monthly Wind Direction at Station 44009 for the Period August to December 2010

Wind Direction (degrees)	August	September	October	November	December	Total
≥0 ~ <30	1.39%	1.93%	0.84%	3.02%	1.20%	**8.39%**
≥30 ~ <60	1.25%	1.50%	2.15%	1.83%	0.16%	**6.89%**
≥60 ~ <90	1.47%	0.63%	1.36%	0.71%	0.25%	**4.41%**
≥90 ~ <120	1.96%	0.98%	0.54%	1.50%	0.25%	**5.23%**
≥120 ~ <150	1.44%	1.23%	0.38%	1.44%	0.74%	**5.23%**
≥150 ~ <180	1.69%	2.29%	0.38%	1.12%	0.38%	**5.86%**
≥180 ~ <210	3.54%	4.11%	2.56%	0.95%	0.74%	**11.90%**
≥210 ~ <240	2.75%	1.77%	2.75%	1.25%	0.68%	**9.21%**
≥240 ~ <270	1.17%	0.68%	1.99%	0.57%	0.33%	**4.74%**
≥270 ~ <300	0.98%	0.93%	2.59%	1.31%	3.35%	**9.15%**
≥300 ~ <330	0.79%	1.63%	2.94%	2.72%	8.36%	**16.45%**
≥330 ~ <360	1.83%	1.93%	1.77%	3.19%	3.81%	**12.53%**
Total	**20.27%**	**19.61%**	**20.27%**	**19.61%**	**20.24%**	**100.00%**

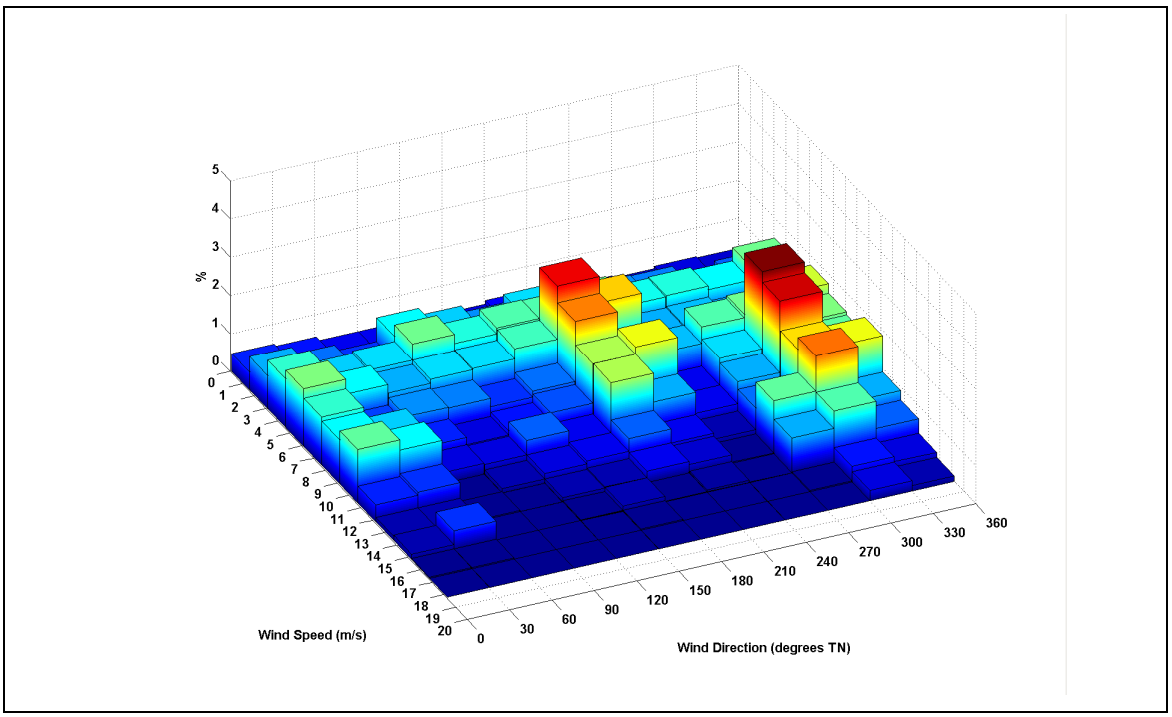

Figure 3-3 Wind Speed/Wind Direction Percentage Occurrence at Station 44009 for the Period September 1st to December 31st 2010

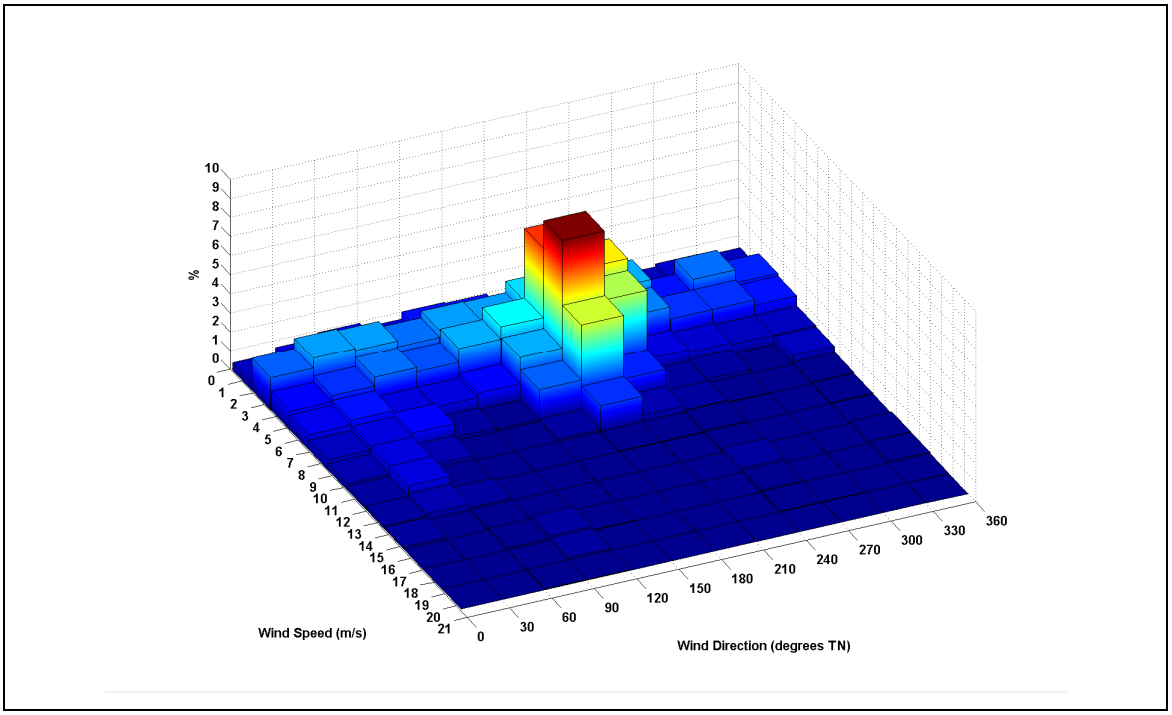

Figure 3-4 Wind Speed/Wind Direction Percentage Occurrence at Station 44009 for the Period July 1st to September 30th 2011

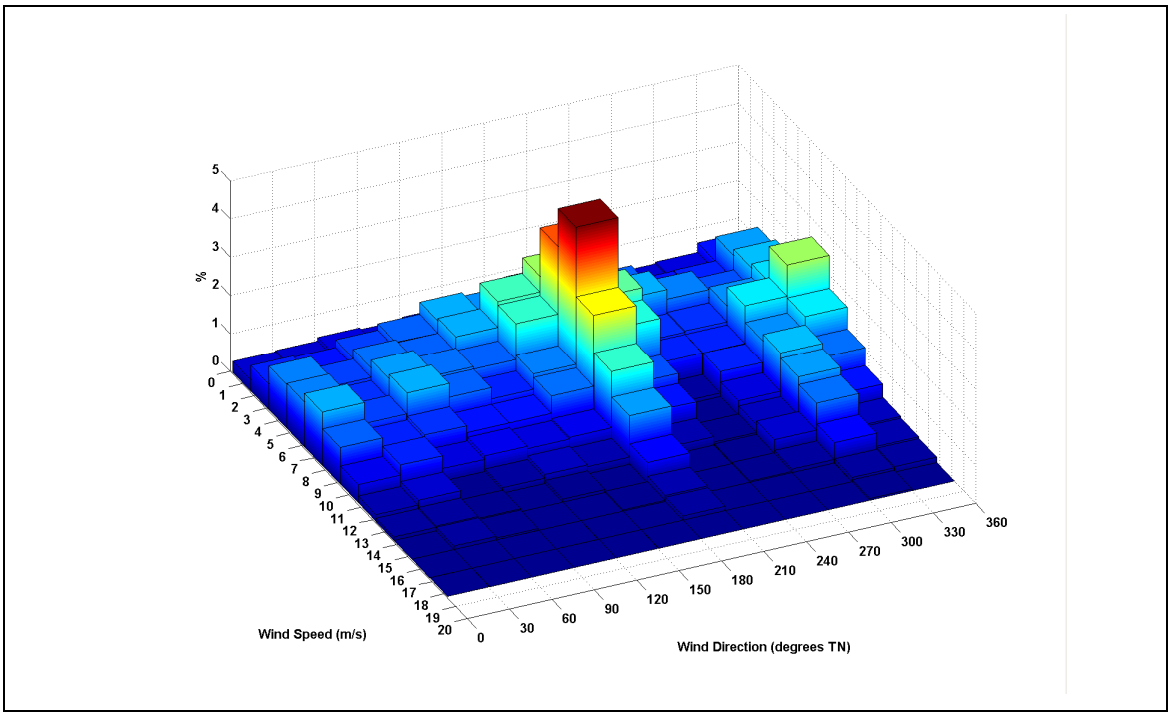

Figure 3-5 Wind Speed/Wind Direction Percentage Occurrence at Station 44009 for the Period January 1st to June 30th 2011

3.4 Wave Data

Wave data has been obtained from Station 44014 (LLNR 550) VIRGINIA BEACH 64 NM East of Virginia Beach, VA, (1 hour interval, 30 year record starting 1980) and consisted of significant wave height, spectral peak wave period and mean wave direction.

3.5 Freshwater Inflows

As indicated above, the Delaware River above Trenton, New Jersey, providing 58% of the freshwater flowing into the Delaware Bay according to Sharp (1984), is used as one of the major forces to drive the simulation. Freshwater inflows included in the analysis have been represented using the U.S. Geological Service daily river discharge record at Trenton for the 2010 period applied approximately 165 km upstream from Cape Henlopen near Bellefonte and adjusted to account for additional sources of freshwater (refer section 4.7.2 for details).

A probability of exceedance curve for the daily river discharge has been derived from the entire set of observations at the nominated location (October 1st 1912 to June 12th 2011). The curve, shown in Figure 3-6, indicates the probability that a daily Delaware river discharge, shown on the vertical axis of the graph, will be exceeded at the location. As determined from the curve and on the basis of approximately a century-long period of observations, a river discharge of 1000 m^3/s is expected to be exceeded 4% of the time, a river discharge of 500 m^3/s is expected to be exceeded 19% of the time and so on.

Using the curve given in Figure 3-6, one can determine the probability of exceedance of the Delaware river discharge recorded during the period of each of the short-term intensive surveys described in section 3.1 and, in association with the conditions measured at the outfall area, establish a correlation between river discharge probability and the probability of encountering vertical stratification in the area of the proposed outfall. This is a valid approach since vertical stratification in the water column has been found to be directly associated with periods of high inflows from the Delaware river (refer section 2.3). Following the described approach, the daily discharges corresponding to the 2010-2011 surveys which were associated with some degree of stratification at the outfall are identified in columns 3 of Table 5 and observed (column 4) to have a relatively low probability of exceedance of 2-6%.

While a larger sample of paired river discharge and short-term intensive measurements is necessary to improve the reliability of this estimate, a less than 6% probability of exceedance of the daily discharges associated with some degree of stratification imply that the probability of stratified conditions developing at the outfall site and caused by river inflows is also relatively low.

In addition, following the methodology presented in section 2.7, all river discharges listed in Table 5 are associated with well-mixed conditions in the Delaware estuary (values of Ri of less than 0.08).

It should be noted that all discharges included in the above analysis have been lagged by 14 days to allow for the time it approximately takes for a flow discharge measured at Trenton to reach the study area.

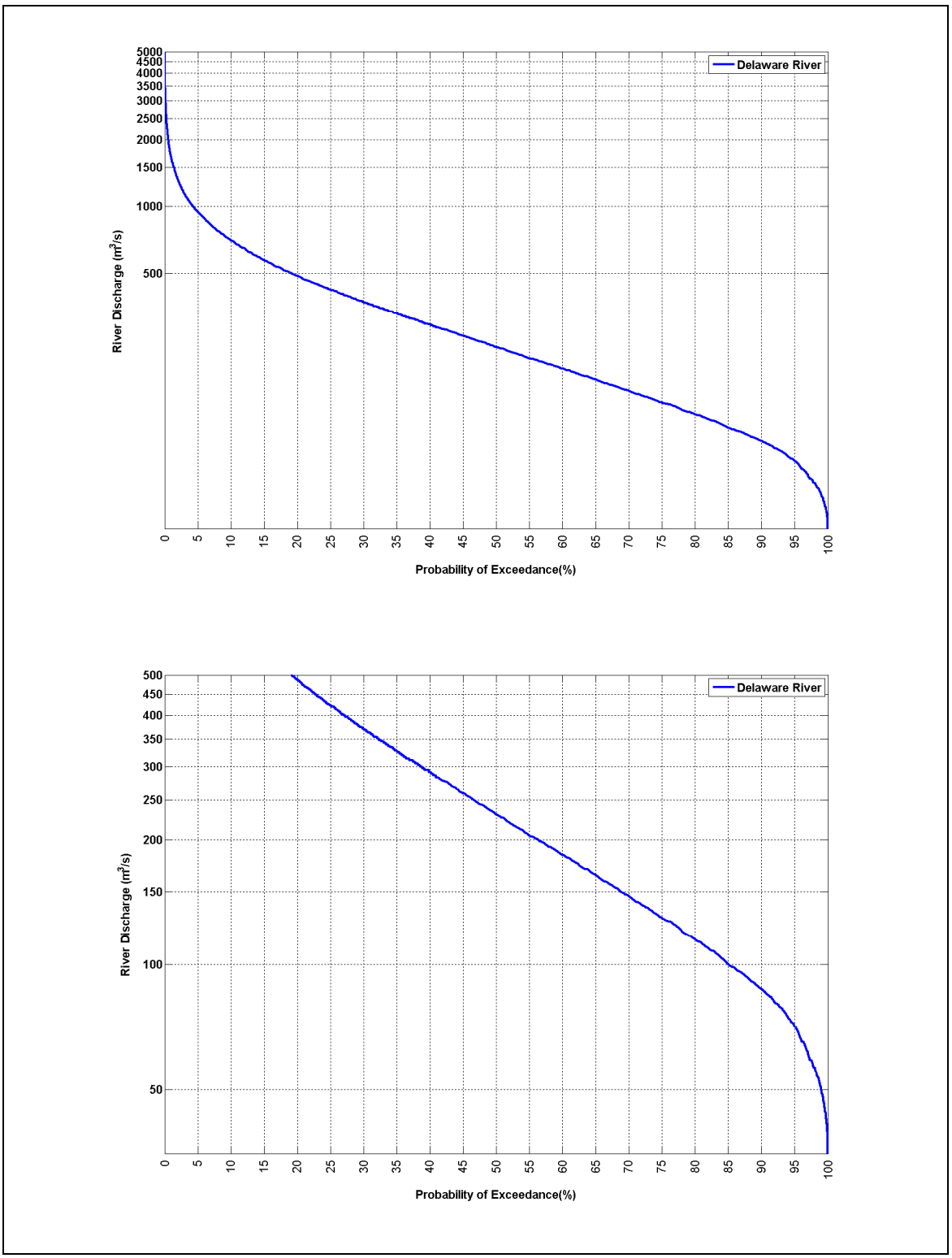

Figure 3-6 Probability of Exceedance of Daily River Discharge in the Delaware River for the Period October 1st 1912 to June 12th 2011

Table 5 Short-term Intensive Surveys - Measured Daily River Discharge, Associated Probability of Exceedance and Receiving Water Condition

Survey #	Date	Measured Daily River Discharge (m^3/s)	Probability of Exceedance (%)	Stratified Conditions
1	November 18th 2010	285.4	33.5	Low
2	January 25th 2011	194	67.5	Low
3	March 17th 2011	1163	2.2	Low to moderate
4	May 25th 2011	738	5.8	Low to moderate
5	July 11th 2011	1112	3.3	Low to moderate
6	September 14th 2011	2773	0.2	Low to moderate

3.6 Bathymetry

Depth measurements for modeling purposes off the coast of Rehoboth Beach were obtained from multiple sources. Primarily, the coastline and bathymetric data were obtained from the C-Map database (Jeppesen) and NOAA. Bathymetric data was also collected during the six short term surveys.

Another source of depth measurements comprised cross-shore profiles generated by the U.S. Army Corp of Engineers. This data only extends a few hundred feet offshore and was not used in the analysis. However, it is expected to play an important role during the design stage of the proposed outfall.

As demonstrated from Figure 3-7, there is a good agreement between model bathymetry (coloured contours) and the underlying NOAA chart. All key bathymetric features offshore of Rehoboth Beach are rendered in the model.

Additional bathymetric features (at different scales) can also be observed in Figure 4-1 and Figure 4-2.

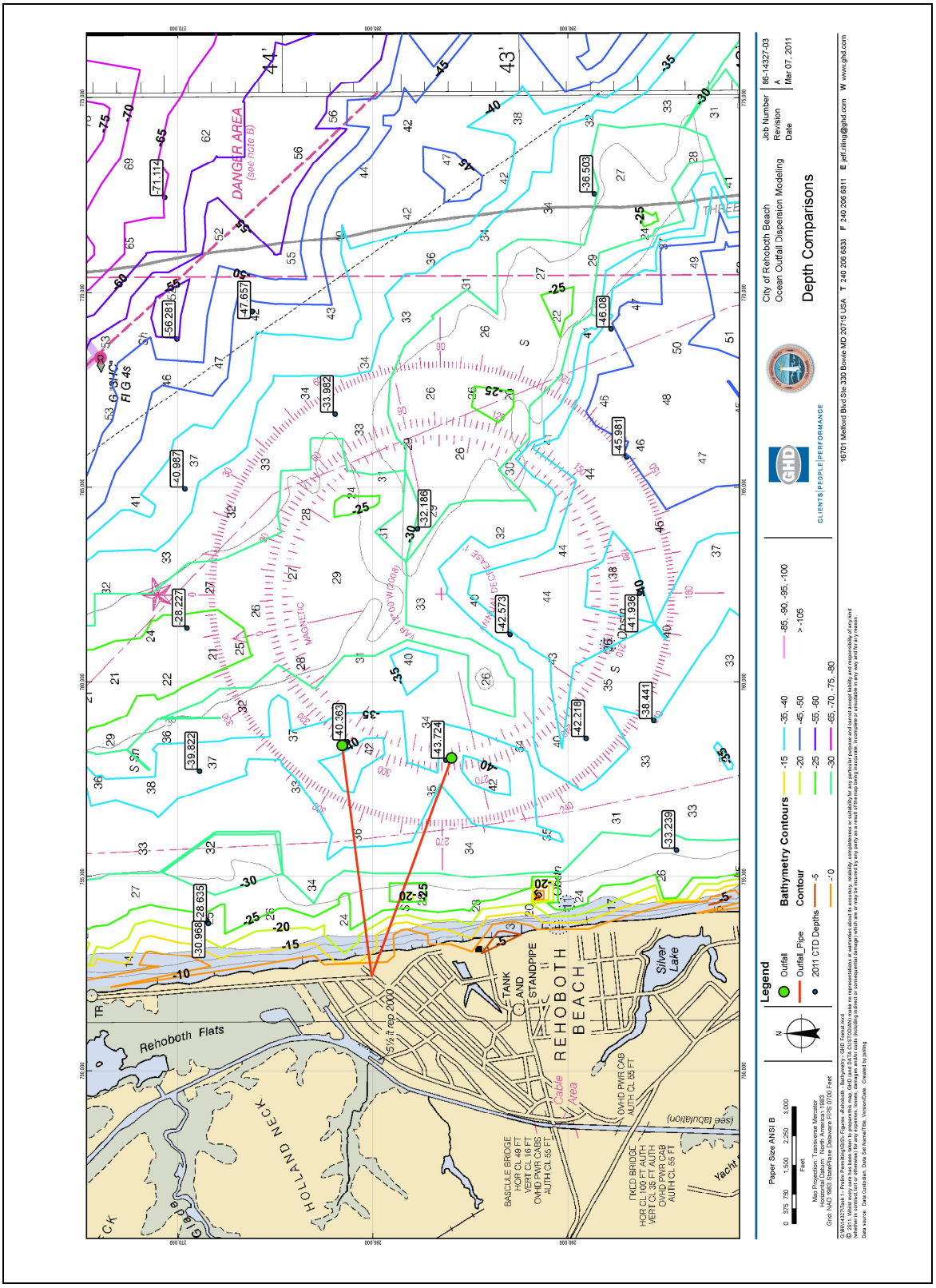

Figure 3-7 Comparison of Model Bathymetry versus NOAA Charts

4. Model Establishment and Calibration

4.1 Introduction

The usefulness of numerical hydrodynamic-transport and water quality models as powerful tools for impact assessment studies has long been recognized, with methodologies for their rigorous implementation well established (STOWA 99-05). Flow and transport are integrally linked, meaning that accurate quantification of the time- and space-varying flow conditions of the receiving waters is required to accurately evaluate the transport of waterborne constituents. Net trends in transport, which may vary on a seasonal basis, must also be properly captured and adequately incorporated into the analysis of the ultimate fate of the effluent.

To ensure that the identification of potential impacts from the proposed works is carried out in an effective manner whilst protecting sensitive habitats and recreational areas, a sound understanding of the dominant physical forces and processes in the coastal area of interest is essential. The acquired knowledge is then synthesized in a numerical model capable of providing a quantitative description of circulation patterns, flushing characteristics and transport trends as well as answers to what-if scenarios which are fundamental to the impact assessment process.

The following sections provide a description of the hydrodynamic and transport modeling system developed for the assessment of the plume dispersion processes at Rehoboth Breach.

4.2 Governing Equations

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 or three-dimensional non-linear, unsteady flow and transport phenomena resulting from the effects of the tide, waves, winds, freshwater inflows, density and the effects of the earth's rotation. Density effects are due to time (seasonally) and spatially varying (non-uniform) temperature and salinity distributions.

The modeling process is based on a system of standard equations comprising:

- The incompressible Reynolds-averaged Navier-Stokes (or RANS) equations describing the conservation of momentum and mass in a Cartesian coordinate system rotating with the earth and subject to the hydrostatic pressure and Boussinesq assumptions;
- Two advection-diffusion equations for the transport of salinity and temperature; and
- The state equation.

It is noted that:

- The fluid is assumed to be incompressible. Accordingly, the density ρ does not depend on the pressure but only the temperature T and the salinity S via the equation of state in the form $\rho = \rho(T,S)$; and
- Use is made of the UNESCO equation of state.

The prognostic variables are the free surface elevation and the two components of transport or velocity. The spatial discretization of the primitive equations is performed using a cell-centred

finite-volume method. In two-dimensional mode, the one adopted for the current analysis, the spatial domain is represented on a flexible (unstructured) mesh of non-overlapping triangular or quadrilateral elements.

Turbulence is modelled using an eddy viscosity concept with sub-grid scale transports represented by an effective eddy viscosity related to a characteristic length scale. This formulation, introduced by Smagorinsky, represents turbulence at scales smaller than the model mesh size.

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 and is an implementation of Mike 21 SW with the discretization of the governing equation in spectral space performed using a cell-centred finite volume method while the time integration is performed using an explicit fractional step approach (Mike 21 SW User's manual).

4.3 Model Domain

The simulation domain (Figure 4-1) includes the entire Delaware estuary and 375 km of the adjacent continental shelf extending some 105 km offshore to maximum depths of approximately 100 m. The included section of continental shelf stretches from the mouth of the Delaware estuary 160 km north past Bamegat Bay reaching Point Pleasant Beach and 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 160-200 m (Figure 4-2).

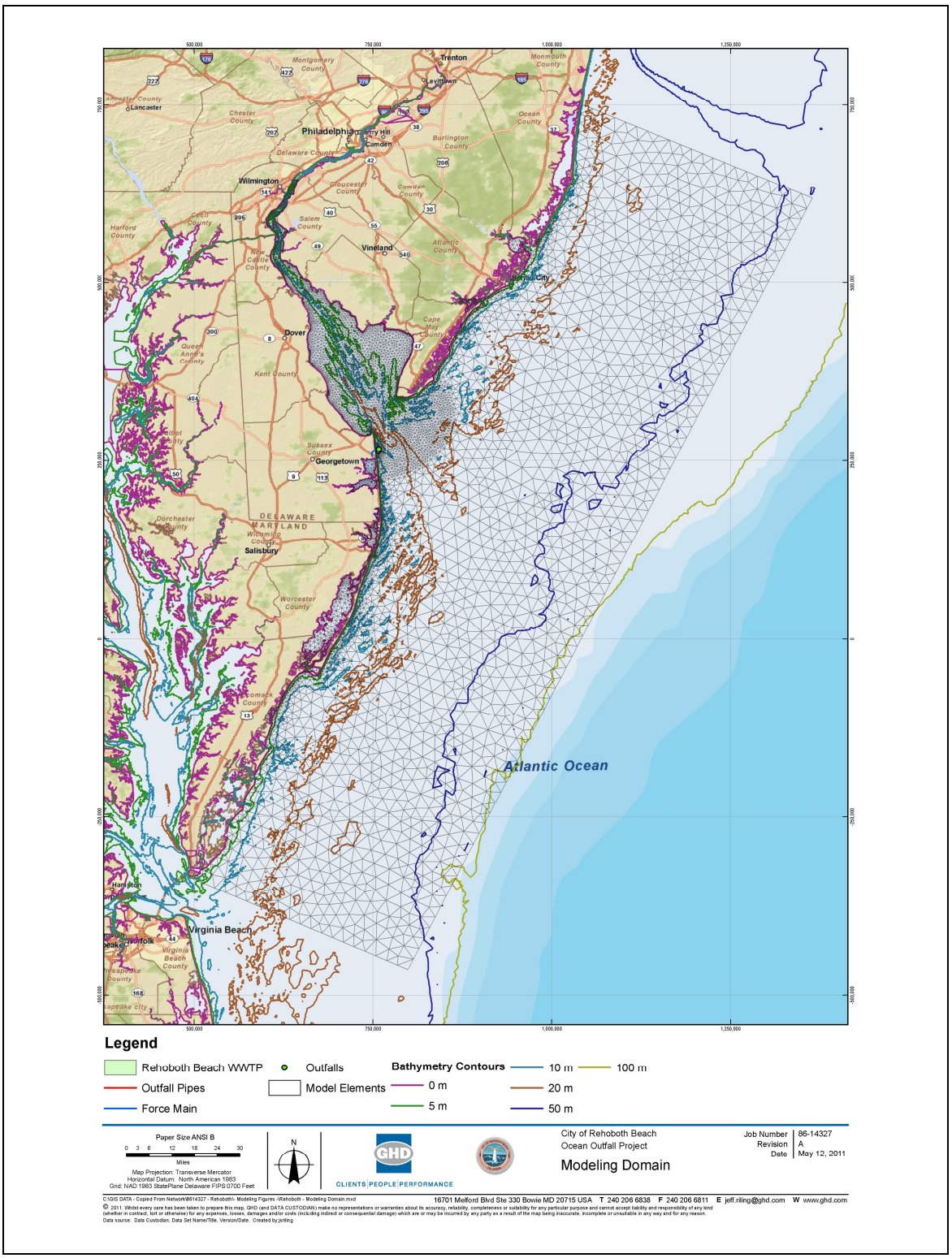

Figure 4-1 Extent of the Model Used for Far-Field Analysis

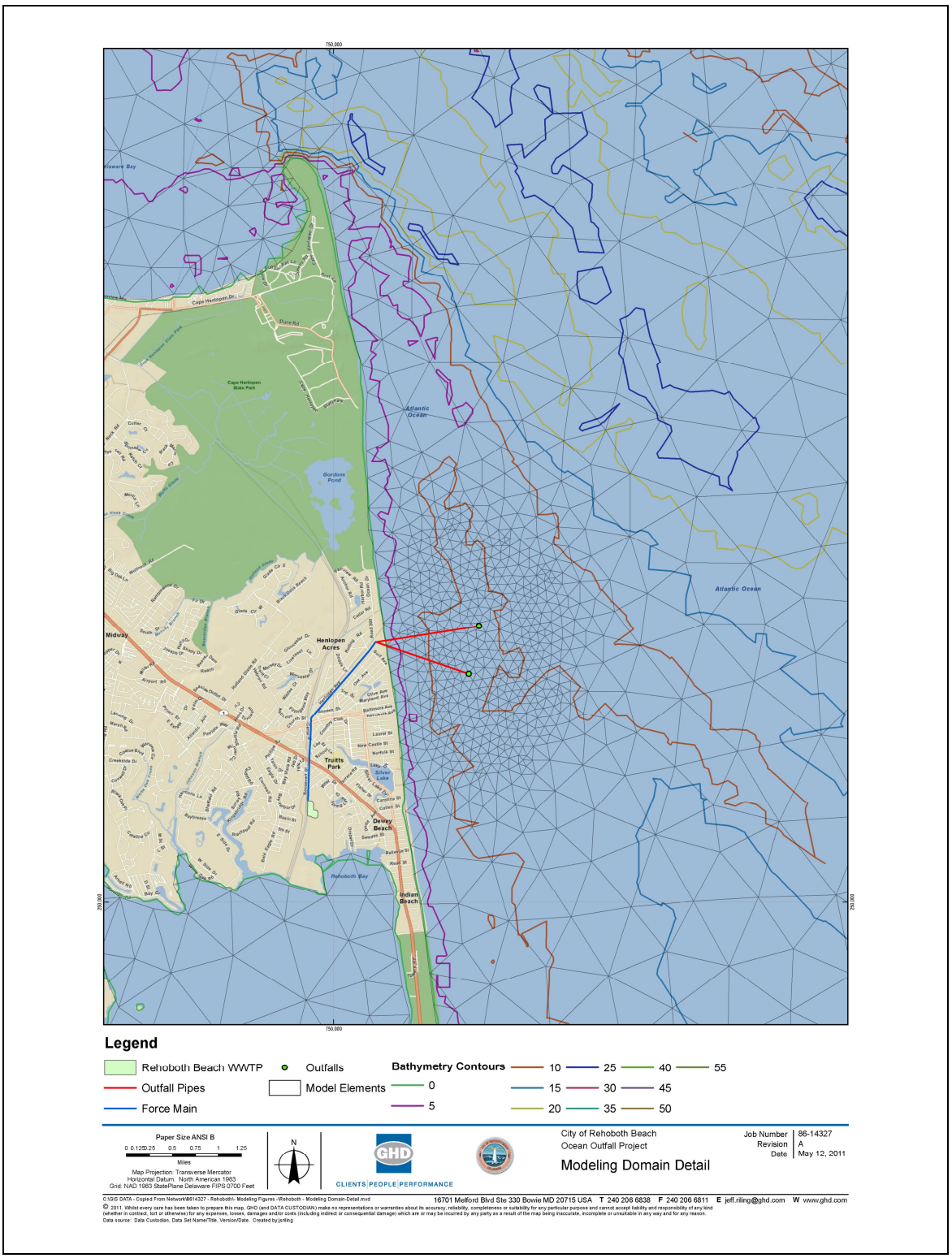

Figure 4-2 Magnified View of the Mesh of the Model at the Proposed Outfall Site

4.4 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. 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.

Two field data collection campaigns were organised during the course of the project that provided independent datasets needed to support the calibration and validation of the model. Calibration was carried out against the first dataset (2010). The second dataset (2011) was used for model validation.

4.5 Forcing of the Hydrodynamic Model

The primary forcing factors included in the analysis are: tides, winds, waves, Delaware River discharge and, in the case of a three-dimensional model, density effects as driven by seasonal changes in salinity and temperature. 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 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.

4.6 Forcing of the Wave Model

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.

4.7 Model Calibration

This section describes the model calibration process. The limitations of assumptions involved in the calibration are also discussed. Calibration of the model to both predictions and field measurements is provided to demonstrate that the model is capable of simulating realistically the water elevations and currents at the outfall site over a prolonged period of time. Further confirmation of the predictive capability of the model is provided by means of validation of the model results against the second independent field dataset (refer section 4.8) and verification of the model results to previous work (section 4.9).

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.

NOAA's tidal predictions for the Lewes station and field data collected offshore of Rehoboth beach during September to November 2010 have been used to calibrate the model.

The key parameter for model calibration is the bottom roughness coefficient. Mesh quality and resolution, coastal bathymetry and offshore boundary conditions also play a major role in the successful calibration and, later on, operation of the model.

In total, 32 scenarios were investigated for calibration purposes. Modeling conditions included:

- Tide only;
- Tide and freshwater river inflow;
- Tide and wind (several datasets described in section 3.3);
- Tide, freshwater river inflow and wind; and
- Tide, freshwater river inflow, wind and wave (dataset described in section 3.4).

Water elevation, current and wave measurements used for calibration of the modeling system were as recorded by the Acoustic Doppler Current Profiler or ADCP deployed near the southern leg of the outfall (38.730°N, 75.058°W) for the period 01 September 2010 to 10 November 2010 (refer section 3.2 for details). For the purpose of calibration, the system was operated for a period of three months starting on 15th August 2010 thus including a two-week warm-up period in the simulation.

Predictions of tidal elevation for the Lewes tidal station were also obtained for the 8 major tidal constituents listed in the previous section and used in the process of calibration of the model to tide.

4.7.1 Model Calibration to Predicted Tides

With respect to tides, the modeling system was calibrated against predictions of water surface elevation sourced from NOAA at Lewes tidal station, the closest to the project site. The results of the calibration, illustrated in Figures C-1 and C-2 presented in Appendix C, are quantitatively analysed in terms of the root-mean-square-error or RMSE. The RMSE is used herein as an objective criteria for the assessment of the performance of the modeling system. Provided a time-series of observed O_i and simulated S_i values, RMSE is calculated as follows:

$$RMSE = \sqrt{\frac{\sum (O_i - S_i)^2}{N}}$$

where N denotes the number of samples included in the statistical measure.

In terms of tidal elevation, a value of RMSE ≤ 0.1 m indicates that there is a good agreement between predicted and simulated tidal elevations.

A total of nine three-month simulations starting on 15th August 2010 were undertaken as part of the calibration process during which Manning's roughness coefficient and tide-only, water level offshore boundary conditions (obtained from the DHI global tidal model) were gradually adjusted. Logically, the simulation period for the calibration exercise was selected to coincide with the period of the most recent field collection program (01 September to 10 November 2010).

The lowest RMSE achieved in the above simulations was 0.06 m. These results (Figures C-1 and C-2, Appendix C) were obtained for a Manning's roughness coefficient of n=0.045, a Smagorinsky formulation of the horizontal eddy viscosity and slightly increased (with reference to the global tidal model) tidal amplitudes at the offshore open boundaries of the model. A factor

of 1.2 applied uniformly across all open boundaries of the model was found to produce the best match with NOAA's predictions.

It is noted that global tidal models such as the one used to supply the offshore boundary conditions for the present study use only the 8 major tidal constituents described in section 4.5. In order to preserve consistency in the analysis, all tidal predictions obtained from NOAA use the same set of constituents.

A comparison of predicted and simulated tidal elevations (at tidal station Lewes) is presented in Figures C-1 and C-2 of Appendix C. In addition, Figures C-3 and C-4 of the appendix compare the simulated tidal elevations at the proposed outfall site (site of deployment of ADCP#1) with the NOAA predictions. With the exception of a minor phase lag that accounts for the distance that the tide has to travel between the two locations, the comparison reveals little difference in the predicted behaviour of the tide at the outfall site and station Lewes.

This is interpreted as an indication that:

- In terms of tidal elevation, the quality of the obtained solution at the outfall site (as expressed by the level of agreement between tidal predictions and tide-only simulations) is good; and
- Tidally-induced mixing processes are expected to be adequately represented in plume dispersion solutions.

4.7.2 Calibration to Tide, Winds, Waves and Freshwater Inflows (*Time histories and polar plots)*

The process of calibration to currents involved:

- Operating the system in two-dimensional mode using as input:
  - the predicted tidal signal generated by the integrated global tidal model;
  - wind fields (varying in time, constant in domain) reconstructed from hourly records of wind speed and direction obtained from station 44009 (LLNR 168) - Delaware Bay, 26 nautical miles Southeast of Cape May, NJ;
  - wave climate (varying in time, constant along the offshore boundaries of the model) reconstructed from hourly records of significant wave height H_s (m), spectral peak wave period T_p (s), mean wave direction MWD (degrees true north) and directional spreading index n obtained from wave station 44014 (LLNR 550) - Virginia Beach, positioned 64 nautical miles East of Virginia Beach, VA;
  - daily freshwater inflows from the Delaware River obtained at station USGS 01463500 Delaware River at Trenton NJ and multiplied by a factor of 1.5 to account for additional sources of freshwater that enter the system downstream of Trenton;
- Assessing the sensitivity of the solution to Manning's roughness coefficient n. The coefficient was varied in the 0.024 to 0.045 range;
- Using a Smagorinsky formulation of the horizontal eddy viscosity; and
- Averaging current direction and current magnitude ADCP records over depth.

The results of the calibration are presented in Figures C-5 to C-9 of Appendix C in the form of:

- Time histories of measured and modelled **water levels** and a time history of the corresponding residuals (measured water levels – modelled water levels), Figure C-5;
- Time histories of measured and modelled (two-dimensional) **current magnitude** at the site of deployment of the ADCP and a time history of the residual (measured current magnitude – modelled current magnitude), Figure C-6;
- Polar plots of measured and modelled currents with the measured currents presented in two ways: (1) as a statistical mean and (2) a 95th percentile graph (Figure C-7);
- Time histories of measured and modelled significant wave heights Hs (m), Figure C-8; and
- Time histories of measured and modelled peak wave periods Tp (s), Figure C-9.

It is noted that:

- All comparisons are referred to the site of deployment of ADCP #1 and have been undertaken for the period of the measurements;
- The residual water level time history shown in Figure C-5 has been obtained by subtracting *modelled* from *measured* water levels over the period of the measurements;
- Similarly, the residual current magnitude time history shown in Figure C-6 has been obtained by subtracting modelled from measured current magnitudes for the period of the measurements, with the measured current magnitudes averaged over the water column;
- The polar plots in Figure C-7 allow a simultaneous assessment of modelled current direction and magnitude against two statistical representations of the measurements – the statistical mean and the 95th percentile of current magnitude;
- The 95th percentile representation of the currents while filtering major spikes in the measurements (which the model cannot represent subject to the adopted forcing datasets and modeling conditions) enhances significantly the comparison between model and measurements.

Following from the comparison in Figure C-5, it is observed that the difference between modelled and measured water levels (or residual) at the outfall site could reach up to ±0.5 m for the period of the measurements. From the comparison of current magnitudes, the estimated difference is estimated to be of the order of ±0.25-0.30 m/s. The underlying assumption in these estimates is that:

- Events associated with a large residual have a low frequency of occurrence, hence little impact on transport trends; and
- All measured physical entities (to which the model results are being compared to) are free of substantial error due to data handling and/or operation of the instrumentation.

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 C) estimates the maximum water level residuals for the three months at 0.5 m, 0.8 m and 0.7 m, respectively. While Lewes is a 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, the model matches well 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 good match of the measured wave heights and peak wave periods is interpreted as evidence of the fact that both wind speed and direction, a major factor in the formation of local sea wave climate, are adequately represented in the modeling system.

4.7.3 Calibration to Tide, Winds, Waves and Freshwater Inflows (*frequency histograms)*

Comparison of ADCP records at 2.5 m above bottom and depth averaged model results (Figure 4-3) has been carried out in terms of probability of exceedance of current magnitude, frequency histogram for current magnitude and frequency histogram for current direction. This has been undertaken 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.

ADCP records at 2.5 m above bottom have been used in the comparison as bottom currents are lower than those near the surface (refer section 3.2) and as such will generate worse case assessment scenarios.

As evidenced from Figure 4-3 the agreement between current measurements and model results is satisfactory in implying that near field analysis (drawing substantially from ADCP data) and model-based far-field analysis (verified against ADCP data) should be highly consistent. This statement is made 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 modelling process, and hence in the final solution.

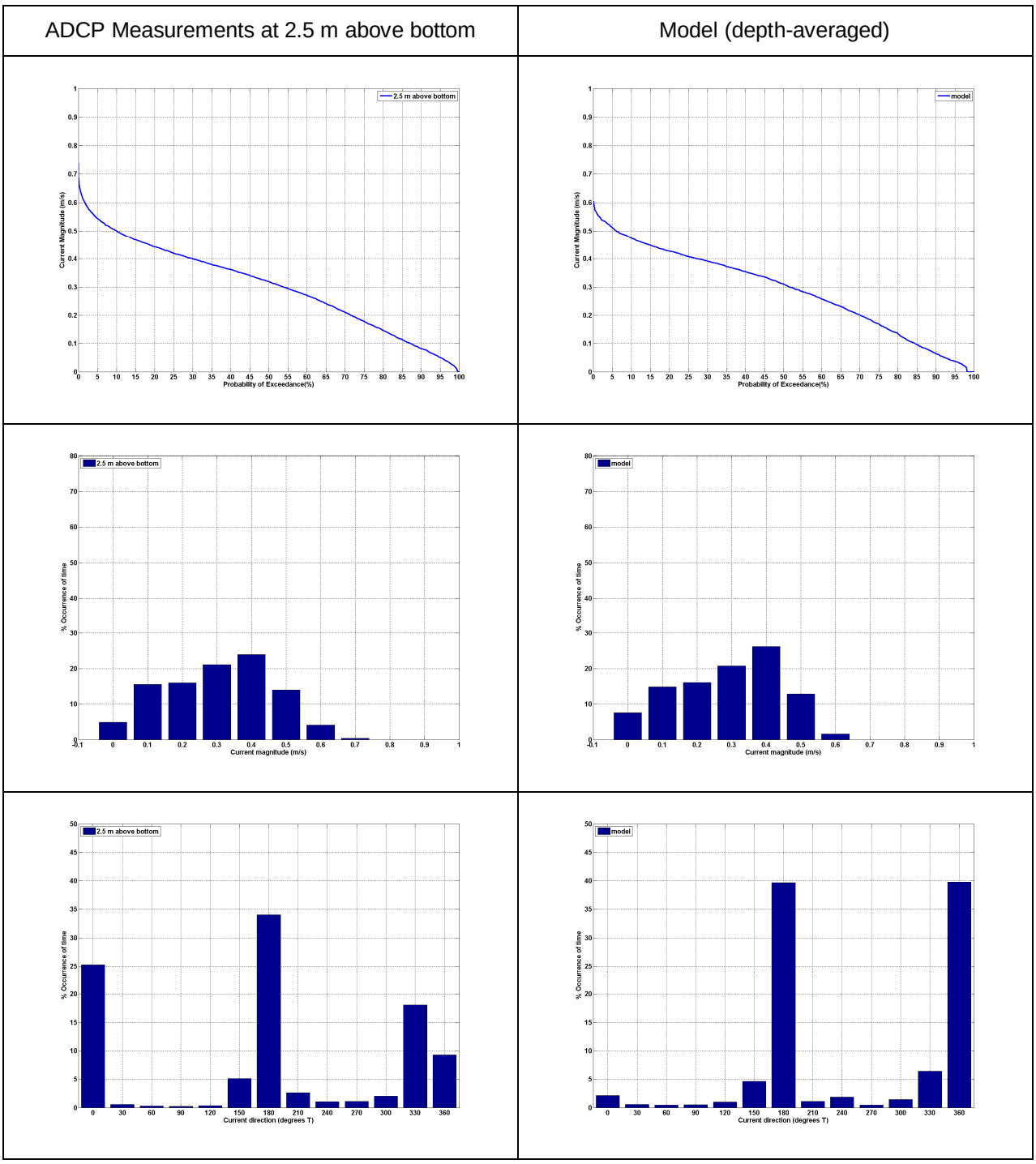

Figure 4-3 Comparison of ADCP records and model results: probability of exceedance of current magnitude (top panel), frequency histogram for current magnitude (middle panel) and frequency histogram for current direction (bottom panel)

4.8 Model Validation

In addition to calibration, the model was subjected to a process of validation which consisted of rerunning the model for a different period of time (from the one adopted during the calibration process) and comparing model results to both predictions and field measurements following the already established procedure. The aim of the validation process was to confirm the predictive capability of the model. This was done by obtaining a second set of predictions and comparing it against a dataset of observations not involved in the calibration process.

The results of the validation process are presented starting with Figure C-21 of Appendix C. 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 0.07 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 (0.06 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 behaviour 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 modelled **water levels** and a time history of the corresponding residuals (measured water levels – modelled water levels), Figure C-25;
- Time histories of measured and modelled (two-dimensional) **current magnitude** at the site of deployment of the ADCP and a time history of the residual (measured current magnitude – modelled current magnitude), Figure C-26;
- Polar plots of measured and modelled currents with the measured currents presented in two ways: (1) as a statistical mean and (2) a 95th percentile graph (Figure C-27);
- Time histories of measured and modelled significant wave heights Hs (m), Figure C-28; and
- Time histories of measured and modelled peak wave periods Tp (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 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 the 27th of August 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.

4.9 Verification to Previous Work

A further assessment of the performance of the model can be made by comparing depth-averaged mean flow patterns from the current model (e.g. for the duration of the 2010 autumn field campaign or monthly) against plots of similar nature obtained from the work of Dr Michael Whitney as reported by Garvine (2003). Despite undertaking the comparison for different periods of time (e.g. autumn of 2010 versus whole of 1993), the results from the current simulation are in good agreement with previously published work (Figure 4-4). This is true both qualitatively and quantitatively. Eddies in both panels of Figure 4-4 are of similar size and form at the same location. Current magnitudes are also very similar and typically of the order of 5 cm/s.

It should be noted, however, that the flow patterns presented in the left panel of Figure 4-4 are driven by tide, wind, freshwater inflow and waves. Those displayed in the right panel of the figure were generated by the University of Delaware and exclude wave effects. Based on this comparison alone, it is concluded that wave effects have only a limited role in the formation of the currents in the area.

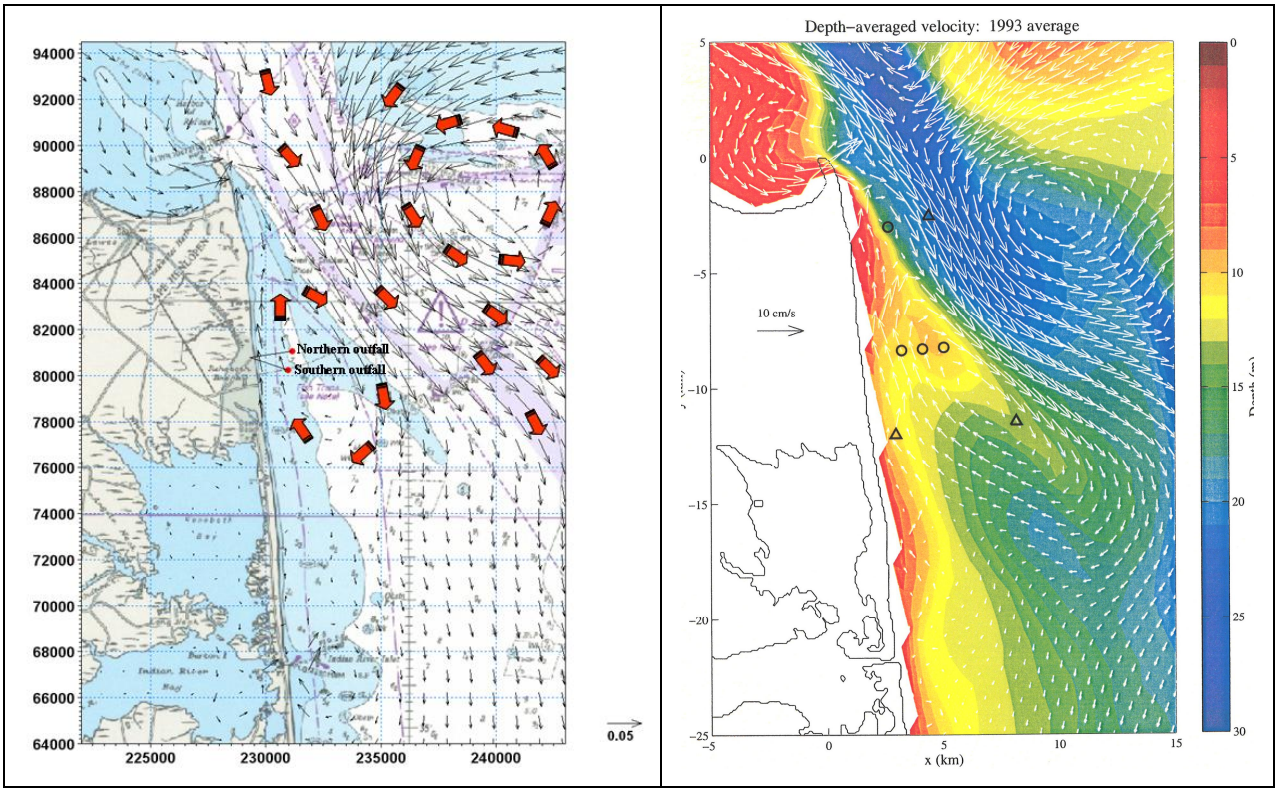

Figure 4-4 Depth-averaged mean flow velocity for the duration of the 2010 autumn field campaign (left) and depth-averaged mean flow velocity for 1993 (right) sourced from the dissertation of Dr. M Whitney (Garvine, 2003).

An interesting observation can be made with respect to the flow patterns presented by Garvine (2003). With reference to Figure 4-5, the mean flow patterns in the right panel, which are the result of tidal action alone, are almost identical to the ones displayed to the left, which are the result of the combined effects of all forces included in the analysis. This similarity indicates that the tide is the key factor in the circulation patterns at the mouth of the estuary.

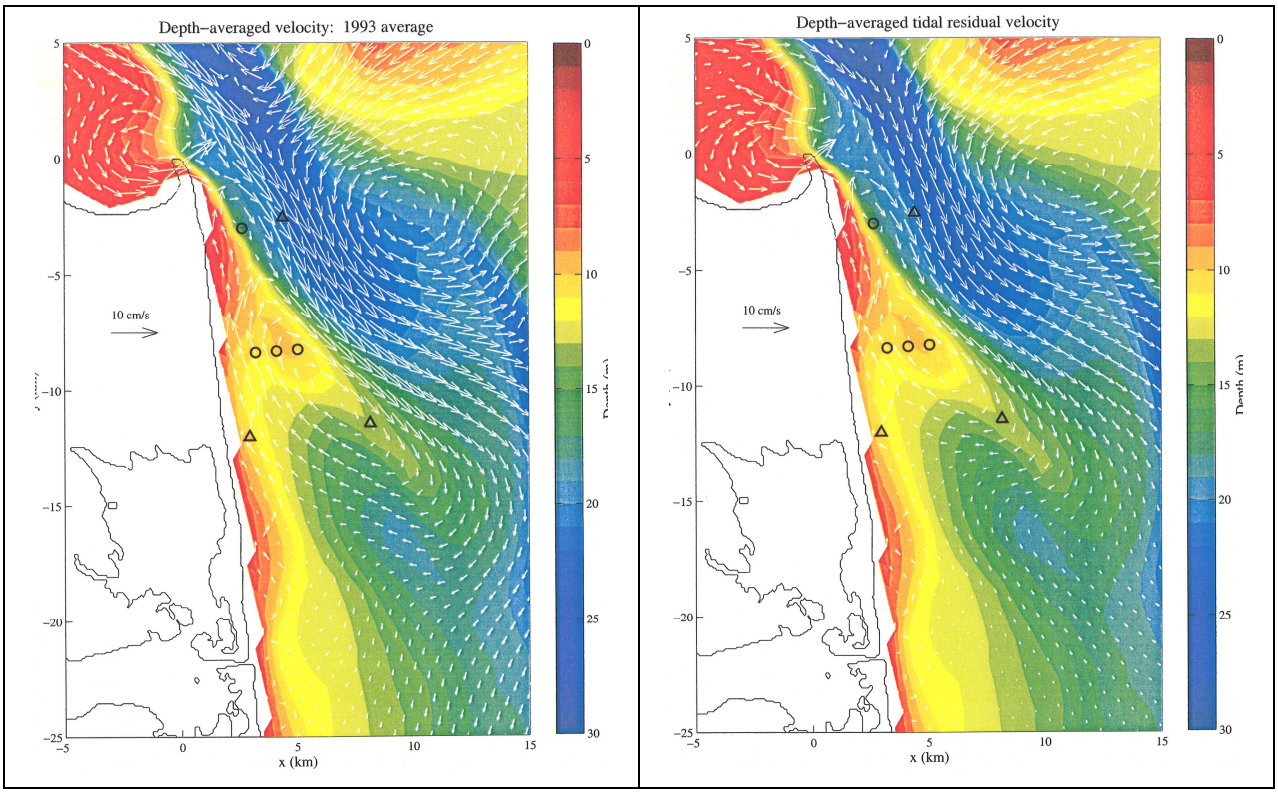

Figure 4-5 Depth-averaged mean flow velocity (left) and depth-averaged mean tidal velocity (right) for 1993 sourced from the dissertation of Dr. M Whitney (Garvine, 2003)

4.10 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 tidal elevation alone, the quality of the obtained solution at the outfall site (as expressed by the level of agreement between tidal predictions and tide-only simulations) is good. Accordingly, tidally-induced mixing processes are expected to be adequately represented in plume dispersion solutions;
- Differences between modelled and measured water levels and current magnitudes observed during the calibration and validation 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 fairly 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 hosting the proposed outfall;
- A 2-D modelling framework is adequate for the project; and
- 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.

5. Far Field Model Results

This chapter presents and discusses the results obtained from the calibrated model described in the previous 4. Two scenarios associated with the operation of the proposed northern and southern outfalls under normal conditions have being assessed over a period of 11 months in two-dimensional mode.

5.1 Scenario Definition

The two long-term far-field scenarios have been investigated with the following common characteristics:

- The proposed discharge of 3.4 MGD (equivalent to 0.1489 m^3/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 kg/m^3;
- The discharge was modelled without interruption for a period of 11 months starting on February 1st, 2010 using flow predictions for the same period provided by the model which was started a month earlier (January 1st 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 this report. The time step for the simulation was 1 second.

Further details of the two scenarios are:

- Southern outfall (38° 43' 19.953" N, 75° 3' 37.854" W) scenario: the discharge was allocated to a mesh cell with an area of 9,150 m^2 (equivalent to a square cell with less than 100 m length) and approximate depth of 10.8 m; and
- Northern outfall (38° 43' 47.220" N, 75° 3' 30.294" W) scenario: the discharge was allocated to a mesh cell with an area of 12,000 m^2 area (equivalent to a square cell with 110 m length) and approximate depth of 12 m;

5.2 Modeling Assumptions

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

- Well-mixed conditions in the Delaware estuary 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 modelled environment as expressed in terms of tidal elevations, circulation patterns and density variation.
- 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 nil.

5.3 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 modelled. This adds conservatism to the adopted modeling approach as concentrations will remain higher if not allowed to decay.
- Buoyancy effects are not represented in the far-field simulations. However, these are taken into consideration in the near-field analysis presented in the next chapter.

5.4 Simulation Results

5.4.1 Presentation

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

- Snapshots or instantaneous plume footprints generated at 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 D);
- Percentile maps of dilution generated using effluent concentration results extracted at 1-hour interval for a period of two and a half months.

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 behaviour is assessed after an initial period of 6.5 months of outfall operation.

One dilution map has been generated for each scenario. The 95th percentile of effluent concentration has been used to generate the maps.

5.4.2 Key Simulation Timeframes

The key simulation timeframes adopted in the analysis are summarised in Table 6.

Table 6 Adopted Timeframes in the Analysis (months)

Hydrodynamic (tide + freshwater inflow + wind + waves) Simulation	Effluent Discharge	95th Percentile Assessment Window
12	11	2.5

5.4.3 Southern Outfall – Instantaneous Plume Footprints

It is noted that very low concentrations of the effluent are plotted 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^3 (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 D capture a sequence of relatively stable states of the plume reaching to the north and south of the proposed outfall.

5.4.4 Southern Outfall – Dilution Map

The dilution map shown in Figure 5-1 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 of any form 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, it could be argued that the 200:1 or 500:1 dilution contours (both enclosing areas that are significantly smaller than the area delimited by the 10,000:1 dilution contour) 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.

Total areas enclosed within the dilution contours are listed in Table 7. As seen from the table, the predicted area enclosed by the 5000:1 dilution contour is as low as 1 ha.

Table 7 Southern Outfall - Total Area within a Given Dilution Contour

Dilution Contour	95% probability area (ha)
10000	6
5000	1

5.4.5 Northern Outfall

For the Northern outfall and with reference to Figure 5-2, 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 Table 8. As seen from the table, the area enclosed by the 5000:1 dilution contour is less than 1 ha.

Table 8 Northern Outfall - Total Area within a Given Dilution Contour

Dilution Contour	95% probability area (ha)
10000	<5
5000	<1

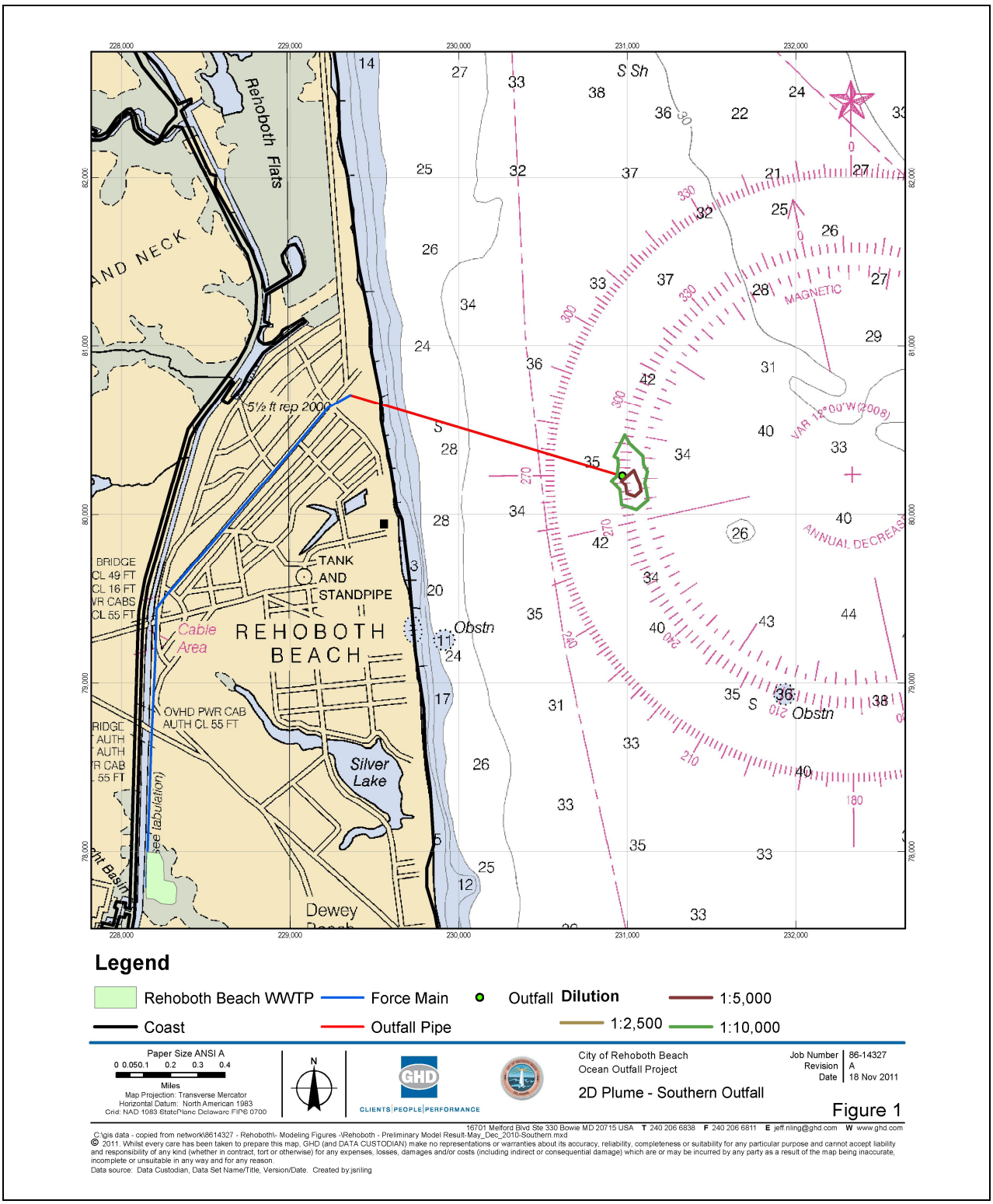

Figure 5-1 Southern Outfall: Contour plot showing the 95th percentile of dilution after 11 month of outfall operation

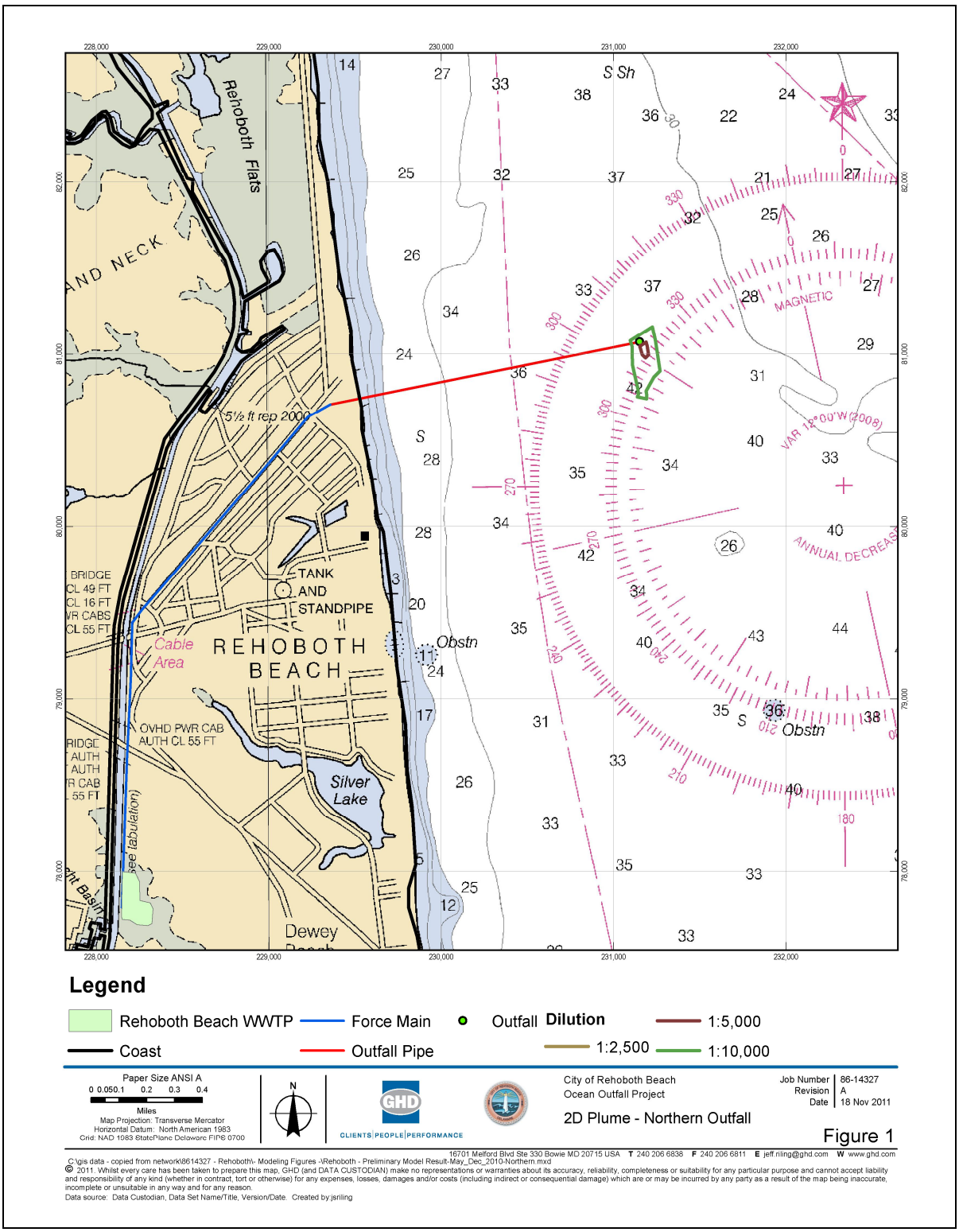

Figure 5-2 Northern Outfall: Contour plot showing the 95th percentile of dilution after 11 month of outfall operation

5.5 Conclusions

Based on the far-field analysis of effluent plume advection and dispersion for both potential outfall locations (north and south) and subject to (1) the discharge characteristics specified in section 5.1, (2) the adopted 2-D modelling frame, (3) year 2010 meteorological conditions and qualifications presented in section 5.3, 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, the choice of outfall site can be based on factors other than hydrodynamics and dilution.

6. Near Field Modeling

6.1 Introduction

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 6-1. Details of the diffuser configuration are presented in Table 9.

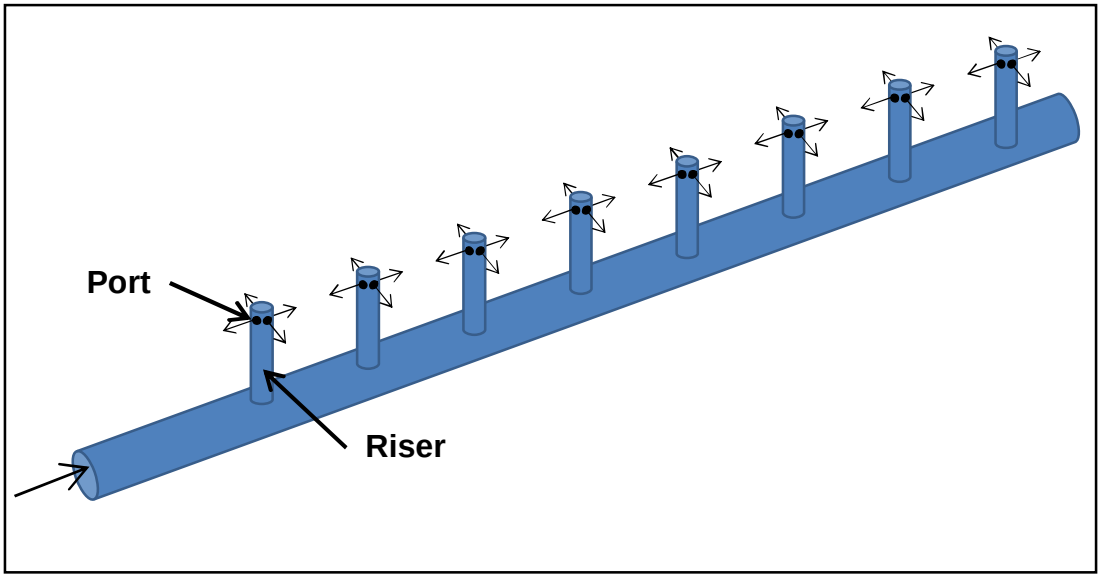

Figure 6-1 Schematic Diagram of Modeled Diffuser

Table 9 Diffuser Configuration as Initially Modeled

Parameter	Value
Diffuser length	120 ft (37 m)
Distance from shore	6,000 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; and
- 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;

6.2 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.

6.3 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.

6.4 Discharge Characteristics

The discharge characteristics utilized in the model are presented in Table 10.

Table 10 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

Notes:

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

6.5 Input Data

The availability of data was addressed in Chapter 3. 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 6-2 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.

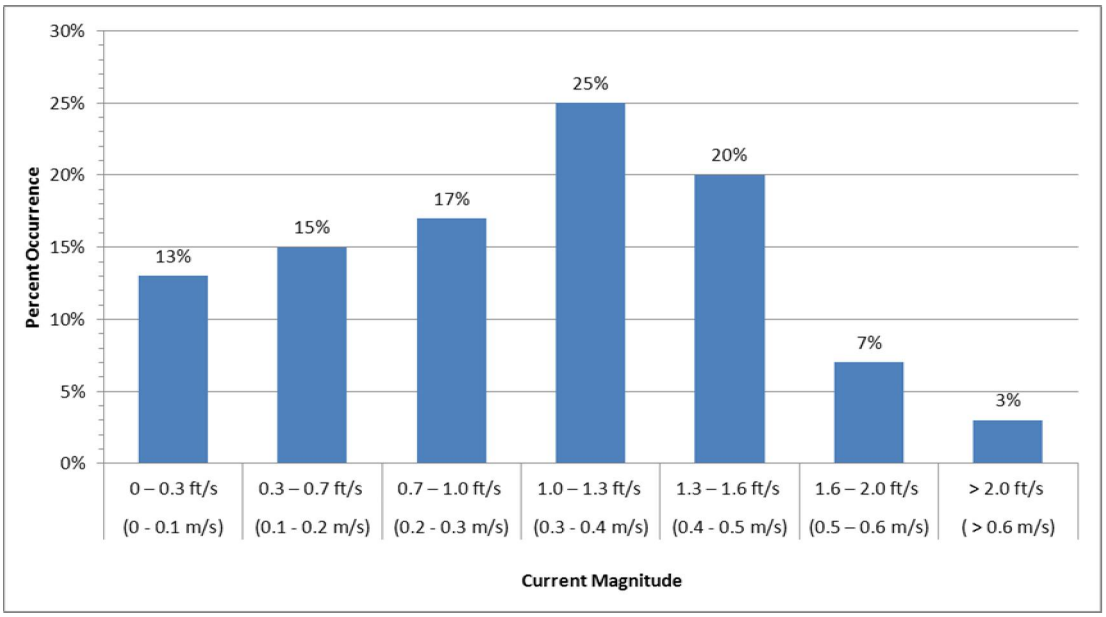

Figure 6-2 Measured Current Magnitude at 8.2 ft (2.5 m) above the seafloor (% Occurrence)

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

6.6 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^3 in November 2010 and January 2011, rising to a fluctuation of approximately 9 kg/m^3 in March. Measurements on March 17, 2011 at Site R17 (see Appendix B) show that the variation between surface and bottom densities was approximately 8 kg/m^3 with 1024 kg/m^3 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^3 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^3 range are expected to be common during the spring and autumn period with peaks reaching in the 6 to 9 kg/m^3 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^3.

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

6.7 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^3.
- Cases 001 to 003 investigate the influence of increasing ambient current. The basis of selection of currents can be seen with reference to Figure 6-2. 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^3. 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^3/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^3 between surface (1016 kg/m^3) and bottom (1024 kg/m^3). 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.

6.8 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 6-3 (Cases 000 – 006) and Figure 6-4 (Cases 007 – 008). Results are also summarized in Table 11.

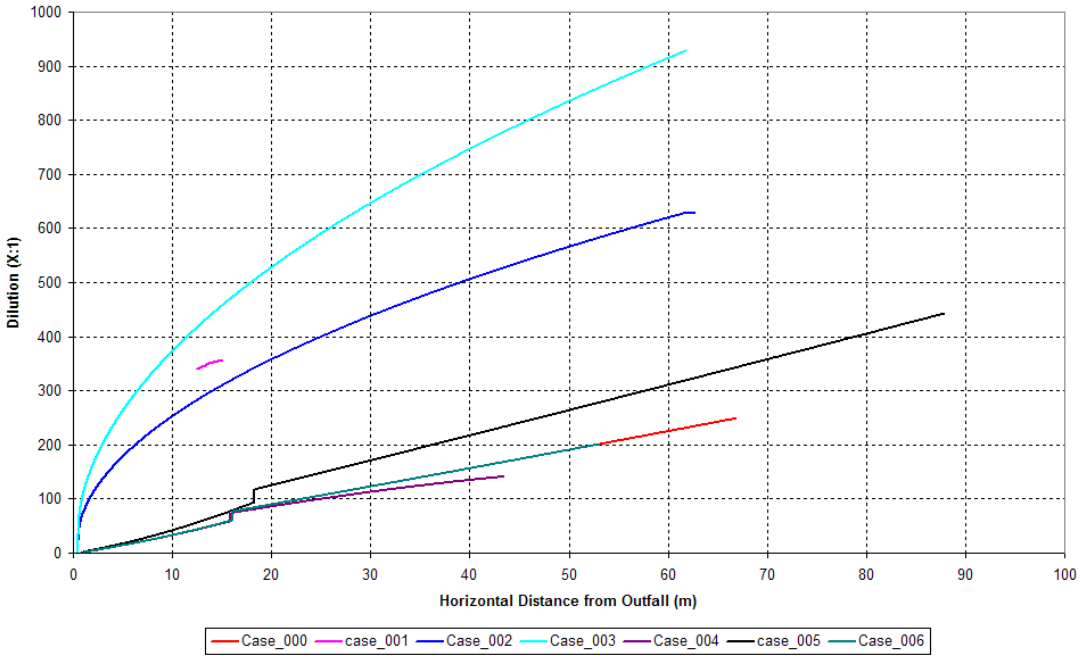

Figure 6-3 Near-Field Dilutions for Simulation Cases 000 to 006

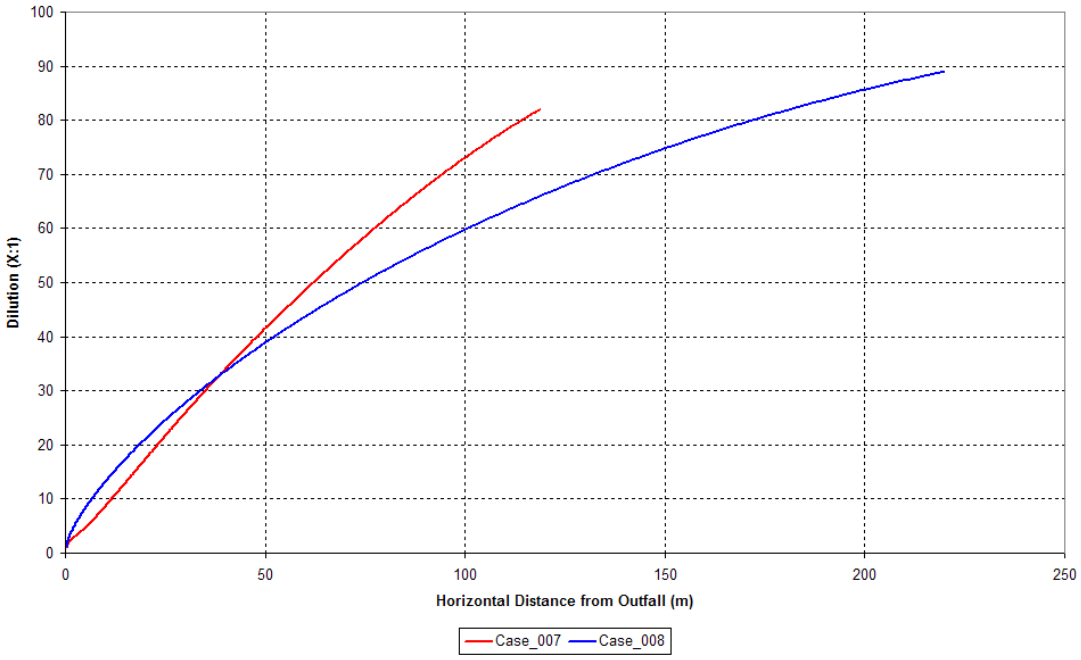

Figure 6-4 Near-Field Dilutions for Simulation cases 007 and 008

Table 11 Dilution Summary

Run Scenario	Distance to end of NFR (m)	Dilution at end of NFR (1:D)	Terminal height of plume above ports (m)
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 6-3 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 Diffuser)

- 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 dilution. 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; and
- 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.

6.9 Conclusions

Near-field dilution performance has been simulated based on a linear diffuser. 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 projected preliminary design is essentially a linear diffuser. 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 un stratified 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^3 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).

6.10 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).

7. Conclusions and Recommendations

7.1 Far Field/Plume Dispersion

Conclusions are offered on the basis of the far-field analysis of effluent plume advection and dispersion for both potential outfall locations (north and south). These are subject to (1) the discharge characteristics specified in section 5.1, (2) the adopted 2-D modelling frame, (3) year 2010 meteorological conditions and qualifications presented in section 5.3. It is observed that for both the north and south location, 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 both proposed outfall sites, total areas enclosed within the 5000:1 dilution contour are as low as 1 ha.

For the 11-month simulation period starting February 1, 2010, the minimum predicted (at 1 hour interval) effluent dilution for the proposed southern outfall was greater than 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 minimum predicted effluent dilution at the proposed northern outfall will be of similar magnitude. Because of the similarity of the results, the choice of outfall site can be based on factors other than hydrodynamics and dilution.

7.2 Near Field/Diffusers

Near-field dilution performance has been simulated based on a linear diffuser. 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 projected preliminary design is essentially a linear diffuser. 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^3 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).

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GHD

201 Charlotte Street Brisbane QLD 4000
GPO Box 668 Brisbane QLD 4001
T: (07) 3316 3000 F: (07) 3316 3333 E: bnemail@ghd.com.au

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