MODELING OF GPA'S OXYGEN INJECTION DEMONSTRATION PROJECT SAVANNAH HARBOR, GEORGIA

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Executive Summary

Tetra Tech, Inc. (Tetra Tech) applied the Savannah Harbor hydrodynamic and water quality models to simulate the fate and transport of dissolved oxygen injection into the Front River. The Georgia Ports Authority (GPA) operated a Demonstration Project that injected approximately 27,000 lbs/day of dissolved oxygen in the harbor at The Industrial Company (TIC) on Hutchinson Island, near Savannah, Georgia. The injection occurred from August 7, 2007 to September 16, 2007 and is described in a separate report by GPA (MACTEC, 2009).

The hydrodynamic (EFDC) and water quality (WASP) models were validated to the 2007 data collected during the Demonstration Project to verify simulation of existing conditions before, during, and after the injection period. The validation was successful by reproducing the tidal salinity dynamics and range of dissolved oxygen during the summer conditions. The original calibration of the EFDC and WASP models was presented in a separate modeling report (Tetra Tech, 2006) and approved by federal and state agencies in March 2006. The Z-grid version of the EFDC and WASP models were used for this analysis. The modeling described in this report for dissolved oxygen injection was divided into the two following efforts: (1) near-field analysis to examine the mixing zone of the injection plume and (2) far-field analysis to determine the overall dissolved oxygen effect in the harbor.

The near-field analysis showed a dynamic dilution ranging from 16 to 85 (average 45) with a plume size of approximately 60 feet in diameter and 16 to 50 feet in length. The dilution is dynamic due to tidal velocities and volumes varying over the tidal cycle, along with the flow and oxygen load rates on the injection. The near-field modeling showed the dissolved oxygen injection was well-mixed within 100 feet from the discharge point. The injection plume had a small mixing zone due to the large tidal velocities in the harbor that readily mixed the oxygen effluent in the harbor. Once the oxygen plume was well-mixed in the horizontal, the vertical stratification/de-stratification of the harbor controlled the longitudinal extent of the dissolved oxygen effect.

The far-field analysis showed an increase (or benefit) in dissolved oxygen concentrations in the surface from 0.12 to 0.18 mg/L and in the bottom from 0.40 to 0.60 mg/L. The median (or 50th percentile) increase in the surface was 0.15 mg/L and the bottom was 0.41 mg/L. The longitudinal extent of the dissolved oxygen increase was on the order of 10 miles in the surface and bottom that was equal or greater than 0.10 mg/L.

In summary, the modeling confirmed the Demonstration Project did have a positive effect on dissolved oxygen concentrations in the harbor. By examining the increase in dissolved oxygen concentrations longitudinally, the oxygen injection has a 0.15 to 0.41 mg/L increase locally and a 0.10 mg/L increase over a 10-mile reach.

1.0 Introduction

Tetra Tech, Inc. (Tetra Tech) was contracted by the Georgia Ports Authority (GPA) to apply the three-dimensional hydrodynamic and water quality models of the Savannah Harbor for the 2007 Demonstration Project. The purpose of the effort was to simulate the effects of the oxygen injection system installed and operated in 2007.

The three-dimensional models include the Environmental Fluid Dynamics Computer Code (EFDC) for hydrodynamics and the Water Quality Analysis Simulation Program (WASP) for water quality. The original application of the models was completed for the Unites States Environmental Protection Agency (EPA) for the Draft TMDL in 2004. Additional funding for enhancing the models was provided by the GPA through the United States Army Corps of Engineers (USACE) Savannah District contract to simulate the effects of deepening the navigation channel for the Savannah Harbor Expansion Project (SHEP). Tetra Tech completed the enhanced models and documented the calibration and verification in a modeling report (Tetra Tech, 2006).

The enhanced hydrodynamic and water quality models were used for assessing environmental impacts of the SHEP. The models were developed in consideration of the following efforts: (1) USACE Savannah Harbor Ecosystem Restoration Project, (2) finalization of the EPA Region 4 Dissolved Oxygen TMDL, and (3) the states of Georgia and South Carolina issuing NPDES permits. Therefore, federal and state agency review of model development and performance were critical to the success of using one model in the Savannah Harbor. In March 2006, Tetra Tech received final acceptance letters from the EPA, Georgia Environmental Protection Division (EPD), South Carolina Department of Health and Environmental Control (DHEC), National Marine Fisheries (NMF), and United States Fish and Wildlife Service (USF&W). The models were used to assess the environmental impacts due to the deepening in the following resource areas: elevated salinity in the river and marsh; lowering of dissolved oxygen in the navigation channel; impact on striped bass, flounder, shad, and shortnose sturgeon habitats; and increased levels of chloride at the City of Savannah's water intake.

Tetra Tech supported the Georgia EPD and EPA Region 4 on water quality modeling to develop a dissolved oxygen standard for the Savannah Harbor. To improve the model's computational efficiency and fidelity of modeling in vicinity of the navigation channel the model was improved by applying hybrid computational grid (Z-grid). The Z-grid EFDC and WASP models were calibrated by EPA Region 4 and ultimately used for the evaluation described in this report to simulate GPA's 2007 Demonstration Project.

The modeling effort described in this report was completed in the following two phases:

- Validation of the model to Summer 2007
- Oxygen injection model runs

The technical approach selected for evaluation of the oxygen injection system in Savannah Harbor used both a near- and far-field simulation. The following tools were used in the analysis:

- the near-field model (Visual PLUMES), which allows evaluating the size of the mixing zone for the oxygen supersaturated water jet from the injection device (Speece cone)
- the far-field model (Z-grid of the EFDC and WASP based), which allows simulating dynamics of hydrodynamic and water quality regimes of the estuary
- the Tetra Tech developed post-processing tool (WAMS), which allows analyzing the far-field model outputs and creating statistics, deltas, visualizations, and other metrics that support evaluation of the estuary responses on oxygen injection and other water management measures.

The models use the 2007 data collection of loads, flows, tides and meteorology. The term "near-field" was adopted to describe the region near the outfall inside the zone of critical initial dilution, and "far-field" was similarly meant to apply to areas possibly impacted beyond this zone.

2.0 Oxygen Injection Demonstration

A new technology that is being considered for improving the dissolved oxygen regime and mitigating impacts due to Savannah Harbor deepening is oxygen injection. The Demonstration Project included two l2-foot diameter Speece cones that pumped water out of the river, supersaturated under pressure in the cone, and discharged back into the river to elevate the dissolved oxygen. During August and September 2007, a Demonstration Project was developed by the GPA and executed by MACTEC to determine if the technology is a viable mitigation option. This effort is described in a separate report (MACTEC, 2009). The 12-foot diameter cones were mounted on a barge at The Industrial Company (TIC) near the Talmadge Bridge and downtown Savannah, GA. The injection point was on a moored barge location at the TIC property on Hutchison Island, the exact injection point from the barge is about 100 feet from the rip-rap shoreline at high tide (shown in Figure 2-1). Figure 2-1 also shows the injection point location with the existing USGS dissolved oxygen monitor.

The depth of dissolved oxygen injection was 30 feet below the water surface (constant-depth injection but moving up and down with the tide). The injection pipe-flow velocity was about 15 feet per second (fps) with the pipe directed toward the center of the river and with an approximate 10-degree downward deflection. The intake water for the oxygen injection system was taken from one end of the barge at a depth of 10 feet (constant-depth intake but moving up and down with the tide). The total injection flow (two cones) was about 16,000 gallons per minute (gpm) and the load is about 27,000 pounds per day (lbs/day). The schematic of the Demonstration Project is shown in Figure 2-2.

Figure 2-1 EFDC and WASP Model Grid with Injection Point

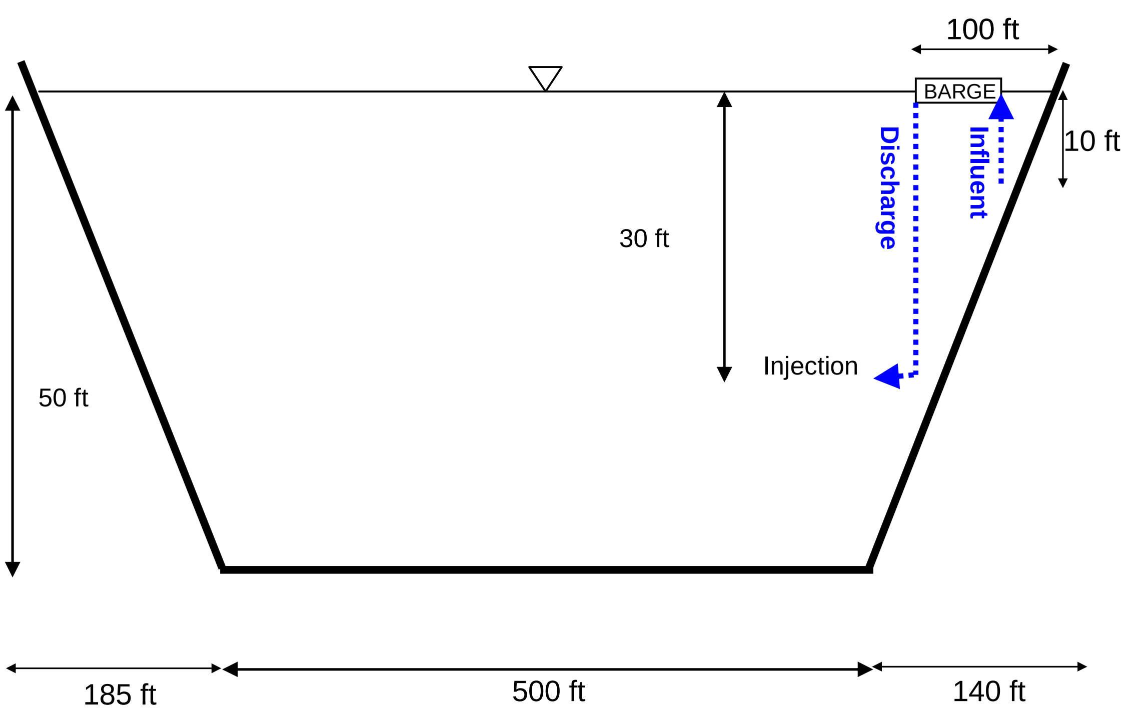

Figure 2-2 Schematic of GPA Dissolved Oxygen Injection Experiment

3.0 Available Data

The modeling simulations were made with actual harbor conditions and dissolved oxygen injections experienced during the Demonstration Project. The model setup uses the summer 2007 measured "forcing" conditions. The hydrodynamic "forcing" conditions include measured tides at the ocean boundary, existing point sources (river and harbor), meteorological conditions, flows at the upstream boundary, and existing bathymetry. The water quality forcing conditions include existing point sources (river and harbor), as well as results of the EPD-Riv1 model simulations that were used as the upstream boundary conditions at Clyo, GA.

The 2007 point source Discharge Monitoring Reports (DMRs) were provided by the Georgia EPD. The simulation period began on June 1, 2007 and ran through the injection period of August 7 through September 16, 2007. The EFDC and WASP models were validated to the following 2007 datasets shown in Figure 3-1: (a) continuous dissolved oxygen data (GPA Sites 1 and 2); (b) the current USGS dissolved oxygen monitor (Site 3); (c) vertical profile stations (1 through 14); and (d) transects (1 through 5) with points A through E.

All data were provided by GPA and MACTEC and the data were added to the Water Resources Database (WRDB) project for Savannah Harbor. Figure 3-2 illustrates some data that were used for the models validation. Figure 3-3 represents the monitored time-series of dissolved oxygen loads that were injected to the estuary during the 2007 Demonstration Project. These data were used for the model setup.

Figure 3-1 EFDC and WASP Model Grid with Summer 2007 Monitoring Stations

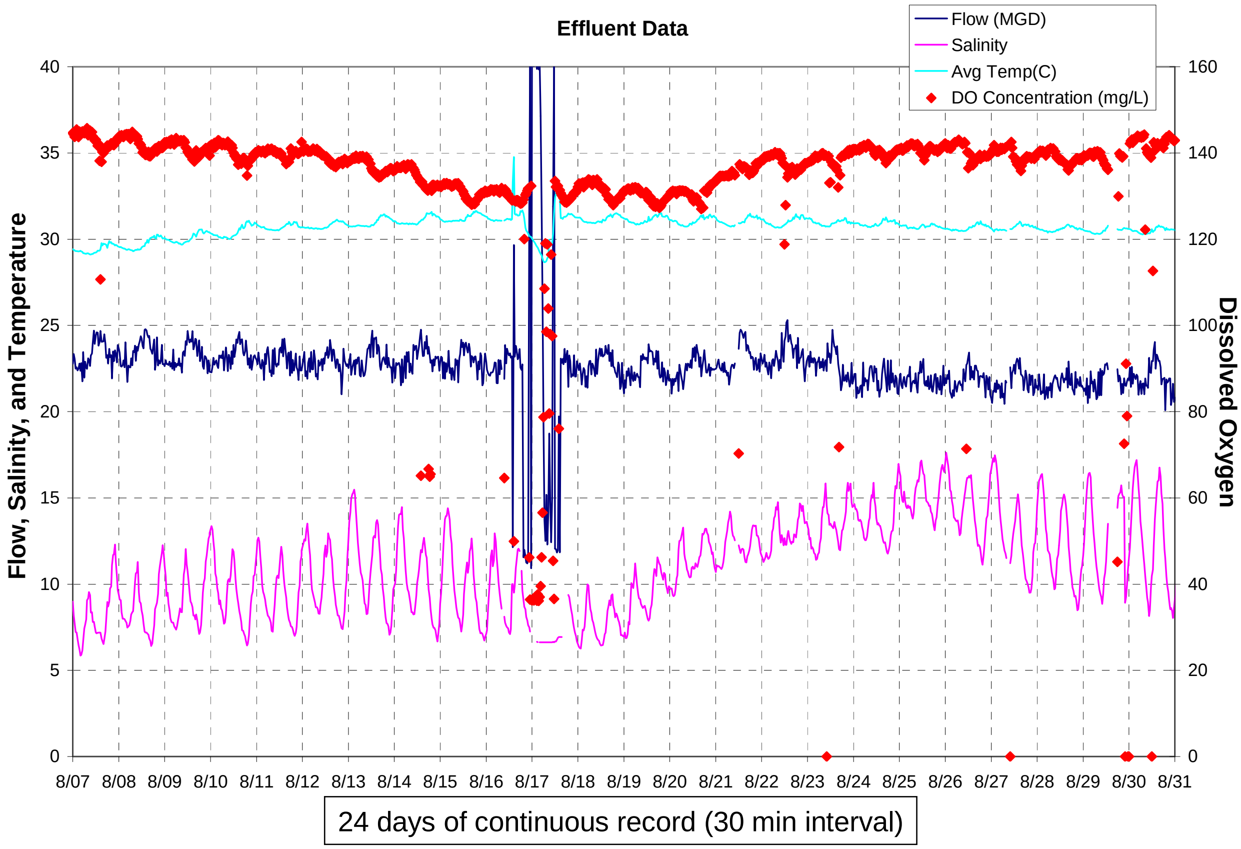

Figure 3-2 Effluent Data Used for EFDC-WASP Validations

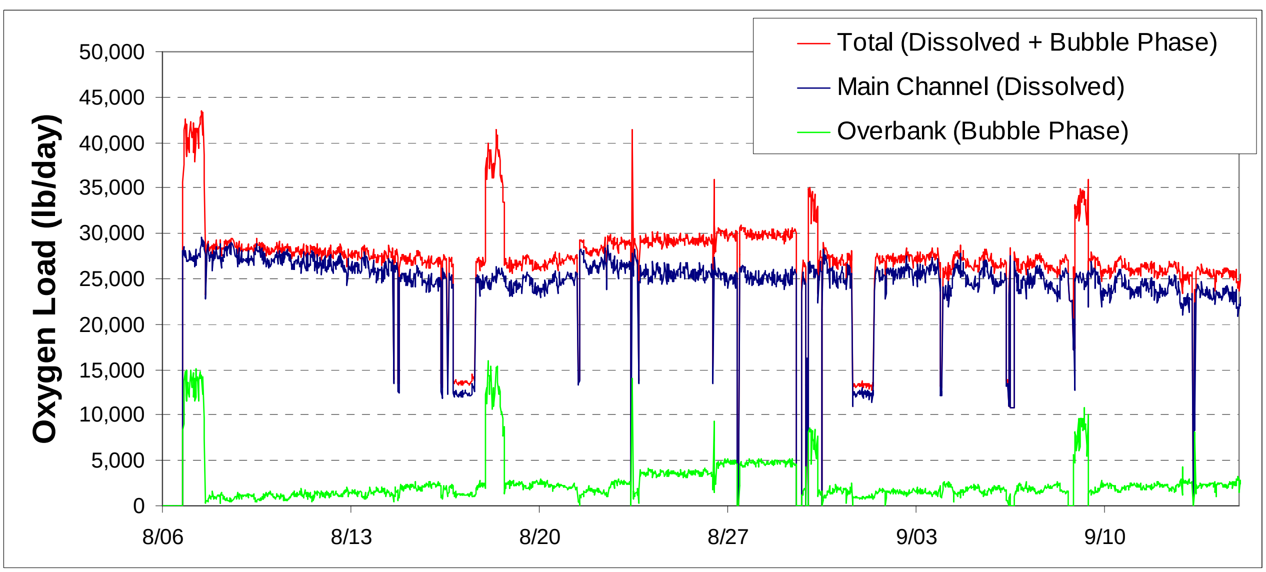

Figure 3-3 Monitoring of Oxygen Loads During the Injection Experiment

4.0 Near-Field Model

In order to predict the near-field plumes dynamics so that accurate estimates of height of rise and fall and initial dilution can be calculated, near-field plume numerical descriptive models have to be used. One of the most widely used choices over the past several years have been Visual Plumes. Visual Plumes (VP) is a family of mixing zone models to simulate surface water jets and plumes for a range of temperature, depth, discharge buoyancy, and ambient velocity conditions.

The VP model is a Windows-based mixing zone modeling application designed to replace the DOS-based PLUMES program (Baumgartner, Frick, and Roberts, 1994). VP was developed by the United States Environmental Protection Agency (USEPA) and supports initial dilution models that simulate single and merging submerged plumes in arbitrarily stratified ambient flow. Predictions include dilution, rise and sink, diameter, and other plume variables. A more detailed description of the VP model is included in Appendix E and can be viewed at http://www.epa.gov/ceampubl/swater/vplume/. There are presently five recommended models in VP: DKHW, NRFIELD/FRFIELD, UM3, PDSW, and DOS PLUMES. For the present work the model UM3 was used. Figure 4-1 shows the output capabilities within the model after running scenarios (typical output).

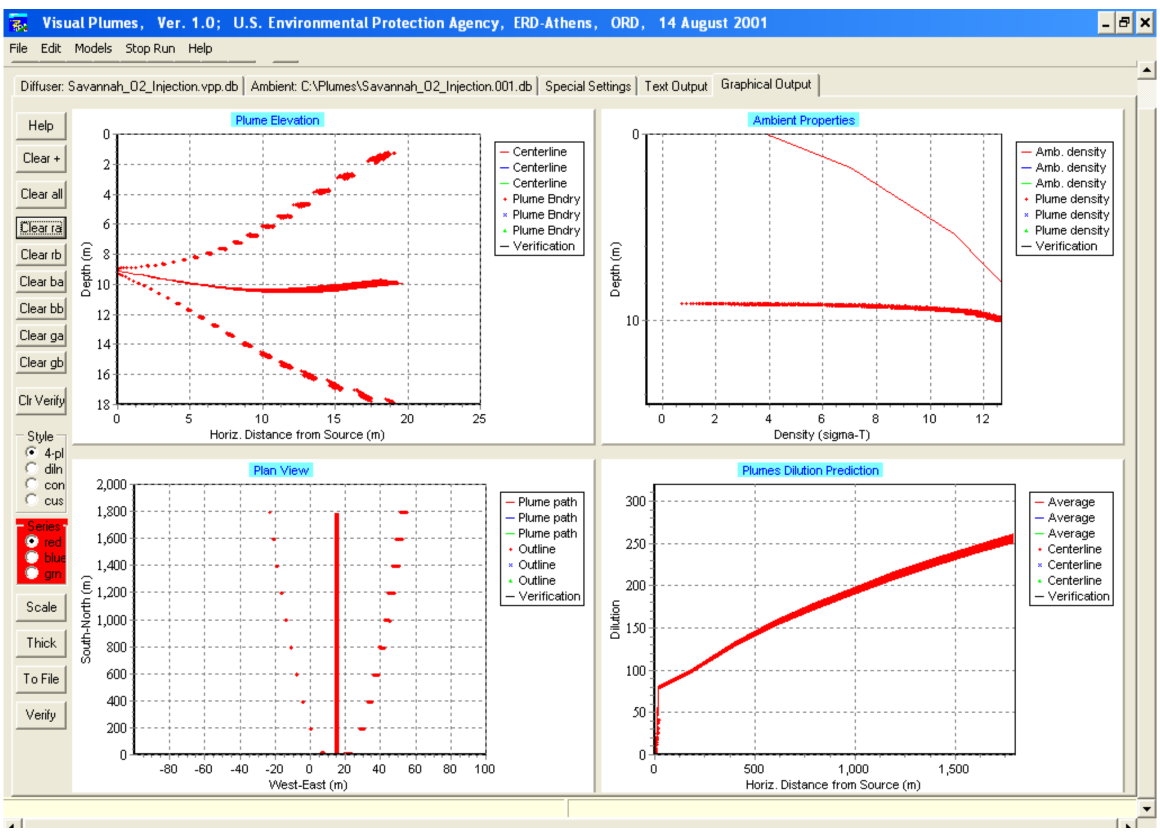

Figure 4-1 Typical Output using Visual Plumes Model

4.1 Plume Model

UM3 is an acronym for the three-dimensional Updated Merge (UM) model for simulating single and multi-port submerged discharges. UM3 is a Lagrangian model that features the projected-area-entrainment (PAE) hypothesis (Winiarski and Frick, 1976; Frick, 1984). This established hypothesis (Rawn, Bowerman, and Brooks, 1960) quantifies forced entrainment, the rate at which mass is incorporated into the plume in the presence of current. In UM3, it is assumed that the plume is in steady state; in the Lagrangian formulation this implies that successive elements follow the same trajectory (Baumgartner et al., 1994). The plume envelope remains invariant while elements moving through it change their shape and position with time. To make UM three-dimensional, the PAE forced entrainment hypothesis has been generalized to include an entrainment term corresponding to the third-dimension: a cross-current term. As a result, single-port plumes are simulated as truly three-dimensional entities. Merged plumes are simulated less rigorously by distributing the cross-current entrainment over all plumes.

The average dilution factor, S_a , used in the EPA model UM is the reciprocal of the volume fraction of effluent, v_e , contained in the diluted plume. An equivalent way of expressing this term is the ratio of effluent volume plus volume of ambient dilution water, v_a , to the effluent volume, as in the following equation:

$$S_a = 1 / (v_e / (v_e + v_a)) = (v_e + v_a) / v_e$$

Thus, in the region immediately outside the discharge orifice the volumetric dilution factor is very nearly 1. In some discussions of this term in other works, the factor is considered to be the ratio of the volume of ambient dilution water, v_a , to the volume of effluent discharged, v_e. In this definition, the volumetric dilution factor approaches zero near the orifice. Above a value of 30, the difference in the two definitions is progressively less than 3 %, an inconsequential amount for most regulatory purposes.

4.2 Near-Field Simulation Results

Tetra Tech used the three-dimensional EFDC Savannah Harbor model (Tetra Tech, 2006) to develop the flow and velocity field under which the simulation was performed. The three-dimensional model was run for the summer of 2007 when the injection test was operated. The ambient river time series of velocity, salinity and temperature were obtained from the EFDC simulation results and shown in Figure 4-2.

Other input information required by the near field model includes the following:

- Physical setup of the discharge
- Physical schematization of the channel cross section at the injection location.

The injection setup is schematized in Figure 4-3, two 18-inch pipes, separated 20-feet discharge at a depth of 30 feet with a downward vertical angle of 10 degrees.

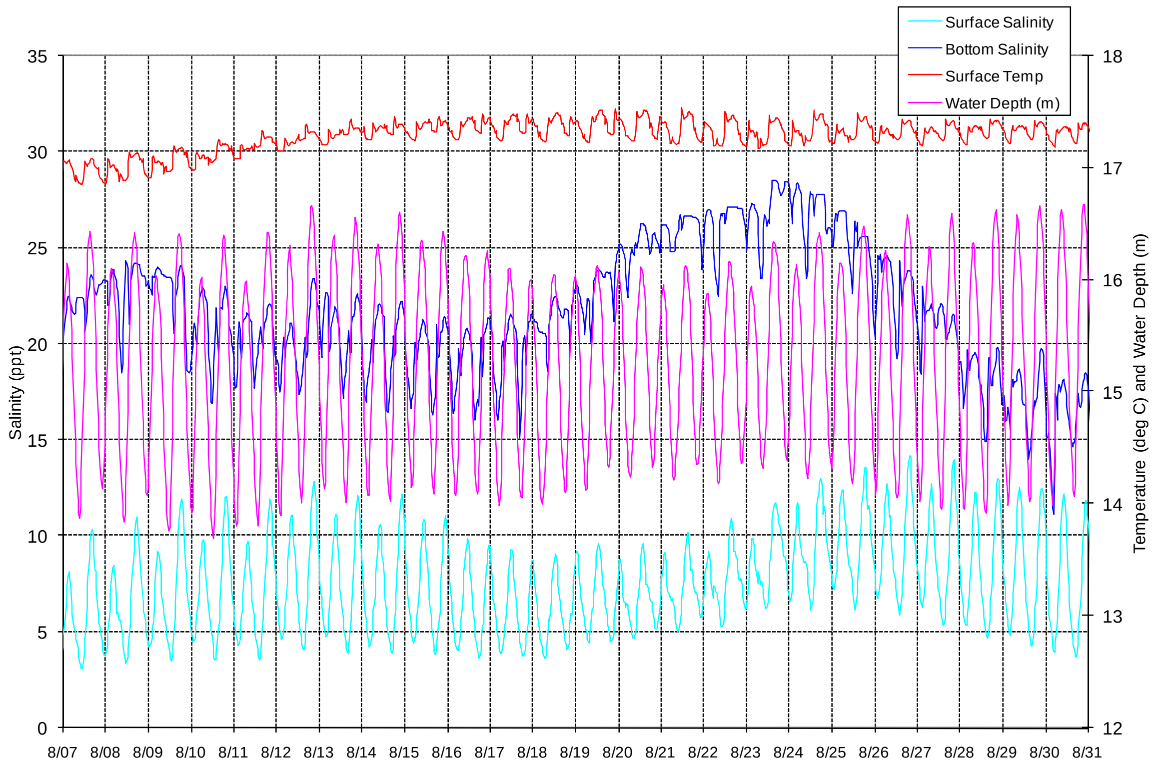

Figure 4-2 Ambient Conditions from the EFDC Model

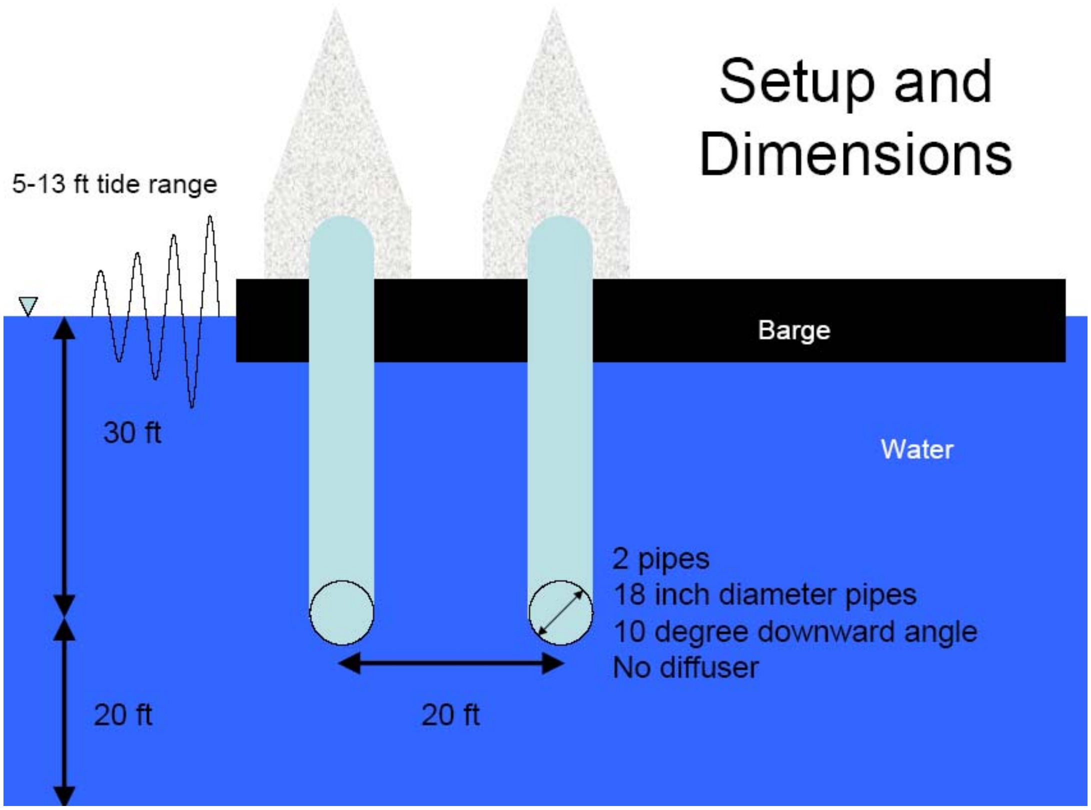

Figure 4-3 Oxygen Demonstration Injection Setup

The injection was performed from a barge located on a side of the river channel. The channel at the injection location was 825 ft wide and 50 ft deep (Figure 2-2). Time series of flow, salinity, temperature and DO for the effluent were also implemented for the near-field model (Figure 4-2).

Figure 4-4 depicts a vertical profile of an instant plume by visualizing the plume in a "vertical-view" 2-D picture. This steady state result was simulated with 15,600 gpm and an effluent concentration of 140.1 mg/L and resulted in a dilution of 67.28. Then, the steady-state model was run in a dynamic model by simulating the time series of ambient river conditions including velocity, salinity, temperature, and dissolved oxygen. The effluent times series conditions included flow, salinity, temperature, and dissolved oxygen. Water depth of the effluent was constant because of the floating barge. Figure 4-5 shows a time series of the dynamic dilution at the edge of the near- field plume based on the dynamic VP model. Figures 4-6 and 4-7 show a close-up window of the dynamic dilution for the periods August 10-13, 2007 and August 20-22, 2007, respectively. Figure 4-8 presents the time series of dissolved oxygen concentrations at the edge of the near-field plume for the simulation period.

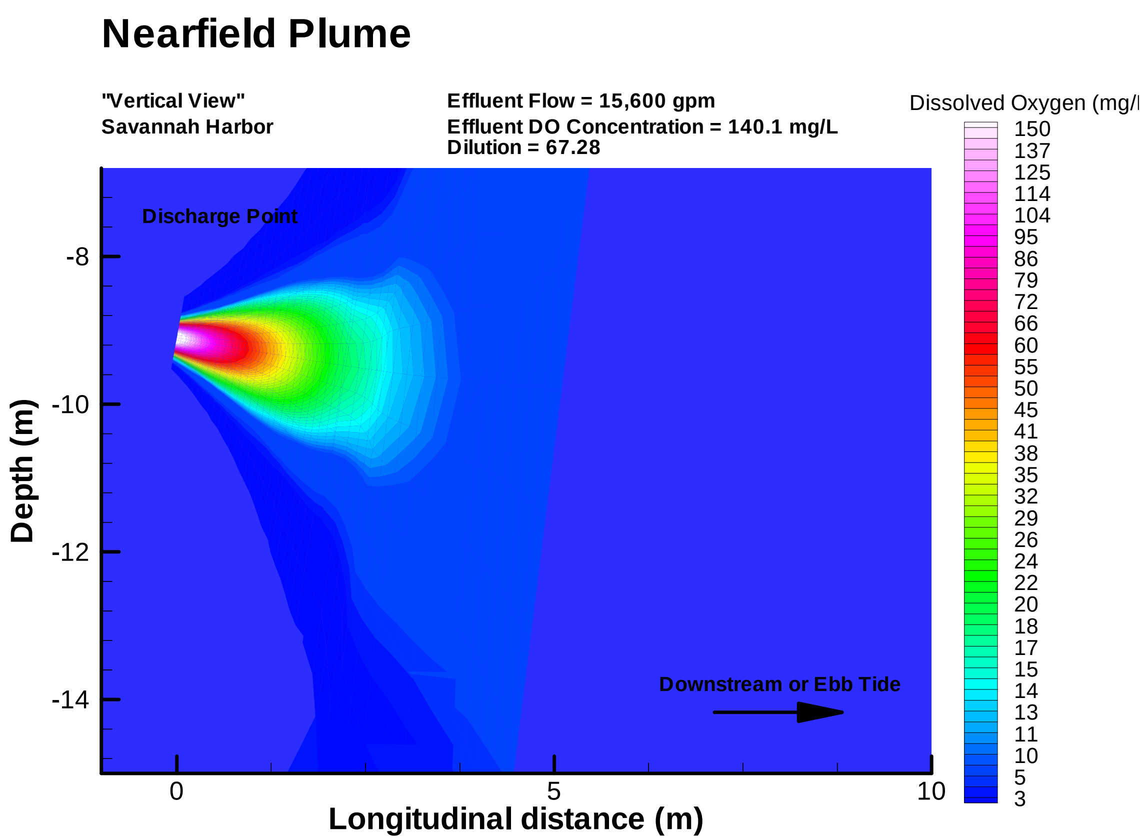

Figure 4-4 Contour Plot of the Near-field plume

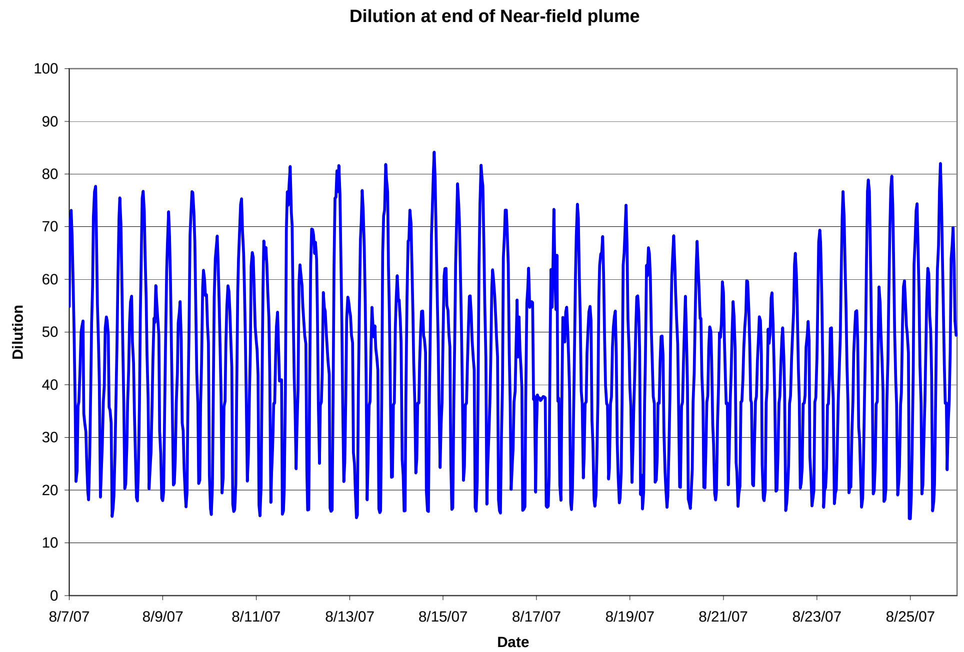

Figure 4-5 Dynamic Dilution at the Edge of the Near-Field Plume from August 7 to August 26, 2007

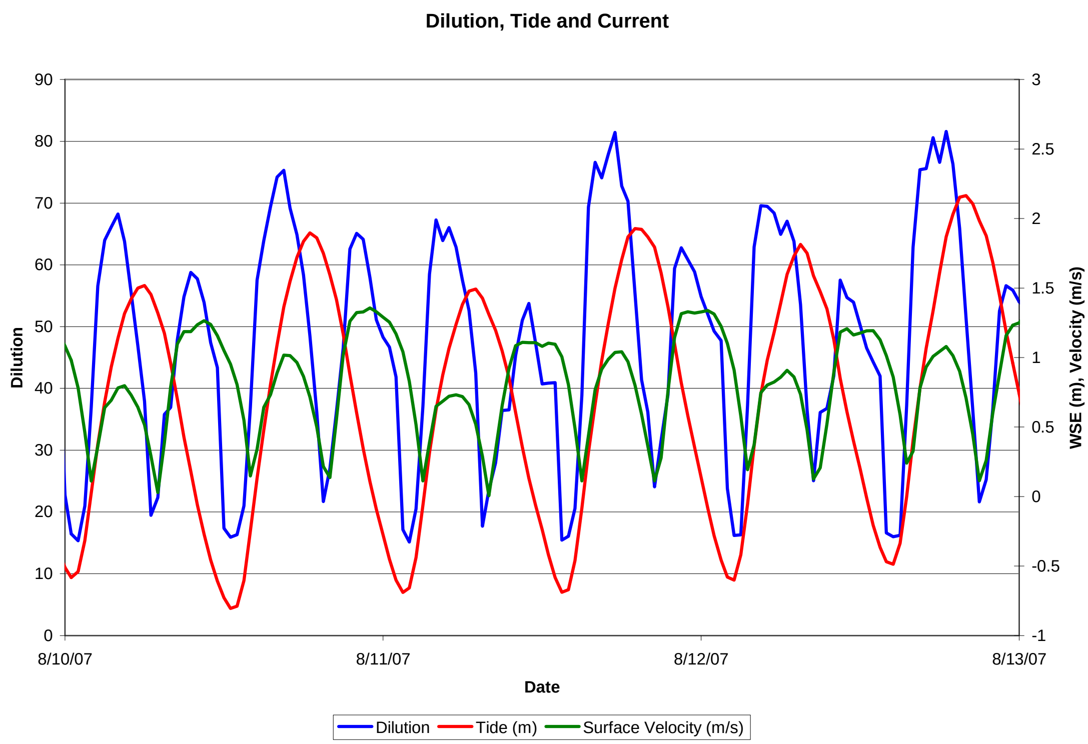

Figure 4-6 Dynamic Dilution at the Edge of the Near-Field Plume from August 10 to August 13, 2007

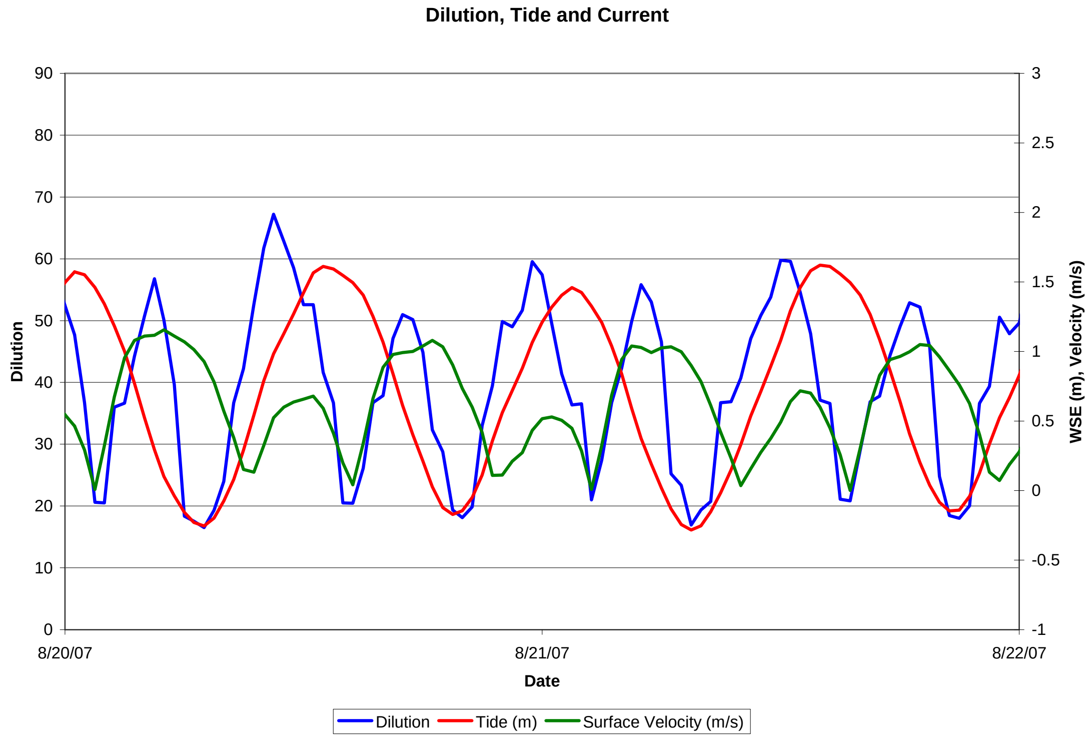

Figure 4-7 Dynamic Dilution at the Edge of the Near-Field Plume from August 20 to August 22, 2007

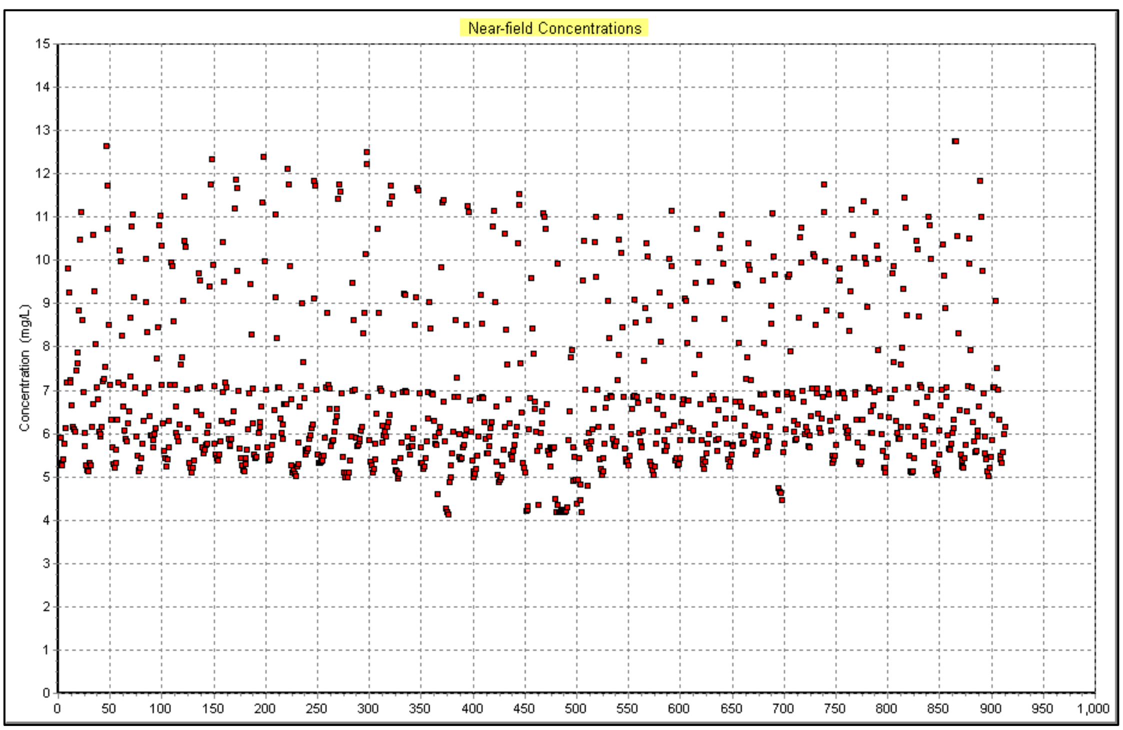

Figure 4-8 Near-field Dissolved Oxygen Concentration

5.0 Far-Field Model

In developing a hydrodynamic and water quality model for the Savannah Harbor, the Environmental Fluid Dynamics Code (EFDC) was selected for the hydrodynamic model. The Water Quality Analysis Simulation Program Version 7.2 (WASP7.2) was used for the water quality model development.

The EFDC model is a part of the USEPA TMDL Modeling Toolbox due to its application in many TMDL-type projects. As such, the code has been peer reviewed and tested and has been freely distributed for public use. EFDC was developed by Dr. John Hamrick and is currently supported by Tetra Tech for USEPA Office of Research and Development (ORD), USEPA Region 4, and USEPA Headquarters. EFDC has proven to capture the complex hydrodynamics in systems similar to that of Savannah Harbor. The EFDC hydrodynamic and sediment transport model linked with the WASP water quality model provides the most appropriate combination of features necessary for this study. The EFDC code is capable of 1, 2, and 3-D spatial resolution. The current version of the code employs a curvilinear-orthogonal horizontal grid and a hybrid vertical grid (Sigma – Cartesian). The EFDC hydrodynamic component employs a semi-implicit, conservative finite volume-finite difference solution scheme for the hydrostatic primitive equations with either two or three-level time stepping (Hamrick, 1992). The EFDC based hydrodynamic model can run independently of a water quality model. For the Savannah Harbor application the EFDC based model simulates the hydrodynamic and constituent (salinity and temperature) transport and then writes a hydrodynamic linkage file for the water quality model (WASP code). This model linkage, from EFDC hydrodynamics to WASP water quality, has been applied for many USEPA Region 4 and GA EPD projects.

WASP is an enhanced Windows version of the USEPA Water Quality Analysis Simulation Program (WASP) and uses the same algorithms to solve water quality problems as those used in the DOS version. WASP is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos. The time-varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the basic program. The water quality model incorporates oxygen dynamics, including: reaeration, sediment oxygen demand (SOD), carbonaceous Biochemical Oxygen Demand (CBOD) and uptake, and Nitrogenous Biochemical Oxygen Demand (NBOD) and uptake. Since there is limited algal activity or primary production in the harbor, EPA Region 4 determined that nutrients were not a significant issue and were not included in the water quality modeling scenarios.

5.1 Calibration

The Savannah Harbor EFDC model was calibrated with graphical time series comparisons (qualitative) and statistical calculations (quantitative) (Tetra Tech, 2006). It included water surface elevation, currents, flow, temperature, and salinity. The calibration period was the summer of 1999 and the confirmation period was the summer of 1997. United States Geological Survey (USGS) long-term data (1997-2003) were also used for confirmation.

The water quality model calibration was performed using the summer 1999 dataset. The WASP based model was run from July 21, 1999 to October 13, 1999 with a 10-day spin up time. The measured values from the data collected during the 1999 summer survey were used for calibration of the WASP based water quality model. Specifically, dissolved oxygen, BOD, and ammonia were used.

The time period for the WASP model validation is from July 5, 1997 through October 13, 1997. In addition to the 1999 summer data collection, the 1997 summer data collection represents the most recent dissolved oxygen and water chemistry data for the system. Model calibration and validation results, as well as the sensitivity analysis for the water quality model, are also presented in the January 2006 report.

5.2 Water Assessment and Management Support Tool – WAMS

Tetra Tech created WAMS–Savannah Estuary (WAMS-SE) as a tool to support GA EPD and USEPA Region 4 water management decisions by statistical and graphical interpretations of results of the estuary water quality modeling. All graphics presented in this report for the far-field modeling results were processed by WAMS–SE.
WAMS is a suite of FORTRAN based modules combined with the Graphical User Interface. Buttons (called “Info”) enable reading of detailed instructions of work with GUI, as well as functionality and outputs of the WAMS modules. The WAMS allows selecting WASP BMD outputs for post processing, analyzing their content and extracting the information to create different statistics and metrics for making quantitatively based assessments and managerial decisions.

The first version of WAMS (so called EFDC-WASP Postprocessor) was developed for the USACE Savannah District to use in analysis of impacts of the Savannah Harbor Expansion Project (SHEP) on salinity and dissolved oxygen regimes, as well as harbor fish habitat. It supplied the necessary information for evaluation of effects of USACE developed mitigation plans and design of the harbor dissolved oxygen improvement system, which is based on Speece cones.

The current version of WAMS (Figure 5-1) was developed based on GA EPD – USEPA Region 4 requirements for the WAMS output. It was also used as a support tool for the harbor dissolved oxygen standards development.

Three options of WAMS- SE were used for the current project. WASP outputs for the injection scenarios were used as baseline BMD files. Subtracted BMD file is the WASP output for the 2007 scenario without oxygen injection. <SHE ANALYSIS> module created the BMD files that snapshot the dissolved oxygen, dissolved oxygen deficit, percent saturation, and salinity 5^{th}, 50^{th} and 95^{th} percentiles distributions in bottom and surface layers of the harbor. <D.O. Analysis> module created the BMD files that snapshot the dissolved oxygen concentration, deficit, and percent saturation longitudinal distributions in surface and bottom layer of the navigation channel. <Subtractor> module created deltas of aforementioned WAMS outputs. The deltas allow assessing effect of supersaturated oxygen injections into the harbor. All figures with the deltas are presented in Appendices A.1, A.2, A.3, B and C.

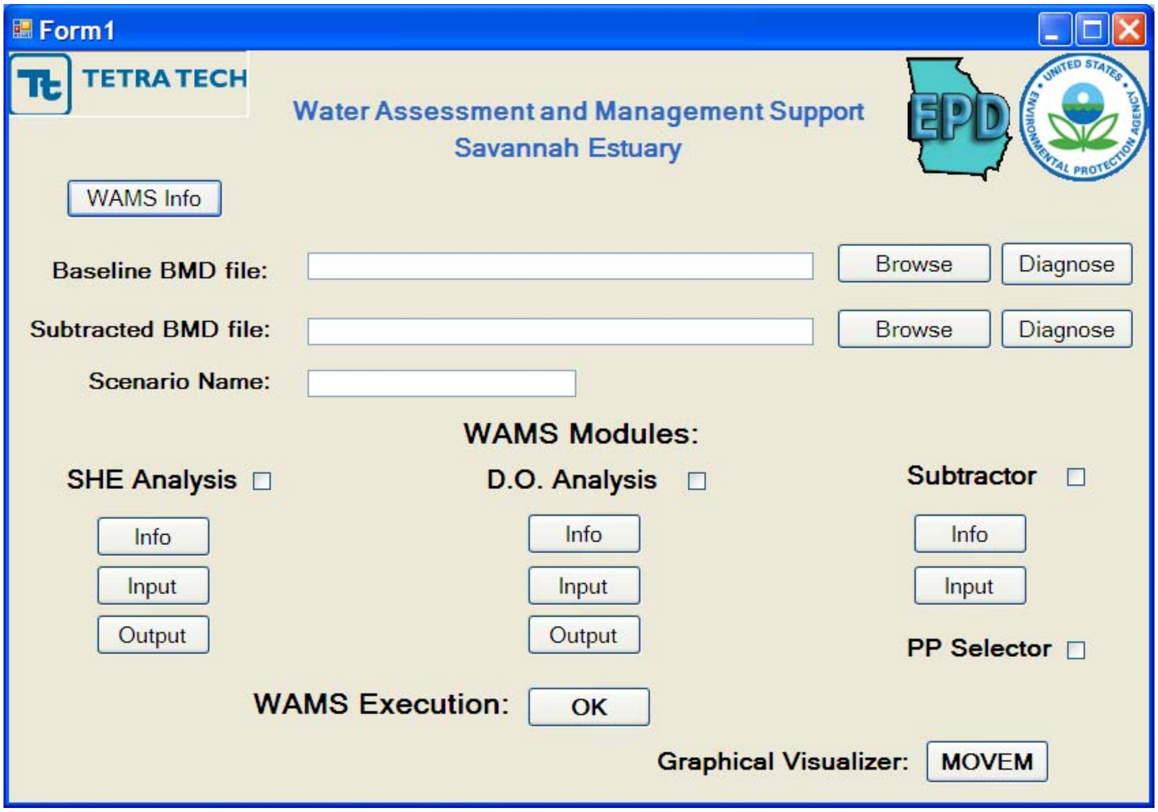

Figure 5-1 GUI of Water Assessment and Management Support (WAMS) Tool

5.3 Validation for 2007 conditions

To use the Savannah hydrodynamic and water quality models for the simulations of the oxygen injection scenarios, the validation tests at 2007 “forcing” conditions need to be passed. The data collected for validation tests were discussed in section “Available Data”.

The water injection setup was previously described in Section 2. The grid cell with Speece cones is presented in Figure 5-2. The distribution of loads between vertical layers at middle channel and overbank is presented in Figure 5-3. This distribution, along with time-series of dissolved oxygen loads (Figure 3-3), was used to calculate the dissolved oxygen injection loads that the water quality model used during validation and assessment runs.

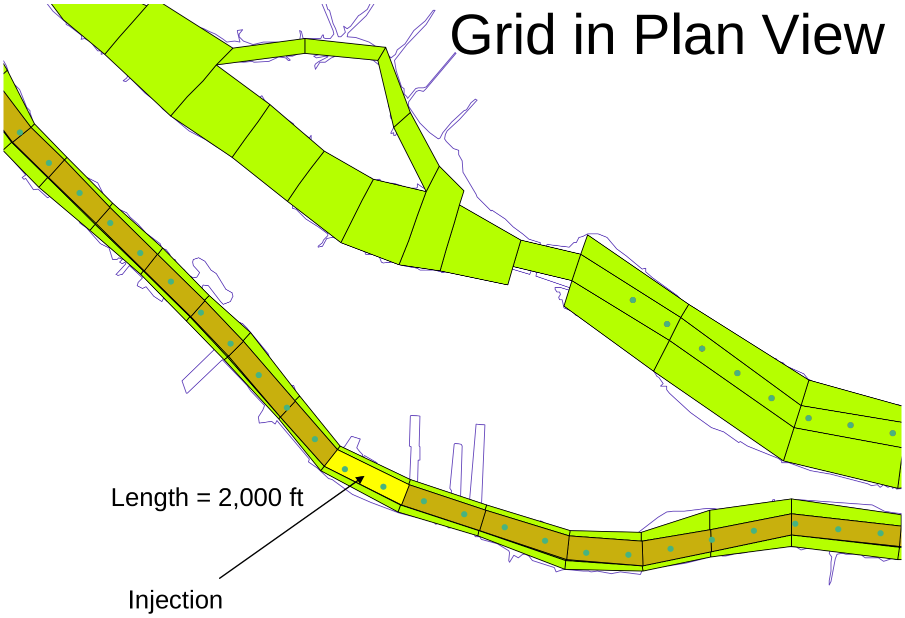

Figure 5-2 Horizontal Location of Cells with Oxygen Injection (darker color represents navigation channel)

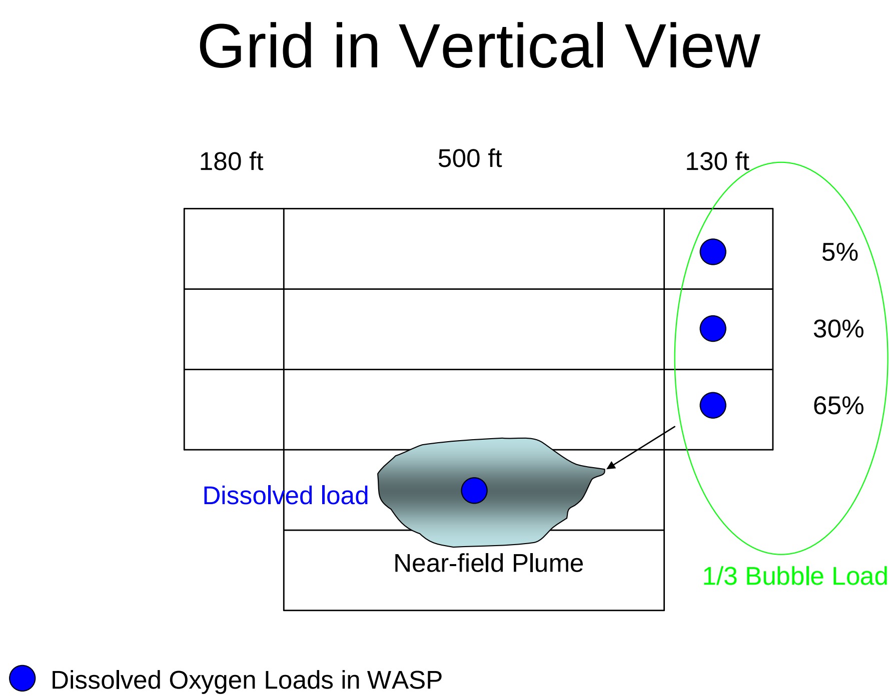

Figure 5-3 Vertical Locations of Cells with Oxygen Injections

Appendix D illustrates visual comparisons of simulation results with the dissolved oxygen monitoring data (Figure 3-2) during the August-September 2007 Demonstration Project.

Figures D-1 through D-8 show the correspondence of dissolved oxygen simulations to continuous data monitored by three stations - GPA, Barge, and USACE Dock monitors – in surface and near-bottom layers of the estuary. Figures D-1 and D-2 illustrate the near-field effects at location of the injection cone. Figures D-3 through D-6 demonstrate the far-field behavior of the model. Dissolved oxygen simulations follow the data general trends and occur within the ranges of data fluctuations.

Figures D-7 and D-8 compare the major range of dissolved oxygen simulations along a mainstream of Savannah River (navigation channel) with data from fourteen vertical profile stations. The range of dissolved oxygen simulated values is limited by 5, 50, and 95 percentiles of dissolved oxygen distributions along the surface and bottom layers of the navigation channel. Surface simulations (Figure D-7) demonstrate a good agreement with the data. Bottom simulations (Figure D-8) show up to 1 mg/L difference with the data. It most likely can be explained by the uncertainty in SOD values assigned to the tested cell.

Table 5-1 illustrates comparison of dissolved oxygen simulations with cross-sectional averages monitored at Transects 1 through 5 with cross-points A-E and 14 recorded times. The time-average relative error for 5 cross-sections changes between 7 and 11 percent. It confirms the acceptable model validation and its ability to supply the information that can be useful for the assessment of the dissolved oxygen Demonstration Project.

Table 5-1 Comparison of Model and Data at Transect Locations

Data	T-1				T-2				T-3				T-4				T-5			
	Time	Meas	Simul	Delta-%	Time	Meas	Simul	Delta-%	Time	Meas	Simul	Delta-%	Time	Meas	Simul	Delta-%	Time	Meas	Simul	Delta-%
3-Jul	9:10	4.16	4.12	1	10:00	4.26	4.13	3	11:10	4.2	4.12	2	12:25	4.25	4.12	3	13:30	4.2	4.3	2
10-Jul	10:55	3.71	3.78	2	12:09	3.56	3.9	9	12:45	3.7	3.9	5	13:26	3.84	3.7	4	13:42	3.86	3.8	2
17-Jul	10:30	3.87	3.4	14	11:00	4.52	3.4	33	11:40	3.84	3.4	13	12:30	3.9	3.5	11	12:45	3.85	3.6	7
24-Jul	11:20	3.86	3.78	2	12:25	3.94	4	2	12:40	3.85	3.8	1	13:25	4	3.9	3	14:05	3.94	3.8	4
2-Aug	12:00	3.61	3.3	9	13:00	3.65	3.4	7	13:30	3.59	3.4	6	14:15	3.68	3.5	5	15:25	3.58	3.6	1
7-Aug	9:25	3.35	4	16	9:50	3.5	4.2	17	10:25	3.4	4.2	19	11:05	3.5	4.1	15	11:35	3.5	4.1	15
10-Aug	12:25	3.2	4.1	22	13:25	3.6	4.1	12	14:25	3.2	4.1	22	15:25	3.3	3.9	15	16:25	3.3	3.8	13
13-Aug	8:30	3.9	3.6	8	9:20	3.8	3.7	3	10:07	4	3.7	8	10:30	3.8	3.7	3	11:00	3.8	3.7	3
21-Aug	9:05	3.8	4.3	12	9:40	3.9	4.4	11	10:05	3.9	4.5	13	10:40	3.8	4.5	16	11:05	3.8	4.3	12
28-Aug	8:00	3.5	3.3	6	8:30	3.5	3.3	6	9:00	3.7	3.4	9	9:20	3.6	3.4	6	10:20	3.5	3.3	6
5-Sep	10:10	3.7	3.7	0	11:10	4.1	3.9	5	11:20	3.8	3.8	0	12:20	4.1	3.9	5	12:30	4	3.9	3
11-Sep	8:40	4.3	3.7	16	9:15	4.4	3.8	16	9:35	4.4	3.8	16	10:00	4.3	3.8	13	11:00	4.2	3.9	8
18-Sep	12:00	4.6	3.6	28	13:00	4.6	3.7	24	14:00	4.5	3.7	22	14:45	4.6	3.6	28	15:15	4.6	3.7	24
24-Sep	11:45	3.9	3.7	5	12:25	4.1	3.7	11	12:45	3.8	3.8	0	13:10	3.8	3.9	3	13:50	3.9	3.9	0
Time-Average		3.8	3.7	10		4.0	3.8	11		3.8	3.8	10		3.9	3.8	9		3.9	3.8	7

5.4 Effect of Oxygen Injection Demonstration Project

Tetra Tech used the following three parameters to measure the effect of the oxygen injection: dissolved oxygen, dissolved oxygen deficit, and percent saturation. WAMS was applied for calculations of 95th, 50th, and 5th percentiles of these parameters. 95th and 5th percentiles define the higher and lower boundaries of dissolved oxygen and percent saturation in cells of surface and bottom area; 50th percentile allows evaluation of median values. Conversely, the 95th and 5th percentiles of dissolved oxygen deficit define the lower and higher boundaries of dissolved oxygen concentrations in the estuary.

To evaluate effectiveness of the Demonstration Project, the delta approach was applied to compare model results. The delta is calculated by the difference between dissolved oxygen simulated under the Injection and No Injection scenarios.

The detailed information about Deltas distribution is presented in following Appendices:

- A.1 – snapshots of 95th, 50th, and 5th percentiles of the delta dissolved oxygen in bottom and surface layers of the estuary
- A.2 – snapshots of 95th, 50th, and 5th percentiles of the delta dissolved oxygen deficit in bottom and surface layers of the estuary
- A.3 – snapshots of 95th, 50th, and 5th percentiles of the delta percent saturation in bottom and surface layers of the estuary
- B – snapshots of 95th, 50th, and 5th percentiles in bottom and surface layers of the navigation channel for deltas - dissolved oxygen, dissolved oxygen deficit, and percent saturation

Appendices A.1 through A.3 allow evaluating deltas for three dissolved oxygen parameters in each cell of the bottom and surface areas of the grid, as well as delineate areas of the injection influence. Roughly the influenced area is spaced between Tide Gate (Back River) and confluences of Savannah and Middle Rivers, and Savannah and Back Rivers.

Appendix B contains graphs of deltas of three dissolved oxygen characteristics for the targeted area of Savannah River navigation channel. The distributions of dissolved oxygen deltas for surface and bottom layers are represented by Figures 5-4 and 5-5. The maximum deltas for 50th percentile of dissolved oxygen concentrations are: 0.15 mg/L in surface layer and 0.41 mg/L in the bottom layer. These deltas can serve as rough estimates of the maximal effect of the Demonstration Project. Appendix B figures show deltas calculated for 95th, 50th and 5th percentiles distributions for all analyzed dissolved oxygen metrics. The locations of delta maximum along the navigation channel are slightly different for surface and bottom layer. It is shifted downstream from the injection site for surface layer, and upstream for the bottom layer. The cause of the phenomena is the specifics of the longitudinal velocity vertical profiles. The profile reflects the summation of average tidal and freshwater flows in surface layer and intrusions of sea waters in bottom layer.

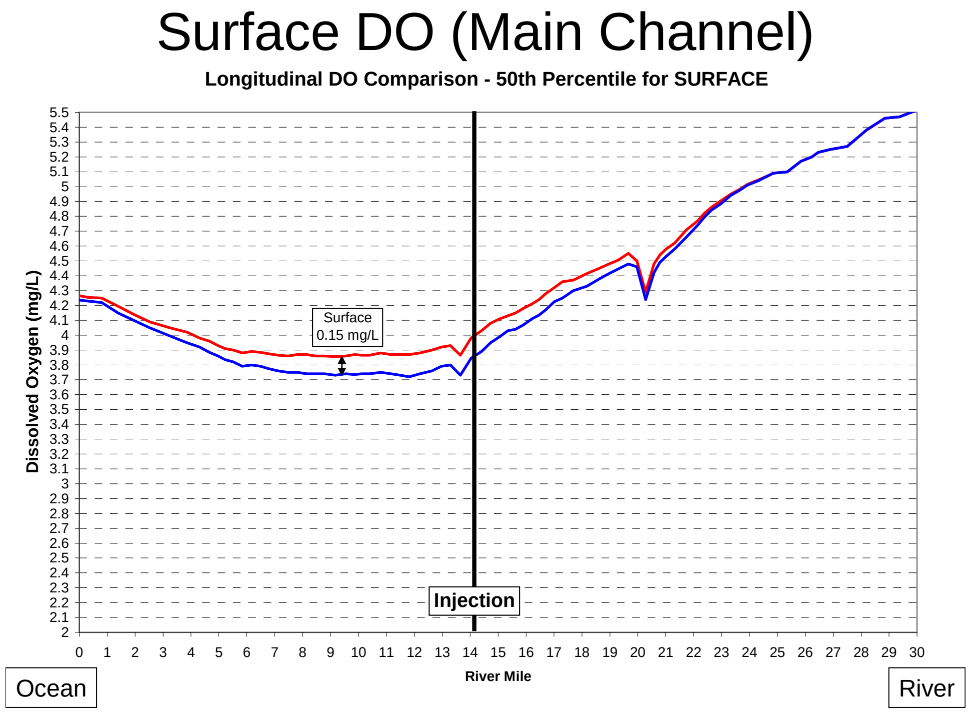

Figure 5-4 Surface Dissolved Oxygen (50th Percentile) Longitudinal Distribution for Injection and No Injection Scenarios

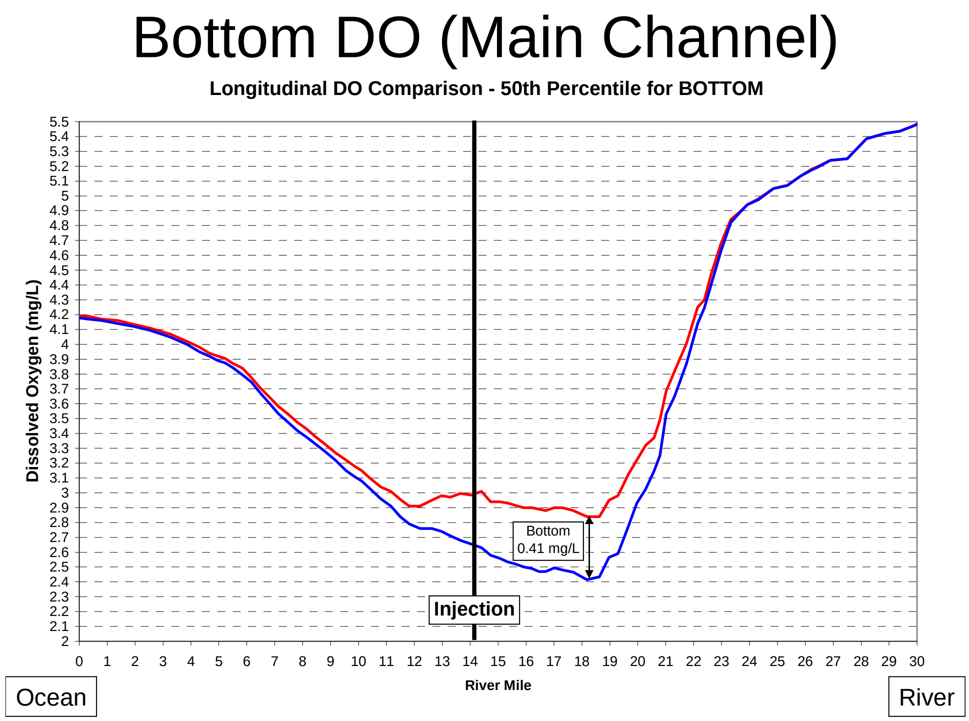

Figure 5-5 Bottom Dissolved Oxygen (50th Percentile) Longitudinal Distribution for Injection and No Injection Scenarios

5.5 Impact of Oxygen Transfer Efficiency

The model was used to determine the oxygen transfer efficiency. The model was used to run several different oxygen transfer efficiencies from 50 to 90 percent to simulate the transfer of oxygen into the water column.

Three scenarios were selected for oxygen transfer efficiency evaluation: 50%, 70% and 90% decrease in oxygen loading from the data measured during the Demonstration Project. The results of the simulation runs are presented in Appendix C in Figures of 5th, 50th, and 95th percentiles distributions of dissolved oxygen and percent saturation in surface and bottom layers of the navigation channel for aforementioned injection scenarios.

Model simulations show that decreasing the oxygen transfer efficiency by 20% (80% efficiency) lowers the calculated dissolved oxygen concentrations by 0.08 to 0.10 mg/L in the bottom layer (extension zone is about 4 river miles) and 0.03 to 0.02 mg/L in the surface layer (extension zone is about 10 river miles).

6.0 Results

A new technology that is being considered for improving the dissolved oxygen and mitigating impacts of the SHEP is oxygen injection. Tetra Tech applied the EFDC and WASP models to simulate the effect of the Demonstration Project operated by GPA and MACTEC during August and September 2007 to discharge approximately 27,000 lbs/day in the harbor at TIC. Data that were collected to measure the overall effect were used to validate the models for the 2007 period and ultimately prove the model is defensible for simulation the Inject and No Injection scenarios.

The models were validated to the 2007 data collected during the Demonstration Project to verify simulation of existing conditions before, during, and after the injection period. The validation was successful be reproducing the tidal salinity dynamics and range of dissolved oxygen. The calibration is presented in a modeling report (Tetra Tech, 2006) and was approved by federal and state agencies in March 2006. The modeling for this effort was divided into the two following efforts: (1) near-field analysis to examine the mixing zone of the inject plume and (2) far-field analysis to determine the overall dissolved oxygen increase in the harbor.

The near-field analysis showed a dynamic dilution from 16 to 85 (average 45) with a plume size on average of 60 feet in diameter and 16 to 50 feet in length. The dilution is dynamic due to tidal velocities and volumes varying over the tidal cycle. The near-field modeling showed the dissolved oxygen injection was well-mixed within 100 feet from the discharge point. The injection plume had a small mixing zone due to the large tidal velocities in the harbor that readily mixed the oxygen effluent in the harbor. Once the oxygen plume was well-mixed in the horizontal, the vertical stratification/de-stratification of the harbor controlled the longitudinal extent of the dissolved oxygen effect.

The far-field analysis showed an increase in dissolved oxygen in the surface of 0.12 to 0.18 mg/L and in the bottom of 0.40 to 0.60 mg/L. The median (or 50^{th} percentile) in the surface was 0.15 mg/L and the bottom was 0.41 mg/L. The longitudinal extent of the dissolved oxygen increase was on the order of 10 miles in the surface and bottom that was equal or greater than 0.1 mg/L. Therefore, the conclusions of the modeling demonstrated there is an increase in dissolved oxygen concentrations in the harbor area of at least 0.1 mg/L over a 10-mile reach. In summary, the far-field modeling clearly shows a positive effect (or increase) of adding oxygen to the Savannah Harbor.

The locations of delta maximums along the navigation channel are slightly different for surface and bottom layer. It is shifted downstream for the surface layer and upstream for the bottom layer. The cause of the phenomena is the specifics of the longitudinal velocity vertical profiles and the profile reflects the summation of average tidal and freshwater flows in surface layer and salinity intrusion in the bottom. This effect “traps” the bottom waters from mixing with the surface waters. Without oxygen injection, the stratification results in lower dissolved oxygen concentrations in the bottom waters. With oxygen injection in the bottom of the navigation channel, the stratification results in higher dissolved oxygen deltas in the bottom waters compared to that of the surface waters.

7.0 References

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Appendix A.1

Dissolved Oxygen Delta Distributions In Savannah Harbor

August-September 2007

Delta = Injection – Existing Scenarios

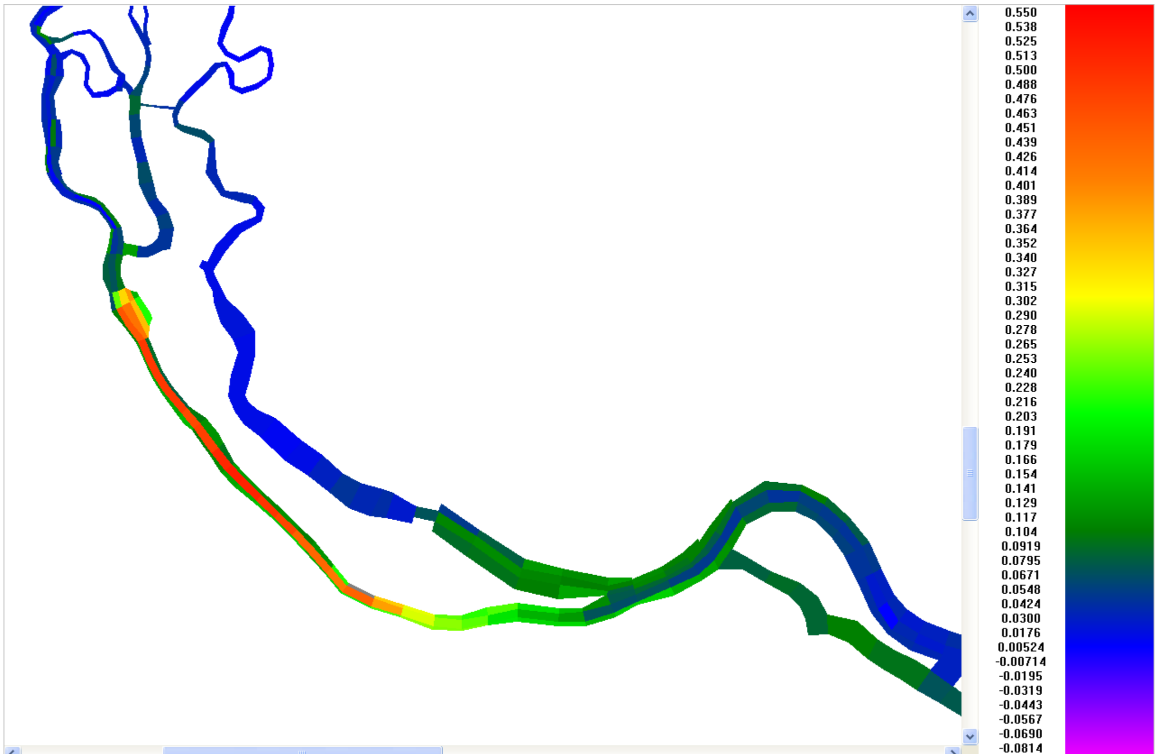

Figure A.1-1 95th percentile of dissolved oxygen delta distribution in bottom layer of the harbor

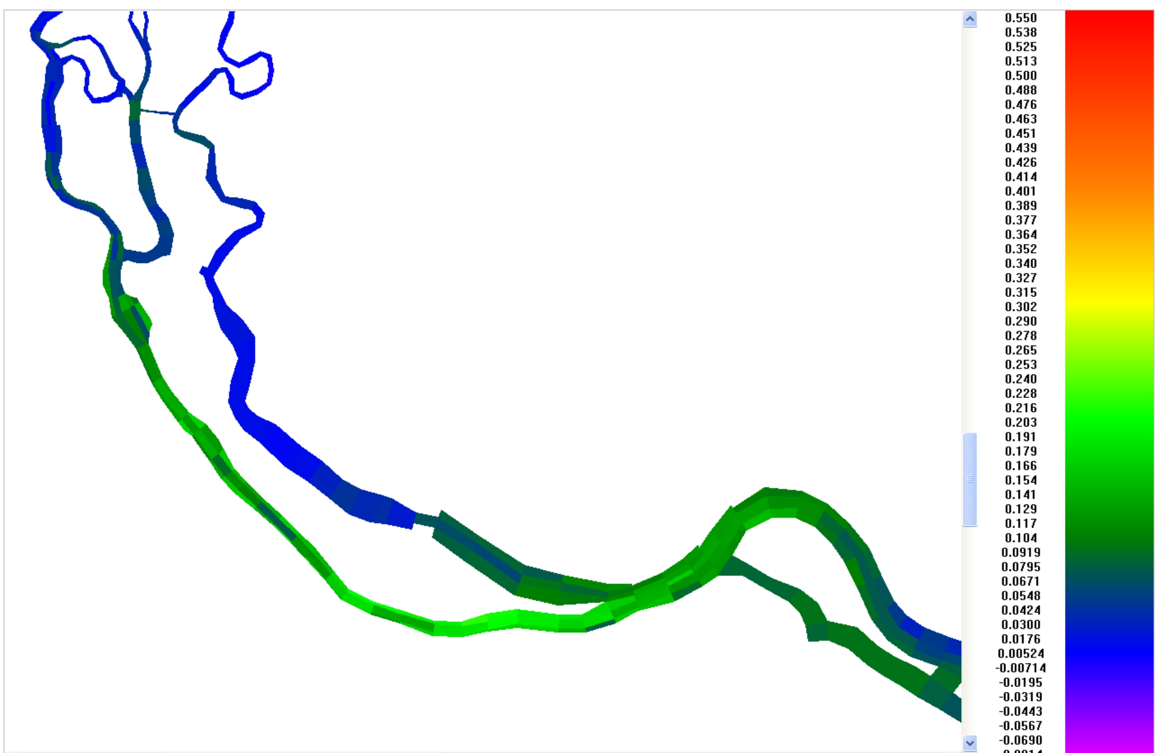

Figure A.1-2 95th percentile of dissolved oxygen delta distribution in surface layer of the harbor

Figure A.1-3 50th percentile of dissolved oxygen delta distribution in bottom layer of the harbor

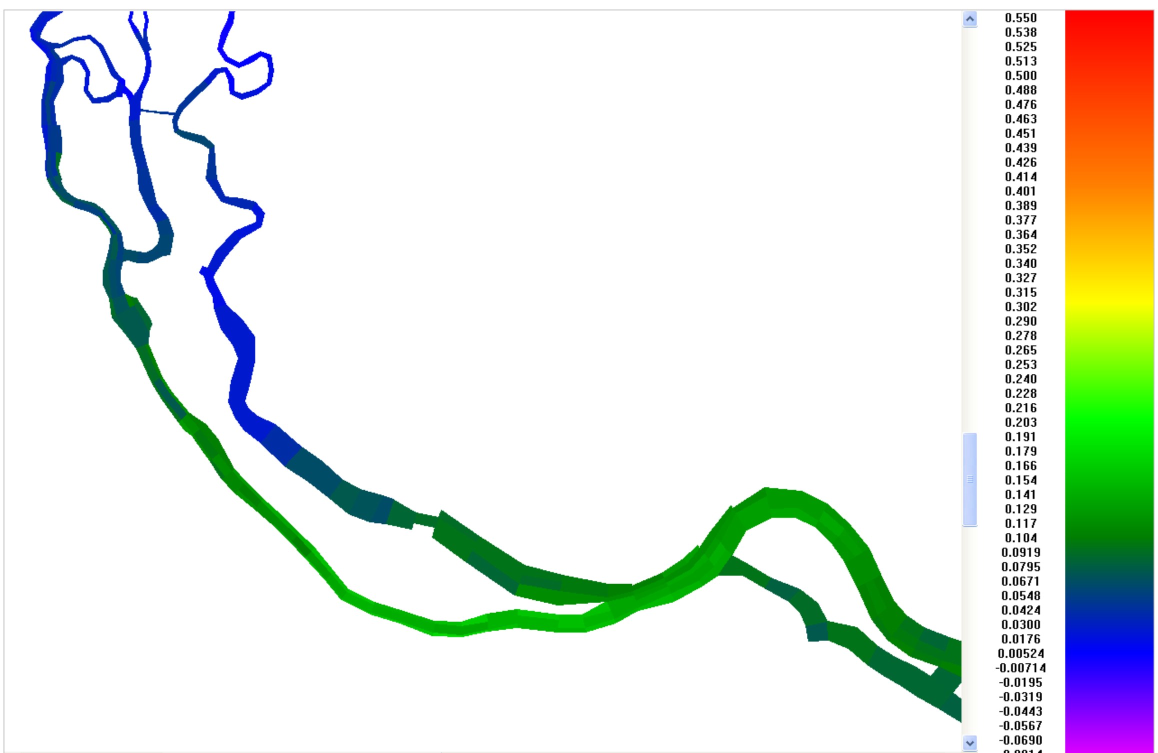

Figure A.1-4 50th percentile of dissolved oxygen delta distribution in surface layer of the harbor

Figure A.1-5 5^{th} percentile of dissolved oxygen delta distribution in bottom layer of the harbor

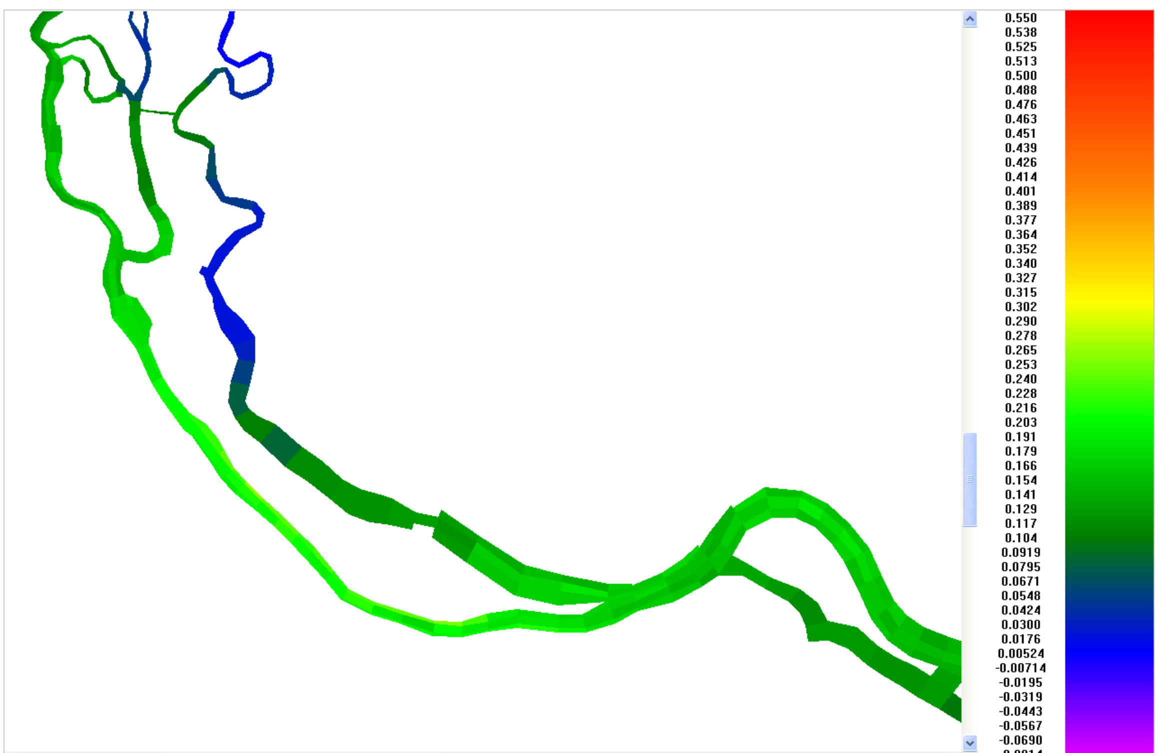

Figure A.1-6 5^{th} percentile of dissolved oxygen delta distribution in surface layer of the harbor

Appendix A.2

Dissolved Oxygen Deficit Delta Distributions In Savannah Harbor

August-September 2007

Delta = Injection – Existing Scenarios

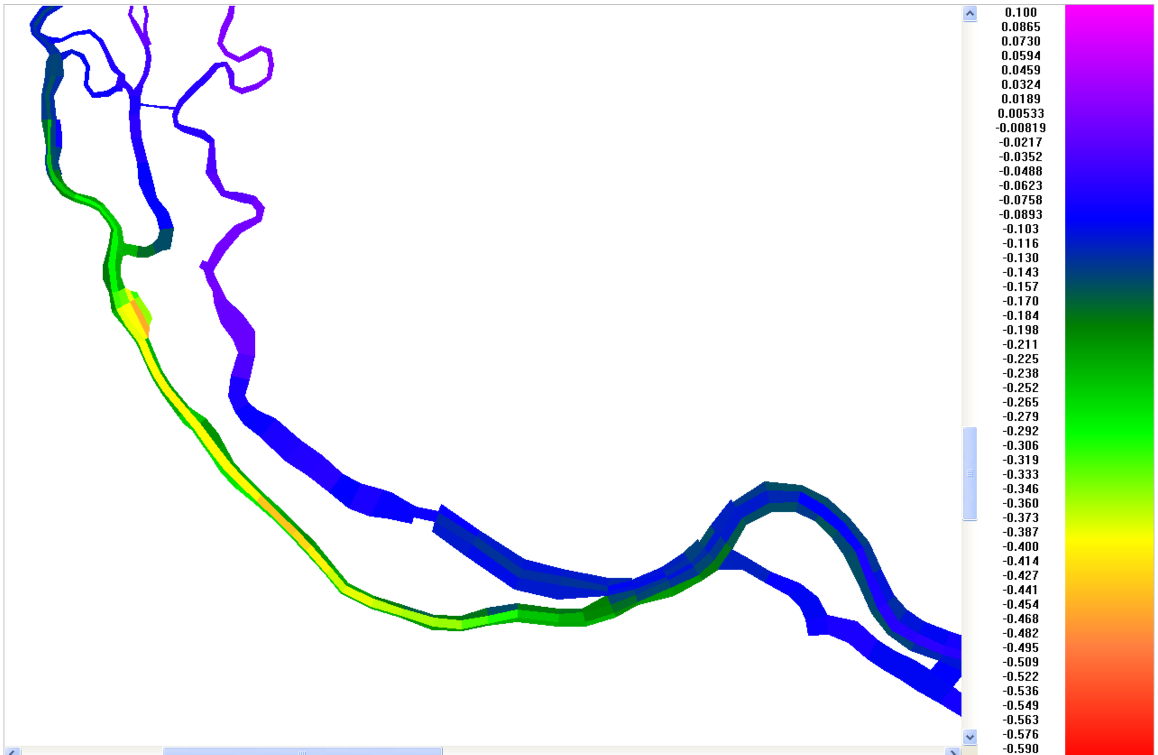

Figure A.2-1 95th percentile of dissolved oxygen deficit delta distribution in bottom layer of the harbor

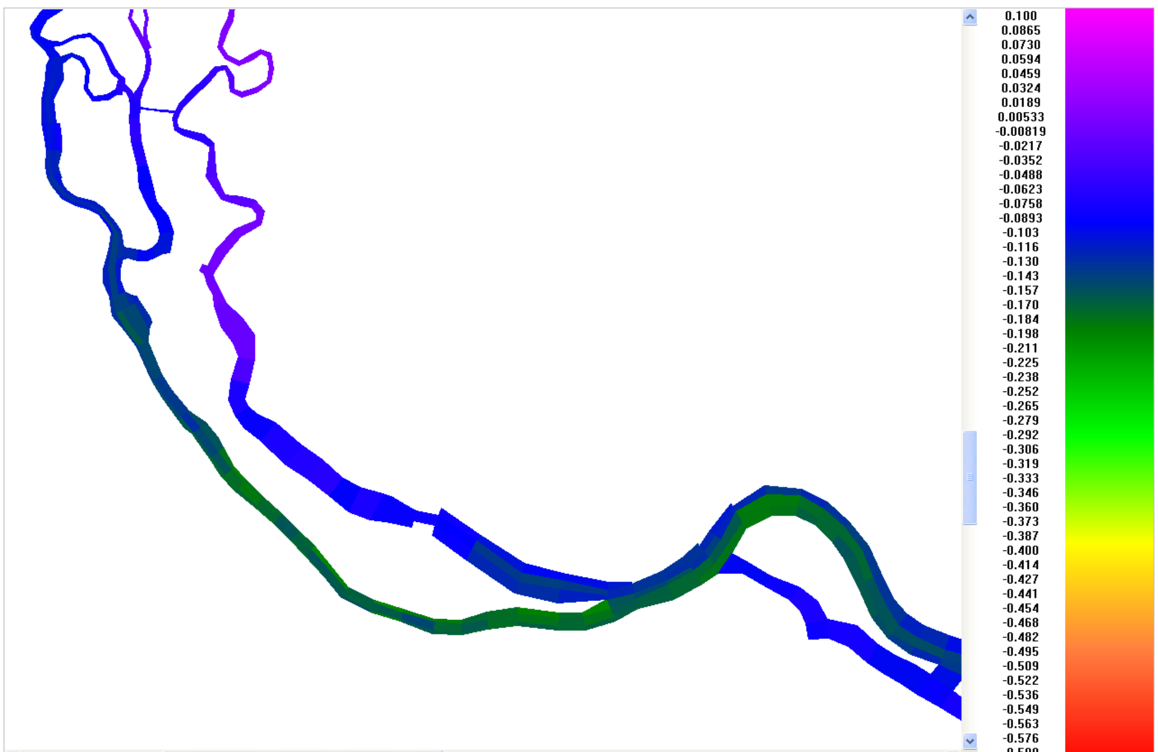

Figure A.2-2 95th percentile of dissolved oxygen deficit delta distribution in surface layer of the harbor

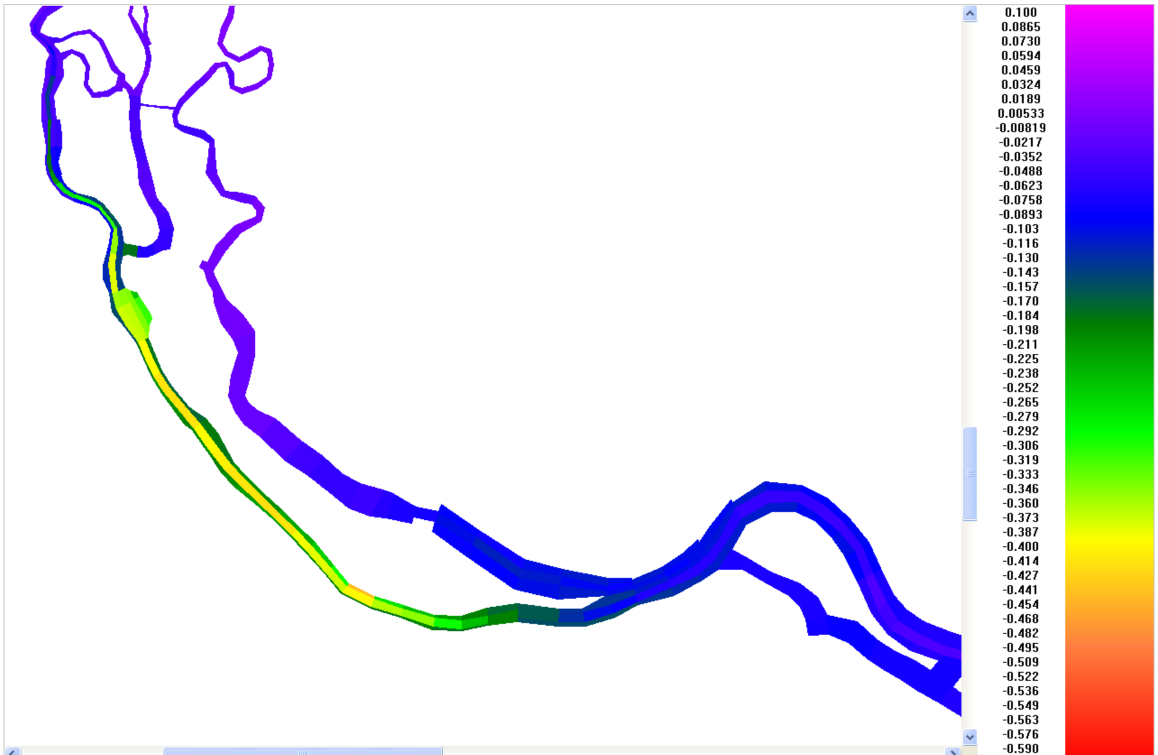

Figure A.2-3 50th percentile of dissolved oxygen deficit delta distribution in bottom layer of the harbor

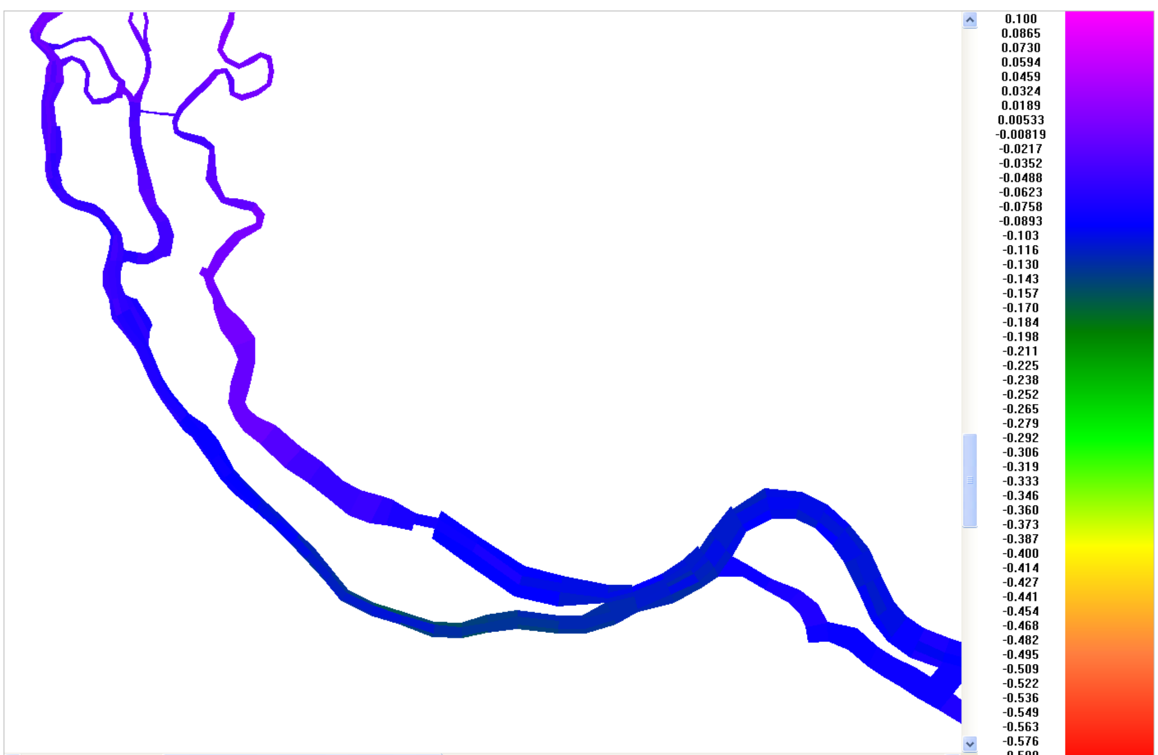

Figure A.2-4 50th percentile of dissolved oxygen deficit delta distribution in surface layer of the harbor

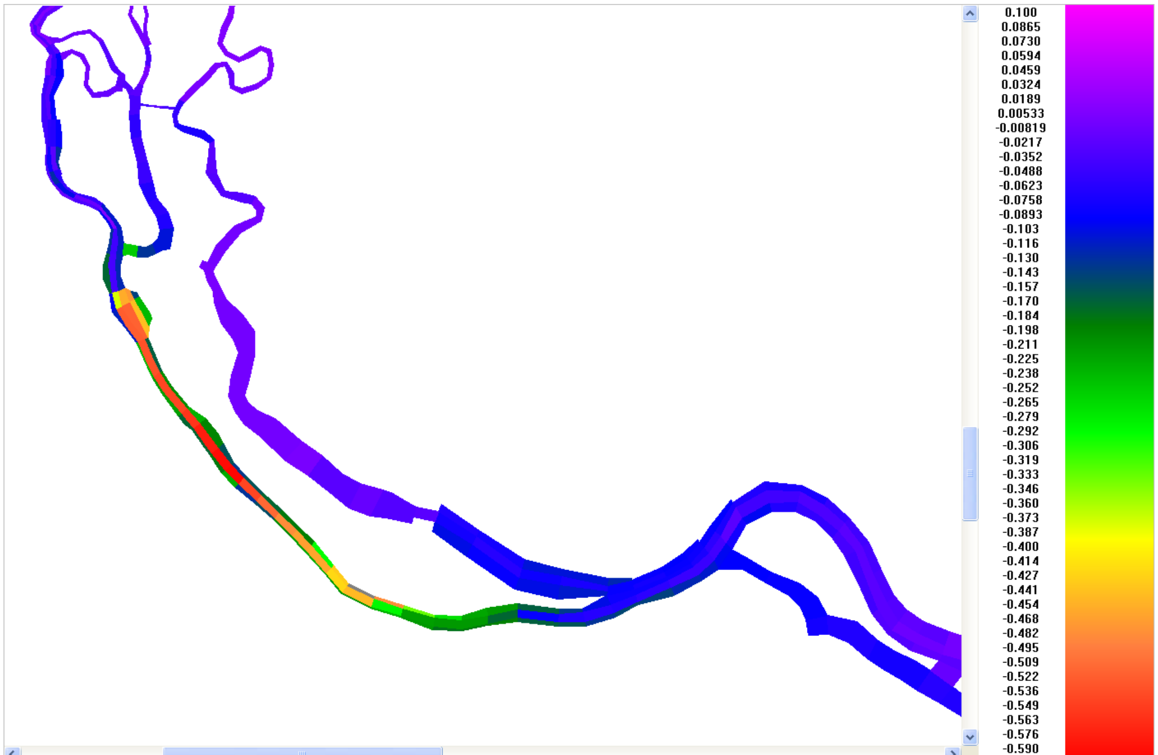

Figure A.2-5 5th percentile of dissolved oxygen deficit delta distribution in bottom layer of the harbor

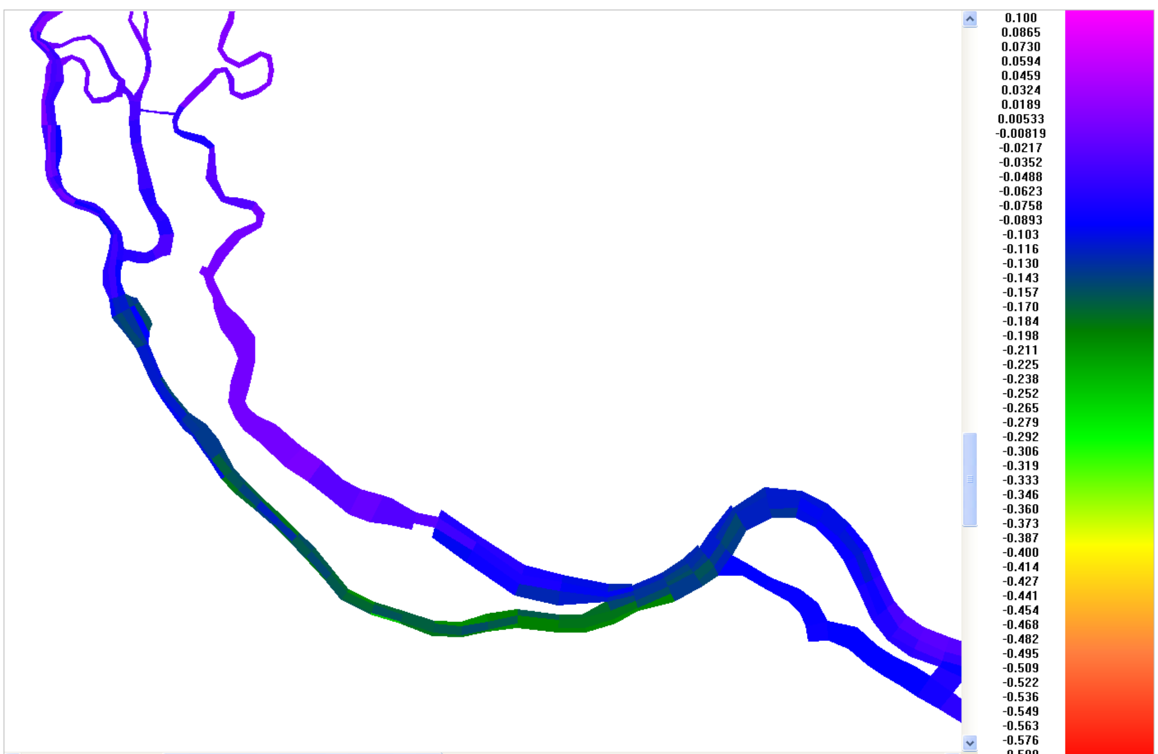

Figure A.2-6 5th percentile of dissolved oxygen deficit delta distribution in surface layer of the harbor

Appendix A.3

Dissolved Oxygen Percent Saturation Delta Distributions In Savannah Harbor

August-September 2007

Delta = Injection – Existing Scenarios

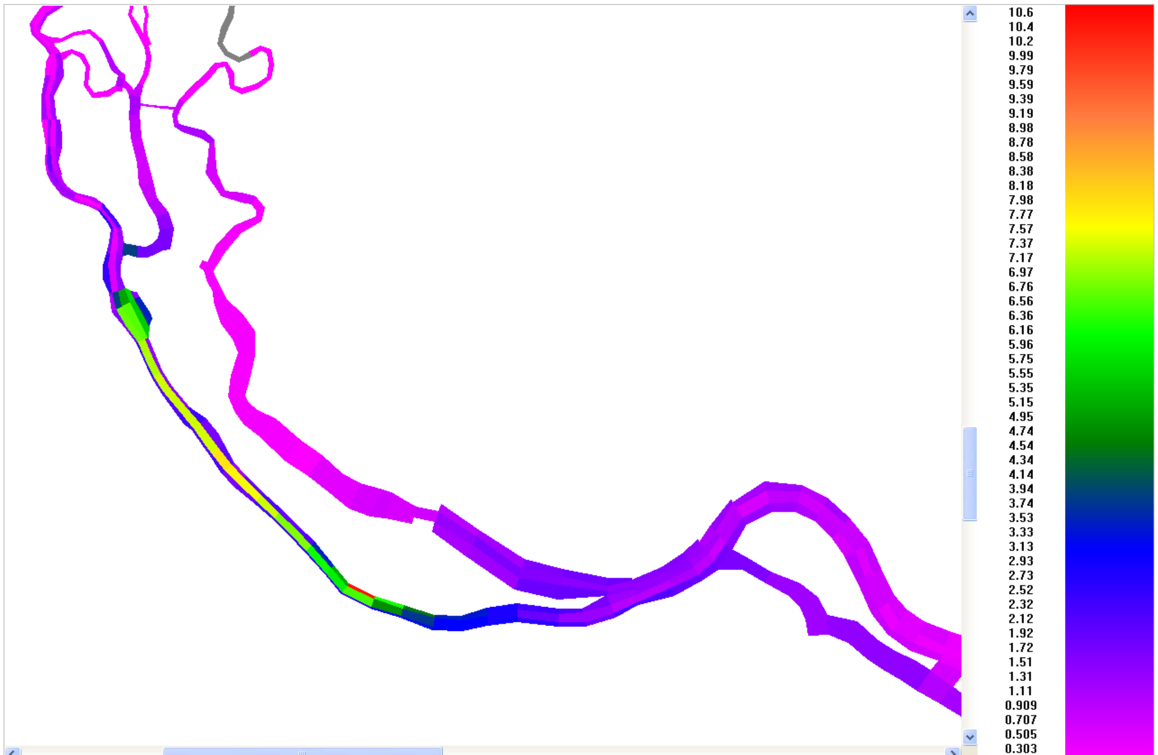

Figure A.3-1 95th percentile of dissolved oxygen saturation (%) delta distribution in bottom layer of the harbor

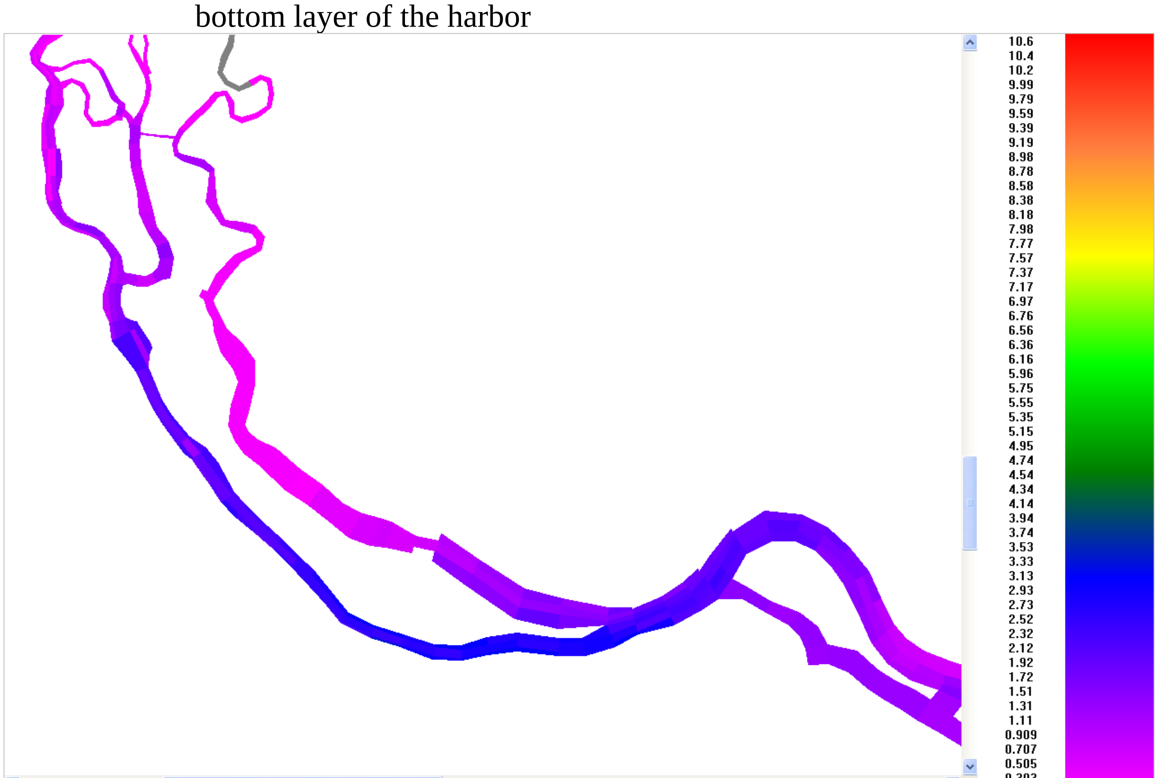

Figure A.3-2 95th percentile of dissolved oxygen saturation (%) delta distribution in surface layer of the harbor

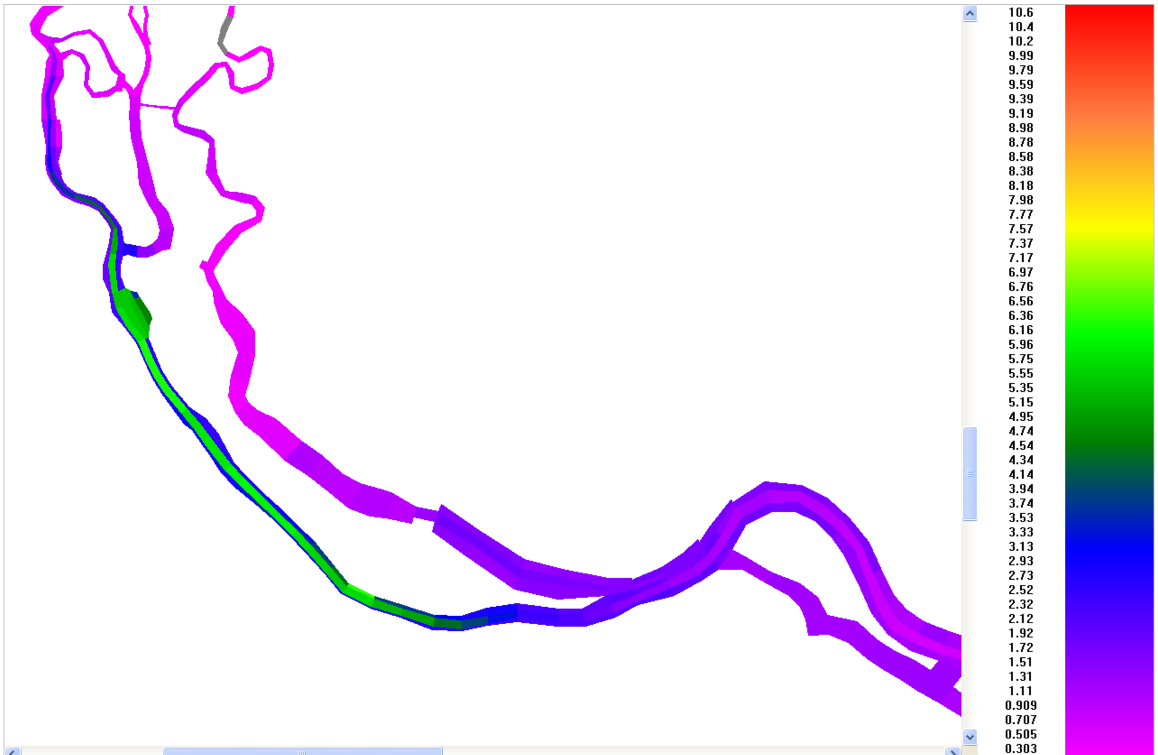

Figure A.3-3 50th percentile of dissolved oxygen saturation (%) delta distribution in bottom layer of the harbor

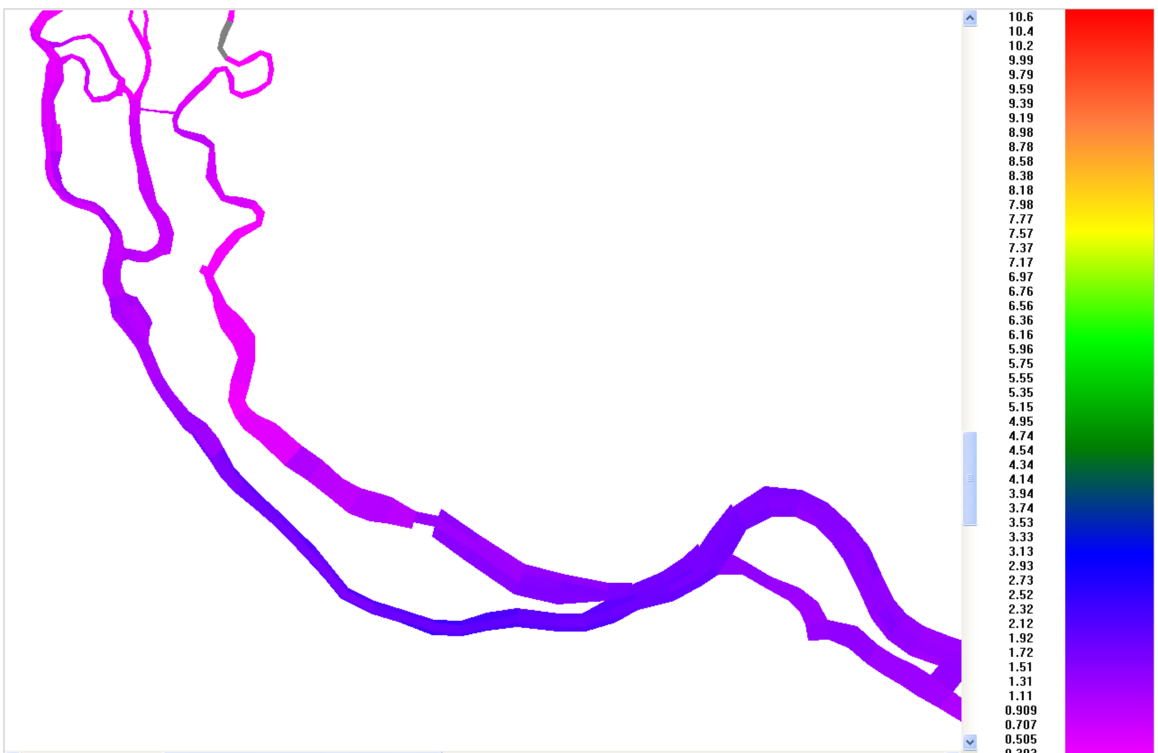

Figure A.3-4 50th percentile of dissolved oxygen saturation (%) delta distribution in surface layer of the harbor

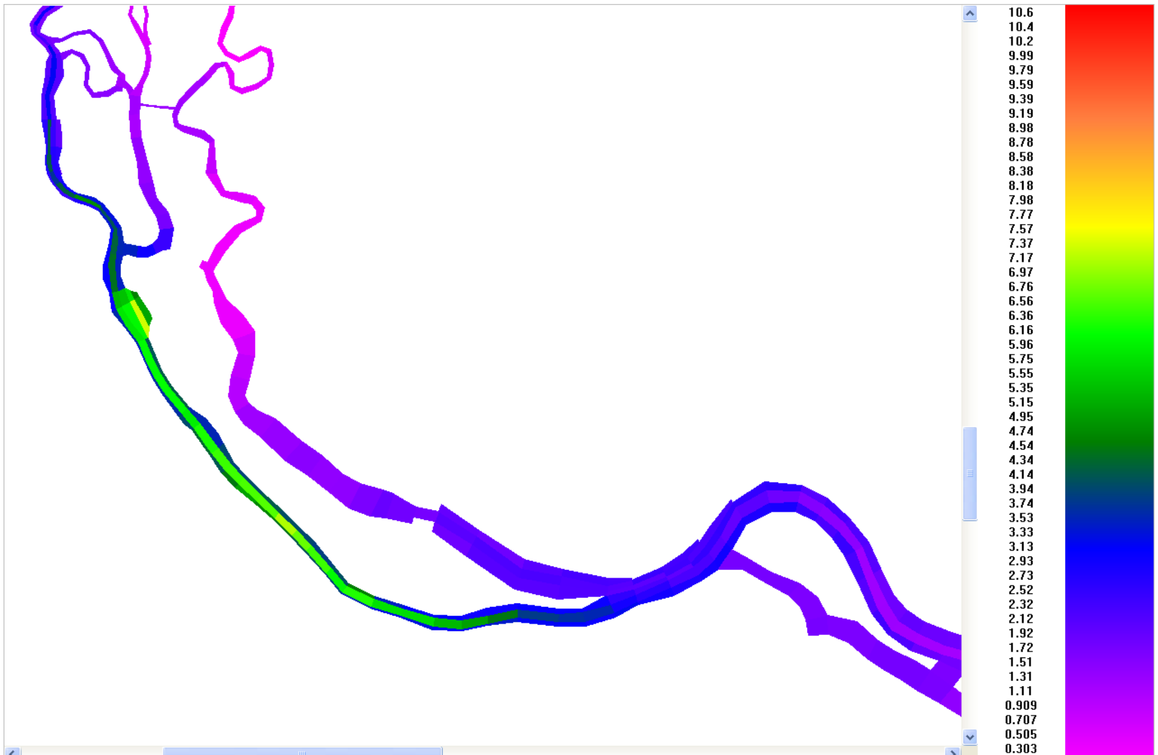

Figure A.3-5 5th percentile of dissolved oxygen saturation (%) delta distribution in bottom layer of the harbor

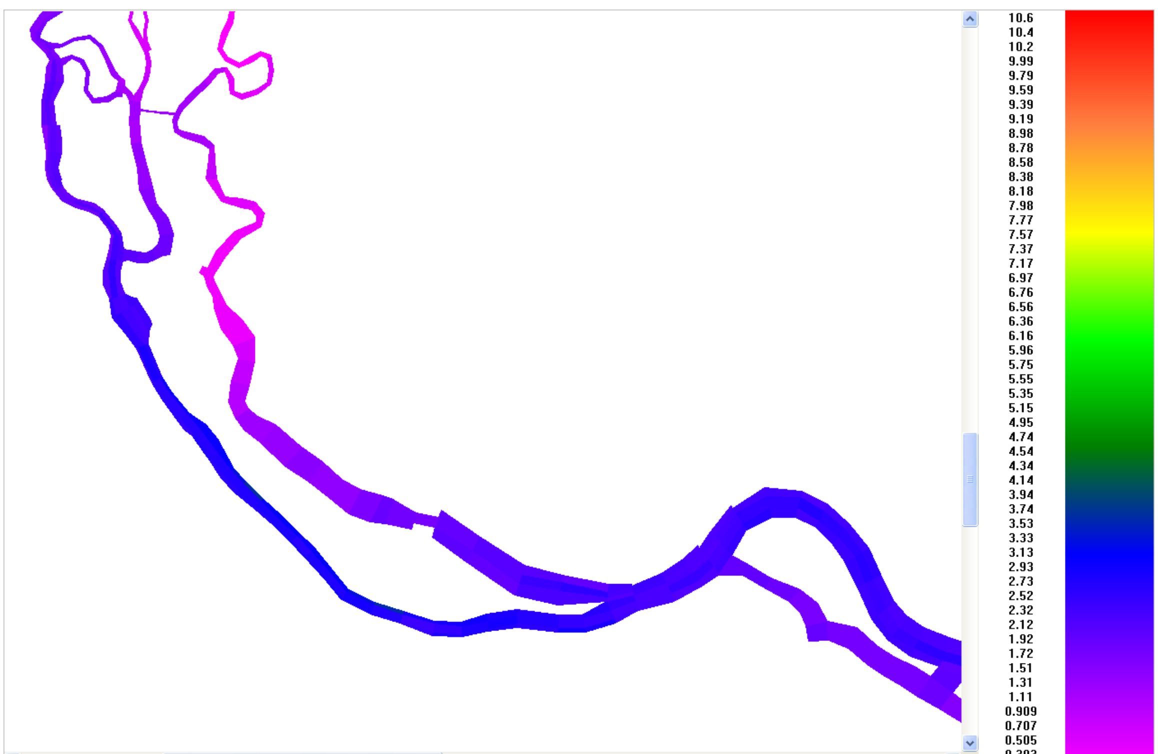

Figure A.3-6 5th percentile of dissolved oxygen saturation (%) delta distribution in surface layer of the harbor

Appendix B

Longitudinal Distributions of Deltas of Dissolved Oxygen Characteristics in Savannah Harbor

August-September 2007

Delta = Injection – Existing Scenarios

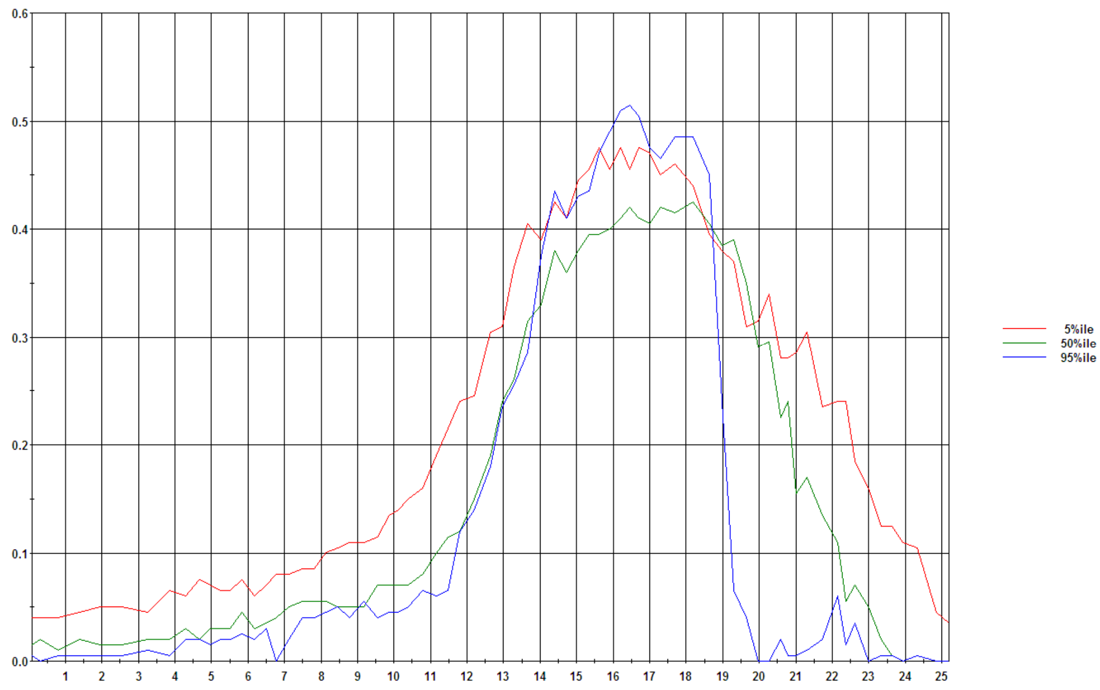

Figure B-1 Dissolved oxygen delta distributions along a bottom layer of the ship channel

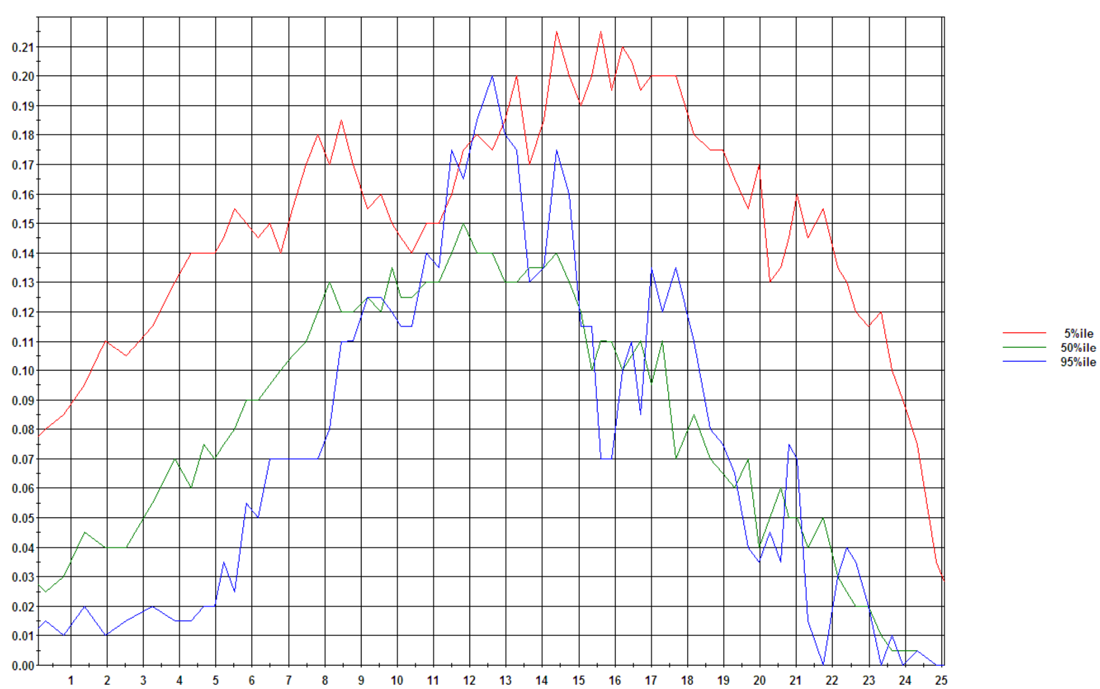

Figure B-2 Dissolved oxygen delta distributions along a surface layer of the ship channel

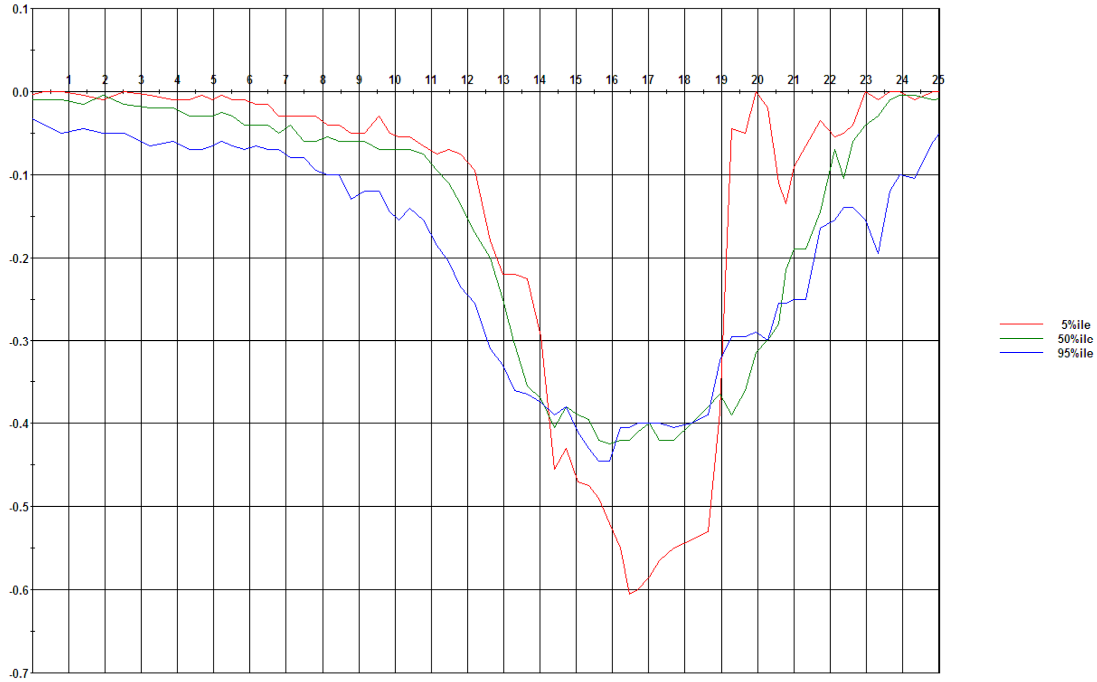

Figure B-3 Dissolved oxygen deficit delta distributions along a bottom layer of the ship channel

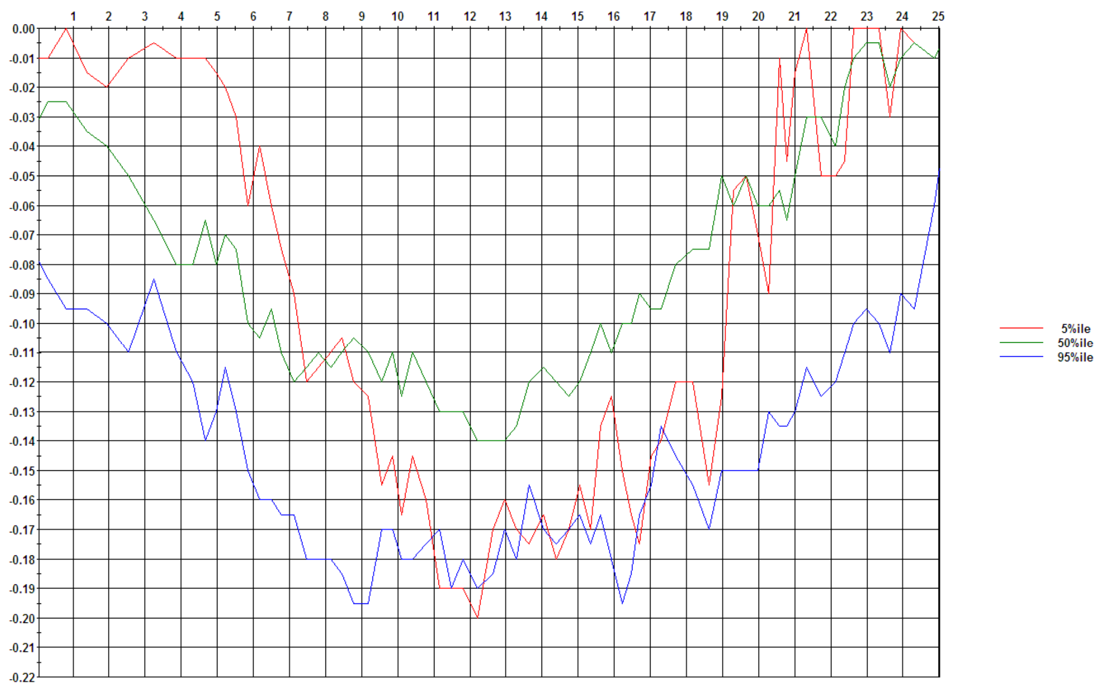

Figure B-4 Dissolved oxygen deficit delta distributions along a surface layer of the ship channel

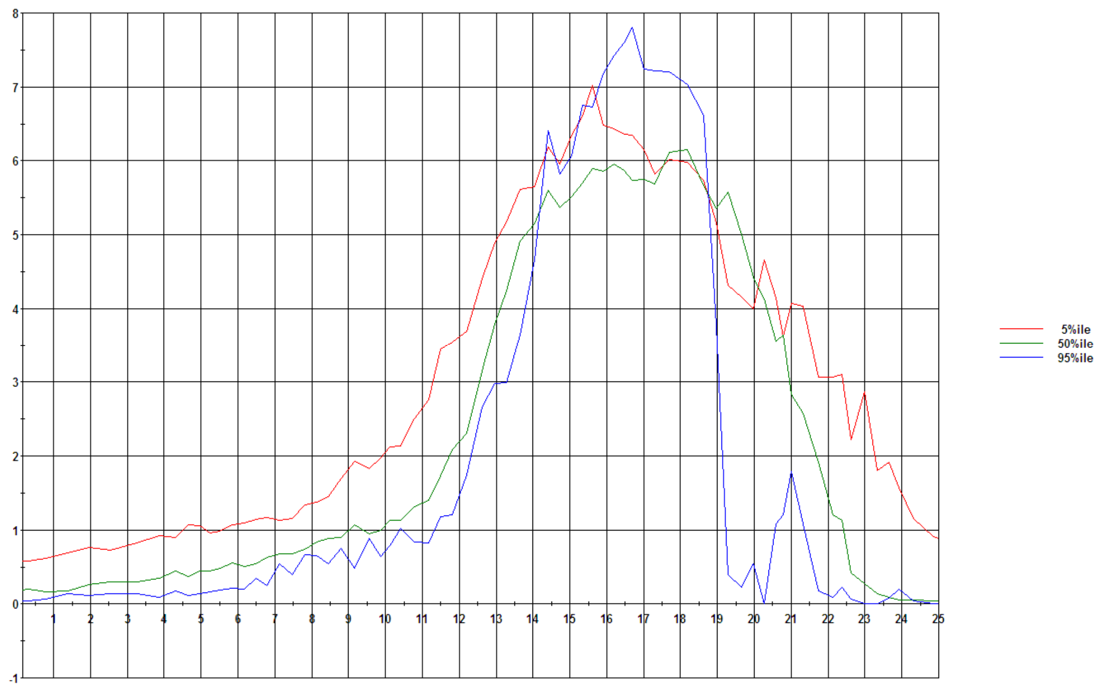

Figure B-5 Dissolved oxygen percent of saturation delta distributions along a bottom layer of the ship channel

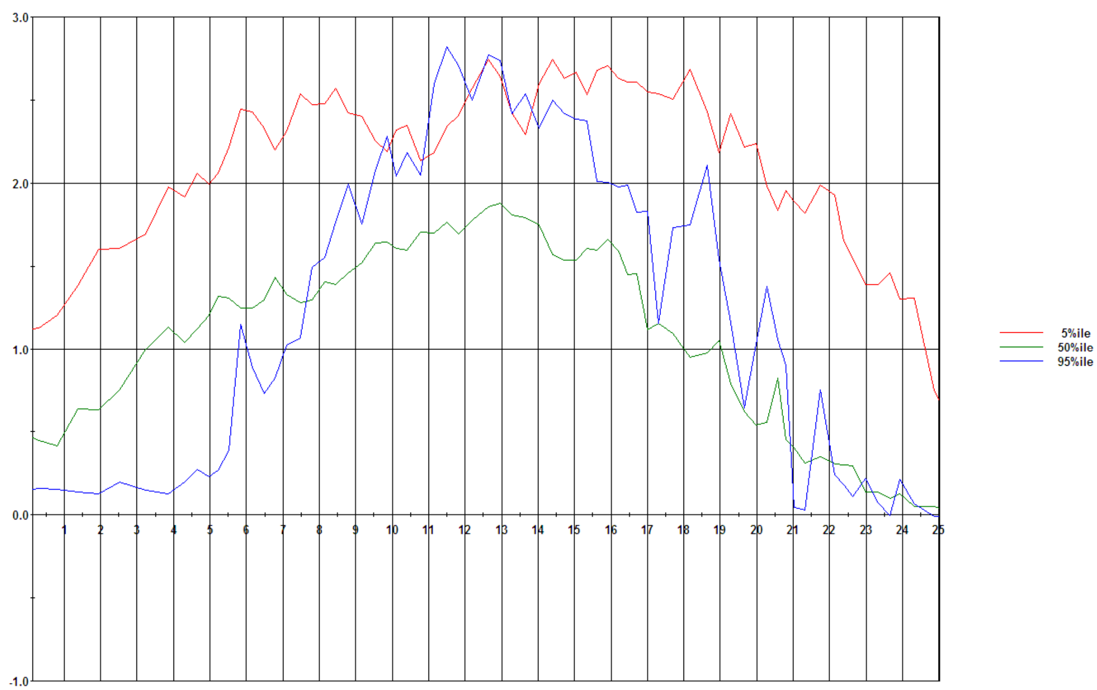

Figure B-6 Dissolved oxygen percent of saturation delta distributions along a surface layer of the ship channel

Appendix C

Model Response to Different Oxygen Transfer Efficiencies

August-September 2007

Delta = Injection – Existing Scenarios

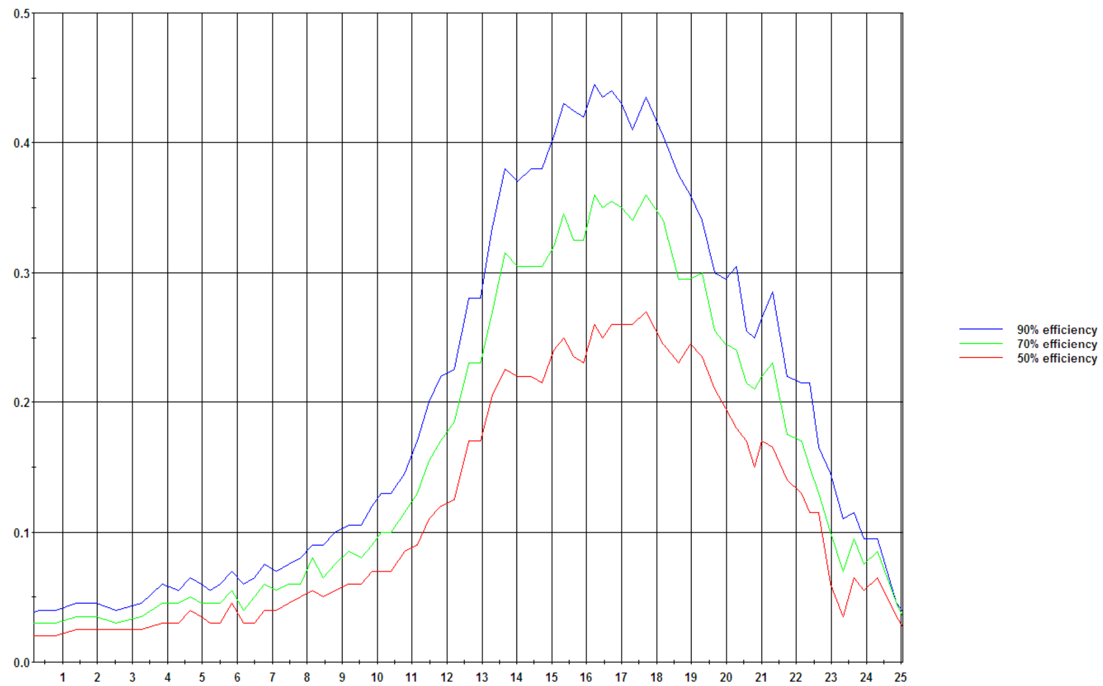

Figure C-1 5th percentile of dissolved oxygen delta distributions along a bottom layer of the ship channel

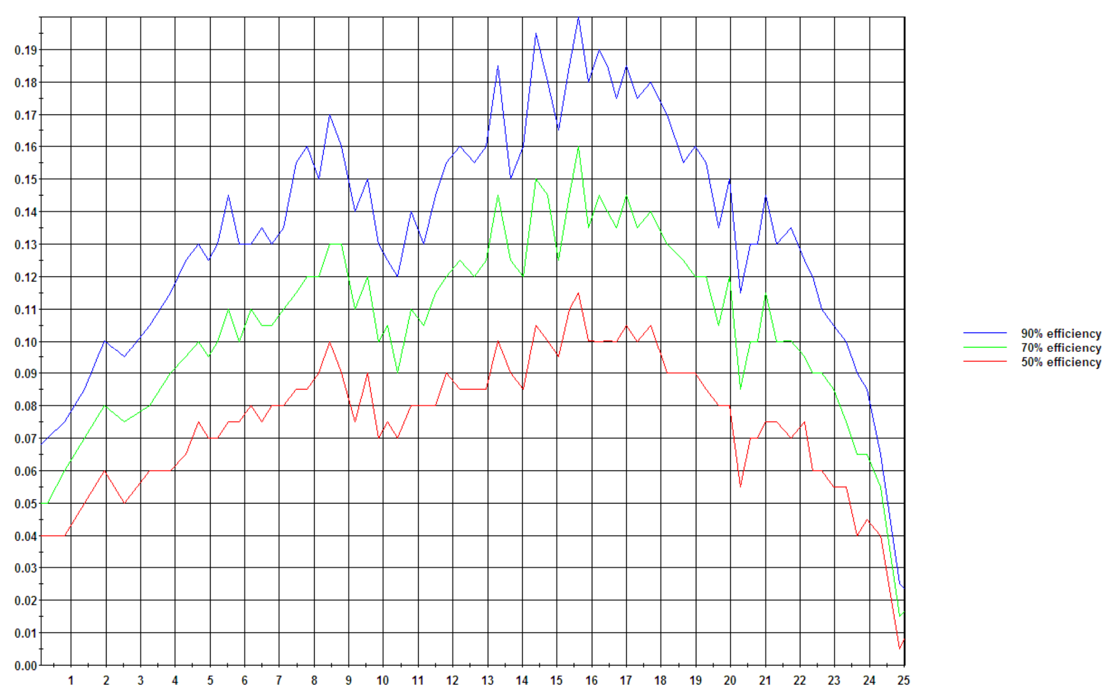

Figure C-2 5th percentile of dissolved oxygen delta distributions along a Surface layer of the ship channel

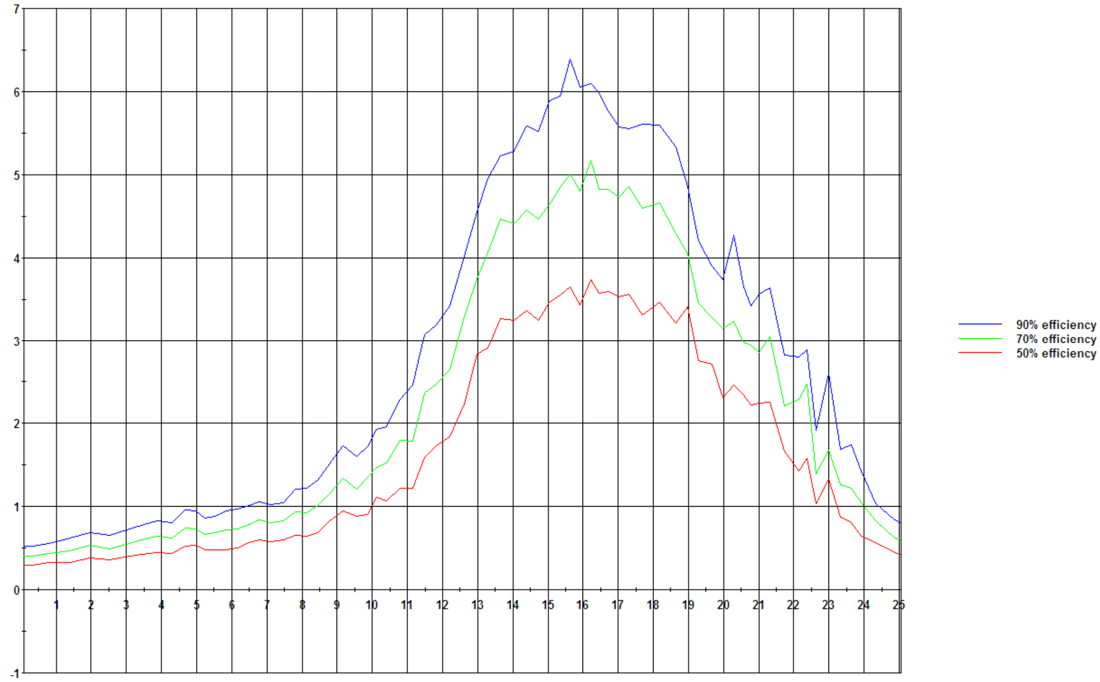

Figure C-3 5th percentile of dissolved oxygen percent of saturation delta distributions along a bottom layer of the ship channel

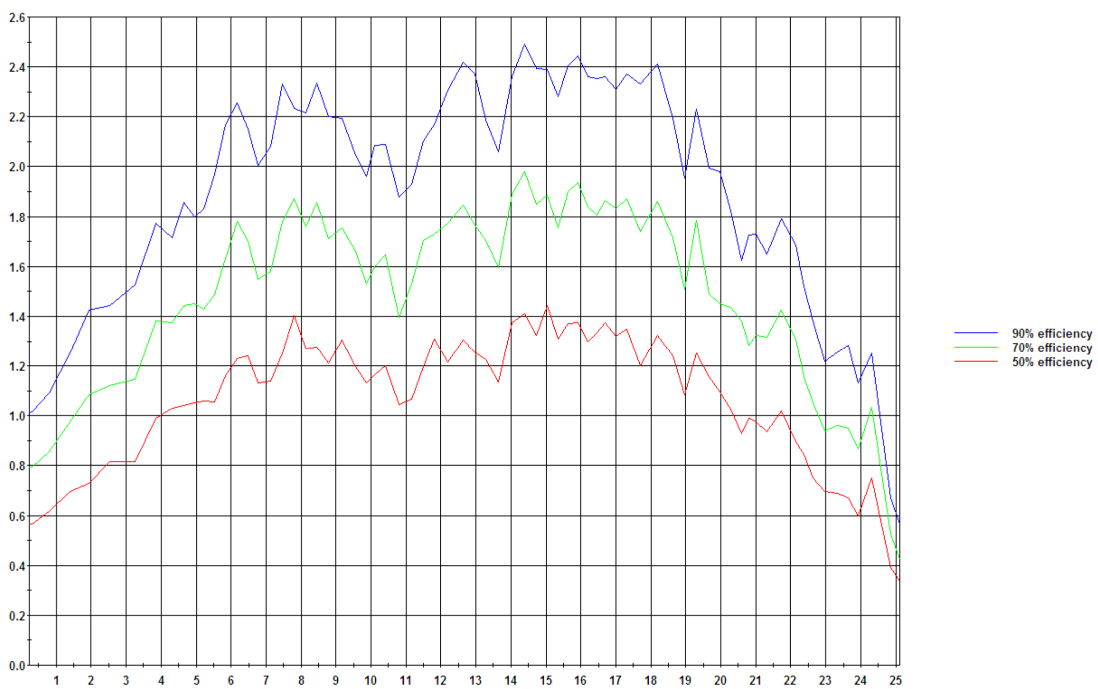

Figure C-4 5th percentile of dissolved oxygen percent of saturation delta distributions along a Surface layer of the ship channel

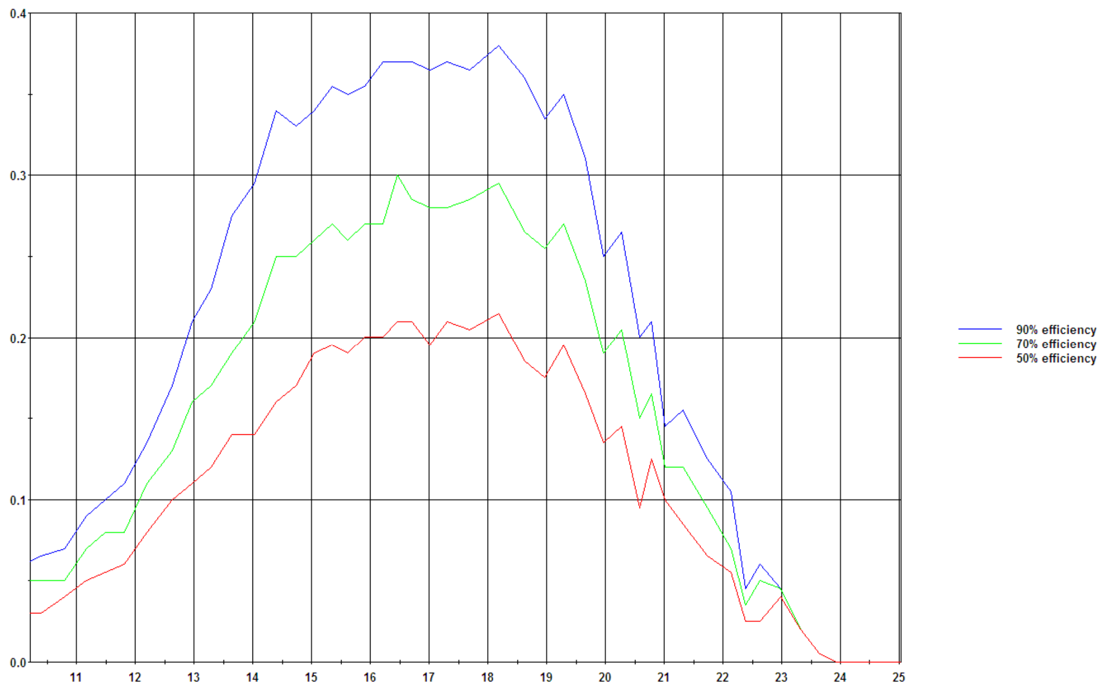

Figure C-5 50th percentile of dissolved oxygen delta distributions along a bottom layer of the ship channel

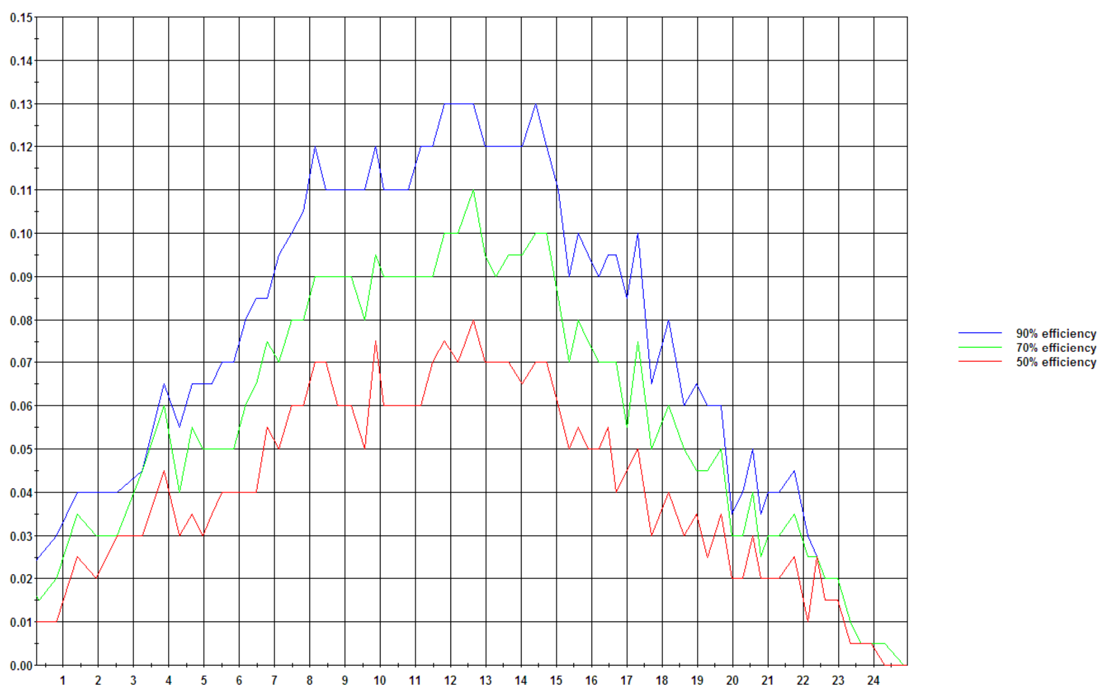

Figure C-6 50th percentile of dissolved oxygen delta distributions along a Surface layer of the ship channel

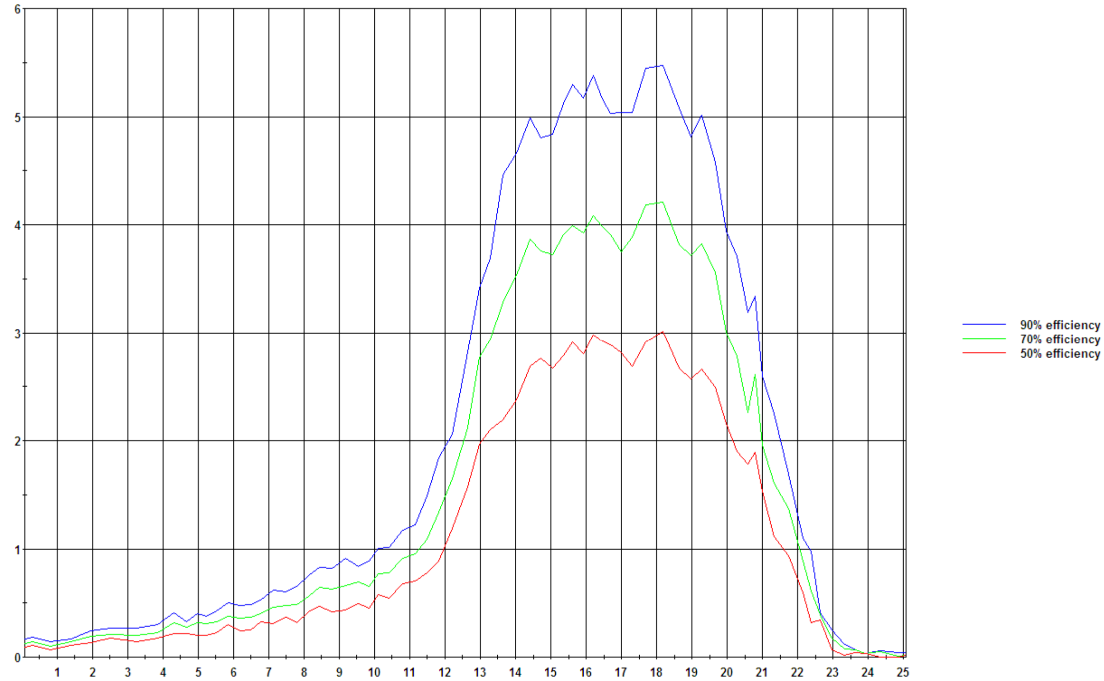

Figure C-7 50th percentile of dissolved oxygen percent of saturation delta distributions along a bottom layer of the ship channel

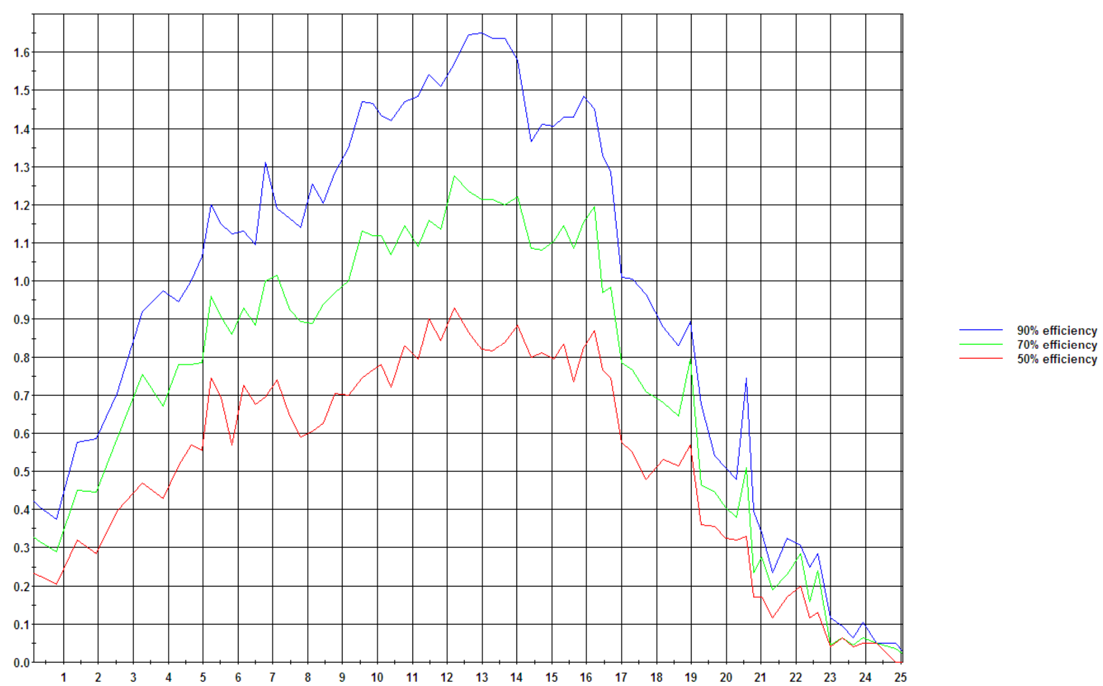

Figure C-8 50th percentile of dissolved oxygen percent of saturation delta distributions along a Surface layer of the ship channel

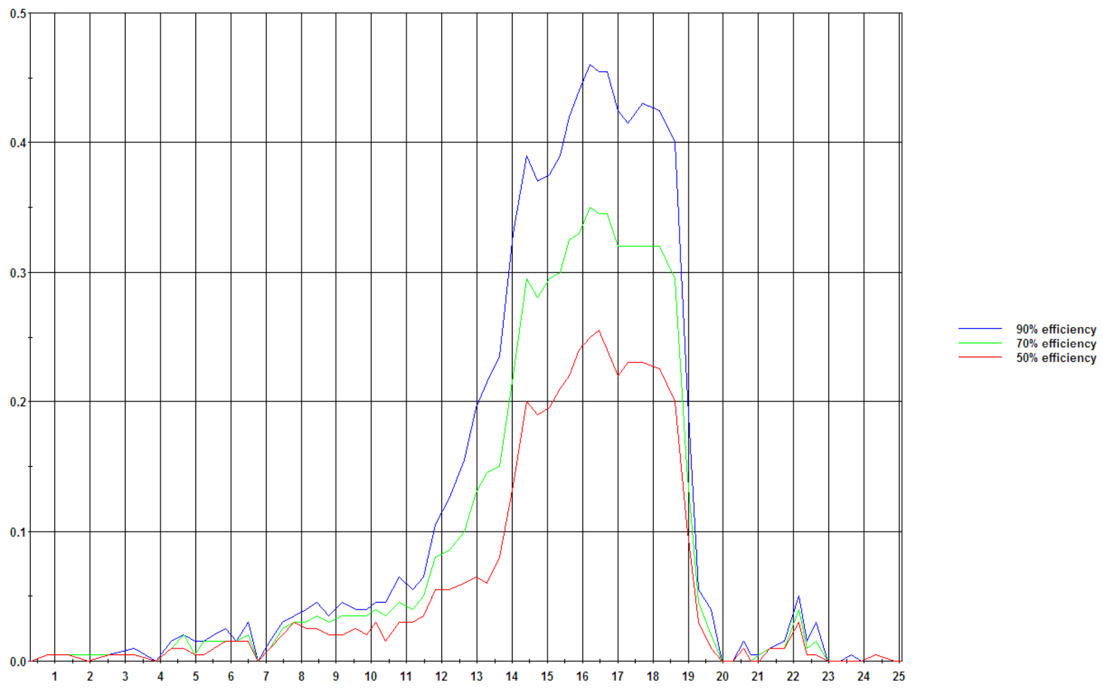

Figure C-9 95th percentile of dissolved oxygen delta distributions along a bottom layer of the ship channel

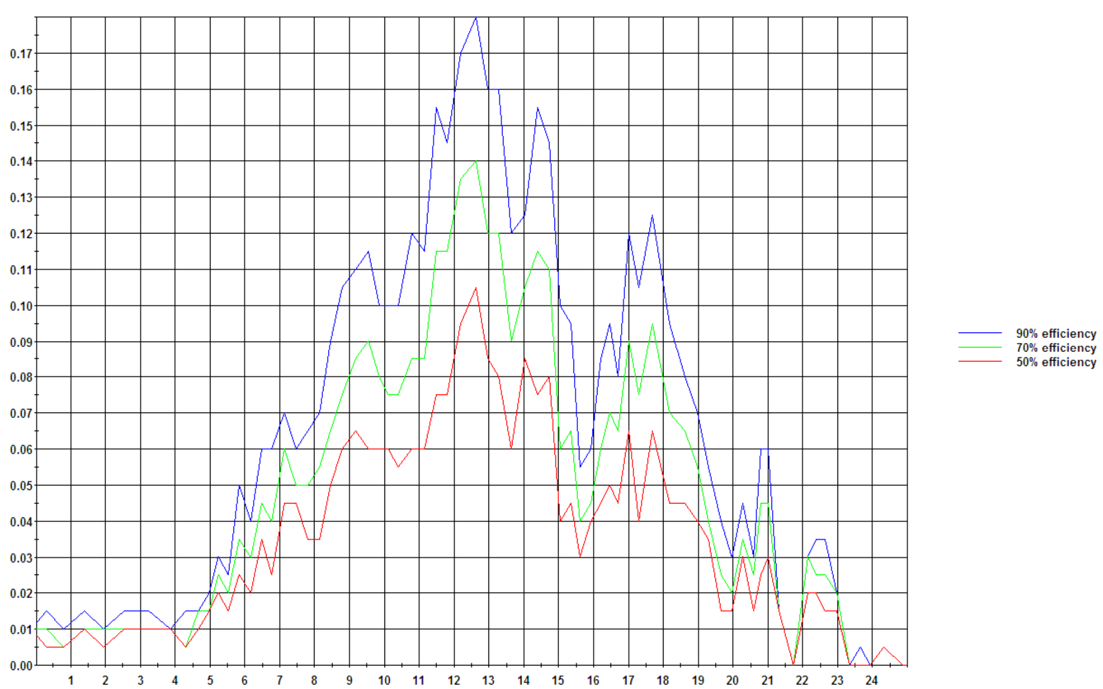

Figure C-10 95th percentile of dissolved oxygen delta distributions along a Surface layer of the ship channel

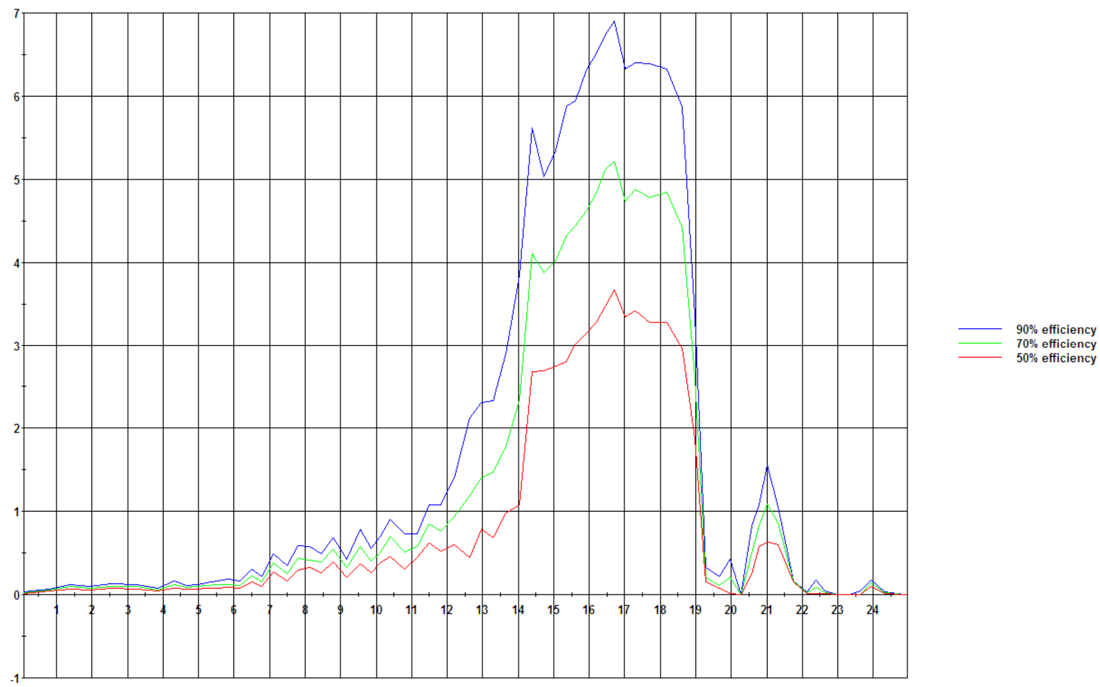

Figure C-11 95th percentile of dissolved oxygen percent of saturation delta distributions along a bottom layer of the ship channel

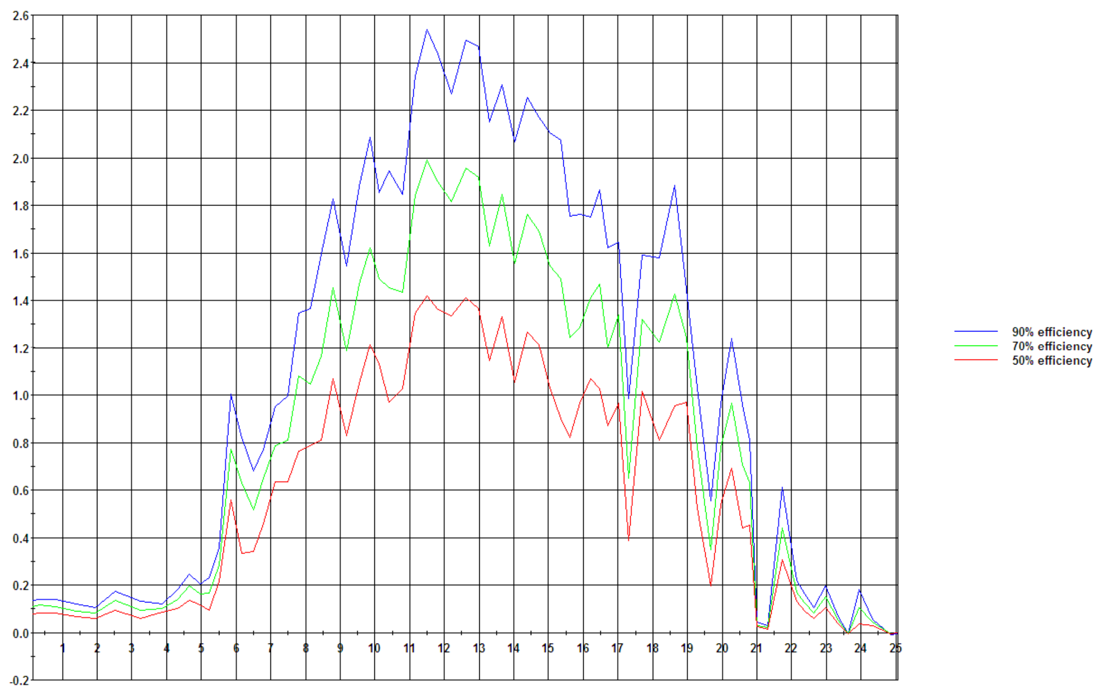

Figure C-12 95th percentile of dissolved oxygen percent of saturation delta distributions along a surface layer of the ship channel

Appendix D

Model Validation:
Comparisons with 2007 Monitoring Data

August-September 2007

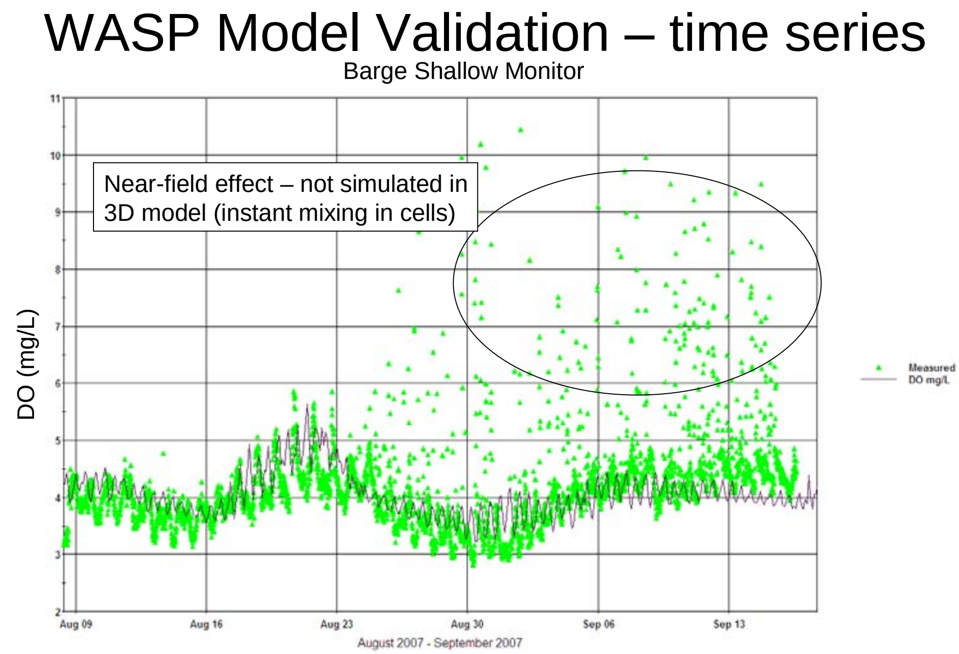

Figure D-1 D.O. surface layer simulation comparisons with data from barge shallow monitor

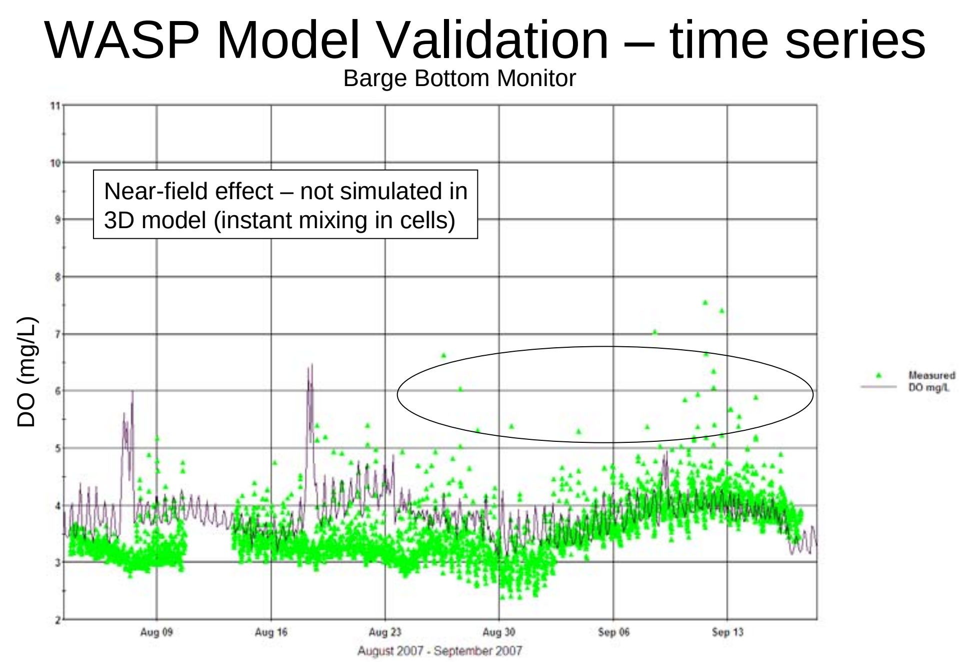

Figure D-2 D.O. bottom layer simulation comparisons with data from barge bottom monitor

WASP Model Validation – time series

USACE Dock Shallow Monitor

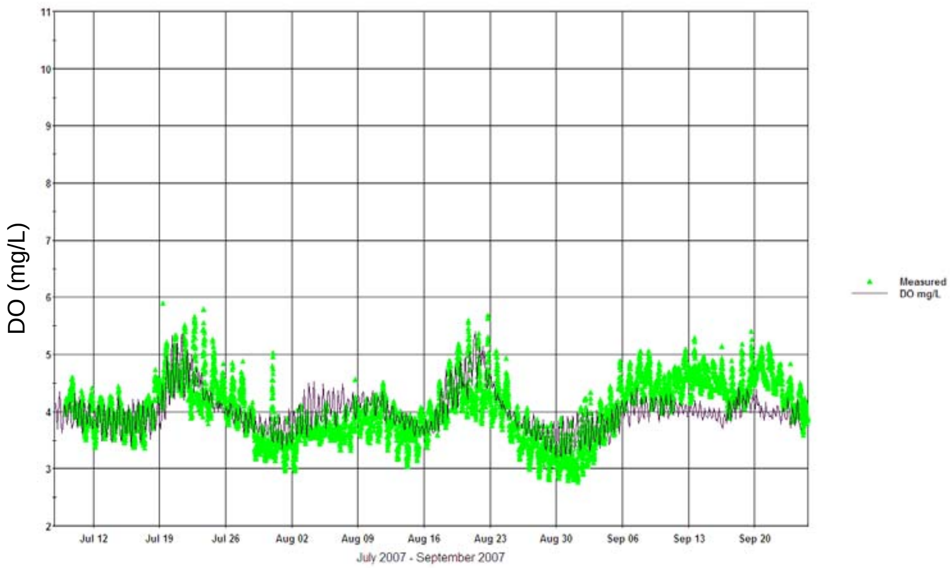

Figure D-3 D.O. surface layer simulation comparisons with data from USACE Dock shallow monitor

WASP Model Validation – time series

USACE Dock Bottom Monitor

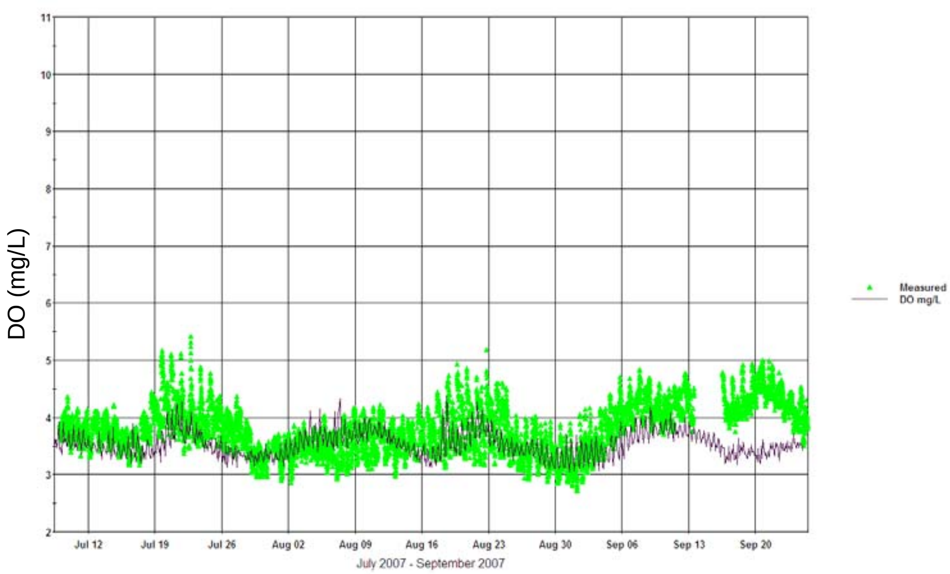

Figure D-4 D.O. bottom layer simulation comparisons with data from USACE Dock bottom monitor

WASP Model Validation – time series

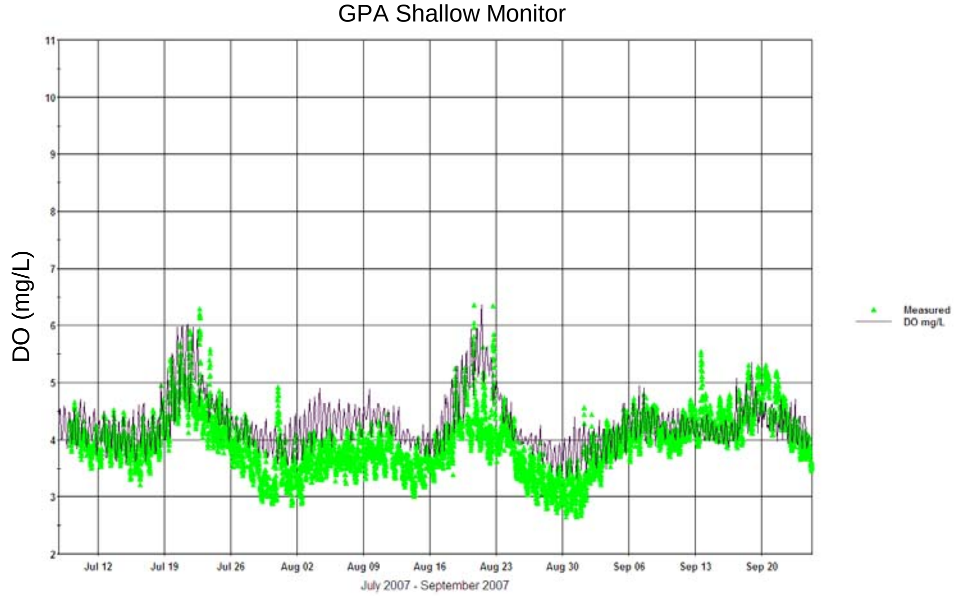

Figure D-5 D.O. surface layer simulation comparisons with data from GPA shallow monitor

WASP Model Validation – time series

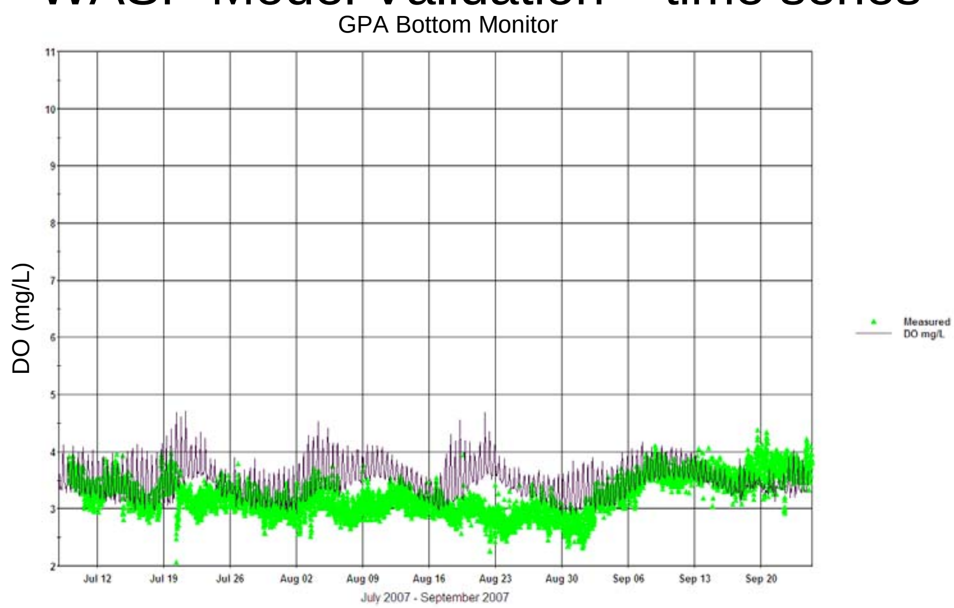

Figure D-6 D.O. bottom layer simulation comparisons with data from GPA bottom monitor

WASP Validation - Surface Longitudinal

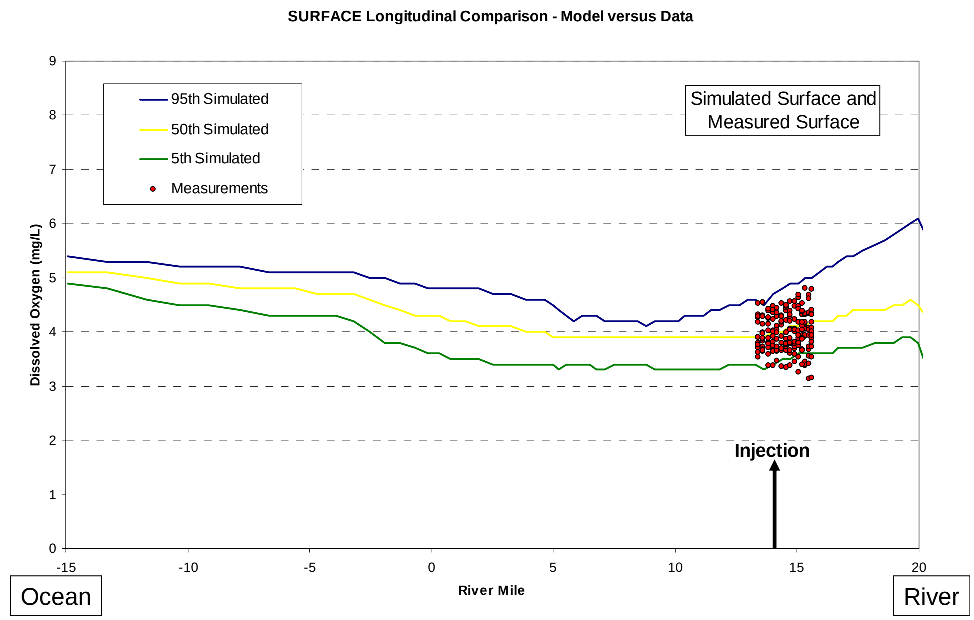

Figure D-7 Comparison of a range of D.O. surface layer simulations with data from longitudinal shallow monitor

WASP Validation - Bottom Longitudinal

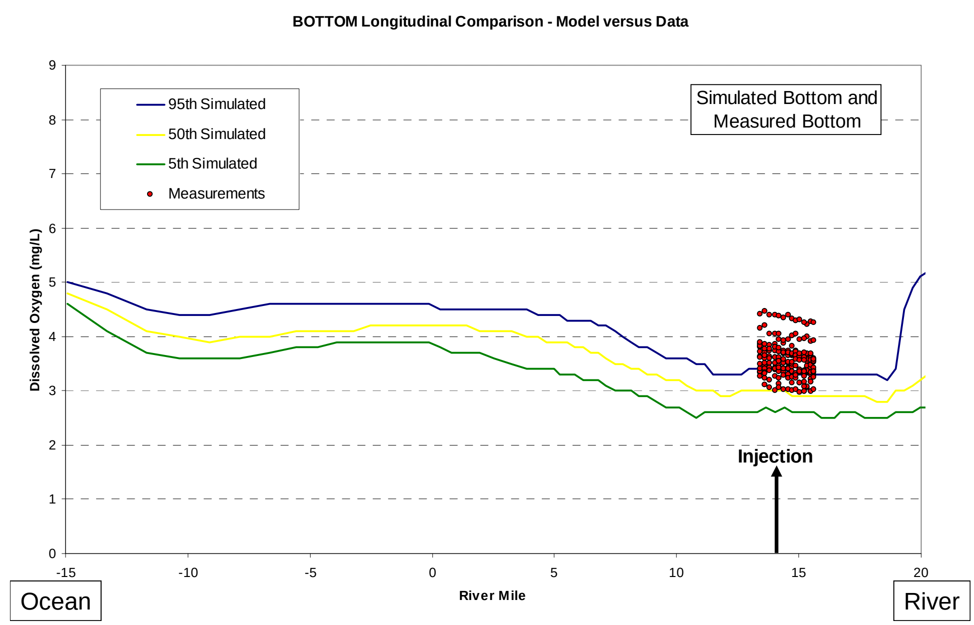

Figure D-8 Comparison of a range of D.O. bottom layer simulations with data from longitudinal bottom monitor

Appendix E

Visual Plumes Model Description

Visual Plumes

Visual Plumes is a Windows-based mixing zone modeling application designed to replace the DOS-based PLUMES program (Baumgartner, Frick, and Roberts, 1994). Like PLUMES, VP supports initial dilution models that simulate single and merging submerged plumes in arbitrarily stratified ambient flow. Predictions include dilution, rise, diameter, and other plume variables. The Brooks algorithm is retained for predicting far-field centerline dilution and waste field width. New features include the surface discharge model (PDS), the multi-stressor bacterial decay model (based on Mancini, 1978), graphics output, time-series input, a sensitivity analysis capability, user-specified units, and a conservative tidal background pollutant build-up capability.

Several models can be run under Visual Plumes, such as UM3, a fully three-dimensional flow version of the single-port Windows UM model. UDKHDEN, also a three-dimensional model, was one of the models in EPA's earlier guidance (Muellenhoff et al., 1985) that is reintroduced under the name DKHW. This addition illustrates a commitment to a comprehensive modeling platform that will foster scientific competition by encouraging modelers to continue to improve their applications.

Like DOS PLUMES, VP allows the user to run many cases, however, multiple cases are easier to set up and to compare. Determining model sensitivity to various input parameters is facilitated. The ability to run different models, such as UM3 and DKHW, side by side and compare the results in graphical form, should facilitate model comparison. The ability to link in and graph verification data from files rounds out the ability to compare models.

Perhaps no other capability sets VP apart from PLUMES more than its ability to link in time-series files. This capability provides a way to simulate outfall performance over a long period of time and, thereby, over many environmental scenarios. Most effluent and ambient variables, such as effluent discharge rate and current direction, can be read from files containing values that change with time over different time intervals. Thus, a 24-hour diurnal flow file, cycled repeatedly, might be combined with a current-meter data set thousands of records long. This is the heart of the pollutant-buildup capability, the ability in one-dimensional tidal rivers or estuaries to estimate background pollution from the source in question. The time-series file linking capability is served by "summary" graphics, i.e., graphics panels that focus on overall performance indicators, like mixing zone dilutions or concentrations.

E.1 General Overview of the Interface

The VP user interface is organized into five tabs: *Diffuser, Ambient, Special Settings, Text Output*, and *Graphics*. For setup and input, several Windows controls and components, such as tables, pull-down and pop-up menus, buttons, and lists are provided. Numerical input is dominated by two input tables, defining the diffuser characteristics and flow conditions and the ambient conditions. Other information is input in a memo box, a number of control panels, lists, and buttons, and, various edit boxes, lists, file dialogs, and radio buttons on the *Special Settings* tab.

A context-sensitive help system allows one to right-click on any component on the screen, or use the help menu. Many help topics contain hypertext links; text displayed in green may be clicked to display further information on the indicated item.

To reduce redundancy, several input interpretation techniques have been written into VP to make input requirements contingent on actual availability of data. In many applications, input tables must be completely filled in with data, whether the data are redundant or not. In VP, data need not be entered into the input tables when their existence is not implied.

To prepare VP to run the user must define the base case and complete at least one ambient profile in the table on the *Ambient* tab. Model selection and case specific information determines which columns require input; columns labeled *n/r* are not required by the specified configuration or target model. For more than one run, or rows, only cell values that are different from the base case need be entered. If a cell is empty, its value is inherited from the previous row. The runtime mode is determined by the setting of the Case selection radio button panel; choices are individual cases, all cases in sequence (running all ambient files or parsing the case range appended to the ambient file name), or all possible combinations of cases.

The organization of the data on different tabs emphasizes that VP diffuser and ambient input data are maintained in separate files with a *db* extension.

VP supports user-specified units. On both *Diffuser* and *Ambient* tabs, the user can click on the row above the input table to select units from a list of up to five choices revealed on a pop-up list. Unless the *Units conversion* radio button is set to *label only*, the data in the affected columns are automatically updated to convert to the new unit. In addition, some of the columns are multi-use columns. For example, the salinity column can be changed to a density column by simply selecting a density unit from the list of unit options.

The *Special Settings* tab provides a choice of output variables and access to other controls, parameters, and options. The *Text Ouput* and *Graphical Output* tabs display the output. Graphics can be customized by double-clicking in the margins of each panel. Other options are provided on the left side of the graphing panels, including the Verify button that opens a verification file dialog box. Many VP settings are stored in the project file with the *lst* extension.

E.2 Models Supported by the Visual Plumes Platform

There are presently five recommended models in VP: DKHW, NRFIELD/FRFIELD, UM3, PDSW, and DOS PLUMES. These and the Brooks far-field algorithm are briefly described below.

UM3

UM3 is an acronym for the three-dimensional Updated Merge (UM) model for simulating single and multi-port submerged discharges. The model is coded in Delphi Pascal, the language of Visual Plumes.

UM3 is a Lagrangian model that features the projected-area-entrainment (PAE) hypothesis. This established hypothesis quantifies forced entrainment, the rate at which mass is incorporated into the plume in the presence of current. In UM3 it is assumed that the plume is in steady state; in the Lagrangian formulation this implies that successive elements follow the same trajectory (Baumgartner et al., 1994). The plume envelope remains invariant while elements moving through it change their shape and position with time. However, ambient and discharge conditions can change as long as they do so over time scales which are long compared to the time in which a discharged element reaches the end of the initial dilution phase, usually at maximum rise.

To make UM three-dimensional, the PAE forced entrainment hypothesis has been generalized to include an entrainment term corresponding to the third-dimension: a cross-current term. As a result, single-port plumes are simulated as truly three-dimensional entities. Merged plumes are simulated less rigorously by distributing the cross-current entrainment over all plumes. Dilution from diffusers oriented parallel to the current is estimated by limiting the effective spacing to correspond to a cross-diffuser flow angle of 20 degrees.

The runtime and display performance of UM3 has been improved by better controlling the simulation time step. In addition to being controlled by the amount of entrainment, the time step is now also sensitive to the amount of trajectory curvature. In some cases, this sensitivity to curvature actually reduces the number of time steps needed to produce a simulation because the sensitivity to entrainment can be reduced.

Due to the fact that UM3 is coded in Delphi Pascal, the native language of VP, UM3 is fully integrated with VP's background build-up capability. Given that a time-series record for tidal flow in a one-dimensional channel can be provided, VP can estimate the buildup of background concentration resulting from the repeated passage of a given fetch of water past the discharge.

DKHW

DKHW is an acronym for the Davis, Kannberg, Hirst model for Windows. Like UM3, DKHW is also a three-dimensional plume model that also applies to single and multi-port submerged discharges. Unlike UM3, DKHW is a Fortran-based executable that is called by VP on demand. This method of implementation plus a more detailed near-field theory carries a penalty in the form of generally greater execution time.

Within VP, DKHW runs from a DOS SHELL evidenced by a DOS window that appears when it is run. Depending on the operating system, one may need to close the DOS window after DKHW is finished running. The word “finished” appears in the window’s title bar to indicate that DKHW is done, at which time the window may be closed.

DKHW is based on UDKHG and UDKHDEN described in *Fundamentals of Environmental Discharge Modeling* (Davis, 1999).

PDSW

PDSW is the VP name for the PDSWIN executable model, an acronym for the Prych, Davis, Shirazi model for Windows, which has been modified to be compatible with VP. PDSWIN is a version of the PDS surface discharge program also described in *Fundamentals of Environmental Discharge Modeling* (Davis, 1999). PDS is a three-dimensional plume model that applies to discharges to water bodies from tributary channels, such as cooling tower discharge canals. Like DKHW, PDSWIN is a Fortran-based executable that is called by VP on demand. PDSWIN provides simulations for temperature and dilution over a wide range of discharge conditions. PDS is an Eulerian integral flux model for the surface discharge of buoyant water into a moving ambient body of water that includes the effects of surface heat transfer.

NRFIELD

NRFIELD (RSB), as its entry on the Model menu suggests, is the successor to the PLUMES RSB model. NRFIELD is an empirical model for multiport diffusers based on the experimental studies on multiport diffusers in stratified. NRFIELD is based on experiments using T-risers, each having two ports, so at least four ports must be specified for it to apply. An important assumption is that the diffuser may be represented by a line source. This assumption may have important implications on small mixing zones, in which the plumes may not have merged.

FRFIELD

The FRFIELD model estimates the long-term distribution of pollutants in the vicinity of the outfall. This model is based on the two-dimensional "visitation-frequency" model and is not currently operational.

DOS PLUMES (DP)

DOS PLUMES, formerly called PLUMES, is the direct predecessor of VP. See the PLUMES users’ guide (Baumgartner, Frick, and Roberts, 1994) for a detail description of the model. DOS PLUMES is linked to VP because of some unique capabilities that may be useful to the VP user.

Brooks far-field algorithm

This “model” is a simple dispersion calculation that is a function of travel time and initial waste-field width.

The algorithm, through the VP time-series capability, can simulate time-dependent behavior. This is very important for estimating the effect of highly variable mechanisms such as bacterial decay, which depends greatly on the variable intensity of ultra-violet radiation.

Appendix F

Agency Comments and Responses

Georgia EPD
Comments were provided by Dr. Elizabeth Booth on a written copy and were made in the report.

South Carolina DHEC
Comments were provided by Mr. Wade Cantrell via email.

Comment: Both the near-field plume modeling and the far-field DO modeling are based on characteristics that vary considerably within the harbor area, so a final DO mitigation plan should include similar modeling for each proposed injection location. Depending on location, additional analysis may be needed to rule out the possibility of vertical turbulence, upward movement of the injected plume, and lower DO transfer efficiency compared to the demonstration site.

Response: We concur and this work has been initiated between the USACE Savannah District and Tetra Tech. Work will be completed by November 2009.

U.S. Fish and Wildlife Service
Comments were provided by Mr. Paul Conrads at the USGS via letter dated April 13, 2009 addressed to Ms. Sandra Tucker. The review focused on the MACTEC report because that report provided analysis of monitoring data rather than modeling predictions. Therefore, there are no comments here to address.

Ed Eudaly supplied a comment supporting the recommendations made by South Carolina DHEC:

Comment: I believe that this is an excellent recommendation and support it. I realize that logistics and infrastructure are considerations in selecting the injection sites. However, the recommended modeling would be very useful in determining whether the proposed injection sites are effective in addressing the predicted impacts. I expect that this recommendation will be discussed at the upcoming meeting.

Response: Same as response for South Carolina DHEC above.

EPA Region 4
Comments were provided by Mr. Jim Greenfield at the EPA Region 4 via memo on April 17, 2009.

Comment: This Overall O2 Transfer Efficiency (OOTE) is an important factor, as illustrated in the modeling report. Appendix C of the Savannah Harbor ReOxygenation Modeling (Tetra Tech 2009) report shows that the difference between 70% and 90% OOTE can be more than 0.1 mg/l DO added to the system.

Response: We concur and Appendix C is interpreted correctly.

Comment: The mixing zone model and the Harbor model (Tetra Tech 2009) with O2 injection provided good insight on how the oxygen is distributed throughout the harbor; however the monitoring data collected was not sufficient to provide a conclusive model calibration. Based on other studies and the models' capabilities, oxygen injected into the Harbor can be simulated fairly accurately if the OOTE is known. If an OOTE of 70% to 80% is used the models can be used to determine the amount of O2 that must be injected to mitigate the impacts of the various deepening alternatives.

Response: We concur.