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Modeling of Oxygen Injection Experiment in Savannah Harbor

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ABSTRACT

A technology that is being considered for improving the dissolved oxygen regime and mitigating impacts due to Savannah Harbor navigation channel deepening is oxygen injection. The injection is exercised by a Speece cone, which pumps water out of the river, supersaturates under pressure, and discharges back into the river to elevate the dissolved oxygen (D.O.). During August 2007, a demonstration project was developed by the Georgia Ports Authority (GPA) to determine if the technology is a viable mitigation option. Tetra Tech, Inc. performed the mathematical modeling as a tool to estimate the effectiveness of the injection experiment. The technical approach uses simulation results of 1) the near-field model (Visual PLUMES), which allows evaluating the size of a mixing zone for the oxygen supersaturated water jet; 2) the far-field model (combination of EFDC and WASP), which allows simulating D.O. dynamics in the harbor; 3) the post processing tool (WAMS), which produces statistics, deltas, visualizations, and other metrics for evaluation of the harbor responses on oxygen injection and other water management measures.

INTRODUCTION

Insufficient depths of U.S. harbors constrain their use for maritime shipping. The need to deepen existing harbors is imperative for expanding operating schedules for vessels and acceleration of business at the nation's ports. The deepening impacts the estuary's environment by increasing salinity intrusions, depleting dissolved oxygen and affecting suitable habitat areas. An acceptance of deepening projects by federal, state and local environmental agencies depends on detailed analyses of potential environmental impacts and development of mitigation plans that adequately address such impacts.

The Savannah District of the United States Army Corps of Engineers (USACE) has partnered with the GPA to evaluate the feasibility of deepening the navigation channel in the Savannah Harbor. This effort is called the Savannah Harbor Extension Project (SHEP). The project developed the studies to identify whether deepening the navigation channel from its presently authorized 42-foot depth Mean Low Water (MLW), up to a depth up to 48-feet MLW is warranted and environmentally acceptable. Hydrodynamic and water quality models for the SHEP was developed and determined to be acceptable (March 2006) by the USACE, United States Environmental Protection Agency (USEPA), United States Fish and Wildlife Services (USFWS), Georgia Environmental Protection Division (GAEPD), and South Carolina

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Department of Health and Environmental Control (SCDHEC) to identify dissolved oxygen and salinity levels throughout the Savannah Harbor. The model uses the Environmental Fluid Dynamics Computer Code (EFDC) for hydrodynamics and the Water Quality Analysis Simulation Program (WASP) for water quality. The model was 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 habitat of striped bass, flounder, shad, and shortnose sturgeon habitats; and increased levels of chloride at the City of Savannah's water intake.

Results of extensive modeling simulations show an increase in salinity levels and frequencies in the harbor due to channel deepening. The increased channel depth allows for more salinity to enter the harbor and stratify during neap tidal conditions. This increased salinity and decreased vertical mixing lowers the dissolved oxygen concentrations in the harbor. A new technology that is being considered for improving the dissolved oxygen regime and mitigating impacts is oxygen injection.

D.O. INJECTION EXPERIMENT

To allow waters in the Savannah Harbor to meet the mitigation purposes, oxygen can be added using super oxygenation systems typically used for water and wastewater treatment. The super oxygenation method is a simple process based upon the principle of Henry's Law. The technology pulls a small sidestream flow from a river, superoxygenates it (using pure oxygen) and dilutes back in the river to satisfy D.O. deficiences. The sidestream is superoxygenated to achieve concentrations of 40 to 100 mg/L. Contrary to popular misconception, the D.O. concentrations of less than 100 mg/L do not spontaneously effervesce, but can be kept in solution under hydrostatic pressure below the water.

During August 2007, a demonstration project was developed by the GPA to determine if the technology is a viable mitigation option. The demonstration project included two 12-foot diameter cones mounted on a barge at The Industrial Company (TIC) near Talmadge Bridge across from River Street in 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 was about 100 feet from the rip-rap shoreline at high tide. 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 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 gpm and the load was about 27,000 lbs/day. The schematic of the experiment is shown in Figure 1.

The injection experiment period was August 6 - September 16, 2007. The locations shown in Figure 2 were collected during the experiment and used for the models validation:

- Continuous dissolved oxygen data (GPA sites 1-2)
- The current USGS dissolved oxygen monitor (Site 3)
- Vertical Profile Stations (1-14)
- Transects (1-5) with cross-points (A-E)

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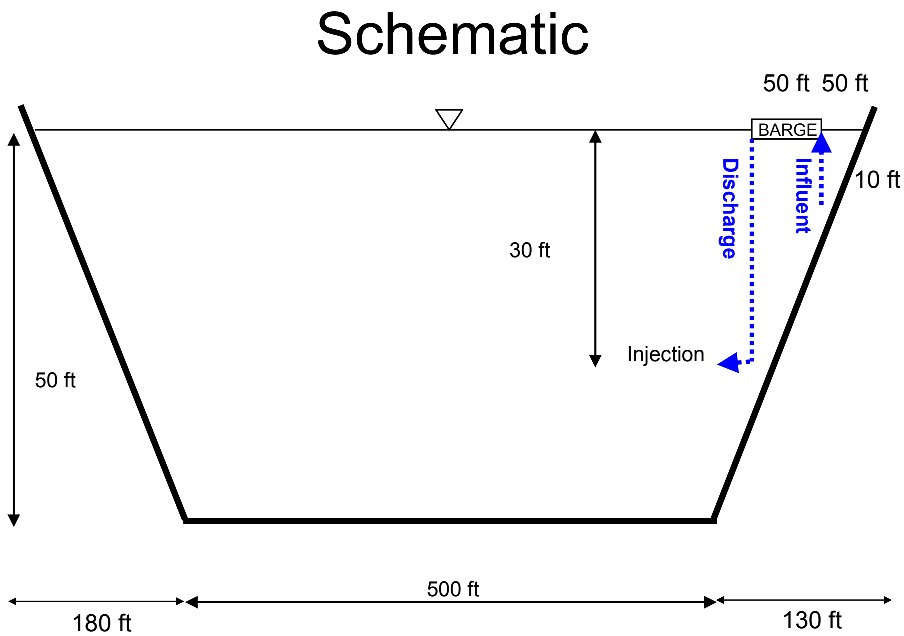

Figure 1 Schematic of GPA dissolved oxygen injection experiment

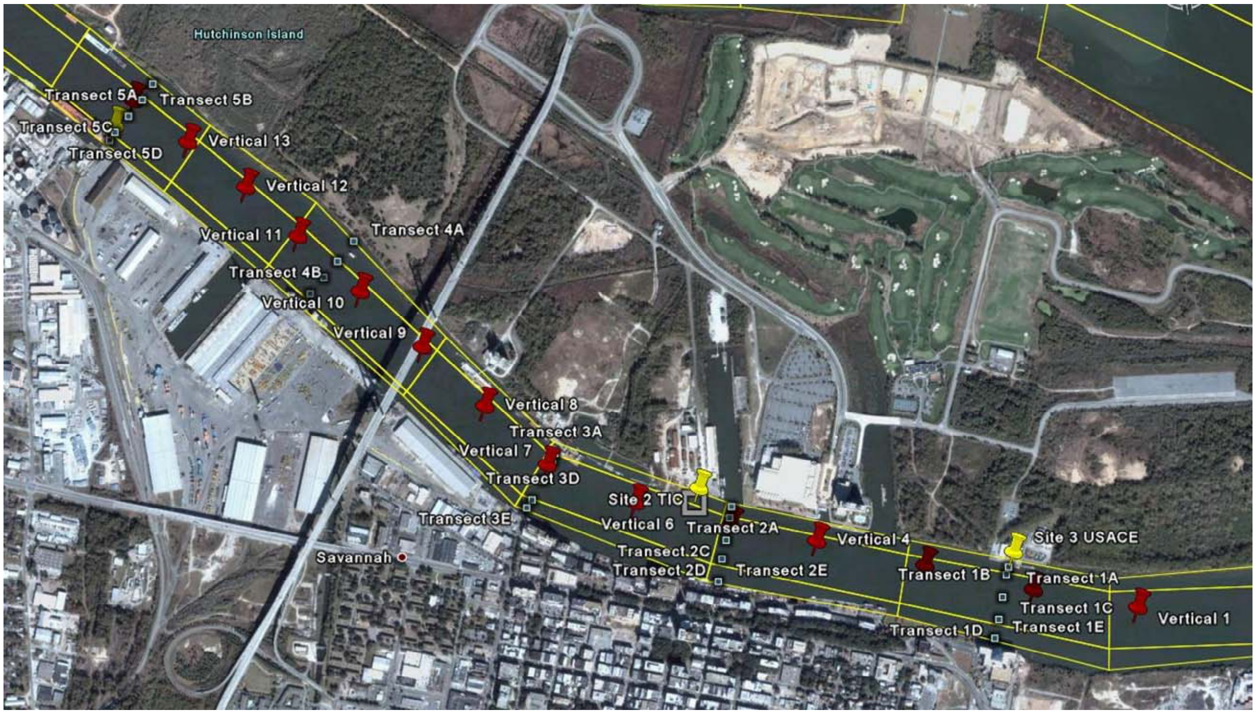

Figure 2 Model grid with summer 2007 monitoring stations

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Figure 3 shows the D.O. loads discharged into the Savannah River during the demonstration project. A portion of the oxygen load was in a "bubble" phase and was released in the side of the channel near the barge, called the overbank of the channel. The dissolved load, which was the majority of the total load, was discharged into the middle of the navigation channel. Figure 3 shows the total load, the main channel (dissolved) load, and the overbank (bubble phase) load.

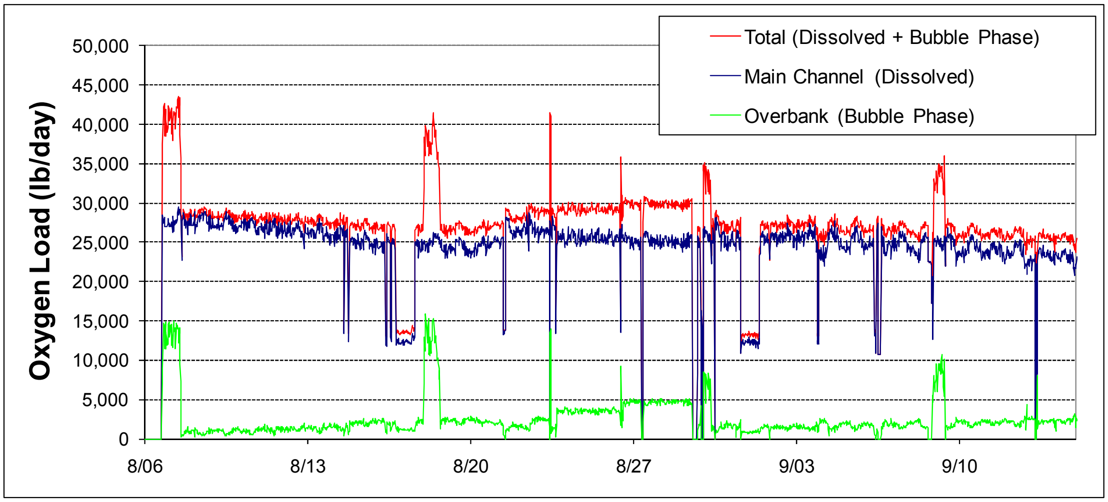

Figure 3 Data of monitoring of oxygen loads during the injection experiment

MODELING APPROACH

Mathematical modeling was applied as a tool to estimate the effectiveness of the conducted injection experiment. The technical approach uses simulation results of:

1. The near-field model Visual PLUMES (VP) was developed by EPA Office of Research and Development (Frick, 2004), which allows evaluating the size of the mixing zone for the oxygen supersaturated water jet from the injection device (Speece cone). VP is a Windows-based mixing zone modeling application. It 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.

2. The far-field model (three-dimensional) EFDC and WASP based Savannah model was developed in 2006. The model allows simulating salinity and dissolved oxygen dynamics. In developing a hydrodynamic and water quality model for the Savannah Harbor Estuary, 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 model was calibrated, validated and accepted by federal and state agencies as the tool for evaluation USACE SHE and Savannah Harbor Ecosystem Restoration Projects, finalization of the USEPA Region 4 Dissolved Oxygen TMDL, and the states of Georgia and South Carolina issuing NPDES permits.

3. The postprocessor (WAMS –Savannah Estuary) was developed as a tool to support USACE Savannah District, USEPA Region 4 and GA EPD water management decisions by statistical and graphical interpretations of results of the estuary hydrodynamics and

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water quality modeling. WAMS is a suite of FORTRAN based modules combined with the Graphical User Interface. WAMS allows selecting EFDC and WASP binary outputs for analyzing their content and extracting the information to create different statistics, tables, visualizations and other metrics for making quantitatively based assessments and managerial decisions.

The models use the 2007 data collection of loads, flows, tides and meteorology experienced during the demonstration project.

NEAR-FIELD MODEL RESULTS

Visual Plumes 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 3-D EFDC Savannah Harbor model was used to develop the flow and velocity field under which the test was done. The 3-D model was run for the summer period of 2007 when the injection test was carried out. The ambient river time series of velocity, salinity and temperature were obtained from the EFDC simulation results. Other input information required by the near-field model includes the physical setup of the discharge and physical schematization of the channel cross section at the injection location. The injection setup represents two 18-inch pipes, separated 20 ft discharge at a depth of 30 feet with a downward vertical angle of 10^o.

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.

FAR-FIELD MODEL RESULTS

To use the far-field model for the simulation of the oxygen injection experiment scenario the validation tests at 2007 "forcing" conditions were passed. The data collected for validation tests were discussed in section "D.O. Injection Experiment".

The grid cell with Speece cones is presented in Figure 4. The distribution of loads between vertical layers at middle channel and overbank is presented in Figure 5. This distribution along with time-series of D.O. loads (Figure 3) allows calculating D.O. injection loads that the water quality model is using during validation and assessment runs.

Figure 4 Location of Injection in the model grid

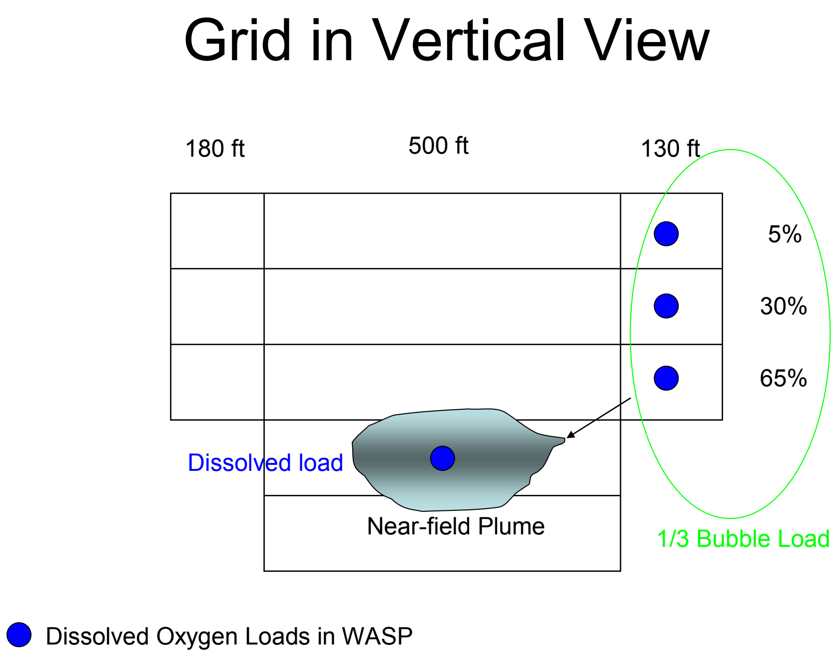

Figure 5 Vertical locations of cells with oxygen injections

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Figures 6 shows the correspondence of D.O. simulations to continuous data monitored at GPA (one of three stations - GPA, Barge, and USACE Dock monitors shown in Figure 2) – in surface layer of the estuary. Even though not shown in this paper, the Barge and USACE Dock locations showed similar trends as with the data.

Figure 7 compares the major range of D.O. simulations along a mainstream of Savannah River (navigation channel) with data from fourteen Vertical Profile stations. The corridor of D.O. simulated values is limited by 5, 50, and 95 percentiles of D.O. distributions along the surface layer of the navigation channel. The simulations demonstrate a good agreement with data.

Comparisons of D.O. simulations with cross-sectional averages monitored at transects 1-5 (Figure 2) with cross-points A-E and 14 recorded moments show that time-average relative errors for 5 cross-sections change between 7 and 11 percents. It confirms the acceptable model validation and its ability to provide the information that is useful for assessment of the D.O. injection experiment effectiveness.

Three D.O. characteristics were used for evaluation of the oxygen injection effectiveness: D.O., D.O. deficit, and D.O. percentage of saturation. WAMS was applied for calculations of 95^{th}, 50^{th}, and 5^{th} percentiles of these D.O. characteristics. 95^{th} and 5^{th} percentiles limit consequently the higher and lower boundaries of D.O. and percentage of D.O saturation in cells of surface and bottom area; 50^{th} percentile allows evaluation of median values. Conversely, the 95^{th} and 5^{th} percentiles of D.O. deficit limit correspondently the lower and higher boundaries of D.O. concentrations in the estuary. The delta approach was applied for evaluation of the oxygen injection system's effectiveness. Delta is calculated as the deference taken between D.O. characteristics simulated under the Injection and No Injection scenarios.

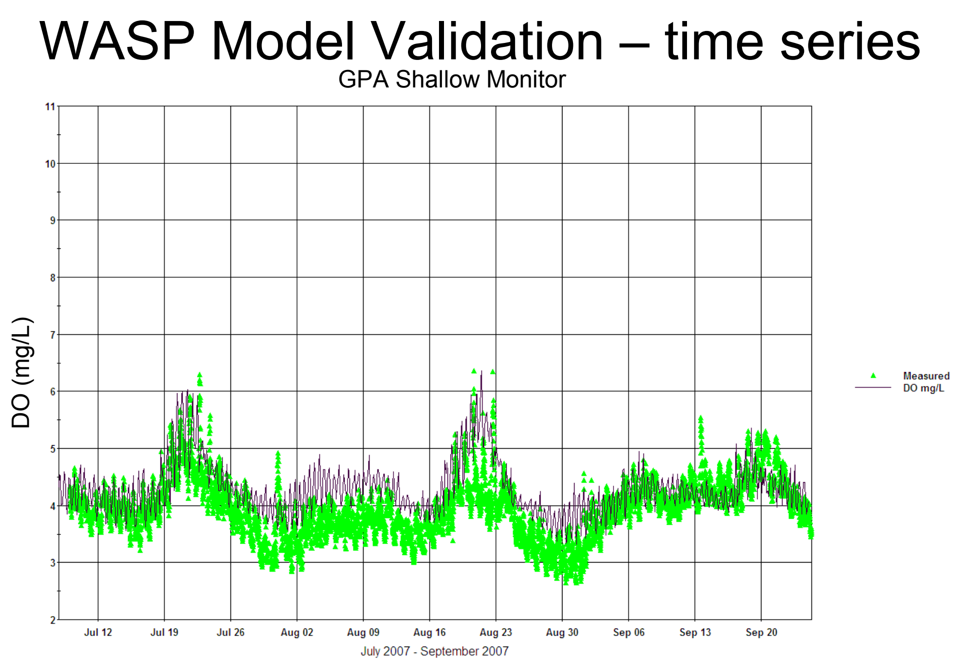

Figure 6 D.O. simulation comparisons with data from GPA shallow monitor

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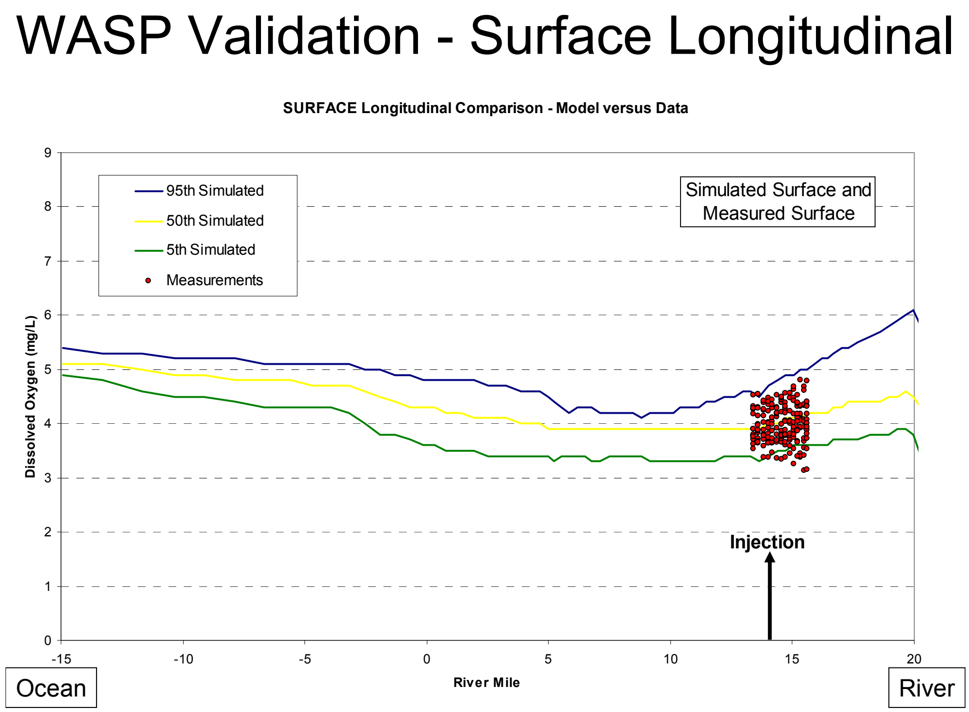

Figure 7 Comparison of D.O. simulations with data from vertical profiles

The distributions of D.O. deltas for surface and bottom layers are represented by Figures 8 and 9. The maximum deltas for 50th percentile of D.O. concentrations are: 0.15 mg/L in surface layer and 0.41 mg/L in bottom area. The 0.15 mg/L maximum in the surface is shown in Figure 8 and the 0.41 mg/L maximum in the bottom is shown in Figure 9. These simulations show that the demonstration preoject of injecting approximately 27,000 lbs/day raises the D.O. concentrations from 0.15 to 0.41 mg/L in the water column. These deltas can serve as rough estimates of the maximal effect of the experimental injection system.

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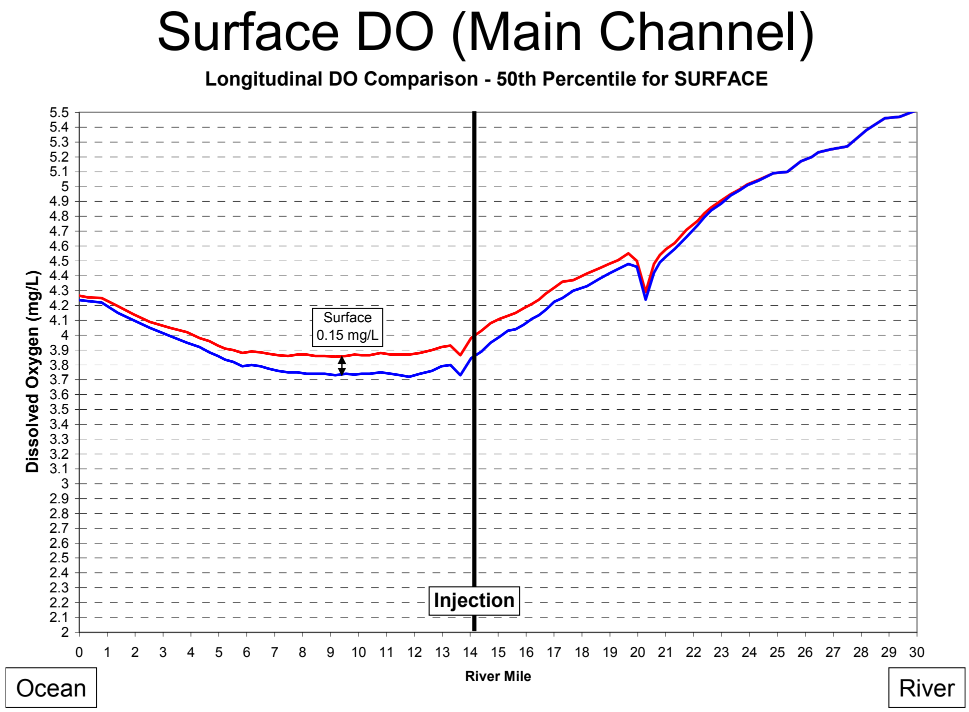

Figure 8 Delta of 50th percentiles of D.O. in the navigation channel

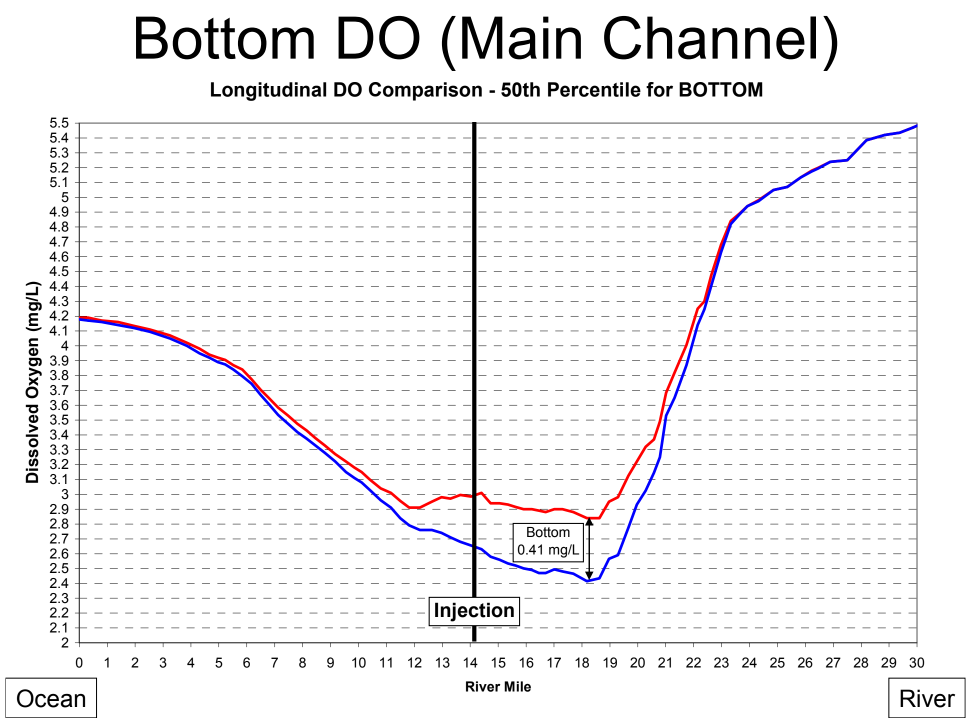

Figure 9 Delta of 50th percentiles of D.O. in the navigation channel

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DISCUSSION AND CONCLUSIONS

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 injection is exercised by a super oxygenation system, which pumps water out of the river, supersaturates under pressure in the cone, and discharges back into the river to elevate D.O.

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Apparent problems with evaluation of the D.O. injection far-field effects were solved by using the well calibrated hydrodynamical and water quality model of Savannah Harbor. The model was 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 extensive validation procedure elevates trust in the model's ability to simulate the harbor's oxygen dynamics. The approach supports including into the simulation scenarios numerous important metheorological and hydrological factors that are specifical for the harbor. The absence of such factors (tides, water temperature and salinity dynamics) may significantly distort the estimates of the injection effectiveness.

The far-field analysis showed an increase 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.

The delta approach was applied for evaluation of effectiveness of the experimental oxygen injection system. Delta was calculated as the difference taken between D.O. characteristics simulated under the Injection and No Injection scenarios.

REFERENCES

Frick, E. F., 2004: Visual Plumes mixing zone modeling software. *Environmental Modeling & Software,* Volume 19, Issues 7-8, July-August 2004, 645-654

Tetra Tech, Inc., 2006: Development of the Hydrodynamic and Water Quality Models for the Savannah Harbor Expansion Project. Atlanta, Georgia.