

**SAVANNAH HARBOR REOXYGENATION
DEMONSTRATION PROJECT**

SUPPLEMENTAL DATA EVALUATION REPORT

SAVANNAH, GEORGIA

Prepared for:



GEORGIA PORTS AUTHORITY
Savannah, Georgia

Prepared by:

MACTEC ENGINEERING AND CONSULTING, INC.
Kennesaw, Georgia

August 19, 2009

MACTEC Project 6110-08-0064

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EXECUTIVE SUMMARY

The Supplemental Data Evaluation Report has been prepared to address comments from state and federal agencies on the data analyses for the Savannah Harbor ReOxygenation Demonstration Project (ReOx Project) performed in the summer (August to mid-September) of 2007 and to provide further information regarding performance of the ReOx system.

The purpose of the Savannah Harbor ReOx Project was to demonstrate at full scale that Speece Cone supplemental oxygenation technology could be successfully adapted and used in tidal Savannah Harbor for mitigation of DO impacts associated with proposed harbor deepening.

The ReOx demonstration system consisted of two barge-mounted 12-foot diameter Speece Cones with a combined nominal design capacity of 30,000 pounds per day of supplemental dissolved oxygen.

The actual amount of molecular oxygen gas that can be dissolved in a Speece Cone is physically governed by internal operating pressure, water temperature and the volume of water pumped through the cone, all in accordance with Henry's Law. Even under optimum conditions, not all of the molecular oxygen added to a Speece Cone gets dissolved in the cone. Inherent to the Speece Cone technology, about 10 percent of the added oxygen gas winds up getting continuously swept through the cone as very fine oxygen bubbles. Upon discharge at depth from the cone, these buoyant oxygen bubbles naturally rise toward the surface, incidentally transferring some of their oxygen to the river water column as they rise, still in accordance with Henry's Law. This inherent fine-bubble loss means that the nominal transfer efficiency for a Speece Cone is about 90 percent. Further, if more than the nominal 10 percent excess oxygen gas is added to the cone beyond the Henry's Law solubility limit for pressure and temperature, that excess oxygen gas will accumulate inside the cone as a coarse oxygen bubble that is periodically belched from the submerged cone discharge.

Both the continuous fine-bubble rise and episodic oxygen-bubble belching were observed during the ReOx demonstration. In order to maximize the total amount of dissolved oxygen added to the deep navigation channel during the demonstration, the Speece Cones were routinely supplied with more oxygen gas flow than could be dissolved for the available pump flow and pressure. This oxygen overloading was particularly the case during the last few weeks of the demonstration period when unknown progressive pump wear and pump-seal failures further diminished available water flow and pressure. Because the oxygen gas flow to the cones was not proportionately reduced as the water flow

and pressure diminished, more frequent oxygen gas belching was observed toward the end of the demonstration period. In any event, by overloading the cones with oxygen gas beyond Henry's Law solubility limits, the maximum possible amount of oxygen was dissolved in the jetted deep plume to the navigation channel but the excess oxygen gas was being lost through undissolved bubbles rising in the shallow overbank water column.

In total, the ReOx demonstration system added an average of 27,000 pounds per day of dissolved oxygen to the river. This added dissolved oxygen was in two components, one by design and the second incidental to system operation: approximately 25,000 pounds per day was jetted outward and downward from the cone discharge at a depth of 33 feet as a high-velocity dissolved-oxygen plume into the deeper layers of the navigation channel; the other 2,700 pounds per day was incidentally dissolved to the shallow overbank layers from oxygen bubbles rising to the surface where the ReOx barge was moored in the overbank. Overall, the limiting factor for oxygen dissolution by the Speece Cones during the demonstration period was the flow and pressure combination available from the barge-mounted water intake pumps. The cones could have dissolved more oxygen to the river had greater pump flow and pressure been available.

A simple mass balance was used with freshwater inflow and salinity data to estimate the fully-mixed average DO increase that the added amount of dissolved oxygen could produce in the river at the DO injection section. These mass-balance estimates range from an average DO increase of 0.04 to 0.76 milligrams per liter (mg/L) with an overall average of 0.53 mg/L during the ReOx demonstration period.

The Savannah Harbor three-dimensional hydrodynamic water quality model was also used and separately reported by others (TetraTech, 2009) to estimate the expected DO increase that the added amount of oxygen could be expected to produce in three dimensions. The Savannah Harbor model results indicated that the largest DO effects (about 0.6 mg/L) would be expected to occur in the deeper layers of the navigation channel and that the minimum DO improvements (about 0.2 mg/L) would be expected to occur in the overbank layers.

Four categories of instream DO water quality monitoring were conducted for the ReOx demonstration project: (1) periodic low- and high-slack-tide DO water quality transects taken at five full-channel cross sections, (2) periodic low- and high-slack-tide DO water quality vertical full-depth profiles taken longitudinally along the navigation channel centerline, (3) one slack-tide DO water quality plume mixing

characterization at the ReOx barge, and (4) continuous multiple-depth DO water quality monitoring sondes deployed at three nearshore overbank locations (GPA Dock 20, ReOx Barge, and USACE Dock).

The periodic slack-tide DO profiles and transects most clearly show evidence of the ReOx effects in the form of reduced DO deficits and spatial gradients that were not evidenced before or after the ReOx demonstration period.

The plume mixing characterization study at the ReOx barge location shows that the superoxygenated DO plume quickly mixed with the deep river water without opportunity for spontaneous effervescence.

Various attempts at statistically separating the relatively small expected DO effect of oxygen addition from the continuous DO monitoring data in the nearshore overbank locations proved unsuccessful. The relatively small expected DO effect in the overbank (only about 0.2 to 0.3 mg/L) was too small to be distinguished from the continuous near shore monitoring data for which the DO standard deviation was roughly double the expected DO effect.

This supplemental data evaluation report was developed to provide further analysis of the continuous monitoring data to evaluate whether the oxygen signal could be discerned from the inherent variability of tidal monitoring data and to correct assumptions presented in the Savannah Harbor ReOxygenation Demonstration Project Report dated January 8, 2008 that did not adequately characterize tidally driven water quality effects.

RECOMMENDATIONS

Overall, the 2007 ReOx project demonstrated in full scale and under field conditions that Speece Cone oxygenation technology can be adapted to the tidal conditions of Savannah Harbor for mitigation of DO impacts associated with proposed harbor deepening. The following actions are recommended:

- Develop a modular land-based ReOx station design specific to Savannah Harbor conditions, taking into account the “lessons learned” from the 2007 demonstration project.
- Identify, characterize, and acquire suitable shore locations for construction of two land-based dual cone ReOx stations.
- Obtain the necessary permits and approvals for construction and operation of the land-based ReOx stations.
- Construct the foundations and permanent shore-based infrastructure and service access for each ReOx station in advance and make the stations ready for subsequent seasonal installation and operation of the ReOx equipment in concert with harbor deepening.

- Until permanent land based ReOx systems are operational, temporary barge mounted systems could be used to provide oxygen for seasonal mitigation.
- Monitor the effects to water quality in an adaptive management approach so that system modifications may be made to increase transfer efficiency until the systems are optimized.
- Develop operation and maintenance plans and activities for a permanent installation. Consider backup systems as a part of the system design and installation.
- Employ the use of conservative overall oxygen transfer efficiency (OOTE) of 70 to 80 percent for design purposes. Once permanent installations are implemented, then actual OOTE may be determined and apply an adaptive management approach.
- In the sampling and analysis program for permanent systems. instream monitoring should include alternative methods for oxygen transfer efficiency monitoring, near-field mixing zone monitoring, and frequent and detailed transect monitoring. Development of the monitoring program should include consideration of continuous monitoring, regular (daily) instream cross sectional measurements taken manually, and dye studies.

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LIST OF ACRONYMS

AIC	Akaike Information Criterion
cfs	cubic feet per second
DO	dissolved oxygen
GPA	Georgia Ports Authority
MACTEC	MACTEC Engineering and Consulting, Inc.
mg/L	milligram per liter
MGD	million gallons per day
MLR	multiple linear regression
OOTE	overall oxygen transfer efficiency
ppt	parts per thousand
RM	river mile
ReOx Project	Savannah Harbor ReOxygenation Demonstration Project
SN	signal-to-noise
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

1.0 INTRODUCTION AND BACKGROUND

The proposed deepening of Savannah Harbor is critically important to the Georgia Ports Authority (GPA) and the State of Georgia. Without deepening, the Port of Savannah and Georgia risk losing significant business and revenue to other east-coast ports that can accommodate the growing number of larger deep-draft ships. Harbor deepening will have the unintended consequence of reducing atmospheric reaeration into the harbor's deepened water. This reduced reaeration can result in reduced dissolved oxygen (DO) concentrations, particularly during the critical season from about mid June through mid October when river temperatures are higher and lower river flows are more prevalent.

The Savannah Harbor ReOxygenation Demonstration Project (ReOx Project) was implemented to demonstrate a technology capable of mitigating for the lost reaeration capacity caused by the planned future deepening of the navigation channel. The total amount of oxygen delivered to the river by the ReOx project was a fraction of the total oxygen needed for mitigation. The locations of permanent ReOx systems and the planned operations of these systems will be different than the temporary ReOx Project installation. For the ReOx Demonstration Project, the systems were pushed to their maximum capacity. Permanent systems will be operating nearer the mid-range of capacity to improve efficiency and to ease operations. Also, permanent system locations will be optimized using the Savannah Harbor Model which was not available for design and implementation of the ReOx Project.

The ReOx Project was located on the Savannah River within the harbor area in Savannah, Georgia (Figure 1.1). The temporary demonstration system was mounted on a barge (110 feet long by 50 feet wide) moored to the Hutchinson Island side of the navigation channel approximately 50 feet from the top of the bank across from the Historic District of downtown Savannah. The ReOx Project oxygen injection systems consisted of two 12-foot diameter Speece Cones and various support equipment including a liquid oxygen storage tank and vaporizers, four four-hundred horsepower pumps, and electrical power equipment (Figure 1.2). Intake pipes for the pump system were located on the seaward (downstream) side of the barge and positioned approximately 10 feet below the water surface. The system return flow inject pipes were located on the riverside, upstream end of the barge approximately 33 feet below the water surface. The return lines were angled approximately 10 to 15 degrees downward to direct, or jet, the return flow as deep as possible into the deeper portions of the dredged navigation channel (Figure 1.3). The two Speece Cones have a combined pure oxygen dissolution design capacity of approximately 30,000 pounds per day, depending on pump flow, pressure, and water temperature.

The ReOx Demonstration Project was conducted during the water-quality critical season of 2007 (from August 7, 2007 through September 16, 2007) to assess the viability of the use of supplemental oxygenation as a DO mitigation measure for proposed harbor deepening. MACTEC Engineering and Consulting, Inc. (MACTEC) issued a project report on the performance of the system in January 2008 (MACTEC, 2008). Details specific to system setup and operation are contained within the 2008 report. Since issuance of the report, several questions and comments were raised by state and federal agencies regarding interpretation of the monitoring data collected during the ReOx Project and system performance. This supplemental data evaluation report was developed to provide further analysis of the continuous monitoring data to evaluate whether the oxygen signal could be discerned from the inherent variability of tidal monitoring data and to correct assumptions presented in the Savannah Harbor ReOxygenation Demonstration Project Report dated January 8, 2008 that did not adequately characterize tidally driven water quality effects. This Supplemental Data Evaluation Report has also been prepared to address these comments and to provide further information regarding system performance.

1.1 SAVANNAH HARBOR MODEL

The Savannah Harbor Model is a 3-dimensional hydrodynamic (Environmental Fluid Dynamic Code – EFDC) and water quality model (Water Quality Analysis Simulation Program – WASP). This model was used to assess baseline conditions in the harbor (had the ReOx system not been in operation) and DO response expected in the harbor due to operation of the ReOx system. Model runs were made using ReOx system performance data presented in Section 2.0 to simulate the effects of the ReOx system on DO concentrations in the river (TetraTech, 2009). The model was used to calculate the DO effect attributed to oxygenation within each cell of the model. As would be expected, the model-calculated maximum DO effect is in the deeper main channel cells where the bulk of the oxygen was injected and less in the left and right overbank cells where the continuous water quality monitoring sondes were situated nearshore. Results of the modeling analysis are contained in a separate report prepared by TetraTech, Inc. titled, “Modeling of GPA’s Oxygen Injection Demonstration Project, Savannah Harbor, Georgia” (TetraTech, 2009).

2.0 ReOx SYSTEM PERFORMANCE ASSESSMENT

2.1 FINDINGS – SYSTEM PERFORMANCE

- Analysis of the system data indicated that the ReOx system transferred approximately 27,000 pounds of dissolved oxygen per day on average over the course of the approximately 6-week operations period.
- Oxygen dissolution in the Speece Cones is a function of Henry's Law. Calculated (theoretical) DO concentrations and DO concentrations periodically measured during operation of the ReOx system indicated that the system transferred the expected quantities of dissolved oxygen to the return-flow river water (average absolute error of 17.7 and 16.2 percent between theoretical and measured DO concentrations in the data for Cone 1 and Cone 2, respectively).
- Complete-mix/steady state mass balance calculations indicated that river DO concentrations in the injection segment of the river would have increased by an average of 0.53 milligrams per liter (mg/L) and ranged from 0.04 mg/L to 0.76 mg/L over the period of system operation.

Details pertaining to the analysis of oxygen transfer efficiency and system performance are contained in this section.

2.2 SYSTEM DESIGN

The ReOx system was designed to transfer up to 30,000 pounds of oxygen per day using two 12-foot diameter Speece Cones. Pumps were sized to provide approximately 8,000 gallons per minute of river water to each Speece Cone. Valves installed at the end of the system return lines (to the river) were partially closed to create approximately 150 feet of pressure head (about 65 pounds per square inch [psi]) within the cones. Oxygen gas entered the system at the top of the Speece cones under approximately 100 psi of pressure. Pump intake lines were screened to prevent debris from entering the pump system and set at a fixed depth of approximately 10 feet below the water surface. The fixed-depth return lines extended approximately 33 feet below the water surface and the superoxygenated water discharged through the open ends of the two return lines (at 10 to 15 degree downward angle) mixing in the river by jet momentum and tidal action, without benefit of a diffuser. A layout of the ReOx system on the barge is shown as Figure 1.3. Actual pump capacity turned out to be slightly less than originally designed, therefore additional pressure was created in the cones (nearer to 70 psi) to maintain the design oxygen transfer of the cones.

2.3 SYSTEM OPERATION

2.3.1 Speece Cone Operating Principals

Figure 2.1 provides an operations schematic of a Speece Cone. The Speece Cone consists of a conical vessel, narrow at the top and an expanding cross section. The small conical diameter at the top facilitates a high inlet velocity, which continually shears the oxygen gas into small bubbles creating an intense bubble swarm, through which all the water must pass. The expanding cross section of the cone progressively decreases the downward velocity of the water until at the bottom. This velocity is less than the buoyant velocity of the gas bubbles. Consequently, the bubbles cannot escape at the top of the cone due to the high inlet velocity and they cannot escape from the bottom due to the low exit velocity. In effect, the bubble swarm is trapped in the cone to achieve the oxygen absorption efficiency required. This trapped bubble swarm creates a very high gas area to water volume ratio with much surface area for gas transfer in the cone. In the Speece Cone, the oxygen is thus efficiently dissolved into the water as it passes through the bubble swarm (Dr. R.E Speece, 2009).

Transfer of oxygen to water by Speece Cones is about 90 percent efficient (Speece, 2007). The downward velocity of the water washes out some of the finer bubbles. These bubbles exit the system at the discharge point and will rise to the surface, until lost to the atmosphere. As these fine bubbles rise, they continue to dissolve transferring additional oxygen to the water column. The estimated oxygen transfer of the rising bubbles specific to the ReOx Project is discussed in Section 2.5.

The following case studies are provided in Appendix D:

- (1) Ashley, K.I, D.S. Mavinic, and K.J. Hall, 2008, "Effect of Orifice Diameter, Depth of Air Injection, and Air Flow Rate on Oxygen Transfer in a Pilot-Scale, Full Lift, Hypolimnetic Aerator," *Canadian Journal of Civil Engineering*, Vol 36, pp. 663-675.
 - In order to increase oxygen transfer in a full lift hypolimnetic aerator design, maximize the surface area of bubbles, use fine pore diameter diffusers, and place the diffusers at a maximum depth to the extent practical
- (2) Ashley, K.I, D.S. Mavinic, and K.J. Hall, 2008, "Oxygenation Performance of Laboratory-Scale Speece Cone Hypolimnetic Aerator: Preliminary Assessment," *Canadian Journal of Civil Engineering*, Vol 35, pp. 663-675.
 - A laboratory-scale Speece Cone was examined with low inlet velocities and it was found that oxygen transfer efficiency was lower than the recommended inlet velocity of full-

scale Speece Cones but was higher than that of a full design Speece Cone operating in air.

(3) Jung, Rodney, J.O. Sanders, Jr.H. and H.H Lai, 1998, “Improving Water Quality Through Lake Oxygenation at Camanche Reservoir,” *Presented at the AWWA Water Quality Technology Conference. November 24, 2008.*

- A hypolimnetic oxygenation system in the Camanche Reservoir near Jackson, California was installed in order to increase oxygen in deeper water of the lake. The oxygenation system proved to increase oxygen levels and was an overall a practical solution.

(4) Moore, B.C., et.al. “A Decade on the Bottom: Performance of a Speece Cone in Neman Lake.” (Unreferenced presentation)

- Lessons learned include the following: the Speece Cone is a practical and economical technology for hypolimnetic aeration; the system should be operated at full design capacity and for long periods of time to meet the total oxygen demand.

2.3.2 Henry’s Law and Theoretical Oxygen Transfer

The dissolution of oxygen in water is governed by Henry’s Law that states that at equilibrium, the ratio of the concentration of a gas in a liquid (water) to the gas’s partial pressure in the vapor phase for the liquid/gas mixture is a constant. To assess the DO delivered to the river during the operation of the ReOx system, operation parameters (water temperature, cone pressure, and water flow) collected at 10-minute intervals were used to calculate the dissolution of oxygen. These data are presented on Figures 2.2 and 2.3 for Cones 1 and 2, respectively.

In addition to the calculation of the mass of oxygen dissolved in water within the cones, spot DO measurements were made on the discharge side of the cones. To facilitate measurement of these superoxygenated DO concentrations, a five-times dilution of water from the river and the discharge from the cones blended. This blended water was measured for DO on the deck of the barge. During the initial measurements, it was learned that blending of superoxygenated water and river water should be accomplished under pressure so that oxygen would not effervesce when the superoxygenated water and river water were discharged from the unpressurized mixing chamber on the barge deck. Once this problem was corrected, discrete measurements were reasonably comparable with Henry’s Law theoretical DO concentrations for Cone 1 and Cone 2. Absolute errors for Cone 1 ranged from 0.4 percent to 37.4 percent with an average of 17.7 percent and 3.0 percent to 41.2 percent with an average of 16.2 percent

for Cone 2. A comparison of the theoretical DO concentrations and the measured DO concentrations for each cone is presented in Table 2.1.

2.4 THEORETICAL (MASS BALANCE) CHANGE IN OXYGEN CONCENTRATION

As part of estimating the expected oxygen addition effect in the river, a simple steady-state mass balance approach was used. This approach provided an estimate of the potential change in DO concentrations in the river at the injection cross section assuming complete mixing and conservation of mass. To make this calculation, the total flow (freshwater river flow and seawater flow) in the river is needed. Upstream, freshwater flows are monitored at the U.S. Geological Survey (USGS) gage on the Savannah River near Clyo, Georgia (USGS 2198500). These Clyo flows were increased by 10 percent to account for the increased contributing watershed at the location of the ReOx system. To estimate seawater flows, the methodology proposed by C.J. Velz (1970) was used. This methodology uses salinity as a flow/dilution tracer. For this calculation, daily flows from the upstream Clyo gage were used and averaged about 5,720 cubic feet per second (cfs) (adjusted to ReOx system location) and offshore seawater salinity was assumed at 33.5 parts per thousand (ppt). The following salinity mass balance equation was used:

$$\frac{Q_F S_F + Q_S S_S}{Q_F + Q_S} = S_{TS}$$

Where:

- Q_F – Freshwater inflow from upstream (cfs)
- S_F – Freshwater salinity (assumed 0 ppt)
- Q_S – Effective seawater flow in test segment (cfs)
- S_S – Seawater Salinity (offshore boundary, assumed 33.5 ppt)
- S_{TS} – average salinity in target tidal segment (measured) (ppt)

Rearranging this equation and solving for Q_S provides an estimate of the seawater flow at the monitored section. Using this estimated seawater flow, the theoretical expected DO increase at the DO injection segment of the river may be calculated using the following equation by solving for C_{DO} :

$$Q_{TF} (MGD) \times C_{DO} (mg/L) \times 8.34 = \text{Oxygen Load (pounds per day)}$$

Where:

- Q_{TF} – Total flow in the river in million gallons per day (MGD)
- C_{DO} – Instream oxygen concentration
- Oxygen Load = Average oxygen input of ReOx System - 27,000 pounds per day

This analysis between August 5 and September 15th, 2007 resulted in calculated increases in DO ranging from 0.04 to 0.76 mg/L with an average DO increase of approximately 0.53 mg/L. The average theoretical increase in DO during the system operation from August 7 to September 15 was 0.55 mg/L. The time series plot showing this calculated theoretical DO concentration increase using the flow data from the Clyo gage is presented as Figure 2.4. To calculate the theoretical DO increase, MACTEC used the median tidal day measured salinity values averaged from the deep and intake barge monitors. The theoretical increase in DO concentration was calculated using the oxygen load to the river (as measured by the Speece Cone instrumentation) as presented in Figures 2.2 and 2.3. Other input data and resulting calculated values for Q_s , Q_{TS} , and C_{DO} have been provided in Table 2.2.

2.5 ReOx SYSTEM – OXYGEN TRANSFER TO THE RIVER

The ReOx system transferred an average of 27,000 pounds of DO per day to the river in two components: in the dissolved form coming from the cones and oxygen dissolved from bubbles released by drag out rising through the overbank segment of the water column where the barged was moored.

Operation of a Speece Cone system has a nominal inherent oxygen loss caused by fine oxygen bubbles being swept through the system from the downward velocity of the water. This inherent loss has been measured (from prototype systems and other full-scale field systems [Speece, 2008]) to be approximately 10 percent. As the bubbles from the oxygen swept through the cone rise in the water column (approximately 33 feet deep), oxygen continues to dissolve. This additional oxygen dissolved in the overbank section of the river has been estimated (from Speece oxygen injection studies for the USACE at Thurmond [Clark Hill] Dam, Speece, 1978) to be approximately one-third of the mass of the oxygen bubbles released. Two-thirds of the mass of oxygen bubbles released is lost to the overlying atmosphere. This process is schematically represented and shown in Figure 2.5.

During the last half of the demonstration period, a decrease in pump efficiency due to wear of the impellers and loss of a seal in one of the pumps on the Cone 2 system decreased the transfer capacity of the Cone 2 system. Transfer capacity remained higher in Cone 1 than in Cone 2 because the pumps did not have as much wear and the seals remained intact. Loss of pump capacity reduced average flow in Cone 2 from approximately 7900 gpm to approximately 6900 gpm and internal cone pressures dropped from 70.6 psi to approximately 69.7 psi, when comparing the first half of system operation to the last half. This decrease in transfer efficiency noted in the last half of operation for Cone 2 was characterized by oxygen escaping from the bubble swarm and collecting at the top within the cone creating a large

“coarse” bubble within the cone. Periodically, the coarse-bubble of oxygen gas would be forced from Cone 2 and released to the water column. This release of the coarse-bubble occurred at intervals varying from 20 minutes to approximately 1-hour and, while noticeably visible, accounted for only a minor additional loss of oxygen from the system.

During system operation, several oxygen flow ramp up studies were performed to assess the range of cone performance. These studies included increasing the oxygen flow incrementally to measure the dissolution efficiency. Because the conditions of pump wear and damage were not known, these studies resulted in a short-term increased loss of oxygen from the system. More oxygen gas was being added to the cones than could be dissolved for the prevailing pump flow and cone pressure conditions. However, because oxygen dissolution is governed by Henry’s Law and is a function of pressure, temperature, and flowrate within the cones, the nominal quantity of oxygen continued to dissolve within the cones and was transferred to the bulk water in the river main channel. Oxygen transfer time series plots for the combined ReOx system, Cone 1, and Cone 2 are shown as Figures 2.6, 2.7 and 2.8. These figures present the estimated oxygen flow to each cone, the mass of oxygen dissolved to the water and delivered to the bulk water in the deepened navigation channel, the quantity of oxygen transferred to the overbank sections as a result of rising bubbles, the total oxygen transferred to the river, and the quantity lost to the atmosphere through bubbles.

The dissolved oxygen transfer capacity for a specific Speece Cone is a function of three factors: (1) Henry’s Law governing gas solubility for the given temperature and pressure inside the cone, (2) the oxygen gas mass-flow rate delivered to the top of the cone and (3) the water flow rate through the cone.

Henry’s Law governs the dissolved oxygen concentration exiting the cone while the cone geometry and water flow rate are configured to provide ample detention time inside the cone for the oxygen-to-water transfer to equilibrate in accordance with Henry’s Law. However, as a practical matter it has been found that about 10 percent of the oxygen gas added to a Speece Cone will not dissolve in the cone but will inevitably “drag through” the cone with the water flow and exit the bottom of the cone as buoyant fine oxygen bubbles. This inherent drag-through effect means that the nominal maximum oxygen transfer efficiency for a Speece Cone (from cone inlet to cone outlet) is 90 percent. So long as the oxygen gas flow rate supplied to the cone is maintained at or below 110 percent of the Henry’s Law oxygen solubility limit for the prevailing temperature and pressure inside the cone, the inlet-to-outlet oxygen transfer efficiency will hold at the nominal 90 percent level.

If still more excess oxygen gas is added to the cone, going beyond 110 percent of the controlling Henry's Law solubility limit, that further excess amount of oxygen gas will not dissolve and will instead accumulate inside the cone and be periodically "belched" from the cone discharge as coarse bubbles. In order to operate at the nominal 90 percent oxygen transfer efficiency, the cone must not be loaded with more oxygen gas than 110 percent of the Henry's Law dissolved oxygen limit for the prevailing temperature and pressure inside the cone.

If less than 110 percent of the Henry's Law dissolved oxygen limit is added to the cone as oxygen gas, less overall oxygen mass will be dissolved to the water exiting the cone but the inlet-to-outlet oxygen transfer efficiency will still hold at the nominal 90 percent. To simultaneously obtain the maximum amount of oxygen transfer from a cone while still maintaining maximum transfer efficiency (i.e., 90 percent) would require close and continuous control of the oxygen gas flow rate to just below 110 percent of the prevailing Henry's Law solubility limit. As an alternative to operating at the very edge of the Henry's Law design envelope, a conservative design operating comfortably below the 110 percent Henry's Law solubility threshold would likely be easier to operate while maintaining the maximum inlet-to-outlet transfer efficiency.

For the demonstration system the oxygen gas flow rate to the cones was typically greater than 110 percent of the Henry's Law solubility limit in order to transfer the maximum possible oxygen to the river at the expense of reduced inlet-to-outlet transfer efficiency. An added site-specific consideration for the ReOx demonstration system configuration was the small additional amount of oxygen locally transferred to the river water column from the excess oxygen bubbles released to the river at the ReOx injection depth of 33 feet.

Assuming the upriver land-based Speece Cones can be sized and operated below 110 percent of the Henry's Law solubility limit, an overall inlet-to-outlet oxygen transfer efficiency of 90 percent should be achievable. Conservatively assuming 80 percent as the inlet-to-outlet transfer efficiency seems reasonable for design purposes. Developing a reliable means (i.e., instrumentation) for monitoring very-high, end-of-pipe DO concentrations in the submerged cone-discharge pipe would (in combination with oxygen gas flow and water flow monitoring) allow continuous monitoring of inlet-to-outlet oxygen transfer efficiency.

3.0 INSTREAM DATA ASSESSMENT

Before, during and after the ReOx demonstration project, water quality parameters in the harbor were monitored including water temperature, DO concentration, DO percent saturation, pH, salinity, conductivity, and instrument depth (measurement point). DO deficits were computed from the measured field values.

Continuous measurements were made at multiple depth near-shore locations along the overbank areas within the harbor at GPA Berth 20 (upstream), US Army Corps of Engineers (USACE) Dock (downstream), and on the river side of the barge during ReOx system operations. Prior to and after ReOx system operations monitoring was conducted at the barge mooring location at TIC (prior to startup), and approximately 0.25 river miles upstream of the barge location at the Savannah Marine Services dock (after system shutdown). These locations are shown on (Figure 3.1).

In addition to the continuous monitoring stations, periodic (weekly) measurements were made at 14 mid-channel locations and at 5 horizontal transects extending from the GPA Berth 20 location to just downstream of the USACE dock (Figures 3.2 and 3.3, respectively). Five mid-channel “long runs” were also conducted at 0.5 mile intervals from approximately river mile (RM) 5 to upstream of the King’s Island Turning Basin at RM 18.7 (Figure 3.4). One nearfield sampling event to assess local mixing of the return flow plume was completed at the ReOx barge location. These data are discussed below.

3.1 DO DEFICIT

DO deficit is calculated as the difference between the DO concentration at saturation for a given temperature, salinity, and pressure and the measured DO concentration at the same temperature, salinity, and pressure. DO deficit helps smooth some of the fluctuations in the DO data caused by changing temperature and salinity conditions in the harbor and is traditionally the parameter of choice when analyzing DO effects in modeling. The smaller the DO deficit, the closer that measurement is to DO saturated conditions.

3.2 CONTINUOUS MONITORS AT 3+ LOCATIONS WITH MULTIPLE DEPTHS

Intensive instream DO monitoring was conducted before, during, and after the 40-day operating period of the ReOx system. Fixed-location continuous monitoring included “shallow,” “middle,” and “deep” zone multi-parameter recording instruments temporarily deployed at three near-shore overbank locations: GPA

Berth 20 dock at RM 15.6, ReOx barge at RM 14.1 (during operations), TIC at RM 14.1 prior to startup, Savannah Marine Services at RM 14.3 after system shutdown, and the USACE dock at RM 13.7. Time series plots showing DO deficit, temperature, salinity, and tidal range for each station and depth are presented as:

- Figures 3.5 to 3.7 for GPA Berth 20 (shallow to deep)
- Figures 3.8 to 3.10 for the USACE Dock (shallow to deep)
- Figures 3.11 and 3.12 at TIC prior to startup (shallow and deep)
- Figures 3.13 to 3.15 at the barge monitoring location (shallow to deep)
- Figures 3.16 to 3.18 at the Savannah Marine monitoring location (shallow to deep).

The continuous data figures also identify the average depth at which the water quality parameters were recorded for each station and show the bathymetry differences in the harbor at each monitoring station. For example, GPA “deep” location had an average depth of 35 feet whereas the USACE “deep” location was only 13 feet.

Time series plots show a strong correlation between DO deficit, salinity and moon phase. Full moon results in higher tides with less change between daily high and low tides (tidal range). This condition results in more inflow of seawater that has higher levels of DO (near saturated with atmospheric oxygen). New moon conditions show poorer water quality with higher DO deficits. Daily fluctuations in DO water quality also occur due to the daily tidal cycles.

A confounding factor with the continuous monitoring stations is that the monitors had to be placed near the shore on permanent structures and not in or near the deeper navigation channel (where the oxygen was injected) so as not to interfere with ship traffic. As later discussed in Sections 3.3.4 and 3.3.5, the near-shore locations had lower DO water quality conditions at high tide and similar DO water quality conditions at low tide than the water in the navigation channel.

3.2.1 Continuous Monitoring Data Analysis

Several methods were used to assess the effects of the ReOx system on the DO as measured at the continuous monitoring stations, including review of time series plots, regression analysis, signal to noise ratio, and effect size assessment. Additionally, data were condensed to daily median values based on a tidal day and additional data analyses were performed as discussed below.

Notably, the ReOx demonstration system was designed to inject superoxygenated water to the deeper layers of the main navigation channel but the continuous monitors at GPA Berth 20 and the USACE dock were, by necessity, located in the near-shore overbank areas of the river approximately 1.5 RM upstream and 0.4 RM downstream of the location of the ReOx System, respectively.

Review of Continuous Time Series Plots

Review of the time series plots for both the GPA Berth 20 and the USACE dock indicate that a definitive DO response signal was not apparent. During operations of the ReOx system, an intermittent DO response signal was noticeable at each depth for the Barge monitors. Because the discharge from the injection system was directed down and away from the barge, a continuous response was not expected. The intermittent responses coincide with various tidal current changes that force oxygenated water across the data sondes. The mid-depth and deep monitors both show a DO response with smaller DO deficits immediately after startup and continuing to shutdown. The shallow monitor, as expected, showed less of a response at startup indicating that the oxygenated water was mixing with the deeper layers and not short-circuiting to the surface.

During the last few weeks of system operation, a greater response was noticed in the shallow barge monitor. This coincides with the oxygen ramp-up testing and the loss of a pump seal in the Cone 2 system and the appearance of the coarse bubbles. The coarse bubbles were noted to drag oxygenated water upward and at slack tide washed the oxygenated river water over the shallow monitoring data sonde as the bubbles broke on the surface. During mid tides, the bubbles were swept up- and downstream and did not cause this phenomenon.

Data Regression Analysis

Due to the complexity of the river system a multiple linear regression (MLR) was used to investigate the interrelations of several continuous monitoring parameters to evaluate if these data could be used to estimate or predict DO effects (Appendix A). The data compared included the tidal range, temperature, and salinity from the continuous monitors at the GPA Berth 20 and USACE dock locations. The MLR method statistically predicts a dependent variable from more than one input value. For the Savannah River continuous monitoring data, the MLR method predicted an overall effect at the USACE and GPA locations were generally more dependant on tidal range than other factors (temperature and salinity, or combinations of each). The GPA deep monitoring location had a higher correlation to DO concentrations

from temperature and tidal range. The USACE deep monitor showed a stronger correlation to salinity. These analyses indicated that DOs in the Savannah River are generally more influenced by tidal range than by other factors such as temperature, pressure, and salinity. The MLR analyses were conducted on the variables with the expected greatest natural effect on the DO response in Savannah Harbor. Because correlations were not identified in the analyses of the daily values, additional more detailed approaches including analysis of the 15-minute data records and additional variables would have been conducted. Additionally, due to the inherent “noise” in the data caused by these numerous contributing factors, additional analysis of the data were not performed.

Signal to Noise Analysis

Examination of the actual DO concentration measurements from the continuous monitoring data suggested that the size of the effect of the ReOx system on DOs at the GPA and USACE nearshore monitoring locations may be hidden by the naturally variable DO conditions in the harbor. To test this hypothesis, analyses were performed to evaluate the “noise” caused by changes in natural DO water quality conditions to the expected (model) change in DO due to the operation of the ReOx system (signal). This analysis, referred to as a signal-to-noise ratio, estimated the signal-to-noise of the actual DO measurements and the expected background, or baseline, variations in oxygen concentration due to natural processes. The analysis for each station is presented in Appendix B.

The signal strength (expected concentration change due to the ReOx system operation) was estimated using output from the Savannah Harbor Model. The difference between the results from the model runs (with and without DO injection) provided an estimate of the expected change in DO concentrations (delta DOs) attributable to operation of the ReOx system.

A synthetic data set was created using the delta DO concentration results from the Savannah Harbor Model. Because the output available for the model is in 2.4 hour increments, the corresponding nearest value from the 15-minute continuous monitoring data was used for comparison. The delta DO values were added to the measured continuous monitoring data to create the synthetic data set.

The difference between predicted oxygen concentrations at the same location (with and without added oxygen [delta DOs]) were used to estimate the expected DO signal strength. The noise was estimated as instantaneous variations in the actual oxygen concentration measurements. Once estimates of both signal and noise were developed, the resulting signal-to-noise ratio value of 1.3 showed the ratios were of the

same order of magnitude, making it difficult to distinguish the effect of the ReOx system at the GPA and USACE dock continuous monitoring locations.

The signal-to-noise ratio helps decipher noticeable signals from measurements. The ratio value of 1.3 is small enough that the signal (expected DO concentration change due to operations of the ReOx system) cannot be detected at the GPA and USACE dock locations. The size of the expected DO signal (0.2 to 0.3 mg/L) is too small to be distinguished from the baseline DO variability at these locations. The ratio predicts the amount of change from the ReOx system is only slightly higher than the baseline variability, or noise, thus it is not possible to definitely detect or rule out the expected DO effect in the continuous nearshore data.

In addition to the signal-to-noise ratio calculation, an “effect size” analysis was performed for each of the continuous monitoring locations. This analysis compares the standard deviation of the measured data to the mean of the expected effect of operation of the ReOx system. The mean of the expected effect for each station was calculated using the modeled delta DO values provided by TetraTech (2009). The standard deviations of the measured data and the means for the expected DO effects are compared in Table 3.1. The DO standard deviations are within the same order of magnitude as the magnitude of the expected DO effect indicating that the data have enough baseline variability to mask the expected small effects of oxygenation from the ReOx system.

3.3 DISCRETE SAMPLE RIVER MONITORING

Weekly (or more frequent) measurements were made in the river along both the mid-channel axis of the deep navigation channel and at transects bracketing the morning or early afternoon slack tide for that day. Data from these measurements were contoured using TecPlot Version 10 and are discussed below.

3.3.1 Nearfield Mixing Zone Monitoring

During the operation of the ReOx system a one-time near-field monitoring event at low slack tide on August 9, 2007 was conducted to assess the mixing of the superoxygenated return flow plume in the river. It was anticipated that the discharged water would mix rapidly in the river and that the pressure head at the depth of the discharge line would effectively prevent effervescence. Figure 3.19 shows the locations of the monitoring points and depicts the measured discharge plume dimensions. Three to four depths were measured at each location and the maximum measured concentration was used to provide input for the plot. The results of this monitoring event indicated the discharge flow was diluted approximately 20

fold and well mixed with the water in the river about 50 feet from the end of the two injection points. Based on the exit velocity of the discharge flow (approximately 10 feet per second), this in-stream mixing would have been completed within 5 seconds of the flow leaving the ReOx system. This slack-tide mixing result confirms that the system performed as expected by superoxygenated return water quickly mixing with the bulk river water.

The near-field DO monitoring event conducted at the ReOx barge location was a one-time reconnaissance-level sampling in response to a concern raised in the field that too much DO might create a problem for aquatic life in the immediate vicinity of the superoxygenated discharge. The near-field sampling consisted of vertical DO profiles taken on a coarse grid in the river around the ReOx barge. The resulting data depicted on Figure 3.19 reflect the maximum observed DO concentration from each vertical profile and the prevailing DO concentrations calculated for the two Speece Cone discharges. For purposes of drawing the near-field two-dimensional DO isopleths for Figure 3.19, a local DO background (baseline) of 3.53 mg/L was selected based on concurrent DO concentrations measured at the GPA dock deep and mid- depth location on 8/9/2007 at 12:30PM average. The purpose of this one-time sampling event was to look for the relative maximum DO concentrations in the plume vicinity.

3.3.2 Mid-Channel Profiles (Low Tide)

Mid-channel measurements were made over a 1.5 to 2 hour (semi-synoptic) period with measurements starting at the most downstream location near the USACE dock (Transect V1). During the low tide measurement period, the tide continued to move seaward, came to a slack condition, and then began to move inland. In addition, there was about a 30-minute phase difference in tidal movement between the surface layers and the deeper layers in the navigation channel. Near slack low tide, surface waters continue to move seaward for about 30 minutes as bottom layers are still moving inland.

Figures 3.20A and 3.20B for the low tide sampling events present the results of the mid-channel profile measurements for the low tide events. Low tide events prior to startup of the ReOx system (7/9/2007 and 8/6/2007), show uniform, and horizontally stratified DO deficit profiles from surface to bottom with a gradient of 0.4 mg/L and 0.3 mg/L, respectively. Just after startup on 8/11/2007, the gradient increases to 0.6 mg/L with the surface layer showing lower DO deficits than mid- and bottom layers.

During system operation (8/20/2007, 9/4/2007, 9/6/2007, and 9/7/2007), the river appeared to remain horizontally stratified. However, while overall gradients were similar to pre-startup conditions, the bottom layers exhibited lower DO deficits than mid-layers. After ReOx system shutdown, uniform DO profiles (similar to pre-startup with deeper layers having higher DO deficits) with similar DO deficit gradients are apparent in the river. Comparison of the DO deficit plots mentioned above to the salinity plots (Figure 3.21A and Figure 3.21B) indicate that some of this layering may be attributed to higher salinities of the deeper layers. However, for two of the events (9/6/2007 and 9/7/2007) salinities in the harbor were similar (vertically stratified and similar salinity concentrations) from surface to bottom to the pre-startup events (7/9/2007 and 8/6/2007). Also, the events of 8/20/2007 and 9/7/2007 show evidence of lower DO deficits in areas where salinity driven DO effects would not be expected. The effects are found in the mid-layer and characterized by a contoured lower DO deficit (3.2 mg/L and 3.3 mg/L, respectively) at the location of the ReOx system (RM 14).

Figures 3.21 A and 3.21 B indicate that during operation of the ReOx system, the river exhibited areas with better DO conditions near the ReOx system location which are indicative of system operation. The general improvements in DO conditions throughout the measured harbor segment can be attributed to lunar driven tidal cycles. However, there are noted variations in the DO deficit transects in the vicinity of the ReOx system not noted prior to or after system operation.

3.3.3 Mid-Channel Profiles (High Tide)

During high slack tide, the tide is moving inland at the beginning of the measurement period starting at Transect V1 and then is moving seaward by the time measurements are made at Transect V14. Because of the phase shift in the tides, surface layers begin to move seaward prior to the bottom layers turning and moving seaward. High tide profiles are shown on Figures 3.22A and 3.22B. Mid-channel measurements made during the high slack tide show the influence of seawater on the DO deficits as compared to the low tide mid-channel profiles. Prior to system startup and after system shutdown, DO deficit gradients appear to be horizontally stratified. During operation of the ReOx system, two events (8/14/2007 and 9/10/2007, with 8/14/2007 having the clearest indication) show signs of DO deficit reduction in the area near the location of the ReOx system. For the mid-channel monitoring events on 8/27/2007 and 9/13/2007 during operation of the ReOx system, there was a greater influence of seawater with higher salinities than the events on 8/14/2007 and 9/10/2007. The higher levels of seawater influence may have masked the smaller effect of the ReOx system.

3.3.4 River Transects (Low Tide)

River water quality transects were conducted at least weekly. Transect 1 represents the downstream monitoring location at the USACE dock with Transect 5 located at the GPA Berth 20. The timing of the transect measurements were centered on slack tides and took between 1.5 to 2 hours to complete. Therefore, at low slack, Transect 1 was measured as tides were still flowing out of the harbor and Transect 5 was measured as tides were coming into the harbor. However, due to the phase difference of the tides there is not a true slack measurement period. Figures 3.23 to 3.28 depict the results of each low tide sampling event.

Figures 3.23 and 3.24 show the transects from the pre-startup monitoring (measured on 7/10/2007 and 8/7/2007, respectively). These profiles indicated that DO deficits had a relatively uniform horizontal gradient across each transect with lower DO deficits occurring at the overbanks and the higher DO deficits occurring in the bottom center area of the deepened navigation channel. Also, left and right bank DO deficits were similar for each of the transects (except Transect 5 due to dredging at the GPA Berth 20 dock). Also, from downstream (USACE dock) to upstream (GPA Berth 20), point average DO deficits ranged from 3.55 mg/L (Transect 5) to 3.84 mg/L (Transect 2) and 3.81 mg/L (Transect 2) to 3.94 mg/L (Transect 3) for the two events, respectively.

A few days after startup of the ReOx system, effects on DO are noticeable in the transects. On 8/10/2007 (Figure 3.25), four days after startup, the right side of the navigation channel overbank (looking upriver) depicts a noticeable decrease in DO deficits (a change from overbank to channel center of 1.6 mg/L as compared to 0.2 mg/L and 0.4 mg/L for the pre-startup events for Transect 2). Transect 2 also has a lower DO deficit average than the other transects (3.63 mg/L) indicating noticeable effects of the ReOx system operation. Transect 2 also showed left and right navigation channel overbank DO deficits of 3.7 mg/L on 7/10 and 3.7 mg/L and 3.6 mg/L (left and right overbanks, respectively) on 8/7 (pre-startup). On 8/10 (Figure 3.25) four days after startup, Transect 2 had a DO deficit of 2.6 mg/L on the right side of the navigation channel, 4.1 mg/L in the center, and 3.8 mg/L on the left side.

After a longer period of operation, DO deficits on 8/21/2007 (Figure 3.26) in both Transect 2 (2.91 mg/L) and 3 (2.92 mg/L) (nearest the location of the ReOx system – downstream and upstream, respectively) showed improvement as compared to transects farther up- and downstream. Similarly, on 9/5/2007 (Figure 3.27), Transects 2 (3.33 mg/L) and 3 (3.54 mg/L) DO deficits were lower than those up- and downstream.

Comparing the DO deficits across individual transects on 8/21/2007 showed effects of the ReOx system operations. Transect 1 showed an effect along the right side (looking upriver) within the navigation channel. DO deficits in this area were a minimum of 2.8 mg/L compared to the left side of the navigation channel with a DO deficit of 3.2 mg/L. Transect 2 showed a more pronounced effect with the right side of the navigation channel showing a DO deficit of 2.4 mg/L as compared to the left side of the channel with a DO deficit of 3.2 mg/L. As the oxygenated plume started to flow upstream, the left side of the navigation channel was affected more by the ReOx system operation with a DO deficit of 2.7 mg/L with the right /center having a DO deficit of 3.1 mg/L. Transect 3 also shows lower DO deficits on the right overbank (2.6 mg/L) as compared to the left overbank (3.0 mg/L). Less effect is notable at Transect 4 and Transect 5; however, the right side (looking upriver) of the overbank for each has lower DO deficits than the left sides (looking upriver). Comparing this to the same transects from the pre-startup data show lower DO deficits on the right side (looking upriver) during operations than before the ReOx system was operating. The 9/5/2007 (Figure 3.27) is similar to the 8/21/2007 event for Transect 2, with effects less apparent in the other transects. However, generally the right side (looking upriver) of the overbank shows lower DO deficits than found on the left overbank.

Figure 3.28 (9/24/2007) depicts the sampling event conducted after operations of the ReOx system ceased on 9/16/2007. This figure shows similar DO conditions within the harbor as compared to pre-startup transects. Left and right overbank DO deficits are again similar and transects are relatively uniform from up- to downstream.

Low tide river transects best demonstrate DO improvements in the harbor attributable to operations of the ReOx system.

It is important to note that the centerline measurements (corresponding to mid-channel measurement locations) for each of the transects would not have picked up much of the effects noted in the transects and mid-channel profiles would be less likely to show definitive effects of system operations. Transect 1 shows the DO deficit that was being measured at the USACE dock continuous monitors (right edge) for the time-frame that the Transect 1 measurements were being made. Generally, DO deficits are slightly lower at this location (very near shore) as compared to measurements made within the channel and overbanks. Transect 5 shows the continuous monitors at the much deeper GPA Berth 20 location (left edge) with similar DO conditions as the overbank and main channel.

Low tide DO concentrations for transects one through five are presented in Figure 3.29 to 3.34. Figures 3.35 to 3.40 show low tide salinity for transects one through five.

3.3.5 River Transects (High Tide)

The high tide transects show a greater degree of influence of seawater than noted in the low tide transects. Figures 3.41 to 3.45 show the high tide transects for each monitoring event. Pre-startup monitoring during high tide was conducted on 7/17/2007 (Figure 3.41). The data for this event show fairly uniform DO deficits throughout the harbor with point averaged DO deficits ranging from 3.25 mg/L (Transect 1) to 3.37 mg/L (Transect 5).

For the sampling events that occurred during ReOx system operation, 8/13/2007, 8/28/2007, and 9/11/2007 (Figures 3.42, 3.43, and 3.44, respectively), the transect plots show effects of the operation of the ReOx system. Transect 3 is the nearest transect upstream from the ReOx system location and due to the timing of the measurements bracketing the high slack tide (tide is flooding), would be the station where DO effects would have been most apparent. On 8/13/2007 (Figure 3.42), Transect 3 has a “bull’s eye” showing lower DO deficits with the minimum DO deficit of 2.2 mg/L along the right side of the navigation channel. Also, average DO deficits compared up- and downstream of Transect 3 showed higher average DO deficits than measured at Transect 3. Similar characteristics were noted on the 8/28/2007 event (Figure 3.43). The 9/11/2007 (Figure 3.44) event does not exhibit the “bull’s eye” that was apparent on the previous sampling events. However, currents may have been different in the harbor during a given time so the profile may have failed to catch the plume. However, the DO deficit average is lower at Transect 3 than the other transects measured on that day.

The post-operation event on 9/18/2009 (Figure 3.45) showed that upstream and downstream conditions had returned to more uniform conditions than was noted during operations of the ReOx system.

It is important to note that the centerline measurements of the transects would not have picked up the influences caused by the higher DO water contained in the plume from the ReOx system. Transect 1 shows the DO deficit that was being measured at the USACE dock continuous monitors (right edge) for the time-frame that the Transect 1 measurements were being made. Generally, DO deficits are higher at this location (very near shore) as compared to measurements made within the channel and overbanks. The plots for Transect 5 show the continuous monitors at the GPA Berth 20 location along the left edge. DO deficits are higher in this area than in the channel and overbank areas.

High tide DO concentrations for transects one through five are presented in Figure 3.46 to 3.50. Figures 3.51 to 3.55 show high tide salinity for transects one through five.

3.3.6 Farfield Monitoring

Mid-channel “long run” profiles were conducted from RM 5 off Bird Island to upstream of the King’s Island Turning Basin at RM 18.7. Long runs were made for 3 low tide events and 2 high tide events and are shown on Figure 3.56. Low tide events during ReOx system operation were conducted on 9/6/2007 and 9/7/2007. These events show a DO sag in the harbor with lower DO deficits up- and downstream and near saturation conditions near RM 5. Impacts of the ReOx system are not readily apparent on these profiles. However, smooth gradients of DO deficit are less notable on the runs made during system operation as compared to the post-shutdown profile made on 9/25/2007. For the two high tide events, the DO deficit gradients are more uniform and a DO sag is not apparent.

A comparison was made for the low-tide events. For the period 9/6 and 9/7 (during operation of the ReOx system) DO deficits in the area near the barge were lower than the same area after ReOx system shutdown. For these events, tidal ranges were similar, but the post shutdown event (9/25/07) salinities were higher.

3.3.7 Discrete River Monitoring Events – Similar Salinity Periods Comparison

Review of the discrete measurements that corresponded to similar salinity events discussed in Section 3.1.1 - Analysis of Central Tendency for Tidal Days, indicated that there were two periods (one prior to startup and one post-startup) that fell in or near similar low salinity and tidal range periods. The pre-startup period (8/3 to 8/5) was followed by days with increasing salinities. The measurements taken on 8/6 and 8/7 had similar salinities and tidal ranges to the post-startup period of 9/2 to 9/5. Increasing salinities noted for the 8/6 and 8/7 days would have likely had better DO conditions than the low salinity period (8/3 to 8/5) noted just prior to these days. Therefore, these data were compared to the post-startup period of 9/2 to 9/5.

Mid-Channel Profile Low Salinity Period Comparison (Low-Tide)

Comparison of mid-channel profiles measured on 8/6 (pre-startup) and 9/4 (post-startup) indicated that the post-startup DO deficits were lower than the period when the ReOx system was not operating (Figure 3.57). DO deficit grid average concentrations were 3.91 mg/L and 3.56 mg/L, respectively.

Since seawater influences (salinities and tidal range) were similar at this low-tide measurement event, the lower DO deficits noted in the post-startup profile may be attributed (at least in part) to operation of the ReOx system.

Transect Profiles Low Salinity Period Comparison (Low-Tide)

Comparisons of the 8/7 (pre-startup) and 9/5 (post-startup) transects in the river indicated that the post-startup DO deficits were lower than the period when the ReOx system was not operating (Figures 3.58 A and 3.58B, respectively). For example, Transect 2 had a point average DO deficit of 3.81 mg/L (pre-startup) and 3.33 mg/L (post-startup). Farther from the ReOx system at Transect 1, DO deficits were more alike for the two periods (although still improved for the post-startup period) 3.88 mg/L (pre-startup) and 3.74 mg/L (post-startup).

Overall, the 5 pre-startup transects measured on 8/7/2007 had a point averaged DO deficit of 3.84 mg/L and the post-startup transects measured on 9/5/2007 averaged 3.37 mg/L. Since the river had similar influences from seawater intrusion and tidal ranges were similar, this difference may be attributed (at least in part) to operation of the ReOx system.

3.4 COMPARISON TO THE COOPER RIVER DATA

A comparison of the tidal effects on DO concentrations for the Savannah Harbor was made to the Cooper River in South Carolina using the USGS gage at the USACE dock (USGS 2198500) and the Cooper River gage (USGS 21720677) for 2007 (Figure 3.59). Data revealed that water temperature was similar in the Savannah River and the Cooper River. Also, the Cooper River data showed that DO concentrations are highly correlated to tidal influences (shown by specific conductivity – higher the specific conductivity the more influence from seawater) as noted by comments received.

The Cooper River Gage is more seaward than the Savannah Harbor gage and has a greater degree of seawater influence. This influence of seawater provides higher DO levels in the Cooper River so DO concentrations in the rivers are not directly comparable.

3.5 SUMMARY OF MONITORING DATA EVALUATION

- Nearfield mixing zone monitoring indicated that the superoxygenated water rapidly mixed with the bulk river water. Data showed that oxygen entered the river and dispersed in the deeper layers of the navigation channel and that effervescence of dissolved oxygen was unlikely.

- Continuous monitoring data from the barge monitors showed a definite DO response due to operation of the ReOx system indicating that oxygen was added to the harbor particularly in the deeper layers of the channel where it was injected.
- Regression analyses showed that at the USACE dock and the GPA Berth 20 DO response was highly influenced by salinities driven by tidal cycles.
- Signal-to-noise analyses using synthesized data and effect size ratio analyses indicated that the expected DO response of the river to operation of the ReOx system were within the same order as the background variability, or “noise”, in the continuous nearshore monitoring data and that the effect size was too small to distinguish from the inherent variability of the DO baseline.
- Comparing periods where salinities and tidal range were similar indicated that DO conditions improved in the harbor during operation of the ReOx system.
- Individual mid-channel profiles made at low tide showed responses in DO deficits particularly near the ReOx system.
- High tide mid-channel profiles exhibit noticeable effects of operation of the ReOx system on 8/14/2007 and 9/10/2007.
- Comparison of the data for individual sampling events for both the low tide and high tide transects showed a definite DO response in the river attributable to the operation of the ReOx system.
- Long run mid-channel DO deficit profiles exhibit an oxygen sag in the river near the location of the ReOx system.
- Comparison of the mid-channel profiles and the transect profiles for similar salinity periods indicated better DO conditions in the harbor when the ReOx system was operating than the period prior to startup.

4.0 SUMMARY AND CONCLUSIONS

Reevaluation of the ReOx Project data was conducted to address comments from State and Federal Agencies which indicated that DO was strongly influenced by tidal influences and that a clear DO response was not noted in the GPA Berth 20 or the USACE dock nearshore continuous monitoring stations (both ReOx Project monitors and the USGS gage). This Supplemental Data Evaluation Report was developed to reevaluate the data collected during the ReOx Project with these comments in mind.

Nearfield mixing zone monitoring indicated that the supersaturated water injected by the ReOx system quickly mixed with the river water reducing DO plume concentrations by almost two orders of magnitude within 5 seconds and effectively eliminating the potential for spontaneous DO effervescence. The plume monitoring demonstrated that higher DO water remained at depth within the navigation channel where it was injected.

Various statistical methods (averaging, regression analysis, signal to noise ratio analysis, and effect size) were used to examine the near-shore continuous monitoring data. These methods showed that DO concentrations were substantially influenced by tidal cycles and that any added DO signal was masked in the natural DO variability, or “noise”, of the continuous monitoring data. This also indicated that the continuous nearshore monitoring did not capture the DO conditions in the deepened navigation channel. Also, the inherent precision of the DO instrumentation used (± 0.1 mg/L) was also within the same order of magnitude as the expected DO effect size. However, examination of the continuous monitoring data revealed that the Barge monitors did show periodic influence (due to localized currents sweeping higher DO water back towards the barge) at each depth monitored indicating that oxygen was being added to the harbor.

Mid-channel profiles for both high and low slack tides showed evidence of an oxygenated plume of water in the vicinity of the ReOx system. Also, transects made at 5 locations showed definitive evidence of the impact of the ReOx system on DO water quality in the river. Transects also revealed that the oxygenated plume was mainly contained in the navigation channel where the oxygen was injected and mid-channel profiles and near-shore continuous monitoring stations were unlikely to discern these effects. This is confirmed by model runs performed by TetraTech (2009). As would be expected, the model-calculated maximum DO effect was in the main channel cells where the oxygen was injected and much less in the overbank cells where the continuous nearshore water quality monitoring sondes were situated.