Contract: # W912HN-15-D-0023

Startup Run Data Collection & Modeling Report

Oxygen Injection System Environmental Testing for the Savannah Harbor Expansion Project

U.S. Army Corps of Engineers

March 2021

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for the

Oxygen Injection System Environmental Testing

for the

Savannah Harbor Expansion Project

Contract# W912HN-15-D-0023
Task: 10
March 2021

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EXECUTIVE SUMMARY

As one of the environmental mitigation projects for the Savannah Harbor Expansion Project (SHEP), two oxygen injection plants were constructed by the United States Army Corps of Engineers (USACE) on the Savannah River (Downriver and Upriver plants) to offset potential decreases in dissolved oxygen (DO) due to navigation channel deepening. The Downriver plant, located on Hutchinson Island in Chatham County, Georgia, discharges super-oxygenated water to the Front River and Back River via two separate diffusers. The Downriver plant is designed to deliver 12,000 pounds of oxygen per day (lbs/day), 8,000 lbs/day to the Front River, and 4,000 lbs/day to the Back River. The Upriver plant is located upstream on the Savannah River in Effingham County, Georgia. The Upriver plant is designed to deliver 28,000 lbs/day via one discharge diffuser. The USACE started operating the Downriver plant in January 2019 and the Upriver plant in July 2020. The system, which includes the generation and injection of high purity oxygen gas into raw river water and subsequent discharge back into the water column, will be operated seasonally during the critical summer months. The SHEP Final Environmental Impact Statement (EIS) and General Re-evaluation Report (GRR), both finalized in 2012, specified the requirement to operate the injection system from June 15 through September 30, during the warmest months of the year when DO concentrations in the river are generally at their lowest.

Two successful test operations of the oxygen injection system, known as the Test Run and Startup Run (SUR), were required to ensure overall SHEP success. The Test Run was completed from March 14 through May 12, 2019. The SUR was a 59-day continuous operation of the combined oxygen injection system, both Upriver and Downriver plants, as specified in the Compromise and Settlement Agreement. The EIS specified a requirement to deliver a daily average equal to or greater than the combined design production oxygen load of 40,000 lbs/day. The SUR occurred from July 25 through September 22, 2020. The USACE was required to extensively monitor the Savannah River and estuary continuously for the duration of the SUR and undertake subsequent modeling and analyses.

The full-scale data collection effort involved monitoring on the Front River, Back River, and Savannah River by collecting data from semi-permanent buoy sondes, profile sondes, and drift sondes. The field team also conducted dye releases before and during the SUR, to track the movement and retention of the dye plumes, and therefore, oxygen injection. In total, the field crew of 15 personnel operated over 84 days and installed 21 buoys, completed 371 profile measurements, sampled 103 drifts, and implemented 10 separate dye releases. Supplementary data were also sourced from the network of publicly available United States Geological Survey (USGS) stations throughout the Savannah River and estuary, and the data collected at both oxygen injection plants. All data were subject to thorough quality assurance/quality control (QA/QC) review prior to analysis.

In 2020, the SHEP model was recalibrated to represent existing conditions more accurately throughout the harbor and predict future outcomes. This included multiple grid and bathymetry updates to the model to better define the cross-sections of the Middle and Back Rivers and the Savannah River upstream of Interstate 95 (I-95) up to the Upriver plant, as well as additional marshes to improve the tidal flow circulation in the system.

Completion of the field monitoring and model updates was the initial step in assessing SUR mitigation impacts. The Success Criteria was defined in the Compromise and Settlement Agreement: **“The purpose of the modeling and monitoring is to confirm that the Oxygen Injection System will mitigate for DO impacts of the Project, as shown by comparing actual DO levels in the modeled area, from Station 0+000 upstream to River Mile (RM) 27.8, to DO levels in the without-Project scenario (the “Success Criteria”).”** In other words, the Success Criteria requires evidence the DO impacts across the estuary caused by deepening have been compensated for in time (tidally and seasonally) and space (vertically and horizontally).

It should be explicitly noted that neither the Success Criteria nor the EIS or GRR, specify a target concentration of increased DO to appropriately mitigate for channel deepening. The dynamic nature of the Savannah River and estuary vertically, spatially, and temporally, means specifying a target concentration increase was impossible. To address the Success Criteria, an alternative approach was needed to prove mitigation was achieved.

A tiered approach was developed whereby the Success Criteria was proven by evaluating four *Success Metrics,* each of which captured a complementary portion of the Success Criteria and were consistent with the EIS and GRR. Further, each of the four *Success Metrics* was able to be assessed by a total of 12 *Lines of Evidence*, three for each *Success Metric*. Successfully demonstrating achievement of the *Lines of Evidence* would prove accomplishment of the *Success Metrics* and ultimately the *Success Criteria*, demonstrating the oxygen injection system is successfully able to inject the required oxygen loads into the river. This would also demonstrate that the injected oxygen can be retained and distributed vertically and spatially, thereby mitigating impacts to DO by harbor deepening.

The *Success Metrics* cover four complementary components essential to oxygen mitigation. The 12 *Lines of Evidence*, three for each *Success Metric*, are presented below:

1) **OXYGEN LOAD DELIVERED** – The requirement was a daily average of 40,000 lbs/day of oxygen over a continuous 59-day period to be injected into the water column during the critical summer months. Success Metric #1 was achieved during the SUR by:
   - (1.1) injecting a total daily average of more than 40,000 lbs/day for 59 days – **42,412 lbs/day were achieved**.
   - (1.2) injecting a daily average of more than 28,000 lbs/day for 59 days from the Upriver plant – **28,838 lbs/day were achieved**.
   - (1.3) injecting a daily average of more than 12,000 lbs/day for 59 days from the Downriver plant – **13,574 lbs/day was achieved**.
2) **OXYGEN LOAD RETAINED** – The requirement was for 90 percent of the delivered oxygen load to the water column to remain dissolved and saturated in the water. Success Metric #2 was achieved during the SUR by:
   - (2.1) Achieved 99 Percent Water Column Transfer Efficiency (WCTE) – **Significantly greater than the 90 percent goal, indicating almost all injected oxygen stayed within the river and was used for mitigation.**
   - (2.2) Oxygen plume retention after injection – **Evidence of oxygen retention was detected up to one month after injection on the Front River and three weeks on the Back River.**
   - (2.3) No effervescence or bubbling observed during field data collection – **No evidence on any of the 84 field sampling days.**
3) **DO MITIGATION IN BOTTOM WATERS** – The requirement was for the SHEP model to show oxygen injection mitigated median DO concentrations in 97 percent of the bottom half of the water column across the estuary. Success Metric #3 was achieved during the SUR by:
   - (3.1) Mitigation in the bottom half of the water column – **The SHEP Model results demonstrated increased DO concentrations in greater than 97 percent of the total volume in bottom waters. More than 98 percent of the cells for the SUR Scenario presented positive DO deltas.**
   - (3.2) Analysis of field data (profile and dye data) – **Successfully demonstrated oxygen retention and vertical distribution of oxygen load.**
   - (3.3) USGS test-control analysis (vertical) – **successfully increased DO concentrations at two depths in the upper and bottom halves of the water column.**
4) **SPATIAL EXTENT OF DO MITIGATION THROUGHOUT ESTUARY** – The requirement was to confirm the oxygen injection system would mitigate for SHEP impacts throughout the Savannah Harbor system

(from Station 0+000 upstream to RM 27.8), including critical zones identified in the EIS as being most affected by navigational channel deepening.

(4.1) Analysis of field data (buoy, drift, and dye data) – **Successfully demonstrated oxygen retention and spatial distribution of oxygen load.**

(4.2) USGS test-control analysis (spatial) – **successfully increased DO concentrations at 10 different locations across the Savannah River and estuary.**

(4.3) Spatial analysis of the SHEP model – **The SHEP Model results demonstrated increased DO concentrations at all nine critical zones as well as the majority of the Savannah River and estuary.**

Based on analyses of both measured data and modeling results, **the conclusion is that the 12 *Lines of Evidence* suitably address the four *Success Metrics*, and therefore the Success Criteria was achieved.** During the SUR period, the system operated in accordance with requirements; demonstrating that the system is capable of meeting the DO mitigation requirements of SHEP.

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ACRONYMS/ABBREVIATIONS

Acronyms/Abbreviations	Definition
BR	Back River
BGA	Phycoerythrin blue-green algae
CBOD	Carbonaceous Biochemical Oxygen Demand
cfs	cubic feet per second
DO	dissolved oxygen
DOsat	saturated dissolved oxygen
EFDC	Environmental Fluid Dynamic Code
EIS	SHEP Final Environmental Impact Statement
Excel	Microsoft Excel
FR	Front River
GA	Georgia
GA 17	Georgia U.S. Highway 17
GA 25	Georgia U.S. Highway 25
GA DNR	Georgia Department of Natural Resources
GPA	Georgia Ports Authority
gpm	gallons per minute
GPS	geospatial positioning system
GRR	General Re-Evaluation Report
I-95	Interstate 95
lbs	pounds
lbs/day	pounds per day
LBR	Little Back River
mg/L	milligrams per liter
MLLW	mean lower low water
MR	Middle River
NH3	Ammonia
NOAA	National Oceanic and Atmospheric Administration
OneDrive	Microsoft OneDrive
Plant	Oxygen Injection Plant
ppt	parts per trillion
QA/QC	quality assurance/quality control
RM	river mile
SCDHEC	South Carolina Department of Health and Environmental Control
SCDNR	South Carolina Department of Natural Resources
SELC	Southern Environmental Law Review

Acronyms/Abbreviations	Definition
SHEP	Savannah Harbor Expansion Project
SPCOND	specific conductivity
SRMC	Savannah River Maritime Commission
SUR	Startup Run
Settlement Agreement	Compromise and Settlement Agreement
SOD	sediment oxygen demand
Total Algae	Chlorophyll + Blue-green Algae
TMDL	Total Maximum Daily Load
UOD	Ultimate Oxygen Demand
U.S.	United States
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
WASP	Water Quality Analysis Simulation Program
WCTE	Water Column Transfer Efficiency
WSE	water surface elevation
µg/L	micrograms per liter

1.0 INTRODUCTION

1.1 BACKGROUND

Shipping traffic within the Savannah Harbor has been an integral part of the area since well before the Revolutionary War. Bathymetric data collected in the Savannah Harbor in 1854 show that the natural depth was approximately 12 to 15 feet Mean Lower Low Water (MLLW). Since this time, it has been deepened over multiple projects to allow access to the Port of Savannah to larger ships. Prior to the Savannah Harbor Expansion Project (SHEP), the authorized depth of the federal navigation channel was 42 feet MLLW. The historical deepening projects depressed dissolved oxygen (DO) in the harbor by an estimated 1.0 milligram per liter (mg/L) due to salinity stratification and lack of vertical mixing, especially during neap tides (USEPA 2006).

The site-specific water quality standard for the Savannah Harbor requires a minimum DO concentration greater than 3.0 mg/L. DO concentrations near the bottom of the water column do not meet this criterion during the *critical period* – the warmest months of the year when DO concentrations in the river are generally at their lowest (USEPA 2006). The Savannah Harbor is unable to achieve this standard year-round, even with the removal of oxygen-demanding substances, such as wastewater discharges and nonpoint sources (USEPA 2006). The United States Environmental Protection Agency (USEPA) issued a “no discharge” DO Total Maximum Daily Load (TMDL) in 2006 (USEPA 2006), which was revised in 2010 to require no more than a 0.10 mg/L deficit from the “natural” DO value and set allowable loads for Ultimate Oxygen Demand (UOD) (USEPA April 2010). Natural UOD background load sources enter the harbor from several points: upstream from the Savannah River, adjacent marshes in the estuary, and downstream at the Atlantic Ocean (USEPA April 2010).

The SHEP Final Environmental Impact Statement (EIS) described the need for the deepening project. At 42 feet MLLW, the Savannah Harbor was too shallow for over 70 percent of vessels to enter at their maximum capacity or design draft. Container vessels needed to be ‘light loaded’, which increased costs to the ocean carrier, freight logistics, and the consumer (USACE 2012a). As part of the Final General Re-evaluation Report (GRR), the United States Army Corps of Engineers (USACE) evaluated a wide range of alternatives to address navigational constraints in the harbor, and the analysis determined that channel deepening was the only way to address navigational issues (USACE 2012b). The SHEP currently being implemented involves deepening the Savannah Harbor federal shipping channel from 42 feet by an additional five feet to its authorized depth of 47 feet MLLW. Once complete, this deepening will produce substantial economic benefits for the nation by enabling larger and more heavily loaded vessels to call on the harbor with fewer tidal delays.

Exhaustive engineering and environmental studies were undertaken in the initial project planning stages through EIS development to identify the environmental impacts that would be expected from the project and ensure those impacts would be offset through mitigation. Environmental mitigation features include installation of an oxygen injection system, constructing a fish bypass upstream at the New Savannah Bluff Lock and Dam, rerouting freshwater flow in the upper harbor, preserving 2,245 acres of freshwater wetlands for the Savannah National Wildlife Refuge, and recovering remnants of the *CSS Georgia* civil war ironclad that rested some 40 feet MLLW below the river's surface.

One of the major environmental impacts from SHEP was the proposed impact on water quality by potentially further decreasing DO concentrations in the Savannah River and estuary during the critical warm summer months (USACE 2012a). The primary mitigation feature designed to offset and mitigate potential decreases in DO caused by navigation channel deepening was the installation of an oxygen injection system. This system contained two oxygen injection plants (Upriver plant and Downriver plant) and three discharge locations (Upriver, Front River, Back River) with a requirement to inject super-oxygenated water into the Savannah River and estuary during the critical period (Compromise and Settlement Agreement 2013, USACE 2012a, USACE 2012b).

Two successful test operations of the oxygen injection system, known as the Test Run and Startup Run (SUR), were required to demonstrate the success of the DO mitigation for SHEP. A summary of the 2019 Test Run is presented in Section 1.5 and the 2020 SUR is introduced in Section 1.6.

1.2 THE SAVANNAH RIVER AND ESTUARY

The Savannah River and estuary is a complex hydrodynamic and water quality system. To understand the dynamics of the estuary and how oxygen injection impacts the DO regime, an understanding of how the Savannah River and estuary behaves is needed, particularly in the critical summer period when DO concentrations are at their lowest.

During summer months, estuaries in the southeastern United States naturally have low DO concentrations due to higher water temperatures, higher salinity concentrations, and lower freshwater flows. The range of DO values within the Savannah estuary is dependent on three primary driving forces:

- Freshwater flow from upstream sources, measured at the United States Geological Service (USGS) Clyo gage, influences saltwater intrusion. Lower freshwater flows result in saline and brackish water extending farther upriver.
- Semi-diurnal tides move water upstream (flood tide) and downstream (ebb tide) in the harbor approximately twice a day.
- Neap and spring tides are driven by lunar cycles. Neap tides have less tidal amplitude (difference between high and low water levels) and less energy to mix vertically, resulting in harbor stratification with higher salinity and lower DO in the bottom waters. Spring tides have larger tidal amplitude, and due to the increased energy, the harbor tends to destratify and mix well through the entire vertical water column.

The Savannah River and estuary is comprised of six estuarine regions, which influence the DO concentrations throughout the estuary, especially in the critical summer months. These six regions are presented in ***Figure 1-1*** and described below.

1. An upstream riverine portion, which starts upstream at the USGS gage at Clyo (River Mile [RM] 45) and flows down to the Interstate 95 (I-95) bridge (RM 27.8). This zone is almost wholly fresh water as saline tidal waters do not usually extend upstream beyond the I-95 bridge. However, it is tidally impacted as the incoming tide slows down the river's flow, causing water levels to rise and fall, approximately 1.0 foot, with the tides. During summertime low flows (below 10,000 cubic feet per second (cfs)), DO levels on average start at 7.0 mg/L measured at the Clyo gage, and decrease to approximately 6.0 mg/L at the I-95 bridge due to lower reaeration caused by the slower flows and the influxes of low DO water from side tributaries and marsh areas.
2. A transition zone starts around the I-95 bridge (RM 27.8) and ends between United States (U.S.) Highway 25 (Georgia [GA] 25) and the turning basin (RM 19). This zone is mainly fresh water during periods of high flows (above 20,000 cfs) and brackish to saline water during the lower flows. During summer low flows, the average DO concentration decreases from 6.0 mg/L to 3.0 mg/L through this transition zone due to a variety of factors. The river's reaeration rate is lower due to slower velocities, sediment oxygen demand (SOD) rates are higher due to more solids settling to the bottom, and the higher salinity water has a lower capacity to hold DO.

3. The inner harbor navigation channel on the Front River runs from the turning basin (RM 19) downstream to Fort Pulaski (RM 0). Salinities vary from approximately 1.0 to 32.0 parts per trillion (ppt) depending on the magnitude of upstream freshwater flows. The Front River is typically stratified with lower DO and salinity concentrations in the lower half of the water column and higher DO and salinity concentrations in the upper half. However, during spring tides, when the tides are the highest, the system becomes destratified whereby the upper and lower layers mix resulting in uniform DO and salinity values top to bottom. Once the regular tidal regime is returned, so too is the stratification.

4. The outer harbor navigation channel extends from Fort Pulaski (RM 0) to approximately 20 miles offshore. The incoming tidal flows range from 150,000 to 400,000 cfs during flood tides and outgoing flows range from 200,000 to 450,000 cfs during ebb tides. This zone delivers high salinity water into the inner harbor navigation channel, along with average summertime DO concentrations of 5.0 mg/L in the top half of the water column and 3.0 mg/L in the lower half.

5. The Back, Little Back, and Middle Rivers form a complex side river system. The upper portion connects to the main channel of the Savannah River around RM 26. There are two further connections to the Front River at RM 20 and RM 12. High DO fresh water enters the upper portion and then mixes with the lower DO and high salinity water that enters on flood tides, through the lower connections. This mixing typically occurs around the GA 25 bridges but varies dependent on flows and tidal conditions.

6. Large areas of tidally impacted freshwater and saltwater marshes and their associated tributaries deliver lower DO water to the system, as identified above in the upstream riverine portion. The amount of low DO water discharged from these marshes is dependent on the rainfall in the area and the amount of tidal intrusion into the marsh area.

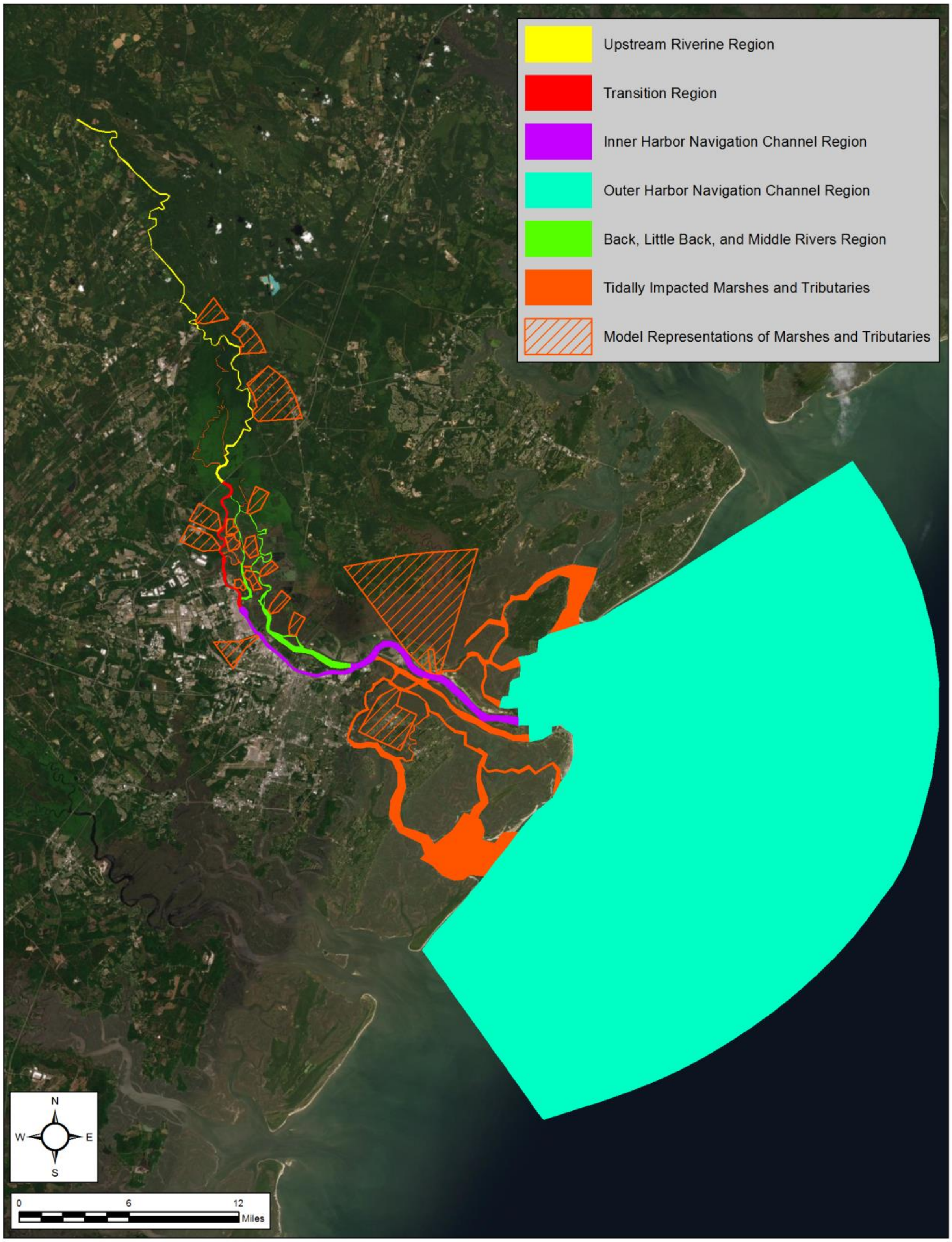

Figure 1-1 The Savannah River and Estuary

To lesser degrees, point source wastewater discharges and water withdrawals also impact the DO of the estuary. The states of Georgia and South Carolina have strict permitting processes to ensure individual and overall compliance.

A typical summertime DO transect of the entire estuary for both the surface waters and bottom waters, without oxygen injection, is presented in ***Figure 1-2***.

The deepening of the navigation channel from 42 to 47 feet MLLW allows for additional lower DO and higher salinity tidal flows to enter the estuary causing the estuaries' DO to be slightly lowered. The Upriver and Downriver plants were designed to mitigate this lowering of the DO during the critical summertime period.

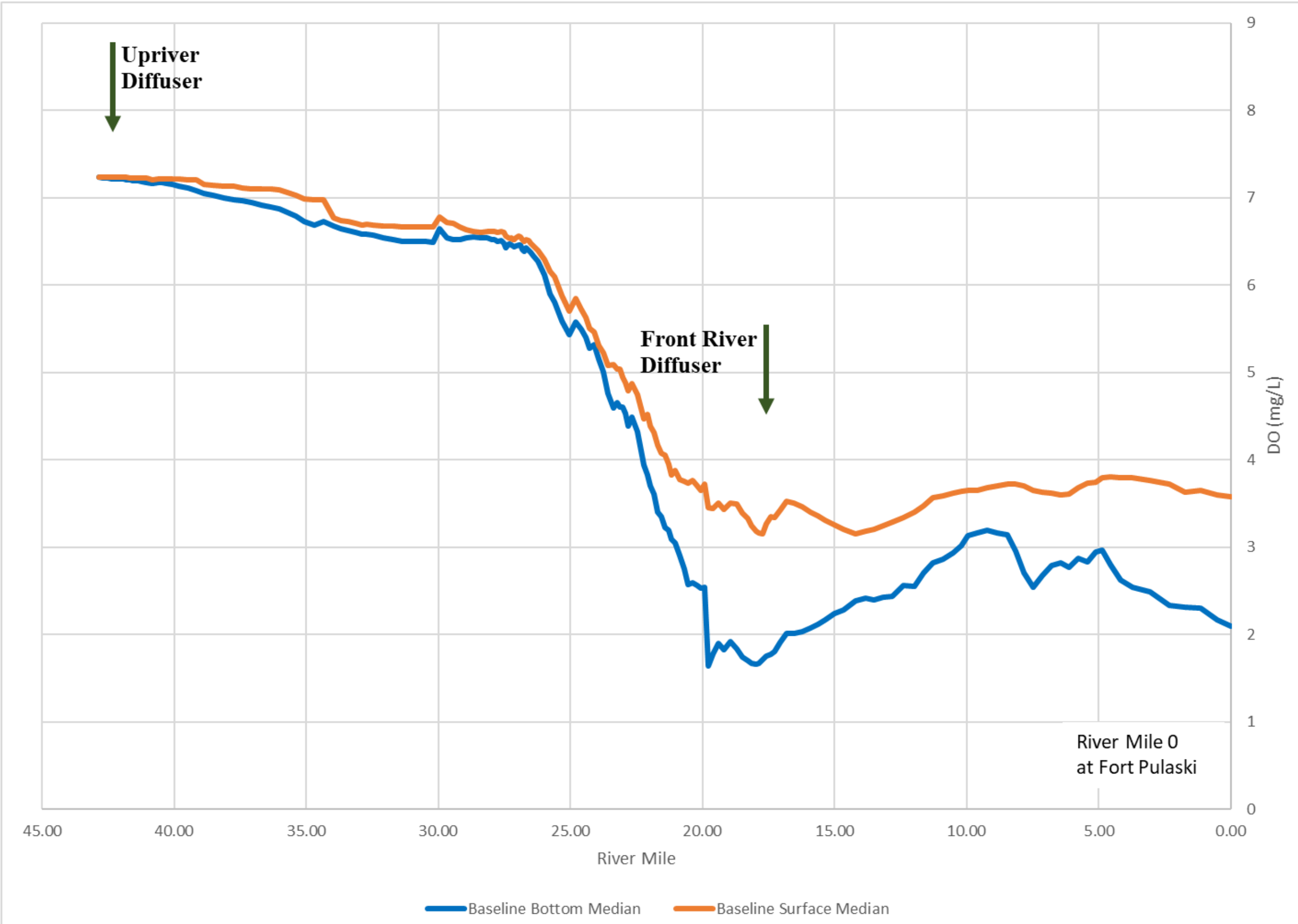

Figure 1-2 Savannah River and Estuary Average Summertime DO Transect

1.3 STAKEHOLDERS

A large group of stakeholders have been involved in the SHEP since its inception and will continue to be involved throughout the project. Collectively, these stakeholders are referred to in this report as *the agencies*. The agencies are made up of the resource agencies and parties of the Compromise and Settlement Agreement (Settlement Agreement) as identified in ***Table 1-1***. The agencies provided input and approval of key stages of the SHEP, including the development of the EIS and the Settlement Agreement (USACE 2012a, Compromise and Settlement Agreement 2013).

Table 1-1 Stakeholders Involved in SHEP, Collectively Known as the Agencies

Resource Agencies	Parties of the Settlement Agreement
U.S. Fish and Wildlife Service (USFWS)	South Carolina Attorney General
National Oceanic and Atmospheric Administration (NOAA)	Southern Environmental Law Center (SELC) - representing the South Carolina Coastal Conservation League, Savannah Riverkeeper, and South Carolina Wildlife Federation
USEPA	SCDHEC
South Carolina Department of Natural Resources (SCDNR)	Savannah River Maritime Commission (SRMC)
South Carolina Department of Health and Environmental Control (SCDHEC)	Georgia Ports Authority (GPA)
Georgia Department of Natural Resources (GA DNR)	USACE
USGS	

1.4 OXYGEN INJECTION SYSTEM

The oxygen injection system is made up of two plants that withdraw raw river water from the Savannah River, super-oxygenate the water, and then discharge the water back to the river. To super-oxygenate the water, high-purity oxygen gas is generated on-site at each plant and injected into water withdrawn from the river water using "Speece" cones, named after the inventor, Dr. Richard Speece. This super-oxygenated water is then returned to the river and mixes with the ambient river water, resulting in elevated DO levels.

The Upriver plant is in Rincon, Georgia (GA), in Effingham County, as presented in ***Figure 1-3*** and ***Figure 1-4***, and has the following characteristics:

- Eight Speece cones (during operation, seven are active and one is on reserve)
- One intake from the Savannah River
- One discharge pipe into the Savannah River
- Target oxygen production of 28,000 pounds per day (lbs/day)
- Target water flow of 70,490 gallons per minute (gpm)

The Upriver plant was designed to increase Upriver DO concentrations as well as in downstream regions. The impact of the Upriver plant is relatively easy to discern due to unidirectional flow, lack of tidal influence, and the confined nature of the upper Savannah River. It can be quantified by comparing background DO concentrations upstream of the Upriver plant diffuser to the DO concentrations measured downstream of the diffuser.

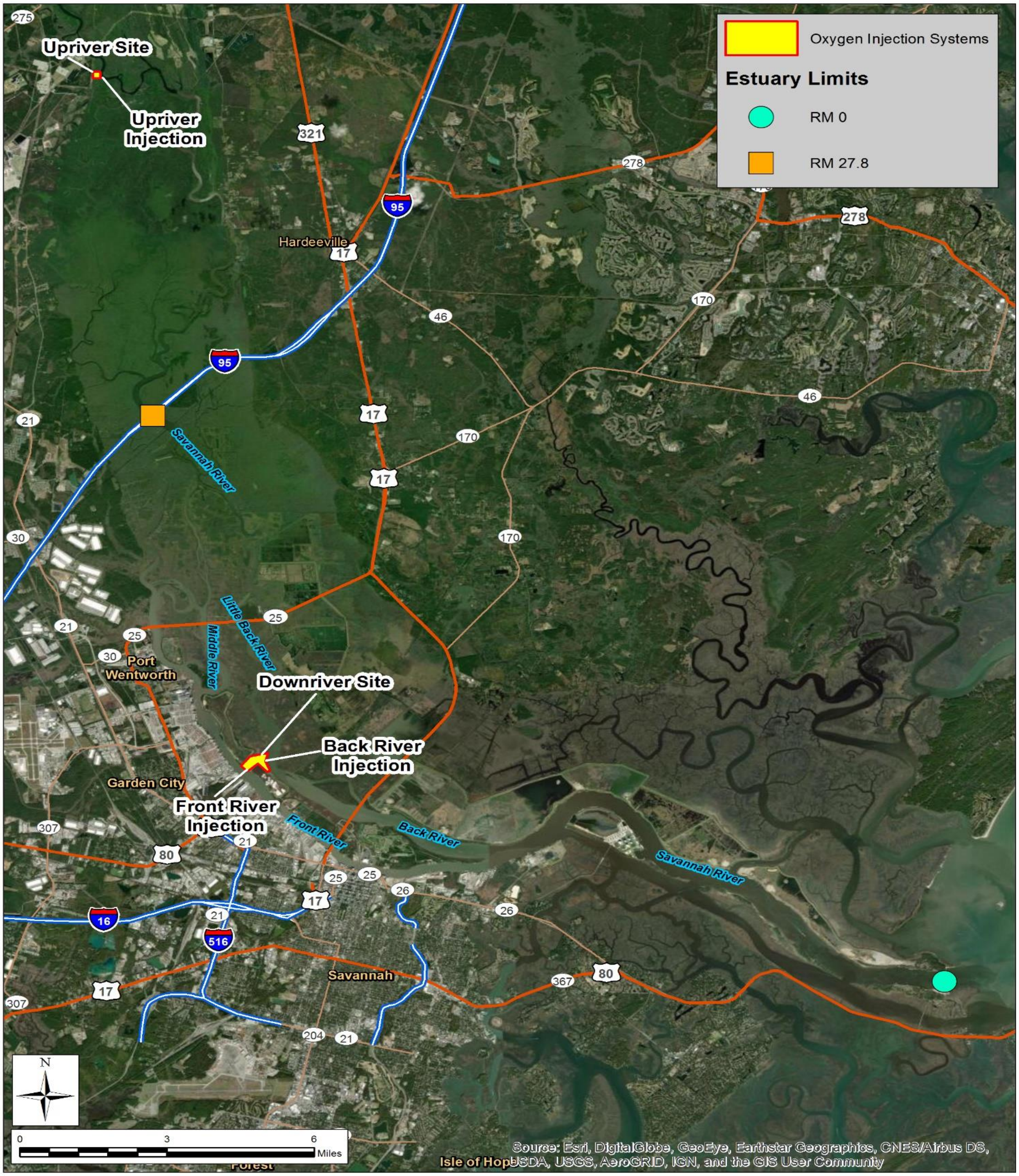

Figure 1-3 Oxygen Injection Plant Locations and Other Important Startup Run Features

Figure 1-4 Upriver Oxygen Injection Plant

The Downriver plant is located on Hutchison Island, GA, in Chatham County, as presented in ***Figure 1-3*** and ***Figure 1-5***, and has the following characteristics:

- Four Speece cones (during operation, three are active and one is on reserve)
- One intake from the Front River
- Two discharge pipes, one to the Front River and one to the Back River
- Target oxygen production of 12,000 lbs/day (8,000 lbs/day to the Front River, 4,000 lbs/day to the Back River)
- Target water flow of 30,210 gpm (20,140 gpm to the Front River, 10,070 gpm to the Back River)

Figure 1-5 Downriver Oxygen Injection Plant

The Downriver plant was designed to increase DO concentrations throughout the inner harbor navigation channel and the Back, Little Back, and Middle Rivers. The impact of the Downriver plant is less easily discernable due to the bidirectional flow, the impact of tides, varying channel widths, complex side river system, and other SHEP mitigation features including the McCoy's Cut freshwater flow rerouting. However, the impact can be quantified using a selection of independent data sources which provide corroborating conclusions.

In addition to the Speece cones and the pipes which transfer water through the plant, important equipment includes the oxygen generators which produce the high-purity oxygen before mixing in the cones, the pumps which generate the pressure to move water through the plant, and the diffusers which are the primary interface between the oxygen generation at the plant and the injection to the river.

Together the oxygen injection system is designed to deliver a daily average of 40,000 pounds (lbs) of DO to the Savannah River and estuary. The USACE started operating the Downriver plant in January 2019 and the Upriver plant in July 2020. The system will be operated seasonally during the critical summer months. The EIS requirement is to operate the injection system from June 15 through September 30, during the warmest months of the year when DO concentrations in the river are generally at their lowest (USACE 2012a).

It should be noted the diffusers at both plants were upgraded to address issues with the original design. Improvements were made at the Downriver plant on both the Front and Back River diffusers in 2019 before the Test Run to address visible localized surface disturbances. Each diffuser has multiple ports, five on the Front River and three on the Back River. Divers inspected both diffusers and noted the rubber check valves had been damaged, due to an inability to handle the high-pressure flows. The issue was addressed by capping ports in shallower water and installing replacement steel components on the deeper ports, which were able to handle the plant flows. These improvements addressed the surface disturbance issue, allowing the injected oxygen to diffuse properly in the bottom waters and mix horizontally and vertically in the river. The learnings from 2019 were applied to the Upriver plant in 2020 prior to the SUR. None of the 11 ports on the Upriver diffuser were capped; however, new steel components replaced the rubber check valves. After the diffusers were repaired and replaced, there was no visual evidence at any of the three diffusers that oxygen was bubbling to the water surface and transferring to the atmosphere. These upgrades were completed as work in kind for the non-federal sponsor, GPA.

1.5 TEST RUN

The Test Run was a 59-day continuous run of the Downriver plant with a requirement to deliver a daily average oxygen load of 12,000 lbs/day (Compromise and Settlement Agreement 2013). The Test Run occurred from March 14 through May 12, 2019, and a report documenting the monitoring and modeling during this period was delivered (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019a). The goal of achieving a daily average of 12,000 lbs/day across the Test Run was achieved, as detailed in ***Table 1-2***.

Table 1-2 Test Run (2019) Daily Averages

Plant	Target (lbs/day)	Actual (lbs/day)
Upriver	NA	NA
Downriver	12,000	13,385
TOTAL	**12,000**	**13,385**

During the Test Run, the field team conducted monitoring on the Front River and Back River by collecting data from platform sondes, semi-permanent buoy sondes, profiling sondes, and drift sondes. Seven dye releases were performed and monitored to visually confirm the directions and migrations of the DO plumes, as well as assess the areal extents of the plumes. This information was also used by the field team to fine-tune data collection methodologies throughout the Test Run.

Results from the SHEP model scenarios indicated that during the Test Run period, the oxygen injection system produced an increase in the surface and bottom layer DO concentrations as shown in ***Table 1-3***.

Table 1-3 Test Run (2019) Modeling Results Summary

Location	Average Increase DO Concentration (mg/L)	Maximum 10th Percentile DO Concentration Increase (mg/L)
Front River (Surface Layer)	0.02	0.10
Front River (Bottom Layer)	2.35	0.15
Back River (Surface Layer)	0.14	0.22
Back River (Bottom Layer)	0.75	0.68

The Test Run Report (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019a) concluded that the analyses of both measured data and model results illustrated the Test Run was a success, for the following reasons:

1. the oxygen injection target was achieved,
2. the injected oxygen was retained within the water column, and
3. mixing of the oxygen occurred vertically and spatially through the lower portion of the Savannah River and estuary.

The Test Run also allowed the monitoring and modeling team to apply lessons learned to the SUR in 2020.

The Test Run did leave several items unanswered. The Test Run did not prove the success of the Upriver plant's operation, nor did it prove the success of both Upriver and Downriver plants operating together. It did not occur in the critical summer period, and it did not occur with the inner harbor dredging underway. The Test Run was always intended to be a precursor to the SUR.

One additional analysis on the Test Run data was undertaken after delivery of the Test Run Report, and therefore has been included in this report. This analysis relied on the independently collected and publicly available USGS dataset and is presented in Section 7.1.

1.6 STARTUP RUN

The SUR was a 59-day continuous run of both the Upriver and Downriver plants with a requirement to deliver a daily average equal to or greater than the combined design production oxygen load of 40,000 lbs/day, as specified in the EIS and GRR Appendix C (USACE 2012a, USACE 2012b). The plants were required to operate for 59 days (approximately two lunar cycles), of which at least one 29.5-day period (one lunar cycle) must have occurred in July, August, or September while the Upriver and Downriver plants were operational (Compromise and Settlement Agreement 2013). The SUR occurred from July 25, 2020, through September 22, 2020.

Similar to the Test Run, a full-scale data collection effort during the SUR was needed to determine how well the injected oxygen delivered into the Savannah River and estuary was retained, and the ability of the injected oxygen to mix vertically and spatially, to mitigate the DO impacts of SHEP. The SUR data collection was performed around the Downriver plant diffusers on the Back River and the Front River and downstream of the Upriver plant on the Savannah River. In addition to the data collected near the diffusers, hydrodynamic and water quality data from USGS stations located in the Savannah River and estuary, and oxygen injection plant data provided by the USACE, were collected, reviewed, and analyzed.

Modeling was also required to evaluate the oxygen injection system performance throughout the estuary and the water column. Specifically, model results could be used at locations where field data were collected to validate the monitoring, and at locations where field data were not collected to fill data gaps. The SHEP models have been a useful tool to predict the future conditions of a completed project. Since outer harbor dredging was completed in March 2018 and inner harbor dredging started in September 2019, there is a need to show a completed SHEP with and without oxygen injection in addition to the actual conditions in the harbor while projects are ongoing.

The purpose of the SUR monitoring and modeling was to confirm that the oxygen injection system could mitigate for the SHEP navigational channel deepening impacts from Station 0+000 upstream to RM 27.8 (Compromise and Settlement Agreement 2013). The station extents from RM 0 to 27.8 are significant because they encompass the main components of the estuary of the Savannah River. RM 0 is adjacent to Fort Pulaski at the mouth of the river and RM 27.8 is the I-95 Bridge. These two demarcations signify the upper and lower extents of the freshwater-saltwater interface. The extent includes the Front River and South Channel near the mouth (downstream); the Front and Back Rivers near downtown Savannah; and the Front, Middle, and Little Back Rivers (upstream) (***Figure 1-3***).

Information in the EIS was used to develop success metrics that have been used to demonstrate the oxygen injection system can achieve the mitigation requirements identified in the EIS. To achieve the success metrics, a combination of monitoring and modeling efforts was required, and the subsequent analyses led to multiple lines of evidence proving the success of harbor deepening mitigation efforts. Additional detail on what quantifies SUR success and how success was achieved is presented in Section 4.0.

The SUR data collection and monitoring and modeling report were Tasks 9 and 10, respectively, of the contract between LG2 Environmental Solutions, their sub-consultants Tetra Tech and GHD, and the USACE Savannah District. SUR data collection and quality assurance/quality control (QA/QC) followed the methodology documented in Appendix A and Appendix B of the *Work Plan (REV9)* for *Dissolved Oxygen Facility Environmental Testing for the Savannah Harbor Expansion Project* (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019b). This report discusses the data collection procedures used by the field team for the SUR data collection period, data QA/QC evaluations conducted by the QA/QC team on the SUR data, and analyses of the monitoring and modeling data to demonstrate the success of the SUR.

2.0 DATA COLLECTION PROCEDURES

The SUR data collection efforts consisted of three major data collection methods which provided a comprehensive understanding of how the Front River, Back River, and Upriver areas of the Savannah River responded to the injected oxygen. These three data collection methods were:

- *Semi-permanent buoys* were deployed at targeted locations upstream and downstream of the diffusers in the Front River, Back River, and Upriver areas of the Savannah River to collect continuous water quality data. Details are provided in Section 2.1.
- *Boat collection methods* were used to obtain "Profile" and "Drift" data upstream and downstream of the diffusers to show how the injected oxygen plume mixed in the water column and where and how far it traveled in the harbor. Daily sampling events were conducted and rotated between the Front River, Back River, and Upriver areas. Details are provided in Section 2.2 and Section 2.3.
- *Periodic Rhodamine dye injections* and subsequent monitoring of dye were conducted to better determine how the DO behaved after injection at the two injection plants. Details are provided in Section 2.4.

Data collection procedures for the SUR event followed the data collection procedures that were validated during the background data collection efforts in 2018 and were similar to the procedures used during the WCTE and Test Run studies conducted in 2019. Data collection methods used from the inception of the monitoring project through 2019 included using monitoring instruments deployed by boats for targeted sampling, semi-permanent buoys at selected locations, and permanent mounts via a fixed floating platform. The data collection efforts completed for the SUR in 2020 were conducted by intensive boat sampling (up to three boats at one time) and semi-permanent buoys to allow quick responses and flexibility for tracking the general movement and behavior of the three injected oxygen plumes. Fixed floating platforms were not installed during the SUR to allow the monitoring team more flexibility with buoyed instruments and targeted sampling.

All data sondes and associated sonde sensors used for the various data collection methods were prepared and calibrated following manufacturer's specifications by field team scientists who were trained by the manufacturer's technicians and completed instrument training classes. The data sondes, according to the YSI manufacturer specifications, were capable of accurately collecting DO data to 0.01 mg/L at various intervals (up to one-second intervals). Preparation and maintenance of the data sondes were performed at the laboratory and workspaces provided by the USACE at the Army Corps Depot located on the north bank of the Savannah River on Hutchinson Island.

A visual summary of the SUR data collection effort is illustrated in ***Figure 2-1*** and a statistical summary of the collected data is in Section 2.5.

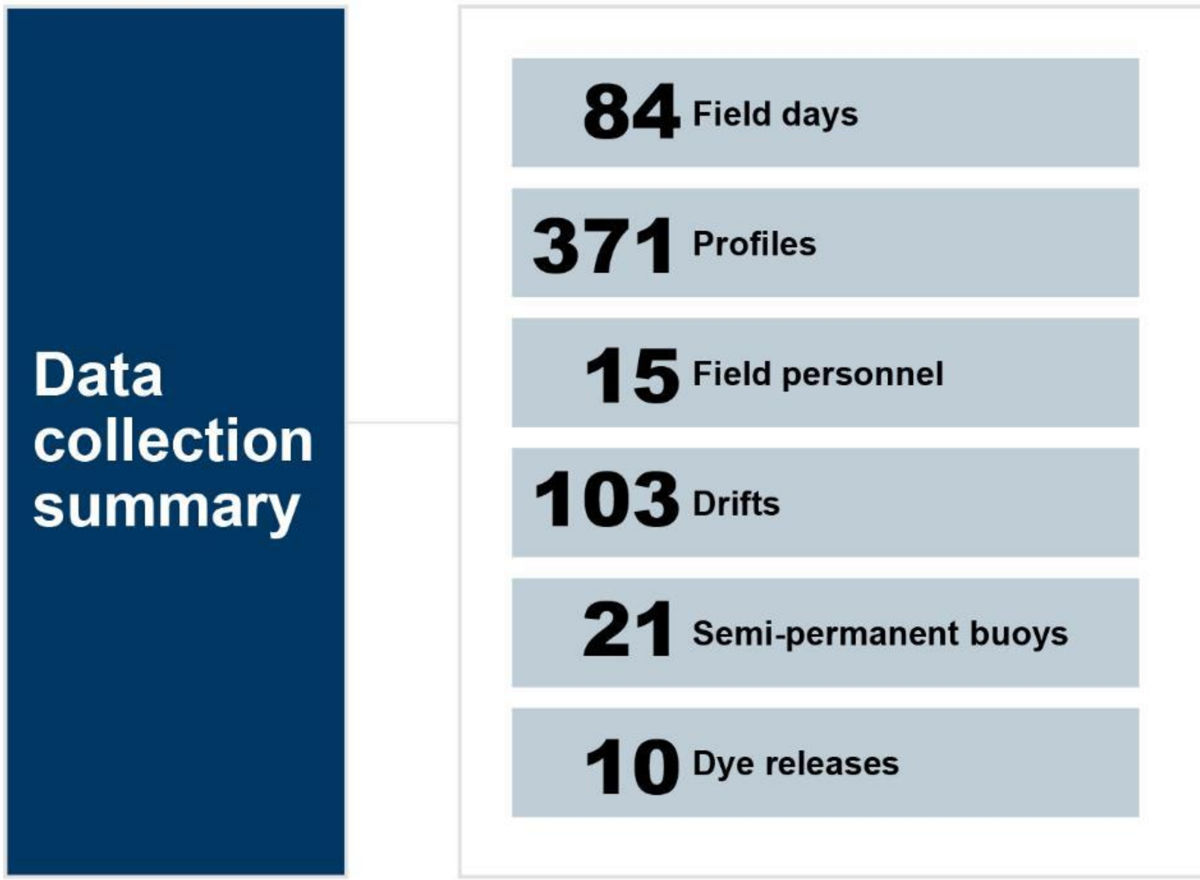

Figure 2-1 Summary of Data Collection Program

2.1 SEMI-PERMANENT BUOY MONITORING / DATA COLLECTION

During the SUR period, water quality data were collected from data sondes deployed at:

- Ten semi-permanent buoys located in the Upriver area with one buoy deployed upstream of the diffuser and nine buoys deployed downstream of the diffuser (photo of installed buoys in ***Figure 2-2*** and map in ***Figure 2-3***). These buoys are labeled UR_9 to UR_18. A sonde was also installed at the discontinued USGS Hardeeville gage (02198760), located approximately two miles downstream of the Upriver diffuser, a few weeks after data collection began to capture DO concentrations downstream and quantify the impact of low DO water entering the Savannah River from tributaries and marshes.
- Three semi-permanent buoys located in the Front River (***Figure 2-4***). These buoys are labeled LFR-A, LFR-N, and LFR-S. All three buoys were removed on July 14, 2020, due to channel dredging activities in this area and were not redeployed for SUR sampling activities. An additional sonde was deployed at USGS station 021989773 at the USACE Depot on Hutchinson Island for the duration of the SUR (***Figure 2-4***).
- Eight semi-permanent buoys located in the Back River with four buoys deployed upstream and four buoys deployed downstream of the diffuser (***Figure 2-4***). These buoys are labeled LBR_8 to LBR_1.

The data sondes and buoys were deployed by July 14, 2020, before the SUR period which began on July 25, 2020. The data sondes were fitted with DO, conductivity, temperature, depth, and salinity sensors. Several of the sondes were also equipped with Phycoerythrin Blue-green Algae (BGA) sensors and/or Rhodamine dye sensors to detect the dye injected periodically during the SUR to mimic the movement of injected oxygen.

The semi-permanent buoy data sondes were designed to be tethered in one location approximately 3.3 feet below the water's surface where they would continuously collect and record data at five-minute intervals. At two of the Upriver buoys downstream of the diffuser, UR_12 and UR_16, additional data sondes were also deployed along the mooring lines at approximately 9.8 feet below the water's surface. The deeper sondes are designated UR_12a and UR_16a, respectively. Data were retrieved from the semi-permanent buoy data sondes weekly.

Additional detail on the semi-permanent buoy data collection is presented in **APPENDIX A** and a statistical summary of the collected data is in Section 2.5. The semi-permanent buoy data is analyzed in Section 8.0 and Section 9.0.

Figure 2-2 Upriver Semi-permanent Buoys, Looking Toward Injection Plant

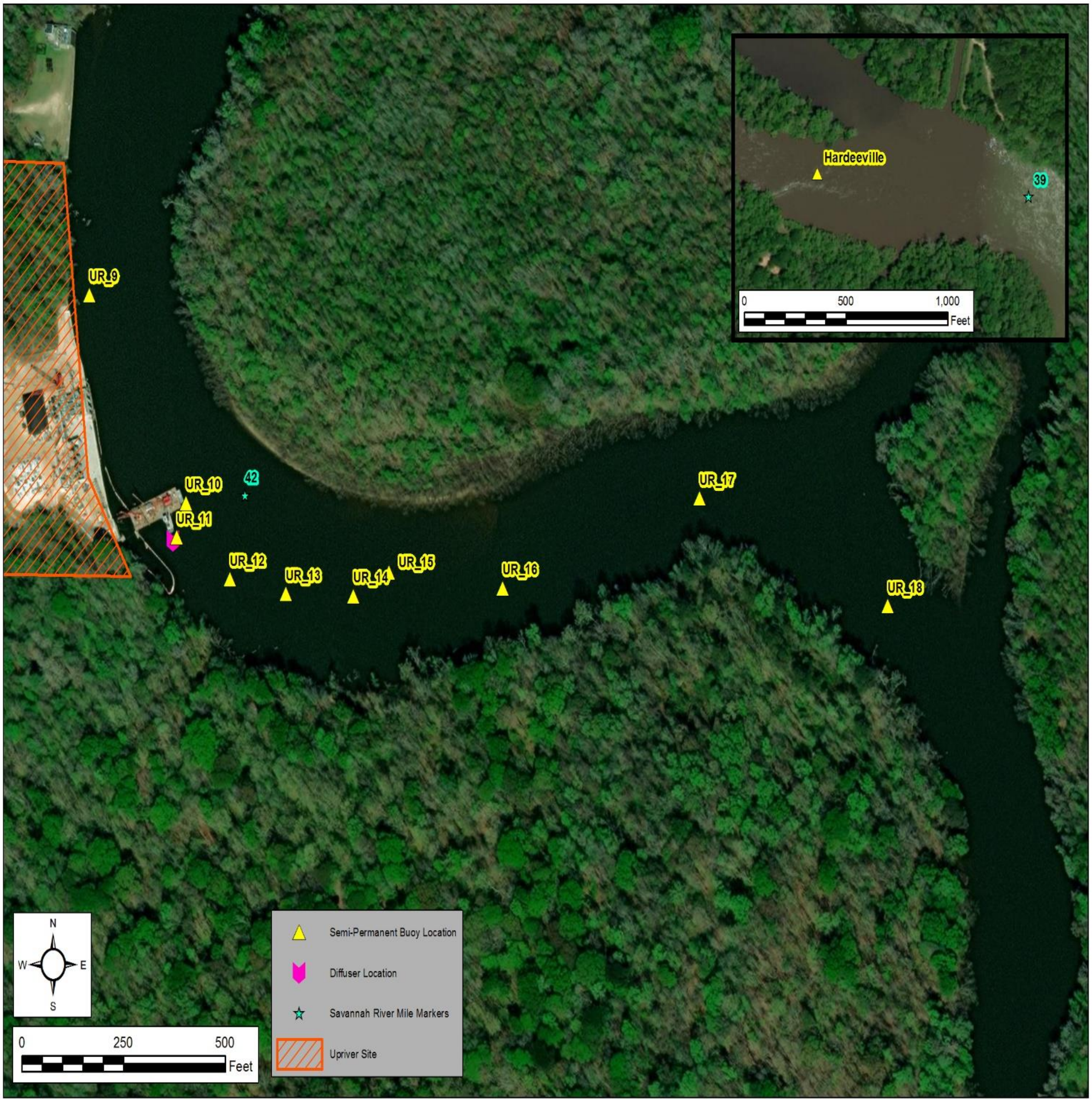

Figure 2-3 Upriver Semi-permanent Buoy Monitoring Locations

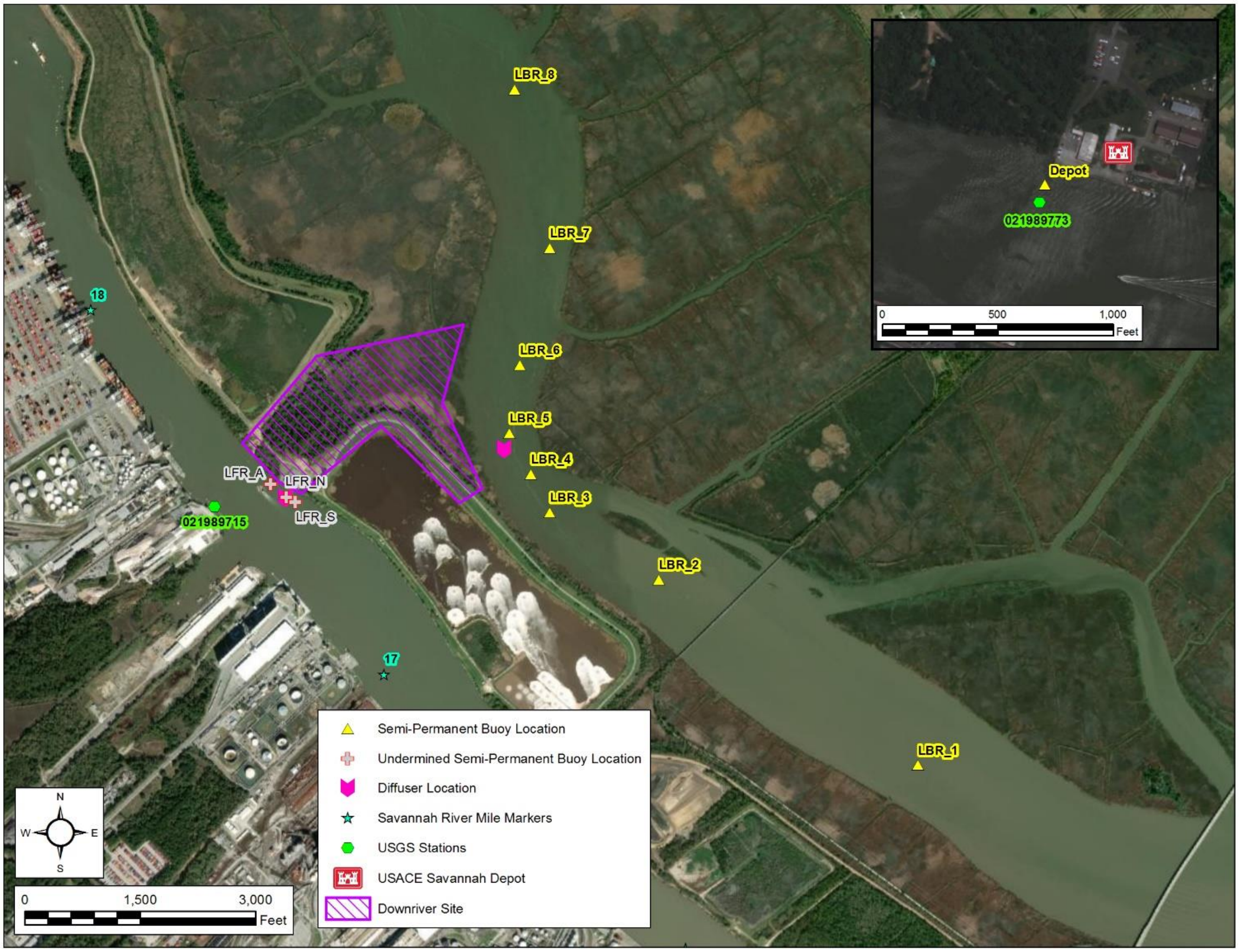

Figure 2-4 Downriver Semi-Permanent Buoy Monitoring Locations

2.2 PROFILE MONITORING / DATA COLLECTION

Profile data collection was conducted by the field team via project boats and consisted of deploying a data sonde over the side of a project boat and lowering and raising it through the water column from the water's surface to the river bottom. The data sonde was suspended 1.0 foot above the river bottom for approximately 30 seconds before raising it to the water's surface. Profile data collection locations were selected by the field team at landmark locations (semi-permanent buoys) or points of interest along the Front River, Back River, and Savannah River areas. These points of interest include various tributaries, physical features (closed channel cuts and diversion structures), and around each of the three diffusers.

Each data sonde recorded DO, DO percent saturation, salinity, specific conductivity (SPCOND), water temperature, date, time, depth, and Geospatial positioning system (GPS) locations of each measurement. Additionally, Chlorophyll and Blue-green Algae (Total Algae) sensors used to detect dye were installed on selected sondes during profiling measurements depending on the timing of dye injection events and/or the locations of the sampling events. When available, Rhodamine dye sensors were installed on several profile sondes per the instruction of the field team leader. The BGA data was converted to an equivalent Rhodamine dye value using a conversion factor developed from the SUR information, allowing for comparable dye values. Water quality measurements were monitored using a hand-held interface device connected to the data sonde by a communication cable allowing real-time viewing of information logged by the data sondes. Profiling data were recorded at a frequency of two seconds.

A general data collection schedule was prepared before starting the SUR monitoring period that identified the dates, tidal conditions, and types of boat data collection techniques that would occur on each part of the river. However, this schedule was visited and refined weekly depending on variables such as weather conditions, data density, and interpretations of previously collected data to better meet the goals of the SUR study.

Additional detail on the profile monitoring undertaken is provided in **APPENDIX B** and a statistical summary of the collected data is in Section 2.5. The profile data is analyzed in Section 8.0 and Section 9.0.

Field notes and daily logs were prepared to document the data collection times and locations, field crew members, weather conditions, and data collection issues if any (**APPENDIX D**). The downloaded data, including GPS locations along with the field notes and daily logs, were transferred to the QA/QC team following the QA/QC procedures in Appendix B of the Work Plan (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019b). Microsoft Excel (Excel) files contained raw data uploaded to the project Microsoft OneDrive (OneDrive) and provided in comma-delimited format. The raw data were reviewed and qualified by the QA/QC team.

2.3 DRIFT MONITORING / DATA COLLECTION

Drift data collection was conducted by the field team via project boats using multiple instruments deployed from a single boat. Typically, one or two data sondes were deployed from a boat, each deployed at different yet constant depth intervals over the side of the sampling boat. The first sonde was deployed at approximately 3.3 feet below the water's surface (shallow) and an additional sonde was deployed between 8.2 and 16.4 feet (deep) if sampling conditions allowed. Drift routes were conducted with the flow of the tide either in zig-zag patterns (roughly bank to bank), or relatively straight routes along the channel parallel to water flows. Data were collected at two-second intervals and monitored in real-time using a hand-held interface device to log the data.

The goal of the drift data collection method was to help determine the spatial and temporal variability inside and outside of detectable oxygen or dye plumes. Each data sonde recorded DO, DO percent saturation, salinity, SPCOND, temperature, date, time, and depths of measurements. Total Algae and Rhodamine dye sensors were installed on various data sondes as needed.

Additional detail on the drift monitoring undertaken is provided in **APPENDIX C** and a statistical summary of the collected data is in Section 2.5. The drift data is analyzed in Section 8.0 and Section 9.0.

2.4 DYE RELEASES AND MONITORING

Rhodamine WT dye injection and tracking were conducted in the Front River, Back River, and Savannah River areas before and during the SUR data collection event. Rhodamine WT dye is a stable, non-toxic, fluorescent, xanthene dye routinely used as a hydrologic tracer in surface water systems and was used to track where the injected flow and the associated oxygen travels. This dye was detected by data sondes equipped with fluorometers and assisted with locating and tracking the DO plumes. This dye has been used in hydrologic studies for decades since the dye has a similar molecular structure to water. The standard procedure in dye fluorometry hydrologic studies is to introduce a quantity of dye into a water body, and subsequently collect water samples over some spatial and temporal regimes. Fluorometer readings show the concentration of the dye that is proportional to its fluorescence. Since this dye mimics the movement of water molecules, a measure of the movement of the dye (i.e., Rhodamine WT) will in effect be a measure of the movement of the water and, therefore, substances transported by the water (i.e., dissolved oxygen) into which it is introduced. Typically, dispersion and mixing occur in all dimensions of the water body. For example, in streams, vertical mixing typically occurs first. Subsequently, and depending on current, channel configuration, and stream characteristics, lateral mixing and longitudinal mixing follow. For other bodies, the sequence of the mixing phenomena may vary, but the mixing principle remains.

The dye was injected into discharge pipes at both DO plants at designated ports using a stainless steel drum pump powered by a 120-volt electric motorhead and fitted with an impeller that could completely pump the contents of a container. Dye injection was regulated at the drum pump with a one-inch ball valve and electronic flow meter to deliver the dye into the discharge pipes at approximately 3.0 gpm. ***Table 2-1*** provides the dates, times, injection areas of the river, tide conditions, dye strengths, and dye volumes used for the SUR event dye releases. An aerial photo of the Front River dye release on August 25, 2020, is presented in ***Figure 2-5***.

The dye releases were used to track the behavior of the injected DO plumes, the potential areal and vertical extents of plumes, as well as how quickly the dye and therefore the DO mixed throughout the waterbody during varying flow and tidal conditions. The dye was monitored instream using both Rhodamine dye and BGA sensors. The BGA data was converted to an equivalent Rhodamine dye value by multiplying by a factor of 0.088. This is based on a regression analysis comparing BGA to Rhodamine dye measurements. Both the Rhodamine dye and converted BGA values are referred to as dye for the remainder of the report.

Due to development by the manufacturer and timing of the release to commercial markets, only BGA sensors were available for the July 2020 dye releases. The Rhodamine dye sensors were still in the development stage; however, upon availability, the preferred Rhodamine sensors were used thereafter. Thirty gallons of undiluted (full strength) dye were injected at all three diffusers on July 15 and July 16, 2020, such that it would be detectable at the three USGS gage BGA sensors at Savannah River near I-95 (USGS 02198840), Back River at U.S Highway 17 (GA 17) (USGS 0219897945), Little Back River at Hog Island (USGS 021989793), and the BGA sensor at the USACE Depot (USGS 021989773). Rhodamine dye sensors were available and installed for the August 10 through August 12, 2020, and remaining SUR dye events. Lower dye concentrations, at one-third full strength, were used for the August 10 through August 12 dye events, to examine the near-field dilution of the dye around the diffusers and to help develop a BGA-Rhodamine dye relationship. A super dye event was conducted from August 24 through August 25, 2020. The purpose of this study was to assess how long the dye would remain in the Front and Little Back Rivers. Sixty gallons of full-strength dye were injected at each diffuser so the dye could be measured and tracked for approximately three to four weeks after release. On September 15, 2020, 45 more gallons were injected at the Upriver plant only to see how the Upriver dye (and therefore oxygen) in isolation (without influence from the Downriver plant), mixed into the Front River.

The dye releases are analyzed in Section 10.0.

Table 2-1 SUR Dye Releases and Locations

Date	Time	River	Tide	Dye Strength	Dye Volume (gallons)
15-Jul-20	10:30	Upriver	N/A	Full	30
16-Jul-20	09:50	Back	13:49 L	Full	30
16-Jul-20	11:07	Front	13:49 L	Full	30
10-Aug-20	10:00	Upriver	N/A	1:3	30
11-Aug-20	09:00	Front	08:40 L	1:3	30
12-Aug-20	10:00	Back	09:31 L	1:3	30
24-Aug-20	10:00	Upriver	N/A	Full	60
25-Aug-20	08:45	Front	08:29 L	Full	60
25-Aug-20	09:45	Back	08:29 L	Full	60
15-Sep-20	08:54	Upriver	N/A	Full	45

Figure 2-5 Dye Plume from Front River Diffuser Near Downriver Plant

2.5 STARTUP RUN DATA SUMMARY

Data were collected from July 7 through September 30, 2020, in the Upriver, Front River, Middle River, and Back and Little Back River, with limited data collected in the first two weeks and for the final week of fieldwork given these were outside of the SUR period. As previously mentioned, the three types of data collection procedures were:

- Drift data collection using a surface sonde (~3.3 feet deep) and at times an additional mid-depth sonde,
- Profile depth data collections at set points in the river, and
- Semi-permanent buoys located around the diffusers.

The main parameters that were collected are:

- DO in mg/L
- Dissolved Oxygen Saturation (DOsat) in percent
- Salinity in ppt
- Temperature in degrees Celsius
- Rhodamine dye in micrograms per liter (µg/L)
- BGA (algal) in relative fluorescence units – this is before conversion to dye in µg/L
- SPCOND

During the field data collection, no effervescence or bubbling was observed above or in the vicinity of the three diffusers.

2.5.1 Upriver Data Summary

Upriver data were collected at 13 sondes and during 62 drift and 30 profile sampling events.

2.5.1.1 Upriver Buoy Data

Thirteen sondes were deployed. Of the 10 semi-permanent buoys, eight had one surface sonde and two had an additional mid-depth sonde. One additional sonde was deployed at the discontinued USGS Hardeeville station (02198760), approximately two miles downstream of the diffuser.

The Upriver buoy upstream of the oxygen injection plant was installed on July 7, 2020, the semi-permanent Upriver buoys downstream of the diffuser were installed on July 9 and 10, 2020, and the Hardeeville sonde on July 15, 2020. ***Table 2-2*** provides a summary of the Upriver buoy data.

Table 2-2 Upriver Buoy Data

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	6.1	6.5	6.9	7.3	7.7	8.0	8.1	280,194	5.6	8.6
DO saturation (%)	76	79	86	92	97	102	105	280,194	65	110
Salinity (ppt)	0.02	0.0	0.0	0.0	0.0	0.0	0.0	280,194	0.0	0
Temp_C (°C)	22	22	27	28	28	29	30	280,194	21	30
BGA_R (RFU)	0.1	1.3	1.7	2.0	2.3	2.7	3.3	39,105	0.0	158
Sp_Cond	55	61	71	77	85	92	95	280,194	21	99

Notes: PCTL – percentile, Min – minimum, Max – maximum

2.5.1.2 Upriver Drift Data

Upriver drift data was collected during the SUR. The drift routes ranged from:

- Detailed sampling around the diffuser,
- Drift sampling upstream of diffuser to one to four miles downstream of the diffuser, and
- Two drift routes from the diffuser to the I-95 bridge.

Table 2-3 provides a summary of the Upriver drift data.

Table 2-3 Upriver Drift Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	6.06	6.34	6.69	7.33	7.61	7.84	8.01	97,452	5.90	8.72
DO saturation (%)	76.5	80.6	84.4	92.45	96.09	99.59	101.3	97,452	73.2	107.7
Salinity (ppt)	0.03	0.03	0.03	0.04	0.04	0.04	0.04	97,452	0	0.05
Temp_C (°C)	23.46	25.53	27.36	27.60	27.87	29.15	29.2	97,452	23.43	29.29
BGA_R (RFU)	1.275	1.38	1.61	1.98	2.5	112.77	157.01	87,941	1.22	158.6
Dye (µg/L)	0.02	0.02	0.03	0.04	2.29	16.65	39.16	40,167	0.02	107.07
Sp_Cond	65	72	74	78	86	94	97	97,452	0	111

Notes: PCTL – percentile, Min – minimum, Max - maximum

The Upriver drift DO data sampling can be divided into three areas:

- Background sampling above the diffuser,
- Oxygen injection impact sampling below the diffuser, and
- Tributary sampling.

Comparing the background DO to the DO downstream from the diffuser shows the overall impact of the injected oxygen. The low DO values from tributaries explain why the DO levels decrease as the river flows down to the I-95 bridge. This comparison is presented in Table 2-4.

Table 2-4 Upriver Background Below Diffuser and Tributary Drift Data Comparison

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	6.06	6.34	6.69	7.33	7.61	7.84	8.01	97,452	5.90	8.72
DO (mg/L)	6.38	6.62	7.26	7.54	7.75	8.01	8.17	195,498	5.61	8.59
DO (mg/L)	4.64	4.87	5.51	5.65	5.79	5.88	5.9	648	4.61	5.9

2.5.1.3 Upriver Profile Data

Upriver profile data was collected during the SUR. Profile data sampling was conducted around the diffuser and buoys to evaluate whether the oxygen was mixing throughout the water column. ***Table 2-5*** provides a summary of the Upriver profile data.

Table 2-5 Upriver Profile Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	6.69	7.07	7.86	7.99	8.02	8.19	8.31	5,287	6.66	9.00
DO saturation (%)	83	90.01	99.7	100.3	100.9	103	104.6	5,287	82.6	115.73
Salinity (ppt)	0.03	0.03	0.04	0.04	0.04	0.04	0.05	5,287	0	0.05
Temp_C (°C)	26.34	26.36	27.03	27.05	27.06	28.40	29.31	5,287	24.73	29.34
BGA_R (RFU)	1.61	1.93	2.33	10.61	84.11	156.96	158.28	5,287	0.54	158.42
Dye (µg/L)	0.04	0.04	0.29	1.92	7.50	35.68	53.03	3,979	0.03	70.27
Sp_Cond	74	76	84	97	98	98	99	5,287	2	99

Notes: PCTL – percentile, Min – minimum, Max – maximum

2.5.2 Front River Data Summary

Front River data were collected at one sonde and during 30 drift and 305 profile sampling events.

2.5.2.1 Front River Buoy Data

Three Front River buoys were deployed on July 9, 2020, but had to be removed on July 14, 2020, due to ongoing dredging activities in the area. A sonde was also deployed at the USACE Depot Dock on July 9, 2020, and removed on September 28, 2020. ***Table 2-6*** provides a Front River buoy data summary.

Table 2-6 Front River Buoy Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	2.4	2.8	3.3	3.8	4.4	5.6	6.0	27,390	1.5	6.5
DO saturation (%)	32.7	38.0	45.4	51.6	58.5	71.0	77.5	27,390	20.6	86.8
Salinity (ppt)	1.5	2.7	5.6	7.4	9.9	13.5	16.2	27,390	0.6	20.2
Temp_C (°C)	23.0	23.6	28.2	28.9	29.5	30.2	30.6	27,390	22.7	31.1
BGA_R (RFU)	0.03	0.03	0.04	0.05	0.06	0.10	0.14	15,905	0.02	0.52
Dye (µg/L)	1.0	1.2	1.7	2.1	2.6	3.4	4.8	13,062	0.8	98.1
Sp_Cond	2,823	5,052	10,033	12,961	16,945	22,473	26,612	27,390	1,269	32,540

Notes: PCTL – percentile, Min – minimum, Max - maximum

2.5.2.2 Front River Drift Data

Front River drift data was collected during the SUR. The drift routes ranged from:

- Detailed sampling around the diffuser, and
- Drift sampling ranging from the I-95 bridge (RM 27) to Fort Pulaski (RM 0).

Table 2-7 provides a summary of the Front River drift data.

Table 2-7 Front River Drift Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	1.9	2.4	3.6	4.3	5.2	6.9	7.8	171,770	0.1	8.2
DO saturation (%)	26.0	33.5	48.2	57.9	67.8	86.8	97.3	171,770	1.3	101.9
Salinity (ppt)	0.0	0.1	1.8	3.8	6.1	9.9	15.9	171,770	0.0	30.4
Temp_C (°C)	25.9	26.4	27.5	28.7	29.3	29.8	29.9	171,770	25.6	30.5
BGA_R (RFU)	0.03	0.04	0.05	0.07	0.12	3.55	38.06	117,693	0.02	182.33
Dye (µg/L)	1.5	1.9	2.3	2.8	3.7	24.4	151.6	149,061	0.5	159.0
Sp_Cond	89	102	3,510	6,954	10,844	16,894	26,068	171,770	5	46,934

Notes: PCTL – percentile, Min – minimum, Max - maximum

2.5.2.3 Front River Profile Data

Front River profile data was collected during the SUR. ***Table 2-8*** provides a summary of the Front River profile data.

Table 2-8 Front River Profile Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	1.9	2.4	3.6	4.3	5.1	6.0	6.7	164,281	0.1	9.0
DO saturation (%)	25.4	33.6	47.8	57.1	66.3	77.4	86.0	164,281	1.3	101.5
Salinity (ppt)	0.1	0.6	2.4	4.2	6.5	12.9	25.4	164,281	0.0	33.5
Temp_C (°C)	23.4	26.8	27.7	28.8	29.3	29.8	29.9	164,281	19.5	30.5
BGA_R (RFU)	0.03	0.04	0.05	0.07	0.12	4.63	40.18	110,208	0.02	182.33
Dye (µg/L)	1.5	1.9	2.4	2.9	3.8	26.5	151.9	144,192	-3.8	159.0
Sp_Cond	355	1,293	4,396	7,374	10,995	16,789	26,359	156,122	5	46,934

Notes: PCTL – percentile, Min – minimum, Max - maximum

The Front River is a stratified estuarine system, with lower salinity values in the upper half of the water column and higher salinity values in the bottom half. All Front River profile data were separated into upper half (depth less than 16.4 feet) shown in ***Table 2-9*** and bottom half (depth greater than or equal to 16.4 feet) shown in ***Table 2-10***.

Table 2-9 Front River (Upper Half) Data Comparison

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	2.4	3.1	4.0	4.5	5.2	6.0	6.7	104,066	0.1	8.1
DO saturation (%)	33.5	42.4	53.2	59.8	67.5	77.5	85.8	104,066	1.7	101.0
Salinity (ppt)	0.1	0.5	2.2	3.8	5.8	8.9	14.8	104,066	0.0	22.9
Temp_C (°C)	26.5	27.0	28.3	28.8	29.3	29.7	29.9	104,066	26.1	30.5
BGA_R (RFU)	0.03	0.04	0.05	0.07	0.14	8.07	53.19	75,237	0.02	182.33
Dye (µg/L)	1.4	1.8	2.2	2.8	3.8	56.4	154.8	88,498	0.5	159.0
Sp_Cond	240	1,073	4,216	6,930	10,258	15,275	24,489	104,066	5	36,467

Notes: PCTL – percentile, Min – minimum, Max - maximum

Table 2-10 Front River (Bottom Half) Data Comparison

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	1.2	1.9	2.8	3.3	3.9	5.2	6.6	28,879	0.1	6.8
DO saturation (%)	16.5	26.2	38.1	45.2	51.9	67.2	86.0	28,879	1.3	88.4
Salinity (ppt)	0.2	1.8	3.8	5.7	7.6	10.6	24.1	28,879	0.1	30.4
Temp_C (°C)	27.2	27.7	29.0	29.3	29.6	29.9	30.0	28,879	26.8	30.1
BGA_R (RFU)	0.04	0.04	0.06	0.08	0.10	0.70	18.54	26,812	0.03	76.09
Dye (µg/L)	1.6	2.1	2.7	3.3	4.2	17.5	104.0	28,118	1.3	157.1
Sp_Cond	387	3,396	6,896	10,133	13,209	18,016	38,195	28,879	170	46,934

Notes: PCTL – percentile, Min – minimum, Max – maximum

2.5.3 Back River Data Summary

Back River data were collected at eight sondes and during 32 drift and 36 profile sampling events.

2.5.3.1 Back River Data Summary

Eight buoys were deployed in the Back River, all with surface sondes. Four sondes were located upstream and four were located downstream of the diffuser. The Back River buoy sondes were installed on July 9, 2020. ***Table 2-11*** provides a summary of the Back River buoy data.

Table 2-11 Back River Buoy Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	3.1	3.7	4.6	5.2	5.6	6.4	7.1	174,433	0.7	9.7
DO saturation (%)	41.9	50.3	60.3	66.9	72.8	85.2	95.6	174,433	9.2	132.5
Salinity (ppt)	0.1	0.1	0.8	3.1	5.5	9.7	12.7	174,433	0.0	17.9
Temp_C (°C)	22.0	23.4	27.9	29.0	29.7	30.6	31.0	174,433	20.9	32.1
BGA_R (RFU)	2.0	2.4	3.3	4.4	6.4	9.9	14.0	44,210	1.4	153.9
Sp_Cond	127	227	1,662	5,835	9,821	16,663	21,299	174,433	82	29,089

Notes: PCTL – percentile, Min – minimum, Max - maximum

2.5.3.2 Back River Drift Data

Back River drift data was collected during the SUR. The drift routes ranged from:

- Detailed sampling around the diffuser,
- Drift sampling ranging from GA 25 bridge to downstream confluence with Front River, and
- Drift sampling of all the Back and Little Back Rivers from upstream confluence to downstream confluence with Front River.

Table 2-12 provides a summary of the Back River drift data.

Table 2-12 Back River Drift Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	3.1	3.7	4.6	5.2	5.6	6.4	7.1	174,433	0.7	9.7
DO saturation (%)	41.9	50.3	60.3	66.9	72.8	85.2	95.6	174,433	9.2	132.5
Salinity (ppt)	0.1	0.1	0.8	3.1	5.5	9.7	12.7	174,433	0.0	17.9
Temp_C (°C)	22.0	23.4	27.9	29.0	29.7	30.6	31.0	174,433	20.9	32.1
BGA_R (RFU)	2.0	2.4	3.3	4.4	6.4	9.9	14.0	44,210	1.4	153.9
Sp_Cond	127	227	1,662	5,835	9,821	16,663	21,299	174,433	82	29,089

Notes: PCTL – percentile, Min – minimum, Max - maximum

2.5.3.3 Back River Profile Data

Due to relatively shallow channel depths, limited Back River profile data were collected during the SUR. ***Table 2-13*** provides a summary of the Back River profile data.

Table 2-13 Back River Profile Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	3.5	3.7	4.5	5.1	5.3	5.4	7.3	1,882	3.4	8.2
DO saturation (%)	45.9	51.7	60.4	66.6	69.8	71.1	87.7	1,882	45.7	95.9
Salinity (ppt)	0.1	0.1	1.2	2.6	6.4	11.3	20.6	1,882	0.1	20.6
Temp_C (°C)	24.0	25.5	28.4	28.8	29.2	30.4	30.6	1,882	22.9	30.6
BGA_R (RFU)	3.0	3.2	3.6	4.0	5.3	6.5	7.1	366	2.9	8.2
Sp_Cond	178	180	2,429	4,862	11,348	19,110	32,971	1,882	178	33,081

Notes: PCTL – percentile, Min – minimum, Max – maximum

2.5.4 Middle River Data Summary

Limited drift sampling data were collected in the Middle River given it was not a priority of the field data collection. Three complete Middle River drifts were completed, along with several profiles near the USGS Middle River Fish Hole gage. ***Table 2-14*** provides a summary of the Middle River data.

Table 2-14 Middle River Data Summary

Parameter	1st PCTL	5th PCTL	25th PCTL	50th PCTL	75th PCTL	95th PCTL	99th PCTL	Total Observations	Min	Max
DO (mg/L)	3.6	4.0	5.4	6.2	6.5	7.0	7.2	23,462	3.1	7.3
DO saturation (%)	48.4	52.6	68.1	75.4	79.4	83.9	86.4	23,462	42.2	88.1
Salinity (ppt)	0.0	0.0	0.0	0.1	0.9	3.3	4.3	23,462	0.0	5.7
Temp_C (°C)	21.4	21.6	26.6	26.7	28.1	28.7	29.0	23,462	21.3	29.2
BGA_R (RFU)	1.0	1.2	1.5	1.7	2.1	3.0	5.5	23,462	0.9	7.9
Sp_Cond	70	71	85	118	1,722	6,044	7,771	23,462	31	10,081

Notes: PCTL – percentile, Min – minimum, Max - maximum

3.0 DATA QA/QC

The QA/QC team conducted a review of the data collected during the SUR data collection effort. The team followed the QA/QC procedures outlined in Appendix B of the Work Plan (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019b) also used during the Test Run (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019a). The semi-permanent buoy, profile, and drift data collection efforts resulted in a total of approximately 8,317,000 raw data points that were retained after QA/QC evaluations. The sections below provide a summary of the SUR data adjustments and removal during QA/QC. Full documentation including figures and tables is provided in **APPENDIX F**.

3.1 SEMI-PERMANENT BUOY DATA

The semi-permanent buoy data were reviewed in time series plots to identify any sample dates and times which contained measured values which were inconsistent with the observed values. Three types of data that were removed are:

- Periods when the field crew was at a buoy retrieving sonde data since the sonde was out of the water when it logged some data.
- A period when the mid-depth data sonde at Upriver station UR_16a provided inconsistent data because the river flows were very low, most likely due to interaction with the river's bottom.
- A period when the sonde at Upriver station UR_9 initially experienced an upward DO drift. These data were corrected using an approved USGS methodology.

Further details of the QA/QC methods are in **APPENDIX F**. Approximately 3,208,000 buoy data points were retained after QA/QC evaluations. **APPENDIX A** presents plots of the processed and accepted data at each semi-permanent buoy collected during the SUR.

3.2 PROFILE AND DRIFT DATA

The raw profile and drift data were reviewed, and any inadvertent data recorded when the sampling boats were moving location were removed. These data were then QA/QC evaluated in time series plots to identify any sample dates and times which contained values that did not appear correct, such as when the sonde was removed from the water to download data. The main parameters collected were DO, DO saturation, salinity, temperature, specific conductivity, and BGA and Rhodamine dye. For the main parameters, approximately 1,600,000 profile data points and 3,200,000 drift data points were collected and over 95 percent were retained after QA/QC evaluations. **APPENDIX B** presents plots of the processed and accepted data for each profile and **APPENDIX C** presents plots of the processed and accepted data for each drift run collected during the SUR.

Profile sampling typically occurred at landmark locations (semi-permanent buoys) to check if oxygen plume was mixing top to bottom or at various points in the Front River to measure the DO and dye stratification between the top and bottom layers. Drift sampling typically occurred upstream and downstream of the diffusers to track the oxygen plume as it moved through the waterbody.

3.3 USGS DATA

The USGS maintains a network of hydrodynamic and water quality monitoring stations within the Savannah River and estuary. The stations measure multiple parameters in real-time and the data are publicly available. Additionally, the stations have been installed for a significant period such that a rich historical dataset dating back to 2007 exists for some locations (e.g., USGS 021989773 – USACE Dock).

It should be noted that not all stations measure the same suite of parameters. Some stations such as the one above Hardeeville measure water surface elevation (WSE) and a limited number of water quality parameters, whereas the station at the USACE Dock on Hutchison Island (Station 021989773) measures all hydrodynamic and water quality parameters of interest including DO. The location of the stations with the full suite of parameters required for DO analysis is presented in ***Figure 3-1***. Other stations, such as the Hardeeville gage, are not presented but their data have been relied upon elsewhere in this report, such as the hydrodynamic model calibration in **APPENDIX K.**

Another clarification is that while the USGS provides the data real-time via its website, all data are labeled as *provisional* until they have been subject to rigorous internal USGS field calibration and verification procedures by USGS personnel in the South Atlantic Water Science Center. Once the *provisional* data have been reviewed, they update to *approved* status. The SUR data evaluations used only *approved* USGS hydrodynamic and water quality data. **APPENDIX G** presents plots of measurements at each USGS station during the SUR. The USGS data have been analyzed in Section 7.0.

3.4 OXYGEN INJECTION PLANT DATA

After completion of the SUR, an independent QA/QC evaluation was performed on the operational data from both oxygen injection plants including flows, water temperatures, and oxygen loads. A project-specific 'oxygen injection plant QA/QC script' using the modeling program *R* was prepared to automate the QA/QC process. The script was used on the 2020 plant data and will be used to review raw data associated with future plant operations as well.

This QA/QC dataset for the entirety of the SUR is included in **APPENDIX H**. The plant data is analyzed in Section 5.0, with additional detail in **APPENDIX H.**

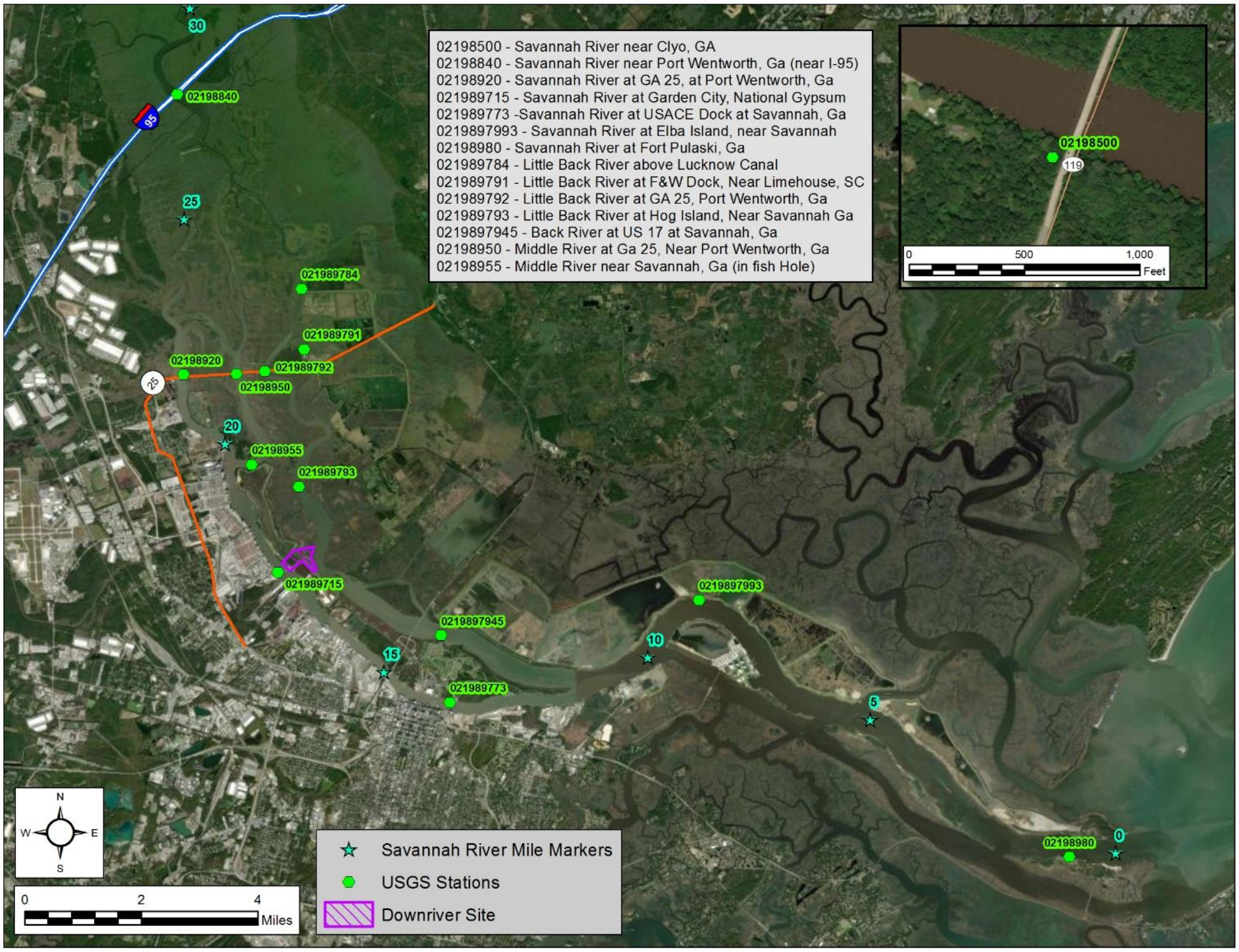

Figure 3-1 Location of USGS Gages Used for SUR Analysis

4.0 SUCCESS EVALUATION APPROACH

4.1 BACKGROUND

To evaluate the impact of the oxygen injection system on the Front River, Back River, and Savannah River, it is necessary to understand how water moves throughout the estuary. There are three primary driving forces:

- Freshwater flow from upstream sources is measured at the USGS Clyo gage (02198500). Lower freshwater flows result in saline and brackish water extending farther upriver (saltwater intrusion).
- Semi-diurnal tides move water upstream (flood tide) and downstream (ebb tide) in the harbor approximately twice a day. The upstream extent of tidal impacts is approximately where I-95 crosses the Savannah River, at RM 27.8.
- Neap and spring tides are driven by lunar cycles. Neap tides have less amplitude (difference between high and low water) and less energy to mix vertically, resulting in harbor stratification with higher salinity and lower DO in the bottom waters. Spring tides have larger tidal amplitude, and due to the increased energy, the harbor tends to destratify and mix well through the entire vertical water column.

Depending on the environmental forces within the harbor, such as tides, flows, and seasonal variation, the injected oxygen will move differently throughout the system. During spring tides, the Downriver oxygen plume moves farther upriver and mixes quicker into the water column (vertically). Conversely, during neap tides, the oxygen plume from the Downriver plant remains stratified and does not spread through the harbor quickly. The Upriver plant oxygen plume travels downstream past I-95 and mixes into the estuary.

The Savannah River and estuary has a natural low DO due to mixing (described above) and the physical slope of the bottom elevation of the river (gradient as the river moves downhill into the estuary). Most estuaries have a stratification of DO and salinity and most have sediment deposition because of the river gradients intersecting the flat estuary and meeting the ocean. According to the EIS, the low DO regime of the estuary has been accentuated by historical deepening projects (USACE 2012a). During the EIS development, several “natural conditions” model scenarios demonstrated a 1.0 mg/L decrease due to manmade channel improvements. The modeling team used an 1854 bathymetric map to characterize the natural bottom elevations of the river and estuary. Compared to the pre-existing 42 feet MLLW channel, the impacts directly related to the SHEP deepening to 47 feet MLLW were predicted to be approximately 0.2 to 0.6 mg/L in the critical areas on the Front River.

The EIS and GRR used modeling to evaluate SHEP impacts and identify the mitigation requirements. The models were used to compute the mitigation required by the following analysis:

1) a 97 percent of volume metric in critical segments (volume approach),
2) examined 5th, 10th, 25th, and 50th percentiles of DO concentrations over time to determine how the mitigation load was offsetting deepening (temporal approach),
3) utilized the bottom three layers of the six-layer model grid with the approval of the agencies to represent “bottom waters” (vertical location approach), and
4) Plan 6A of the EIS calls for an injection of 40,000 lbs/day of oxygen at three discharge locations in the harbor (Upriver, Downriver Front River, and Downriver Back River) (horizontal location approach) (Tetra Tech, Inc. 2010).

The EIS and GRR mitigation requirements were:

- An average of 40,000 lbs/day of DO must be injected and entrained into the water column to mitigate project impacts, with 28,000 lbs/day injected by the Upriver plant and 12,000 lbs/day injected by the Downriver plant, based on modeling performed for the EIS and GRR (USACE 2012a, USACE 2012b). To calculate the number of Speece cones required, 4,000 lbs/day per cone was used based on the 80 percent efficiency resulting from loss estimate during oxygen generation, injection, and retention (5,000 lbs/day per cone by manufacturer, ECO_2). This efficiency percentage was determined from lessons learned after the 2007 demonstration project and required by the federal and state agencies (Tetra Tech, Inc. 2010).
- The oxygen injection system must mitigate for the median (50^{th} percentile) DO concentration reductions in 97 percent of the bottom half of the Savannah River and estuary waters caused by deepening the navigational channel. (Tetra Tech, Inc. 2015, USACE 2012a, USACE 2012b).
- Out of 27 zones evaluated, water quality in zones Front River (FR) 07, FR08, FR011, Middle River (MR) 01, MR05, Back River (BR)01, BR02, BR03, and Little Back River (LBR)03 will be the most affected by navigational channel deepening. Therefore, impacts to DO concentrations should be mitigated in these zones by the oxygen injection (Tetra Tech, Inc. 2010). These zones are presented in ***Figure 11-13***, ***Figure 11-14***, and ***Figure 11-15***.

While the SUR monitoring data and model output evaluations provide numerous indications that the oxygen injection system is providing the oxygen loads required to offset SHEP impacts, a thorough and comprehensive approach was needed to assess if the SUR was a success.

4.2 THE SUCCESS CRITERIA

The Success Criteria were defined in the Compromise and Settlement Agreement (2013, bullet 11, pg. 3, Exhibit A):

"The purpose of the modeling and monitoring is to confirm that the Oxygen Injection System will mitigate for the DO impacts of the Project, as shown by comparing actual DO levels in the modeled area, from Station 0+000 upstream to RM 27.8, to DO levels in the without-Project scenario (the "Success Criteria")."

Simply stated, the Success Criteria are to prove the DO impacts caused by deepening the Front River have been compensated for in time (tidally and seasonally) and space (vertically in the water column and horizontally in the estuary).

It should be explicitly noted that neither the Success Criteria nor the EIS or GRR specify a target concentration of increased DO to appropriately mitigate for channel deepening. As identified in Section 4.1, the dynamic nature of the Savannah River and estuary vertically, spatially, and temporally, mean specifying a target concentration increase was impossible. To address the Success Criteria, an alternative approach was needed to prove mitigation was achieved.

4.3 THE LINES OF EVIDENCE APPROACH

No single, overarching piece of evidence exists which proves the Success Criteria has been achieved. Instead, a tiered approach needed to be developed whereby the Success Criteria was proven by evaluating four *Success Metrics* which each captured a complementary portion of the Success Criteria and were consistent with the EIS and GRR. A graphic of the four *Success Metrics* is presented in ***Figure 4-1.*** Further, each of the four *Success Metrics* was able to be assessed by a total of 12 *Lines of Evidence*, three for each *Success Metric*. This *Lines of Evidence* approach, visually illustrated in ***Figure 4-2***, proves that the oxygen injection system is successfully able to inject the required oxygen loads into the river and that the injected oxygen can be retained and distributed vertically and spatially, thereby mitigating impacts to DO by harbor deepening.

Detail on each of the four *Success Metrics* and their *Lines of Evidence* are described further in this section.

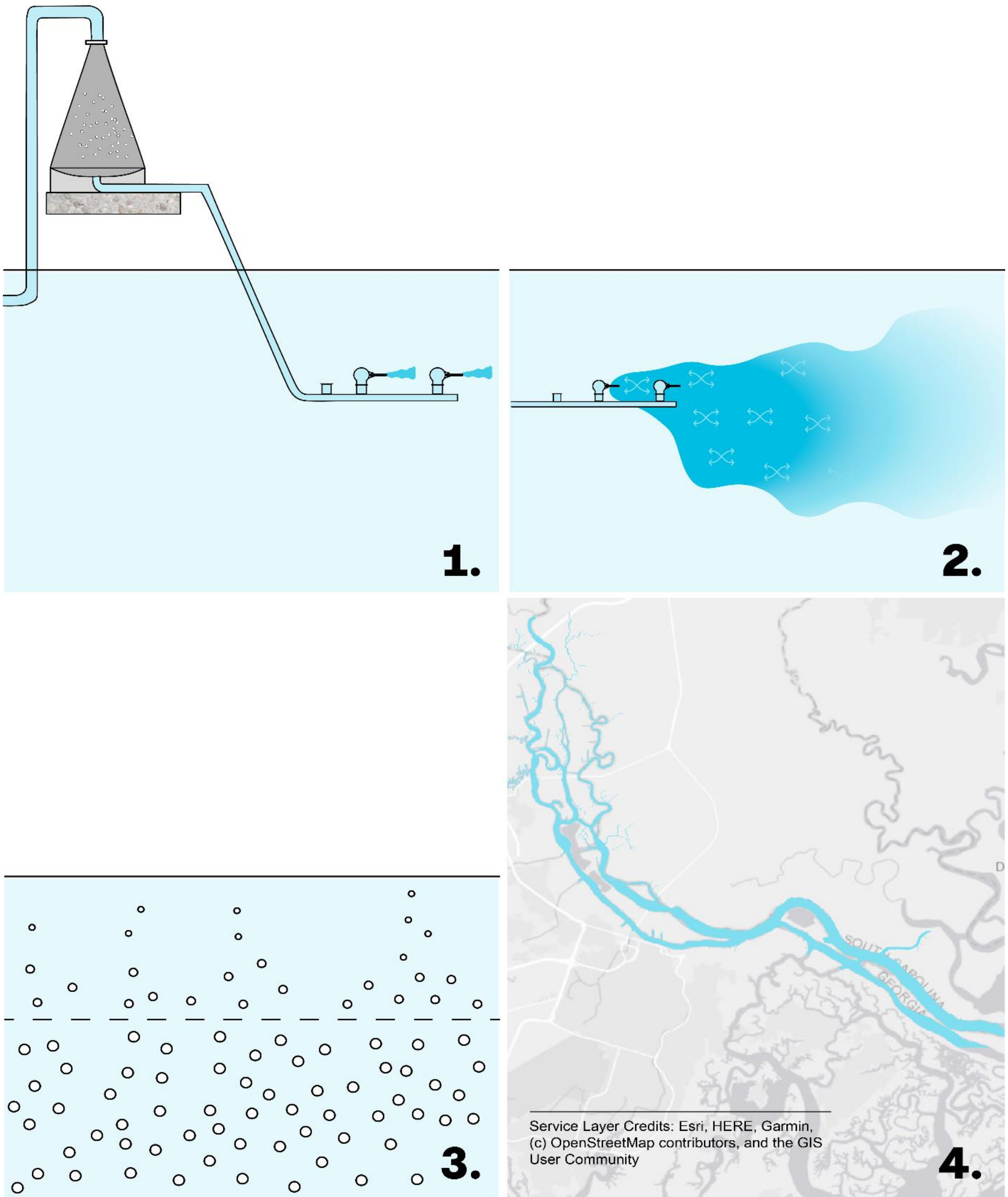

Figure 4-1 The Four Success Metrics

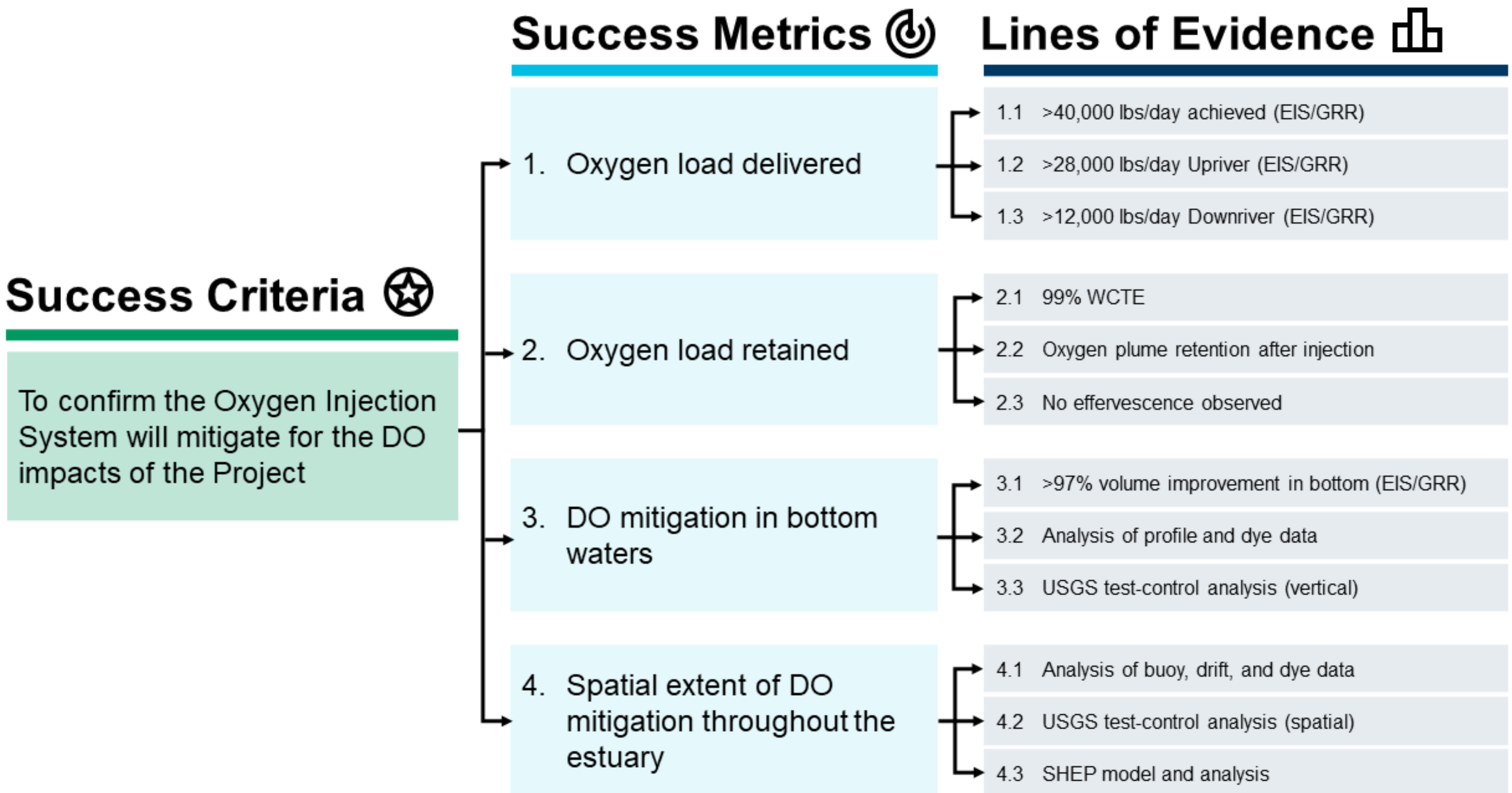

Figure 4-2 Lines of Evidence Approach Summary

Success Metric #1 – Evaluate if the oxygen injection system delivered the required oxygen load

The requirement is a daily average injection and retention of 40,000 lbs/day of oxygen over a continuous 59-day period during the critical summer months. To achieve this, two oxygen injection plants were constructed. One at Georgia Power's Plant McIntosh called the Upriver plant and a second on Hutchinson Island which is called the Downriver plant. 28,000 lbs/day were specified for the Upriver plant and the remaining 12,000 lbs/day from the Downriver plant (8,000 lbs/day via the Front River diffuser and 4,000 lbs/day via the Back River diffuser). These values are specified in the EIS and GRR Appendix C (USACE 2012a, USACE 2012b).

Success Metric #1, illustrated in ***Figure 4-3***, was achieved during the SUR by:

- injecting a total daily average of more than 40,000 lbs/day for 59 days – **Line of Evidence 1.1**.
- injecting a daily average of more than 28,000 lbs/day for 59 days from the Upriver plant – **Line of Evidence 1.2**.
- injecting a daily average of more than 12,000 lbs/day for 59 days from the Downriver plant – **Line of Evidence 1.3**.

Details on the oxygen injection are provided in Section 5.0.

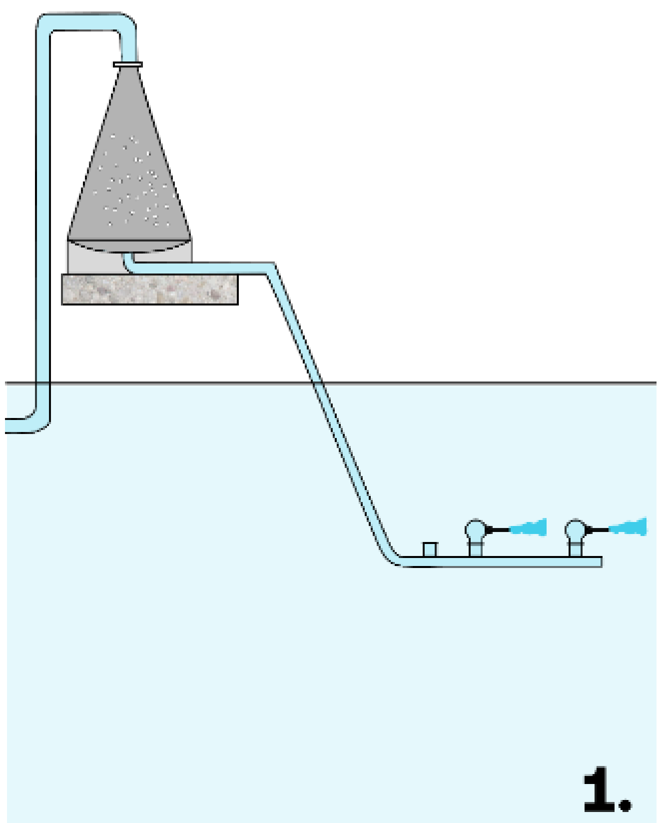

Figure 4-3 Success Metric #1 – Oxygen Load Delivered

Success Metric #2 – Determine if the injected oxygen is being retained in the water column

The requirement is based on agency feedback on the oxygen transfer efficiency. This process involves producing oxygen at the generators, pumping the oxygen through a Speece cone with pumps and pipes, and directing it into the water column to the bottom waters through pipes, bends, and diffusers. The agencies required 80 percent efficiency for the entire oxygen delivery process (from oxygen production to delivery to bottom waters) (Tetra Tech, Inc. 2010). The 80 percent efficiency was applied to the load of each Speece cone of 5,000 lbs/day to produce a design condition of 4,000 lbs/day per cone. From Success Metric #1, 40,000 lbs/day divided by 4,000 lbs/cone equals 10 cones in total for the system. As identified in Section 1.4, The Upriver plant operates with seven active Speece cones and the Downriver plant operates with three. The calculation of WCTE, a method used to estimate the percentage of oxygen retained in the Savannah River and estuary, excludes any potential losses from production, piping, and pumping operations. The WCTE goal was to achieve 90 percent retention. At least 90 percent of the delivered load to the water column needed to remain dissolved and saturated in the water column. Conversely, a maximum allowable transfer of oxygen from the river to the atmosphere would be 10 percent.

Success Metric #2, illustrated in ***Figure 4-4***, was achieved during the SUR by:

- Achieved 99 percent WCTE – **Line of Evidence 2.1**. Details on oxygen retention are provided in Section 6.0.
- Oxygen plume retention after injection – **Line of Evidence 2.2**. Details are provided in Section 7.3 for the retention of oxygen after operations cease, and Section 10.0 whereby dye plumes were tracked and detected weeks after each release.
- No effervescence or bubbling observed during field data collection – **Line of Evidence 2.3**. Details are provided in Section 8.0, Section 9.0, and Section 10.0.

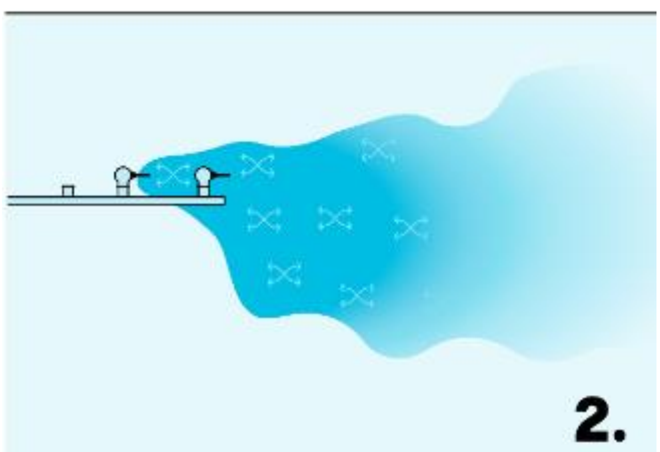

Figure 4-4 Success Metric #2 – Oxygen Load Retained

Success Metric #3 – Evaluate if the retained oxygen is mixing vertically and mitigating the bottom half of the water column

The requirement is for oxygen injection to mitigate median DO concentrations in 97 percent of the bottom half of the water column. This value is specified in the EIS Appendix C (Mitigation Planning) (USACE 2012a).

During the EIS development, the agencies were consulted and provided input on how modeling could be used to demonstrate the requirements of the mitigation. With a dynamic model outputting DO results by cell, by segment, and over time, it was necessary to determine which statistics could be compared when examining a model run with and without oxygen injection. The agencies agreed that the analysis should examine the effects in the lower half of the water column rather than the bottom grid layer. The lower half of the water column includes the bottom three layers of the six-layer model grid at the time of EIS development; the upgraded 2020 SHEP model is 10 layers, so the bottom half is five layers. Generally, DO decreases with channel depth, so analyses of conditions at the river bottom would represent worst-case conditions. Analyses of the bottom half of the water column would be more representative (but still somewhat conservative) of average conditions throughout the vertical profile. Attempts to achieve 100 percent of the total volume were not possible due to the numerical solution technique of the model, such that a surrogate of 97 percent of the total volume was used to compare model runs with and without mitigation. Also, by adding the flow volume of oxygen load to the model in the “with mitigation” scenarios, there was always a small difference in the with and without model scenarios. Therefore, the goal of 97 percent of the bottom half of the water column was determined to be the complete mitigation surrogate for total volume.

The SHEP model was the most encompassing tool to assess this requirement but supporting evidence was provided by the profile and dye data, which measured the impact of the oxygen injection plume across the water column, and by the USGS Front River Garden City gage where data for two separate depths was available for analysis.

Success Metric #3, illustrated in ***Figure 4-5***, was achieved during the SUR by:

- SHEP model showed achievement of 97 percent of the total volume in bottom waters with DO equal or greater when comparing with and without model scenarios – **Line of Evidence 3.1**. Details are provided in **Section 11.0**.
- Analysis of field data collection (profile and dye data) – **Line of Evidence 3.2**. Details on the profile analysis are provided in **Section 8.0** for Upriver and **Section 9.0** for Downriver, with the dye releases documented and analyzed in **Section 10.0**.
- USGS test-control analysis (vertical) – **Line of Evidence 3.3**. Details are provided in **Section 7.2**.

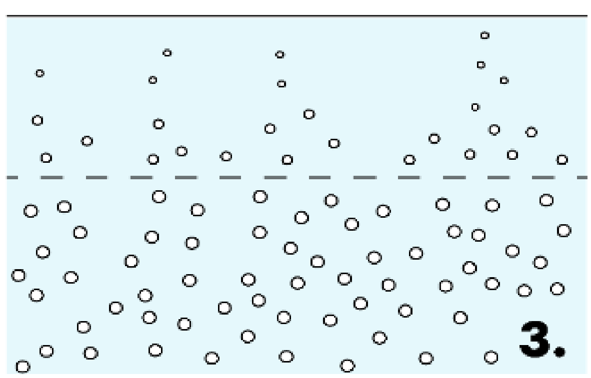

Figure 4-5 Success Metric #3 – DO Mitigation in Bottom Waters

Success Metric #4 – Evaluate if the retained oxygen is mixing spatially to provide the necessary mitigation throughout the Savannah River and estuary

The requirement is to confirm the oxygen injection system will mitigate for SHEP impacts throughout the Savannah River and estuary (from Station 0+000 upstream to RM 27.8), including critical zones identified in the EIS as being most affected by navigational channel deepening (identified in Section 4.1). Field data collected by the monitoring team was analyzed including drift data and measurements from semi-permanent buoys. Drift data helped determine where the oxygen plume was moving and how quickly it mixed with receiving waters, both side to side horizontally and longitudinally through the river. Semi-permanent buoy data provided continuous data and information around the oxygen injection diffusers to show how the oxygen plume was influenced by various freshwater flows and tides.

Additionally, long-term and publicly available data collected by USGS was analyzed to determine the impact of oxygen injection at various locations throughout the harbor. The SHEP model results provided supporting evidence to the findings of field measured data analysis.

Success Metric #4, illustrated in ***Figure 4-6***, was achieved during the SUR by:

- Analysis of field data collection (buoy, drift, and dye data) – **Line of Evidence 4.1**. Details are provided in **Section 8.0** for Upriver and **Section 9.0** for Downriver, with the dye releases documented and analyzed in Section 10.0.
- USGS test-control analysis (spatial) – **Line of Evidence 4.2**. Details are provided in Section 7.2.
- Spatial analysis of the SHEP model – **Line of Evidence 4.3**. Details are provided in Section 11.0.

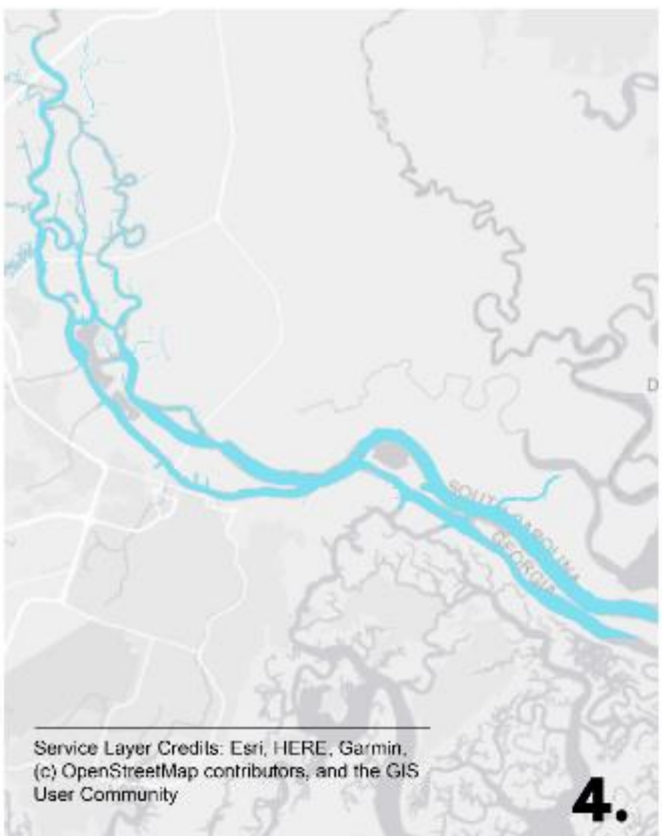

Figure 4-6 Success Metric #4 – Spatial Extent of DO Mitigation Throughout the Estuary

4.4 SUPPORTING ANECDOTAL EVIDENCE

In addition to the four *Success Metrics* and 12 *Lines of Evidence*, there was visual, anecdotal, and other evidence that support the DO mitigation conclusions observed during the SUR. These are listed below:

- Dye injections stayed in the main channels for a longer period than expected.
- No fish kills were documented or observed by the monitoring teams.
- No marine mammals were observed to be attracted to the diffusers.
- No navigation impacts or vessel strikes to the diffusers and equipment.
- No air or noise impacts from the operations of the injection equipment.

5.0 OXYGEN INJECTION SYSTEM DATA ANALYSIS

THIS CHAPTER ADDRESSES SUCCESS METRIC #1 AS IDENTIFIED IN SECTION 4.0

Success Metric #1 – Evaluate if the oxygen injection system delivered the required oxygen load

5.1 OXYGEN INJECTION SYSTEM

Details of the operational procedures of the oxygen injection plants are provided in Section 1.4.

5.2 STARTUP RUN OPERATIONS

Both oxygen injection plants have internal computer programs that measure, record, analyze, display, and store data. These data are analyzed by programmed logic controls built-in to both plants, which automates plant operations and makes real-time adjustments. For example, changing water levels at the intakes, due to upstream flows at the Upriver plant or tidal conditions at the Downriver plant, require slightly different pump operating pressures to maintain a constant rate of water withdrawal. The raw data are stored such that they can be retrieved and analyzed later.

The raw data collected during the SUR were independently reviewed. Further detail on this process can be found in Section 3.4 and **APPENDIX H**.

The SUR occurred from July 25, 2020, to September 22, 2020, during which the plants operated nearly continuously. Like any industrial plant with mechanical parts including pumps, generators, and valves, scheduled and unscheduled maintenance activities were necessary to maintain overall function. The oxygen injection system is no different. There were periods when one or both plants were offline to undertake necessary maintenance. However, the goal of achieving a daily average of 40,000 lbs/day across the SUR was achieved. Additionally, the daily average goal for the Upriver and Downriver plants was also achieved, as detailed in ***Table 5-1***.

Table 5-1 SUR Daily Averages

Plant	Target (lbs/day)	Actual (lbs/day)
Upriver	28,000	28,838
Downriver	12,000	13,574
TOTAL	**40,000**	**42,412**

The daily total oxygen loads are presented in **APPENDIX H**. While the daily averages were achieved over the entire SUR, the daily target was not achieved every single day due to unavoidable plant maintenance. This is considered reasonable, given the goal was to achieve the target loads as an average over the 59-day duration and this goal was achieved for the whole system and at each plant. Also, not achieving the daily target load every single day is acceptable from an environmental and scientific perspective. The high residence time of retained oxygen in the estuary, as identified in Section 7.3 and Section 10.0, means the effectiveness of mitigation is not instantaneous. Instead, the benefits are retained for weeks. Further, the varying conditions throughout the lunar cycle mean the injected oxygen is more critical in some periods (e.g., neap tides) than others (e.g., spring tides).

LINE OF EVIDENCE 1.1 – INJECT AVERAGE 40,000 LBS/DAY

LINE OF EVIDENCE 1.2 – INJECT AVERAGE 28,000 LBS/DAY UPRIVER

LINE OF EVIDENCE 1.3 – INJECT AVERAGE 12,000 LBS/DAY DOWNRIVER

The total flows through the Upriver and Downriver plants are shown in ***Figure 5-1***, ***Figure 5-2***, and ***Figure 5-3***. The occasional drops in flow correspond to the periods when the plant was completely or partially offline for maintenance purposes. Some maintenance works can occur without completely shutting down the plant, rather, by isolating specific parts such as a Speece cone, pump, or oxygen generator. For the SUR, the Upriver and Downriver plants were injecting oxygen 99.8 and 98.3 percent of the time, respectively.

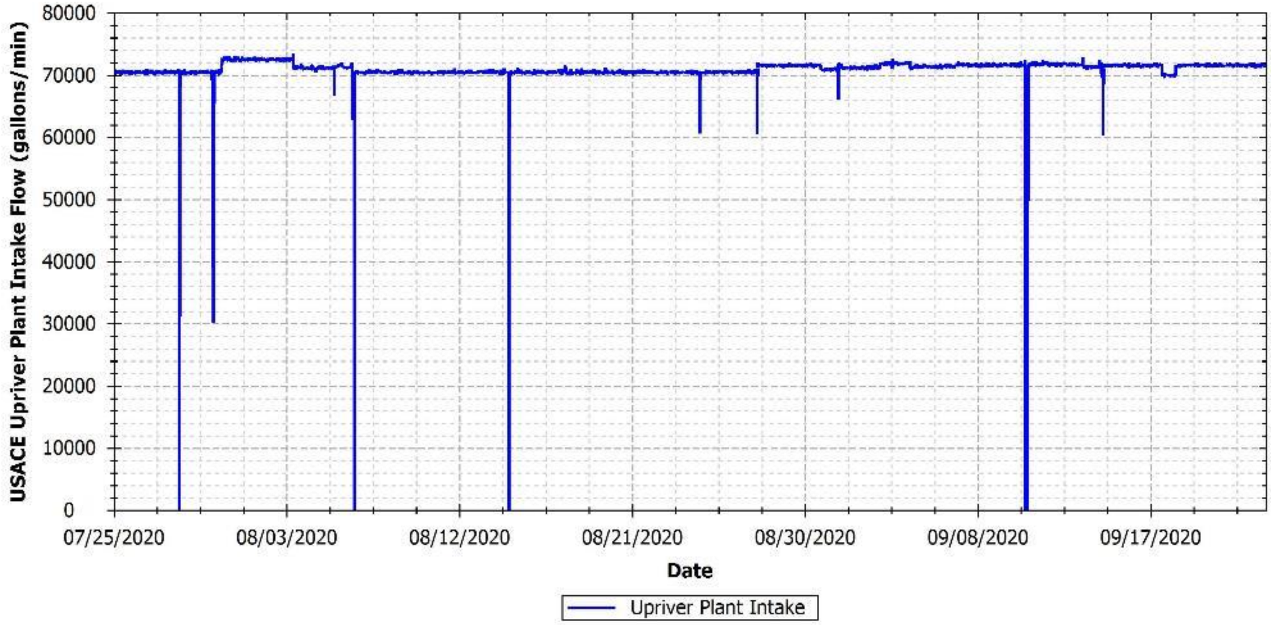

Figure 5-1 Upriver Plant Flow During SUR

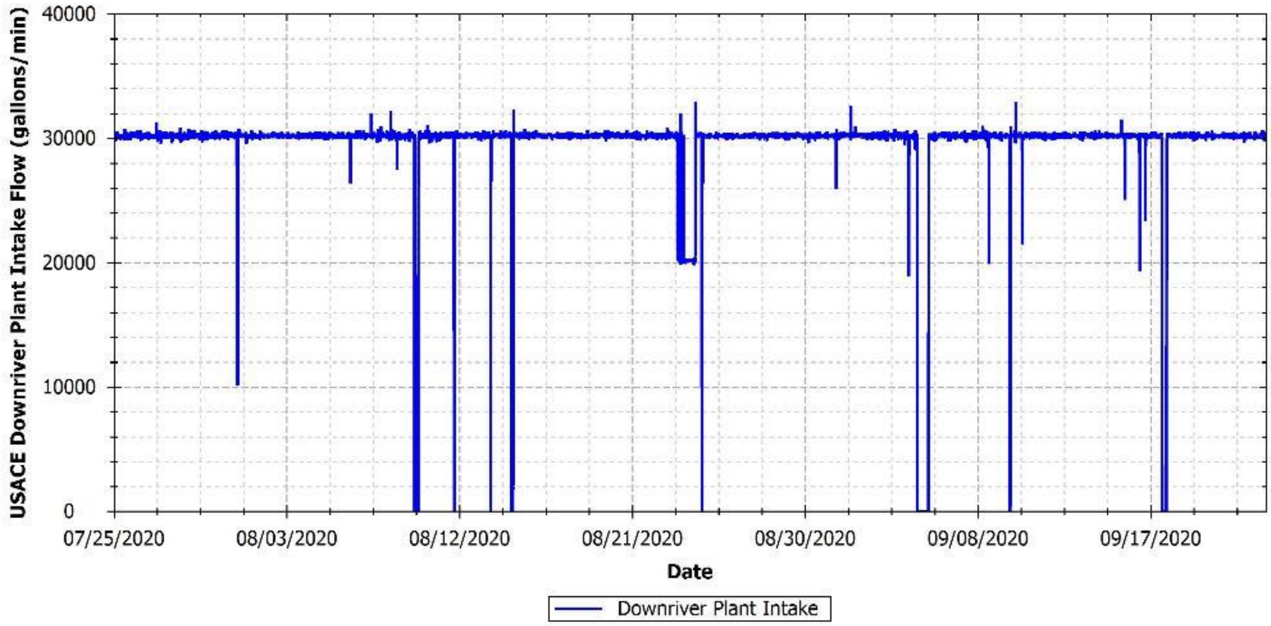

Figure 5-2 Downriver Plant Flow During SUR (total)

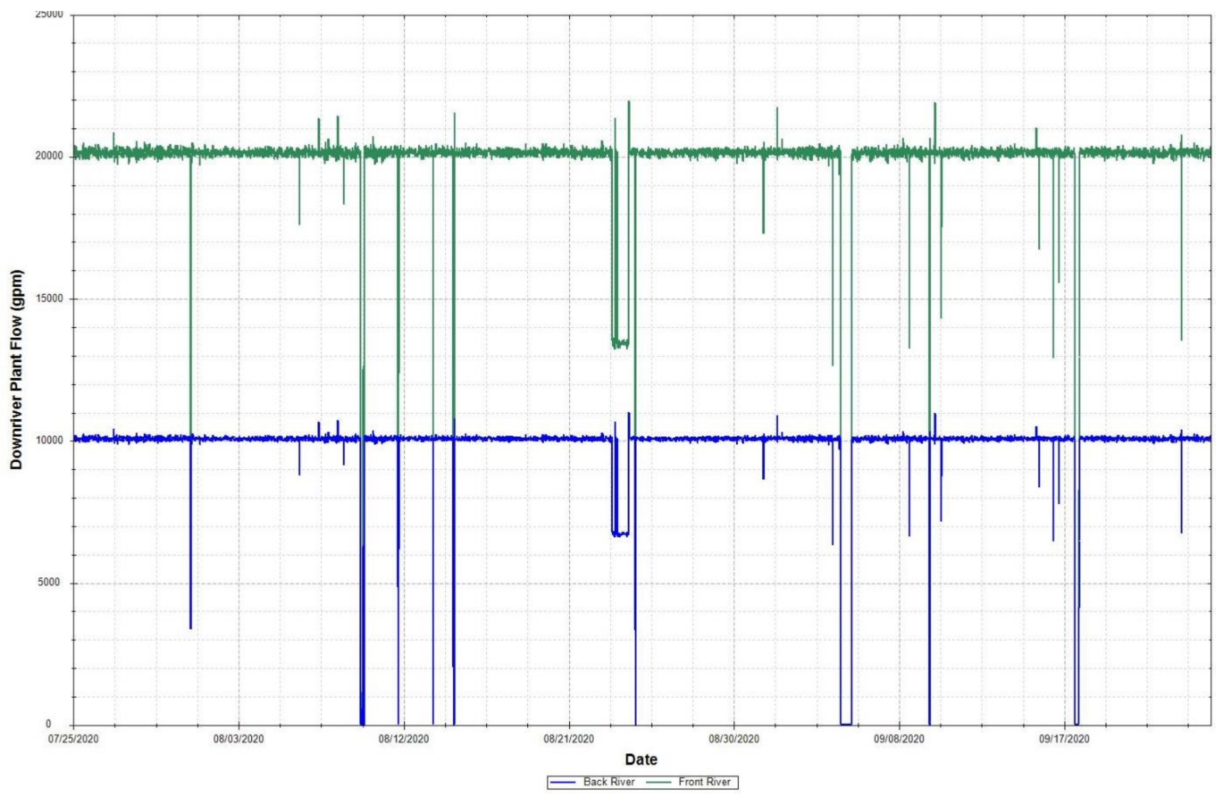

Figure 5-3 Downriver Plant Flow During SUR (Front and Back River)

Figure 5-4 Upriver Plant Oxygen Loads

The raw, net, and gross oxygen loads at the Upriver and Downriver plants are presented in ***Figure 5-4*** and ***Figure 5-5***. The total raw oxygen load is the background oxygen load in the water withdrawn from the Savannah River and is determined using the measured DO in the raw intake water and the measured flow. The total gross oxygen load is the total oxygen load in the water prior to discharge and is determined using the measured DO in the water after exiting the Speece cones and the measured flow. The total net oxygen load is the difference between the raw and gross oxygen loads. The net oxygen load is the value of interest given this quantifies how much oxygen was added to the river. ***Figure 5-4*** and ***Figure 5-5*** illustrate that both plants consistently produced more than their target loads, which agrees with the average daily values presented in ***Table 5-1***. Similar to ***Figure 5-3***, ***Figure 5-6*** presents the oxygen loads delivered to the Back River and Front River from the Downriver plant.

It should be noted that the drops in flow correspond with the drops in oxygen load, as this is when the plant pumps were undergoing maintenance. This is intuitive as, without any plant flow, no load can be injected into the river. The opposite is not true, and this accounts for the rare events where there is a drop in oxygen load without a corresponding drop in flow. This is because of one or multiple oxygen generators undergoing maintenance while the plant was still partially operating and pumping water.

Another important point to consider is that despite these drops in injected oxygen load, which were typically in the range of 15 minutes to three hours (excluding one 14-hour outage at the Downriver plant from 8 pm on September 4 to 10 am on September 5, 2020, and one five-hour outage at the Downriver plant on September 17, 2020), they do not necessarily equate to a noticeable drop in DO in the critical areas of the estuary. This is because of the retention time of the DO, which is in the order of days to weeks depending on location in the estuary. Evidence of this retention time is presented in Section 7.3 and Section 10.0.

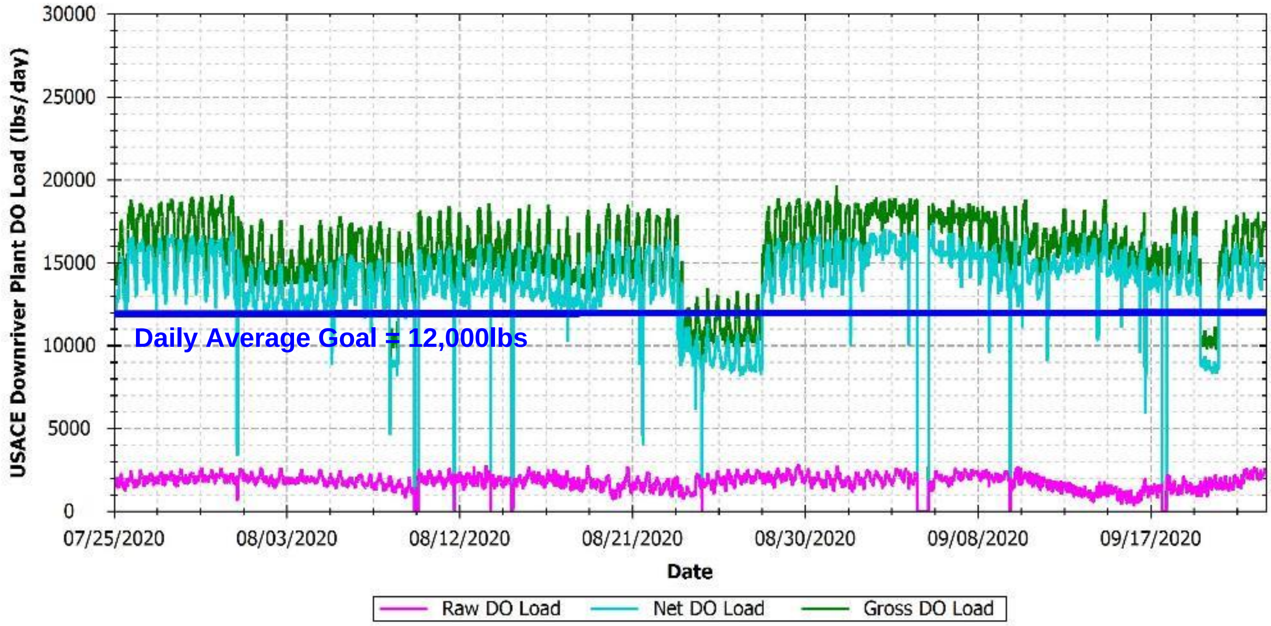

Figure 5-5 Downriver Plant Oxygen Loads (Total)

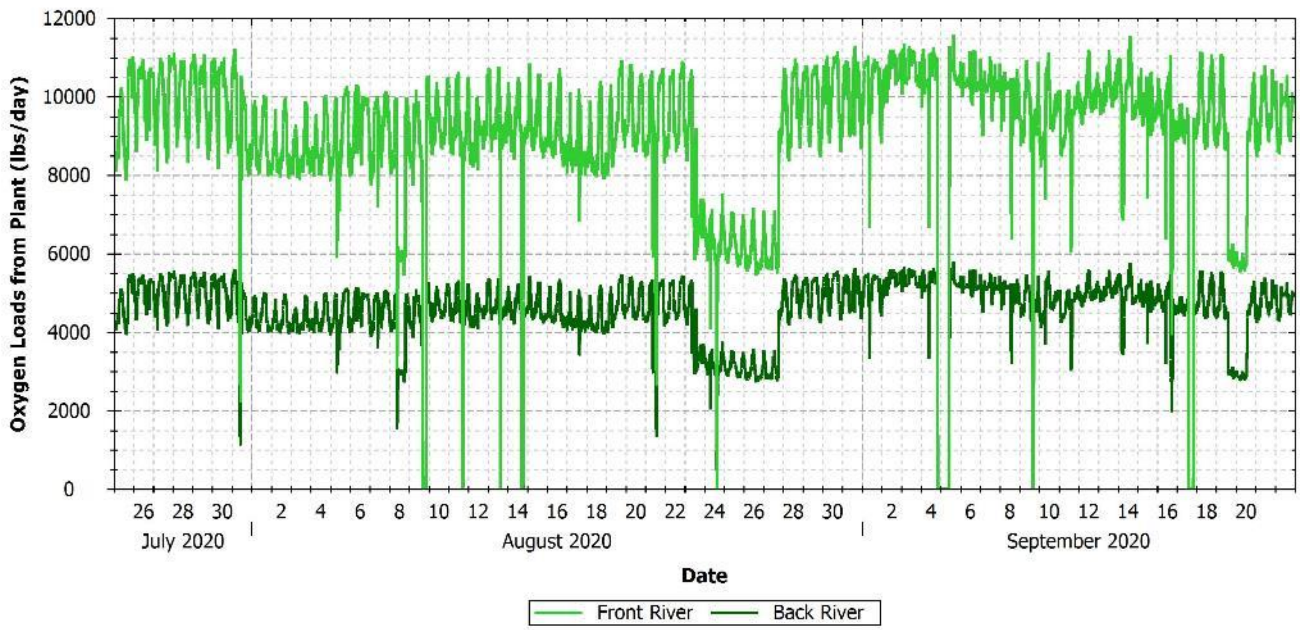

Figure 5-6 Downriver Plant Net Oxygen Loads (Front and Back River)

5.3 SUMMARY

Across the SUR, there was variation in the injected oxygen load. However, the required loads of a daily average of 40,000 lbs/day from the combined system, 28,000 lbs/day from the Upriver plant, and 12,000 lbs/day from the Downriver plant were all exceeded. Therefore, the required oxygen loads were delivered and injection was successfully achieved.

6.0 WATER COLUMN TRANSFER EFFICIENCY

THIS CHAPTER ADDRESSES SUCCESS METRIC #2 AS IDENTIFIED IN SECTION 4.0

Success Metric #2 – Determine if the injected oxygen is being retained in the water column

After successfully producing and injecting oxygen into the river, the injected oxygen should be retained by the receiving waters such that it mixes, both vertically throughout the water column and spatially throughout the Savannah River and estuary. Ideally, the oxygen load delivered by the plants through the diffusers would be completely mixed with the ambient water. However, if the injected plume of super-saturated water reached the surface, oxygen could be transferred from the water column to the atmosphere, resulting in reduced oxygen retention. To evaluate oxygen retention, WCTE (introduced in Section 1.6) is a calculation used to estimate the percentage of oxygen that remained in the Savannah River and estuary. The goal WCTE for the SUR was 90 percent, as described in Section 4.3. To calculate WCTE, the following is needed:

1. the mass of oxygen injected, and
2. the mass of oxygen transferred to the atmosphere if any.

Oxygen loads delivered by each oxygen injection plant were determined by oxygen sensors and flow measuring devices installed on each Speece cone discharge pipe. These sensors provided flow and oxygen concentration measurements of the super-saturated DO water that was discharged into the water columns. Additional details are provided in Section 5.2 and **APPENDIX H.**

The monitoring data collected during the SUR were used to estimate the mass of oxygen transferred to the atmosphere across the air-water interface when conditions were present that allowed for a plume of super-saturated water to reach the water column surface. DO was available for transfer to the atmosphere when the DO saturation at the air-water interface was greater than 100 percent, resulting in a WCTE of less than 100 percent. When DO saturation was less than or equal to 100 percent, DO was able to be fully retained in the water column and therefore WCTE was 100 percent. A detailed discussion of the methodologies used to calculate WCTE is provided in the WCTE Report (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2020) and summarized in **APPENDIX I.** The WCTE calculation method identified periods when DO transfer conditions (DO saturation greater than 100 percent in the top 4.9 feet) were present. During these periods, the method calculated: (1) the length of time oxygen could be transferred; (2) the area from which oxygen could be transferred; (3) the amount of oxygen above atmospheric equilibrium (i.e., excess oxygen); and (4) the rate (not instantaneous) at which oxygen is transferred to the atmosphere (i.e., interfacial transfer coefficient).

General DO transfer observations at each of the discharge locations are summarized below and plotted in ***Figure 6-1*** against the 90 percent WCTE goal:

- Upriver: DO Transfer conditions were frequently observed in the continuous dataset (buoys and USGS gages) and were occasionally observed in the intermittent (profile and drift) dataset. Throughout the SUR, the daily WCTE varied from 97.8 percent to 100.0 percent, with an average of 99.9 percent over the SUR period. WCTE values dropped below 100 percent only when river flows were relatively low. These periods were from July 25 through August 8, 2020, and July 12 through July 17, 2020. Low flows, below 7,000 cfs, are expected to contribute to some atmospheric transfer due to the reduced vertical distance between the diffuser and river level, and therefore reduced ability for mixing all the oxygen injected into the water column.
- Front River: DO Transfer conditions were not observed in the continuous and intermittent datasets. Throughout the SUR, the daily WCTE had a constant value of 100 percent over the SUR period. This is

likely due to the high demand for oxygen in the Front River during the critical period, as well as the success of the diffusers in delivering and diluting the oxygen load allowing for strong vertical and horizontal mixing.

- Back River: DO Transfer conditions were occasionally observed in the continuous dataset but were not evident in the intermittent dataset. Throughout the SUR, the daily WCTE varied from 99.7 percent to 100 percent, with an average of 100 percent over the SUR period. The only periods when WCTE dropped below 100 percent was from August 14 through August 16, 2020, when there were a spring tide and high temperatures. As identified in Section 1.2, spring tides result in the oxygen plume residing longer in the water column causing the DO to build up. The increase in water temperature also lowers the saturation point. This build-up led to supersaturation and therefore some transfer of oxygen to the atmosphere. This phenomenon only last for a few days each summer.

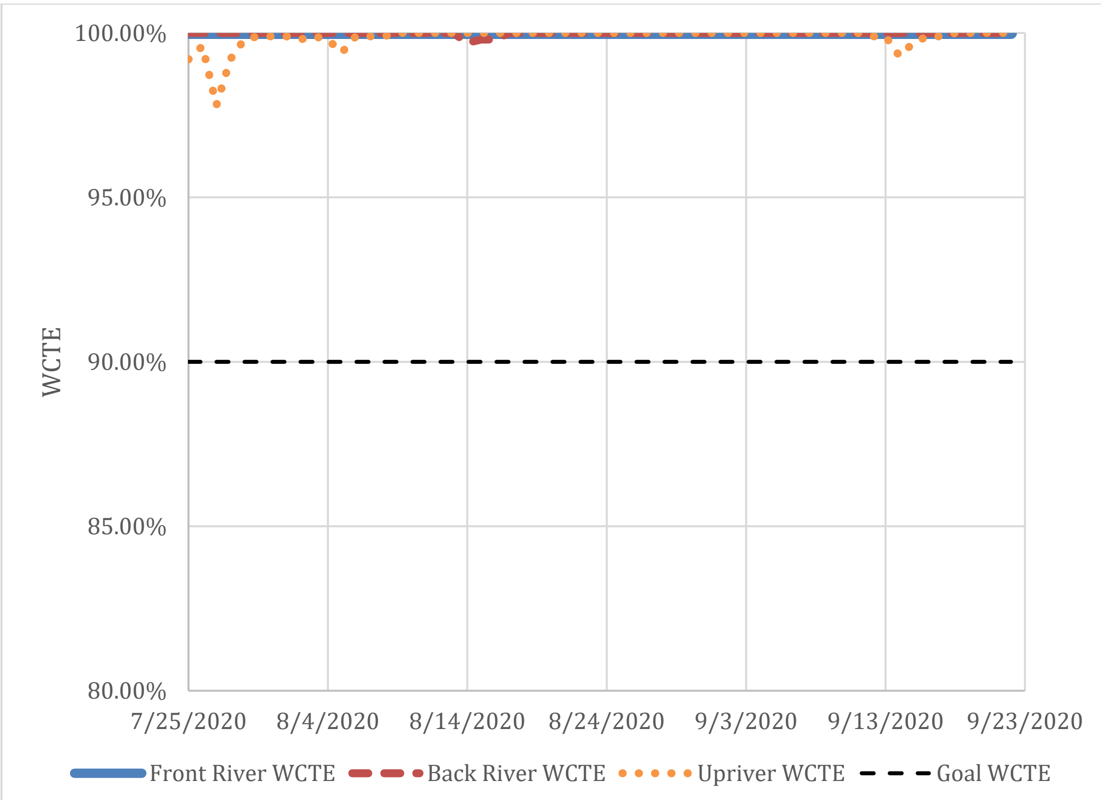

Figure 6-1 Daily Average WCTE Values for Front River, Back River, and Upriver

APPENDIX I includes tables presenting the river-specific plant loads and WCTEs.

The average combined WCTE over the SUR was calculated at 99.9 percent but has been conservatively rounded to 99 percent. In comparison to the Test Run (March 14 to May 12, 2019, WCTE of approximately 98 percent, see Section 1.5 for detail), conditions during the SUR resulted in less oxygen transfer across the air-water interface and therefore higher WCTE values. A key driver was the higher biological activity and higher temperatures given the SUR occurred in the critical summer period. This caused reduced background DO saturation levels, thereby increasing the water's ability to assimilate the injected oxygen.

The SUR had WCTE values significantly greater than the goal of 90 percent. This was consistent when looking at the Savannah River and estuary combined over the 59-day period, as well as looking at each location daily. The high WCTE values validate the design and implementation of the diffusers.

LINE OF EVIDENCE 2.1 – 99 PERCENT WCTE ACHIEVED

The conservative combined WCTE value of 99 percent was applied to the oxygen load injected to determine the oxygen load entrained in the Savannah River and estuary during the SUR. The oxygen loads injected and entrained by the Speece cone systems were greater than the loads required for harbor deepening mitigation. Results are summarized in **Table 6.1**.

Table 6-1 Oxygen Load Retained Summary

Plant	Load Injected* (lbs/day)	Load Retained (with WCTE value of 99 percent) (lbs/day)	Load Required for Mitigation (lbs/day)
Upriver	28,838	28,549	28,000
Downriver (Front River and Back River)	13,574	13,438	12,000
Totals	**42,412**	**41,987**	**40,000**
* Load injected sourced from ***Table 5-1***			

6.1 SUMMARY

A key feature of the oxygen injection system is the ability of the injected oxygen to be retained by the river, such that it can then be mixed and distributed vertically and spatially to the areas that require mitigation. The WCTE goal was 90 percent, and this was exceeded emphatically with an average of 99 percent achieved. This means that almost all of the injected load was able to be retained. High temperatures that occur in the critical period help with the retention. Factors that reduce WCTE are low freshwater flows from Upriver, and neap tides.

7.0 USGS DATA ANALYSIS

THIS CHAPTER ADDRESSES SUCCESS METRIC #2, #3 AND #4 AS IDENTIFIED IN SECTION 4.0

Success Metric #2 – Determine if the injected oxygen is being retained in the water column
Success Metric #3 – Evaluate if the retained oxygen is mixing vertically and mitigating the bottom half of the water column
Success Metric #4 – Evaluate if the retained oxygen is mixing spatially to provide the necessary mitigation throughout the Savannah River and estuary

The network of USGS stations positioned throughout the Savannah River and estuary, and its associated long-term, publicly available, and continuous dataset, provides an excellent opportunity to independently assess the impact of the oxygen injection system. A simple analysis would involve comparing the DO from the SUR against the DO from corresponding periods in previous years. This would be an idealized condition. However, continuous periods of identical conditions do not exist in a dynamic system. The comparison would not account for interannual variation in applicable parameters, such as gage height (otherwise WSE), temperature, salinity, and tidal direction, that can impact DO concentrations. There is also the fact that the Savannah Harbor has changed physically in recent years due to the harbor deepening plus other mitigation projects (McCoy's Cut, closure of Rifle and McCoombs Cut, tide gate removal). Another simple analysis would be to analyze various statistics such as daily minimums. As identified in Section 5.2, the plants do not operate at a constant rate. Rather, their oxygen output varies with factors such as water level or scheduled and unscheduled maintenance. Consequently, the entire operational period should be assessed instead of daily statistics.

A more accurate approach is to develop a dataset where for every individual data point in the test period, there is a corresponding "paired" data point in the control period (i.e., any time without oxygen injection for which the USGS gages have been operational, some of which date back to 2007) with near-identical water quality parameters (gage height, temperature, salinity, and tidal direction). These paired test/control observations were then evaluated for absolute DO concentration and percent saturation. The average difference in DO at each USGS gage was considered attributable to the oxygen injection.

The network of USGS stations is presented in ***Figure 3-1*** with additional details in **APPENDIX G.**

7.1 TEST RUN

This paired test/control analysis was first used to assess the success of the Test Run. It should be disclosed that the analysis was undertaken in May 2020, after the Test Run report was delivered (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019a). It was developed using independently collected and long-term publicly available data, and therefore it is a valuable line of evidence and warrants inclusion in this report.

The algorithm works by identifying a data point in the Test Run period and comparing it to every other data point from the same station outside the Test Run period, otherwise known as the control period. Specifically, the data are compared for gage height, temperature, salinity, and tidal direction. By using a Euclidean distance approach for each of the four parameters compared, the data point from the control period most similar to the data point from the Test Run period is matched, forming a test/control pair of data points. This approach was applied for every data point in the Test Run, such that there were 5,664 test/control pairs for each USGS station in the overall network. Given the complexity of this algorithm, it is not possible manually and therefore required computer programming. The DO values were not controlled for and therefore the differences between the test and control data points could be assessed. The median value of all test/control pairs was considered the most appropriate statistic for comparison to negate the potential impact of outliers.

Overall, the algorithm was successful in identifying control points where independent variable values nearly perfectly matched those of the Test Run. Using these points to compare concentrations demonstrates that at all stations' DO were significantly greater during the Test Run than for the control points, except for the I-95 gage. Differences in DO concentration were highly significant (except for the I-95 gage) and consistent with expectations from previous modeling.

A method to evaluate the effect of the oxygen injection was the use of t-tests between the test/control data. Two sets of observations are directly compared and used to determine if differences between observations are random or are statistically significant. The typical accepted scientific standard of a successful t-test is achieving less than five percent chance of a false positive ($p<0.05$, two-tailed test). For the purposes of this analysis, achieving a *p*-value of less than 0.05 indicated the algorithm was successful in identifying suitable test/control pairs.

The results of the t-tests presented in ***Table 7-1*** indicate that nearly all *p*-values exceed the accepted scientific standard of a five percent chance of a false positive. Most values exceeded 10^{-9}, indicating that the likelihood of observing this difference by chance alone is infinitesimal. The one exception was the I-95 gage, which had a near-zero difference and *p*-value much greater than five percent. This was expected given I-95 is typically considered the upper limit of tidal influence, and only the Downriver plant was in operation during the Test Run. As discussed in Section 7.2, the I-95 station was influenced by the oxygen injection from the Upriver plant during the SUR.

Results of the analyses are presented in ***Table 7-1***, arranged in order from upstream at RM 27.8 downstream toward RM 0. They are also presented graphically in

Figure 7-1. Further details on the analyses are presented in **APPENDIX J.**

Table 7-1 Test Run DO Differences – Median Absolute DO Concentration (mg/L)

Station	Name	Test Run	Control	Difference	*p*-value
02198840	I-95	7.82	7.84	-0.02	0.20
02198920	Savannah River-Port Wentworth	7.18	6.92	0.26	1.25E-09
02198950	Middle River- Port Wentworth	7.40	6.95	0.45	2.83E-43
021989792	Little Back-Port Wentworth	7.60	6.93	0.67	5.60E-185
021989715	Garden City 13.3 feet	6.91	6.35	0.56	1.06E-110
021989715	Garden City 23.3 feet	6.80	6.13	0.68	1.2E-8
021989773	USACE Dock	6.99	6.36	0.64	2.42E-165
0219897993	Elba Island	6.88	6.41	0.47	1.51E-115

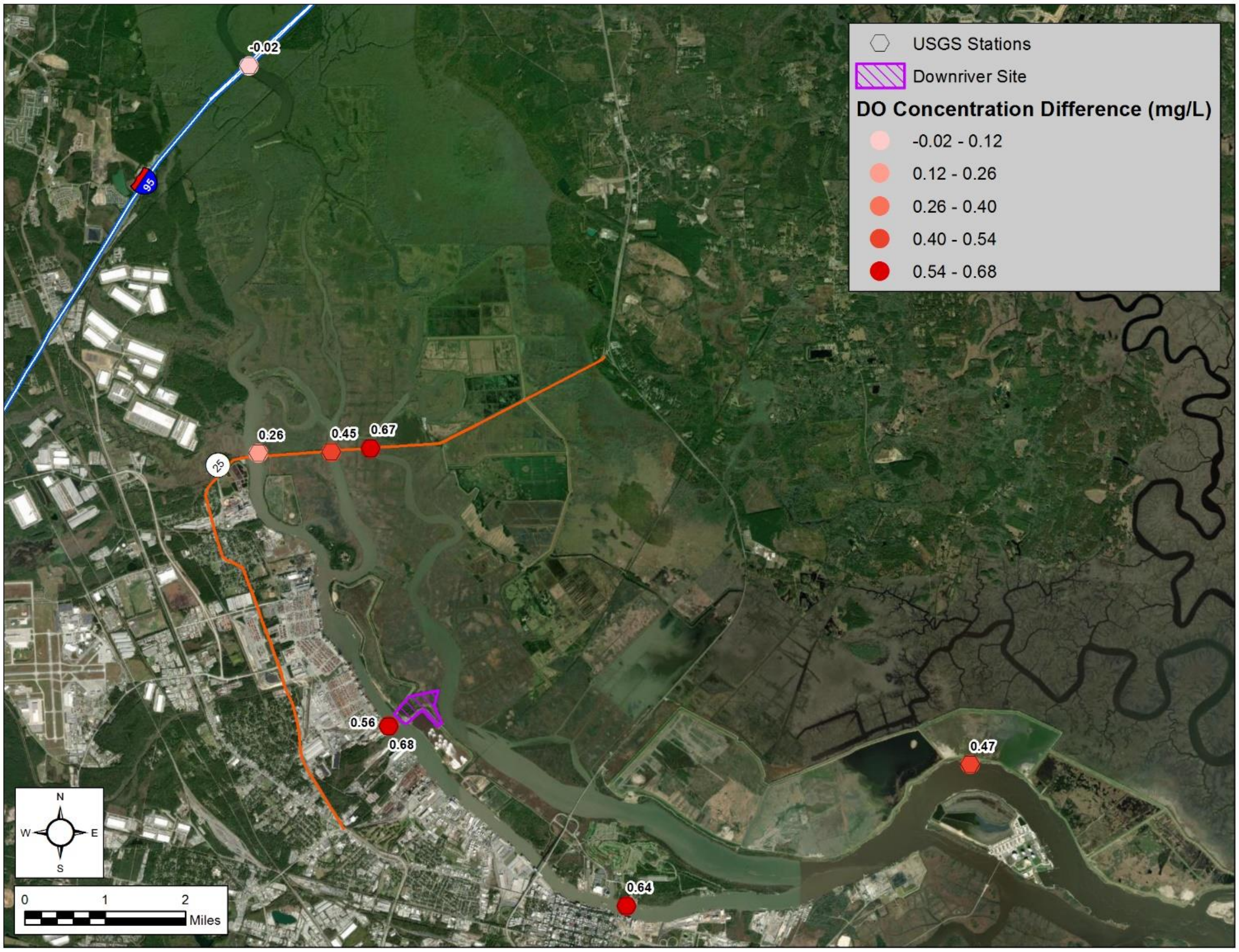

Figure 7-1 Test Run DO Differences – Median Absolute DO Concentration (mg/L)

7.2 STARTUP RUN

The analysis undertaken for the Test Run was repeated to determine the impact of the SUR, with a few minor additions made to the algorithm. Firstly, the Test Run dates plus approximately three weeks after completion were excluded from consideration for the control dataset given the need for the control data to be free of injected oxygen influence. Similarly, the period from July 1 to July 24, 2020, was excluded because the plants were being tested intermittently in the lead up to the SUR. Also, three additional gages were included (02198955 Middle River Savannah, 02198979 Little Back - Hog Island, 0219897945 Back River at GA 17). These three gages do not measure WSE, but they do measure the other water quality parameters of interest (i.e., salinity, temperature and DO). Therefore, a synthetic WSE was determined by interpolating measured values from the nearest hydrodynamically connected gages. This approach allowed for the full potential for the test/control algorithm to be realized.

Overall, the algorithm was successful in identifying control points where independent variable values nearly perfectly matched those of the SUR. Using these points to compare concentrations demonstrates that at all stations, DO was significantly greater during the SUR than for the control points.

At all USGS stations, the median DO concentrations during the SUR were higher than the control concentrations by 0.12 mg/L to 0.86 mg/L (***Table 7-2***). The one exception to this is the gage on the Little Back River near GA 25 (021989792) where a near-zero change between the SUR and the control dataset was determined. This was an unexpected conclusion and is investigated further below.

The only USGS station assessed that did not achieve such low values was the Little Back River near GA 25 (021989792). The *p*-value for the Little Back River is 5.4 percent, indicating the algorithm at this location was not as successful in identifying control points where independent variable values nearly perfectly matched those of data points in the SUR. Interestingly, the *p*-value for this station was significantly less than 10^{-9} in the Test Run, and a notable increase in DO was determined. This success at identifying suitable control points in 2019 and relative struggle at identifying suitable control points in 2020 suggests something significant changed in the system which affected this individual location. The McCoy's Cut flow rerouting mitigation project, constructed to deliver additional high DO freshwater flow to the Little Back and Middle Rivers and prevent saltwater intrusion, was completed in early 2020. Therefore, despite the dataset at this USGS gage beginning in 2013, only a small period (approximately six months between completion and SUR beginning) existed with increased freshwater flows, the majority of which occurred in winter and spring with low water temperatures. Given the SUR occurred with freshwater flow from upstream, the suitable control dataset was significantly reduced, and the algorithm was not as successful in finding near identical test/control data pairs, particularly due to salinity. Also, the additional freshwater flow reduced the potential for retained oxygen to extend that far upstream, except under spring tide conditions (supporting analysis presented in Section 9.2.5). This is the reason for the near-zero change between the SUR and the control dataset at the Little Back River near GA 25, and therefore the results are considered inconclusive at this singular location. It should be noted that the Middle River near GA 25 USGS station (02198950) was successful in showing a positive delta between the SUR and control dataset and had a *p*-value significantly less than 10^{-9}. Despite additional freshwater flow being diverted down the Middle River in addition to the Little Back River from the McCoy's Cut freshwater flow rerouting project, the connections the Middle River has with the Front River immediately upstream and downstream of the GA 25 bridge meant no discernable impact was observed.

Results of the analysis are presented in ***Table 7-2***, arranged in order from upstream toward the ocean. They are also presented graphically in ***Figure 7-2***. Further details on the analyses are presented in **APPENDIX J.**

Table 7-2 SUR DO differences – median absolute DO concentration (mg/L)

Station	Name	SUR	Control	Difference	*p*-value
02198840	I-95	6.91	6.67	0.24	4.93E-163
02198920	Savannah River-Port Wentworth	4.77	4.24	0.53	5.66E-312
02198950	Middle River- Port Wentworth	5.28	4.69	0.60	0
021989792+	Little Back-Port Wentworth	5.17	5.21	-0.03	0.054
02198955*^	Middle River Savannah in Fish Hole	4.30	3.65	0.65	0
021989793*^	Little Back River at Hog Island	5.22	4.96	0.26	6.76E-71
021989715	Garden City 13.3 feet	3.98	3.12	0.86	0
021989715	Garden City 23.3 feet	3.33	2.77	0.56	0
0219897945*^	Back River at GA 17	4.67	4.22	0.45	5.50E-149
021989773	USACE Dock	3.65	3.25	0.40	2.69E-158
0219897993	Elba Island	4.11	3.99	0.12	3.10E-18

* Interpolated WSE derived based on measured values from the nearest hydrodynamically connected gages

^ New gage used for SUR only, not included in Test Run analysis

+ Results inconclusive due to limited control dataset

The high differences in median DO concentrations of 0.86 mg/L and 0.56 mg/L at USGS station 021989715, located adjacent to the Front River diffuser, show that the DO plume was retained and mixed vertically throughout the water column. The difference in DO concentrations was lower at the deeper 23.3 feet depth, likely due to the higher SOD that occurs at depth in the critical period, but still significantly positive. It should be noted that despite station 021989715 being located immediately across the Front River from the Downriver plant, this positive result is not due to the plume reaching the gage immediately upon injection. Instead, as illustrated by the drift data and dye releases in Section 0 and Section 10.2 respectively, the oxygen plume does not reach the other side of the Front River until fully mixed by successive tidal changes.

LINE OF EVIDENCE 3.3 – USGS TEST-CONTROL ANALYSIS (VERTICAL)

Increases at other USGS stations on the Front River both upstream and downstream of the diffuser validate the improvement caused by the oxygen injection. More than 1.75 miles downstream of the Back River diffuser at USGS station 0219897945, the median DO concentration difference was 0.45 mg/L. Approximately 1.5 miles upstream of the diffuser at USGS station 021989793, the DO difference was 0.26 mg/L. The relatively high median DO concentration differences upstream and downstream of the Back River diffuser confirm that the injected DO mixed in the water column and was distributed throughout the Back River. Farther upstream in the Little Back River at USGS station 021989792, the median DO concentration was near zero, for the reasons described previously, and therefore this individual result is considered inconclusive and not representative of the overall test/control analysis.

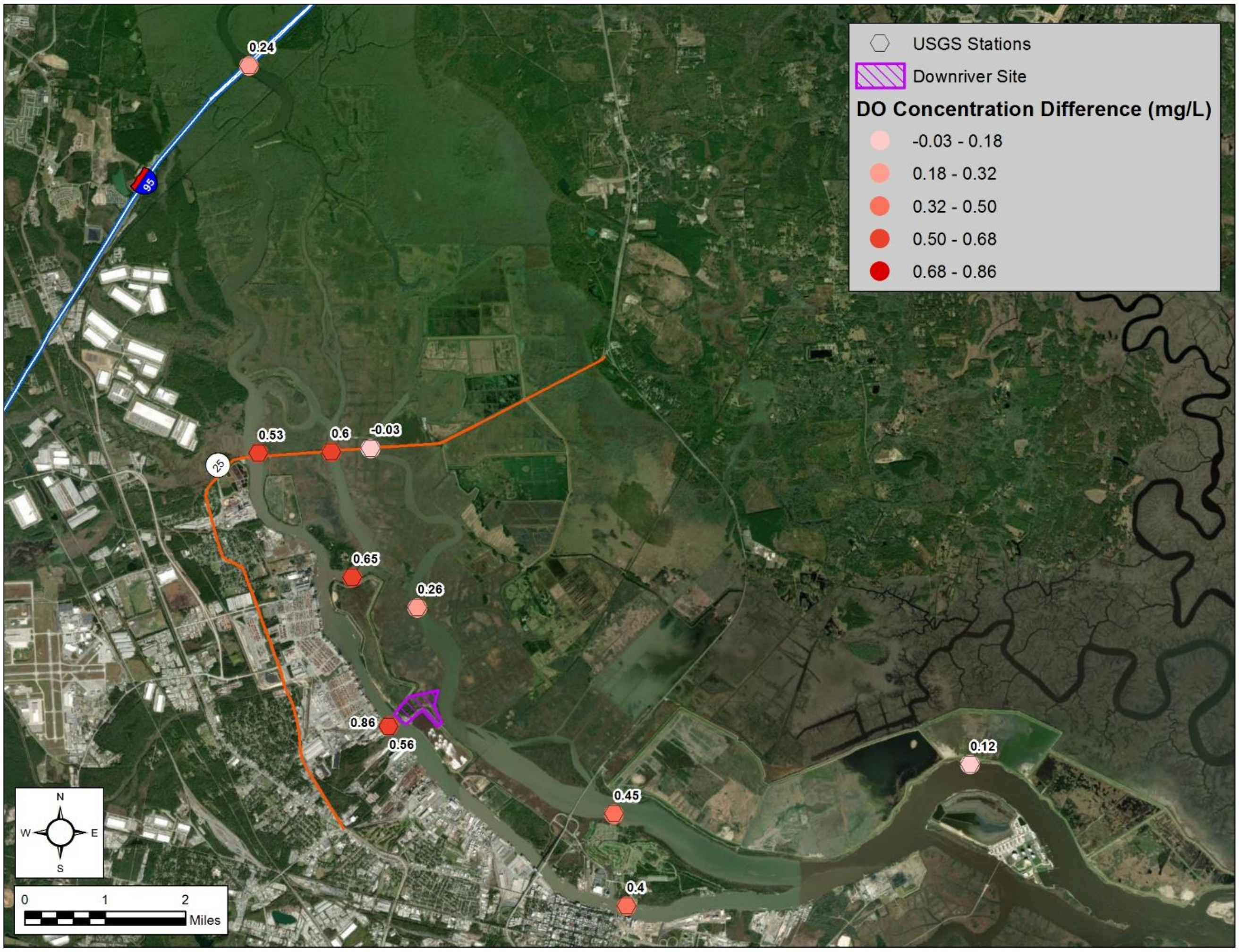

Figure 7-2 Startup Run DO Differences – Median Absolute DO Concentration (mg/L)

The closest station to the Upriver plant which measures the necessary parameters is the gage located at I-95 (02198840). Despite being located approximately 17 RMs downstream of the plant and subject to numerous influxes of low DO water from the adjacent tributaries, a median DO increase of 0.24 mg/L was observed during the SUR. Given no improvement was observed at this station during the Test Run, this increase is considered purely attributable to the oxygen injection from the Upriver plant.

LINE OF EVIDENCE 4.2 – USGS TEST-CONTROL ANALYSIS (SPATIAL)

7.3 ASSESSMENT OF OXYGEN RETENTION AFTER OPERATIONS CEASE

The USGS data have been successfully analyzed to determine the impacts of the oxygen injection when the plants are in operation (Section 7.1 and Section 7.2). The data can also be analyzed to determine the long-term effects of oxygen injection. One item not addressed in the test-control analysis was if the injected oxygen remains in the system after the plants cease operating or if the benefits are only realized when the plants are in operation. There are several factors that cause DO reduction at an individual point, such as a USGS station, when plants cease operating. They are:

- As the DO plume mixes throughout the estuary, the improvement in an individual location will diminish.
- The DO is consumed by the SOD. Further detail on SOD is available in Section K.5 in **APPENDIX K.**
- The plume naturally moves toward the ocean over time, despite tidal cycles, due to the constant flow from Upriver.
- Loss of DO via atmospheric transfer (albeit minimal due to 99 percent WCTE as identified in Section 6.0 and only occur during neap tides or periods of freshwater flow below 7,000 cfs).

Based on this, the expectation is for the injected DO to remain within the Savannah River system after oxygen injection ceases and gradually reduces until returning to typical background concentrations. Additionally, residual effects are likely to be more long-lasting at USGS stations closer to the ocean.

To test the expectation, DO plots for all analyzed USGS gages have been prepared for the years 2013 through 2020. This graphical assessment technique does not account for interannual variations in salinity and gage height, but temperature variations are negated given DO saturation considers the effect of temperature. The DO saturations are presented on the y-axis and the date is on the x-axis. Only the months of May and June are presented for the Test Run, and September to October for the SUR, for ease of comparison. The Test Run ended May 12, 2019, and the SUR ended September 22, 2020. It should be noted that both oxygen injection plants continued operating for a week after the SUR concluded. The periods when the oxygen injection system was operating (Test Run and SUR plus an extra week) are shown in blue while all other data are red, to help distinguish when oxygen injection ceased. The plots for Garden City at 23.28 feet depth (USGS station 021989715_2) and the USACE Dock (USGS station 021989773) for both Test Run and SUR are presented in ***Figure 7-4*** through ***Figure 7-6***. The corresponding plots for all other USGS gages are presented in **APPENDIX J**.

The increases in DO saturation after the Test Run and SUR, compared to corresponding periods from other years, are visually noticeable. Additionally, the SUR retention appears greater than the Test Run, due to the additional load from the Upriver plant. This qualitative assessment indicated oxygen plumes in downstream gages retained the positive impact of the oxygen injection for more than a week after plant operations ceased. Farther upstream, the retention was reduced. The retention at the I-95 gage, the approximate tidal limits of the Savannah River, and the most upstream gage that measures DO were not visually detectable, which was to be expected given the unidirectional flow and the approximate 24-hour travel time from the Upriver plant to this station (See Section 10.1.3).

It is worth recognizing that this assessment technique is more qualitative and less robust than the test/control analysis used in Section 7.1 and 7.2. However, the conclusion is assured and supports the findings on oxygen retention in Section 10.0.

LINE OF EVIDENCE 2.2 – OXYGEN PLUME RETENTION AFTER INJECTION

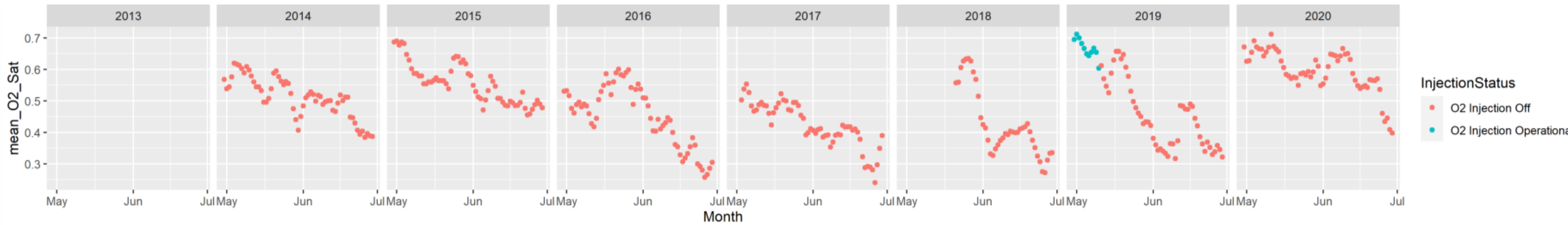

Figure 7-3 DO Saturation at USGS station 021989715_2 for Test Run

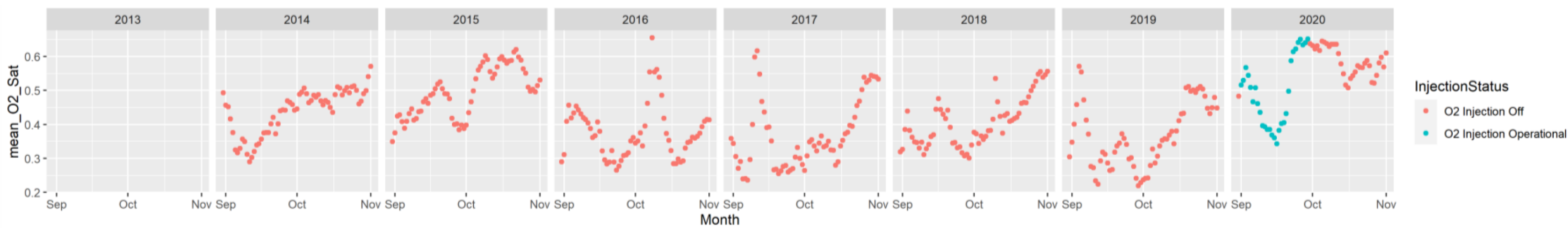

Figure 7-4 DO Saturation at USGS station 021989715_2 for SUR

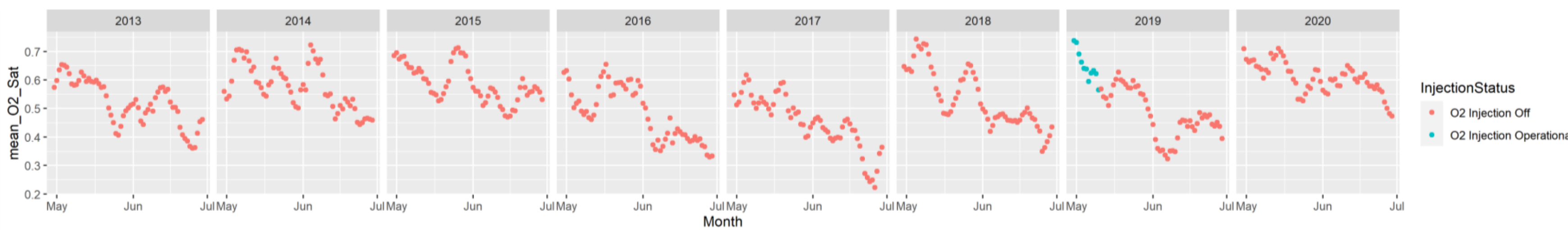

Figure 7-5 DO Saturation at USGS station 021989773 for Test Run

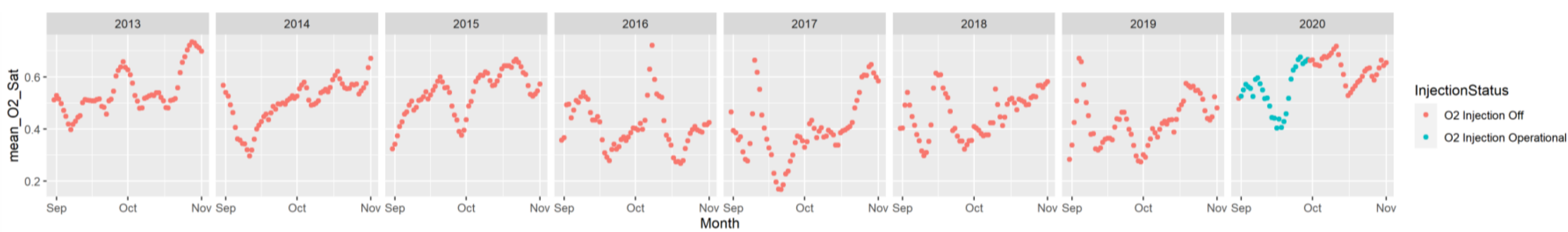

Figure 7-6 DO Saturation at USGS station 021989773 for SUR

7.4 SUMMARY

The long-term, independently collected, and publicly available data record that the network of USGS gages provides was a perfect opportunity to assess the impact of the oxygen injection system. A test/control analysis, whereby the interannual effects of gage height, temperature, salinity, and tidal direction were controlled for, allowed a pure analysis of DO change. The positive results support the assertion that the retained oxygen load is being successfully mixed throughout the estuary, both spatially and vertically.

In addition, a graphical comparative analysis identified significant retention in the lower regions of the estuary after oxygen injection had ceased. This analysis supports long-term retention findings presented in Section 10.0 and supports the assertion that short-term drops in injected oxygen below the 40,000 lbs/day target do not reduce the effectiveness of mitigation, as described in Section 5.0.

8.0 UPRIVER MONITORING DATA ANALYSIS

THIS CHAPTER ADDRESSES SUCCESS METRIC #2, #3 AND #4 AS IDENTIFIED IN SECTION 4.0
Success Metric #2 – Determine if the injected oxygen is being retained in the water column
Success Metric #3 – Evaluate if the retained oxygen is mixing vertically and mitigating the bottom half of the water column
Success Metric #4 – Evaluate if the retained oxygen is mixing spatially to provide the necessary mitigation throughout the Savannah River and estuary

As detailed in Section 2.0 and summarized in Section 2.5.1, Upriver data were collected at 13 sondes and during 62 drift and 30 profile sampling events. This chapter describes the analysis of these data.

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

8.1 UPRIVER SEMI-PERMANENT BUOYS

Ten Upriver semi-permanent buoys collected monitoring data during the SUR period at a depth of approximately 3.3 feet with two buoys, UR_12 and UR_16, each equipped with an additional sonde mounted along the mooring lines at approximately 9.8 feet deep (***Figure 8-1***). All buoys were in the main Savannah River channel, except for UR_15 which was located outside the channel and was used to help determine how quickly the DO was mixing across the channel. The diffuser injected oxygen at a depth near the bottom of the main channel between buoys UR_9 and UR_10. During setup for the SUR, an additional sonde was deployed in an existing standpipe near Hardeeville, located approximately two miles downstream of the diffuser. This sonde at Hardeeville was installed to capture downstream DO concentrations and quantify the impact of low DO water entering the Savannah River from tributaries and marshes. A total of 13 sondes were deployed to evaluate Upriver conditions.

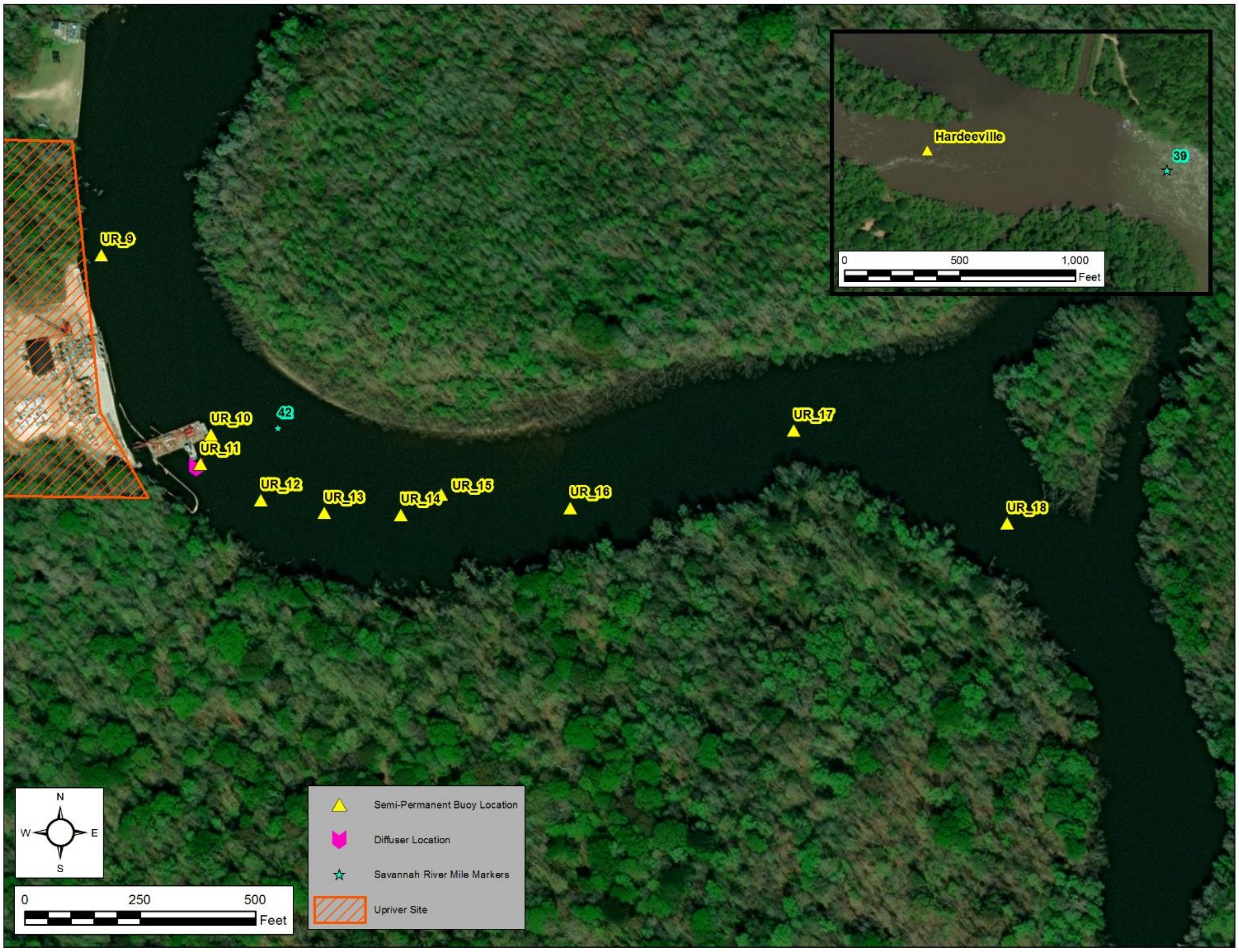

Figure 8-1 Upriver Semi-Permanent Buoy Locations

The surface buoy data are shown in ***Figure 8-2*** via box and whisker plots. The *box* identifies the 25th, 50th, and 75th percentiles (bottom, middle, and top of box) while the whisker and dots identify the upper and lower DO concentrations. The lower DO concentrations occurred during the early September high freshwater flows. The box and whisker plots showed a significant increase in DO concentrations downstream of the diffuser. The following observations were made:

- Buoy UR_9 was located upstream of the oxygen injection diffuser, while Buoys UR_10 and UR_11 were in the vicinity of the diffuser but too close to the diffuser for injected oxygen to mix vertically and reach the surface sondes. The DO measurements here represent background river DO levels.
- Buoy UR_12 was located approximately 200 feet downstream of the diffuser and had two sondes collecting data, one at 3.3 feet below the surface and the second at mid-depth, about 9.8 feet deep. Both sondes had DO concentrations above background concentrations, with the surface sonde's DO concentration lower indicating the oxygen plume has started to reach the surface around this location.

- Buoy UR_15 was intentionally located outside the main river channel to help determine when the oxygen plume was mixed across the river. The DO was not completely mixed across the river at this location as shown by the lower DO concentrations.
- Buoy UR_16 was deployed with two sondes to collect data, one at 3.3 feet below the surface and the second at mid-depth, about 9.8 feet deep. These two sondes had similar DO transects confirming the oxygen was mixed top to bottom (***Figure 8-3***).
- Buoy UR_18 was located and detected where the oxygen plume was mixed across the river channel.
- The Hardeeville sonde was located approximately two miles downstream of the diffuser and showed DO concentrations that were still approximately 0.6 mg/L higher than background concentrations but lower than UR_18 due to low DO water being introduced by the tributaries between the two stations.

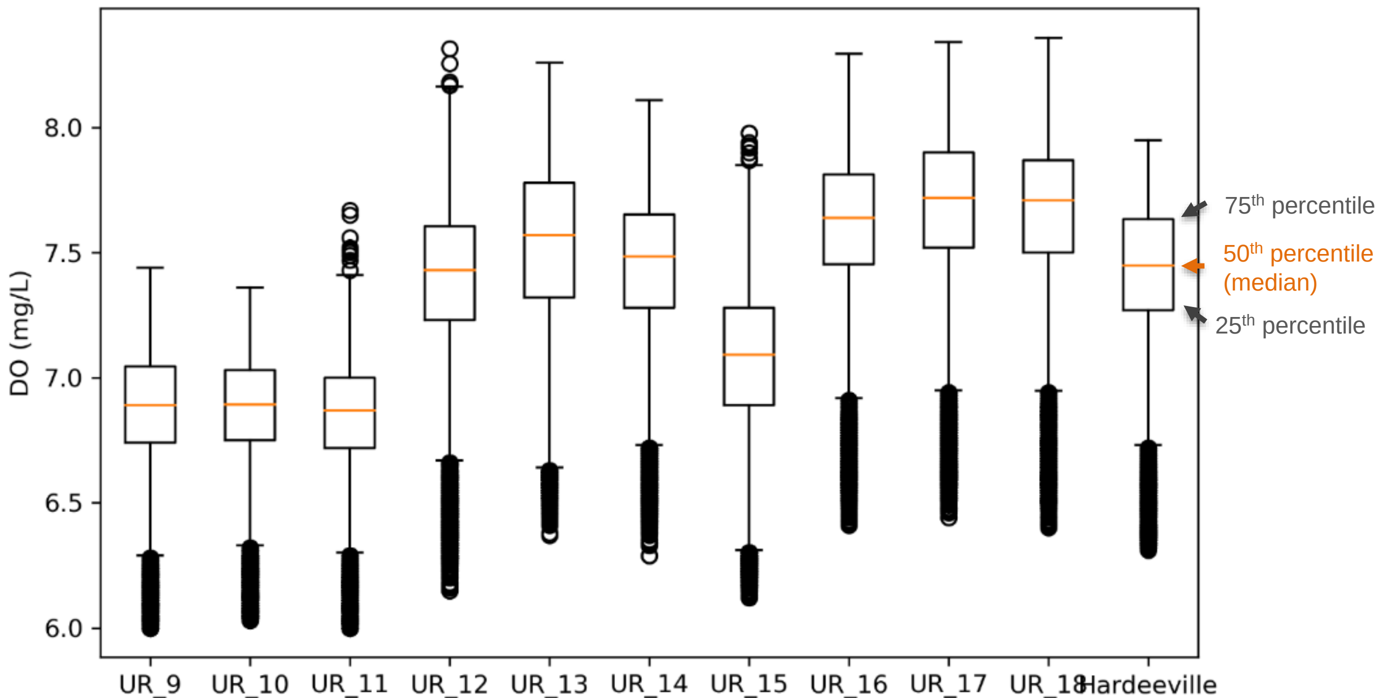

Figure 8-2 Box and Whisker Plots of DO Concentrations at the Upriver Buoys During the SUR, Diffuser located near UR_10

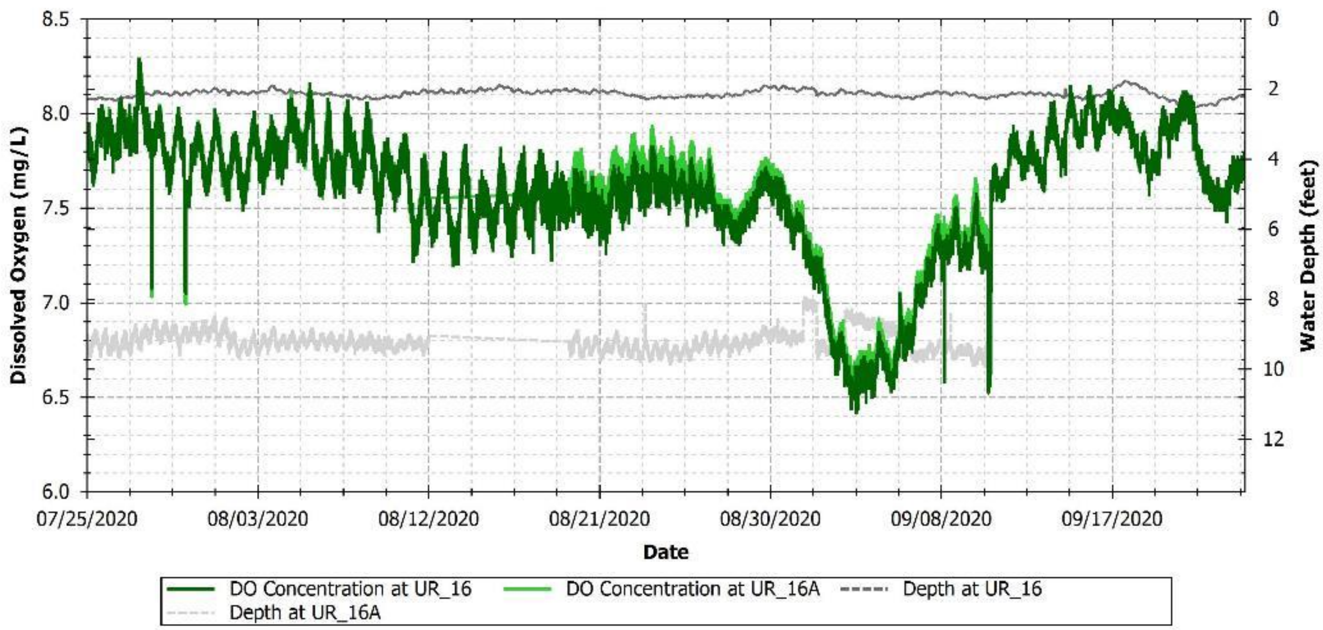

Figure 8-3 Upriver 16 and 16a Observed DO Concentration

All semi-permanent buoy data are presented in **APPENDIX A**.

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

8.2 UPRIVER DRIFT AND PROFILE DATA

Sixty-two drift and 30 profile datasets were collected during boat sampling events throughout the SUR. A summary of the data is presented in Section 2.5.1.2. The sampling varied in time and distance depending on the objective of the event. All drift sampling began upstream of the Upriver plant and moved slowly downstream either by following the channel or taking a zigzag route (bank to bank). Certain sampling events focused on data collection in the vicinity of the diffuser, to help determine the dispersion of the oxygen plume. Other sampling events focused on extending data collection farther downstream and included sampling of the downstream tributaries, to help determine the extent of the oxygen plume and the impact of low DO water entering the river from adjacent tributaries. All Upriver drift sampling events are documented in **APPENDIX C**, including maps of the sampling event extent and drift sampling of the collected data. During dye releases (see Section 2.4 and Section 10.0), the boat sondes were also equipped with Rhodamine dye sensors. In general, the DO plume mixed in the water column quickly resulting in an elevated increase in DO ranging from 0.6 to 0.8 mg/L above background concentrations.

Five drift sampling events were selected to illustrate the impact of the oxygen injection during various river flow conditions, ranging from 6,700 to 12,000 cfs. These five were selected specifically as they encapsulate the following observations:

- The oxygen plume was mixed across the river within one mile downstream of the diffuser (***Figure 8-5***) under low flow conditions, and within 0.4 miles of the diffuser under high flow conditions (***Figure 8-10*** and ***Figure 8-11***).
- DO concentrations downstream of the oxygen injection diffuser ranged from 0.6 to 0.8 mg/L higher than background (upstream) DO concentrations (***Figure 8-5***).
- The tributaries flowing into the Savannah River contributed water with low DO concentrations and gradually lowered the river's DO as they flowed downstream (***Figure 8-11***).
- The extent of tidal influence is approximately RM 27.8, near the I-95 bridge. The benefits of Upriver oxygen injection were detected downstream to RM 21 near the GA 25 bridge (***Figure 8-12***).

8.2.1 Upriver Drift Sampling – July 24, 2020

The July 24, 2020 boat drift conducted a zig-zag pattern route for the first mile downstream of the diffuser, as illustrated in ***Figure 8-4***, then directly down the main channel for a further two miles downstream. The Savannah River flow was approximately 6,700 cfs at the time of this sampling event.

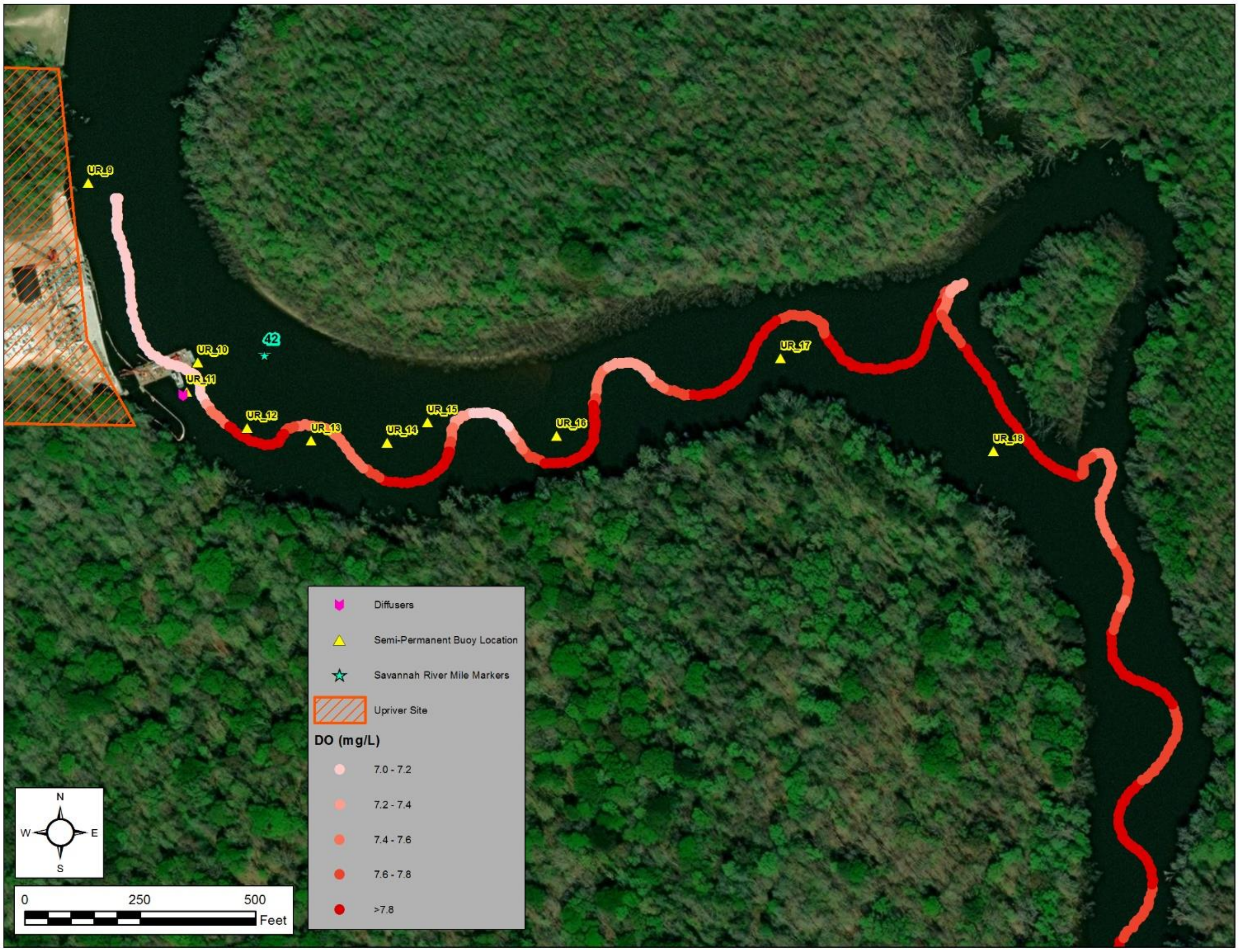

Figure 8-4 Upriver Drift Sampling – July 24, 2020

The following observations were made from the sampling event and the results presented in ***Figure 8-4*** and ***Figure 8-5***:

- The oxygen plume mixed across the river by the time it reached one mile downstream of the diffuser. Due to the low river flows, the oxygen plume took longer to mix into the water column than it would under a high flow condition (see Section 8.2.4 for comparison).
- Upstream DO concentrations were 6.9 mg/L, and at one mile downstream the DO levels were 7.6 mg/L.
- The tributaries flowing into the lower Savannah River had low DO (see RM 40.3) in ***Figure 8-5***.

The DO concentrations in the lower two-mile section remained relatively constant, only decreasing slightly due to incoming tributary flows with low DO concentrations. This indicated that most of the injected oxygen was mixed throughout the water column and was retained in the water, not transferring to the atmosphere, even during low river flows.

LINE OF EVIDENCE 2.3 – NO EFFERVESCENCE OBSERVED

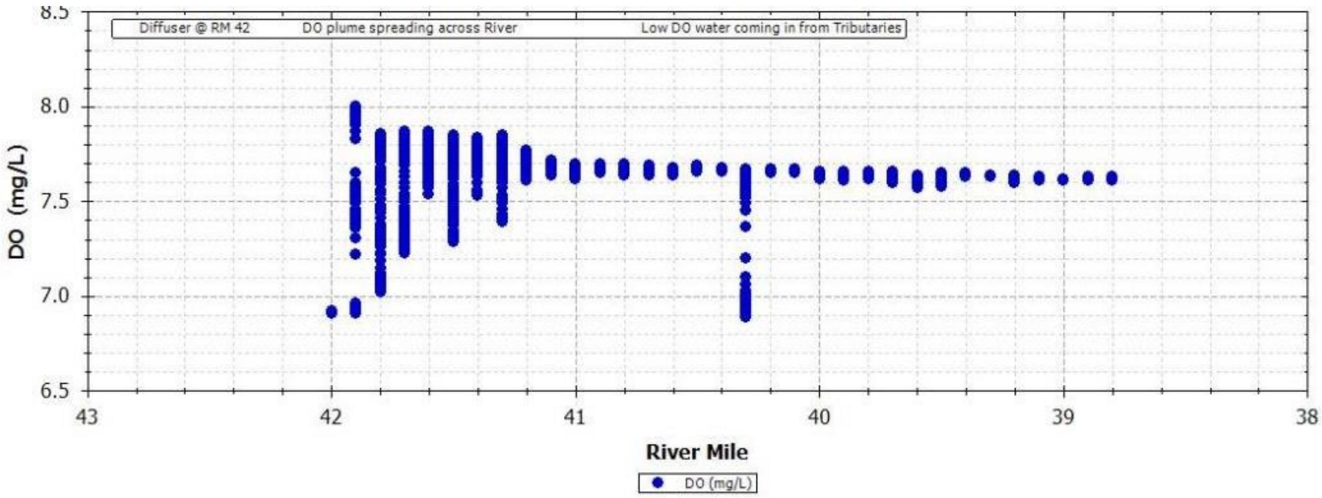

Figure 8-5 Savannah River DO transect – July 24, 2020

8.2.2 Upriver Drift Sampling – July 28, 2020

The July 28, 2020 drift event was conducted at a higher river flow of 8,500 cfs and is illustrated in ***Figure 8-6***. This event provides further evidence of the impact of the injected oxygen system during a period of drift data collection when the plant was not operating (that is, undergoing maintenance). At 9 am, before the start of data collection, the instantaneous plant load was measured at 26,265.6 lbs/day. DO measurements (top of ***Figure 8-6***) were collected upstream and downstream of the diffuser while the plant was operating, with the surface DO concentrations downstream of the diffuser ranged between 0.1 mg/L and 0.8 mg/L higher than the upstream background concentrations.

At approximately 9:30 am, the oxygen load from the plant began to decline and reached a plant load of zero at 9:45 am. DO measurements (bottom of ***Figure 8-6***) were collected upstream and downstream of the diffuser when the oxygen system was not operating. No discernible difference in DO concentrations was detected between upstream and downstream of the diffuser, indicating the increased DO seen in top figure is solely due to the injected oxygen.

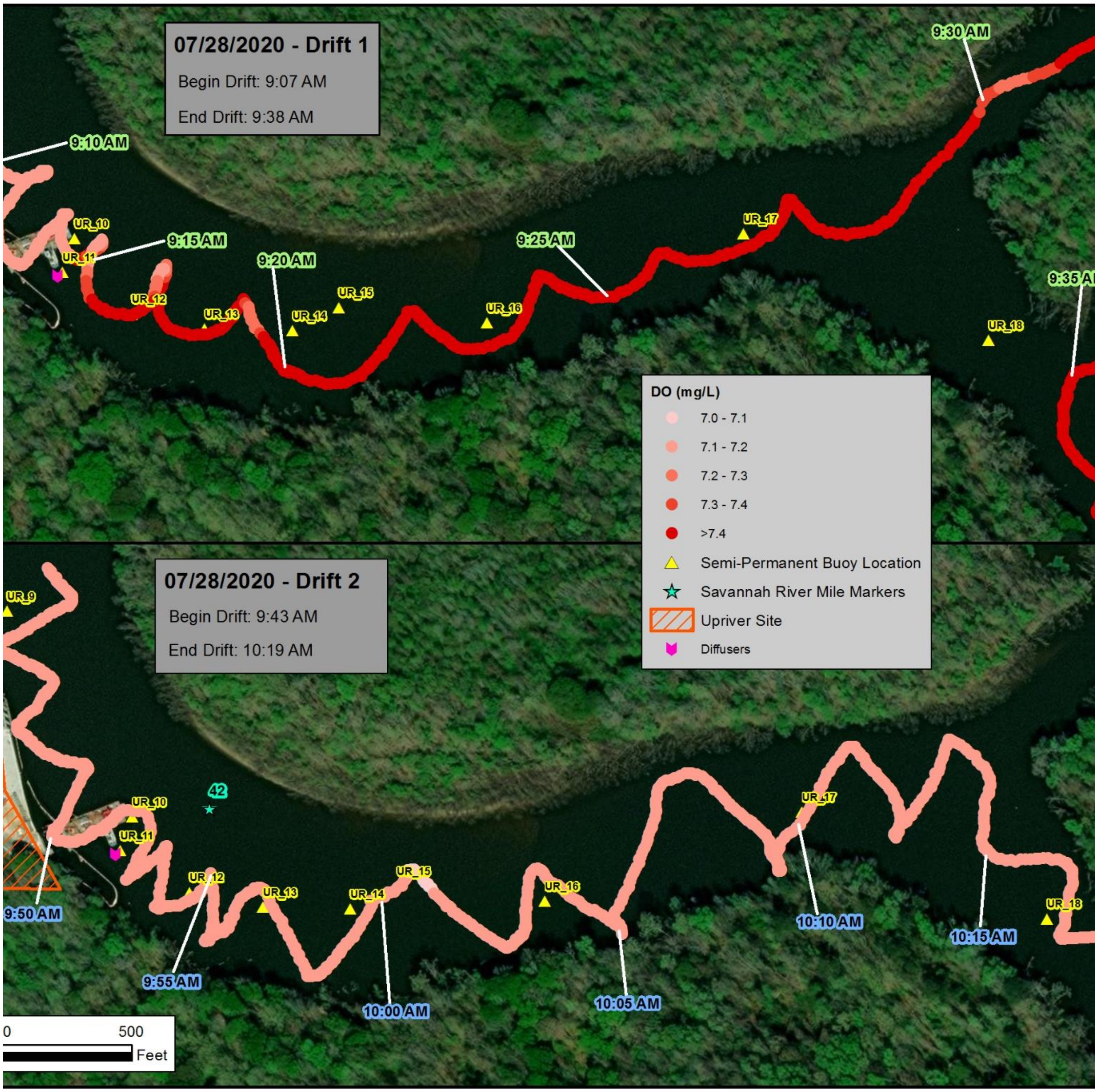

Figure 8-6 Upriver Drift Sampling – July 28, 2020

8.2.3 Upriver Drift Sampling – August 5, 2020

The August 5, 2020 boat drift conducted a zig-zag pattern route from upstream of the diffuser to three miles downstream, as illustrated in ***Figure 8-7*** and ***Figure 8-8***. The Savannah River flow was approximately 8,000 cfs. The DO was completely mixed throughout the water column by UR_18, as indicated by the uniform coverage (red dots) bank to bank. Also, the tributaries flowing into the lower Savannah River contributed water with low DOs in comparison, slightly lowering the river's DO concentrations (see ***Figure 8-8*** immediately downstream of UR_18 where low DO water enters from the oxbow).

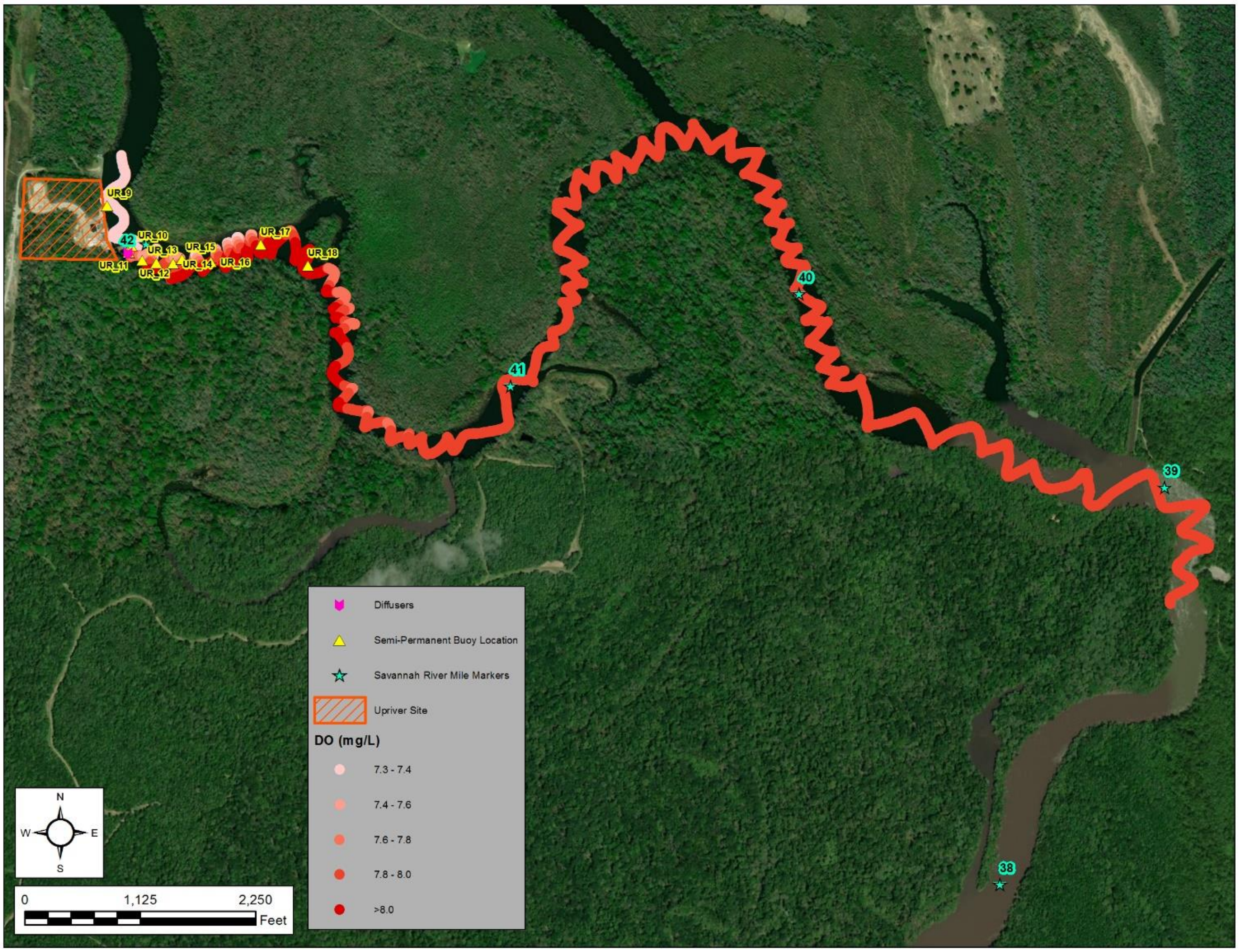

Figure 8-7 Upriver Drift Sampling – August 5, 2020

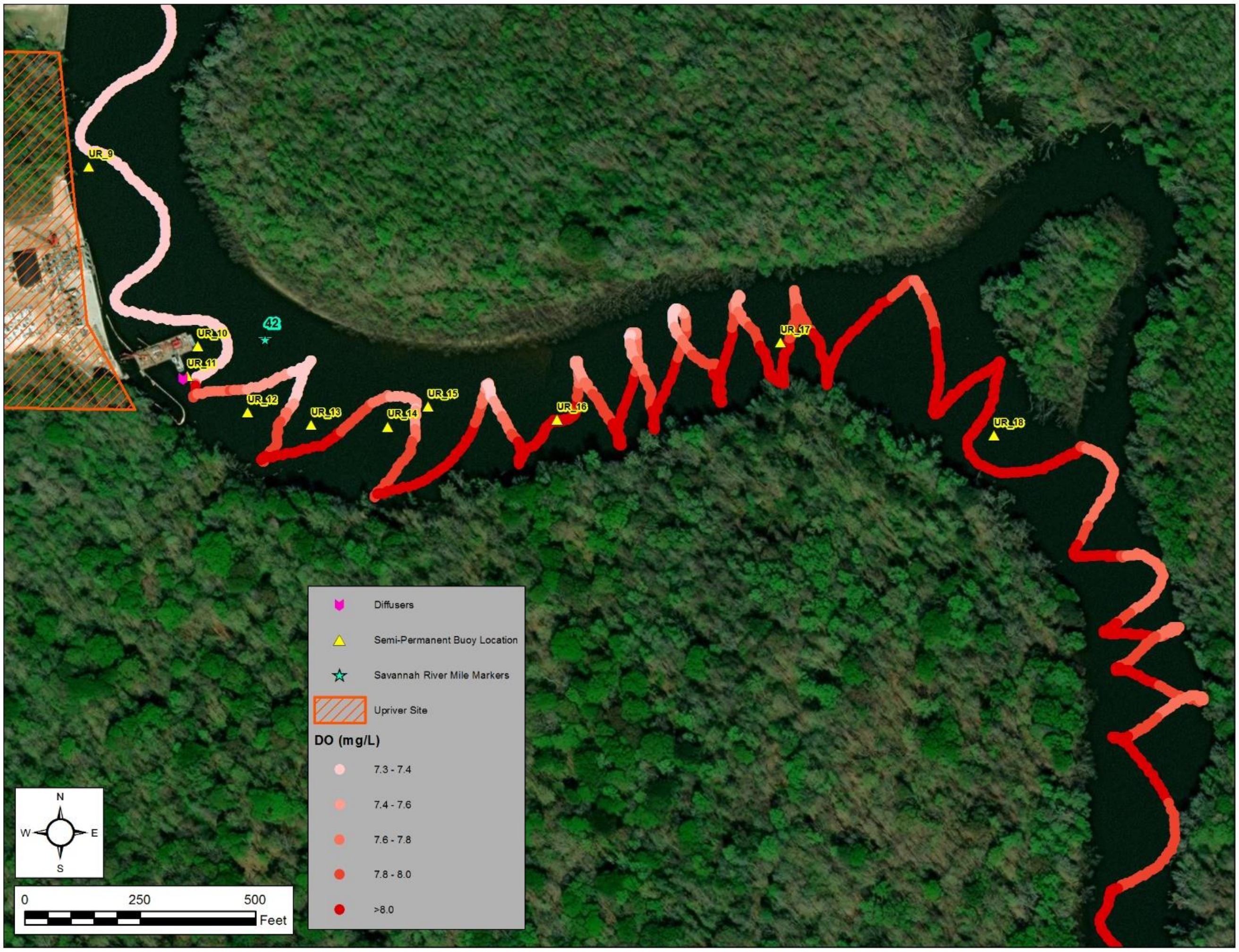

Figure 8-8 Upriver Drift Sampling – August 5, 2020 (inset)

Figure 8-9 shows the DO versus RM cross-section measurements averaged over each 0.1 miles. The injected oxygen load was completely mixed by RM 41.5, indicated by the narrow band in recorded concentrations. Here, injected oxygen raised the Savannah River's DO by 0.6 mg/L (from 6.85 to 7.45 mg/L). At RM 41.4, low DO water flowed in from the oxbow tributary and then was completely mixed again at RM 41 with a resultant river DO of 7.4 mg/L, a small but noticeable reduction of 0.05 mg/L.

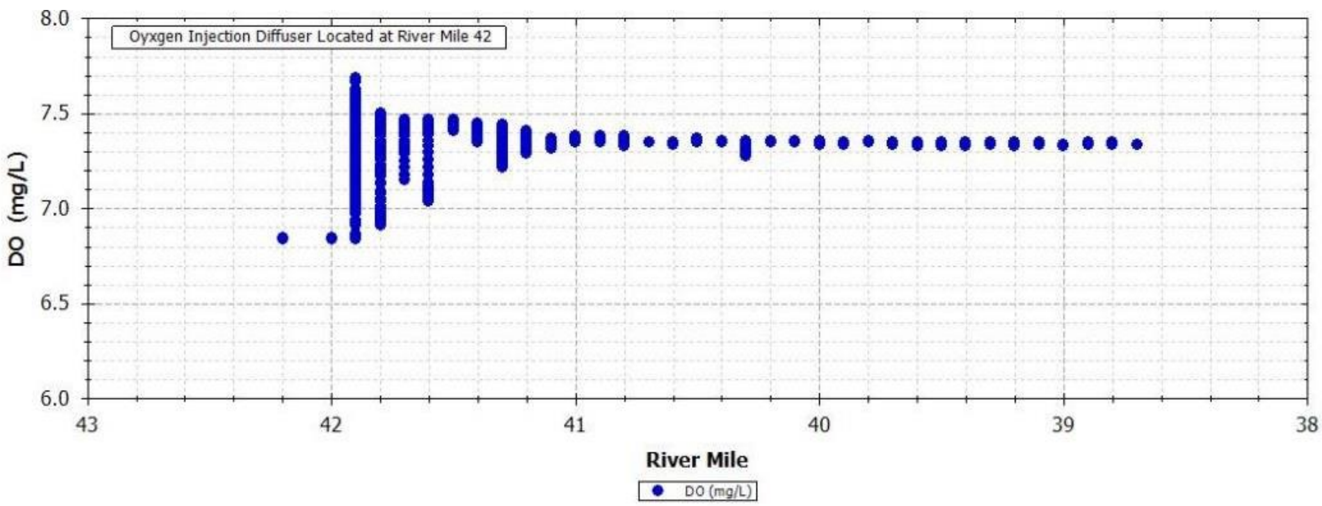

Figure 8-9 Savannah River DO Transect – August 05, 2020

8.2.4 Upriver Drift Sampling – September 1, 2020

The September 1, 2020 boat drift conducted a detailed zig-zag sampling from upstream of the diffuser to three miles downstream, as illustrated in ***Figure 8-10***. The Savannah River flow was high, approximately 12,000 cfs, at the time of this sampling event.

The results were similar to the August 5, 2020 event, but additional emphasis was placed on obtaining more detailed tributary samples and evaluating the effect of high river flows. The following observations were made:

- The oxygen plume mixed across the river by the time it reached buoy UR_18, 0.4 miles downstream of the diffuser. Prior to that, the plume had not mixed bank to bank, as indicated by the white data points near the northern bank. This is significantly less than the one mile it took for complete mixing to occur under a low flow condition, as previously described in Section 8.2.1.
- Upstream DO concentrations were 6.8 mg/L; however, at buoy UR_18 the DO levels had increased 0.6 mg/L to 7.4 mg/L, where the DO was completely mixed throughout the water column.
- The tributaries flowing into the lower Savannah River contributed water with low DOs. These can be seen in ***Figure 8-11*** at RM 41.3, 40.3, and 39.1.

The DO concentrations in the three-mile stretch remained relatively constant, only being lowered slightly by incoming tributary flows with low DO. This indicated the injected oxygen was mixed throughout the water column, was retained in the water, and did not transfer to the atmosphere.

LINE OF EVIDENCE 2.3 – NO EFFERVESCENCE OBSERVED

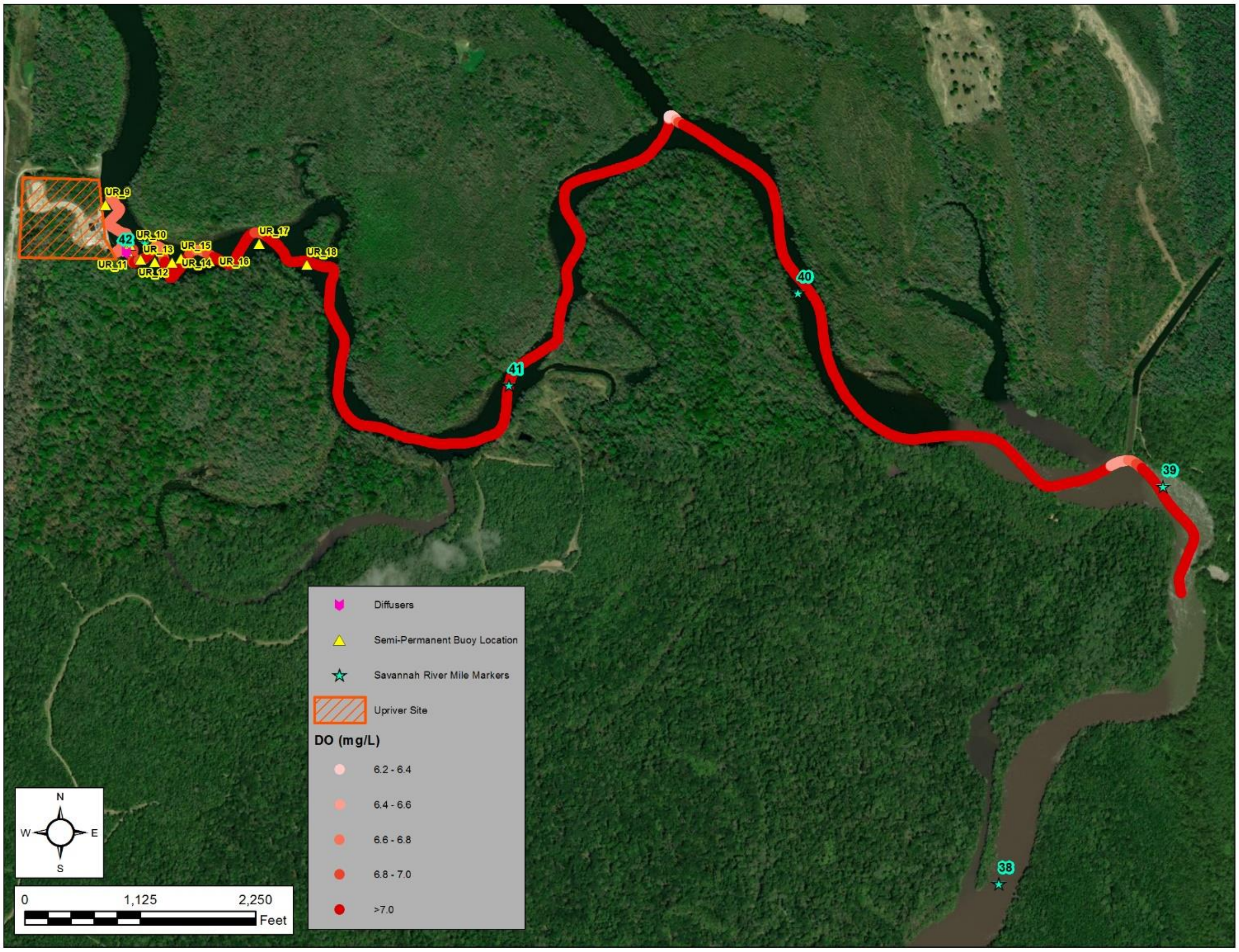

Figure 8-10 Upriver Drift Sampling – September 1, 2020

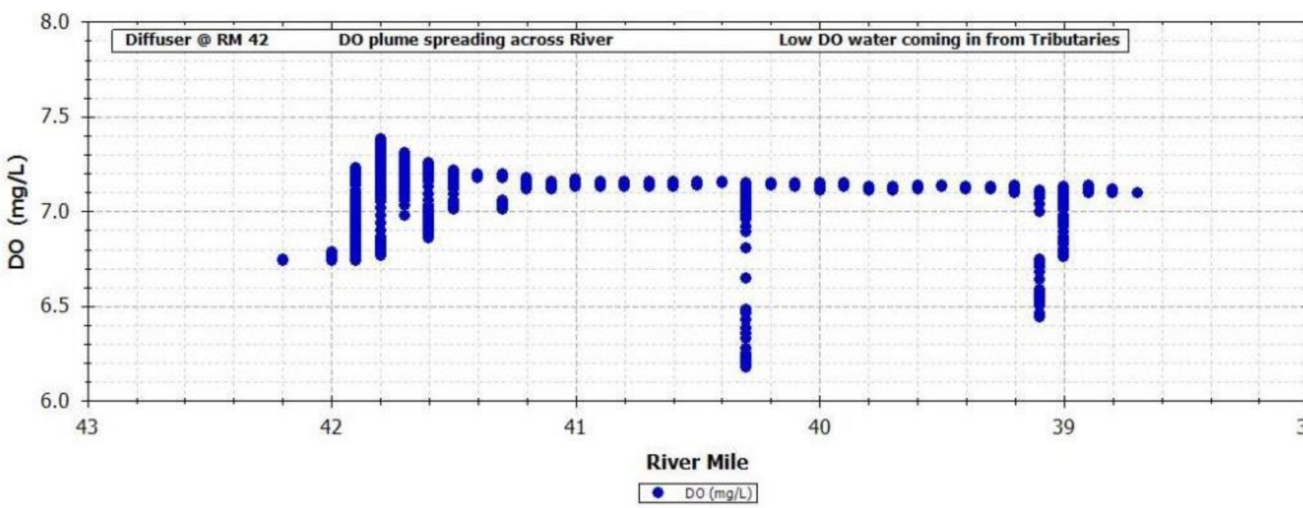

Figure 8-11 Savannah River DO Transect – September 01, 2020

8.2.5 Upriver Drift Sampling – September 16, 2020

The September 16, 2020 boat drift consisted of extensive main channel sampling from upstream of the Upriver diffuser downstream to RM 21, below the I-95 bridge. The longitudinal DO transect per RM is presented in ***Figure 8-12***. The Savannah River flow had reduced since early September 2020 to approximately 7,400 cfs. The Savannah River DO decreased downstream, both due to the low DO from incoming tributaries and the impact of the tides moving lower Harbor DO water upstream. The limit of tidal influence is approximately RM 27.8, as identified in Section 7.1, and this is supported by the results in ***Figure 8-12***, given a noticeable reduction occurs here. Another sizeable reduction is evident at RM 21 near the GA 25 bridge and the extent of harbor deepening.

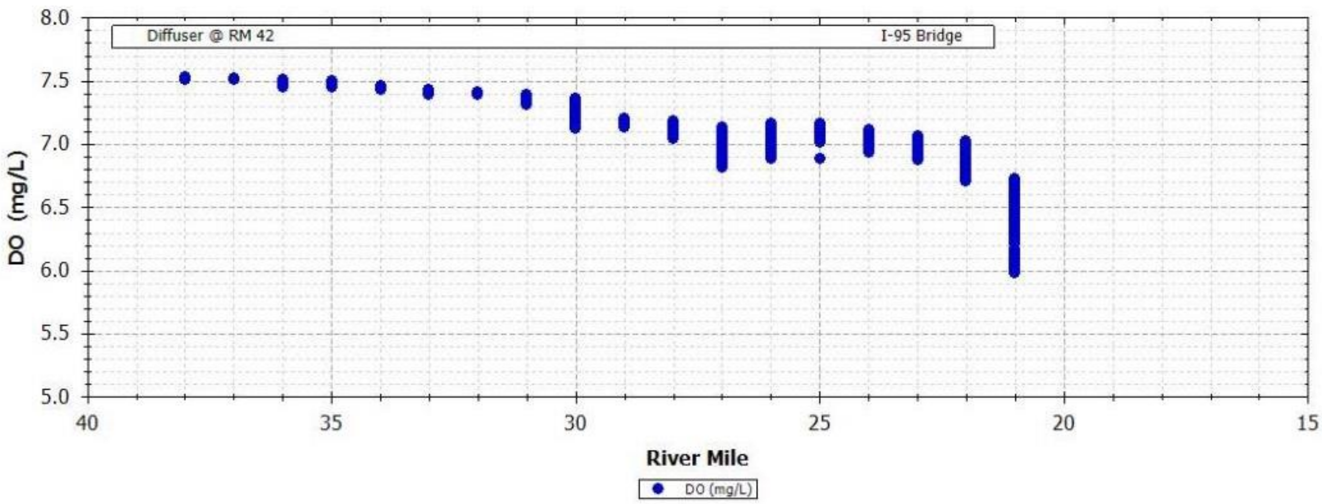

Figure 8-12 Savannah River DO Transect – September 16, 2020

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

8.3 SUMMARY

The impact of the Upriver oxygen injection plant was relatively easy to discern due to unidirectional flow, lack of tidal influence, and the confined nature of the upper Savannah River. It can be quantified by comparing background DO concentrations upstream of the Upriver plant diffuser to the DO concentrations measured downstream of the diffuser.

Upriver semi-permanent buoy, profile, and boat drift data were collected during the SUR period. With the oxygen injection system operating, DO concentrations downstream of the Upriver plant increased between 0.5 and 1.0 mg/L, depending on the flow of the Savannah River and the output of the Upriver plant. The injected oxygen plume expanded as it moved downstream of the Upriver diffuser dispersing from bottom to surface and side to side. By the time the plume traveled 0.4 miles downstream from the diffuser, the oxygen was well mixed throughout the water column. The plume was also well mixed spatially across the river by this location under high flow conditions, but under low flow conditions, full mixing did not occur until one mile downstream of the diffuser.

Along with the injected oxygen plume being well mixed into the receiving water, there was no observed effervescence, bubbling or surface disturbances near the Upriver diffuser.

The benefits of the injected oxygen from the Upriver plant were detected downstream of the I-95 bridge and into the zone of tidal influence.

9.0 DOWNRIVER MONITORING DATA ANALYSIS

THIS CHAPTER ADDRESSES SUCCESS METRIC #2, #3 AND #4 AS IDENTIFIED IN SECTION 4.0

Success Metric #2 – Determine if the injected oxygen is being retained in the water column
Success Metric #3 – Evaluate if the retained oxygen is mixing vertically and mitigating the bottom half of the water column
Success Metric #4 – Evaluate if the retained oxygen is mixing spatially to provide the necessary mitigation throughout the Savannah River and estuary

9.1 FRONT RIVER DRIFT AND PROFILE DATA

As detailed in Section 2.0 and summarized in Section 2.5.2, Front River data were collected at one sonde and during 30 drift and 305 profile sampling events. Three semi-permanent buoys were deployed but removed before the start of the SUR due to channel dredging activities in this area. This chapter describes the analysis of these data.

Similar to approaches employed Upriver, boat sampling drifts either followed the channel or took a zig-zag route going bank to bank. The observed DO increased in the vicinity of the oxygen injection diffuser. The direction of drift sampling was selected depending on the tide. During incoming (flood) tides, the oxygen plume moved upstream and during outgoing (ebb) tides, the oxygen plume moved downstream. The injected oxygen plume was initially concentrated along the west bank and expanded as it moved upstream or downstream of the diffuser, mixing bottom to surface and side to side. Because of the tidal and dynamic nature of the Front River, determining the spatial and vertical DO improvements caused by oxygen injection could not be quantified by boat sampling alone. The Front River field monitoring analysis was augmented by evaluating the USGS station data and the modeling data to provide a more complete assessment approach. The USGS data are in Section 7.0 and the modeling results are in Section 11.0. During the SUR sampling events, there was no observed effervescence, bubbling, or surface disturbances near the Front River diffuser.

Three drift and profile sampling events were selected to illustrate the impact of the oxygen injection in the Front River. These three were selected specifically as they encapsulate the following observations:

- During all the sampling events, there was no observed effervescence, bubbling, or surface disturbances near the diffuser.
- The injected oxygen was more pronounced at mid-depth (***Figure 9-2***) than the surface (***Figure 9-1***).
- Injected oxygen was mixed throughout the water column and dispersed into both the bottom and the top of the water column layers during spring tides (***Figure 9-6***). Stratification was evident during neap tides (***Figure 9-5***). The Front River behaved differently during neap and spring tides.
- Increased DO levels were measured upstream beyond the turning basin (RM 19) and downstream beyond the GA 17 bridge (***Figure 9-3***).
- Analyses of the Front River dye data (Section 10.2), collected during selected boat sampling events, indicated the injected oxygen remained in the Front River system for over a month during summer low flow conditions.

All profile and drift sampling events are documented in **APPENDIX B** and **APPENDIX C**, including maps of the sampling extent and graphs of the collected data. During dye releases, the boat sondes were also equipped with Rhodamine dye sensors (Section 10.2).

9.1.1 Front River Drift Sampling – August 17, 2020

On August 17, 2020, targeted boat sampling was conducted in the vicinity of the Front River oxygen injection diffuser. Sampling consisted of multiple zig-zag patterns around the diffuser over a two-hour high slack tide using two sondes, one at the surface (3.3 feet deep) and the other sonde at mid-depth (13.2 feet deep). ***Figure 9-1*** illustrates results collected using the surface sonde. The white dots represent the background DO levels around 2.6 to 3.0 mg/L and the pink to red dots represent DO values ranging from 3.0 to 5.2 mg/L, demonstrating the positive effects of the injected oxygen. ***Figure 9-2*** illustrates the results collected using the mid-depth sonde, with more red dots evident than in ***Figure 9-1*** as the injected oxygen was well distributed at the lower depth. This outcome agreed with the design intent of the diffuser whereby oxygen is injected into and retained primarily in bottom waters.

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

During this sampling event when a significant portion of time was spent in the vicinity of the Front River diffuser, there was no observed effervescence, bubbling, or surface disturbances.

LINE OF EVIDENCE 2.3 – NO EFFERVESCENCE OBSERVED

Figure 9-1 Front River Drift Sampling – August 17, 2020 (surface)

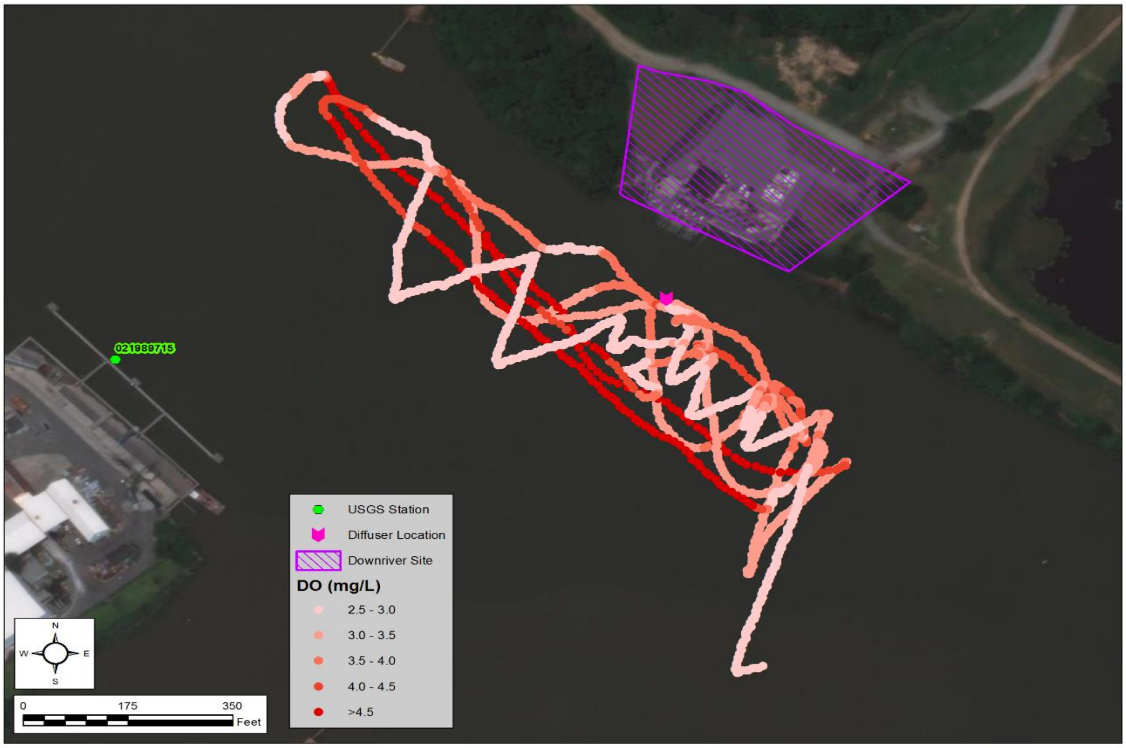

Figure 9-2 Front River Drift Sampling – August 17, 2020 (mid-depth)

9.1.2 Front River Profile Sampling – August 28, 2020

On August 28, 2020, multiple Front River DO profiles were measured on an ebb tide between the I-95 bridge and Fort Pulaski. High DO concentrations entered the Front River from upstream, aided by the oxygen injection from the Upriver plant (Section 8.2.5), sharply decreased around the turning basin (RM 19), then increased by the Front River diffuser, and then decreased downstream near Fort Pulaski. ***Figure 9-3*** illustrates the change in surface DO values in the Front River, as described. While DO concentrations change, the beneficial effects of both the Upriver and Front River oxygen injection are evident from these profiles. ***Figure 9-4*** shows the stratified upper and lower layer over a longitudinal DO profile.

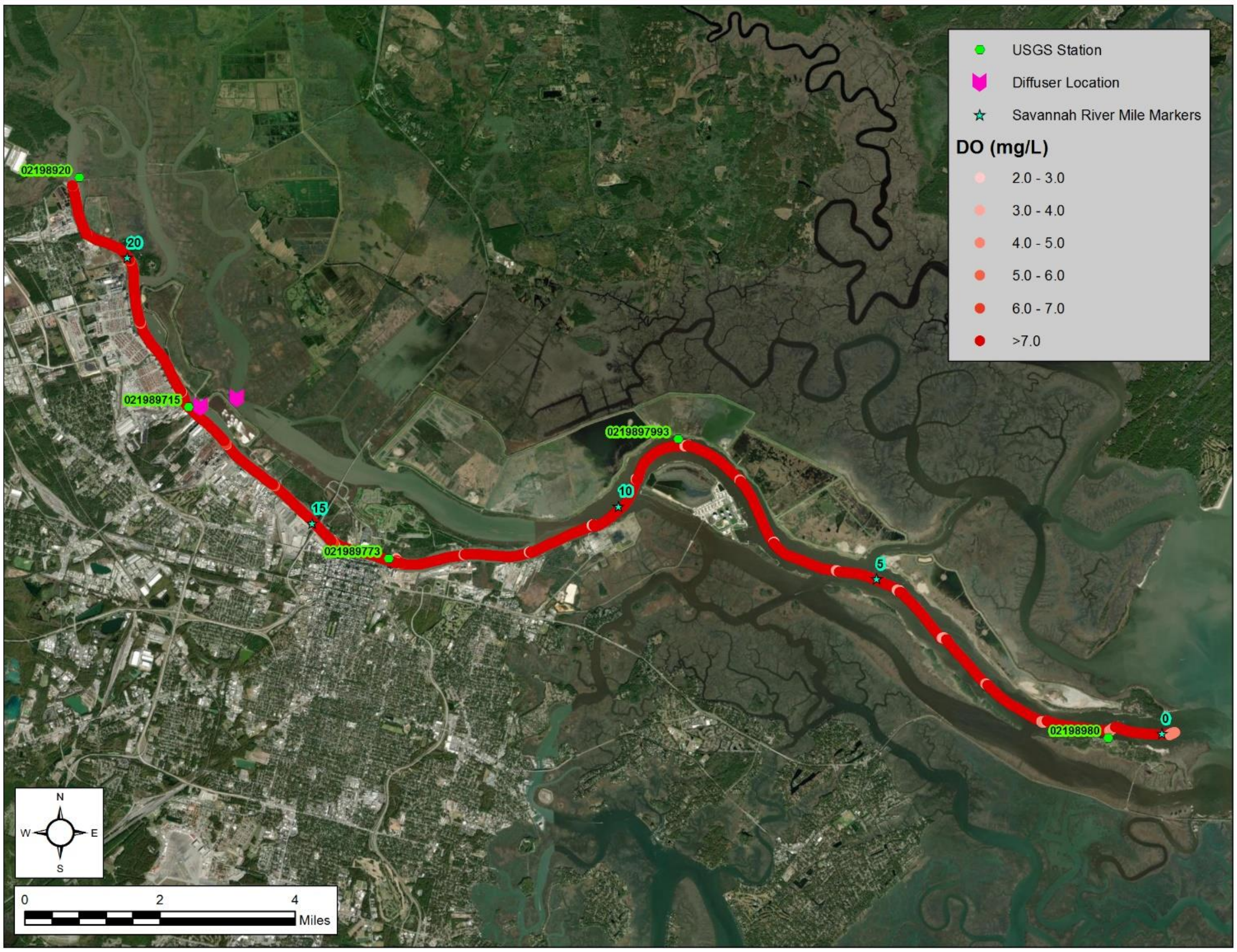

Figure 9-3 Front River Profile Sampling – August 28, 2020

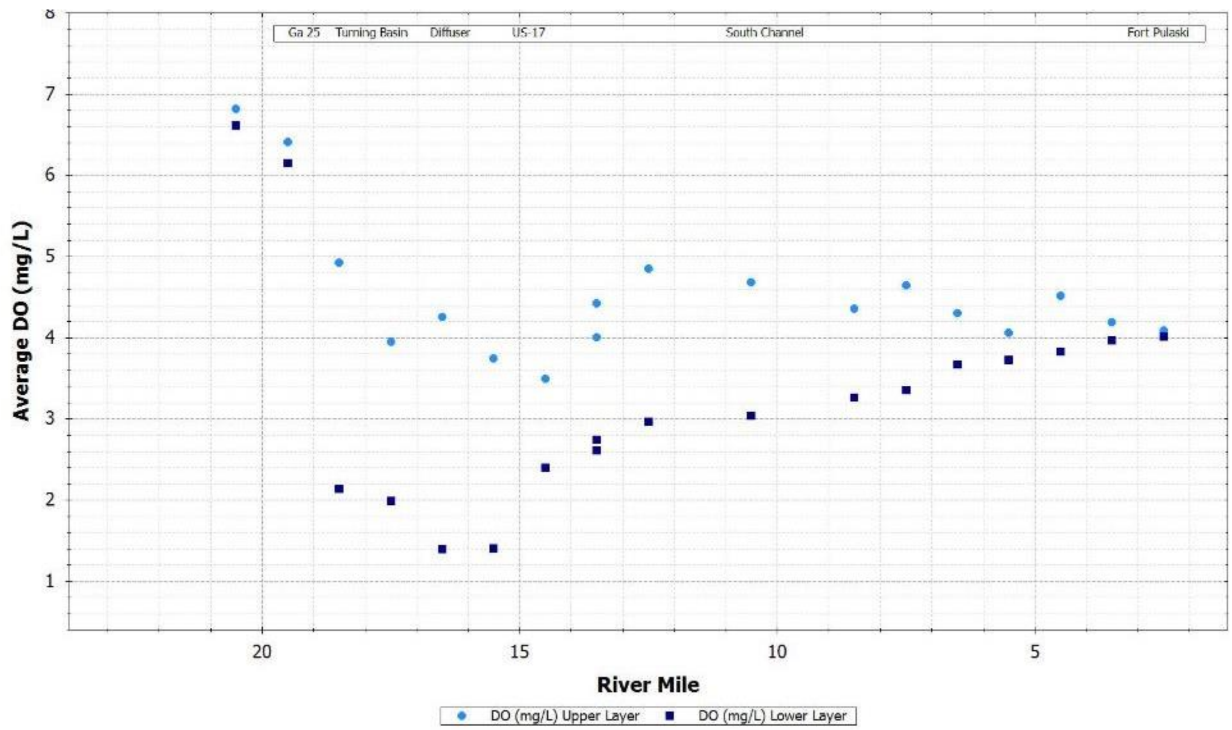

Figure 9-4 Front River DO Profiles – August 28, 2020

9.1.3 Front River Profile Sampling – September 04 and 17, 2020

During a neap tide on September 04, 2020, and a spring tide on September 17, 2020, detailed Front River profile sampling was conducted. The difference between concentrations in the upper and lower layer in ***Figure 9-5*** and the similarities in concentrations in the upper and lower layers in ***Figure 9-6*** illustrate the stratification that occurred during neap tides and the top-to-bottom mixing that occurred during spring tides. During spring tides, the injected DO mixes throughout the water column as the Front River destratified and the impacts of the injected oxygen mixed throughout the system.

LINE OF EVIDENCE 3.2 – ANALYSIS OF PROFILE AND DYE DATA

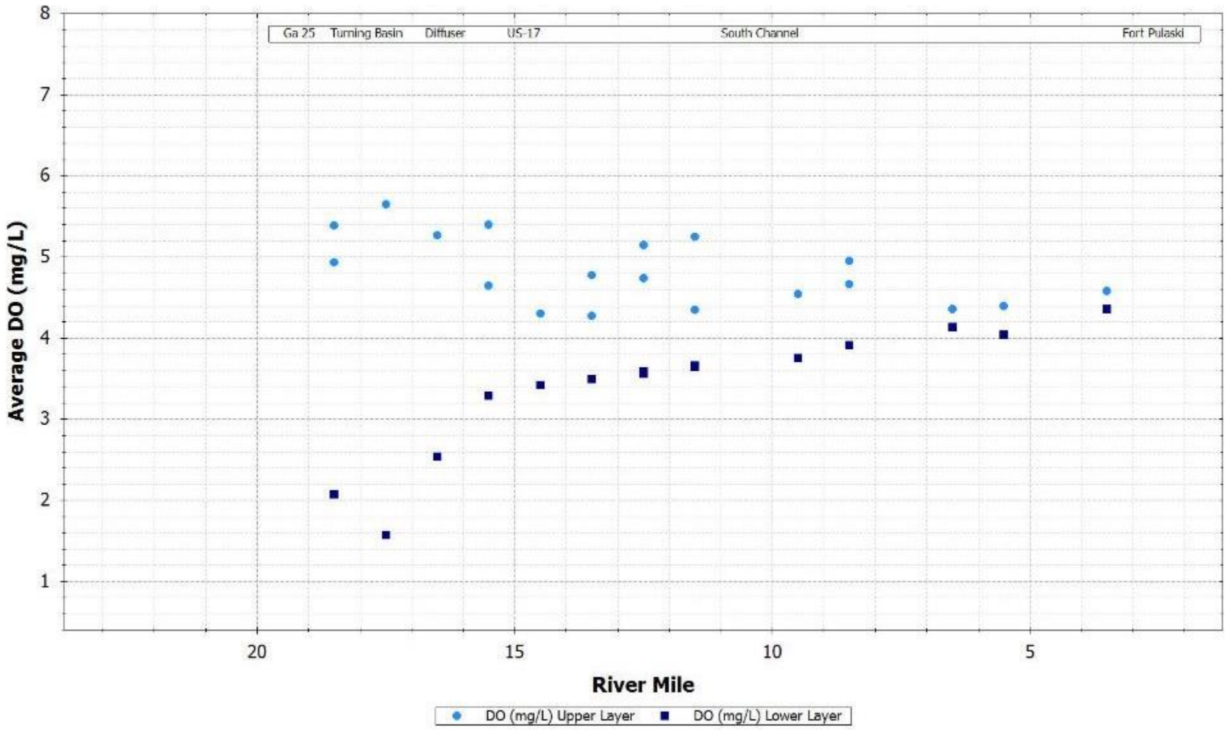

Figure 9-5 Front River DO Profiles – September 04, 2020 (Neap Tide)

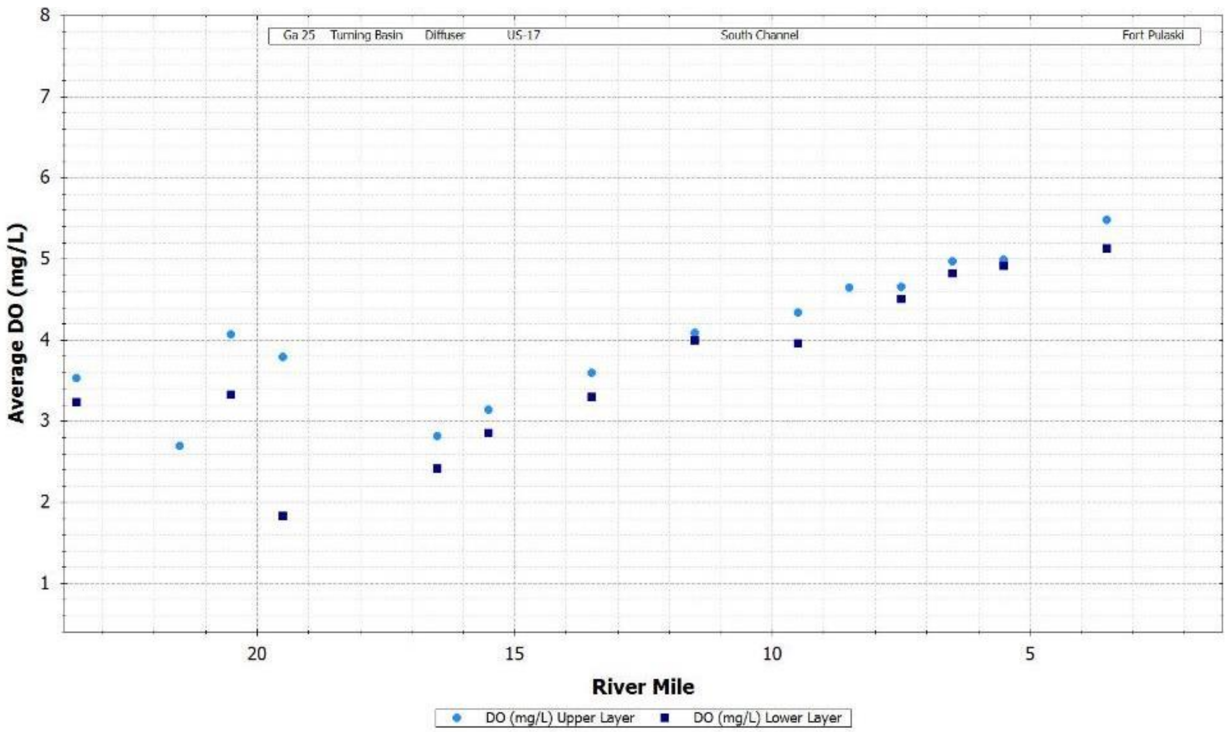

Figure 9-6 Front River DO Profiles – September 17, 2020 (Spring Tide)

9.2 BACK RIVER MONITORING DATA

As detailed in Section 2.0 and summarized in Section 2.5.3, Back River data were collected at eight sondes and during 32 drift and 36 profile sampling events. This chapter describes the analysis of these data.

Because of the tidal and dynamic nature of the Back River and Little Back River, determining the vertical and spatial DO improvements caused by oxygen injection could not be quantified by just the buoy or boat sampling alone. The buoy and drift sampling measured the oxygen plume as the plume mixed into the Back River but could not measure the cumulative impact of the injected oxygen over several weeks. The Back River field monitoring analysis was augmented by evaluating the USGS station data and the modeling data to provide a more complete assessment approach. The USGS data are in Section 7.0 and the modeling results are in Section 11.0. During all the sampling events, there was no observed effervescence, bubbling, or surface disturbances near the Back River diffuser.

LINE OF EVIDENCE 2.3 – NO EFFERVESCENCE OBSERVED

9.2.1 Back River Buoy Data Analysis

Eight semi-permanent buoys were placed in the Back River. Buoys LBR_8 through LBR_5 were located upstream of the Back River diffuser, and buoys LBR_4 through LBR_1 were located downstream of the Back River diffuser (as labeled in ***Figure 9-8***). During ebb tides, the river flows downstream and during flood tides, the river flows upstream. Therefore, the injected oxygen plume would transport downstream of the diffuser during ebb tides and upstream of the diffuser during flood tides. Since the injected oxygen plume was being moved both up and downstream and was being well mixed in the system, the average DO values at all eight buoys were relatively similar. The lack of discernible difference between buoys in ***Figure 9-7*** for both flood and ebb tides supports this statement.

Additional details regarding the Back River buoy data are provided in **APPENDIX A.**

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

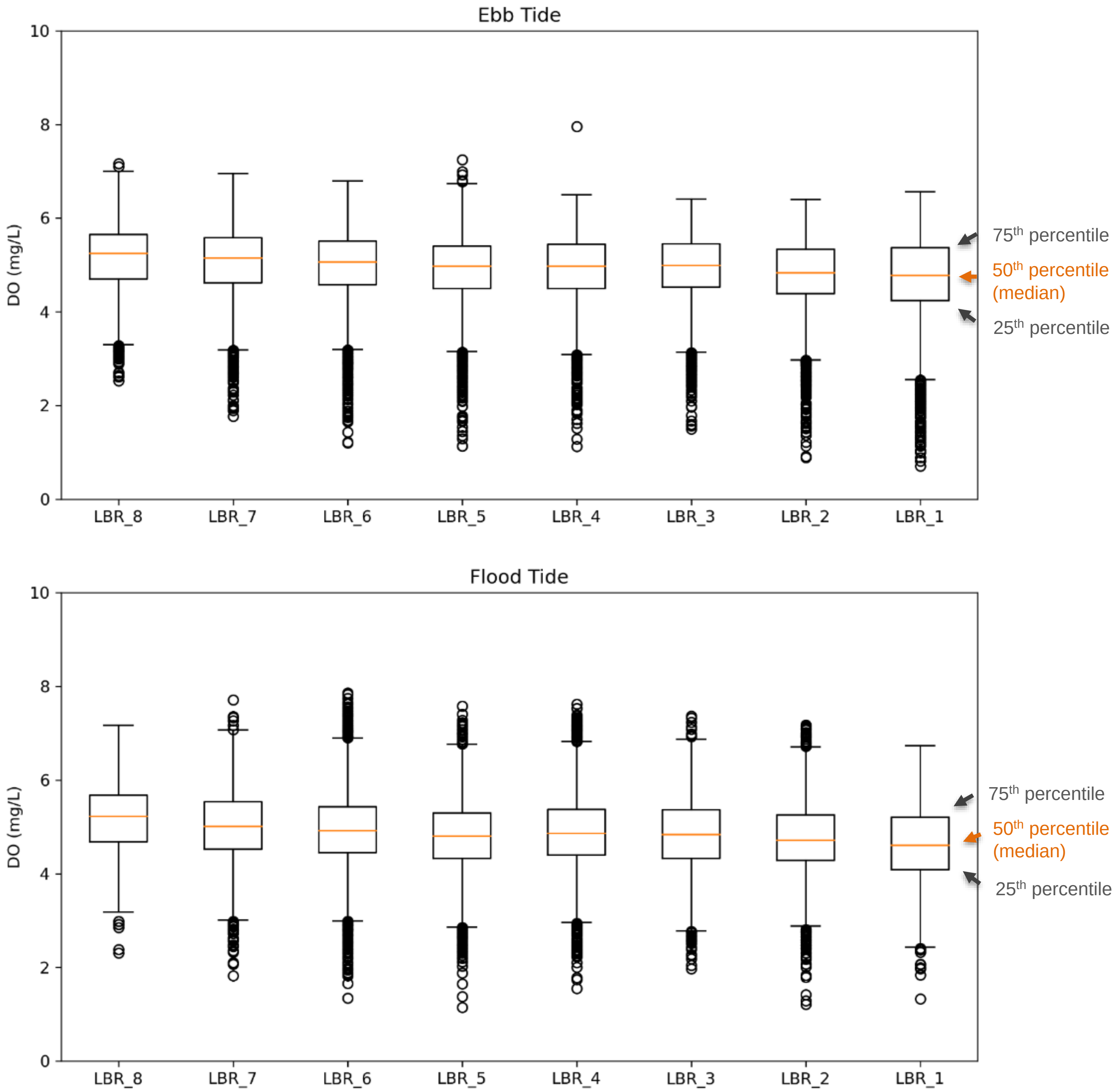

Figure 9-7 Box and Whisker Plots of Back River Buoy Data During Flood and Ebb Tides. The Back River Diffuser is Located Between LBR_5 and LBR_4.

9.2.2 Back River Drift and Profile Data

Data were collected during 32 separate boat drift and 36 profile sampling events during the SUR period. The sampling events varied in time and distance depending on the objectives for sample collection. Certain sampling events focused on data collection in the vicinity of the diffuser, to help determine the dispersion of the oxygen plume, while other sampling events focused on data collection extending farther upstream and downstream to determine the overall DO longitudinal profile of the Little Back River. All profile and drift sampling events are documented in **APPENDIX B** and **APPENDIX C**, including maps of the sampling extent and graphs of the collected data. During dye releases, the boat sondes were also equipped with Rhodamine dye sensors (Section 10.3).

Three drift and profile events were selected to illustrate the various impacts of the oxygen injection in the Back River. These three were selected specifically as they encapsulate the following observations:

- During all the sampling events, there was no observed effervescence, bubbling, or surface disturbances near the diffuser.
- The injected oxygen mixed vertically throughout the water column.
- The injected oxygen plume did not completely mix across the channel until the tide reversed (***Figure 9-9***).
- The injected oxygen stayed in the Back River over several tidal cycles raising the DO.
- The amount of time the DO stayed in the Little Back River depended on upstream flows and tidal conditions. The benefits of the Downriver plant, the Upriver plant, and a separate mitigation project (McCoy's Cut freshwater flow rerouting) were evident (***Figure 9-11***).

LINE OF EVIDENCE 2.3 – NO EFFERVESCENCE OBSERVED

9.2.3 Back River Drift Sampling – July 23, 2020

On July 23, 2020, drift data were collected during a flood tide around the Back River diffuser. Upstream, DO concentrations were approximately 1.0 mg/L higher near the central and west side of the channel than DO concentrations in the water flowing in from the Front River on the downstream side. The higher DO concentrations are shown in red in ***Figure 9-8***. The plume was well mixed vertically but still not mixed side to side.

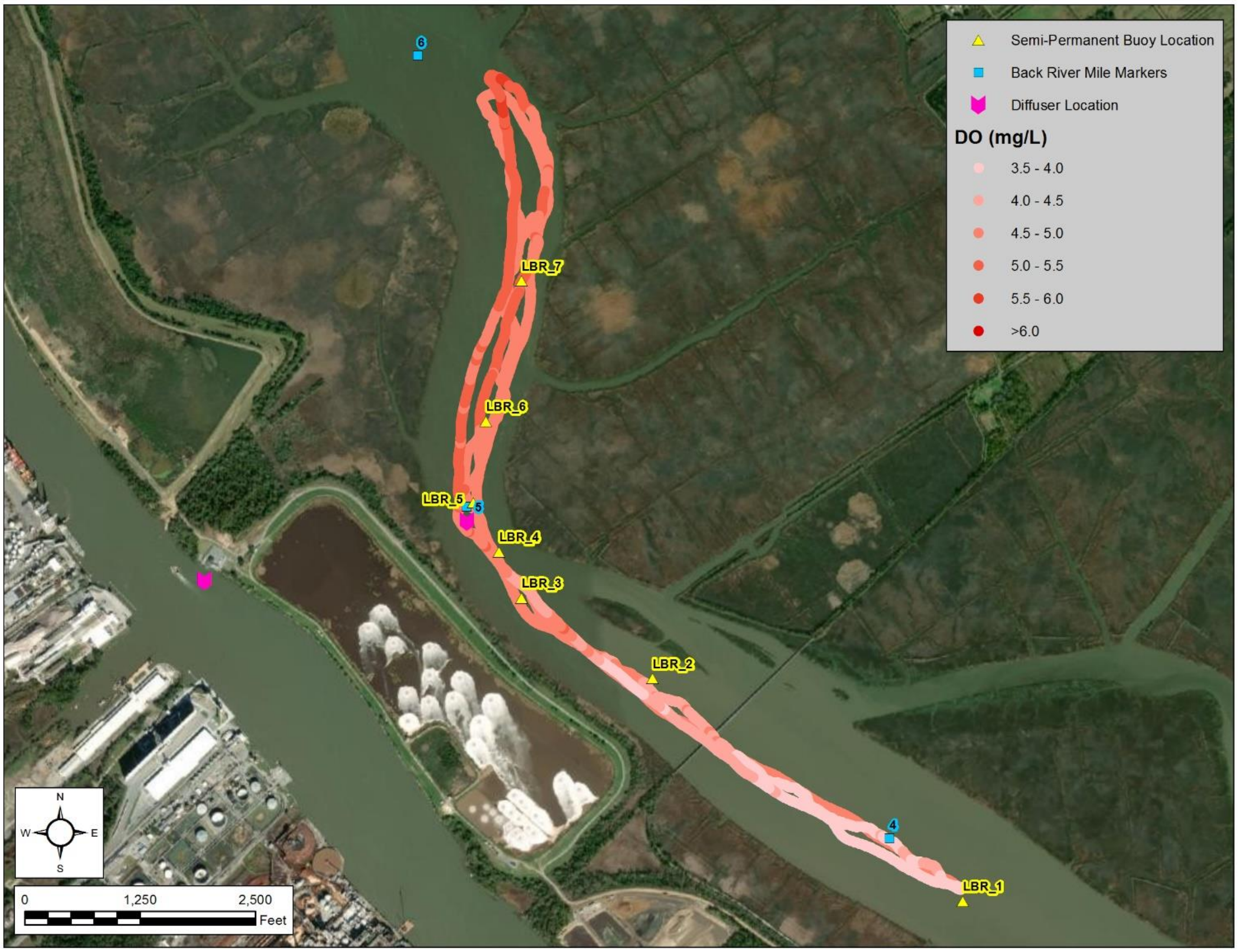

Figure 9-8 Back River Drift Sampling – July 23, 2020

9.2.4 Back River Drift Sampling – August 17, 2020

On August 17, 2020, detailed sampling was taken around the Back River diffuser by both a surface and mid-depth sonde during high tide. The drift data show that the higher DO plume was detectable in the vicinity of and downstream of the Back River diffuser. ***Figure 9-9*** shows the surface oxygen plume (darker red dots) primarily hugging the eastern bank of the channel upstream of the diffuser but completely mixed across the channel downstream of the diffuser. The drift data collected using the mid-depth sonde showed a similar pattern, indicating the oxygen plume was well mixed vertically.

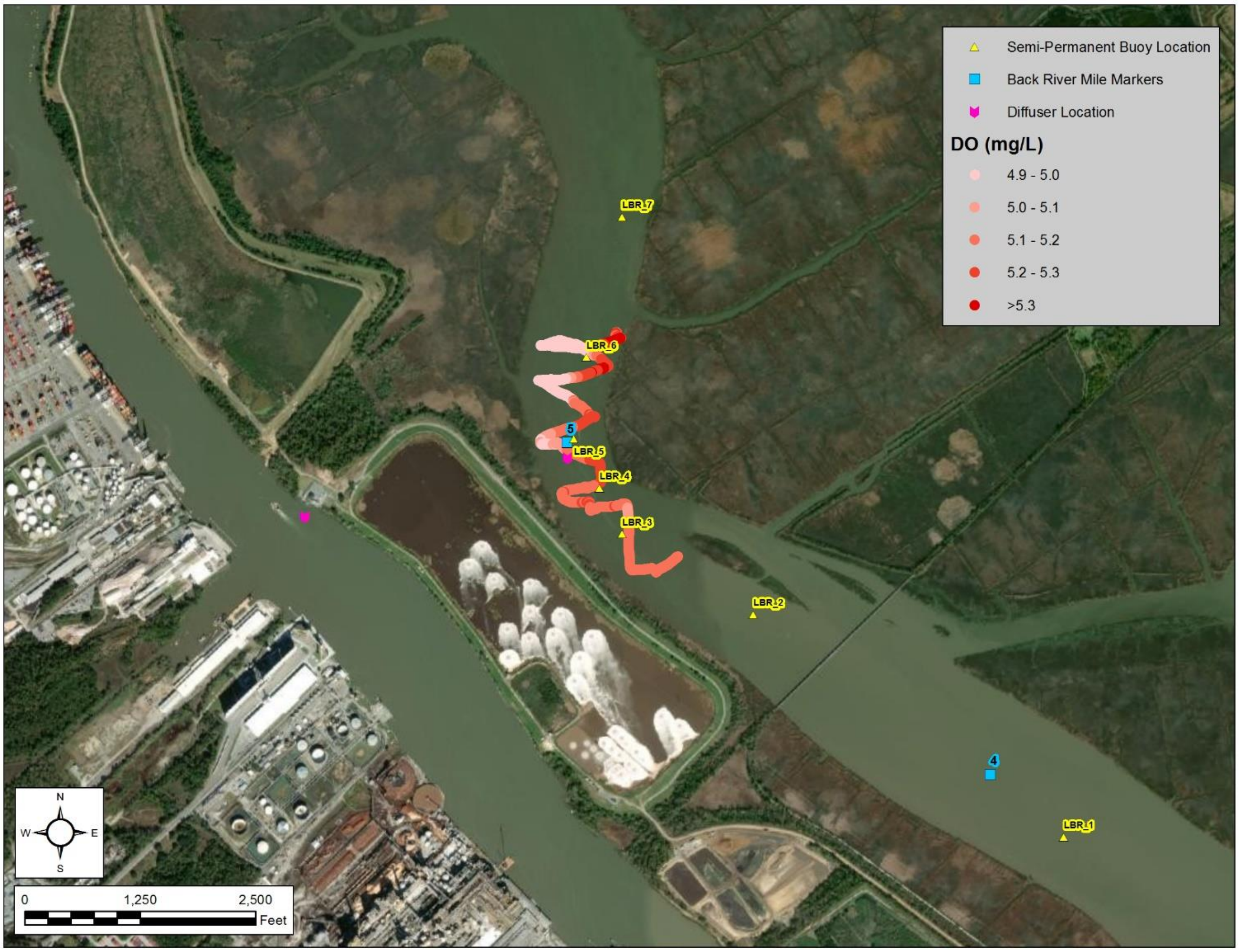

Figure 9-9 Back River Drift Sampling – August 17, 2020 (surface)

9.2.5 Back River and Little Back River Drift and Profile Sampling – September 17, 2020

During the sampling event on September 17, 2020, spring tides moved the oxygen plume further upstream past the GA 25 bridge (RM 9) as seen in ***Figure 9-10*** and illustrated by the depth averaged longitudinal DO profile in ***Figure 9-11***. The injected oxygen is retained within the water column, shifting back and forth with the tides. Without the injected oxygen, it is estimated the DO during this sampling event would peak at 4.2 mg/L. The injected oxygen from the Back River diffuser appears to contribute up to 1.0 mg/L more. The findings from this event agree with the description in Section 7.2, whereby the oxygen plume from the Back River diffuser is only able to reach GA 25 and the USGS station (021989792) during spring tides. The influx of high DO freshwater flow from upstream, aided by the McCoy's Cut freshwater flow rerouting mitigation project, is evident in both ***Figure 9-10*** and ***Figure 9-11*** and prevents the oxygen plume from moving significantly up the Little Back River under other tidal conditions.

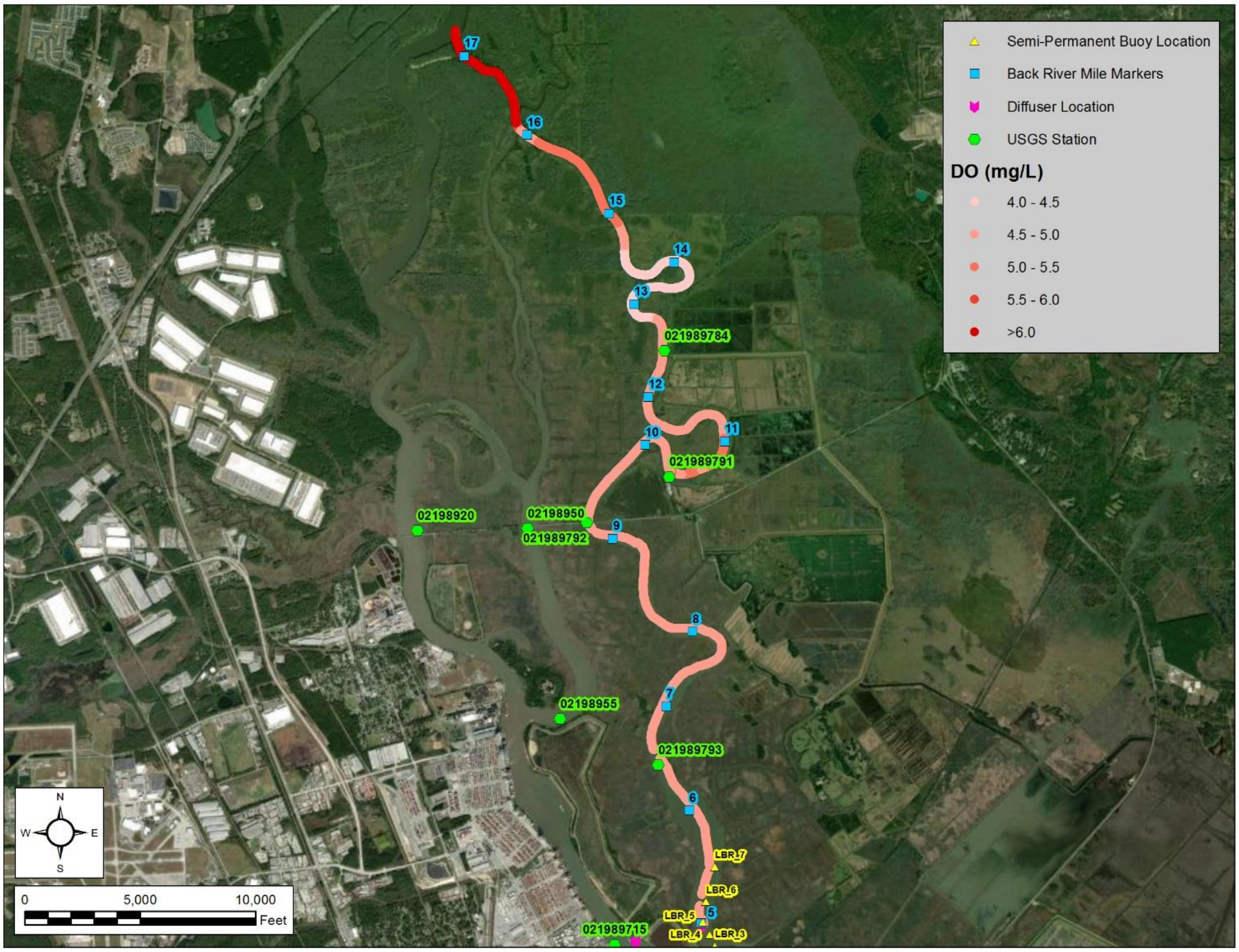

Figure 9-10 Back River and Little Back River Drift Sampling – September 17, 2020 (surface)

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

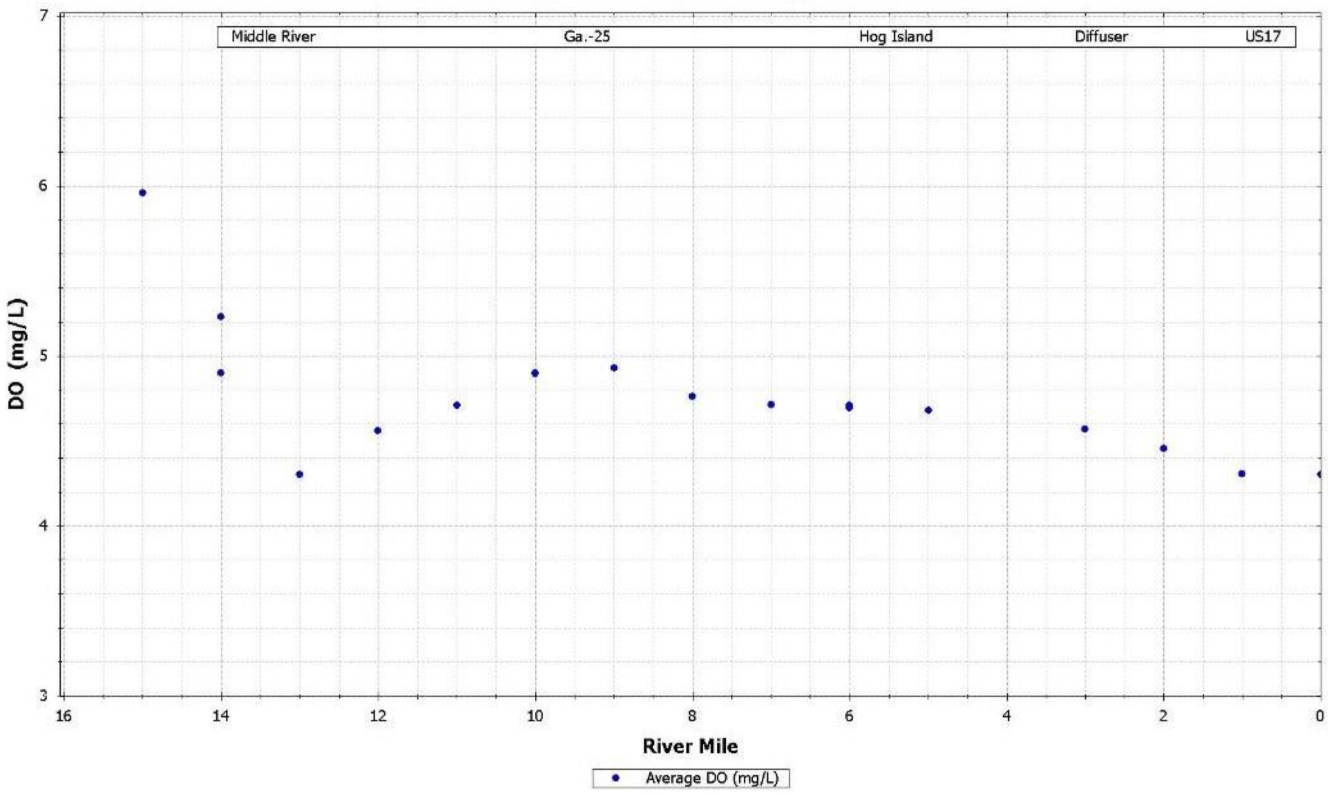

Figure 9-11 Back River and Little Back River DO Profile – September 17, 2020

LINE OF EVIDENCE 3.2 – ANALYSIS OF PROFILE AND DYE DATA

9.3 SUMMARY

The Downriver plant was designed to increase DO concentrations throughout the inner harbor navigation channel and the Back, Little Back, and Middle Rivers. The impact of the Downriver plant is less easily discernable than the Upriver plant, due to the bidirectional flow, the impact of tides, varying channel widths, complex side river system, and other SHEP mitigation features. However, the impact can be quantified by analyzing field data in addition to independent data sources which provide corroborating conclusions.

Along with the injected oxygen plumes being well mixed into the receiving water, there was no observed effervescence, bubbling, or surface disturbances near the Front River or Back River diffusers.

The benefits of the injected oxygen from the Front River diffuser were detected upstream beyond the turning basin (RM 19) and downstream beyond the GA 17 bridge.

The benefits of the injected oxygen from the Back River diffuser were detected throughout the Back River and upstream beyond the GA 25 bridge in the Little Back River.

10.0 DYE RELEASES AND ANALYSIS

THIS CHAPTER ADDRESSES SUCCESS METRIC #2, #3 AND #4 AS IDENTIFIED IN SECTION 4.0

Success Metric #2 – Determine if the injected oxygen is being retained in the water column
Success Metric #3 – Evaluate if the retained oxygen is mixing vertically and mitigating the bottom half of the water column
Success Metric #4 – Evaluate if the retained oxygen is mixing spatially to provide the necessary mitigation throughout the Savannah River and estuary

Details on the dye releases are presented in Section 2.4. This chapter focuses on the analysis of these releases.

Rhodamine dye releases were conducted in the Front River, Back River, and Upriver before and during the SUR data collection. Rhodamine WT is a fluorescent xanthene dye and is routinely used as a hydrologic tracer in surface water systems. The dye was injected into the injected oxygen discharge pipe and was dispersed through the diffuser. The dye mimics how the injected oxygen is dispersed and migrates throughout the estuary. The dye releases were used to determine:

- Where the potential areal and vertical extents of dye plumes are and therefore the oxygen plumes.
- How the dye and injected oxygen mixed under varying hydrodynamic conditions.
- Where the dye and oxygen plumes migrated.
- What regions of the Savannah River and estuary are impacted by the dye and injected oxygen.
- How quickly the dye and oxygen mixed into the water column.
- How long the dye and the injected oxygen remained in the waterbody.

Table 2-1 provides the dates, times, injection areas of the river, tide conditions, dye strengths, and dye volumes used for the SUR data collection dye releases. These are presented once again below in ***Table 10-1***. Each release had a specific purpose, as described in Section 2.4 and the remainder of this section.

Table 10-1 SUR Dye Releases Details

Date	Time	River	Tide	Dye Strength	Dye Volume (gallons)
15-Jul-20	10:30	Upriver	N/A	Full	30
16-Jul-20	09:50	Back	13:49 L	Full	30
16-Jul-20	11:07	Front	13:49 L	Full	30
10-Aug-20	10:00	Upriver	N/A	1:3	30
11-Aug-20	09:00	Front	08:40 L	1:3	30
12-Aug-20	10:00	Back	09:31 L	1:3	30
24-Aug-20	10:00	Upriver	N/A	Full	60
25-Aug-20	08:45	Front	08:29 L	Full	60
25-Aug-20	09:45	Back	08:29 L	Full	60
15-Sep-20	08:54	Upriver	N/A	Full	45

Additional detail on each of the dye releases is presented in **APPENDIX E**.

On the day of the dye releases, detailed receiving water sampling was conducted just before dye release to gather background dye values. During and after the dye release, dye concentrations were measured for two to four hours. The dye and other parameters were sampled to track where the dye, and therefore oxygen plume, were moving and how quickly it mixed into the water column. The visible impacts from the dye release on August 24, 2020, are presented in ***Figure 10-1***, taken from one of the sampling boats looking upstream. The Upriver plant can be seen in the background.

Figure 10-1 August 24, 2020 Dye Release Showing Dye Dispersing Below the Upriver Diffuser

10.1 UPRIVER DYE RELEASES

Four Upriver dye releases were completed to help determine how quickly the injected oxygen mixed with the river water and how fast the oxygen moved downstream. The July 15 and August 10, 2020, dye releases were planned to investigate the dye dispersion in the vicinity of the Upriver diffuser and extending two to three miles downstream. The quicker the injected oxygen mixed into the water column, the less likely any of the injected oxygen would be transferred to the atmosphere. The August 24, 2020 super dye release, which included an additional 30 gallons of dye, traced the dye movement initially around the Upriver diffuser and on August 25, 2020, measured the dye in the Savannah Harbor area downstream of the I-95 bridge. The September 15, 2020 dye release further examined the impact of the dye and Upriver oxygen injection on the Front River.

The dye sampling was conducted by boat with a probe located about 3.3 feet below the surface with the boats moving in and out of the dye plume as it traveled downstream. Profile samples were taken at deeper depths to measure the mixing top to bottom.

The USGS Georgia District collected an independent set of data during the July 15 to 16 and August 24 to 25, 2020 dye injection events. The USGS also installed dye monitors at Savannah River near I-95 (USGS 02198840), Back River at GA 17 (USGS 0219897945), and Little Back River at Hog Island (USGS 021989793) to assist in tracking the dye movements in the Savannah River and estuary. USGS used a BGA algal dye sensor at their I-95 gage, which detected the Upriver dye as it moved past the I-95 gage approximately one day after each dye injection. The BGA measurements were converted to Rhodamine dye concentrations by multiplying by a factor of 0.088. This is based on a regression analysis comparing BGA to Rhodamine dye measurements.

The July 15 and August 24, 2020 dye results are presented below and additional detail on each of the four dye releases is presented in **APPENDIX E**.

10.1.1 July 15, 2020 Dye Release

The July 15, 2020 dye sampling event measured how the dye, and therefore the injected oxygen, mixed with the Upriver flow. Thirty gallons of undiluted dye were injected into the Savannah River. The immediate dilution after the diffuser ports was a ratio of three to one. Dilution, when dye reached the surface, was a ratio of 10 to one and the dye had completely mixed throughout the water column within 0.6 miles downstream. ***Figure 10-2*** shows the boats' July 15, 2020 sampling routes with the redder dots indicating higher dye concentrations, while ***Figure 10-3*** illustrates the dye mixing side to side. ***Figure 10-3*** also shows the impact of the oxbow significantly reducing the dye concentration, supporting the finding from Section 8.2 that the tributaries flowing into the Savannah River have low DO, which helps explain why the river's DO gradually lowered as it flowed downstream. High river flows of 12,500 cfs were measured at the upstream USGS Clyo gage (02198500) at the time of this release.

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

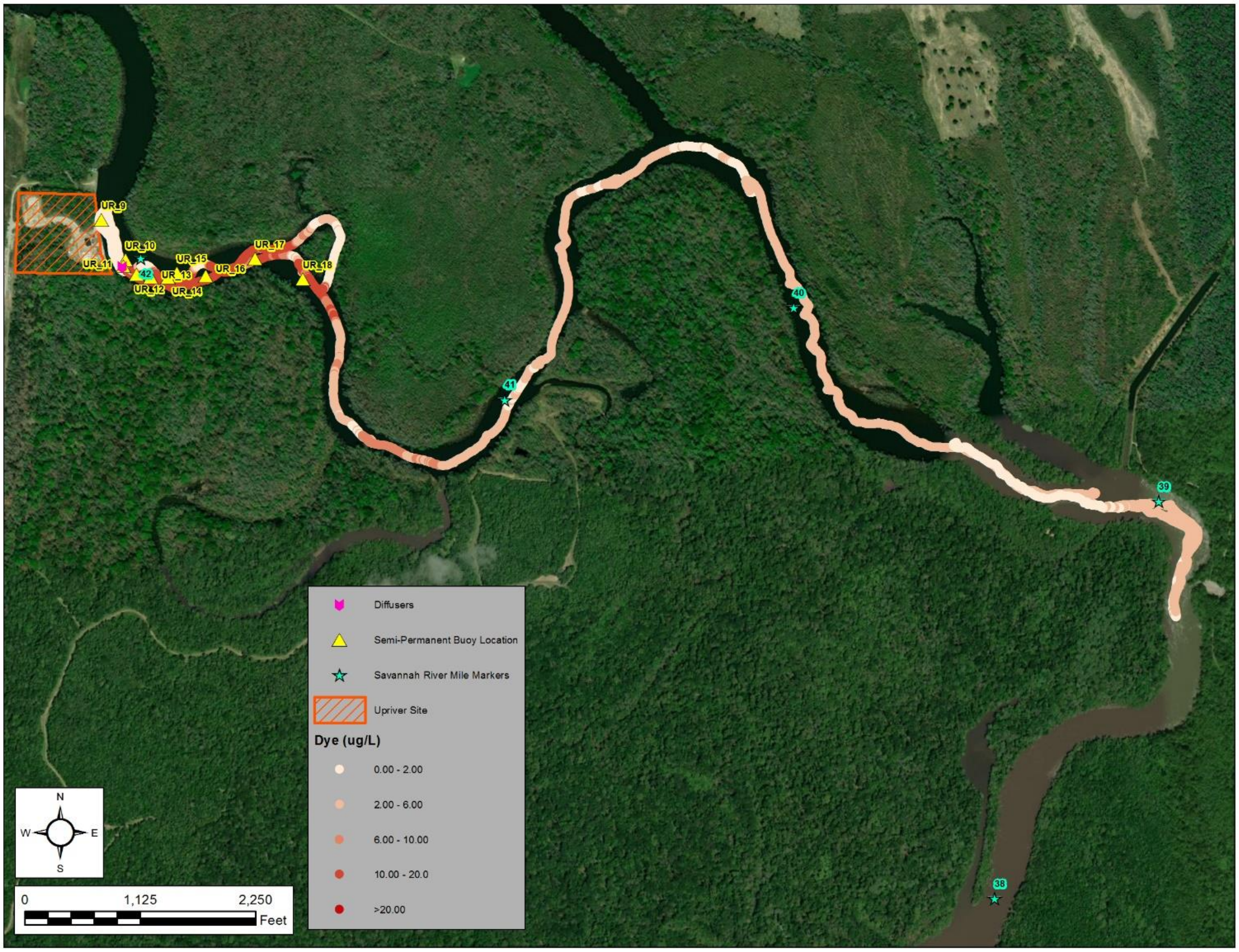

Figure 10-2 Upriver Dye Sampling – July 15, 2020

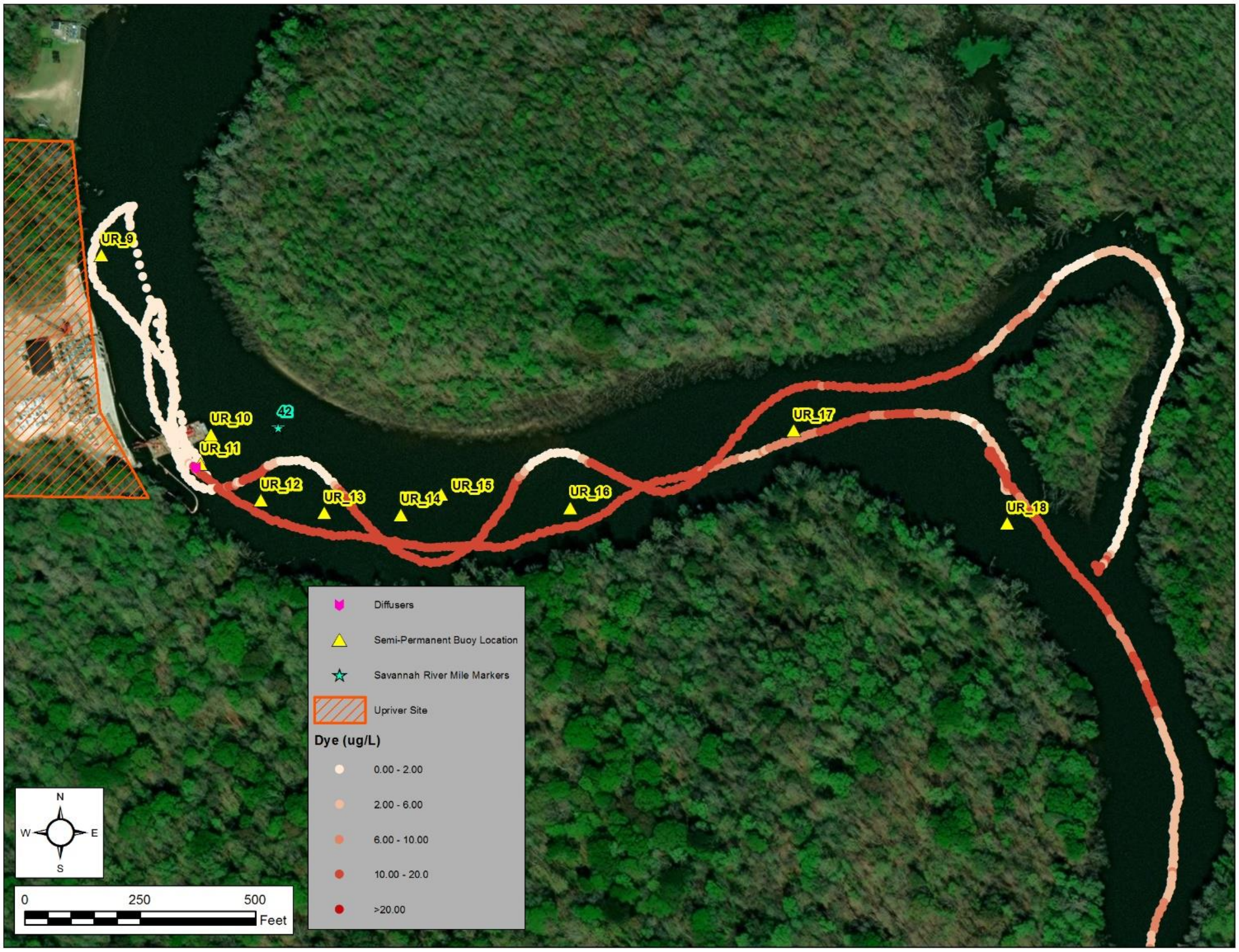

Figure 10-3 Upriver Dye Sampling – July 15, 2020 (inset)

Figure 10-4 shows the concentration of dye, measured in µg/L, versus RM as the dye flows downstream. The dye is mixed side to side around RM 41.4 then decreases going downstream as tributaries flow into the Savannah River. The measured dye concentrations show a similar pattern as the DO values previously presented in Section 8.2, dropping between RM 41.4 and 39 due to the incoming tributary flows.

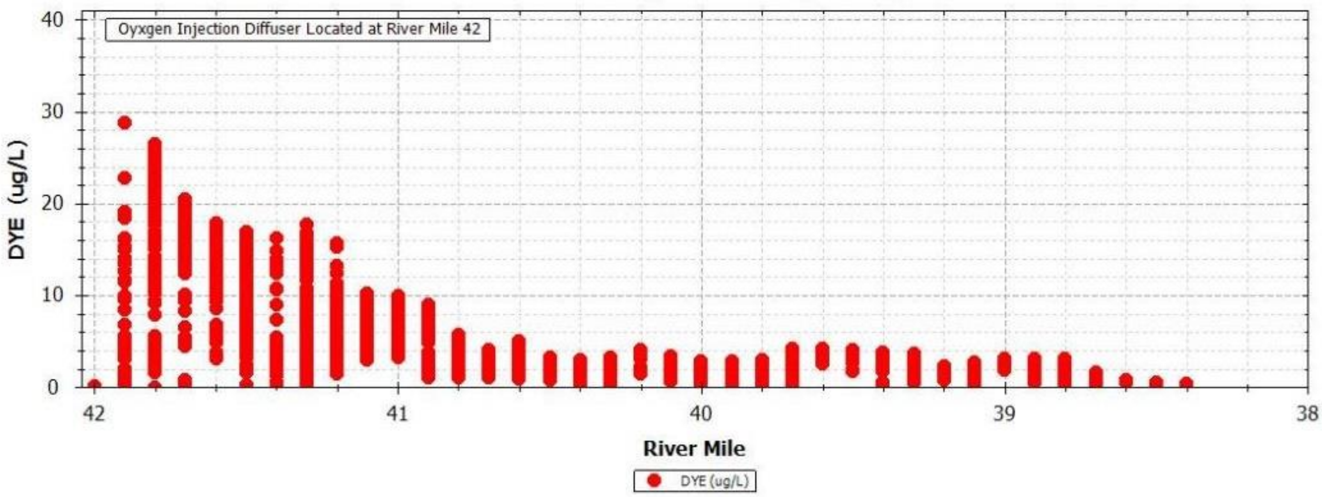

Figure 10-4 Upriver Dye Transect – July 15, 2020

The USGS Georgia District collected independent sampling data during the July 15, 2020 dye release. The dye was injected around 10:00 AM from the Upriver plant. The cross-section location was approximately 220 feet upstream from the Hardeeville gage, and the dye took approximately two hours to travel the approximate two-mile distance to this location. ***Figure 10-5*** shows the cross-section dye concentrations at the top, middle, and bottom depths of the river along with a cross-section profile of the river. The dye was well-mixed top to bottom with the highest concentration in the main channel. Further details are in **Appendix E**.

LINE OF EVIDENCE 3.2 – ANALYSIS OF PROFILE AND DYE DATA

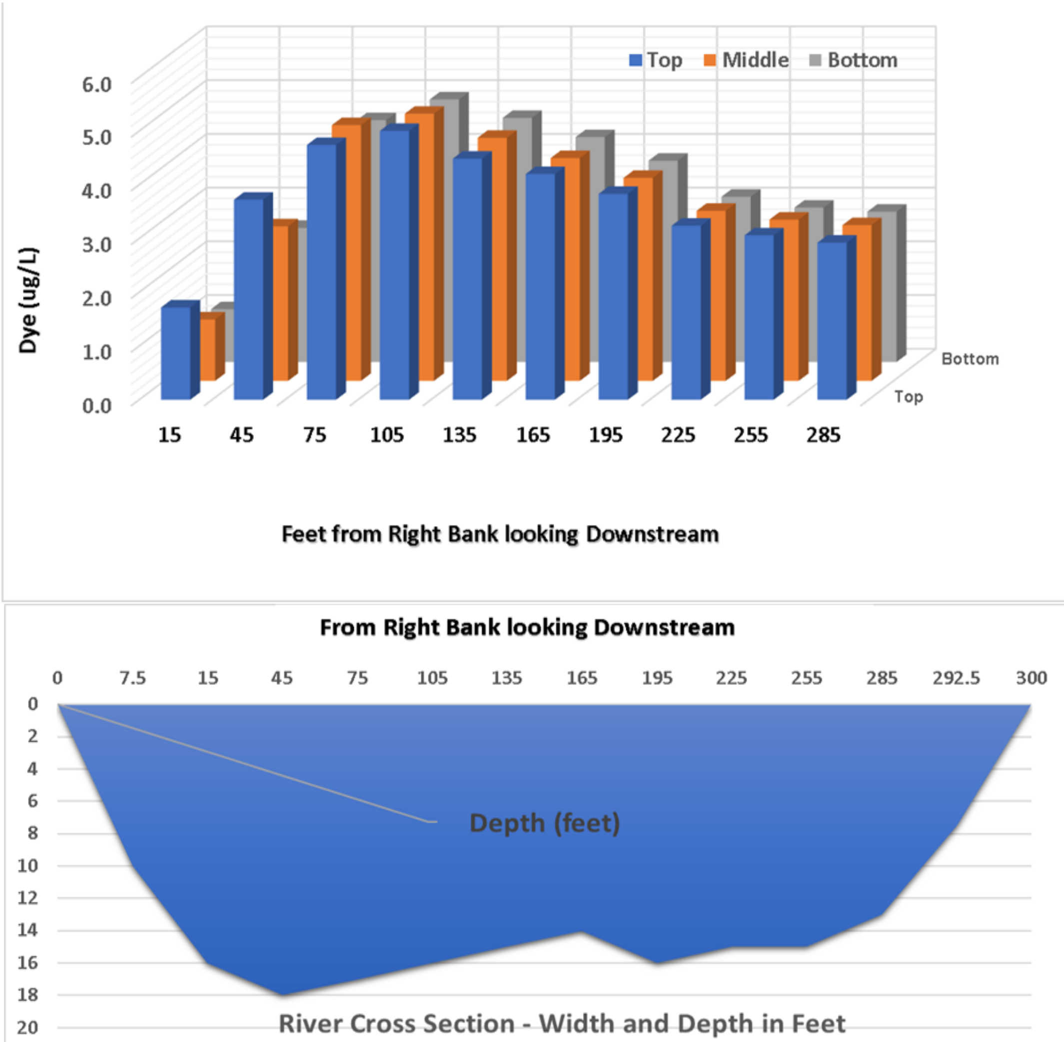

Figure 10-5 Upriver USGS Dye Cross-section – July 15, 2020 (Hardeeville)

10.1.2 August 24, 2020 Super Dye Release

On August 24, 2020, 60 gallons of dye were injected into the Savannah River via the Upriver diffuser. The dye was released at 10:05 AM. The main purpose of this release was to track the dye downstream and into the lower reaches of the Savannah River. Detailed dye sampling around and downstream of the diffuser was also completed during the dye injection. A contour plot of the dye distribution is shown in ***Figure 10-6***. Relatively low river flows of 7,500 cfs were measured at the upstream USGS Clyo gage (02198500) at the time of this release.

Figure 10-6 Upriver Dye Sampling – August 24, 2020

Similarly to the July 15, 2020 dye release, the USGS Georgia District collected independent sampling data during the August 24, 2020 dye release at a cross-section near the discontinued Hardeeville gage (USGS Hardeeville station 02198760). The cross-section sampling was collected from 11:27 to 11:49, given the dye required nearly two hours to cover the distance from the diffuser to the cross-section location. The dye was highly visible during cross-section sampling. ***Figure 10-7*** shows the cross-section dye concentrations at the top, middle, and bottom depths of the river along with a cross-section of the river. The dye was well mixed top to bottom and therefore the injected oxygen will be well mixed in the water column. Additional cross-section data and further details are in **Appendix E.**

LINE OF EVIDENCE 3.2 – ANALYSIS OF PROFILE AND DYE DATA

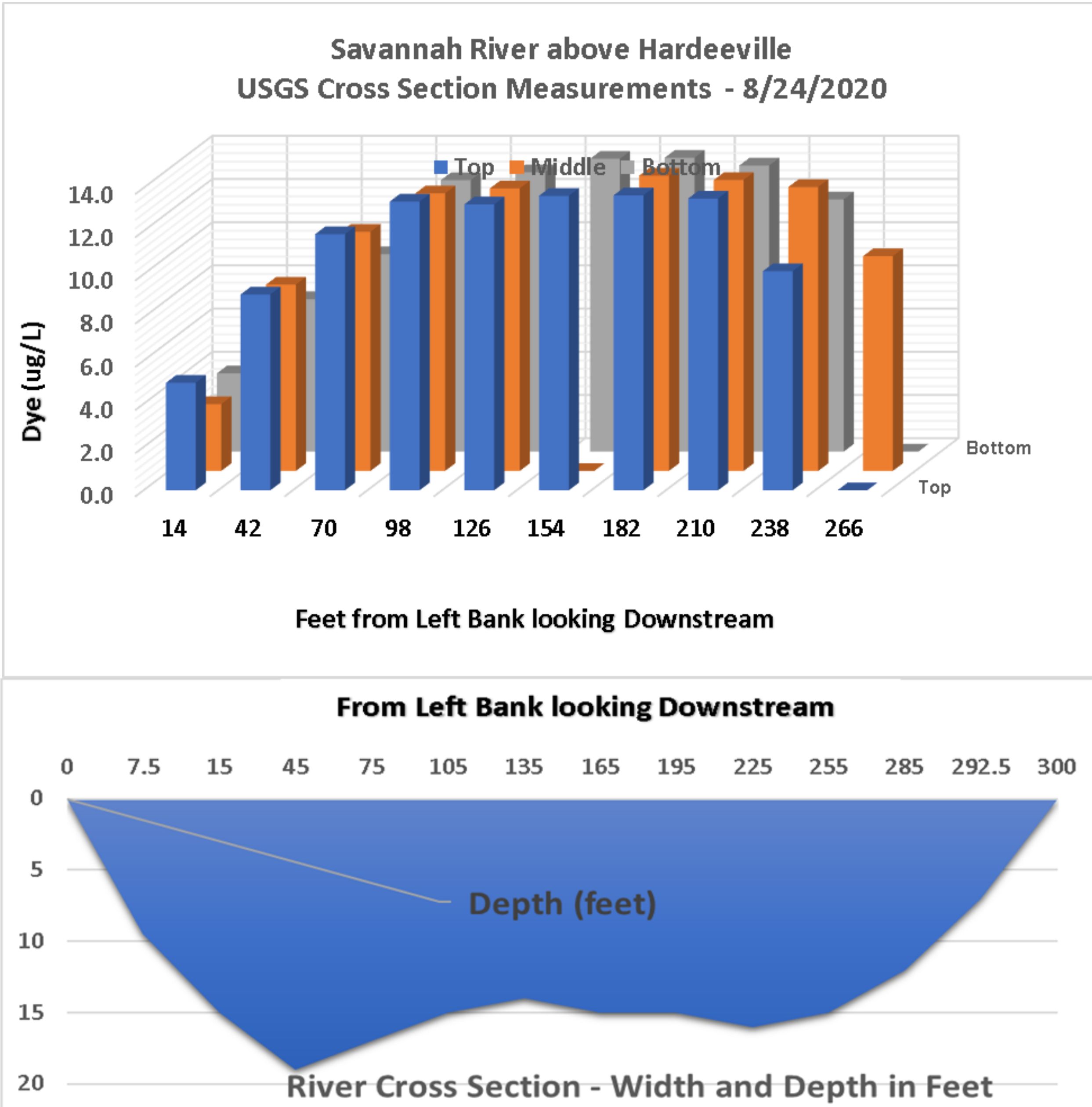

Figure 10-7 Upriver USGS Dye Cross-section – August 24, 2020 (Hardeeville)

After successfully measuring the dye dispersion in the vicinity of the Upriver diffuser and downstream of the August 24, 2020 dye release, additional sampling was undertaken. One day later, on August 25, 2020, extended boat sampling was completed from above the Upriver diffuser downstream past the I-95 bridge. The dual objectives were to locate the dye from the previous days release and identify its movement, and to measure a longitudinal DO transect of the Upriver and Front River. River flow measured at the upstream USGS Clyo gage (02198500) was 7,500 cfs. As shown in ***Figure 10-8***, the dye peak was located four miles downstream of the I-95 bridge, indicating the dye plume had traveled approximately 16 RMs over the 24-hour period. This peak, located near USGS station 0219820 in a pink color, is not to be confused with the dye peak in dark red from the Front River diffuser, a further five miles downstream. The DO transect was successfully captured, as shown in ***Figure 10-9***. DO gradually declined from 7.9 mg/L at the Upriver diffuser to 6.5 mg/L below I-95 Bridge. These results support the assertion that low DO from tributaries joining the Savannah River reduce DO concentrations, but also that the dye plume, and therefore oxygen plume, is well mixed and being retained within the water column over a very significant distance.

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

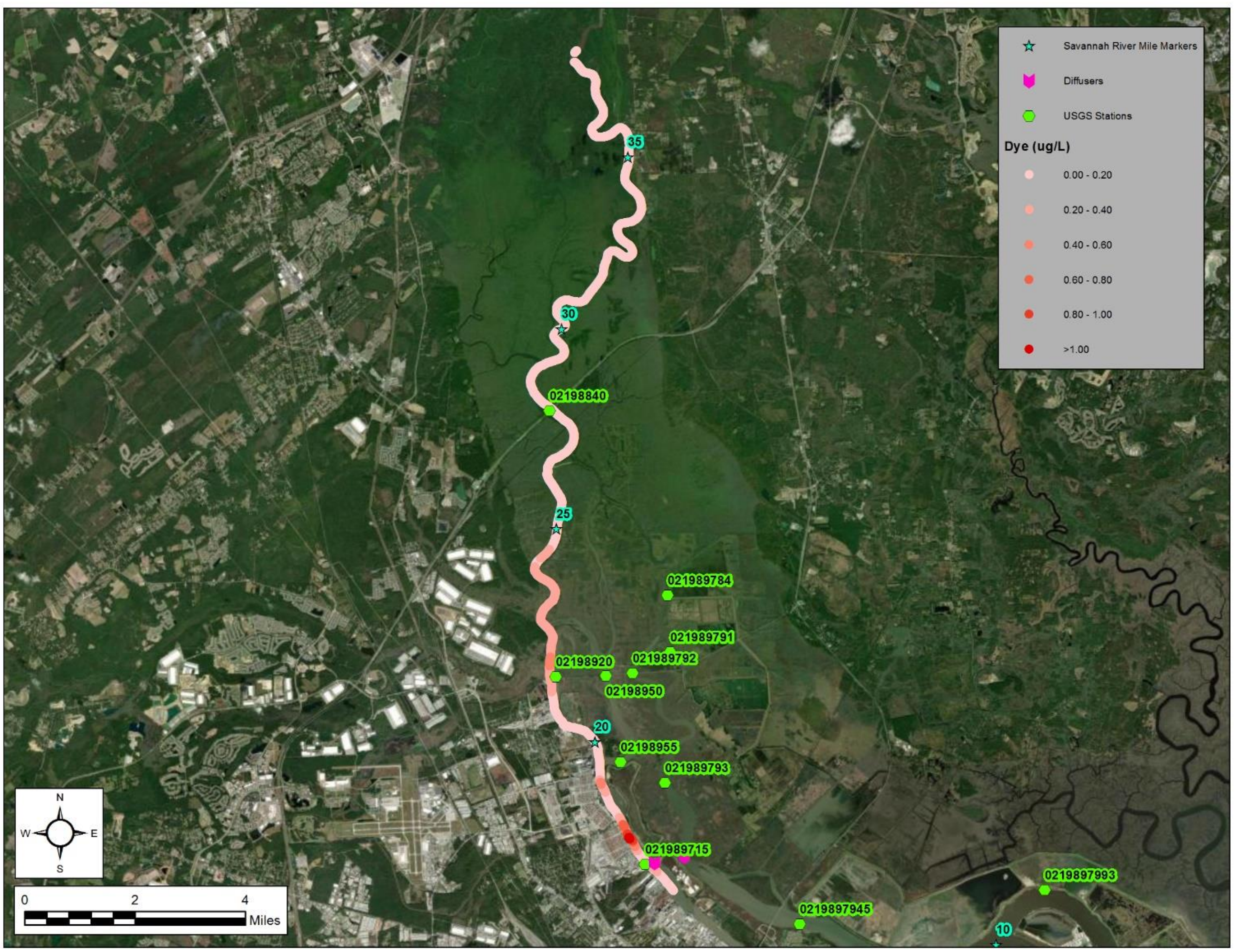

Figure 10-8 August 25, 2020 Dye sampling

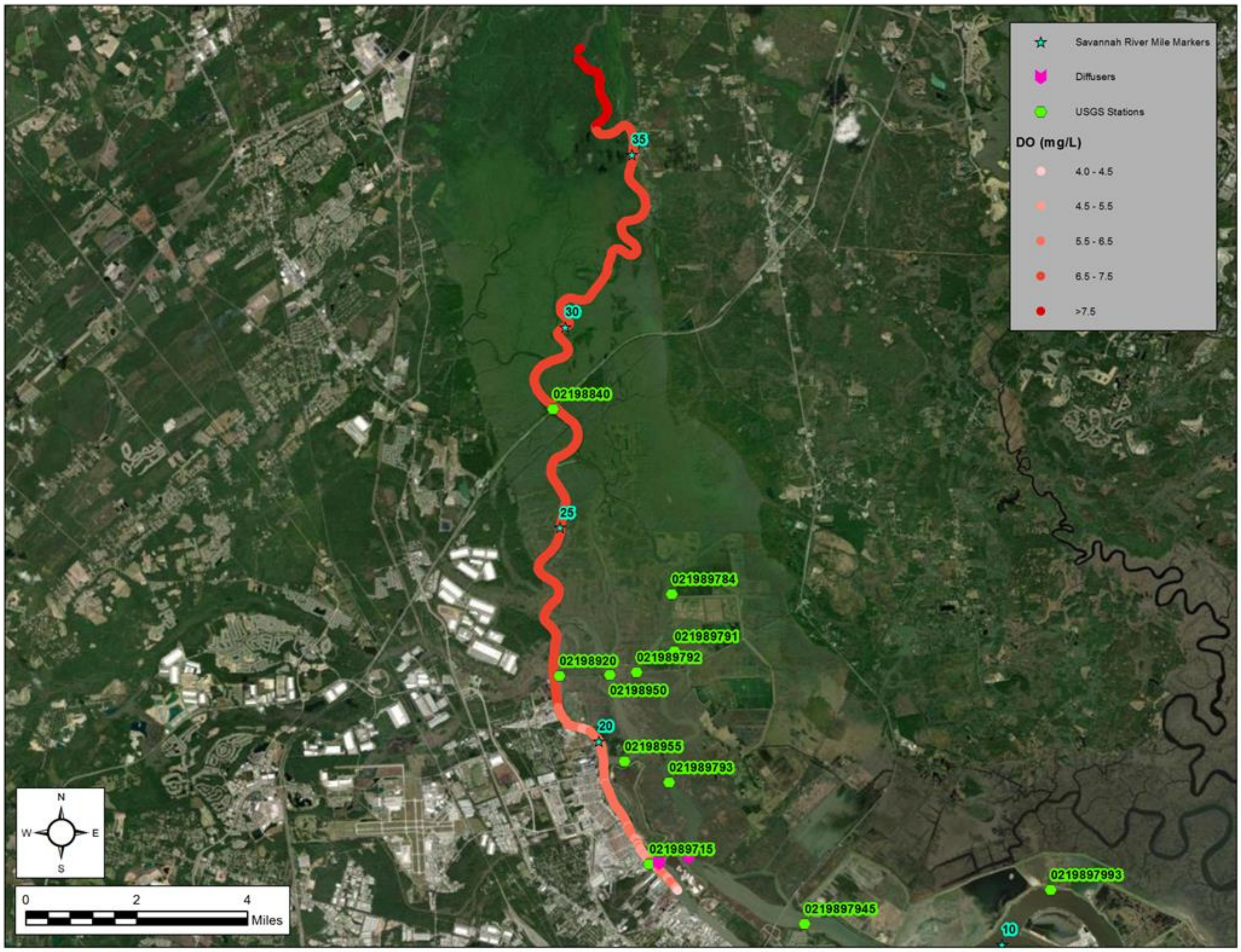

Figure 10-9 August 25, 2020 DO sampling

10.1.3 USGS I-95 Gage

The USGS gage at the I-95 bridge (02198840) included a BGA sensor which detected the Upriver injected dye as it moved past approximately one day after each dye injection (***Figure 10-10***). This is significant because it shows the injected dye, and therefore the injected oxygen, was retained within the water column to I-95 (RM 27.8) and beyond. All four dye releases (July 15, August 10, August 24, and September 15) are evident given the spikes in dye concentrations above background. However, the August 24, 2020 release is most noticeable. This makes sense given it was the largest dye volume and was full strength (undiluted). Conversely, the August 10 had the equal lowest volume and was diluted to one-third full strength. Out of the four releases, this recorded the lowest spike at I-95.

LINE OF EVIDENCE 2.2 – OXYGEN PLUME RETENTION AFTER INJECTION

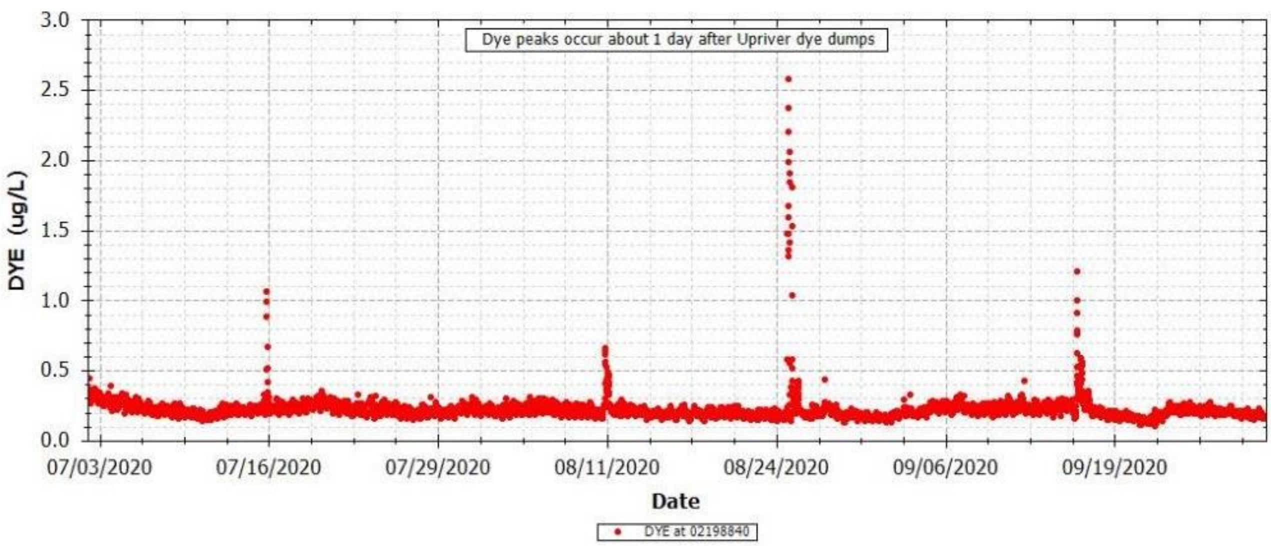

Figure 10-10 Dye Measurements at USGS Gage 02198840 (I-95)

10.2 FRONT RIVER DYE RELEASES

Three Front River dye releases were conducted during the SUR. The primary goal of the Front River dye releases was to determine where the dye and therefore injected oxygen, was distributed and how long the dye and injected oxygen stayed in the Front River. Detailed near-field dye and DO measurements were taken during the 2019 Test Run sampling that detailed the initial mixing and near field distribution of the dye and oxygen plumes, and therefore were not repeated during the SUR sampling (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019a). The dates and details of the three Front River dye releases are presented in ***Table 2-1*** and again in ***Table 10-1***. Additional detail on each of the dye releases is presented in **APPENDIX E**.

10.2.1 July 16 and August 11, 2020 Dye Releases

The July 16 and August 11, 2020 dye releases occurred at approximately 10:00 AM and both occurred on ebb tides. The dye in both releases headed downstream and hugged the west bank, in accordance with the findings from Section 7.0. ***Figure 10-11*** shows the results for the July 16 dye release. August 11 dye details is presented in **APPENDIX E**.

Figure 10-11 Front River Dye Sampling – July 16, 2020

10.2.2 August 25, 2020 Dye Release

The August 25, 2020 Front River dye release best illustrated where the dye, and therefore injected oxygen, traveled and how long it remained in the Front River. After the 60 gallons of dye was injected, profile sampling of the Front River was conducted almost daily to see how long the dye, and the associated injected oxygen, would remain in the Front River.

The dye was injected on a low slack tide, so the dye initially dispersed around the diffuser, moving slightly downstream, and then moved upstream on the incoming tide. A time-lapse of all sampling from August 25, 2020, is shown in ***Figure 10-12*** through ***Figure 10-15***, where each successive figure shows the mid-depth dye concentrations decreased from 180 µg/L near the diffuser to 0.5 µg/L as the dye entered the turning basin. This illustrates how the dye, and the injected oxygen, mixed spatially as the tide turned from ebb to flood tide.

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

Figure 10-12 Front River Dye Sampling – August 25, 2020 (mid-depth) (100 to 180 µg/L)

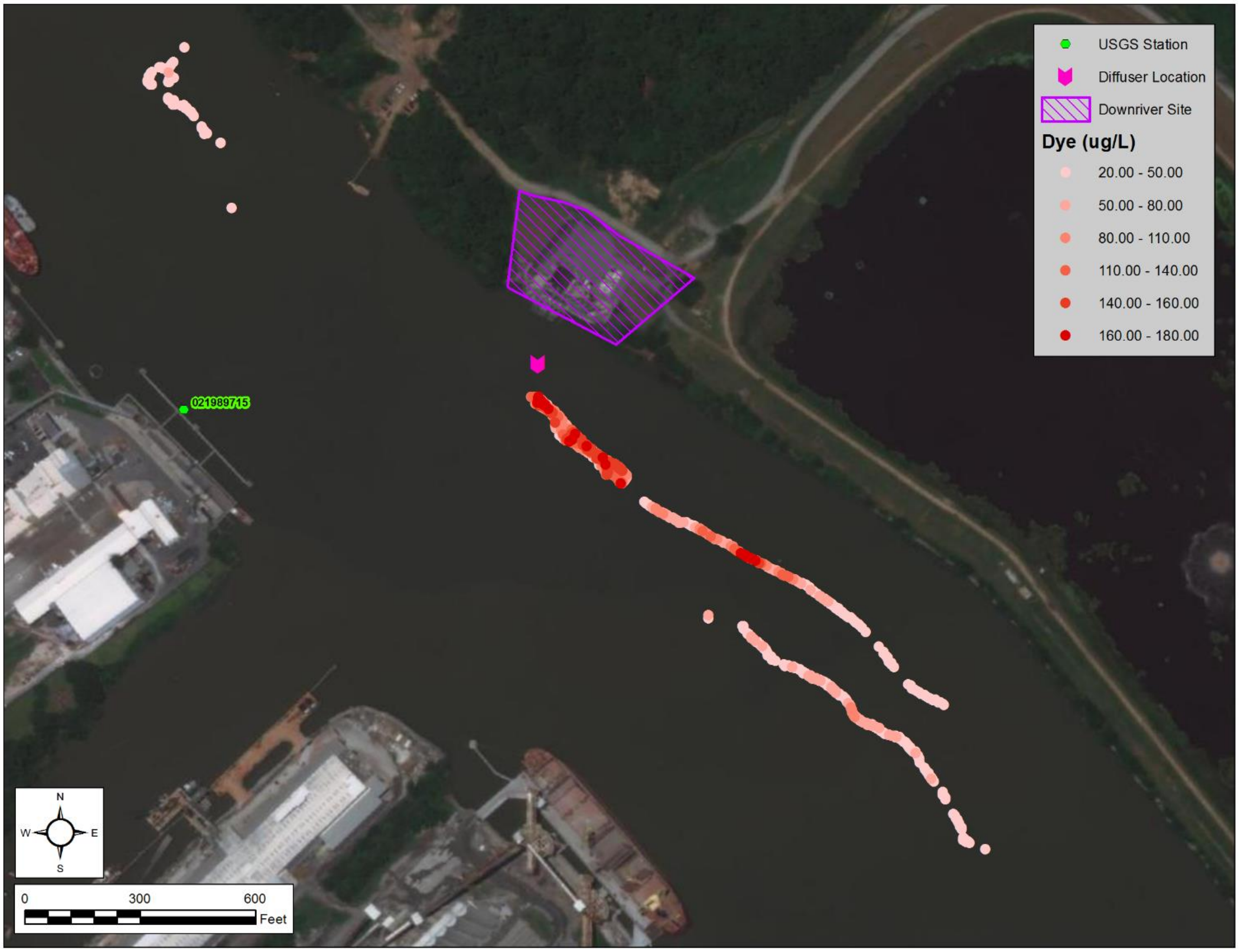

Figure 10-13 Front River Dye Sampling – August 25, 2020 (mid-depth) (20 to 180 µg/L)

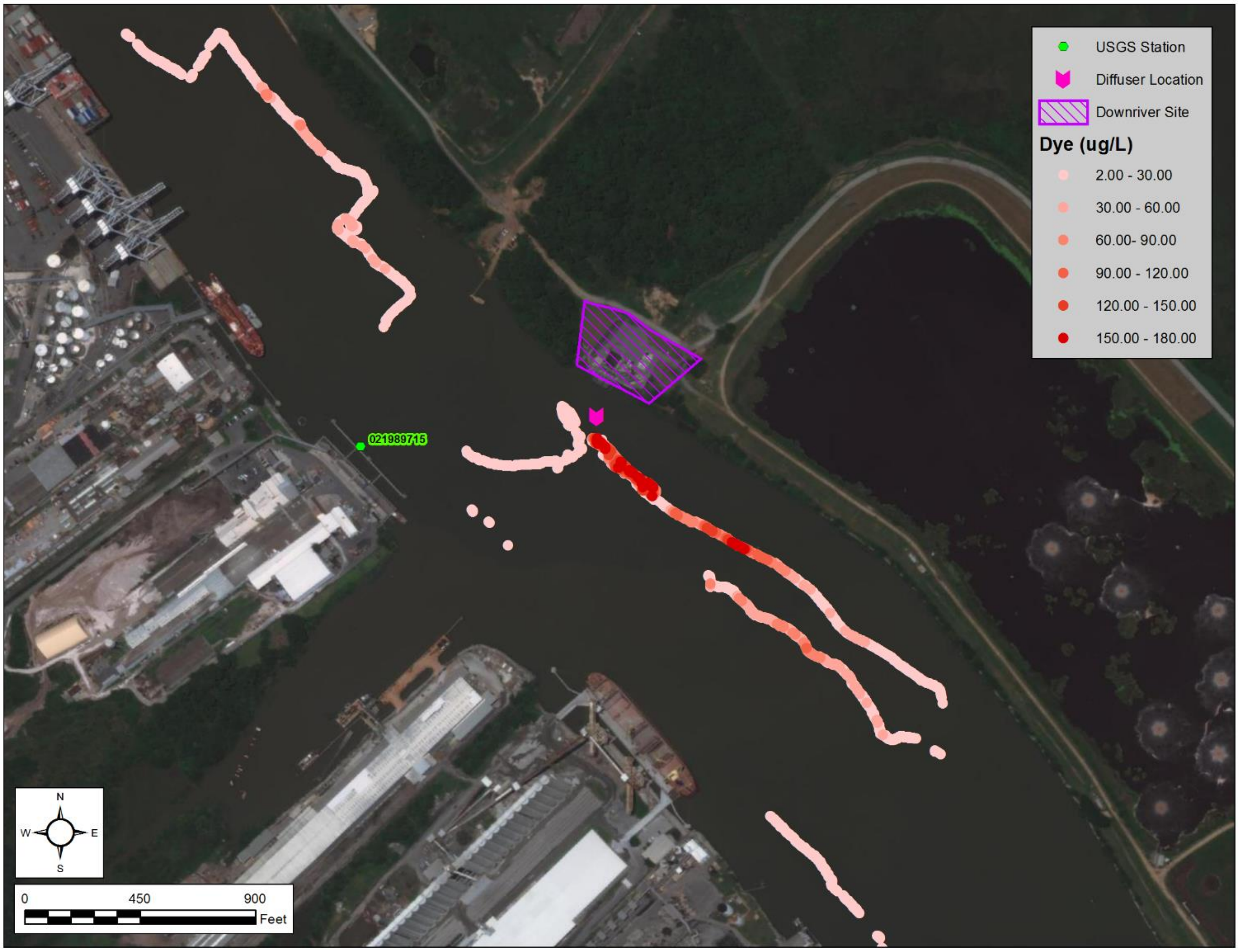

Figure 10-14 Front River Dye Sampling – August 25, 2020 (mid-depth) (2 to 180 µg/L)

Figure 10-15 Front River Dye Sampling – August 25, 2020 (mid-depth) (100 to 180 µg/L)

Detailed Front River profile sampling was conducted from August 26, 2020, to September 15, 2020, to track the movement of the dye in the Front River from the release on August 25, 2020. The sampling locations varied day to day depending on the tidal conditions. To illustrate dye movement, the profile sampling locations were converted to approximate RMs with RM 0 being the mouth of the Savannah River, near Fort Pulaski (refer ***Figure 11-9***). The dye profile samples were averaged between the upper (top 15 feet) and bottom layers and the results, by day, are presented in ***Figure 10-16*** through ***Figure 10-18***.

From August 27, 2020, through August 31, 2020, the dye was well distributed throughout the Front River, with higher dye concentrations in the bottom layers (***Figure 10-16***).

From September 02, 2020, to September 07, 2020, the dye was still well distributed throughout the Front River, with the higher dye concentrations reduced to 0.35 µg/L. Then from September 09, 2020, to September 17, 2020, the dye was still present in the Front River, with the higher dye concentrations reduced to 0.2 µg/L.

From September 18, 2020, to September 23, 2020, the impact of the September 15, 2020 Upriver dye injection is seen with an increase in dye concentrations to 0.3 µg/L. The Upriver dye injection caused an increase of approximately 0.1 µg/L in the bottom layers and 0.05 µg/L increase in the upper layers throughout the Front River (***Figure 10-17***).

On September 25, 2020, the last day of the SUR sampling, dye concentrations of up to 0.25 µg/L were still present, with the dye plume moving gradually downstream (***Figure 10-18***).

LINE OF EVIDENCE 3.2 – ANALYSIS OF PROFILE AND DYE DATA

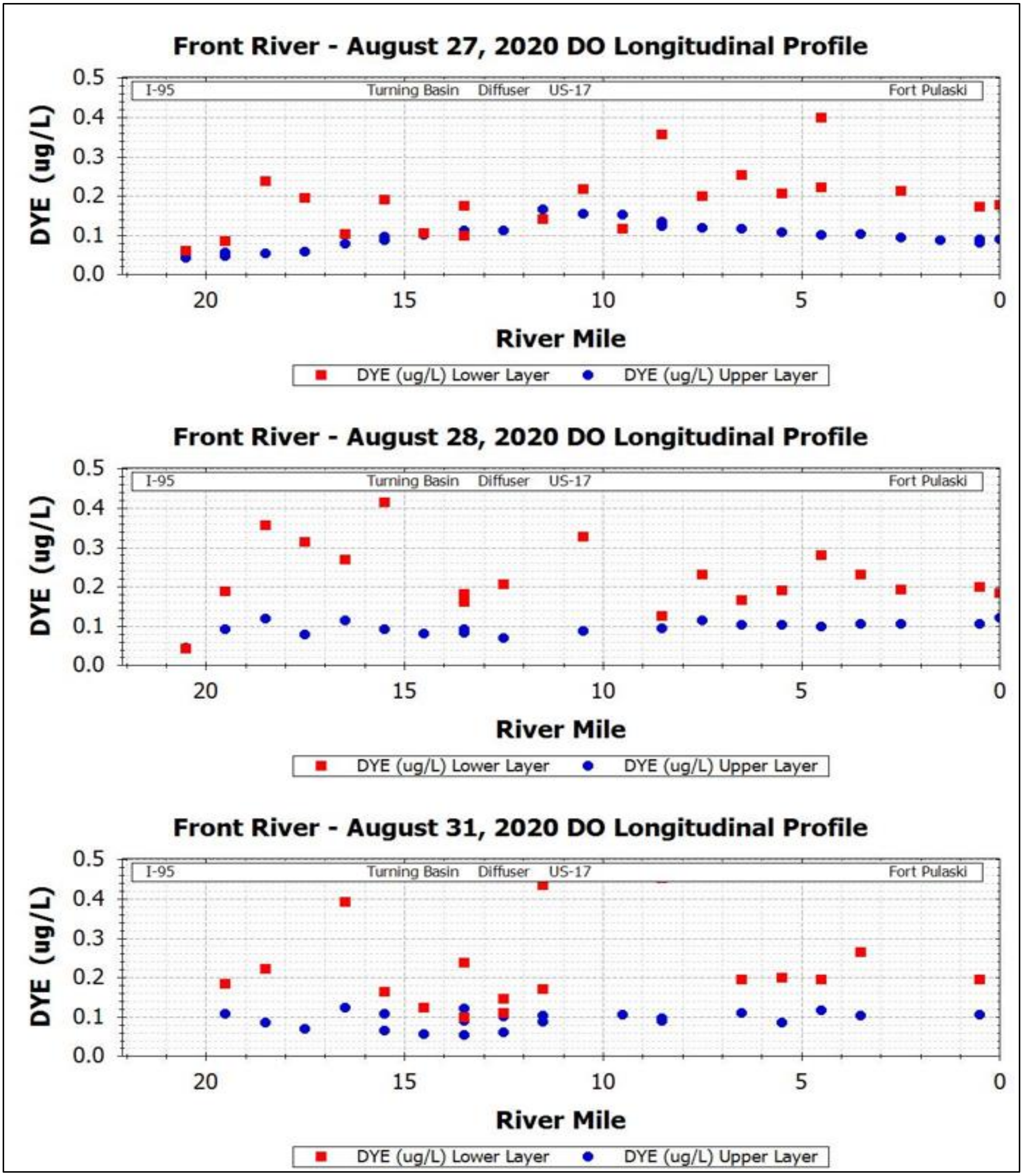

Figure 10-16 Front River Dye Profile – August 27 through August 31, 2020

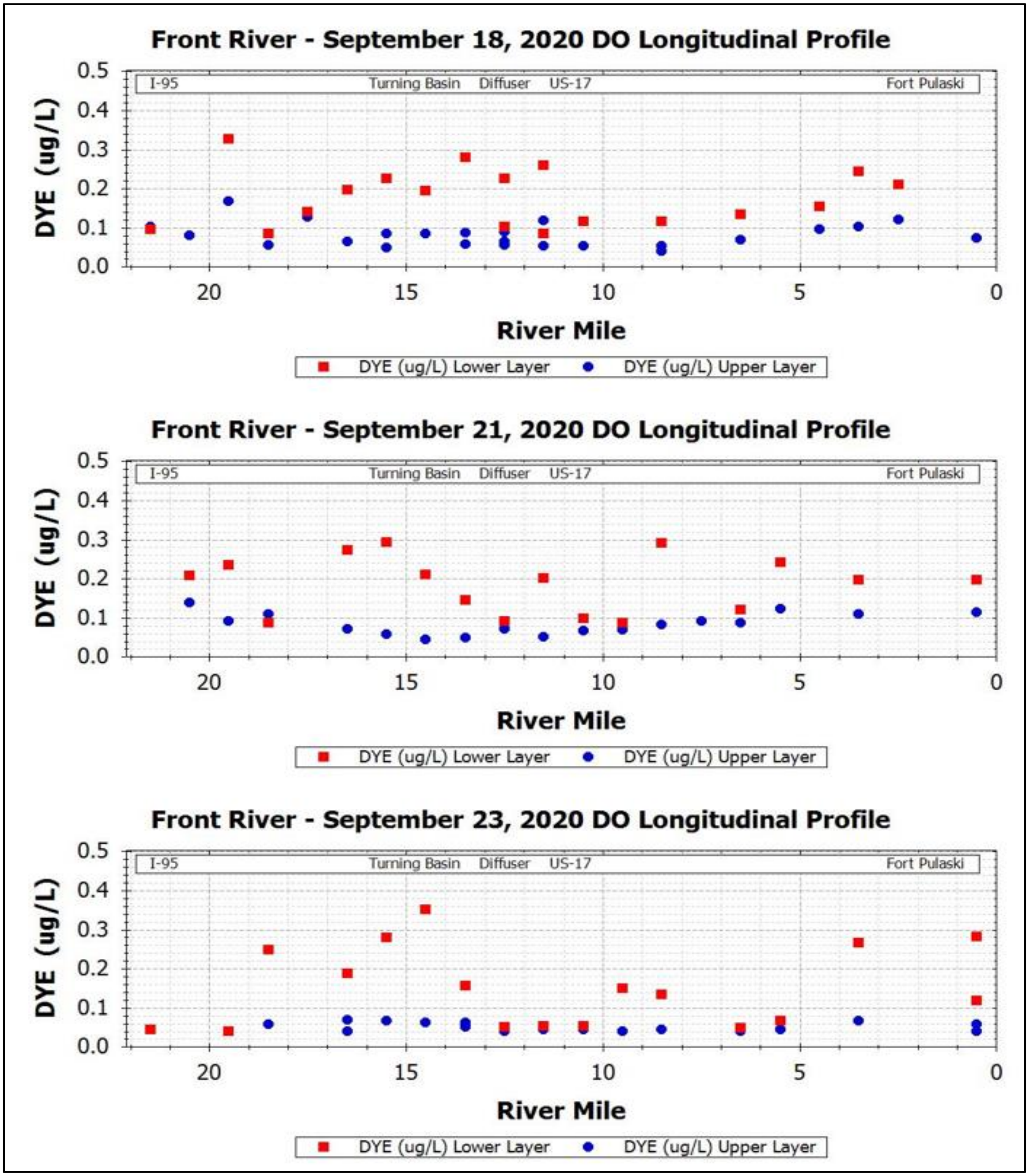

Figure 10-17 Front River Dye Profile – September 18 through September 23, 2020

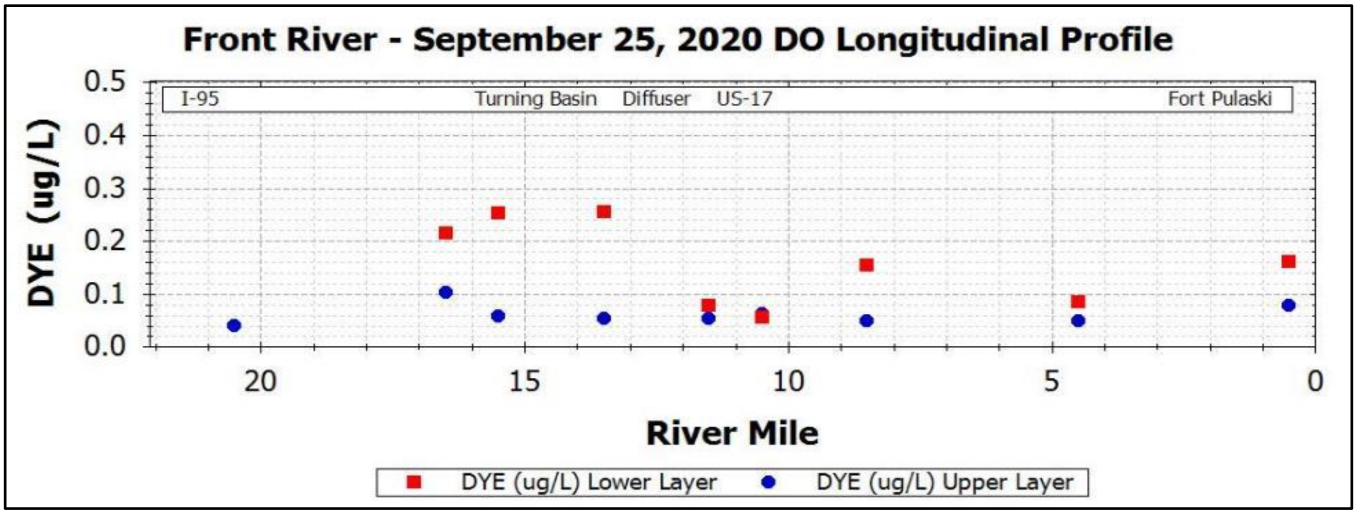

Figure 10-18 Front River Dye Profile – September 25, 2020

The dye concentrations at Fort Pulaski and the turning basin (RM 19) are presented in ***Figure 10-19*** and ***Figure 10-20***. The dye release from Upriver on September 15, 2020, is evident at both locations, as indicated by the increase in late September 2020. Based on these figures, it was roughly estimated the dye and the injected oxygen would stay in the Front River for three weeks to a month, dependent on upstream flows and tidal conditions. This supports the findings from Section 7.3, where DO increases were observed to remain for over a week.

LINE OF EVIDENCE 2.2 – OXYGEN PLUME RETENTION AFTER INJECTION

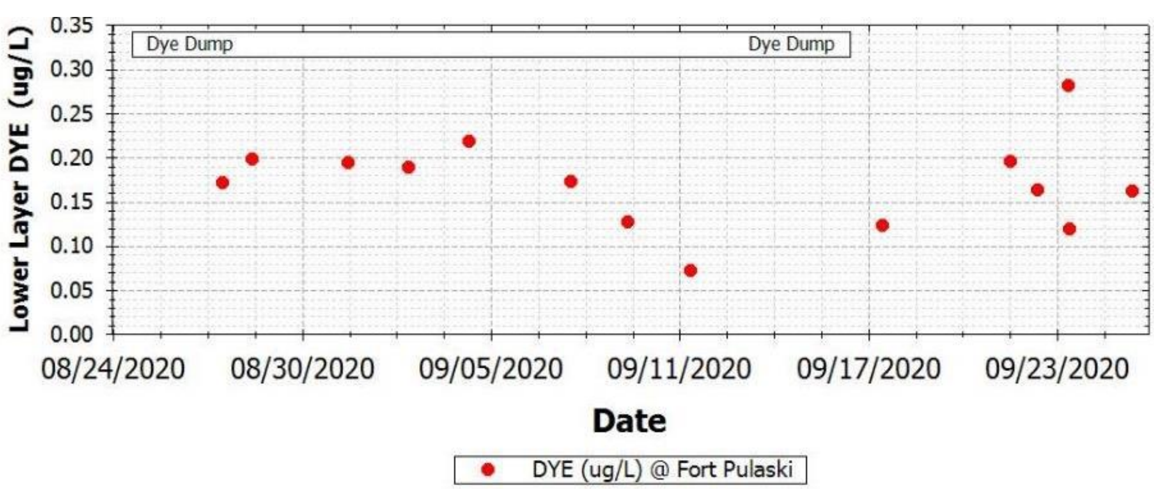

Figure 10-19 Front River - Fort Pulaski Dye Concentrations (bottom)

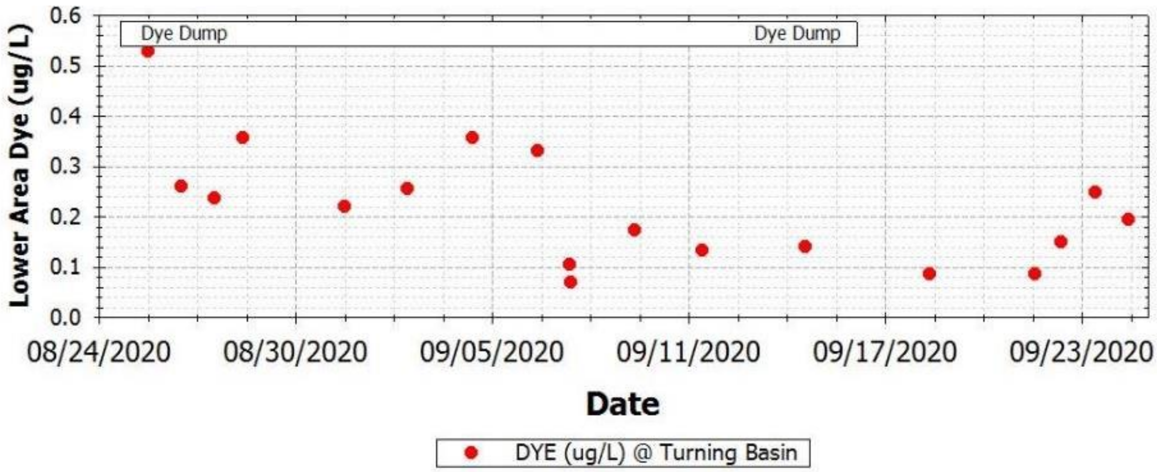

Figure 10-20 Front River – Turning Basin Dye Concentrations (bottom)

10.3 BACK RIVER DYE RELEASES

Three Back River dye releases were conducted during the SUR. The primary goal of the dye releases was to determine where in the river the dye migrated and therefore where injected oxygen was entrained. Detailed near-field dye and DO measurements were collected during the 2019 Test Run sampling that detailed the initial mixing and near field distribution of the dye and oxygen plumes and therefore were not repeated during the SUR sampling (LG2 Environmental Solutions, Inc. and Tetra Tech, Inc. 2019a). The dates and details of the three Back River dye releases are presented in ***Table 10-1***. Additional detail on each dye release is presented in **APPENDIX E**.

10.3.1 July 16 and August 12, 2020 Dye Releases

The July 16, 2020 dye release was conducted during an ebb tide. ***Figure 10-21*** shows the dye plume moving downstream toward the GA 17 bridge and mixing side to side.

LINE OF EVIDENCE 4.1 – ANALYSIS OF BUOY, DRIFT, AND DYE DATA

The August 12, 2020 dye release was conducted on a low slack tide, and detailed depth profiles were taken that showed the dye was mixing vertically by the time it reached LBR_5 buoy, just upstream of the diffuser.

LINE OF EVIDENCE 3.2 – ANALYSIS OF PROFILE AND DYE DATA

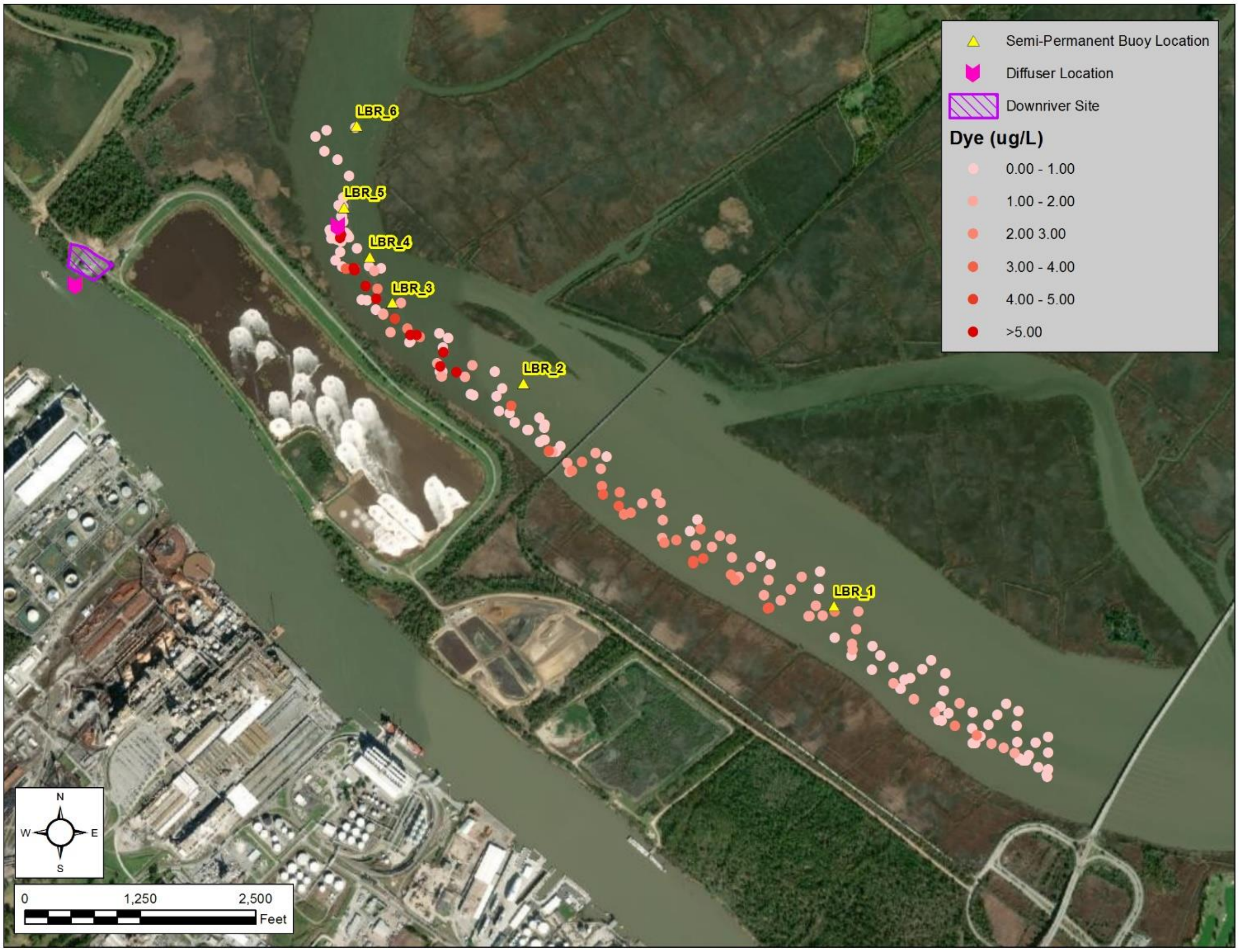

Figure 10-21 Back River Dye Sampling – July 16, 2020

10.3.2 August 25 to September 24, 2020 Dye Sampling Results

Similar to the Front River dye releases, the August 25, 2020 event best illustrates where the dye, and therefore injected oxygen, traveled and how long it remained in the Back River. After the dye was injected, profile sampling of the river was conducted weekly to see how long the dye and the associated injected oxygen would remain in the Back River. The following figures (***Figure 10-22*** and ***Figure 10-23***) show the dye sampling from August 26, 2020, to September 24, 2020. Dye from the August 25, 2020 release was retained in the river for two to three weeks until the dye reached a background concentration of around 0.06 µg/L. Dye from the Upriver dye releases undertaken September 15, 2020, were detected in the Little Back River on September 17 and September 24, 2020, as seen by the small spikes between RM 16 and RM 12 in ***Figure 10-23***.

LINE OF EVIDENCE 2.2 – OXYGEN PLUME RETENTION AFTER INJECTION

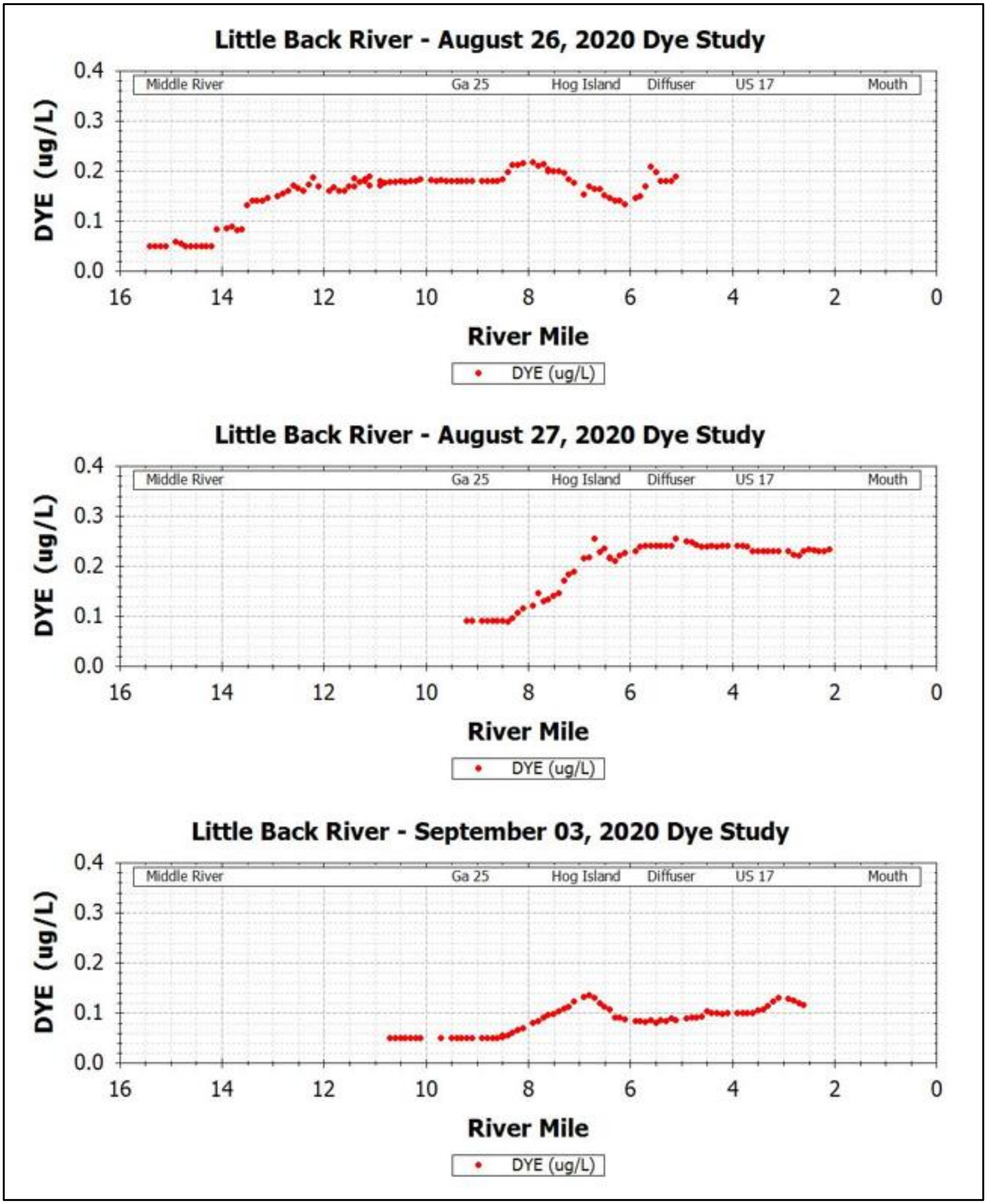

Figure 10-22 Back River Dye Profile – August 26 to September 03, 2020

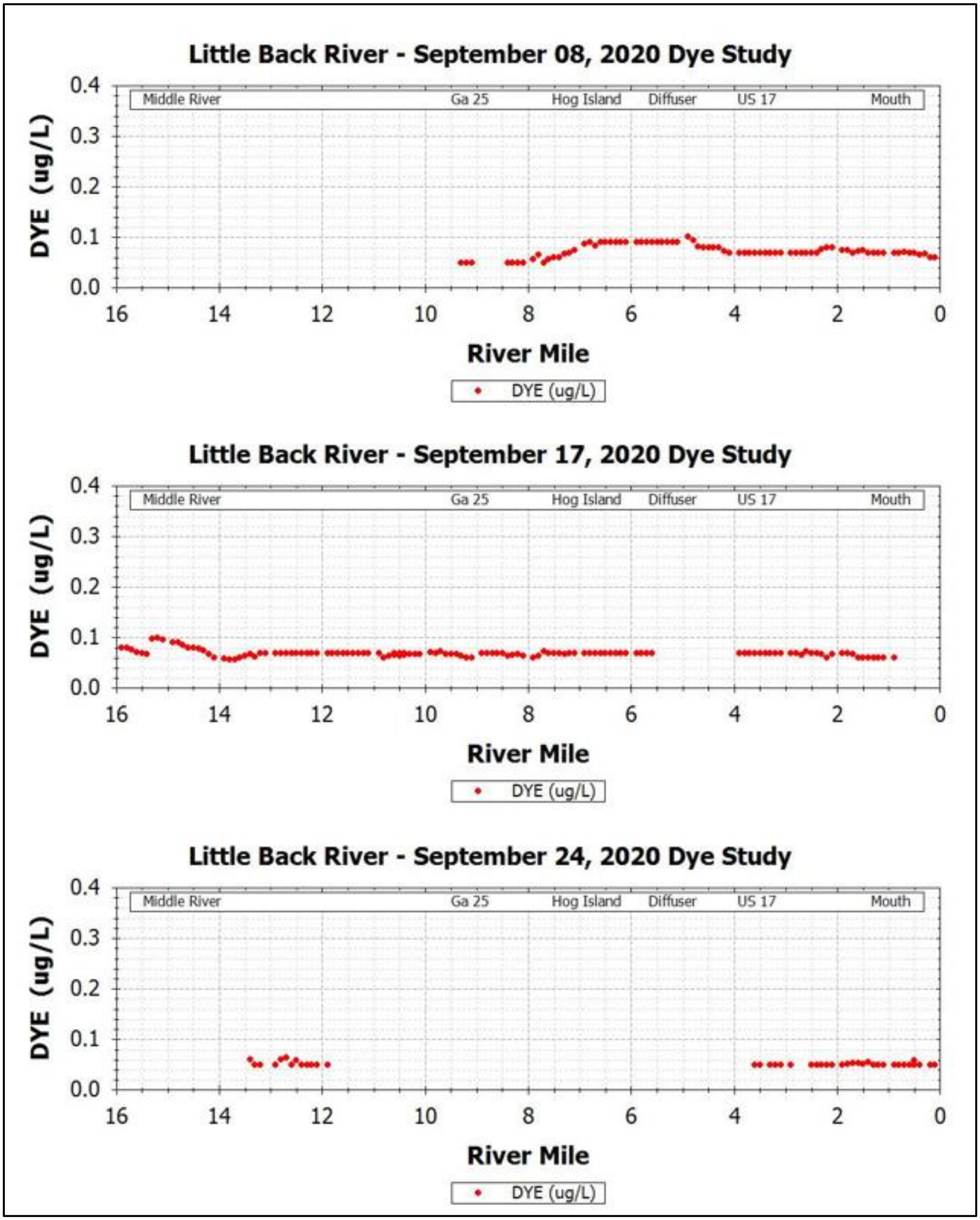

Figure 10-23 Back River Dye Profile – September 08, 2020, to September 24, 2020

In ***Figure 10-24***, time series plots of dye concentrations at the river mouth, Back River diffuser, and GA 25 show how the dye decreased to background levels in two to three weeks. This long retention time supports the assertion that the Savannah River and estuary is successful at retaining injected oxygen, as proposed in Sections 7.3 and 10.2.

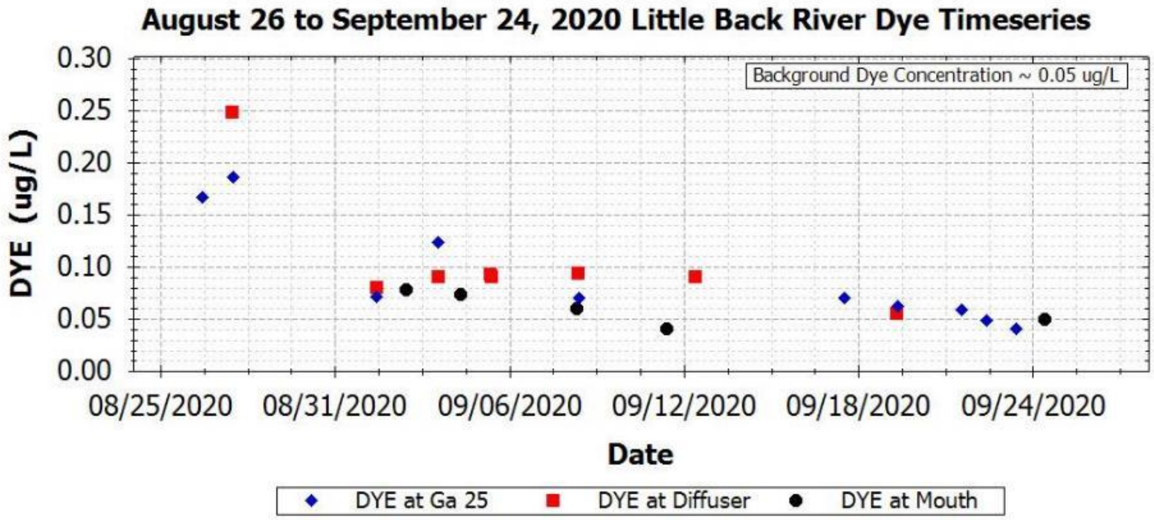

Figure 10-24 Dye concentrations at the Little Back River Mouth

LINE OF EVIDENCE 2.2 – OXYGEN PLUME RETENTION AFTER INJECTION

10.4 SUMMARY

The 10 dye releases and the subsequent field sampling undertaken before and during the SUR were successful.

The Upriver dye releases supported the findings from the buoy, drift, and profile data. Dye, and therefore injected oxygen, mixed well both vertically and spatially. Additionally, evidence of the Upriver releases was detected significantly far downstream on the Front River as far as Fort Pulaski. This confirms the importance of both Upriver and Downriver plants to the overall oxygen injection system.

The Front River dye releases supported the findings from the buoy, drift, and profile data. Dye, and therefore injected oxygen, mixed well both vertically and spatially, particularly on ebb tides. Also, the injected dye, and therefore the injected oxygen, stays in the Back River for about two to three, depending on flow and tidal conditions. This is significant as it proves the benefits of oxygen injection are not instantaneous but instead provide ongoing mitigation. Further, dye from the Upriver plant was present in the upper portion of the Little Back River, indicating another SHEP mitigation project, the McCoy's Cut flow rerouting, has been successful.

11.0 2020 SHEP MODEL

THIS CHAPTER ADDRESSES SUCCESS METRIC #3 AND #4 AS IDENTIFIED IN SECTION 4.0

Success Metric #3 – Evaluate if the retained oxygen is mixing vertically and mitigating the bottom half of the water column

Success Metric #4 – Evaluate if the retained oxygen is mixing spatially to provide the necessary mitigation throughout the Savannah River and estuary

11.1 BACKGROUND

A mechanistic modeling approach using the Environmental Fluid Dynamics Code (EFDC) and Water Quality Analysis Simulation Program (WASP) models has been used to simulate the circulation, transport, and biochemical processes impacting hydrodynamics and water quality in the Savannah River and Harbor. The EFDC model simulates the hydrodynamic transport (velocities and water surface elevation), salinity exchange between the ocean and the river, temperature, and the interaction between those parameters. The WASP model simulates the relevant water quality processes impacting DO in the system (Tetra Tech, Inc. 2015). The SHEP model was developed in 2006 and has been updated several times over 15 years. The purpose of the model is to evaluate changes to hydrodynamics and water quality in the Savannah River and estuary from a variety of sources, including the SHEP channel deepening and mitigation features.

A history of the model development, beginning in 2006, is presented in **APPENDIX K.**

11.1.1 The 2020 SHEP Model

Due to changes in the harbor and additional data collected since 2015, the 2020 SHEP model update included significant grid modifications to improve the representation of flows in and out of the estuary. The 2020 SHEP model was calibrated to the January 1 through December 31, 2019 period for WSE, salinity, water temperature, flow, velocity, and DO at 10 USGS stations. Reasons for the latest calibration included the opportunity to capture the full seasonality of the Savannah River system, construction of the majority of SHEP features which included McCoy's Cut and the outer harbor dredging, and bathymetric surveys completed in 2020.

Figure 11-1 presents the 2020 SHEP model computational grids for EFDC and WASP. The EFDC grid extends further offshore since WASP open boundary conditions are generated by EFDC and must be prescribed at an internal region of the EFDC grid. Grid cells vary in size but were approximately 250 feet by 650 feet, 400 feet by 750 feet, and 150 feet by 650 feet at the Front River, Back River, and Upriver diffuser area, respectively. The model contains 10 layers that vary in thickness depending on water depth.

Detailed information about model setup, grid improvements, and calibration for the 2020 SHEP model is provided in **APPENDIX K**

The calibrated 2020 SHEP model was utilized to evaluate the levels of DO in the Savannah River and estuary during the SUR period and to evaluate the performance of the oxygen injection system when operating under EIS conditions. The model was utilized for the evaluation of far-field impacts where the injected oxygen has fully mixed with the receiving waters, and for spatial and temporally averaged conditions. Plume dynamics in the proximity of the diffusers were analyzed and evaluated using analysis of the dye releases as presented in Section 10.0 and monitoring data collected at buoys deployed during the SUR and presented in Section 8.0 and Section 9.0.

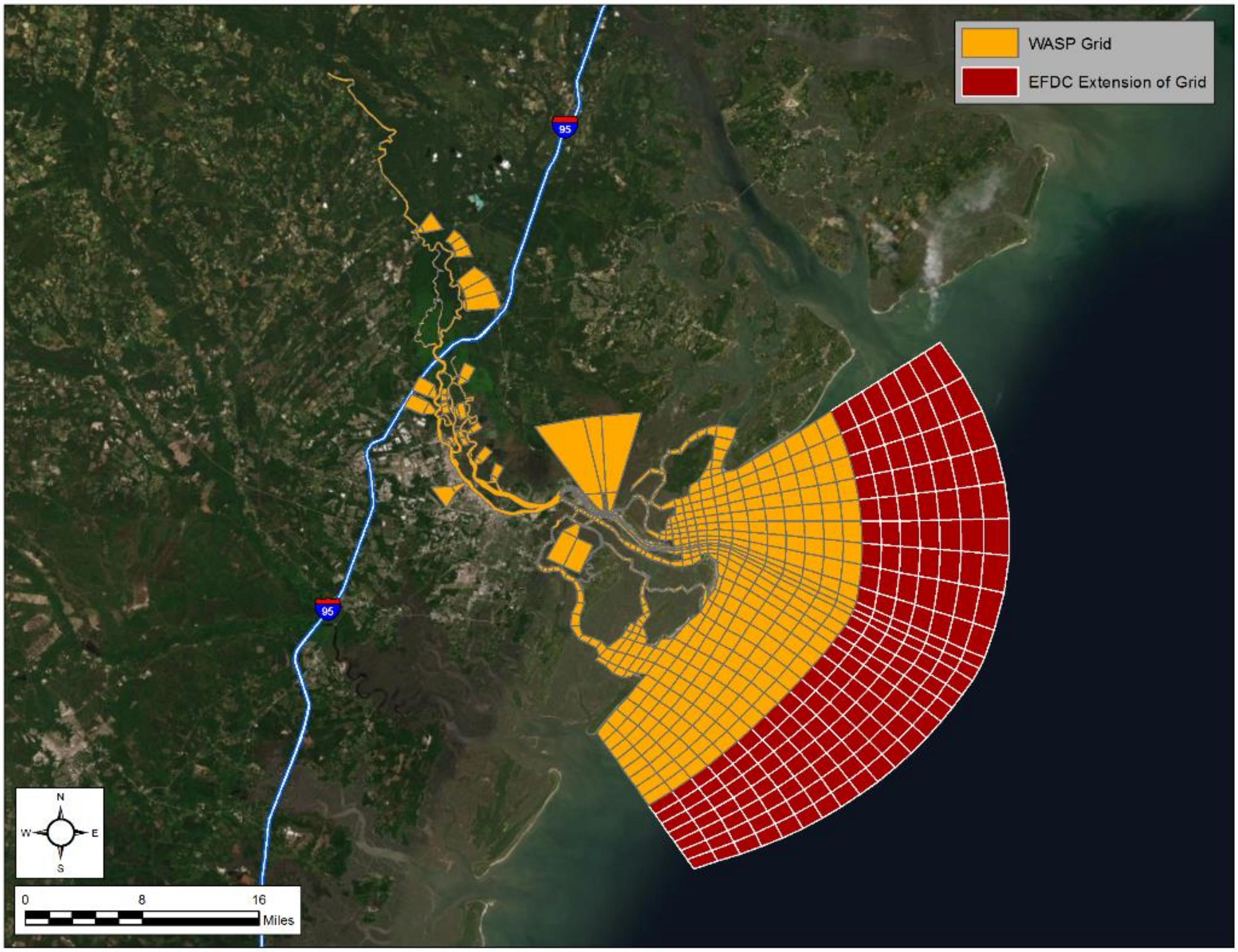

Figure 11-1 SHEP 2020 EFDC and WASP Computational Grids

11.2 MODEL SETUP

The 2020 SHEP model was used as another line of evidence to confirm that the oxygen injection system improved DO concentrations throughout the estuary and mitigated the DO impacts of the project. Simulated DO levels for different scenarios that included the oxygen injection system were compared to DO levels simulated without oxygen injection.

The model was set up and calibrated for the period January 1, 2019, to December 31, 2019. In November 2020, the model was extended through September 30, 2020, to include SUR conditions in the simulations.

The intake locations of the Downriver and Upriver plants on the Front River and Savannah River, respectively, were represented as flow withdrawals, in addition to other permitted withdrawals, in the EFDC Model. The plant inflows and outflows were determined using the reviewed plant data as described in Section 5.2. A raw water DO concentration time series, measured at the intakes of both plants, was included in the WASP Model at the Downriver and Upriver intake locations (***Figure 11-2*** and ***Figure 11-3***).

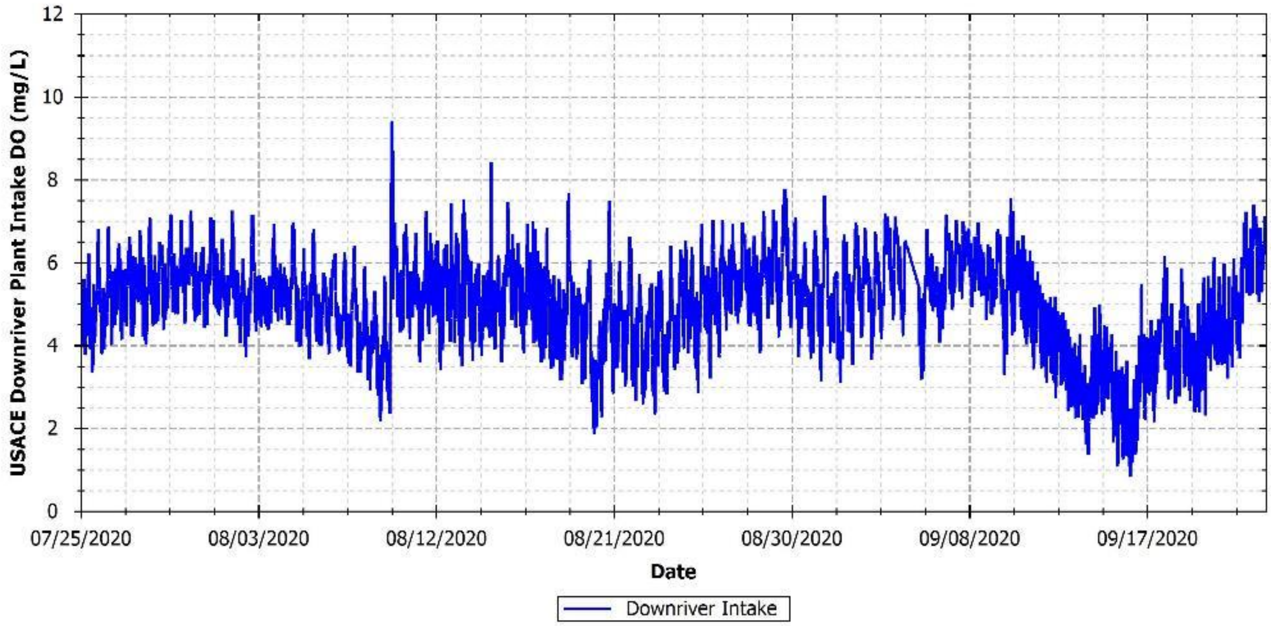

Figure 11-2 Raw DO Intake Time Series at Front River

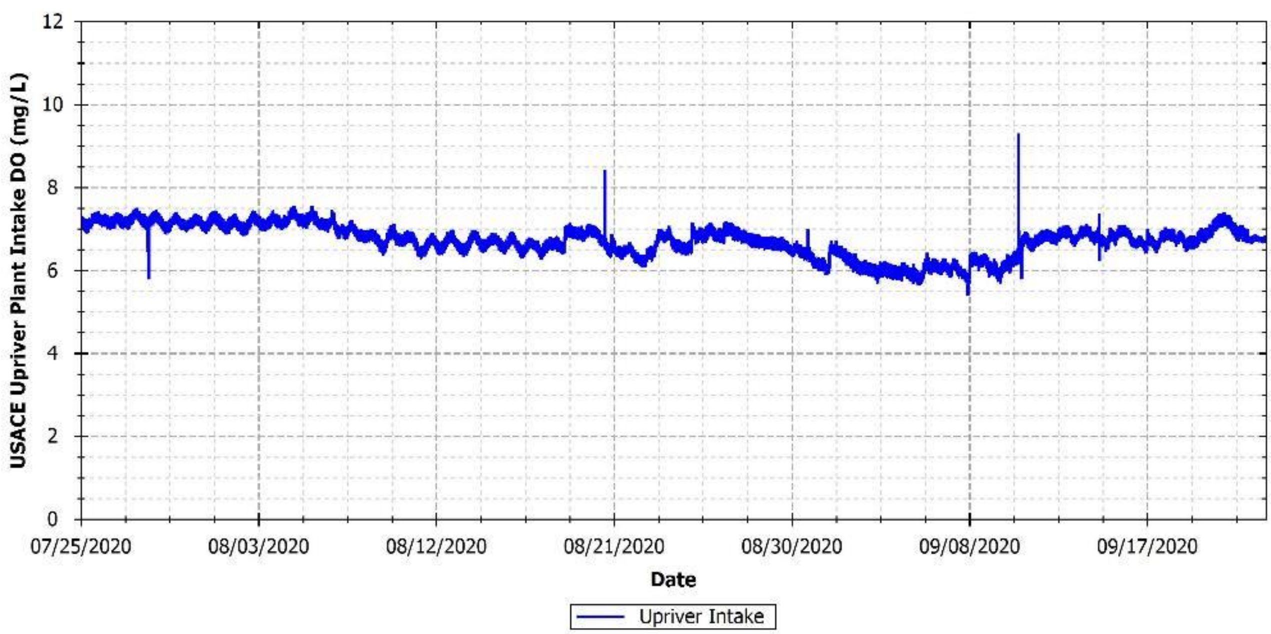

Figure 11-3 Raw DO Intake Time Series at Savannah River

The flows, temperatures, salinity, and DO concentrations from the Front River, Back River, and Upriver diffusers were represented as point sources in the model. The 15-minute plant data for the SUR from July 25, 2020, through September 22, 2020 (Section 3.3 and **APPENDIX H**), consisted of information on the flow distribution of the super-oxygenated water to the Back River, Front River, and Upriver, and the total raw, gross, and net oxygen loads. These were used to develop the plant discharge representation in the model. The reviewed plant flows were converted from gpm (***Figure 11-4*** and ***Figure 11-5***) to cfs, as required in the model, and included in the EFDC Model at the Back River, Front River, and Upriver diffusers.

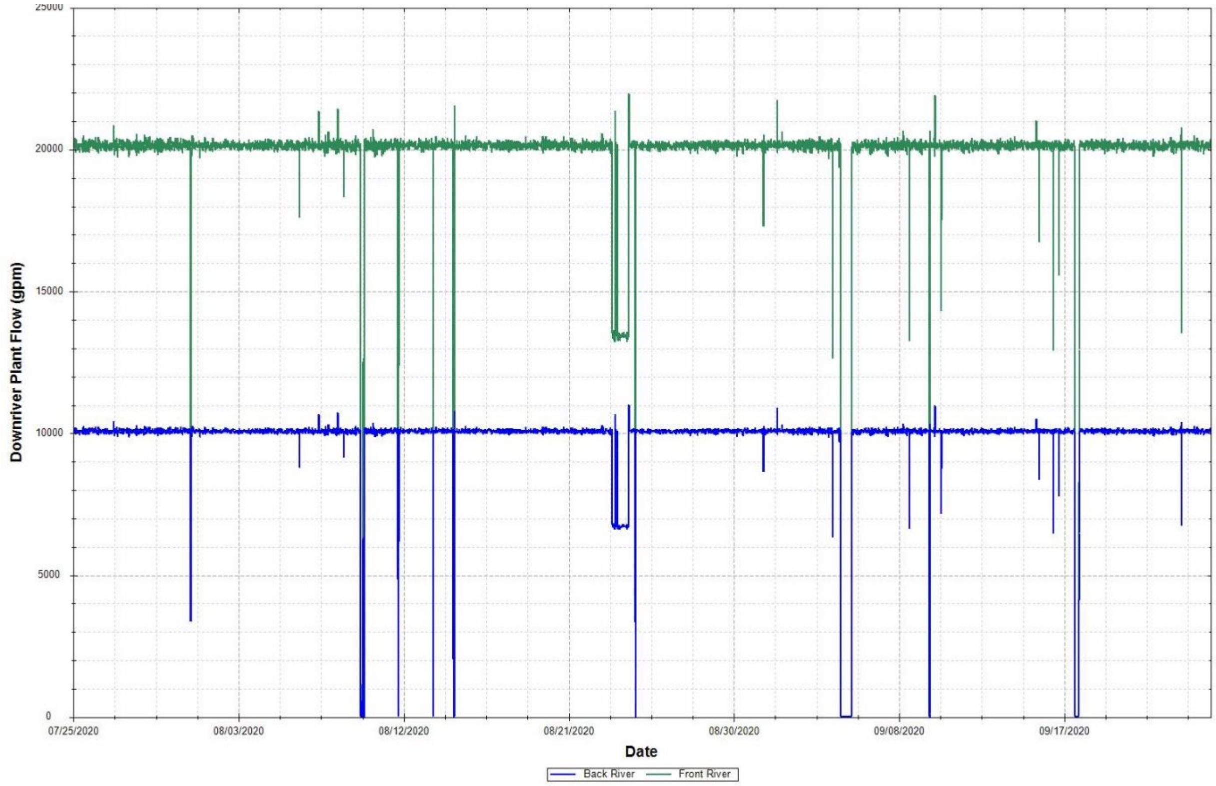

Figure 11-4 Downriver Plant Flow

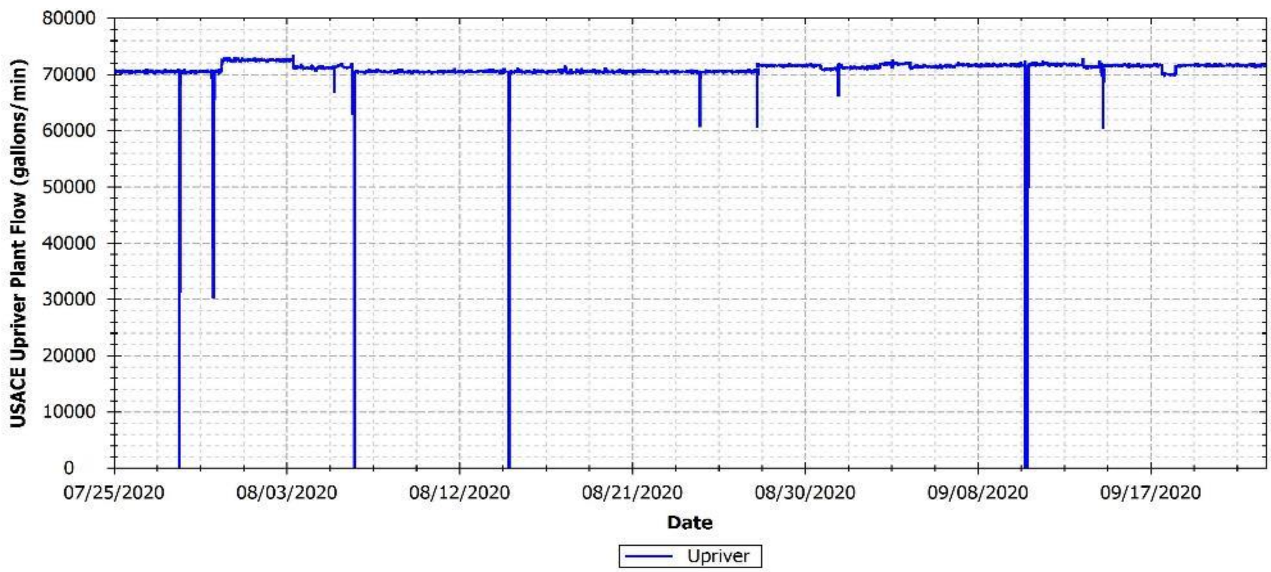

Figure 11-5 Upriver Plant Flow

The 15-minute raw temperature data at the Downriver plant were not available, but they were available at the Upriver plant. Raw plant data consisted of temperatures at each of the eight Upriver Speece cones. These were flow-weighted using each Speece cone flow to calculate a composite water temperature time series for the Upriver plant. To determine the temperature at the Downriver plant, modeled water temperatures at the intake location were applied at the Back River and Front River diffuser locations. The temperatures were converted from Fahrenheit to Celsius, as per the requirements of the model, and included in the EFDC Model at the Back River, Front River, and Upriver diffusers (***Figure 11-6***).

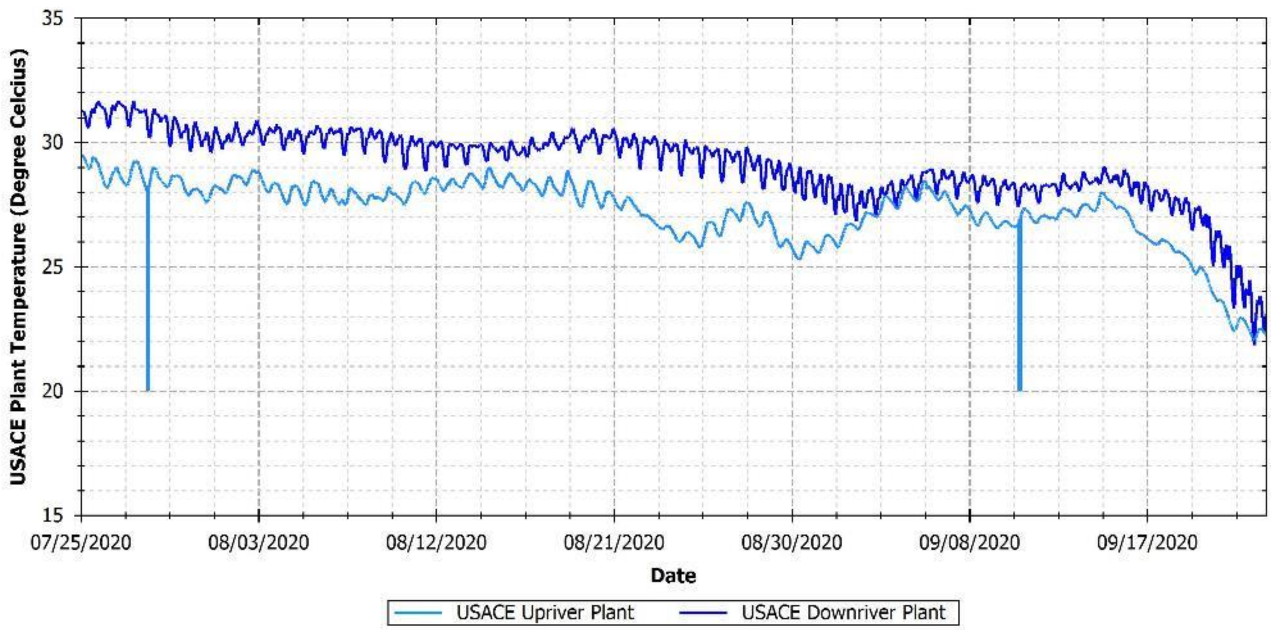

Figure 11-6 Oxygen Injection Plant Temperature Data

Salinity, Carbonaceous Biochemical Oxygen Demand (CBOD), and Ammonia (NH3) were not measured at either plant intake. Therefore, to represent the concentrations from the plant flows, modeled salinity concentrations at the intake location were applied at the Front River, Back River, and Savannah River diffuser locations in the EFDC Model, and modeled CBOD and NH3 concentrations were applied at the diffuser locations in the WASP Model.

The total net DO concentration, calculated from the reviewed plant load and the flow distribution data, was input into the WASP model at the Back River, Front River, and Upriver diffusers (***Figure 11-7*** and ***Figure 11-8***).

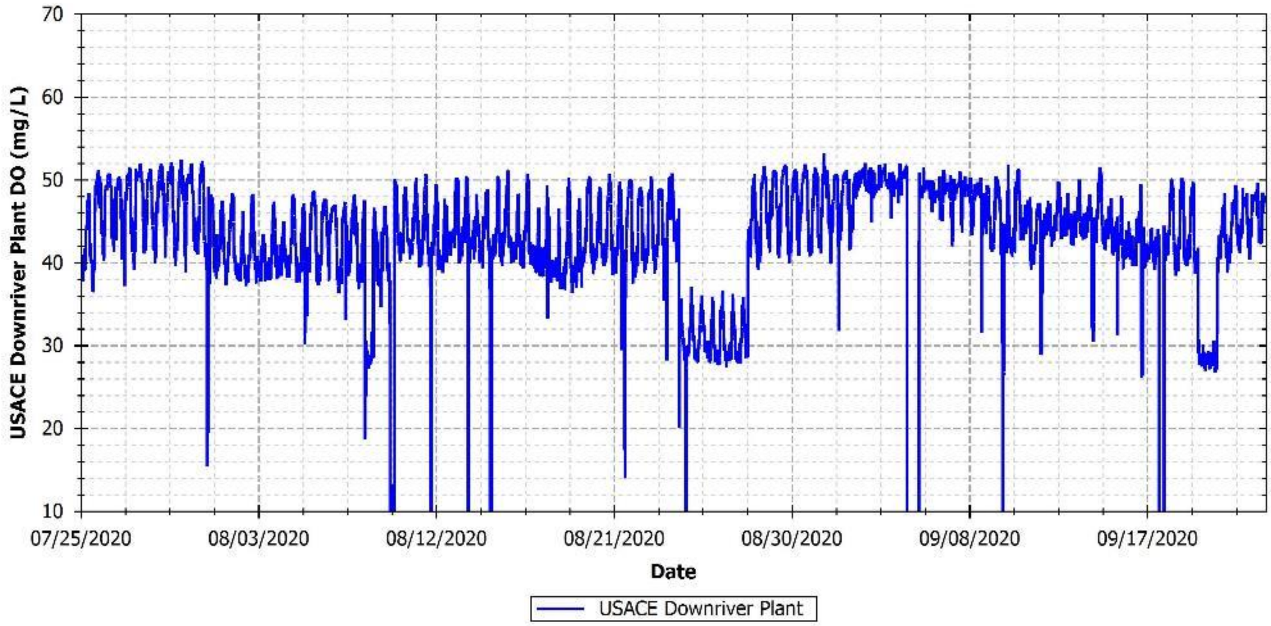

Figure 11-7 Downriver plant DO concentrations

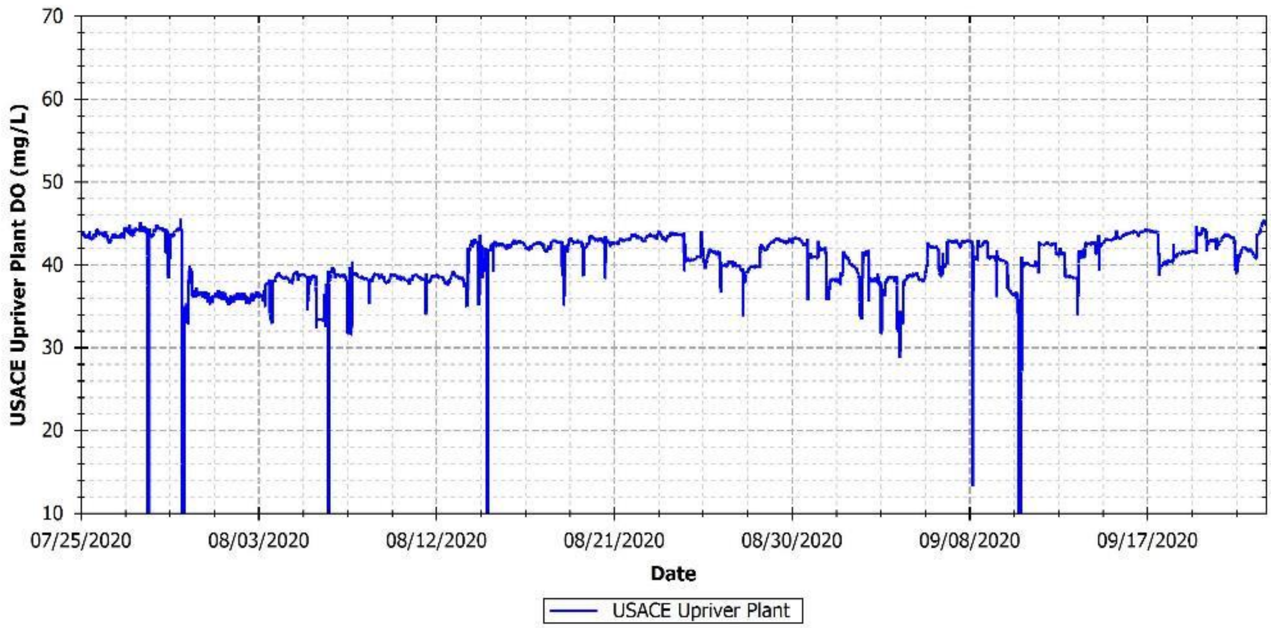

Figure 11-8 Upriver plant DO concentrations

11.2.1 Modeling Scenarios

To evaluate the oxygen injection system impacts, three runs were simulated:

- *SUR* – The model was run from July 15, 2020, to September 25, 2020, allowing for a suitable model warm-up period, with the actual flows and oxygen loads injected into Front River, Back River, and Savannah River during the SUR.
- *Baseline* – The model was run from May 1, 2019, to September 30, 2020, with the SHEP deepening included but without including the oxygen injection system.
- *Post-Project* – The model was run from May 1, 2019, to September 30, 2020, with the SHEP deepening included and with the oxygen injection system operating under EIS conditions (USACE 2012a).

The *Baseline* and *Post-Project* runs were intended to finish October 31, 2020, but instead were run until September 30, 2020, since the necessary data required to extend it until October 31, 2020, were not available during the preparation of this report.

The three runs described above were used to process data for three scenarios:

- SUR Scenario. Data from the *SUR* and the *Baseline* runs were processed from July 15, 2020, to September 25, 2020. DO and DO deltas between the *SUR* and *Baseline* runs for the entire water column and the bottom half of the water column were evaluated and analyzed to determine the mitigation success of the oxygen injection system (Section 11.3).
- 2019 Scenario. Data from the *Post-Project* and *Baseline* runs were processed for the period of operation of the injection system from May 1, 2019, to October 31, 2019. This 180-day period is called for in the GRR engineering supplemental studies (Tetra Tech, Inc. 2010). DO and DO deltas between the *Post-Project* and *Baseline* runs for the entire water column and the bottom half of the water column were evaluated and analyzed to determine the mitigation success of the oxygen injection system (Section 11.4).
- 2020 Scenario. Similar to the 2019 Scenario, data from the *Post-Project* and *Baseline* runs were processed for the period of operation of the injection system from May 1, 2020, to September 30, 2020. DO and DO deltas between the *Post-Project* and *Baseline* runs for the entire water column and the bottom half of the water column were evaluated and analyzed to determine the mitigation success of the oxygen injection system (Section 11.4).

DO concentrations and incremental deltas in DO were evaluated for the bottom layers (defined as the model layers at the bottom half of the water column at each model cell, in the case of the 2020 SHEP model, five layers). One of the requirements is for the oxygen injection system to mitigate median DO concentrations in 97 percent of the volume in the bottom half of the water column as specified in the EIS Appendix C (USACE 2012a) and engineering supplemental studies (Tetra Tech, Inc. 2010). DO concentrations and incremental deltas in DO were also calculated for the entire water column given the Savannah River TMDL was evaluated for the entire water column (USEPA 2010). The results for the bottom half of the water column are presented below while the results for the entire water column are presented in **APPENDIX K**.

11.3 MODEL EVALUATION FOR THE STARTUP RUN

To evaluate the mitigation capability of the oxygen injection system during SUR, a comprehensive analysis was undertaken. Changes in DO were evaluated for longitudinal profiles of the rivers, for spatial zones identified in the EIS, and at the individual cell level.

11.3.1 DO Longitudinal Profiles

The changes in DO in the Savannah Harbor due to the oxygen injection system were evaluated throughout the Savannah River, Front River, Middle River, and Back River using longitudinal profiles. The RMs for each river are used as reference points and are presented in ***Figure 11-9*** (Front River and Savannah River in red, Middle River in green, and Back River and Little Back River in yellow).

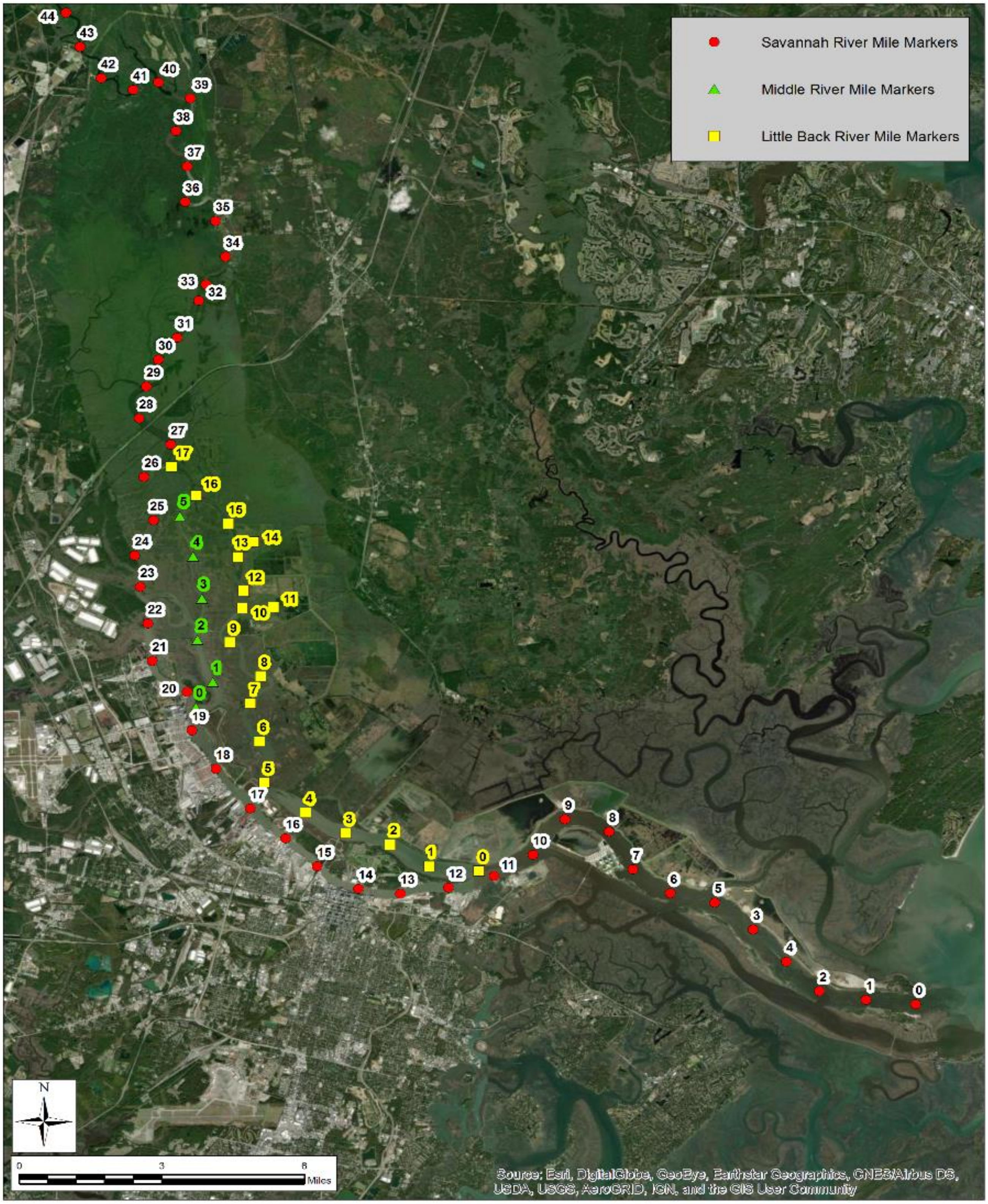

Figure 11-9 River Mile Markers for the Savannah, Little Back, and Middle Rivers

The longitudinal profiles plot DO against RMs and used all modeled outputs from the SUR period. The profiles were created for the 10th, median, and 90th percentiles. The profiles also show the location of the zones, analyzed in Section 11.3.2. Separate profiles were generated for both the bottom half and the entire water column. The profiles for the entire water column are presented in **APPENDIX K**.

The longitudinal profile for the Front and Savannah River were calculated along the navigation channel. The bottom layers results (***Figure 11-10***) showed that there was a positive median DO delta for the entire profile except for the lower five miles of the river to Fort Pulaski, where open ocean conditions dominate, and the effect of the oxygen injection was negligible but also did not show deterioration of the previous condition. Along the Savannah River downstream of the Upriver plant, between approximately RM 40 and the I-95 bridge at RM 27.8, the DO delta created by the Upriver plant gradually decreased from 1.0 mg/L to 0.4 mg/L. This agrees with the trends observed in Section 8.0 and Section 10.1. This Upriver area is mostly riverine with no tidal influence that could cause a reversal of flow direction. The residence time in this region is smaller than downstream, allowing the oxygen to move downstream to the areas that require mitigation. The region between RM 27 and RM 10 showed a significant reduction in DO both for the SUR conditions as well as the baseline conditions. In this area, retention times were larger due to the bidirectional tidal flows and the mixing with the river water. Also, the upper extent of the navigation channel is in this region causing a sudden change in depth that contributes to lowering the DO. Sediments are deposited in the deeper waters due to the reduction in velocity and the effect of the tide, thereby increasing the SOD. All these factors contribute to the DO sag in this region. Despite being the most sensitive part of the estuary for DO, the Upriver and Downriver injection plants contribute to keeping the DO delta positive throughout with values ranging from 0.1 to 0.6 mg/L. The influence of the tide on the injected oxygen load from the Front River diffuser can be perceived by the slight increase in DO deltas both upstream and downstream of the diffuser. During flood tide, the injected DO was transported upstream while during ebb tides the injected DO was transported downstream.

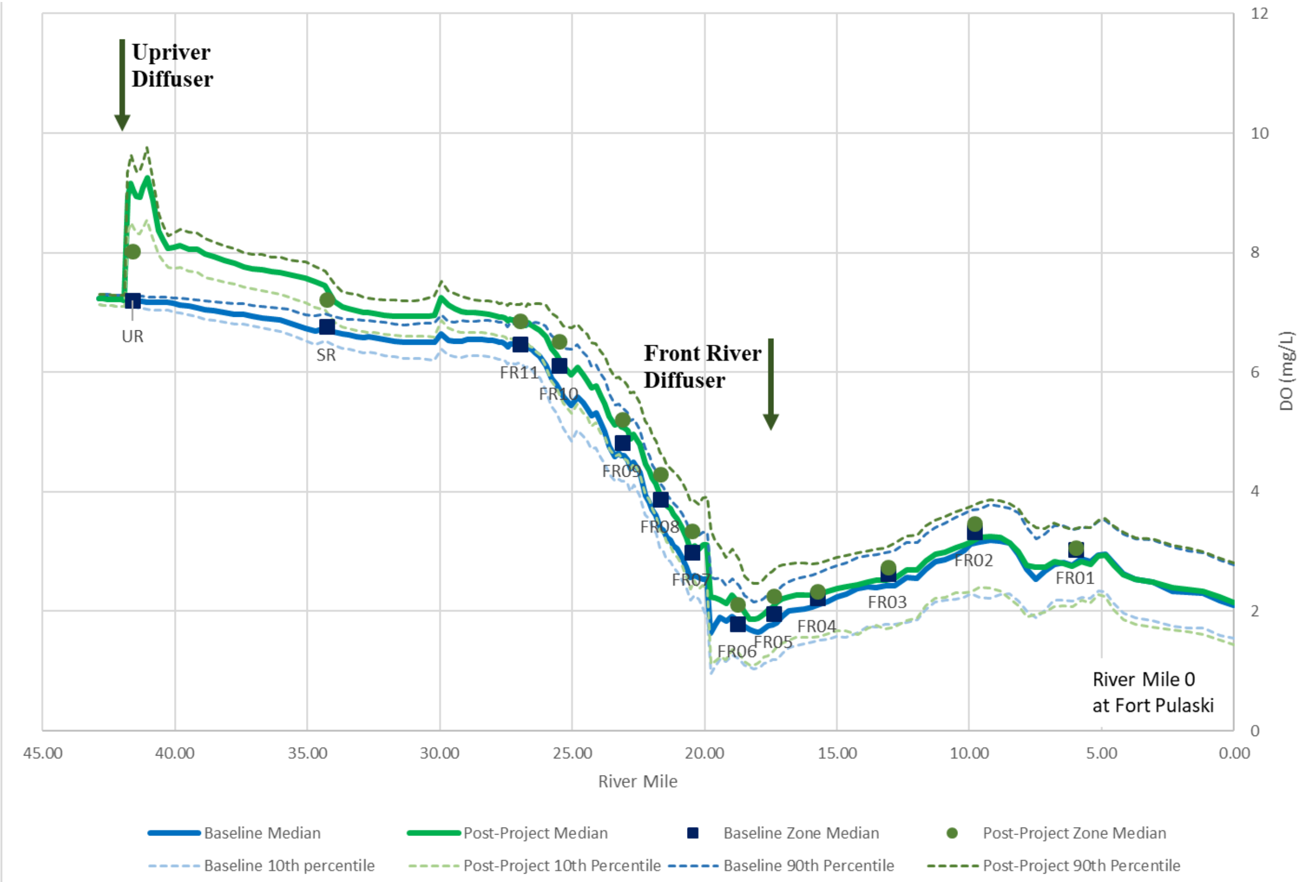

Figure 11-10 Savannah River Longitudinal Profile of DO – SUR Scenario (bottom half)

The longitudinal profile for the bottom half of the Back River and Little Back River showed positive DO deltas along the entire profile confirmed by the zones' values (***Figure 11-11***). The depth and width of the channel were relatively consistent with a widening of the cross-section between RM 2.0 and RM 3.0, where the river enters the sediment basin, causing a sudden drop in DO. The DO deltas were uniform with a median value of 0.3 mg/L and a minimum of 0.2 mg/L. A maximum median value of 0.6 mg/L was simulated at the location of the Back River diffuser (***Table 11-1***).

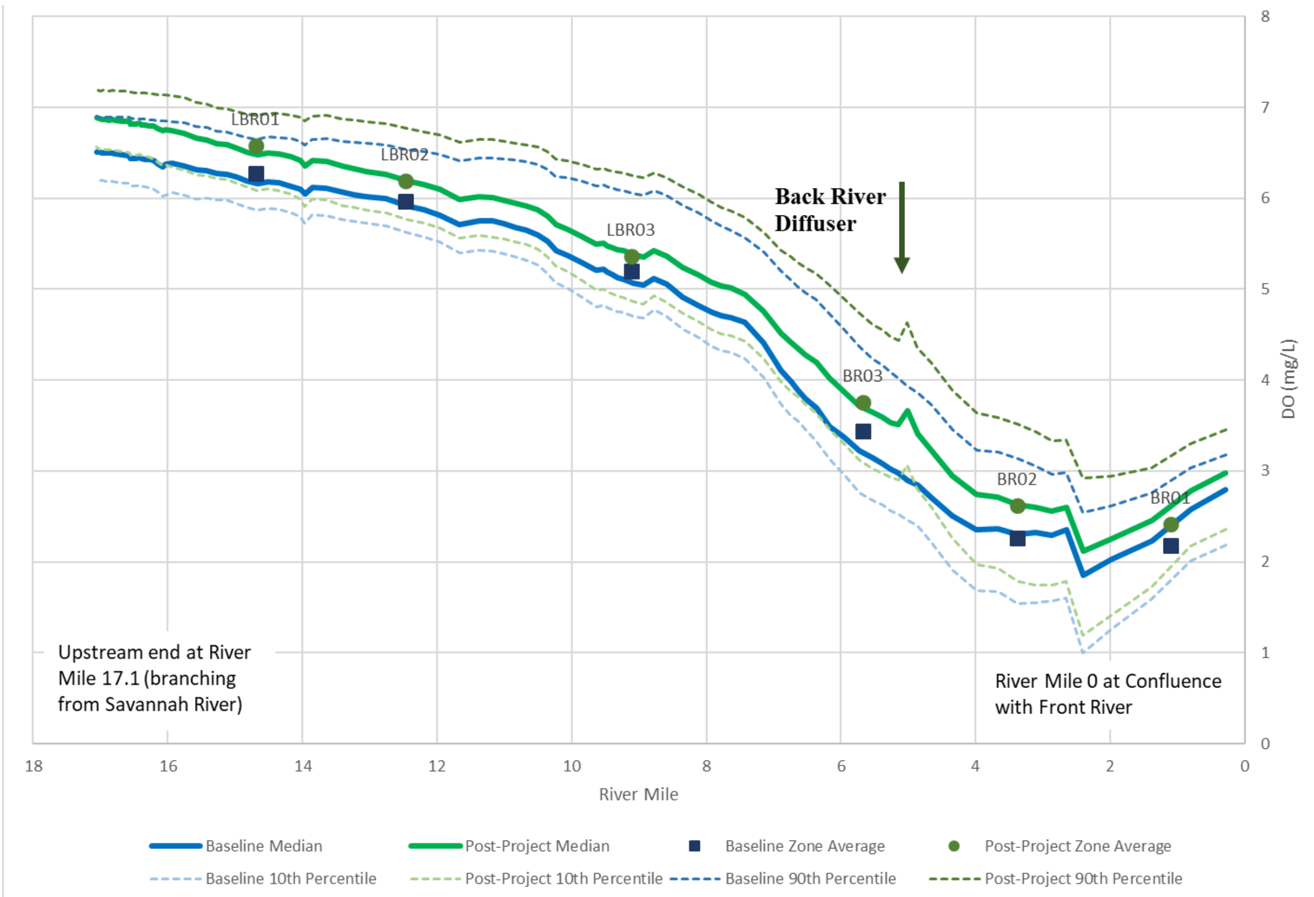

Figure 11-11 Back River Longitudinal Profile of DO – SUR Scenario (bottom half)

Table 11-1 Maximum DO Deltas for Longitudinal Profiles – SUR Scenario (bottom half)

Location	Bottom Layer DO Maximum Delta (mg/L)		
	10th Percentile	Median	90th Percentile
Savannah River	1.37	2.07	2.72
Front River	0.37	0.62	0.90
Middle River	0.27	0.39	0.47
Back River	0.49	0.61	0.74

The Middle River showed the most uniform DO delta with values ranging from 0.3 to 0.5 mg/L with an average of 0.4 mg/L (***Figure 11-12***, ***Table 11-1***). Despite not having an oxygen injection diffuser along the Middle River, the benefits from the Upriver and Downriver plants are evident by the positive deltas at both upper and lower extents.

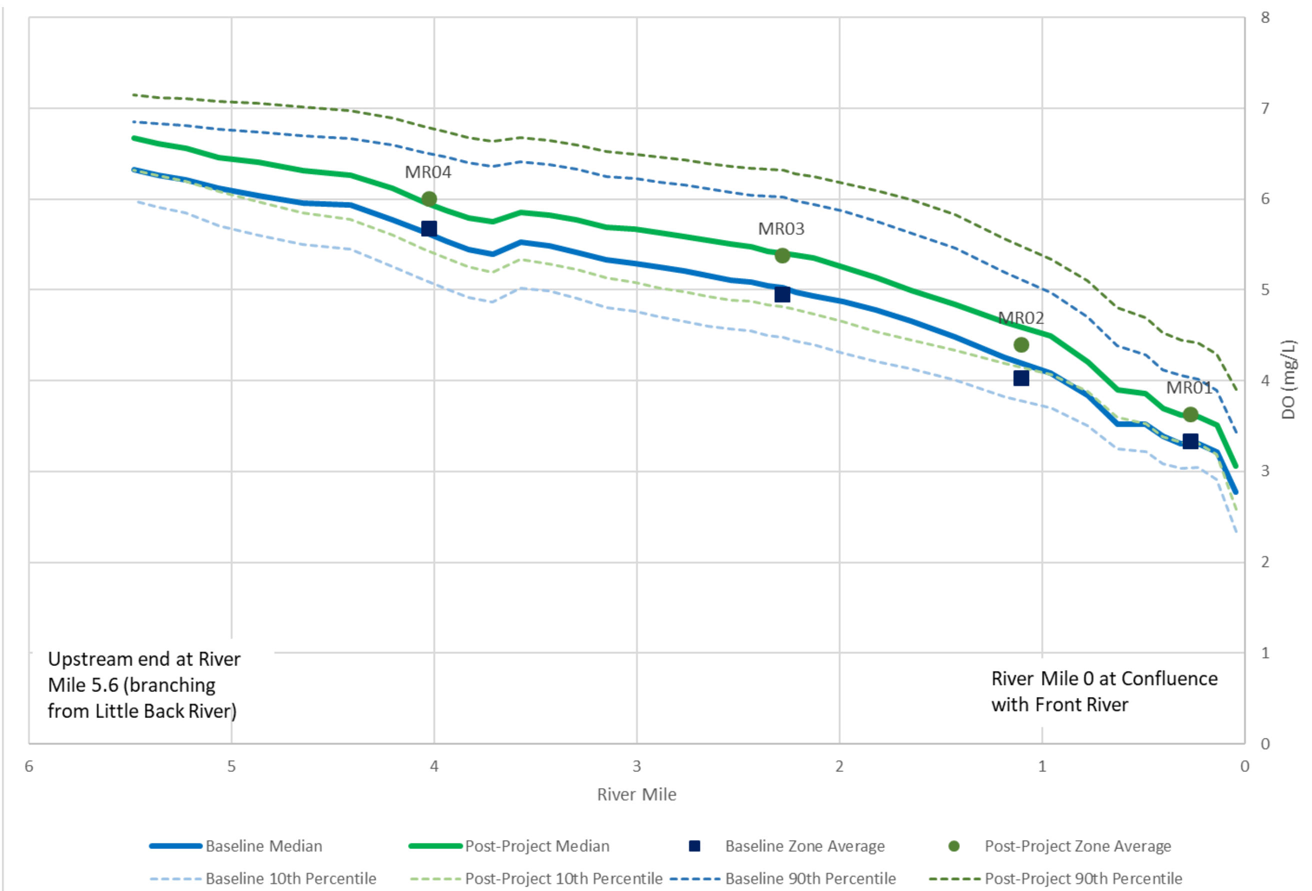

Figure 11-12 Middle River Longitudinal Profile of DO – SUR Scenario (bottom half)

11.3.2 DO Zonal Analysis

DO spatial zones defined by the EIS (USACE 2012a) were delineated to evaluate average conditions over them (***Figure 11-13*** to ***Figure 11-15***). The median values for the zones were added to the profiles in Section 11.3.1 for reference.

During the design phase of the oxygen injection system, the USACE and agencies determined that the design must mitigate 97 percent of the estuary waters, which was computed by comparing zones' volume-weighted DO concentrations for existing and project scenarios (Tetra Tech, Inc. 2010). Twenty-seven zones were delineated which covered the area to be mitigated, from RM 0 to RM 27.8 (***Figure 11-13*** to ***Figure 11-15***). Eleven zones were defined along the Front River, two along the Savannah River, six along the Little Back River, five along the Middle River, two in the South Channel, and one in Steamboat River (the Horseshoe). For both the bottom half and the entire water column, 10th percentile, median, and 90th percentile DO values were calculated for all zones. The results from the DO zonal analysis indicated that the oxygen injection system positively impacted the DO in the bottom half of the water column by increasing the median zonal concentrations by values ranging from 0.02 to 0.82 mg/L (***Figure 11-16*** and ***Figure 11-17***). This results in 100 percent of the zonal volume-weighted DO concentrations being mitigated by the oxygen injection system during the SUR. Areas that were identified as most affected by the navigational channel deepening were the following nine zones: FR07, FR08, FR11, MR01, MR05, BR01, BR02, BR03, and LBR03 (Tetra Tech, Inc. 2010). The DO zonal analysis showed that the oxygen injection system increased DO concentrations in the bottom half of the most affected zones during the SUR period compared to baseline conditions. The median oxygen levels increased from 0.18 mg/L to 0.46 mg/L in the critical zones, with an average oxygen increase of 0.34 mg/L. Full details for all zones are presented in ***Table 11-2***.

LINE OF EVIDENCE 3.1 – 97% VOLUME IMPROVEMENT ACHIEVED IN BOTTOM WATERS

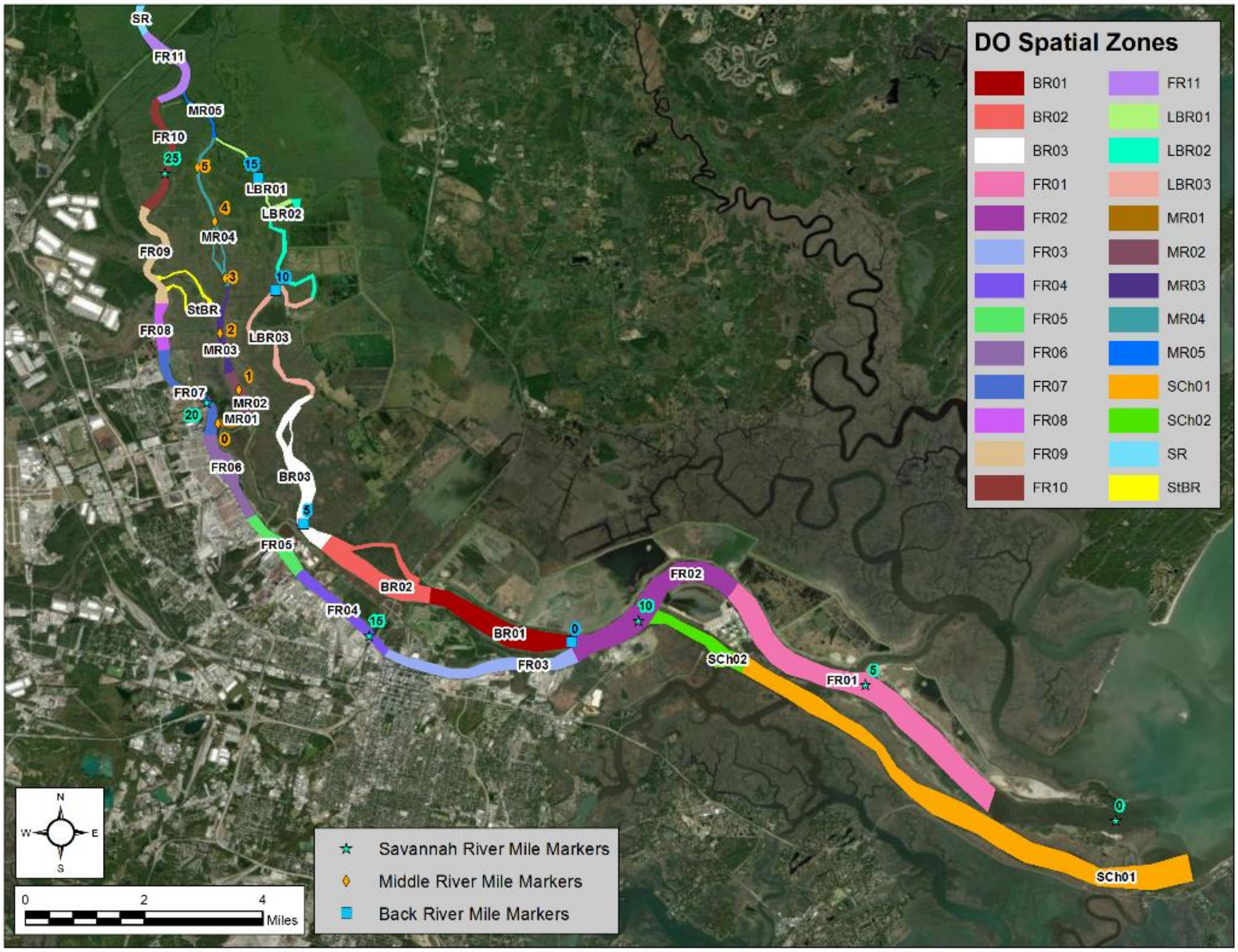

Figure 11-13 Location of DO Spatial Zones from RM 0 to RM 27.8

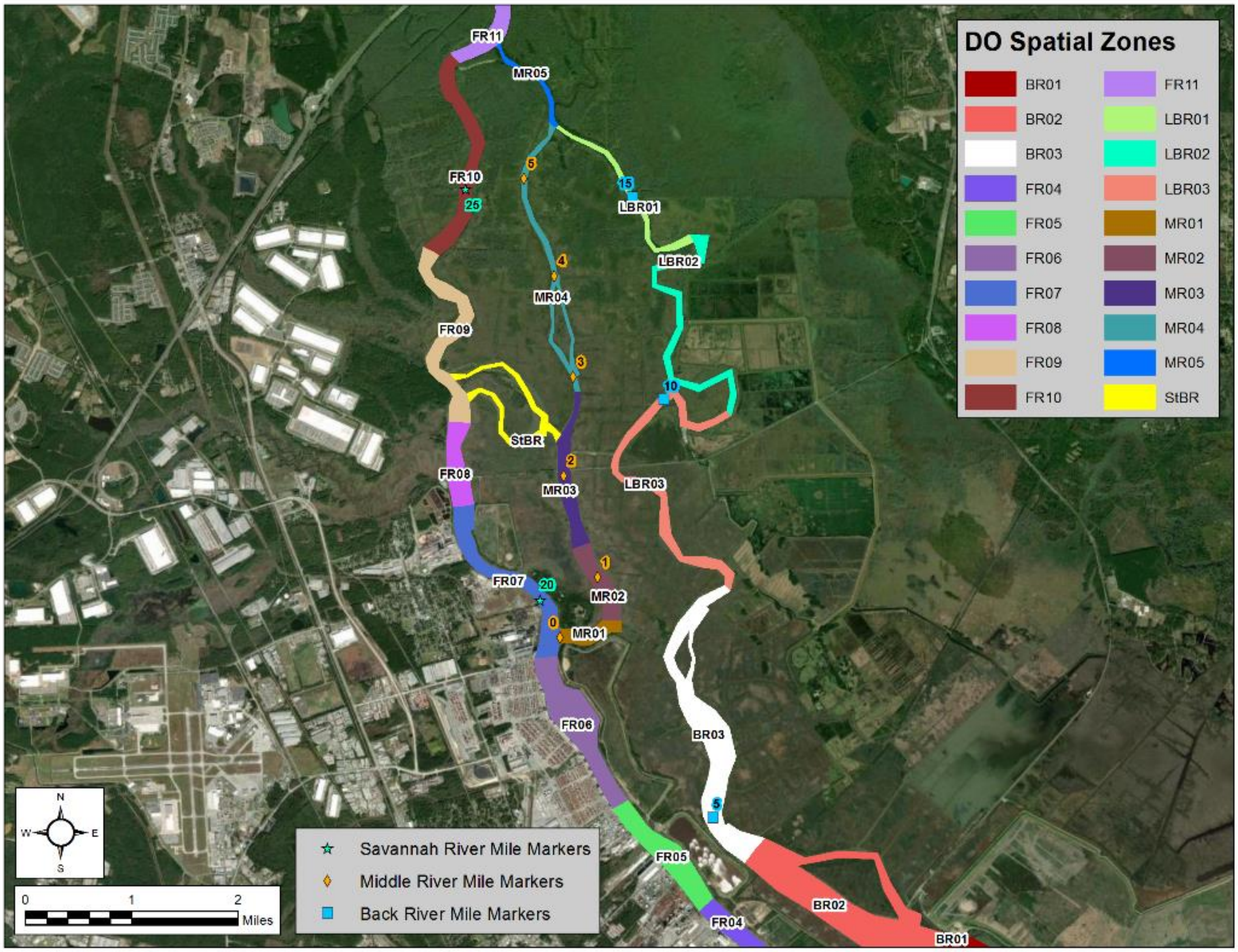

Figure 11-14 Location of DO Spatial Zones in the Front, Middle and Little Back Rivers

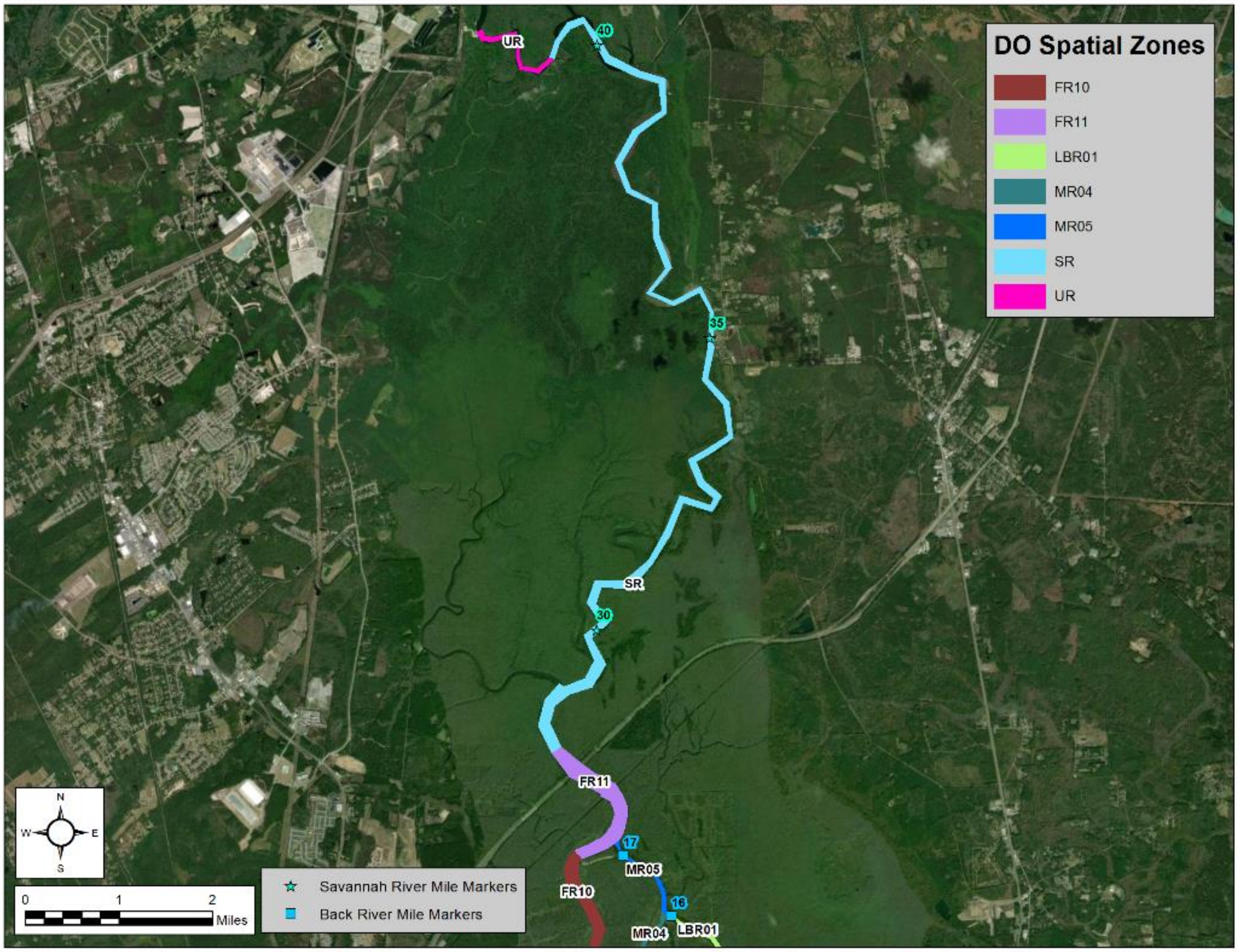

Figure 11-15 Location of DO Spatial Zones in the Savannah River

Table 11-2 DO Deltas by Zone for SUR Scenario – Bottom Half

Bottom Layers Dissolved Oxygen for SUR (mg/L)									
Zone Name	**Baseline**			**SUR**			**Delta**		
	10th Percentile	Median	90th Percentile	10th Percentile	Median	90th Percentile	10th Percentile	Median	90th Percentile
FR01	2.47	3.03	3.58	2.40	3.07	3.62	-0.10	0.02	0.06
FR02	2.77	3.33	3.71	2.87	3.47	3.83	0.08	0.12	0.16
FR03	2.05	2.62	3.10	2.06	2.74	3.20	-0.01	0.13	0.19
FR04	1.64	2.22	2.68	1.66	2.34	2.88	-0.01	0.16	0.25
FR05	1.36	1.96	2.43	1.50	2.26	2.81	0.09	0.30	0.43
FR06	1.14	1.79	2.46	1.15	2.12	2.93	-0.01	0.32	0.43
FR07	**2.62**	**2.99**	**3.66**	**2.89**	**3.35**	**4.19**	**0.19**	**0.44**	**0.52**
FR08	**3.58**	**3.88**	**4.64**	**3.93**	**4.29**	**5.14**	**0.26**	**0.46**	**0.53**
FR09	4.34	4.82	5.64	4.77	5.22	6.08	0.31	0.42	0.49
FR10	5.71	6.11	6.70	6.12	6.52	7.05	0.28	0.41	0.47
FR11	**6.17**	**6.47**	**6.82**	**6.56**	**6.86**	**7.15**	**0.27**	**0.39**	**0.47**
SR	6.56	6.76	7.00	6.91	7.21	7.43	0.28	0.44	0.53
UR	7.08	7.20	7.28	7.68	8.02	8.24	0.55	0.82	1.06
BR01	**1.55**	**2.18**	**2.72**	**1.73**	**2.42**	**2.98**	**0.18**	**0.25**	**0.33**
BR02	**1.54**	**2.26**	**3.03**	**1.74**	**2.62**	**3.41**	**0.22**	**0.33**	**0.40**
BR03	**3.08**	**3.44**	**4.58**	**3.42**	**3.76**	**4.93**	**0.25**	**0.32**	**0.37**
LBR03	**4.82**	**5.20**	**6.12**	**5.00**	**5.36**	**6.32**	**0.12**	**0.18**	**0.20**
LBR02	5.66	5.96	6.56	5.81	6.19	6.79	0.15	0.24	0.26
LBR01	5.98	6.28	6.75	6.21	6.58	7.01	0.19	0.30	0.33
MR01	**3.06**	**3.33**	**4.08**	**3.36**	**3.64**	**4.48**	**0.22**	**0.37**	**0.44**
MR02	3.69	4.03	4.94	4.06	4.40	5.33	0.26	0.39	0.45
MR03	4.41	4.96	5.92	4.75	5.38	6.23	0.25	0.34	0.38
MR04	5.19	5.68	6.50	5.54	6.01	6.81	0.23	0.33	0.38
MR05	**6.14**	**6.46**	**6.87**	**6.47**	**6.81**	**7.16**	**0.23**	**0.34**	**0.40**
SCh01	2.24	2.58	2.93	2.27	2.59	2.96	0.00	0.02	0.04
SCh02	3.40	3.73	3.99	3.46	3.80	4.10	0.05	0.08	0.11
StBR	3.86	4.21	5.20	4.22	4.58	5.59	0.27	0.40	0.46

Note – indicates critical DO zone (Tetra Tech, Inc. 2010)

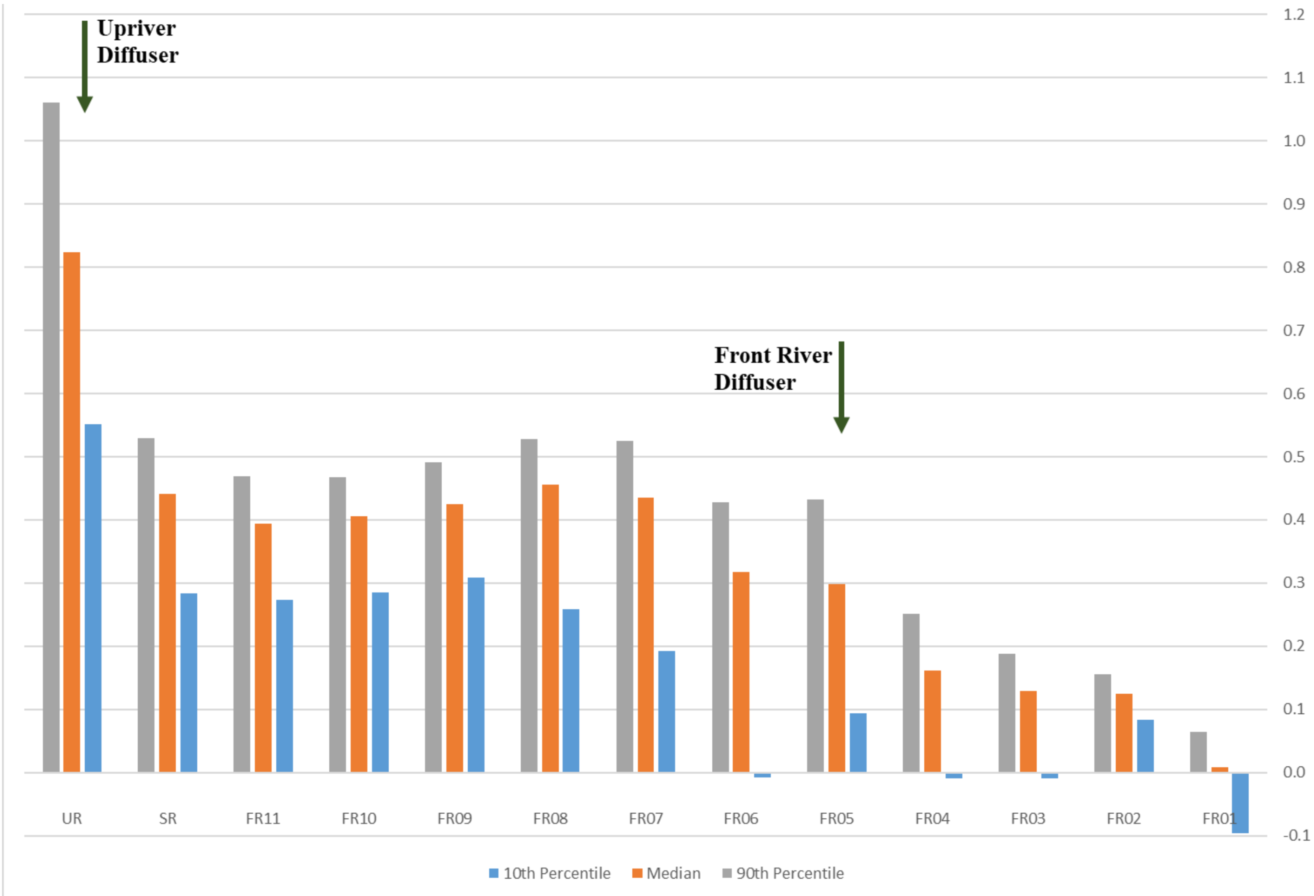

Figure 11-16 Savannah River Spatial Zone DO Deltas – SUR Scenario (bottom half)

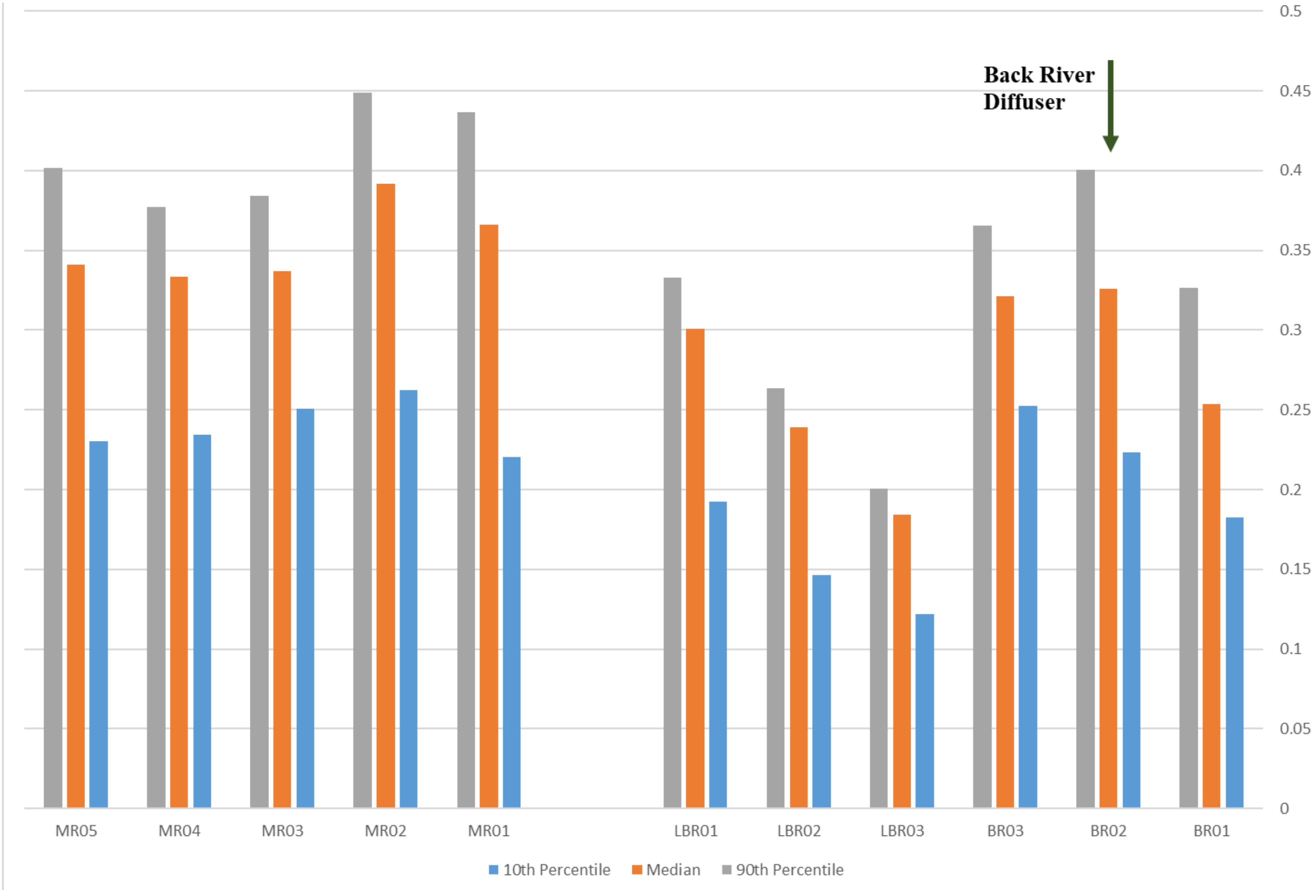

Figure 11-17 Middle River and Back River Spatial Zone DO Deltas – SUR Scenario (bottom half)

The same analysis shown for the bottom layers was completed for the whole water column. Similar results were obtained, particularly in areas that were well mixed vertically and not subject to tidal stratification. In the areas close to the injection diffuser (two to three cells) the delta values for the whole water column tend to be lower than the bottom half since the oxygen load is injected at the bottom. Results for the water column analysis are shown in **APPENDIX K.**

LINE OF EVIDENCE 4.3 – SPATIAL ANALYSIS OF THE SHEP MODEL

11.3.3 DO Cell Analysis

Changes in DO resulting from the oxygen injection system were also evaluated by calculating the changes in DO in the bottom half for each cell in the Savannah River for the SUR Scenario (***Figure 11-18***). The system was designed to mitigate the incremental effect of navigational channel deepening in 97 percent of the bottom half of the water column volume (USACE 2012a, USACE 2012b).

More than 98 percent of the cells for the SUR Scenario presented positive DO deltas complying with the criteria. Cells with no incremental values were mostly in the area between Fort Pulaski and RM 5, due to the dominance of open ocean conditions.

LINE OF EVIDENCE 3.1 – 97 PERCENT VOLUME IMPROVEMENT ACHIEVED IN BOTTOM WATERS

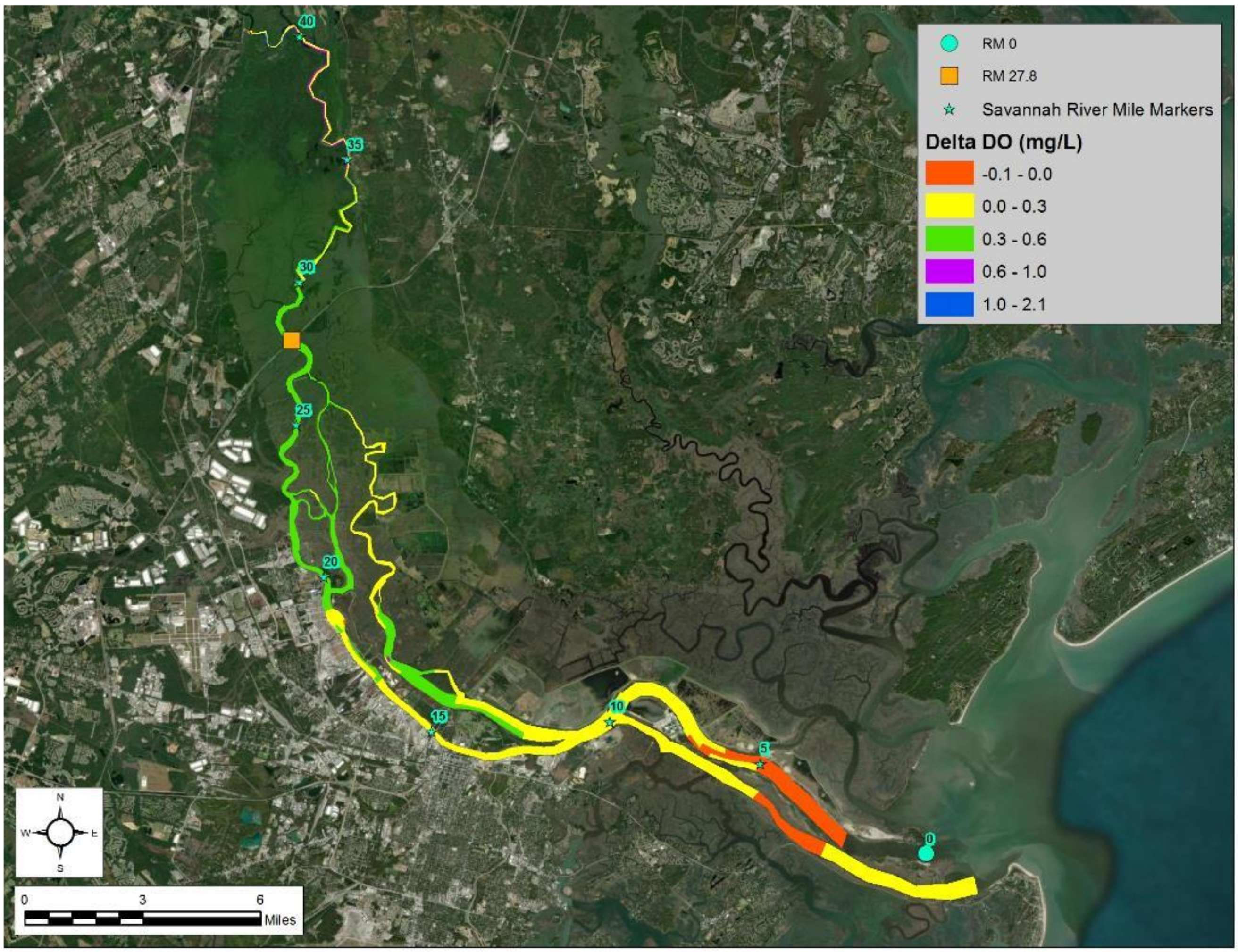

Figure 11-18 Spatial Bottom Layers Delta DO by Model Cells

LINE OF EVIDENCE 4.3 – SPATIAL ANALYSIS OF THE SHEP MODEL

11.4 MODEL EVALUATION FOR THE POST-PROJECT 2019 AND 2020 SCENARIOS

As another source of evidence of the success of the injection system, changes in DO were also evaluated for the 2019 and 2020 *Post-Project* scenarios where a constant 40,000 lbs/day were injected constantly for six and five months respectively. Similar to Section 11.3, the median, 10th, and 90th percentile of the deltas were once again calculated for longitudinal profiles and the spatial zones.

11.4.1 DO Longitudinal Profiles

Both years (2019 and 2020) presented different flow conditions during the period considered. Higher flows were evident in 2020 (***Figure 11-19***). Average flows were 7,580 cfs for 2019 and 11,311 cfs for 2020 with maximums of 20,300 cfs and 22,800 cfs respectively. The maximum DO deltas for the bottom half of the water column (***Table 11-3***) showed similar values across both years for the Middle and Back Rivers. This suggests that differences in Upriver freshwater flows do not affect them. This behavior can be explained by these two rivers being more affected by tidal flows than the riverine flow. There is also the influence of the McCoy's Cut freshwater flow rerouting project to consider, completed at the beginning of 2020. Compared to the SUR Scenario the maximum values for the Back River, which corresponds to the Back River diffuser location, were higher than for the post-project scenario in 2020 and 2019. This is due to the SUR injection having variable oxygen loads with peak injection values exceeding the constant 40,000 lbs/day considered for the 2019 and 2020 post-project scenarios.

The Front and the Savannah Rivers showed that they were influenced by the Upriver flows. The maximum delta for the Savannah River for both 2019 and 2020 was at the location of the UR diffuser, although a higher delta was determined in 2019. This is due to the lower flows and therefore lower velocities. The deltas downstream of the Upriver diffuser were larger for 2020 than 2019. Higher flow and velocities result in faster movement in the upstream reaches, allowing the injected oxygen to be transported more efficiently to the downstream estuarine areas. In particular, higher deltas were noticeable in zones FR06 to FR02 (RM 20 to RM 10) (***Figure 11-20*** and ***Figure 11-21***).

Similar to the maximum values, the longitudinal behavior of the DO deltas in the Back River and Middle River was similar for 2019 and 2020. Uniform increases in DO were present in both rivers along their entire length with average median DO deltas of 0.22 mg/L for both 2019 and 2020 for the Back River, and 0.27 and 0.32 mg/L for the Middle River (***Figure 11-22*** through to ***Figure 11-25***).

LINE OF EVIDENCE 4.3 – SPATIAL ANALYSIS OF THE SHEP MODEL

Table 11-3 Maximum DO Deltas for Longitudinal Profiles – 2019 and 2020 Post-Project Scenario (bottom half)

Scenario	Location	Bottom Layers DO Maximum Delta (mg/L)		
		10th Percentile	Median	90th Percentile
2019	Savannah River	1.26	2.16	2.88
	Front River	0.30	0.37	0.68
	Middle River	0.24	0.32	0.43
	Little Back River	0.38	0.46	0.53
2020	Savannah River	0.83	1.48	1.96
	Front River	0.37	0.58	0.86
	Middle River	0.23	0.32	0.44
	Little Back River	0.38	0.47	0.54

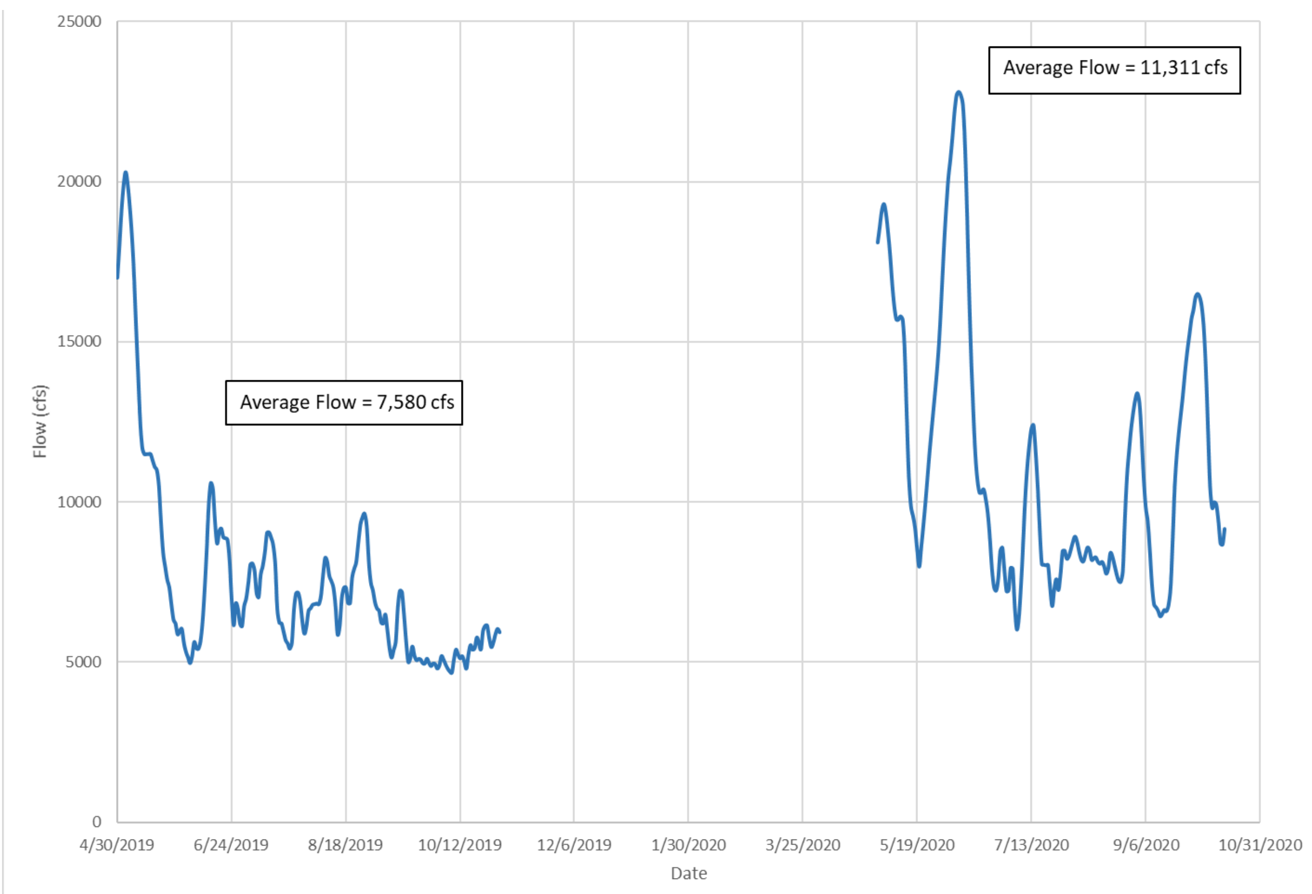

Figure 11-19 Flow at USGS Clyo (02198500)

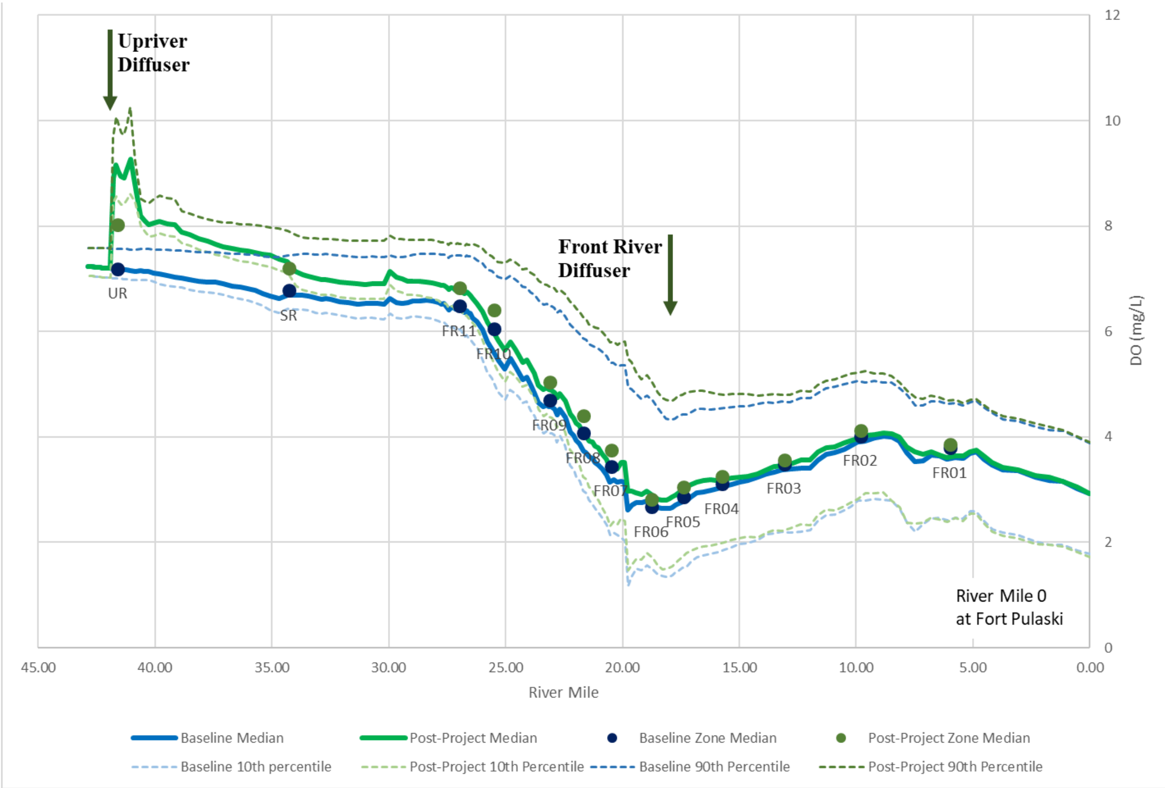

Figure 11-20 Savannah River Longitudinal Profile of DO – 2019 Post-Project Scenario (bottom half)

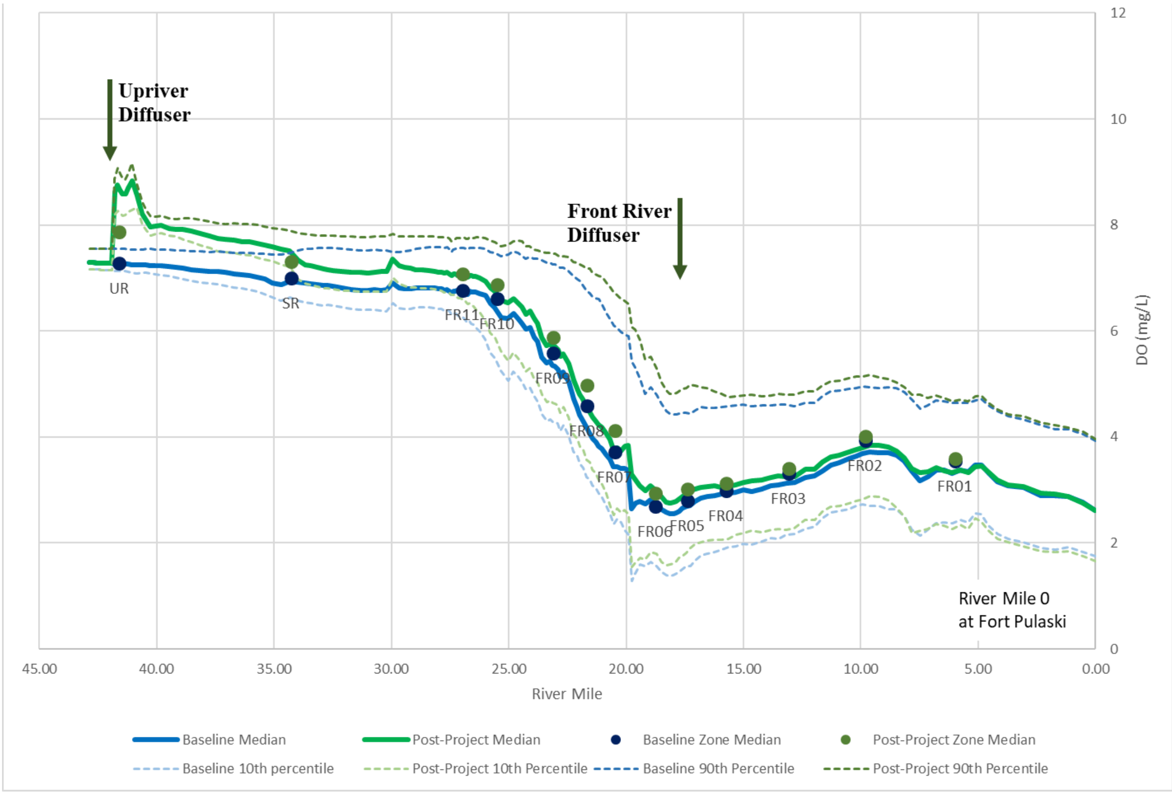

Figure 11-21 Savannah River Longitudinal Profile of DO – 2020 Post-Project Scenario (bottom half)

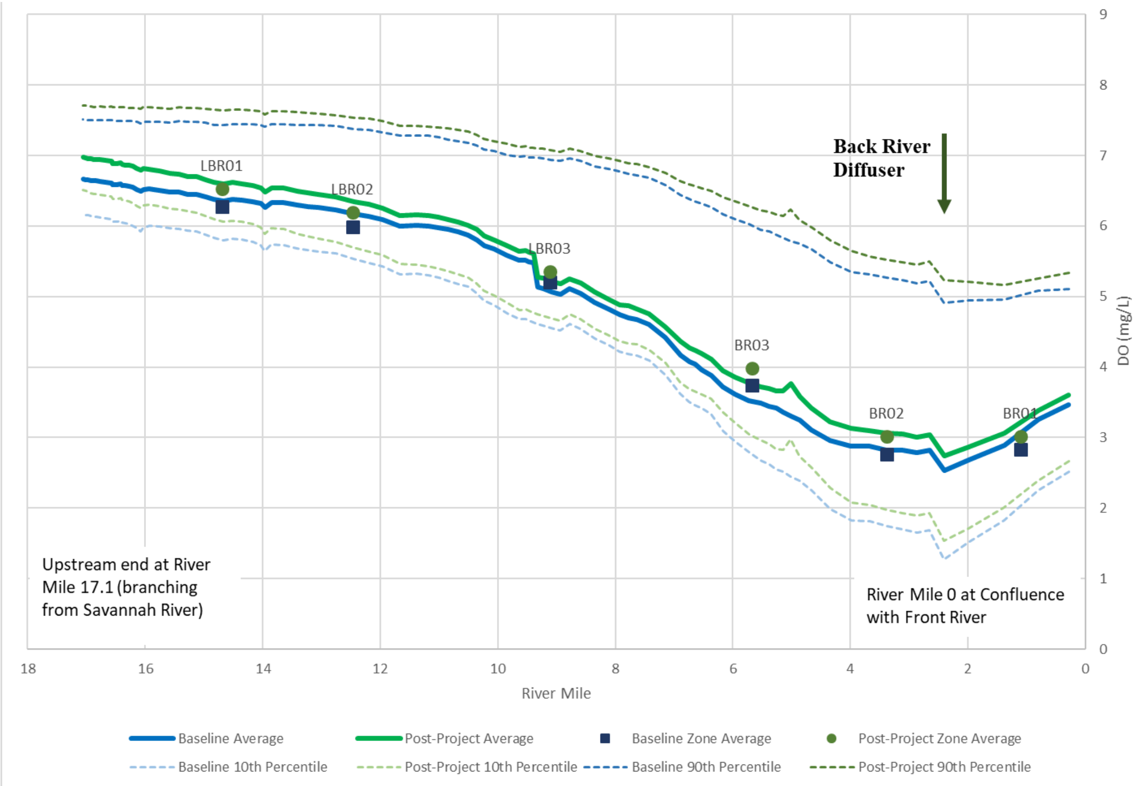

Figure 11-22 Back River Longitudinal Profile of DO – 2019 Post-Project Scenario (bottom half)

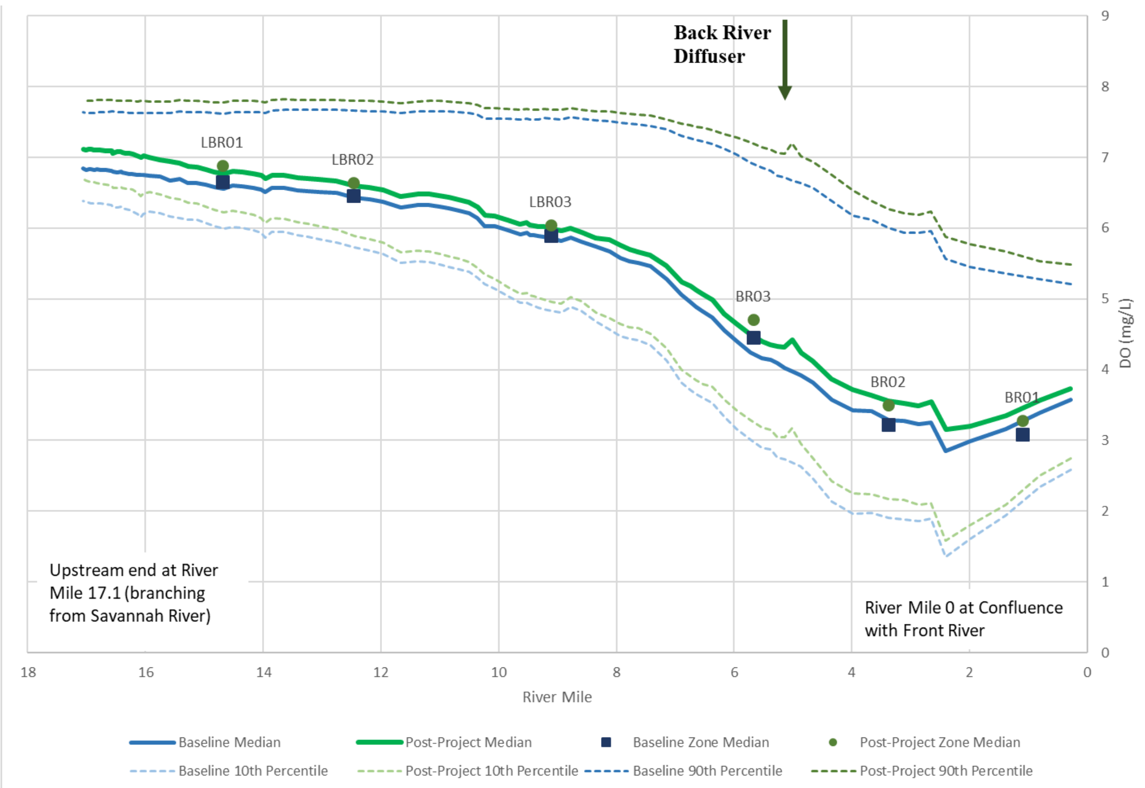

Figure 11-23 Back River Longitudinal Profile of DO – 2020 Post-Project Scenario (bottom half)

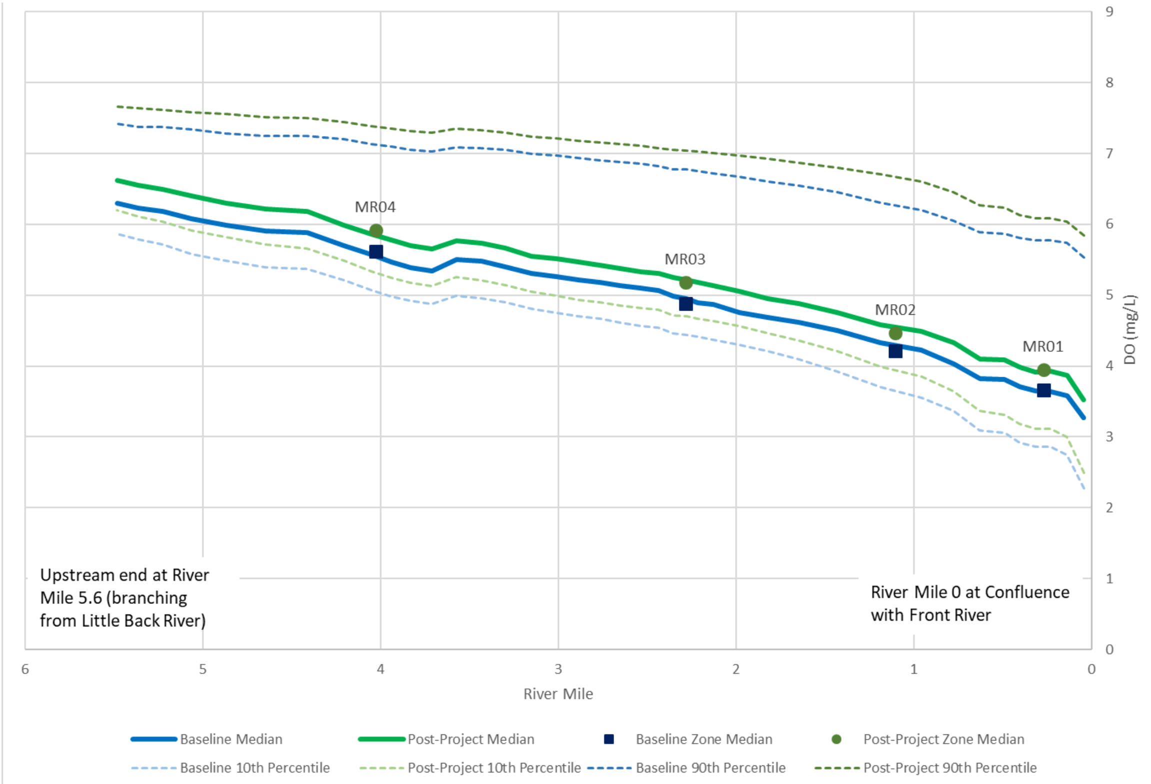

Figure 11-24 Middle River Longitudinal Profile of DO – 2019 Post-Project Scenario (bottom half)

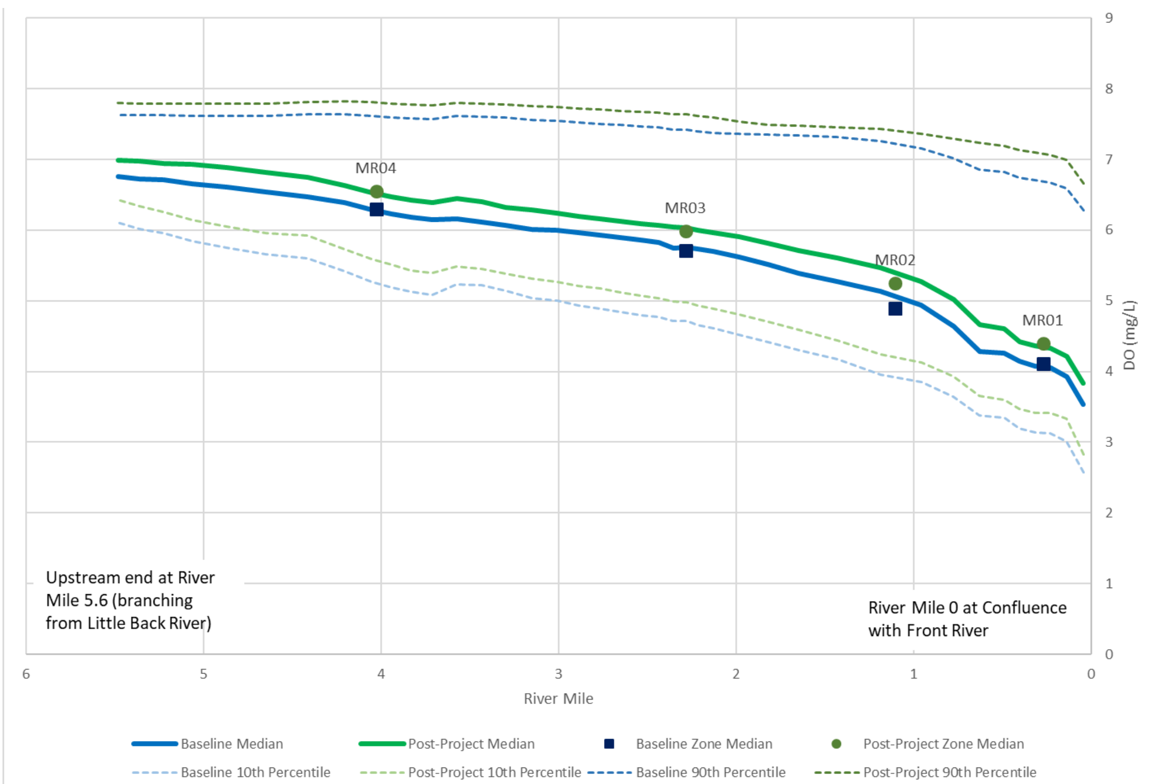

Figure 11-25 Middle River Longitudinal Profile of DO – 2020 Post-Project Scenario (bottom half)

11.4.2 DO Zonal Analysis

The DO zonal analysis indicates that the oxygen injection system positively impacts the DO in the bottom half of the water column under both freshwater flow conditions considered. The median zonal concentrations increase by values ranging from 0.02 to 0.80 mg/L for 2019 and 0.01 to 0.60 mg/L for 2020 (***Table 11-4*** and ***Table 11-5***, and ***Figure 11-26*** to ***Figure 11-29***) These results indicate that 100 percent of the zonal volume-weighted DO concentrations in the bottom half are mitigated for by the oxygen injection system during the summer period for both years and conditions.

Results for the whole water column DO and deltas are presented in **APPENDIX K.**

LINE OF EVIDENCE 3.1 – 97 PERCENT VOLUME IMPROVEMENT ACHIEVED IN BOTTOM WATERS

Table 11-4 DO Deltas by Zone for 2019 Post-Project Scenario – Bottom Half

Bottom Layers Dissolved Oxygen for 2019 (mg/L)									
Zone Name	**Baseline**			**Post-Project**			**Delta**		
	10th Percentile	**Median**	**90th Percentile**	**10th Percentile**	**Median**	**90th Percentile**	**10th Percentile**	**Median**	**90th Percentile**
FR01	2.69	3.79	4.81	2.68	3.85	4.89	-0.06	0.04	0.08
FR02	3.13	4.02	5.23	3.23	4.13	5.40	0.05	0.10	0.18
FR03	2.41	3.49	4.82	2.46	3.57	4.95	-0.04	0.09	0.23
FR04	1.93	3.11	4.66	2.02	3.26	4.89	-0.05	0.10	0.28
FR05	1.64	2.86	4.61	1.84	3.06	4.92	0.04	0.21	0.41
FR06	1.40	2.67	4.74	1.58	2.81	5.10	-0.04	0.19	0.44
FR07	**2.53**	**3.44**	**5.62**	**2.78**	**3.75**	**6.00**	**0.12**	**0.28**	**0.48**
FR08	**3.42**	**4.07**	**6.09**	**3.74**	**4.41**	**6.53**	**0.19**	**0.31**	**0.44**
FR09	4.26	4.70	6.62	4.59	5.03	6.97	0.24	0.32	0.40
FR10	5.52	6.05	7.29	5.91	6.40	7.57	0.27	0.36	0.39
FR11	**6.11**	**6.48**	**7.45**	**6.48**	**6.83**	**7.68**	**0.26**	**0.37**	**0.42**
SR	6.55	6.77	7.51	6.95	7.21	7.81	0.30	0.42	0.51
UR	7.02	7.19	7.58	7.82	8.03	8.53	0.51	0.84	1.09
BR01	**1.78**	**2.83**	**4.94**	**1.97**	**3.02**	**5.12**	**0.12**	**0.18**	**0.28**
BR02	**1.71**	**2.77**	**5.31**	**1.96**	**3.02**	**5.59**	**0.20**	**0.25**	**0.32**
BR03	**3.09**	**3.74**	**6.12**	**3.35**	**3.99**	**6.38**	**0.21**	**0.25**	**0.28**
LBR03	**4.70**	**5.20**	**6.98**	**4.84**	**5.35**	**7.12**	**0.11**	**0.14**	**0.16**
LBR02	5.57	5.98	7.40	5.75	6.19	7.56	0.15	0.19	0.21
LBR01	5.93	6.28	7.49	6.18	6.53	7.68	0.20	0.25	0.29
MR01	**2.88**	**3.66**	**5.81**	**3.15**	**3.95**	**6.12**	**0.14**	**0.26**	**0.39**
MR02	3.54	4.21	6.20	3.83	4.47	6.59	0.18	0.28	0.37
MR03	4.40	4.89	6.73	4.67	5.18	7.01	0.20	0.26	0.32
MR04	5.15	5.62	7.14	5.42	5.92	7.39	0.23	0.28	0.31
MR05	**6.07**	**6.46**	**7.49**	**6.39**	**6.76**	**7.68**	**0.23**	**0.31**	**0.35**
SCh01	2.27	3.22	4.77	2.29	3.24	4.80	0.00	0.02	0.04
SCh02	3.43	4.14	5.56	3.51	4.21	5.61	0.03	0.07	0.11
StBR	3.79	4.69	6.30	4.09	4.99	6.66	0.21	0.29	0.37

Note – indicates critical DO zone (Tetra Tech, Inc. 2010)

Table 11-5 DO Deltas by Zone for 2020 Post-Project Scenario – Bottom Half

Bottom Layers Dissolved Oxygen for 2020 (mg/L)									
Zone Name	**Baseline**			**Post-Project**			**Delta**		
	10th Percentile	Median	90th Percentile	10th Percentile	Median	90th Percentile	10th Percentile	Median	90th Percentile
FR01	2.68	3.54	4.81	2.59	3.59	4.89	0.04	0.02	0.08
FR02	3.08	3.93	5.21	3.19	4.01	5.39	0.08	0.12	0.21
FR03	2.37	3.31	4.74	2.50	3.41	4.93	0.01	0.13	0.28
FR04	1.98	2.98	4.67	2.13	3.12	4.90	0.02	0.16	0.34
FR05	1.68	2.80	4.66	1.98	3.01	5.17	0.11	0.27	0.53
FR06	1.48	2.68	4.97	1.62	2.95	5.48	0.04	0.29	0.55
FR07	**2.81**	**3.72**	**6.38**	**3.05**	**4.12**	**6.87**	**0.20**	**0.38**	**0.50**
FR08	**3.68**	**4.59**	**7.00**	**4.04**	**4.98**	**7.30**	**0.24**	**0.36**	**0.44**
FR09	4.49	5.58	7.31	4.86	5.88	7.46	0.23	0.33	0.40
FR10	5.85	6.61	7.53	6.19	6.88	7.72	0.17	0.31	0.36
FR11	**6.34**	**6.77**	**7.57**	**6.68**	**7.07**	**7.75**	**0.17**	**0.31**	**0.34**
SR	6.67	7.00	7.57	7.02	7.31	7.81	0.22	0.34	0.39
UR	7.13	7.27	7.56	7.77	7.87	8.07	0.33	0.60	0.77
BR01	**1.91**	**3.09**	**5.26**	**2.11**	**3.29**	**5.57**	**0.16**	**0.23**	**0.34**
BR02	**1.84**	**3.23**	**6.09**	**2.05**	**3.50**	**6.33**	**0.21**	**0.28**	**0.34**
BR03	**3.29**	**4.46**	**7.00**	**3.55**	**4.71**	**7.27**	**0.19**	**0.25**	**0.27**
LBR03	**4.95**	**5.90**	**7.56**	**5.09**	**6.04**	**7.69**	**0.11**	**0.14**	**0.15**
LBR02	5.78	6.46	7.66	5.95	6.64	7.80	0.13	0.18	0.20
LBR01	6.12	6.65	7.65	6.35	6.89	7.81	0.14	0.22	0.25
MR01	**3.16**	**4.11**	**6.70**	**3.46**	**4.40**	**7.09**	**0.22**	**0.30**	**0.39**
MR02	3.84	4.90	7.15	4.12	5.25	7.37	0.22	0.31	0.37
MR03	4.65	5.71	7.38	4.91	5.98	7.59	0.17	0.26	0.31
MR04	5.36	6.30	7.60	5.65	6.55	7.79	0.16	0.25	0.30
MR05	**6.29**	**6.79**	**7.63**	**6.58**	**7.08**	**7.80**	**0.16**	**0.26**	**0.30**
SCh01	2.40	3.09	5.11	2.41	3.08	5.10	0.01	0.01	0.04
SCh02	3.48	4.20	5.86	3.52	4.28	5.94	0.04	0.07	0.12
StBR	3.96	4.93	7.08	4.26	5.31	7.24	0.24	0.32	0.39

Note – indicates critical DO zone (Tetra Tech, Inc. 2010)

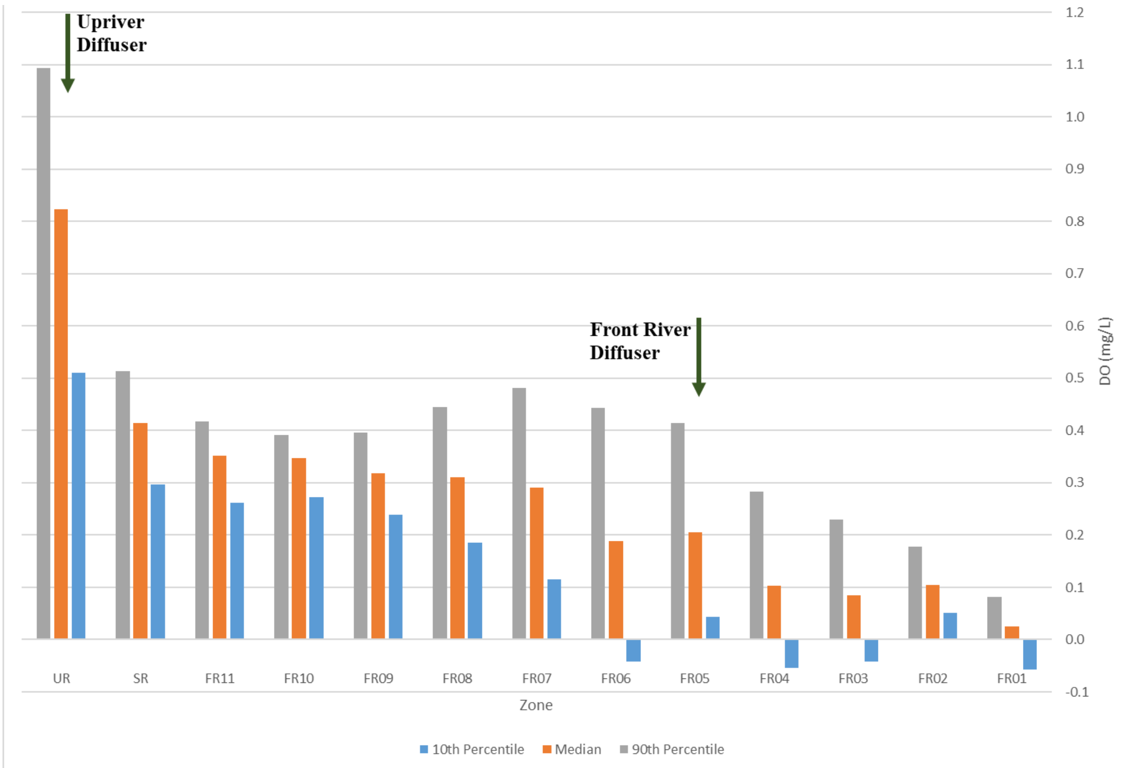

Figure 11-26 Savannah River Spatial Zone DO Deltas – 2019 Post-Project Scenario (bottom half)

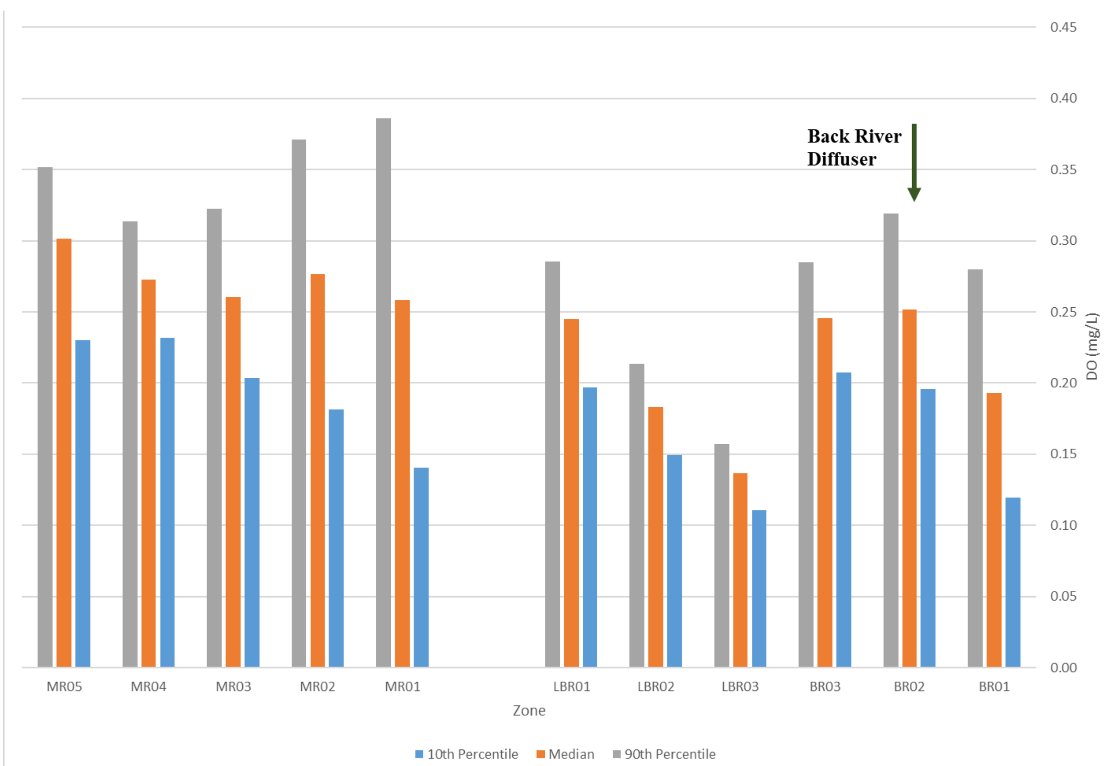

Figure 11-27 Middle River and Back River Spatial Zone DO Deltas – 2019 Post-Project Scenario (bottom half)

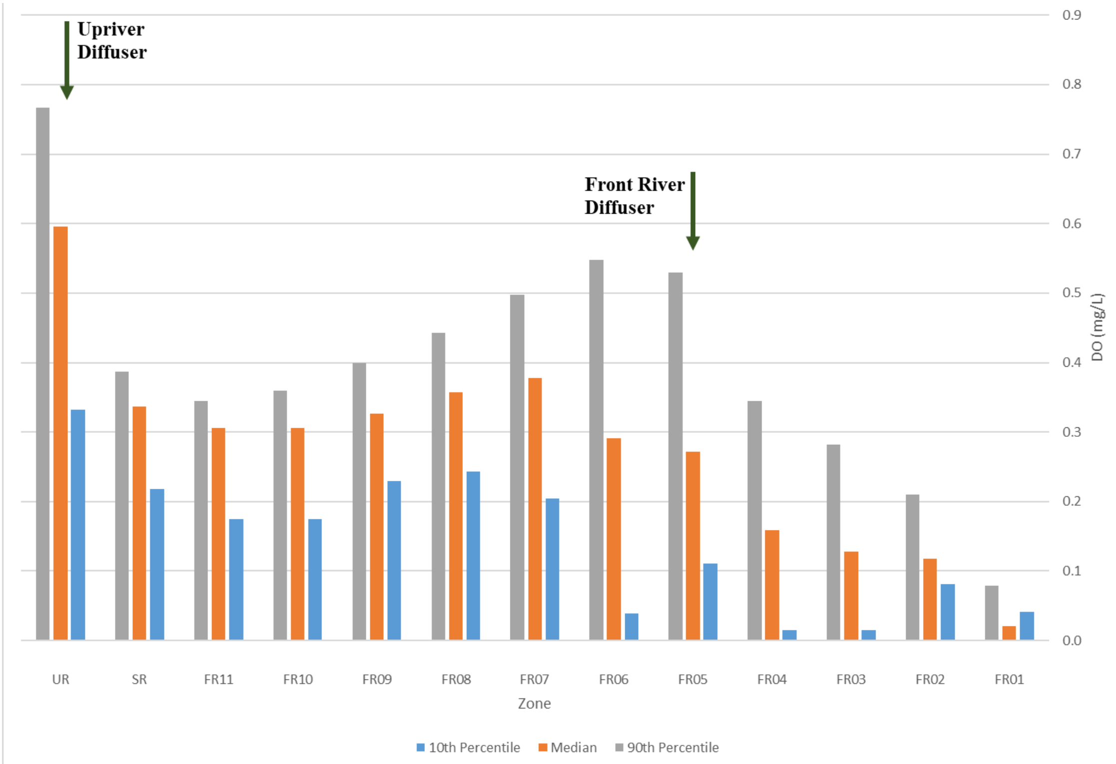

Figure 11-28 Savannah River Spatial Zone DO Deltas – 2019 Post-Project Scenario (bottom half)

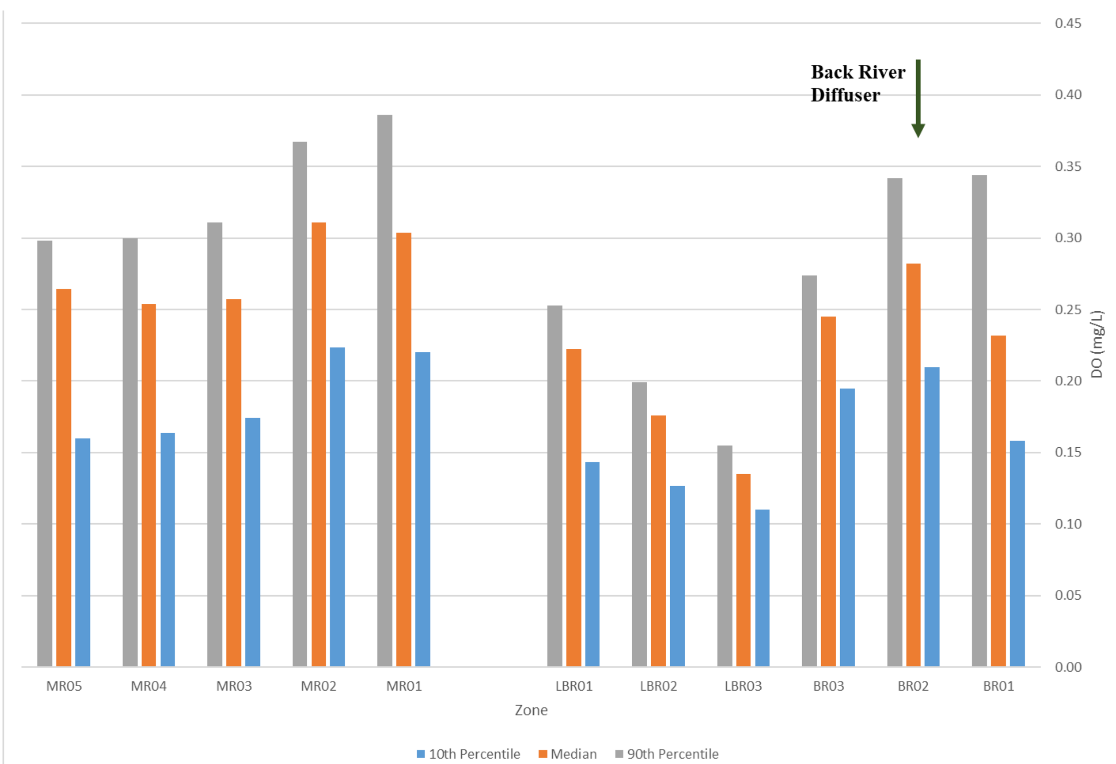

Figure 11-29 Middle River and Back River Spatial Zone DO Deltas – 2020 Post-Project Scenario (bottom half)

11.5 SUMMARY

The 2020 SHEP model has been used successfully to prove the injected and retained oxygen loads are being distributed both spatially and vertically to the areas that require mitigation. Three separate scenarios, as specified in the EIS and engineering supplemental studies, were modeled and analyzed. Significant increases in DO because of oxygen injection were observed across the Savannah River, Front River, and Back River. In addition, improvements were evident at all nine critical zones. The only region of the estuary where benefits were negligible was in the lower reaches of the Front River, between Fort Pulaski and RM 5, due to the dominance of the open ocean. Therefore, the SHEP model validates the SUR and the successful mitigation caused by oxygen injection.

12.0 CONCLUSIONS

The SUR was a continuous operation of both Upriver and Downriver oxygen injection plants with a requirement to deliver a daily average equal to or greater than the combined design production oxygen load of 40,000 lbs/day. The plants were required to operate for 59 days (two lunar cycles), of which at least one 29.5-day testing (one lunar cycle) must occur in July, August, or September, while the Upriver and Downriver plants are operational. The SUR occurred from July 25, 2020, through September 22, 2020. The USACE was required to extensively monitor the Savannah River and estuary continuously for the duration of the SUR and undertake subsequent modeling and analysis.

During the SUR data collection period, the field team successfully conducted monitoring on the Front River, Back River, and Savannah River by collecting data from semi-permanent buoy sondes, profile sondes, and drift sondes. The field data were subject to thorough QA/QC. After reviews, raw data quality was observed to be good and acceptance rates were greater than 90 percent. The field team also conducted dye releases, to track the movement and retention of the dye plumes, and therefore, oxygen injection. In total, the field crew of 15 personnel operated over 84 days and installed 21 buoys, completed 371 profile measurements, sampled 103 drifts, and implemented 10 separate dye releases. Supplementary data were also sourced from the network of publicly available USGS gages throughout the Savannah River and estuary, and the data collected at both oxygen injection plants.

The SHEP model was recalibrated to represent existing conditions more accurately throughout the Savannah River and estuary and predict future outcomes. This included multiple grid and bathymetry updates to the model to better define the cross-sections of the Middle and Back Rivers and the Savannah River upstream of I-95 up to the Upriver oxygen injection plant, as well as additional marshes to improve the tidal flow circulation in the system.

Completion of the field monitoring and model updates was the initial step in assessing SUR mitigation impacts. The Success Criteria were defined in the Compromise and Settlement Agreement (2013, bullet 11, pg. 3, Exhibit A), "**The purpose of the modeling and monitoring is to confirm that the Oxygen Injection System will mitigate for the DO impacts of the Project, as shown by comparing actual DO levels in the modeled area, from Station 0+000 upstream to RM 27.8, to DO levels in the without-Project scenario (the "Success Criteria").**" Simply stated, the Success Criteria requires evidence that DO impacts across the estuary caused by deepening the Front River have been compensated for in time (tidally and seasonally) and space (vertically and horizontally).

Neither the Success Criteria nor the EIS or GRR specify a target concentration of increased DO to appropriately mitigate for channel deepening. The dynamic nature of the Savannah River and estuary vertically, spatially, and temporally, mean specifying a target concentration increase was impossible. To address the Success Criteria, an alternative approach was needed to prove mitigation was achieved.

A tiered approach was developed whereby the Success Criteria was proven by evaluating four *Success Metrics*, each of which captured a complementary portion of the Success Criteria and were consistent with the EIS and GRR. Further, each of the four *Success Metrics* was able to be assessed by a total of 12 *Lines of Evidence*, three for each *Success Metric*. Successfully demonstrating the *Lines of Evidence* were able to be achieved would prove accomplishment of the *Success Metrics* and ultimately the *Success Criteria*, demonstrating the oxygen injection system is successfully able to inject the required oxygen loads into the river and that the injected oxygen can be retained and distributed vertically and spatially, thereby mitigating impacts to DO by harbor deepening.

The *Success Metrics* cover four complementary components essential to oxygen mitigation. The 12 *Lines of Evidence*, three for each *Success Metric*, are presented below:

1) **OXYGEN LOAD DELIVERED** – The requirement was a daily average of 40,000 lbs/day of oxygen over a continuous 59-day period to be injected into the water column during the critical summer months. Success Metric #1 was achieved during the SUR by:
   - (1.1) injecting a total daily average of more than 40,000 lbs/day for 59 days – **42,412 lbs/day were achieved**.
   - (1.2) injecting a daily average of more than 28,000 lbs/day for 59 days from the Upriver plant – **28,838 lbs/day were achieved**.
   - (1.3) injecting a daily average of more than 12,000 lbs/day for 59 days from the Downriver plant – **13,574 lbs/day were achieved**.
2) **OXYGEN LOAD RETAINED** – The requirement was for 90 percent of the delivered oxygen load to the water column to remain dissolved and saturated in the water. Success Metric #2 was achieved during the SUR by:
   - (2.1) Achieved 99 Percent Water Column Transfer Efficiency (WCTE) – **Significantly greater than the 90 percent goal, indicating almost all injected oxygen stayed within the river and was used for mitigation.**
   - (2.2) Oxygen plume retention after injection – **Evidence of oxygen retention was detected up to one month after injection on the Front River and three weeks on the Back River.**
   - (2.3) No effervescence or bubbling observed during field data collection – **No evidence on any of the 84 field sampling days.**
3) **DO MITIGATION IN BOTTOM WATERS** – The requirement was for the SHEP model to show oxygen injection mitigated median DO concentrations in 97 percent of the bottom half of the water column across the estuary. Success Metric #3 was achieved during the SUR by:
   - (3.1) Mitigation in the bottom half of the water column – **The SHEP model results demonstrated increased DO concentrations in greater than 97 percent of the total volume in bottom waters. More than 98 percent of the cells for the SUR Scenario presented positive DO deltas.**
   - (3.2) Analysis of field data (profile and dye data) – **Successfully demonstrated oxygen retention and vertical distribution of oxygen load.**
   - (3.3) USGS test-control analysis (vertical) – **successfully increased DO concentrations at two depths in the upper and bottom halves of the water column.**
4) **SPATIAL EXTENT OF DO MITIGATION THROUGHOUT ESTUARY** – The requirement was to confirm the oxygen injection system would mitigate for SHEP impacts throughout the Savannah Harbor system (from Station 0+000 upstream to RM 27.8), including critical zones identified in the EIS as being most affected by navigational channel deepening.
   - (4.1) Analysis of field data (buoy, drift, and dye data) – **Successfully demonstrated oxygen retention and spatial distribution of oxygen load.**
   - (4.2) USGS test-control analysis (spatial) – **successfully increased DO concentrations at 10 different locations across the Savannah River and estuary.**
   - (4.3) Spatial analysis of the SHEP model – **The SHEP model results demonstrated increased DO concentrations at all nine critical zones as well as the majority of the Savannah River and estuary.**

Based on analyses of both measured data and modeling results, **the conclusion is that the 12 *Lines of Evidence* suitably address the four *Success Metrics*, and therefore the Success Criteria was achieved.** During the SUR period, the system operated in accordance with requirements; demonstrating that the system is capable of meeting the DO mitigation requirements of SHEP.

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APPENDIX A SEMI-PERMANENT BUOY DATA

APPENDIX B PROFILE DATA

APPENDIX C DRIFT DATA

APPENDIX D FIELD NOTE LOGS/CALIBRATION

APPENDIX E DYE RELEASES

APPENDIX F DATA COLLECTION QA/QC

APPENDIX G USGS DATA

APPENDIX H PLANT DATA

APPENDIX I WATER COLUMN TRANSFER EFFICIENCY

APPENDIX J USGS ANALYSIS

APPENDIX K SHEP MODEL ADDITIONAL DETAIL

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