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## 1.0 INTRODUCTION

### 1.1 **PROJECT DESCRIPTION**

Applied Technology and Management, Inc. (ATM) was retained by the Georgia Ports Authority (GPA) to evaluate the environmental impacts of the proposed Savannah Harbor deepening project using two models; a three-dimensional hydrodynamic model of the Lower Savannah River Estuary; and a three-dimensional water quality model of the Lower Savannah River Estuary. The goal of the modeling effort is to provide tools capable of; (1) simulating the existing water surface elevation, currents, temperature, salinity, and dissolved oxygen (DO) in the estuary; and (2) projecting the spatial and temporal distribution of the parameters listed above under various altered conditions of physical geometry (deepening), boundary forcing, and loading conditions.

In support of the overall model development, two extensive field data collection programs were conducted, one in 1997 and one in 1999. The 1997 study was implemented in order to provide data for calibration of the hydrodynamic model as well as a simplified dissolved oxygen model. The results of the 1997 data collection are summarized in a report entitled "*Hydrodynamic and Water Quality Monitoring within the Lower Savannah River Estuary, July-September 1997*" (Applied Technology and Management, 1998b). A three-dimensional boundary-fitted model was constructed based on the 1997 data collection and the geometry of the Savannah River Estuary. Following calibration of the hydrodynamic and salinity model, a simplified DO model was developed. The model description, calibration and results were summarized in the report entitled "*Hydrodynamic and Water Quality Modeling of the Lower Savannah River Estuary*" (Applied Technology and Management and Applied Science Associates, 1998). Additionally, the model results were incorporated into the Tier I Environmental Impact Statement (EIS) for the deepening project (Applied Technology and Management and Lockwood Greene, 1998).

Following review of the EIS and the modeling report by state and federal agencies and the Modeling Technical Review Group (MTRG), it was determined that a Tier II EIS document would be required to further evaluate the potential environmental impacts of the proposed Savannah Harbor Deepening. Under the Tier II EIS a recommendation was made for providing an improved water quality model based upon a more comprehensive data set to be collected in the summer of 1999. Additionally, the 1999 data collection would provide further refinements to the hydrodynamic model. The results of the 1999 data collection effort are

summarized in a report entitled “Hydrodynamic and Water Quality Monitoring within the Lower Savannah River Estuary, July-September 1997” (Applied Technology and Management, 1998b).

In Volume 1 of this report, a detailed presentation of the calibration and validation of the Hydrodynamic Model was presented. This report (Volume II) provides a detailed presentation of the calibration and validation of the Water Quality Model along with all assumptions, inputs, formulations and analyses conducted throughout this study.

## **1.2 STUDY AREA DESCRIPTION, BASELINE HYDROLOGY AND BASELINE HYDRODYNAMICS**

The Savannah River originates in the mountains of Georgia, South Carolina, and North Carolina and flows south-southeasterly 312 miles to the Atlantic Ocean near the port city of Savannah, Georgia. The Savannah River is formed at Hartwell Reservoir by the Seneca and Tugaloo Rivers. The Savannah River, flowing in a south-southeasterly direction, forms the border between the states of Georgia and South Carolina.

The Savannah River Basin has a surface area of 10,577 square miles, of which 4,581 square miles are in South Carolina, 5,821 square miles are in Georgia, and approximately 175 square miles are in North Carolina. Like other basins of large rivers in the Southeast that flow into the Atlantic Ocean, the Savannah River Basin embraces three distinct areas: the Mountain Province, the Piedmont Province, and the Coastal Plain.

The primary area of concern for the evaluation of the proposed deepening is within the Coastal Plain region, from approximately 2 miles upstream of where the river crosses I-95 to its confluence with the Atlantic Ocean. Through this region, the river transitions from fresh to saline while passing through a highly dynamic zone with tidal ranges on the order of 8 feet, extensive tidal marshes, and current velocities exceeding 2 meters per second in places. Figure 1-1 presents the geometry of the Savannah River below the I-95 Bridge. The figure outlines the extents of the deepened channel, the river miles system within the study area, and the location of the City of Savannah in relation to the river. While this is the primary area of concern, the model grid was extended upstream to the City of Clio (RM 60) to provide flow input from the furthest downstream U.S. Geological Survey (USGS) flow gaging station.

The primary forcing mechanisms for circulation and transport within the estuarine portions of the Savannah River are the offshore tides and the freshwater inflow from the watershed.

Table 1-1 presents the tidal statistics for the Ft. Pulaski gage at the mouth of the river. The statistics show the magnitude of the tidal range within the system with a mean range on the order of 6-7 feet and a maximum range on the order of 9-10 feet. The tidal influence within the system extends well upstream of the entrance channel along the Front River, Back River and Little Back River. During periods of low flow, brackish water extends upriver as high as the crossing at I-95 (RM 27.7) and reversing flow conditions are measured as far upstream as Ebenezer Creek. Tidal fluctuations within the river extend upstream of Hardeeville (RM 34.5).

The Clio gaging station (USGS station 02198500) has been monitored continuously since 1929 and provides a comprehensive record of the freshwater flow conditions to the estuarine portions of the Savannah River. Figure 1-2 presents the historic flow conditions from 1930 to the present along with a distribution of the daily flows. The bottom plot shows the influence of the dams (put into the system in the 1950's) which reduced the maximum flow conditions; prior to 1950 the flows at times exceeded 60,000 cubic feet per second (cfs) (1699 cubic meters per second - cms). Additionally, the dams increased the minimum flow conditions on the river, and the lowest recorded daily average flow value post dam construction is 4,710 cfs (133 cms) on Nov 22, 1981. On both the distribution plot and the time series of average flows in Figure 1-2, the flow conditions for 1999 and 1997 are presented. The data shows that the average flow in 1999 was low in comparison to past years as the system entered into the extensive drought period from 1999 to 2002. The minimum daily average flow measured during the study period of August to September of 1999 was 5,600 cfs, and 5,900 in 1997.

### **1.3 STUDY GOALS**

The general goal of this study was to develop a three-dimensional water quality model that is capable of accurately simulating the temporal and spatial distribution of the dissolved oxygen within the Lower Savannah River Estuary under existing conditions as well as under a proposed deepened condition. Additionally, the model must accurately reflect the distribution of the chemical and physical parameters that govern the dissolved oxygen due to internal and external loading.


An extensive review of the model development work by representatives of the United States Army Corps of Engineers (USACE), the Environmental Protection Agency (EPA), the United States Fish and Wildlife Service (USF&W), the United States Geologic Survey (USGS), the

Georgia Environmental Protection Division (GAEPD), the South Carolina Department of Health and Environmental Control (SCDHEC), and representatives of industry and municipal discharges along the river, occurred from 1999 through the present with frequent technical review meetings. During this process, guidelines for model performance were developed by representatives from the Federal Agencies. These guidelines specified performance criteria for the simulation of the dissolved oxygen. The draft performance criteria are presented within Appendix GG (the document was not finalized through this process). The criteria provide guidelines for model performance and acceptability, but based upon discussion with the technical reviewers, do not reflect absolute criteria that must be met for the model to be deemed acceptable. The basis for model acceptability is to be based upon a weight of evidence approach, the accurate simulation of the key processes in the system within the limits of present accepted technology, and the needs of the model for predictive purposes.

The following section outlines the report components that are to provide the basis for a weight of evidence review of the Water Quality Model for the Lower Savannah River Estuary. The model was calibrated to the 1999 data set, and validated to the 1997 dataset. An important point to note is that the 1999 data collection effort was initiated primarily due to the identified insufficiencies of the 1997 data set for use in development of a water quality model that simulates absolute dissolved oxygen concentrations. The 1999 data set was far more comprehensive and included a number of specialized studies to provide sufficient data for application of the water quality model.

#### **1.4 REPORT OUTLINE**

This report will present the calibration and validation of the Water Quality Model to the data sets from 1999 and 1997 respectively. In addition, it will summarize results and studies presented within other reports that are relevant to the development and calibration of the water quality model. The following outlines the specific chapters of this report:

-  **Section 2.0: Characterization of the Water Quality in the Lower Savannah River Estuary** – Outlines key water quality aspects of the system (determined from analysis of the measured data in 1999 and 1997 and presented in Appendix L), and provides the groundwork for evaluation of the model's ability to capture key processes in the system.

- ✚ **Section 3.0: Water Quality Model Formulation** – Presents the formulation of the transport and kinetics within the BFWASP Water Quality Model.
- ✚ **Section 4.0: BFWASP Transport Tests and Mass Balance Tests** – Presents the results of the mass balance test and the test of the transport scheme within BFWASP.
- ✚ **Section 5.0: Application of the BFWASP Model to the Lower Savannah River Estuary** – Presents the development of the baseline water quality model for the Lower Savannah River Estuary using the BFWASP model including the linkage to the hydrodynamic model, the simulation periods, model geometry, boundary condition inputs, and model coefficients for both the calibration period in 1999 and the validation period in 1997.
- ✚ **Section 6.0: Water Quality Model Calibration Methodology** – Presents the graphical and statistical methods used in the model calibration.
- ✚ **Section 7.0: Water Quality Model Calibration** – Presents, the results of the calibration of the water quality model to the 1999 data set, including the graphical and statistical comparisons.
- ✚ **Section 8.0: Water Quality Model Validation** – Presents, the results of the validation of the water quality model to the 1997 data set, including the graphical and statistical comparisons.
- ✚ **Section 9.0: Water Quality Model Sensitivity Analysis** – Presents results from sensitivity analysis of the water quality model.
- ✚ **Section 10.0: Summary and Conclusions**

## 2.0 DISSOLVED OXYGEN CHARACTERIZATION FOR THE LOWER SAVANNAH RIVER ESTUARY

This section describes the physical, biological and chemical environment of the Lower Savannah River Estuary and the resulting instream dissolved oxygen and chemical characteristics that are to be modeled. The descriptions are based upon the data collection efforts conducted in 1997 and 1999 and other available data. The 1999 and 1997 data sets are described in detail below.

### 2.1 LOCATION

The drainage basin of the Savannah River consists of an area of 10,577 square miles, of which 175 square miles are in southwestern North Carolina, 4,581 are in western South Carolina, and 5,821 are in Georgia (Figure 2-1). The headwaters are located in the high-forested slopes of the Blue Ridge Mountains. The principal headwater streams, the Tugaloo and the Seneca, combine near Hartwell, Georgia, to form the Savannah River. From that point, the river flows about 300 miles southeasterly to discharge into the Atlantic Ocean near Savannah, Georgia. The major downstream tributaries include the Broad River in Georgia, the two Little Rivers in Georgia and South Carolina, Brier Creek in Georgia, and Stevens Creek in South Carolina. The basin is predominantly forested, with wetlands existing along the river floodplains. Extensive wetlands occur at the coast due to the flat topography and high tidal range.

For the purposes of this study, the Lower Savannah River Estuary consists primarily of the following sections and these are the main focus of this study (Figure 1-1):

- The main trunk of the Savannah River from the Interstate-95 (I-95) Bridge down to the river mouth at Fort Pulaski;
- The Back River, the Little Back River, and the Middle River, including the areas within the Savannah National Wildlife Refuge (SNWR), and;
- The South Channel from Fort Jackson to the Atlantic Ocean.

The harbor comprises the lower 21.3 miles of the Savannah River and about 11 miles of channel across the bar to the Atlantic Ocean. The City of Savannah, Georgia, dominates the mainland on the south side of the harbor. Savannah's historic downtown area is located on a bluff approximately 18 miles above the River's mouth. Heavy industry and shipping facilities line the harbor upstream from the City's historic downtown area to the head of the harbor. More heavy industries and a few shipping facilities line the harbor downstream from the historic downtown area to the Atlantic Intracoastal Waterway (AIWW). From the AIWW to the River's mouth, both sides of the harbor are predominantly undeveloped areas consisting of islands, marshes, dredged material disposal areas, and other natural sites. Dredged material disposal areas, former rice fields constructed in the 18th and 19th centuries, and marshes characterize the areas along the South Carolina side of the harbor. Land use on the South Carolina side of the Savannah River is basically agricultural and silvicultural, with some recreational land use. Wetland habitat types found along Savannah Harbor include saltwater aquatic, saltwater coastal flats, saltwater marshes, freshwater aquatic, freshwater flats, and freshwater marsh.

## **2.2 HYDROLOGY**

Freshwater flows near Clyo, Georgia, (RM 61) average 11,600 cfs (329 cms) with maximum and minimum annual mean discharges of 20,900 cfs (592 cms) and 9,820 cfs (278 cms), respectively, since 1962. The U. S. Geological Survey (USGS) station at Clyo, approximately 61 miles upstream of the mouth of the Savannah River, is the most downstream gage that records river discharges. Below this point, the Savannah River is tidal and USGS personnel have indicated that flow measurements would prove unreliable.

The Savannah Harbor experiences a large semi-diurnal tide. Tidal fluctuations average 6.8 feet (2.1 meters) at the mouth of the estuary and 7.9 feet (2.4 meters) at the upper limit of the harbor. The tidal influence extends approximately 45 miles upstream to Ebenezer Landing, Georgia. Maximum velocities encountered in the navigation channel are approximately 4 feet per second (fps) (1.2 meters per second - mps) on the flood tide and 5 fps (1.5 mps) on ebb tide. Ebb velocities are usually somewhat higher than flood velocities.

## 2.3 ANTHROPOGENIC IMPACTS TO THE SYSTEM

Anthropogenic impacts to the Lower Savannah Estuary are numerous due to Savannah's long history as a significant US port city. Major efforts to deepen the harbor began in 1873 when General Gilmore submitted a project for the formation of a channel, 22 feet (6.7 m) deep at Mean High Water (MHW) from Savannah to the sea. This was to be accomplished by building a dam at the Cross Tides, by widening the waterway opposite the city and by dredging the lower reach. In 1874, Congress authorized a 22-foot deep project based on this plan. This project was successfully modified and enlarged, and work under it continued until 1890.

In 1890 Lieutenant Carter submitted a plan for a 26-foot (7.9 m) MHW channel from Tybee Roads to Savannah. Since that time, the design depth of the channel has increased down to 42 feet (12.8 m) MLW with varying depths along specific reaches. The history of the federal project authorization is as follows:

- June 23, 1874: Regulating works. Annual Report 1873, p. 747.
- March 2, 1907: Tentative Provisions for a 26-foot channel from the Quarantine Station to the Seaboard Air Line Railway Bridge. H. Doc. 181, 59th Cong., 1st sess.
- June 25, 1910: Definite Provision for the 26-foot channel.
- July 25, 1912: A 21-foot channel from the Seaboard Air Line Railway Bridge to the foot of Kings Island. H. Doc. 563, 62d Cong., 2d sess.
- August 8, 1917: A 30-foot depth from the sea to the Quarantine Station. H. Doc. 1471, 64th Cong., 2d sess.
- January 21, 1927: A 21-foot channel above Kings Island. H. Doc. 261, 69th Cong., 1st sess.
- January 21, 1927: Channel 30 feet deep, with general width 500 feet, from the ocean to the Quarantine Station, thence 26 feet deep, general width 400 feet, to the Seaboard Air Line Railway Bridge, thence 21 feet deep and 300 feet wide to Kings Island. Widening at West Broad and Barnard Streets; anchorage basin; mooring dolphins; regulating dam across South Channel; relocation of the Inland Waterway; dredging Drakes Cut to 13 feet; widening to 525 feet at Kings Island; extension of training walls, revetments, and

jetties. Consolidation of projects relating to Savannah Harbor. H. Doc. 262, 69th Cong., 1st sess.

- July 3, 1930: Channel 26 feet deep and 300 feet wide from the Seaboard Air Line Railway Bridge to the foot of the Kings Island. S. Doc. 39, 71st Cong., 1st sess.
- August 30, 1935: Authorized the 30-foot project and eliminated from the project (a) the relating dam across South Channel; (b) the relocation of the Inland Waterway; and (c) the further extension of training walls, revetments, and jetties. H. Doc. 276, 73d Cong., 2d sess.
- March 2, 1945: Deepening the channel and turning basin above the Seaboard Air Line Railway Bridge from 26 to 30 feet and widening the channel opposite the Atlantic Coast Line Terminals to a maximum of 550 feet for a length of 5,000 feet. H. Doc. 283, 76th Cong., 1st sess. (1)
- November 7, 1945: Deepening the channels to 36 feet deep and 500 feet wide across the ocean bar; 34 feet deep and generally 400 feet wide, increased to 550 feet opposite the Atlantic Coast Line Terminals, with a turning basin 34 feet deep at the Mexican Petroleum Corp. Refinery; and with such modifications thereof as the Secretary of War and the Chief of Engineers may consider desirable. H. Doc. 227, 79th Cong., 1st sess. (1)
- July 24, 1946: Extending channel 30 feet deep, 200 feet wide, upstream from Atlantic Creosoting Terminal to a point 1,500 feet below the Atlantic Coastal Highway Bridge, with turning basin 30 feet deep at upper end. H. Doc. 678, 79th Cong., 2d sess. (1)
- September 3, 1954: Deepening the channel to 34 feet and widening to 400 feet, from the upper end of the presently authorized 34-foot channel in the vicinity of the American Oil Company Refinery wharf, to the Savannah Sugar Refinery with a turning basin at the upper end of the proposed improvement made by widening the channel to 600 feet for a length of 700 feet and providing approaches. H. Doc. 110, 83d Cong., 1st sess. (1)
- October 23, 1962: Enlargement of turning basin near Kings Island to a width of 900 feet and a length of 1,000 feet, with suitable approaches, at a depth of 34 feet. S. Doc. 115, 87th Cong., 1st sess.

- October 27, 1965: Deepening the bar channel from 36 feet to 40 feet, the channel between the bar channel and Garden City Terminal from 34 feet to 38 feet, and the channel from the Garden City Terminal to the vicinity of the Savannah Sugar Refinery from 30 feet to 36 feet; widening the bar channel from 500 feet to 600 feet, the channel between Fort Pulaski and Atlantic Coast Line Terminal from 400 feet to 500 feet, and the channel between Garden City Terminal and the Savannah Sugar Refinery from 200 feet to 400 feet; providing necessary wideners of the bends; constructing a new turning basin 900 feet wide by 1,000 feet long by 34 feet deep opposite the Atlantic Coast Line Terminals; and enlargement of existing turning basin at the American Oil Company Terminal from 600 feet wide by 600 feet long to 900 feet wide by 1,000 feet long. H. Doc. 226, 89th Cong., 1st sess.
- October 27, 1965: Providing sediment control works consisting of tide gate structure across Back River; sediment basin 40 feet deep, 600 feet wide, about 2 miles long, with entrance channel 38 to 40 feet deep and 300 feet wide; drainage canal across Argyle Island 15 feet deep and 300 feet wide; control works and canals for supplying fresh water to Savannah National Wildlife Refuge; and facilities to mitigate damages to presently improved areas other than refuge lands. H. Doc. 223, 89th Cong., 1st sess.
- SPCW Resolution June 15, 1976 and HPWTC of June 9, 1976 under authority of Sec. 201 of Flood Control Act of 1965: Provided for modification of the existing project to include (1) incorporation of the LASH Turning Basin as an element of the existing Federal navigation project for maintenance purposes, (2) provided for the enlargement of the Kings Island Turning Basin to 1,500 feet wide, 1,600 feet long, and 38 feet deep, and for the incorporation of the existing Oyster Bed Island Turning Basin into the Federal Navigation Project. H. Doc. 94-520, 94th Cong., 1st sess, June 8, 1976.
- July 16, 1984: Construction of 3 new work curve wideners in the inner harbor channel. Curve Widener No. 1 is between mile 11.1 and 11.9. Curve Widener No. 2 is between mile 13.2 and 13.8. Curve Widener No. 3 is between mile 14.0 and 14.8. The wideners are located on the north side of the channel. Cost of new construction \$1,711,940. PL 98-360.
- WRDA 1986 - October 17, 1986: Savannah Harbor Widening as described in Report of Chief of Engineers, dated December 19, 1978. Authorized widening channel from 400

feet to 500 feet from Fig Island Turning Basin to Kings Island Turning Basin, a distance of 5.6 miles. PL 99-662. H. Doc 6, 99th Cong., 2d sess, dated October 17, 1986, Sec. 201.

- Section 867: Allows planning, engineering and design to remove drift and debris as part of operations and maintenance.
- Section 1135: Implemented a fish and wildlife habitat restoration project which utilized material dredged from Federal navigation projects to improve salinity levels in the Back River area by filling in an existing canal.
- WRDA 1992 - October 31, 1992: Savannah Harbor Deepening - Deepened harbor by 4 feet, from -38 feet MLW to -42 feet MLW in the Inner Harbor and from -40 feet MLW to -44 feet MLW in the Bar Channel for a total of 31 miles of harbor improvements.

The effects of the continued deepening of the harbor on water quality conditions has been to greatly increase the degree of salinity intrusion into the system, and to create a much stronger degree of stratification, thereby reducing aeration of the lower waters. Additionally, maintenance dredging records have shown that the continued deepening has caused the volume of sedimentation in the harbor to significantly increase to the point where it has been determined that the full sediment load coming down the river is deposited within the navigation channel and does not reach offshore.

Another anthropogenic impact to the system has been the introduction of point source and non-point source discharges. Presently there are 8 permitted major point source discharges along the Front River below the I-95 bridge, and two above I-95 to the Clio gaging station. Non-point source discharges from the urban areas of the City of Savannah and other municipalities also discharge to the Front River.

## **2.4 JULY TO SEPTEMBER 1997 MONITORING**

The 1997 monitoring effort collected data for the purpose of calibrating a simplified dissolved oxygen model that was to examine relative impacts on dissolved oxygen from the proposed deepening effort. Under this monitoring effort a total of 14 continuous monitoring stations which measured dissolved oxygen and pH (along with hydrodynamic parameters outlined in Volume 1) were established and maintained from July 1997 through September 1997. The continuous monitoring stations consisted of permanently mounted instruments, which

recorded data at 15-minute intervals. The stations within the navigation channel generally recorded surface and bottom concentrations, while those outside of the channel recorded near-bottom concentrations. The instruments were placed near the bottom (i.e., approximately 3 feet above the bottom) in the reaches outside of the channel.

Detailed descriptions of the methodologies utilized, the locations of stations, the data collected, and findings from the field monitoring program are presented in a report entitled "*Hydrodynamic and Water Quality Monitoring of the Lower Savannah River Estuary, July-September 1997*" (Applied Technology and Management, 1998b). The following provides brief descriptions of the water quality data collected. Appendices C, E, and G present the raw continuous dissolved oxygen data, the water chemistry data, and the vertical profiles respectively for 1997.

#### **2.4.1 Continuous Dissolved Oxygen and Temperature**

Figure 2-2 shows the locations of the continuous dissolved oxygen measurements throughout the system. The stations are distributed up the Front River, Back River, Middle River, and Little Back River from offshore up to the I-95 Bridge. As the legend shows, all of the stations measured either; bottom and surface (in the channel areas along the Front River), or bottom dissolved oxygen (outside of the channel). A single station that measured the offshore dissolved oxygen (GPA-01) was positioned in the middle of the water column. Plots of the continuous dissolved oxygen data, collected in 1997, are presented in Appendix C.

#### **2.4.2 Discrete Water Chemistry Samples and Vertical Profiles**

Figure 2-3 presents the locations of stations where discrete water quality samples and vertical profiles were taken in 1997. Some of the stations had vertical profiles only and some had vertical profiles and discrete water chemistry samples.

#### **2.4.3 Point Source Discharges**

No direct point source discharge data were collected as part of the 1997 study. Available data are from DMR records and the wastewater characterization conducted in 1999 which is

discussed in detail in Section 2.5.3. Figures 2-4a and 2-4b present the locations of the point source discharges operating in 1997 and in 1999.

#### **2.4.4 Meteorological Data**

It was anticipated that the Savannah Airport would provide meteorological data that could be utilized within the water quality model for the 1997 data collection. Unfortunately, during this time period the weather station was not recording data and no local meteorological data were available.

### **2.5 AUGUST TO OCTOBER 1999 MONITORING**

The following provides a summary of the water quality data collected in 1999 and utilized in the calibration of the water quality model. These data are presented in detail within a report entitled "Hydrodynamic and Water Quality Monitoring of the Lower Savannah River Estuary, August 2 through October 9, 1999" (ATM 2000). The summary is presented as a means of identifying the data sets that were utilized in the model development and calibration process. Additional data analyses and discussion are presented within Appendix L which contains the Dissolved Oxygen Characterization Report submitted to the SMART in May of 2003.

#### **2.5.1 Continuous Dissolved Oxygen Data**

The primary data set for quantifying dissolved oxygen in the estuary consists of continuous monitoring records from 29 YSI datasondes deployed at 21 stations between the mouth of the Savannah River and the freshwater reach at river mile 43. Locations of these monitoring stations, with the deployment types and station names are shown in Figures 2-5a and 2-5b. Eight of the stations, those in the navigational channel on the Front River, consisted of two sondes, placed about a meter above the bottom and below the surface of the water. At other stations, sondes were placed near the bottom, below the surface, or at mid mean water depth, depending on location and conditions. While some of the surface meters were installed such that they move vertically with the water surface, others were set approximately 1 meter below the lower low water and did not move with the water surface.

The dissolved oxygen record at each station is a unique signal that is the result of a variety of conditions that occur at a range of time scales. These conditions include the location of the station and the sensor depth, as well as conditions at some distance from the station that are within the range of tidal excursions. Short-term and long-term tide range differences, changes in the local current regime, solar and meteorological influences, temporal variations in loading, and the history and condition of the instrument deployment may all have varying levels of influence on the resulting DO concentrations. These data were utilized to provide statistical comparison with model projections and to provide direct graphical comparison with the water quality time series of dissolved oxygen projected by the model.

### **2.5.2 Instream Water Chemistry**

Three categories of instream water chemistry data were collected and used in the model development, these were;

- Conventional water chemistry at continuous data stations;
- Long-Term Biochemical Oxygen Demand (LTBOD); and
- Marsh transect samples.

The following sections summarize the data collected under each category.

#### **2.5.2.1 Conventional Water Chemistry**

The water chemistry sampling was performed in coordination with the continuous instream water quality measurements discussed under Section 2.5.1. The sampling program included 7 weeks of sampling that occurred from August 4 through October 9, 1999. Figures 2-6a and 2-6b show the locations of the water chemistry sampling stations, which generally were coincident with the continuous stations.

The sampling program consisted of collecting a water sample at each of the instrument locations (32 locations including top and bottom instruments in the channel) on a high-slack tide, and on a low-slack tide once per week beginning August 4. Another station was added in the Savannah River near Clio, GA at the USGS Gauging Station Number 02198500 to

monitor the upstream loading into the estuary. One water sample was collected at Clio each week.

The analyses performed for each sample included:

- CBOD (inhibited)
- BOD5
- Ammonia
- Nitrate-Nitrite
- TKN
- Total phosphorus
- Ortho phosphorus

These conventional parameters were utilized, in conjunction with other data and model simulations, to provide the upstream and downstream boundary conditions. Additionally they were used for comparison with the longitudinal distribution projected by the water quality model. The complete data set is presented within Appendix F. In conjunction with the water chemistry samples, vertical profiles of dissolved oxygen were taken at each sampling. Appendix H presents the vertical profiles.

#### **2.5.2.2 Long-Term Biochemical Oxygen Demand (LTBOD)**

In a separate program, samples were collected for LTBOD analysis during Weeks 2, 4, and 6 of the weekly water chemistry sampling program. Samples were collected at low slack and high slack tides from six sites in the lower river and were also collected at the Clio site. Sample locations are shown in Figure 2-7. The LTBOD analyses were performed to provide a more detailed characterization of the BOD in the river. The analysis of the LTBOD samples provides a better measure of both total CBOD and NBOD. The analysis provides estimates of  $K_d$  and  $K_n$  (the rates at which the oxidations of carbon and nitrogenous materials occur, respectively), and it provides factors to quantify total BOD (UBOD) given BOD5. The results from the LTBOD tests are presented in Table 5-1 and in Appendix X.

### **2.5.2.3 Marsh Transect Samples**

The marsh exchange event was one of the special events of the 1999 water quality monitoring study. The purpose of this marsh study was to quantify the exchange of nutrients, DO and BOD between selected marshes and the adjacent waters. This was accomplished by monitoring water chemistry in feeder creeks that flood and drain the marsh systems. Two creeks off the Little Back River (Transects 2 and 5) and three creeks off the Middle River (Transects 1, 3 and 4) were sampled, all within the Savannah National Wildlife Refuge. Transect locations are shown in Figure 2-11. At each creek, hourly samples were collected during a single flood-ebb cycle and analyzed for a suite of parameters, including BOD<sub>5</sub>, CBOD<sub>5</sub>, nitrite plus nitrate, ammonia, and TKN. In addition, hourly measurements of temperature, salinity, and DO were taken. Two marshes were sampled on September 9 (Day 252) and the other three marshes were sampled on September 21 (Day 264). Each of these systems was also sampled for LT<sub>BOD</sub> in a separate sample collection. One sample on the flood tide and one sample on the ebb tide were collected at each of the five creeks on September 22 and analyzed for LT<sub>BOD</sub>. The LT<sub>BOD</sub> results for the marsh samples were presented in Table 5-1.

### **2.5.3 Meteorological Data**

For the 1999 monitoring efforts, 3 meteorological stations were established that measured wind, rainfall, solar radiation, relative humidity, atmospheric pressure, and air temperature. Figures 2-8a and b present the locations of these instruments. The instruments were placed as close as possible to an elevation 10 meters above the surface. Where the sensors were lower, corrections to the measured data were made.

### **2.5.4 Sediment Oxygen Demand**

Three studies measured SOD in the Savannah Harbor, these are:

- A study conducted by scientists with the EPA laboratory in Athens, GA in the summer of 1999. Results are contained in a report: *Dissolved Oxygen Diffusion Study and Sediment Oxygen Demand Study, Savannah River, Savannah, Georgia* (August 2-14, 1999, USEPA Science and Ecosystem Support Division, Ecological Assessment Branch, Athens, Georgia), (USEPA, 1999). This report is presented in Appendix CC.

- In October 1985, GAEPD and EPA cooperatively undertook a series of SOD measurements at eight stations in the estuary. The results are reported in *Savannah River Classification Study – October 1985, Sediment Oxygen*, (GAEPD, 1985). This report is presented in Appendix EE.
- A third data set, collected October 1-5, 1980, comes from *Application of CE-QUAL-W2 to the Savannah River Estuary," Technical Report EL-87-4, US Army Engineer Waterways Experiment Station, Vicksburg, MS* (Hall, Ross W., 1987).

The results of these three studies are presented in Table 5-2. These data were utilized collectively in the development of the spatial distribution of SOD throughout the system in the water quality model.

### **2.5.5 Point Source Characterization**

Ten permitted major point sources discharge to the receiving waters within the study area. Figures 2-4a and 2-4b present the locations of these point sources, and Table 5-3 summarizes the permit levels along with the minimum, maximum, and average discharge values for the period of the study, August 1999 to September 1999. These data were derived from a Wastewater Characterization Study performed by Law Engineering coincident with the data collection effort in 1999. Appendix K presents plots of the point source discharges for the period of August-September of 1999. The results of the Wastewater Characterization Study are presented in detail in a report entitled "*Savannah Harbor Wastewater Characterization Study Savannah Georgia*", (Law, 2000) (Appendix Y).

### **2.5.6 EPD Sampling Stations**

Studies conducted in the 1980s by GAEPD performed synoptic profile measurements of salinity and temperature at 10 stations along the main stem of the Front River (Figure 2-10). For the 1999 monitoring period, these stations were again sampled synoptically three times. The dates for the synoptic measurements were August 8<sup>th</sup>, 1999 and September 20<sup>th</sup> and 27<sup>th</sup>, 1999. During the August sampling efforts were made to provide cross-sectional representations of the system as well as synoptic measurements. This slowed down the sampling a sufficient degree that synoptic high and low tide measurements did not occur

using the number of crews available. The number of boats and crew were modified for the September samplings, and synoptic high and low tide measurements were taken.

## **2.6 SUMMARY OF KEY WATER QUALITY PROCESSES AFFECTING DISSOLVED OXYGEN**

In any modeling study of a complex system, a critical factor in the success is the identification of the goals of the model, (i.e. how the model is to be used); and focusing the model development on the simulation of the key processes associated. For the water quality model the goals are:

- Accurate simulation of the temporal and spatial distribution of the dissolved oxygen in the system with specific focus upon the critical reaches of the Front River navigation channel above Fort Jackson;
- accurate quantification and partitioning of the sources of oxygen demand in the system including the point source loads, marsh loads, non-point source loads, upstream river inputs, and sediment oxygen demand;
- accurate simulation of the distribution of the water chemistry influencing dissolved oxygen throughout the harbor and adjacent waters;
- accurate simulation of the instream rates of decay and decomposition of oxygen demanding material; and
- accurate representation of the primary productivity throughout the system with specific focus on the harbor areas.

To develop a model that meets the goals listed above, key water quality characteristics and processes need to be identified. For the Savannah Harbor Water Quality Model these key processes were determined through analysis of the data and presented in a report entitled “Characterization of the Dissolved Oxygen Environment of the Lower Savannah River Estuary” (Appendix L). This report was completed prior to the initiation of the final water quality model calibration, and provided the basis for the initial model set up and calibration. Subsequent data analysis through the model calibration/validation also provided insight into other processes influencing dissolved oxygen conditions in the Harbor and adjacent waters. The following summarizes the results from the data analyses and quantifies key characteristics and processes to be simulated.

### **2.6.1 Primary Productivity**

Historic studies of the harbor have generally concluded that primary productivity within the harbor area is not a significant process influencing dissolved oxygen. The findings from the 1999 data collection support this. The chlorophyll-a concentrations at the mouth of the estuary range from 4-9 ug/L with higher values in the deeper waters. Surface and bottom measurements in the entrance and moving upstream show higher values in the bottom than at the surface indicating offshore sources. The values of chlorophyll a rapidly drop off moving upstream and drop off to below 3 ug/L above Fort Jackson. The secci depth readings support this aspect with all readings between 1.0 and 1.3 meters. Appendix L presents a more detailed discussion of the primary productivity in the system.

### **2.6.2 Distribution of Loads to Savannah River Estuary**

Based upon the available data, calculations were made of the distribution of loads to the Lower Savannah River Estuary to provide an understanding of the sources of oxygen demanding material. Five source categories were identified for loading to the harbor, these were point sources, upstream watershed, urban stormwater below I-95, marshes above Fort Jackson and below I-95, and bottom sediments.

Figures 2-12 and 2-13 present the carbonaceous and nitrogenous loading rates respectively as calculated in g/s and lb/day. These values represent the average loads that occurred over the August-September 1999 data collection period. Details of how each of these were determined from the available data are presented in Appendix M. While certainly not exact calculations, they do provide a characterization of the sources coming into the system and their relative contributions. It should be noted that the sediment flux of carbonaceous oxygen demand shown represents an equivalent uptake of dissolved oxygen based upon the distribution of sediment oxygen demand; whereas the nitrogenous component represents a direct flux of ammonia from the sediments. As the results show, the carbonaceous load is on the order of 10 times the nitrogenous load, with the largest source being the marshes followed by the sediments, the upstream boundary and the point sources. In general the local stormwater loads are insignificant to the system.

### **2.6.3 Instream Water Chemistry**

The loads to the system described in Section 2.6.2 create the temporal and spatial distribution of oxygen demanding material throughout the system. Because it has been determined that primary productivity is a relatively insignificant component of the dissolved oxygen cycle within the Savannah River estuary, it is possible to examine the distribution of direct carbonaceous and nitrogenous oxygen demand in evaluating instream chemistry effects on dissolved oxygen. In both the 1999 and 1997 monitoring efforts, numerous types of measurements were taken to quantify the carbonaceous and nitrogenous oxygen demand, these included:

- 5-day biochemical oxygen demand (BOD-5)
- 5-day nitrogen inhibited carbonaceous oxygen demand (CBOD-5)
- ammonia concentrations; and
- Long-term Biochemical Oxygen Demand (LTBOD) tests with nitrogen sampling to determine nitrogenous component.

Weekly samples at each station were collected at high and low tides for the 5-day and ammonia tests. A total of 3 samples at 6 locations were taken for LTBOD tests. By determining the CBOD and NBOD components of the LTBOD tests, and using an average instream f-ratio based upon the average of the LTBOD test and converting the BOD-5 and ammonia data to CBOD and NBOD, respectively, a relatively large data set of CBOD and NBOD instream results were tabulated. While the absolute levels of the CBOD data converted from the BOD-5 data appear somewhat higher than expected some trends from the data can be examined. Figures 2-14 and 2-15 present all of the CBOD and NBOD data longitudinally along the Front River for 1997 and 1999.

In both the 1997 and 1999 data sets the data show a high area of CBOD and NBOD within the main harbor area between RM 13 and 18. (GPA-21 to GPA-08). This indicates measureable local sources in the system at this location that must be simulated by the model. In addition the relative level of increase over background concentrations coming down the river must be simulated.

#### **2.6.4 Dissolved Oxygen Characteristics and Responses**

The loads and oxygen demands presented in Section 2.6.2, influence the temporal and spatial distribution of dissolved oxygen, and dissolved oxygen deficit, within the harbor in conjunction with a number of physical characteristics as discussed in Appendix L. The most significant physical processes are;

- The daily tidal fluctuations and tidal currents and the resultant temporal changes in salinity and temperature;
- the residual flows (i.e. non-tidal) and salinity intrusion variations under spring and neap tide conditions;
- the spring-neap tide variations in vertical stratification; and
- the channel depth.

Figures 2-16 through 2-19 present the longitudinal distribution of dissolved oxygen and dissolved oxygen deficit statistics for the data collection period in 1999 and in 1997. The plots present the median value at each station along with the 10<sup>th</sup> and 90<sup>th</sup> percentiles which represent the more extreme conditions and give an idea of the degree of variation at each station.

While the 1997 data set is not as nearly complete and comprehensive as the 1999 data set, it does provide some comparisons of variations from one summer critical period to the next and represents a more normal flow condition. Both 1999 and 1997 show similar characteristics longitudinally with relatively high constant dissolved oxygen upstream of the end of the channel (RM 23). Between RM 23 and RM 18 is an area of very strong transition where both surface and bottom dissolved oxygen drops off with a very sharp drop in bottom dissolved oxygen and significant stratification. The main harbor area along the Front River from RM 18 down to RM 10 is characterized by more steady low dissolved oxygen with less stratification and lower surface values. Moving from Fort Jackson out to the offshore areas there is a steady rise in both surface and bottom values with a transition point where the surface values (representing the outgoing harbor waters) are lower than the bottom values (representing the incoming more oxygenated offshore waters). These overall characteristics are consistent for the 1999 and 1997 monitoring periods. The simulation of the overall statistical characteristics of the system will be one component of model calibration.

Another aspect of the system is the temporal response of the dissolved oxygen in the bottom waters of the harbor area (an area of critical concern in regard to the deepening project) to the various loads and other forcing mechanism. Looking at the 5 sources described in Section 2.6.2, the sediment flux is a relatively constant demand on the system, and it is not expected that significant temporal variation will occur over the 90 day monitoring period. The marshes in comparison are also relatively steady with each high tide washing material into the system. While some variation may occur between spring and neap tides, it is not expected that this variation is significant. This leaves the response to the point sources and the upstream watershed.

In order to evaluate the long-term response of the system, the continuous dissolved oxygen deficit data at key bottom stations within the harbor were filtered using a 24-hour running average to remove the tidal fluctuation components. The dissolved oxygen deficit is the dissolved oxygen saturation concentration minus the observed dissolved oxygen concentration. The dissolved oxygen deficit is useful to evaluate response of the system to loads because it does not include variations resulting from temperature and salinity effects (in contrast, the dissolved oxygen concentration is affected by salinity and temperature variations and is more difficult to interpret in regard to determining cause and effect relationships between the dissolved oxygen and the loads). Figures 2-20 and 2-21 present the filtered dissolved oxygen deficit for August and September of 1999 versus the total BOD (nitrogenous plus carbonaceous) from the upstream and point sources. The stations shown are GPA-21, GPA-06, GPA-22, and GPA-08. These are the stations within the navigation channel above Fort Jackson where the lowest measured dissolved oxygen levels were found. Examination of the loads shows that while the upstream BOD loads are relatively constant ranging from 90,000 to 130,000 lb/day, the point source loads vary significantly from as low as 10,000 lb/day up to 120,000 lb/day. Evaluation of the point source loads to the system showed that approximately 85 percent of the total BOD load comes from a single discharge located upstream of GPA-06 and downstream of GPA-22. This means that the point source loads are relatively concentrated within one area, and come in at a much higher concentration than the upstream load, thereby creating a "hot spot" in the harbor. An additional aspect of the monitoring period was that a near shutdown of the primary point source discharge occurred during the monitoring following a period of high load. This allowed the system to respond to a significant change in the point source load.

These results reveal a measurable correlation between the dissolved oxygen deficit at GPA-06 and GPA-22, and the point source discharge located between them. It is interesting to note that during this period there were two extreme neap events that occurred. The first was around August 24 when the point source load was near peak (around 120,000 lb/day), and the second around September 17 just following the point of lowest load (around 10,000 lb/day). Figure 2-22 demonstrates these by showing the salinity intrusion measured at GPA-08 (black line in Figure 2-22) versus the dissolved oxygen deficit response. While GPA-08 dissolved oxygen appears to correlate with the salinity intrusion, GPA-06 and GPA-22 appear to remain correlated with the point source load. Even under a significant neap event, the dissolved oxygen deficit at GPA-06 and GPA-22 continue to reflect the point source load to the system.

From these results an explanation of what occurred through this period was developed. During normal periods the point source load coming in at high concentrations creates an area of deficit around GPA-06 and GPA-22 which is primarily a function of the point source loads entering the system. During periods of significant salinity intrusion (neap tides) the bottom waters in this area, are pushed upstream and moves across GPA-08. As the intrusion event subsides the net movement is one of higher dissolved oxygen water from upstream moving back downstream and the mean dissolved oxygen deficit levels at GPA-08 decrease. Superimposed on this process are the daily tidal fluctuations that create significant longitudinal movement of the waters, thereby creating a highly dynamic and complex pattern of temporal and spatial variations in dissolved oxygen.

The characteristics presented herein have identified important processes that guided the calibration process presented in Section 7.0 and 8.0. The model application, calibration, and validation, were geared toward doing the best job possible under the data limitations in simulating the key processes defined herein.

### 3.0 WATER QUALITY AND TRANSPORT MODEL KINETICS AND EQUATIONS

This section presents the water quality model transport and biochemical process equations used in the model. While multiple levels of complexity are available within the model, the equations and formulations presented herein reflect those components directly utilized in the Savannah Harbor water quality simulations.

#### 3.1 TRANSPORT FORMULATION

The transport equations are derived from an Eulerian approach, using a control volume formulation. In this method, the time rate of change of the concentration of any substance within the control volume is the net result of (1) concentration fluxes through the sides of the control volume, and (2) production and sink inside the control volume. The conservation equation for any water quality parameter (C) is given by:

$$\frac{\partial C}{\partial t} + \nabla \cdot (Cu) = \nabla \cdot [D_H \nabla(Cu)] + Q \quad (1)$$

(i)      (ii)      (iii)      (iv)

where, (i) is the evolution term (rate of change of concentration in the control volume), (ii) is the advection term (fluxes into/out of the control volume due to advection of the flow field), (iii) is the dispersion term (fluxes into/out of the control volume due to turbulent diffusion of the flow field), and (iv) is the sink/source term, representing the water quality kinetics simulated in the system. Figure 3-1 presents a schematic of a water quality cell in the model.

The transport equation in the curvilinear non-orthogonal boundary-fitted system  $(\xi, \eta, \sigma)$  is given by (here shown in 2-dimensional form for simplicity:

$$\frac{\partial C}{\partial t} + \frac{U^C}{R} C \frac{\partial C}{\partial \xi} + \frac{V^C}{R} C \frac{\partial C}{\partial \eta} = \frac{D_H}{R^2 J^2} \left[ \left( \frac{\theta_\eta \theta_\eta}{\cos^2 \theta} + \phi_\eta \phi_\eta \right) \frac{\partial^2 C}{\partial \xi^2} \right. \quad (2)$$

$$\left. - 2 \left( \frac{\theta_\xi \theta_\eta}{\cos^2 \theta} + \phi_\eta \phi_\xi \right) \frac{\partial^2 C}{\partial \xi \partial \eta} + \left( \frac{\theta_\xi \theta_\xi}{\cos^2 \theta} + \phi_\xi \phi_\xi \right) \frac{\partial^2 C}{\partial \eta^2} \right] + Q$$

where C represents any water quality parameter,  $(U^c, V^c)$  are the contravariant velocities,  $D_H$  is the horizontal eddy diffusivity, J is the Jacobian of horizontal transformation,  $(\theta, \phi)$  are the spherical coordinates,  $(\theta_\eta, \theta_\xi, \phi_\eta, \phi_\xi)$  are the spatial derivatives, R is the radius of Earth, and Q represents the biogeochemical processes.

Within the BFWASP water quality model, the advection term solution utilizes a first order upwind scheme which is identical to that used in the hydrodynamic model. This solution scheme is tested between the WASP model and the hydrodynamic model. The results of the test of the solution scheme are presented in Chapter 4.0.

In the following sections, the biogeochemical processes controlling the sink/source term of Equation (2) will be discussed in detail for the water quality model of the Savannah Estuary.

### 3.2 WATER QUALITY MODEL KINETICS

The water quality model component of WQMAP is based on the same boundary-fitted grid as the hydrodynamic model. It uses the hydrodynamic model output plus additional parameters to estimate the dynamic distribution of 8 state variables in the water column and underlying benthos. The EPA WASP5 eutrophication model (Ambrose et al., 1994) forms the basis of the water quality model kinetics (Figure 3-1). The WASP5 kinetic rate equations have been incorporated into WQMAP to form a fully non-linear, eutrophication, 3-dimensional, time-dependent, advection-diffusion model system in boundary-fitted, general curvilinear coordinates.

Within the WASP formulation, in order to predict the dissolved oxygen concentrations, various levels of complexity can be used to simulate some or all of the physical and chemical processes. For the Savannah simulations, these processes include the transport and

interaction among the nutrients, carbonaceous material, DO, reaeration, and sediment oxygen demand. The primary constituents affecting the dissolved oxygen balance are:

- Uptake of dissolved oxygen from Carbonaceous Biochemical Oxygen Demanding (CBOD) material in the water column.
- Uptake of dissolved oxygen through the process of nitrification of ammonium (NH<sub>4</sub>) to Nitrate/Nitrite.
- Uptake of dissolved oxygen through bottom sediments (SOD).
- Reaeration of the surface water column, and the dynamic vertical exchange associated with stratification/de-stratification of the water column.

Within the BFWASP model, kinetic balance equations are solved for each of the state variables chosen. For the Savannah simulations, the full 8-state variable model was run including the primary productivity. The following presents a brief discussion of the individual kinetic rate equations solved within the BFWASP model that affect the oxygen balance within Savannah Harbor.

### **3.2.1 Dissolved Oxygen Balance**

The time rate of change of dissolved oxygen (DO) within the system depends on the balance between oxidation in the water column of carbonaceous and nitrogenous material, flux of oxygen to the sediments (SOD), residual and lateral transport of materials and dissolved oxygen, exchanges with the atmosphere, and retardation of vertical exchange due to stratification.

The general equation for the oxygen balance within the BFWASP model is represented by a linear equation where the water column DO concentration ( $C_{i6}$ ) is given by (Ambrose et al., 1994):

$$\frac{\partial C_{i6}}{\partial t} = k_2 \Theta_2^{(T-20)} (C_s - C_{i6}) + G_{Pi} C_{i4} \left[ \frac{32}{12} + \frac{48}{14} a_{NC} (1 - P_{NH3}) \right]$$

*reaeration*

*photosynthesis (algae growth)*

$$- k_d \Theta_d^{(T-20)} \left( \frac{C_{i6}}{K_{BOD} + C_{i6}} \right) C_{i5} - \frac{32}{12} K_{1R} \Theta_{1R}^{(T-20)} C_{i4} - \frac{SOD}{D_j} \Theta_S^{(T-20)}$$

*oxidation*

*respiration*

*sediment demand*

$$- \frac{64}{14} K_{12} \Theta_{12}^{(T-20)} \left( \frac{C_{i6}}{K_{NIT} + C_{i6}} \right) C_{i1} \quad (3)$$

*nitrification*

where,

Coefficient	Symbol	Units	Literature Range
Reaeration rate @ 20 °C	K <sub>2</sub>	1/day	0 ~100
Temperature coefficient	Θ <sub>2</sub>	-	1.008~1.047
DO saturation	C <sub>s</sub>	mg O <sub>2</sub> / L	Formula
Phytoplankton growth rate	G <sub>P1</sub>	1/day	Formula
Phytoplankton concentration	C <sub>i4</sub>	mg C / L	State Variable
Nitrogen / Carbon ratio	a <sub>NC</sub>	-	0.05~0.43
Ammonia preference factor	P <sub>NH3</sub>	-	Formula
Deoxygenation rate @ 20 °C	K <sub>d</sub>	1/day	0.02~4.24
Temperature coefficient	Θ <sub>d</sub>	-	1.02~1.06
Half saturation constant for oxygen limitation	K <sub>BOD</sub>	mg O <sub>2</sub> /L	0.5

Coefficient	Symbol	Units	Literature Range
CBOD concentration	$C_{i5}$	mg / L	State Variable
Endogenous respiration constant rate @ 20 °C	$K_{1R}$	1/day	0.05~0.8
Temperature coefficient	$\Theta_{1R}$	-	1.02~1.08
Sediment Oxygen Demand	SOD	g/m <sup>2</sup> -day	0.05~10
Temperature coefficient	$\Theta_s$	-	1.02~1.08
Nitrification constant rate @ 20 °C	$K_{12}$	1/day	0.001~0.6
Temperature coefficient	$\Theta_{12}$	-	1.02~1.08
Half-saturation constant for oxygen limitation	$K_{NIT}$	-	0.1~2.0
Ammonium Nitrogen concentration	$C_{i1}$	mg / L	State Variable
Benthic layer depth	$D_j$	M	0.0-0.7
Benthic layer index	J	-	
Water column index	I	-	

The DO fluxes on the air-water interface are determined as a product of a reaeration coefficient multiplied by the difference between DO saturation and the DO concentration at the surface layer. The reaeration coefficient is assumed to be proportional to the water velocity, depth, and wind speed (Thomann and Fitzpatrick, 1982). In BFWASP, there are three user-defined options for the reaeration coefficient:

- Constant reaeration (defined in the interface).
- Time variable (function defined in the interface).
- Calculated internally as a function of depth-averaged water velocity, depth, wind, and temperature.

For the Lower Savannah River Estuary, the third option is being used. The water velocity dependent reaeration is based on the O'Connor Dobbins formulation, and it is calculated as a function of water depth, and velocity (Ambrose et al., 1994). The BFWASP model was modified for this application to correctly implement the reaeration for a three-dimensional model. The modification was to have the model utilize the vertically integrated velocity and the total depth to calculate the surface exchange coefficient,  $K_i$ . The reaeration of the surface

layer,  $K_a$ , is then calculated by dividing the surface exchange coefficient by the depth of the surface layer. This formulation is consistent with the initial development of the O'Conner Dobbins formulation, which used the total depth and vertically averaged velocity in the development of its formulation.

### 3.2.2 Carbonaceous Oxygen Demand

The use of ultimate carbonaceous oxygen demand ( $CBOD_U$ ) as a measure of the oxygen-demanding processes simplifies modeling efforts by aggregating their potential effects (Ambrose et al., 1994). The kinetic pathway of  $CBOD_U$  ( $C_{5i}$ ) is represented in the source term of Equation (2) as:

$$\frac{\partial C_{15}}{\partial t} = \underbrace{K_{1D} C_{14} a_{OC}}_{\text{mortality/ resp.}} - \underbrace{k_d \Theta_d^{(T-20)} \left( \frac{C_{i6}}{K_{BOD} + C_{i6}} \right) C_{i5}}_{\text{oxidation}} - \underbrace{\frac{v_{s3} (1-f_{D5})}{D_i} C_{i5}}_{\text{settling}} - \underbrace{OPVX_i}_{\text{vertical exchange}} - \underbrace{\frac{5}{4} \frac{32}{14} K_{2D} \Theta_{2D}^{(T-20)} \left( \frac{K_{NO3}}{K_{NO3} + C_{i6}} \right) C_{i2}}_{\text{denitrification}} \quad (4)$$

where,

Coefficient	Symbol	Units	Literature Range
Non-predatory mortality constant rate @ 20 °C	$K_{1D}$	1/day	0.01~0.1
Oxygen / Carbon ratio in phytoplankton	$a_{OC}$	mgO <sub>2</sub> /mgC	2.67
Organic matter settling velocity	$v_{s3}$	m/day	0.5 - 2.0
Fraction dissolved UBOD	$f_{D5}$	-	0.0~0.5
Denitrification constant rate @ 20 °C	$K_{2D}$	1/day	0.02~1.0
Temperature coefficient	$\Theta_{2D}$	-	1.02~1.08
Michaelis constant for denitrification	$K_{NO3}$	mg O <sub>2</sub> / L	0~0.1
Diffusive exchange coefficient (sediment-water)	$E_{DIF}$	m <sup>2</sup> /day	0.0~2.0 x 10 <sup>-4</sup>

Coefficient	Symbol	Units	Literature Range
Benthic layer depth	$D_j$	m	0.0-0.7
Benthic layer	J	-	
Water column	I	-	

With the vertical exchange term calculated by:

$$OPVX_i = \frac{E_{DIF}}{D_j^2} (C_{j5} f_{D5} - C_{i5} f_{D5}) \quad (5)$$

diffusion

As with the dissolved oxygen, the primary productivity within the system is not a significant component; therefore, the sources/interactions of CBOD within the system are limited to external loads (these come from various sources including point sources, non-point sources, marshes, upstream boundaries, and downstream boundaries), settling to the benthos, oxidation, vertical exchange, and denitrification.

### 3.2.3 Nutrients Dynamics

For the simulations in Savannah Harbor, the nutrient dynamics are generally limited due to the insignificant level of primary productivity. While primary productivity is simulated within the model to assure that the kinetics are responding properly to the light limitation, it is not a significant process in the system. Therefore in general only the nitrogen will provide direct influence on the dissolved oxygen in the system. The processes related to the nitrogen cycle simulated in this study include;

- a) nitrification of ammonium; and
- b) denitrification of nitrate.

The following outlines the general equations for the nitrogen components and how each of the terms influences the simulations.

#### **Dissolved Ammonium Nitrogen**

Nitrogen fixation is a biogeochemical process mediated by a variety of autotrophic and heterotrophic bacteria, by which nitrogen gas is reduced to ammonium:



The kinetic pathway of ammonium nitrogen (WASP5 state variable Ci1) is represented in the source term of Equation (2) by a series of first-order reactions:

$$\frac{\partial C_{i1}}{\partial t} = D_{P1} a_{NC} (1-f_{ON}) C_{i4} + K_{71} \Theta_{71}^{(T-20)} \left( \frac{C_{i4}}{K_{mPc} + C_{i4}} \right) C_{i7}$$

*algae excr./mort.*                      *mineralization*

$$- G_{P1} a_{NC} P_{NH3} C_{i4} - K_{12} \Theta_{12}^{(T-20)} \left( \frac{C_{i6}}{K_{NIT} + C_{i6}} \right) C_{i1} + External\ Flux \quad (7)$$

*algae uptake*                      *nitrification*

where

Coefficient	Symbol	Units	Literature Range
Rate of Organic Nitrogen Mineralization at 20 deg C	$K_{71}$	1/day	.001 – 0.4
Half Saturation Constant for Phytoplankton Limitation of Phosphorus Recycle	$K_{mPc}$	mgC/L	1.0
Temperature coefficient	$\Theta_{71}$	-	1.08
Organic Nitrogen Concentration	$C_{i7}$	mg/L	State Variable

$K_{71}$ , the rate of organic nitrogen mineralization, is a function of water temperature, pH, and the C/N ratio of the residue (Reddy and Patrick, 1984).  $K_{12}$  is the nitrification rate constant, and  $K_{NIT}$  is the half saturation constant for oxygen limitation.  $P_{NH3}$  is the ammonium preference factor for algae uptake,  $G_{P1}$  is the algae growth rate,  $D_{P1}$  is the algae non-predatory mortality constant rate. Once again the terms related to primary productivity do not play a major role for the simulations presented herein, therefore the time rate of change of ammonia within any one cell in the model is mostly a function of nitrification which becomes a constant loss of ammonium in the water column.

## Nitrite/Nitrate Nitrogen

In this study, the kinetic pathway of nitrite/nitrate (WASP5 state variable  $C_{i2}$ ) is represented in the source term of Equation (2) as a sequence of first-order reactions, limited by the dissolved oxygen concentration:

$$\begin{aligned} \frac{\partial C_{i2}}{\partial t} = & K_{12} \Theta_{12}^{(T-20)} \left( \frac{C_{i6}}{K_{NIT} + C_{i6}} \right) C_{i1} - G_{P1} a_{NC} (1 - P_{NH3}) C_{i4} - \\ & \text{nitri\textit{fication}} \qquad \qquad \qquad \text{algae uptake} \\ & K_{2D} \Theta_{2D}^{(T-20)} \left( \frac{K_{NO3}}{K_{NO3} + C_{i6}} \right) C_{i2} \end{aligned} \quad (10)$$

*denitrification*

where  $K_{2D}$  is the denitrification rate constant, and  $K_{NO3}$  is the half saturation constant for oxygen limitation, which can be calibrated to only allow the denitrification process to occur under low dissolved oxygen conditions (Ambrose et al., 1994). The rate of change of Nitrate/Nitrite in the system is therefore a function of the nitrification (source) and denitrification (sink).

## Organic Nitrogen

Besides  $N_2$ , the largest pool of nitrogen in estuarine systems is dissolved and particulate organic nitrogen (WASP state variable  $C_{i7}$ ). For soluble organic nitrogen, the source term of Equation (2) can be represented by:

$$\begin{aligned} \frac{\partial C_{i7}}{\partial t} = & D_{P1} a_{NC} f_{ON} C_{i4} - K_{71} \Theta_{71}^{(T-20)} \left( \frac{C_{i4}}{K_{mpc} + C_{i4}} \right) C_{i7} \\ & \text{algal ex\textit{cr.}/mort.} \qquad \text{min\textit{eralization}} \\ & + \frac{E_{DIF}}{D_i^2} (C_{j7} f_{D7} - C_{i7} f_{D7}) \end{aligned} \quad (11)$$

*sediment / water exchange*

Based upon the limitation of the primary productivity in the system and the low levels of chlorophyll a, organic nitrogen dynamics within the system are limited.

## 4.0 WASP TRANSPORT AND MASS BALANCE TEST

Based upon recommendations made by the MTRG and the SMART, various tests were performed on the water quality model. The first tested the transport within the BFWASP model in comparison with the transport in the BFHYDRO model. The second test looked at the mass balance within the BFWASP model. The following discusses the results of those tests.

### 4.1 **WASP TRANSPORT TEST**

The calibration of the salinity transport within the BFHYDRO model presented in Volume 1 provided the basis for assuring that the transport of all constituents is sufficiently accurate. The structure of the BFHYDRO/BFWASP models within the WQMAP system are such that to run the BFWASP model the BFHYDRO model produces a hydrodynamic forcing file that is transferred to BFWASP. BFWASP then solves the advection/diffusion equation, as discussed in Chapter 3, using output from BFHYDRO; i.e. the advective velocities (in 3-dimensions) and the vertical and horizontal diffusivities. These terms are also used within the BFHYDRO model directly when it solves the advection/diffusion equations for salinity transport internally. For the internal BFHYDRO transport of salinity, these terms are recalculated at each time step and provided directly to the salinity transport routines at the time step of the model.

For the Savannah Harbor simulations the time step of the Hydrodynamic Model is 2 minutes. Due to space and run time limitations, the hydrodynamic forcing file from the BFHYDRO model outputs forcing functions every 1 hour. Within the BFWASP model the time step is 1 minute meaning the outputs from the hydrodynamic forcing file must be interpolated in order to provide values at each time step within BFWASP for the advection/diffusion equation solution. The interpolation can create errors within BFWASP relative to the terms used in BFHYDRO for the salinity transport. Therefore a test was done to demonstrate that the error in the transport within BFWASP is not significant relative to the BFHYDRO transport.

In order to demonstrate the accuracy of the BFWASP transport, simulations of the salinity were performed in BFWASP using a conservative substance with identical boundary and input conditions as the salinity run within BFHYDRO. The two are then compared to show the relative difference and the potential error introduced through the interpolation of the

hydrodynamic forcing file. In addition, a comparison between the measured salinity and the simulated salinity from BFWASP are compared using the same statistical methods used in the hydrodynamic model calibration to see how any errors reflect in the direct calibration.

Appendix O presents a detailed discussion of the WASP test along with graphs and tables of the results. The test showed that while there were some minor differences in the WASP simulation of salinity relative to the hydrodynamic simulations, those differences are not significant and do not increase over time. The transport within BFWASP is sufficient for use in the water quality model and will demonstrate the same overall transport characteristics as the hydrodynamic model.

#### **4.1 MASS BALANCE TEST**

Appendix O also presents the results from the mass balance tests on the BFWASP model. The test evaluated the change in mass over time within the system in comparison with the net input and flux of material across the boundaries.

## 5.0 APPLICATION OF THE BFWASP MODEL TO THE LOWER SAVANNAH RIVER ESTUARY

This section presents the model boundary conditions, the model coefficients, and the simulation periods for the water quality model calibration and validation. These inputs represent the best available data from the 1997 and 1999 data collection programs, and where necessary, data from other available sources.

### 5.1 **LINKAGE OF WATER QUALITY MODEL TO HYDRODYNAMIC MODEL**

As discussed in Chapter 4 on the BFWASP transport test, the BFHYDRO model provides the drivers for transport to the BFWASP model using a hydrodynamic forcing file that passes the velocities, cell volumes, volume fluxes, water surface elevation, salinity, temperature, and vertical and horizontal mixing terms. This forcing file is saved at 1 hour time steps as the hydrodynamic model is being run, and then used to drive the transport within the BFWASP model. Chapter 4 and Appendix O presented tests to demonstrate that this transfer of data does not create significant errors in the transport within BFWASP.

### 5.2 **SIMULATION PERIODS**

#### 5.2.1 **Model Calibration**

The calibration of the water quality model was performed using the data from the 1999 monitoring effort. The data collection began on July 26<sup>th</sup>, 1999 and was completed on October 9<sup>th</sup>, 1999. During this period not all instruments were operating simultaneously but data were collected through this entire period. For the 1999 water quality simulations, the model was spun up over a 2 week period from July 7, 1999 to July 23, 1999. This spin up period was to allow instream concentrations of the 8-state variables in BFWASP to come to equilibrium with the external loadings, meteorological inputs, and the transport. The model was then run for a full 3-month period, from July 24, 1999 to October 31, 1999. Model comparisons are discussed and presented for the calibration period discussed above in Chapter 7. Requested sub-period calibration tables and complete plots are presented within Appendix U.

### **5.2.2 Model Validation**

The validation of the water quality model was performed using the data from the 1997 monitoring effort. The data collection began on July 1, 1997 and was completed on October 31, 1997. During this period not all instruments were operating simultaneously but data were collected through this entire period. For the 1997 water quality simulations, the model was spun up over a 2 week period from July 1, 1997 to July 14, 1997. The model was then run for a full 3.5-month period from July 15, 1997 to October 31, 1997. It should be noted that the data collection effort conducted in 1997 was not nearly as rigorous as the data collection effort for 1999. Numerous assumptions and carryovers from the 1999 inputs were applied to the 1997 run that may or may not be fully applicable. The validation needs to be examined in this light.

## **5.3 MODEL GRID AND BATHYMETRY**

The model grid and bathymetry were presented and discussed in detail within the hydrodynamic model report (Volume 1). As the model grid and bathymetry used within the water quality model are identical to that used in the hydrodynamic model, the grid and bathymetry are presented and summarized below to provide a complete description of the water quality model inputs. A more detailed discussion of the data that was utilized to create the model grid and bathymetry is presented in Volume 1: Hydrodynamic Model.

### **5.3.1 Model Grid**

The model grid was constructed based on the study area high water shoreline. For the purposes of this study, a single shoreline base map was created which covered the entire study area. This base map was created in GIS from existing National Oceanographic and Atmospheric Association (NOAA) shoreline base maps, and updated and corrected to the most recent rectified aerial photography in the region.

Figure 5-1 presents the computational grid used in the model simulations. The grid extends from offshore Tybee Island (RM -6.0) to the USGS gauging station at Clyo (RM 61). It includes the Front River, South Channel, Back River, Middle River, and the Little Back River. The extensive freshwater marsh areas of the system are represented by storage cells that

are attached to secondary tributaries and feeder creeks. In addition, Union Creek, Knoxboro Creek, and Abercorn Creek were also represented in the grid.

For the Lower Savannah River Estuary grid, the resolution along the Front River is roughly 200 meter lengths along the primary flow direction, with the river cross-section represented by 5 grid cells. Along the Back River, the longitudinal scale is similar to the Front River with 3 cells representing the cross-section. Along the Middle River and Little Back River, the longitudinal resolution is roughly 100 meters, with 3 to 4 cells representing the cross-section. As the shoreline that is utilized to generate the grid is based upon a high water line, there are multiple regions where extensive marshes and tidal flats are included within the flooded area, but are not part of the primary flow pathways. In these instances the grid is designed to accurately represent the primary flow pathways. This is most evident along the Back River above the former location of the tide gate. The model has a total of 2808 computational horizontal grid cells with 11 cells in the vertical. The vertical resolution is governed primarily by the need to represent the vertical stratification conditions along the main channel. The same baseline grid was used for both the 1997 and 1999 model simulations.

### **5.3.2 Model Bathymetry**

Figure 5-2 presents a contour plot of the bathymetry used in both the 1999 and 1997 simulations. Figure 5-3 presents a longitudinal plot of the depths used in the model versus those measured in 1999 and 1997 respectively along the Front River. A detailed description of how the bathymetric data were developed is presented within the hydrodynamic model report (Volume 1).

## **5.4 DISTRIBUTION OF LOADS TO THE LOWER SAVANNAH RIVER ESTUARY**

In order to provide initial estimates of CBOD<sub>u</sub> and nitrogen series loads to the Lower Savannah River Estuary, five source categories from which these parameters are expected were first established. These categories are:

- Point sources (municipal and industrial)
- Upstream watershed above Clyn
- Urban stormwater

- Marshes
- Estuarine/riverine sediments

CBODu and nitrogen series loads were estimated for each source category using the methods outlined in Appendix M, Evaluation and Comparison of Estimated Loading Rates to the Savannah River Estuary. Those methods are summarized here.

For the 10 point sources discharging to the Lower Savannah River, daily loading rate information for CBODu, NH<sub>4</sub>, and NO<sub>3</sub> and organic nitrogen was extracted from the Law Engineering document, Savannah Harbor Wastewater Characterization Study, Savannah, Georgia (May 17, 2000) to calculate total loads for August – October 1999 (Law, 2000). For days when actual measurements were not available, interpolation techniques were applied.

The upstream boundary (Clyo) loads were calculated using hourly flow data from the USGS gauge at Clyo, and CBODu, NH<sub>4</sub>, NO<sub>3</sub>, and organic nitrogen concentrations provided by EPA Region 4 and the Georgia EPD. These concentrations resulted from a specific 1999 application of the EPA Region IV, EPD-RIV1 water quality model (Whitlock, 2002).

Daily urban stormwater loading rates for NH<sub>4</sub>, NO<sub>3</sub>, TKN, and BOD<sub>5</sub> were provided for 8 Savannah catchments by MACTEC Engineering and Consulting in their January 10, 2003 report to the Savannah Harbor Committee (Report of Results, Savannah Harbor-Stormwater Quality Modeling, Savannah Harbor Expansion). Daily loads and total loads for each catchment and each parameter were summed for the period between August 1 and October 31, 1999. Total BOD<sub>5</sub> loads were converted to total CBODu loads using a f-ratio multiplier established from the point source analyses (3.91).

CBODu and nitrogen series loads from the Savannah Estuary marshes were estimated using ebb and flood tide nitrogen series concentrations from Appendix I, “Measured Marsh Water Quality Transects for 1999” and from the Law Engineering document, “Long Term Biochemical Oxygen Demand Test, Marsh Samples, Lower Savannah River, Savannah, Georgia, September 1999 through January 2000 (Law 2000)” (Appendix FF). The nitrogen series and BOD concentrations were recorded for 5 transects within the Savannah National Wildlife Refuge (Figure 2-11). These concentration values were used in concert with marsh volumetric fluxes estimated using a GIS layer of the delineated marsh areas, along with assumptions for the average depth of marsh drainage, and the average percentage of marsh areas inundated. Daily estimated ebb and flood loads were calculated for organic nitrogen,

ammonia, nitrate-nitrite, and CBODu by taking the product of the calculated daily marsh exchange volumes and the appropriate (flood or ebb) concentration.

As a quality check on the process and assumptions used to estimate the marsh CBODu loadings, a second assessment of loadings, based on primary productivity in the marshes, was also performed. The quality check used an average productivity rate for mixed-species communities from the US Fish and Wildlife Service document "The Ecology of Tidal Freshwater Marshes of the United States East Coast: A Community Profile" (FWS/OBS-83/17), along with assumptions of growing season length, carbon to biomass ratio, marsh biomass export coefficient, dissolved to total carbon ratio, and average percentage of marsh areas inundated. The estimated CBODu loading rate calculated using this approach compares well with the loading rate calculated from the transect concentration information, and is within a factor of 2. Appendix M presents the details of the calculations.

Equivalent Sediment Oxygen Demand (SOD) and ammonia (NH<sub>4</sub>) loads from Savannah estuary sediments were calculated using the WQMAP grid of the estuary and SOD rates from 14 stations in the estuary, as shown in Table 5-2. SOD rate values for all WQMAP grid cells were calculated via linear interpolation between the 14 stations. The total equivalent SOD for the Savannah estuary between Fort Pulaski and GPA-14 was calculated within ArcView 3.2 by calculating the product of SOD rate and cell area for each grid cell. NH<sub>4</sub> load from the sediments was calculated using the SOD for each WQMAP grid cell and the sediment excretion relationship of 0.07 grams NH<sub>4</sub>-N/gram SOD. This value is in accordance with the Georgia EPD document, Savannah River Classification Study – October 1985, Sediment Oxygen Demand Surveys (Appendix EE).

Figures 5-4 through 5-7 show the resultant source category loading distributions within the Lower Savannah River for CBODu, ammonia (NH<sub>4</sub>), nitrate-nitrite (NO<sub>3</sub>), and organic nitrogen. Loads are expressed in grams/second (as used in model) and lbs/day. It should be noted that, for the CBODu plot, sediment flux SOD is plotted along with the CBODu values for the other source categories. This is not exactly a direct comparison as the sediment flux represents the actual rate of oxygen depleted from the system through the simulation period, while the other loads represent a potential and may not fully exert themselves prior to leaving the system.

For the organic nitrogen plot, both sediment flux and point sources show no contribution of organic nitrogen. This is because (a) no organic nitrogen measurement data was available for the sediments and (b) no organic nitrogen or total kjeldahl nitrogen data was available for

point sources. Finally, no contribution (or loss) of NO<sub>3</sub> from sediment flux is included in that plot, since no NO<sub>3</sub>-N measurement data was available for the sediments.

The results show that for the most part the primary oxygen demands to the system come from four of the sources; the sediments, the marshes, the upstream boundary, and the point sources. The point sources represent around 20 percent of the overall load of oxygen demanding material to the harbor but they differ from the other sources in two ways, these are;

- Nearly 85 percent of the point source loads come in at one location within a relatively confined area.
- The direct concentrations discharged to the system are much higher for the point sources than the other sources which are more dilute and distributed around the harbor and adjacent waters.

This load distribution evaluation formed the basis for assuring that the model was partitioning the loads to the system accurately and that an accurate and fair proportioning was applied.

## **5.5 MODEL INPUTS AND BOUNDARY CONDITIONS FOR 1999**

Constituent concentrations, in several forms, are specified at all of the model boundaries (i.e., the upriver boundary, the marsh boundaries, and the offshore boundary). Each of the boundary conditions will be described in the sections below.

### **5.5.1 Offshore Boundary**

Constant concentrations for all of the state variables were specified at the open boundary, with the exception of DO where a percent of the calculated saturation value was specified. The boundary condition concentrations are given in Table 5-5.

As a part of this study however, the WASP model was modified to allow for a time series input of water chemistry constituent concentrations at the offshore boundary. The hydrodynamic and salinity model calibration process showed that the offshore concentration of salinity was an important variable in determining the salinity distribution in the estuary. The model calibration was improved during periods when a dynamic offshore salinity boundary

could be provided from measured data. Using a constant offshore salinity based on the average of the measured data resulted in poorer model-to-measured data salinity comparisons in the estuary. Similarly, it is expected that a dynamic offshore boundary for water chemistry constituents will result in better model-to-measured data comparisons in the estuary.

The dynamic offshore boundary concentrations were not available for the model simulations presented within this report. These were to be provided by the output from a DO data mining analysis to be performed by the USGS and Advanced Data Mining (ADM). At present, adequate measured data in the offshore area are not available to provide a dynamic offshore boundary of measured concentration time series without the data mining effort.

### **5.5.2 Upstream Boundary**

Similar to the offshore boundary, the WASP model was modified to allow for a time series input of water chemistry constituent concentrations at the upriver boundary. The river boundary concentrations are provided by upstream river modeling results. The EPD-RIV1 model developed by the GAEPD and USEPA was used to simulate the 1999 period (Whitlock, 2002). The results of this model were used as a time series input to the upriver boundary in the model with minor modifications. A report presenting the results of the EPD-RIV1 model is presented in Appendix DD.

The output from the EPD-RIV1 model generally agreed with data and provided reasonable values for the upstream concentrations at Clyo. Comparison of the results of the BFWASP model to data at GPA-17 and GPA-14 using the EPD-RIV1 input indicated that while the trends of the predictions were reasonable, some of the levels were high or low coming into the estuarine portion of the system. This indicated that processes occurring from Clyo down to the area of interest in the water quality model (below GPA-17) may not be accurately simulated by the model, or that the upstream EPD-RIV1 simulations did not completely capture the absolute levels of the parameters. This is not unexpected given that the area above GPA-17 was not an area of interest for this project and no data were gathered in this region to define processes. It was always assumed that under this modeling effort, the goal would be to assure that the upstream concentrations entering the area of interest (below GPA-17 and GPA-14) would be as accurate as possible. To correct this problem, boundary matching was performed on the model such that the upstream concentrations of the model

input were adjusted (while keeping the overall trends in the data) to match conditions at GPA-17. This assured that the concentrations coming into the estuary were reasonable in relation to the measured data. The boundary matching concept was presented to the SMART for review and it was agreed that this would be a reasonable change to make in the model. Figures 5-8a through 5-8d presents the time series upstream boundary concentrations used in the model, along with the available measured data at Clio.

### **5.5.3 Marsh Boundaries**

The marsh boundaries used in the WASP model were modified for this study from the original constraint of constant concentration specification only, to also allow the specification of a decay or growth rate (positive, negative or zero) for each constituent. For the growth term, a logistics curve was used rather than a simple exponential growth term which was determined to be unstable. The modifications were intended to act as a simple model of the marsh kinetics.

The baseline run used an average decay rate, approximated based on the observed change in flood and ebb constituent concentrations at the marsh stations monitored in 1999, and concentrations measured in the water as it exited from the marsh. Based on preliminary simulations, the calibration run used the coefficients shown in the Table 5-6. The table presents the first order decay coefficient that governs the concentrations output along with the maximum concentrations that the marshes can discharge. The coefficients show that ammonia and CBODu are sources from the marshes, and that their growth is similar to each other with the maximum output concentration for CBODu at 5.0 mg/L and the maximum concentration of ammonia at 0.39 mg/L.

The dissolved oxygen constituent is an exception, and was specified as a percent of predicted saturation. The percent saturation was determined based on the average percent saturation observed in the water ebbing from the marshes at the marsh monitoring stations and is calculated based on the model predicted water temperature. The measured marsh water chemistry is presented in Appendix I.

#### 5.5.4 Sediment Oxygen Demand

The spatial distribution of sediment oxygen demand in the Savannah River was established using measured SOD values at fourteen stations, as noted in Table 5-2. These stations were monitored as part of studies undertaken by the USEPA, Georgia EPD, and US Army Corps of Engineers. Mean SOD rates varied from 0.55 to 4.82 g-O<sub>2</sub>/m<sup>2</sup>/day.

The spatial distribution of SOD input to the model was accomplished by assigning the observed values to all grid cells in the immediate area of each station. Additional assignment of SOD values were also accomplished through recommendations made by the Savannah MTRG. For example, sedimentation basin grid cells were assigned the same SOD values as those assigned to the turning basin, based on MTRG recommendation. The resultant distribution of SOD at 20 deg C on the model grid is shown in Figure 5-9. In the initial model set up, the range of SOD values based upon the available data was 0.53 to 2.58 g-O<sub>2</sub>/m<sup>2</sup>/day. Through the calibration process, the overall distribution of the SOD did not change but the values utilized in the harbor area were adjusted from 2.58 to 2.9 g-O<sub>2</sub>/m<sup>2</sup>/day. This range (0.53 to 2.9 g-O<sub>2</sub>/m<sup>2</sup>/day) provided the best overall fit.

Based upon the data presented, there is a high degree of uncertainty in the sediment oxygen demand. Many stations took measurements along the side of the channel, or other locations outside of the main channel, due to the logistic difficulties of obtaining measurements directly in the channel. The concept of a higher SOD rate along the Front River, and within the sedimentation basin, does make sense given the amount of material dredged from these areas on a yearly basis. Therefore, the pattern of SOD distribution is reasonable but actual magnitude may vary significantly. This uncertainty needs to be considered in evaluating the model simulations and performance. The final values represent the conditions within measured limits that provided the best fit of model to data for the 1999 simulations.

In addition to the SOD, an NH<sub>4</sub> load from the sediments was also implemented. The loading is calculated using the SOD for each WQMAP grid cell (Figure 5-10) and the sediment excretion relationship of 0.07 grams NH<sub>4</sub>-N/gram SOD. This value is in accordance with the Georgia EPD document, Savannah River Classification Study – October 1985, Sediment Oxygen Demand Surveys (Burke, 1987) presented in Appendix EE. Based on the SOD range, the range in the NH<sub>4</sub> loading rate is 0.06 – 0.20 grams NH<sub>4</sub>-N/m<sup>2</sup>-day.

### **5.5.5 Point Source Discharges**

The point source discharges input to the model include the facilities shown in Figure 2-4. A total of 10 discharges are simulated in the model for 1999. Tables 5-3a and 5-3b present the discharge characteristics for each of the facilities, including the measured minimum, average, and maximum Ammonia and BOD loads in g/s for the 1999 August-September period, as well as the permitted loads.

The constituents input to the model for the point source discharges include: nitrate (NO<sub>3</sub>), ammonium (NH<sub>3</sub>), carbonaceous BOD (CBOD), organic nitrogen (O-N), dissolved oxygen (DO), inorganic phosphorus (PO<sub>4</sub>), and organic phosphorus (O-P). The point source discharges are specified in the model as time series mass loading rates for each constituent. The mass loading rates were calculated based on measured (or assumed) constituent concentrations multiplied by the measured flow rate. Appendix K presents the time series of flows, concentrations, and loads for each constituent and facility. The loads were directly input to the model, and were provided to ATM by the Harbor Committee. The locations of the discharges were based upon the best available information on the locations of pipes and diffusers. The scale of the load graphs is kept constant for all of the facilities to allow easy comparison of the relative contributions of each. Appendix Y presents the detailed Wastewater Characterization report developed by Law Engineering, this report contains all data and assumptions used to develop the point sources loads.

The flow from each point source discharge is not input to the water quality model. The assumption is made that the contribution of the flow for each discharger is insignificant in relation to the tidal prism and upstream freshwater inflow. However, plots of the measured flow rates are presented in Appendix K because they are used to calculate the input mass loading rate for the input constituents (flow multiplied by constituent concentration). For all of the point source loads, the inputs were distributed evenly over the vertical within the discharge cell.

### **5.5.6 Local Non-Point Source Discharges**

Daily stormwater loading rates for ammonia (NH<sub>3</sub>-N), nitrate + nitrite (NO<sub>x</sub>-N), total kjeldahl nitrogen (TKN), total suspended solids (TSS), total phosphorus (TP), and 5-day biochemical oxygen demand (BOD<sub>5</sub>), were provided for 8 Savannah catchments by MACTEC

Engineering and Consulting in their January 10, 2003 report to the Savannah Harbor Committee (Report of Results, Savannah Harbor-Stormwater Quality Modeling, Savannah Harbor Expansion). Loading time series were established for each catchments outlet. Organic nitrogen time series were calculated as the difference between TKN and NH<sub>3</sub>-N. The BOD<sub>5</sub> loading time series were converted to BOD<sub>u</sub> using an f-ratio of 3.91, or the average of the f-ratios calculated for the 10 point source discharges.

### **5.5.7 Reaeration**

The O'Connor-Dobbins formula was used for reaeration. The formulation used in the BFWASP model was described in Chapter 3. The formula uses the vertically averaged current speed and the full water column depth to calculate the transfer rate across the air water interface,  $K_l$  (m/day). The calculated  $K_l$  is then compared with the predicted wind driven value of  $K_l$  and the larger of the two is chosen. The reaeration transfer coefficient,  $K_a$  (1/day) is then determined by dividing the  $K_l$  by the surface layer depth, and the reaeration subsequently calculated from  $K_a$  and the difference between the DO in the water and saturation. The range of reaeration values calculated by the model was from 0.35 to 1.60 1/day.

### **5.5.8 WASP Model Coefficients**

The WASP model constants and coefficients for the calibration scenario are given in Table 5-4. The constants and coefficients have been broken down into six major groups for clarity. These are coefficients that directly relate to the dissolved oxygen cycle, the nitrogen cycle, the phosphorus cycle, primary productivity (or phytoplankton), and spatial functions or transport functions. The majority of the coefficients assigned for the base case are equivalent to those specified in the literature, particularly the WASP Manual (Ambrose et al., 1993), with a few exceptions.

For the present modeling effort, the Savannah LT<sub>BOD</sub> Curve Fitting Discussion Group recommended that a single oxidation rate would be sufficient to accurately represent the Lower Savannah River Estuary System and that an oxidation rate of 0.06 1/day be used. This is at the lower end of the literature range, but was determined through analysis of LT<sub>BOD</sub> data. During the model calibration process it was determined that a value of 0.09 1/day was

necessary to capture the DO deficit change process under the varying point source loads discussed in detail in Section 2.6.4. This is also discussed in more detail in Chapter 7 (model calibration).

The nitrogen group coefficients are primarily set from literature values for the calibration run setup. The exception is for the nitrification rate which was recommended to be 0.035 1/day by the LTBOB Curve Fitting Discussion Group based on the long term data analysis. A more detailed discussion of the kinetic rates, constants and coefficients can be found in Appendix N - Determination of Baseline Water Quality Input Parameters.

### **5.5.9 Light Extinction and Chlorophyll a**

Historic studies and results from the 1999 monitoring have shown that primary productivity within the Lower Savannah River Estuary does not play a major role in the dissolved oxygen dynamics. In previous applications of the BFWASP model, the primary productivity terms were turned off. Based upon recommendations by the SMART, the BFWASP model was run with the full eutrophication kinetics and allowed to come to equilibrium with the primary productivity relative to the actual conditions in the system. The reasoning was that if the model was set up correctly and running properly, it would be light limited and the primary productivity would equilibrate to the instream conditions and not be a significant factor in the dissolved oxygen cycle. If this was not the case it would be an indication that certain parameters within the model were not behaving properly.

In support of this run, a spatial distribution of the light extinction was developed from the 1999 data. Secchi measurements were made as part of the chemistry and profiling of the system. Secchi depths were related to the light attenuation coefficient using the relationship;

$$K_e = 1.8/D$$

where;  $K_e$  = Light Extinction Coefficient (1/m)

D = Secchi Depth

From these measurements a static spatial distribution of the light extinction coefficient was developed. Figure 5-11 presents the spatial distribution. Along the main channel the light attenuation is highest along the Front River from Fort Jackson to upstream of the King's Island Turning Basin. Within this reach the light extinction is between 1 and 1.5 1/m. The

values increase upstream and downstream with the highest values along the Back River and Middle River.

In addition to the light extinction coefficient, the model was initialized to the average chlorophyll-a distribution up the river. Figure 5-12 presents the chlorophyll a distribution ranging from 13 ug/L in the offshore, to less than 3 ug/L above the Kings Island Turning Basin.

## **5.6 MODEL INPUTS AND BOUNDARY CONDITIONS FOR 1997**

As stated earlier, the 1999 data collection effort was initiated in order to provide a more comprehensive data set for use in calibration of the water quality model. The 1997 data were limited in relation to the 1999 data. Therefore, many of the inputs used in the 1997 simulations were taken directly from the 1999 effort. The following describes the input data used in the 1997 simulation.

### **5.6.1 Offshore Boundary**

Constant concentrations for all of the state variables were specified at the open boundary, with the exception of DO where a percent of the calculated saturation value was specified. The boundary condition concentrations are the same as those used in 1999 and are presented in Table 5-7.

### **5.6.2 Upstream Boundary**

The time dependant upstream boundary developed for 1999 using the EPD-RIV1 output was not available for the 1997 time period. Therefore, constant upstream boundary concentrations were utilized based upon the available data. Table 5-9 presents the upstream concentrations used in the model. The concentrations represented boundary matching of concentrations at the most upstream 1997 station GPA-14.

### **5.6.3 Marsh Boundaries**

The marsh boundary conditions used in the 1997 simulations are identical to those used in the 1999 simulations. Table 5-8 presents the values used in 1997.

### **5.6.4 Sediment Oxygen Demand**

The spatial distribution of sediment oxygen demand used in the 1997 simulations was identical to that used in the 1999 simulations and presented in Figure 5-9. The ammonia flux was also identical to that utilized in 1999 and presented in Figure 5-10.

### **5.6.5 Point Source Discharges**

The detailed point source load characterization performed for the 1999 simulations was not duplicated by the Harbor Committee for the 1997 simulations. Therefore loads for the 1997 verification runs were taken from available DMR data. Multipliers utilized in the 1999 load determination were carried over to create the loading files used for the 1997 simulation. Appendix J presents the time series loads used for the 1997 verification runs. As the loading data represent more average conditions over this time period, more weight should be placed in the verification on the accurate simulation of the overall period (August-September) statistics rather than the evaluation of temporal changes that was done for the 1999 simulations.

### **5.6.6 Local Non-Point Source Discharges**

For the 1997 simulations there were no available non-point source discharges like those calculated for the 1999 simulations. As these loads were relatively insignificant in the 1999 simulations it was assumed that neglecting them for the 1997 verification runs would not create significant errors.

### **5.6.7 Reaeration**

The reaeration formulation for the 1997 simulations is identical to the 1999 simulations and discussed in Section 5.5.7

### **5.6.8 WASP Model Coefficients**

The WASP model constants and coefficients for the verification runs are identical to the coefficients from the 1999 calibration presented in Table 5-4.

## 6.0 WATER QUALITY MODEL CALIBRATION METHODOLOGY

The assessment of the accuracy of numerical models is a complex process. The methodical application, testing and evaluation of a model to predict field data for a specific study domain is often referred to as model calibration/validation. Much literature has been published over the past few decades describing various approaches (Hess and Bosley, 1992; Lynch and Davies, 1995; McCutcheon et al., 1990). In general, the calibration process is an organized procedure to select model coefficients and improve the accuracy of model inputs such that model predictions best match measured data and simulate key processes. Table 6-1 presents the simulation, calibration and validation periods for the water quality model calibration.

Throughout the development of the water quality model, two technical review groups have provided guidance on the methodologies and criteria for model performance evaluation; the Modeling Technical Review Group (MTRG), and the Savannah Model Agency Review Team (SMART). Through the review process, two agencies (EPA and USGS) developed a guidance document that outlines methodologies for model comparison as well as guidance on acceptable level of error. The guidance document entitled "Savannah Harbor Data Analysis and Modeling Expectations of Federal Agencies" outlines specific methodologies for model to data comparison along with guidelines for acceptable model performance (Appendix GG). Table 6-2 outlines the criteria for the water quality model, including salinity which needs to be simulated as accurately in the water quality model as in the hydrodynamic model.

While the criteria outlined in Table 6-2, and the comparison methods discussed within the Federal Agency Expectations Document (Appendix GG), provide guidance for evaluation of the model performance, the determination of model acceptability will be based upon a weight of evidence approach. In support of a weight of evidence approach, the MTRG and SMART requested specific model comparison methodologies be presented within this document, these are:

- BFWASP transport test that shows that salinity is transported identically in the hydrodynamic and water quality model.
- Time series graphical comparisons of simulated versus measured dissolved oxygen and dissolved oxygen deficit.

- Time series plots of CBODu, Ammonia, Nitrate/Nitrite, Organic Nitrogen, Total Phosphorus, Ortho-Phosphorus, and Chlorophyll a, for all chemical sampling stations
- Longitudinal plots of simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentiles for CBODu, Ammonia, Nitrate/Nitrite, Organic Nitrogen, Total Phosphorus, Ortho-Phosphorus, and Chlorophyll a, versus the measured water chemistry at all chemical sampling stations
- Tabular and graphical presentation of the mean error, absolute mean error, relative mean error, Root Mean Square (RMS) error, at all measurement stations for dissolved oxygen, and dissolved oxygen deficit.
- Tabular and graphical presentation of the comparison of the measured versus simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentiles at all data collection stations for dissolved oxygen, and dissolved oxygen deficit.
- Graphical comparison of measured versus simulated snapshots of vertical profiles for dissolved oxygen and dissolved oxygen deficit.

As with the hydrodynamic model, comparisons of the simulations versus measurements in a tidally dominant system such as the Lower Savannah River Estuary, must isolate two components of the error, the phase error and the magnitude error. For the statistical comparisons presented herein, the phase errors for each constituent are determined first and then the signals are shifted prior to calculation of the error statistics.

Other comparison methods that are presented include;

- Graphical comparison of filtered (24-hour running average) time series of dissolved oxygen deficit over time for the measured and simulated bottom dissolved oxygen at key stations within the upper harbor area.

Another point to consider in the evaluation of the water quality model calibration/validation is that the 1999 data set was collected specifically for the purpose of providing the additional data needs for the development of a more comprehensive water quality model. The 1997 data set did not include specific measurements of input parameters that were determined for the 1999 study. While some of the measurements made in 1999 can provide inputs to the 1997 model runs, such as sediment oxygen demand, reaeration, and marsh loadings, others,

such as the detailed wastewater characterization and the instream sampling are not as comprehensive. This needs to be considered in the evaluation of the 1997 validation runs.

The comparisons described above will support the weight of evidence evaluation of the water quality model calibration/validation which is presented in detail within Sections 7 and 8. The following provides descriptions of the statistical methods utilized within this study for model to data comparison.

## 6.1 MEAN ERROR

The mean error measures the average difference between calculated and observed values and can be defined in a variety of ways. The *mean error* is defined as the difference of the means

$$ME = \frac{\sum x - c}{N}$$

where,  $x$  is the observed values,  $c$  is the model-predicted or calculated values and  $N$  is the number of data pairs compared. Where data are missing, the error is not computed and therefore not included in the calculation.

## 6.2 ABSOLUTE MEAN ERROR

The absolute mean error is determined similarly to the mean error except that the absolute value of the difference between calculated and observed values is taken. The *absolute mean error* is defined as;

$$AME = \frac{\sum |x - c|}{N}$$

where,  $x$  is the observed values,  $c$  is the model-predicted or calculated values and  $N$  is again the number of data pairs. This error provides a measure of the difference of the measured versus modeled signal whether negative or positive.

### 6.3 ROOT MEAN SQUARE ERROR

The *root mean square error* is defined as

$$\text{rmse} = \sqrt{\frac{\sum (x_i - c_i)^2}{N}}$$

where  $N$  is the total number of measurements in space or time. It is statistically well behaved and is a direct measure of model error.

### 6.4 PERCENTILES

Another method used to evaluate the variations in a random data set is the percentile calculation. The  $n^{\text{th}}$  percentile of a sample is a number  $P_n$  such that at least  $n\%$  of the sample values are smaller than or equal to  $P_n$  and that at least  $(100 - n\%)$  of those values are larger than or equal to  $P_n$ .

One advantage of percentiles is that for highly variable parameters they provide a statistical quantification of the signal. For instance for dissolved oxygen the 50<sup>th</sup> percentile is a representative of the average conditions, while a 10<sup>th</sup> percentile is a representative of the more extreme or minimum conditions.

In Sections 7 and 8 percentiles are used as a means of evaluating the dissolved oxygen and dissolved oxygen deficit changes. They provide a snapshot or static representation of a highly variable system. As percentiles are used as a basis for model performance using the Federal Criteria, it is necessary to examine how the model performs in terms of the percentiles.

## 7.0 WATER QUALITY MODEL CALIBRATION TO 1999 DATASET

This Chapter presents the results of the calibration of the water quality model to the comprehensive data set collected in 1999. The following presents the background of the water quality model development followed by comparison to the measured instream water chemistry, the dissolved oxygen, the dissolved oxygen deficit, and an evaluation of the results of the model calibration against the federal expectations criteria.

### 7.1 BACKGROUND

The three-dimensional water quality model for the Lower Savannah River Estuary, was first begun under the Tier 1 EIS. The model proposed was for the evaluation of the net change in the dissolved oxygen conditions under the proposed deepening and was a simplified DO balance model. Through the review of the Tier 1 EIS, it was recommended that a more comprehensive water quality model be developed that could provide for full simulation of the dissolved oxygen cycle within the estuary including, if necessary, the primary productivity. In support of this new model, it was recommended that a comprehensive data set was collected in 1999. This data set was described in detail in Section 2, and it included studies that attempted to quantify all of the processes that impact the dissolved oxygen cycle. Studies completed were;

- a detailed wastewater characterization performed by Law Engineering for the Harbor Committee,
- measurement of the net flux of nutrients and BOD from the marshes
- measurements of the sediment oxygen demand and the reaeration by EPA personnel,
- a more comprehensive continuous dissolved oxygen record within the main harbor area,
- Long-Term Biochemical Oxygen Demand (LTBOD) measurements within the main harbor, upstream, and marshes, to quantify the net loadings, instream decay rates, and nitrification rates

- Measurement of the vertical profiles of dissolved oxygen along a transect within the main harbor (EPD Stations)

The following presents comparisons of the simulated to measured results for the calibration of the water quality to the 1999 data set along with discussion of how the model captures key processes presented and discussed in Section 2.0.

## **7.2 IN-STREAM WATER CHEMISTRY**

The first step in the model calibration process is the development of the loads to the system and the evaluation of the simulation of the instream temporal and spatial distribution of the water chemistry. By first establishing that the instream water chemistry is in balance and properly distributed, it is possible to evaluate the resultant effects on dissolved oxygen. The instream constituents evaluated are the CBOD<sub>u</sub>, ammonia, nitrate/nitrite, organic nitrogen and to a lesser extent the total phosphorus and orthophosphate. Additionally, the model was run with the full eutrophication kinetics so the chlorophyll-a was also evaluated.

Chapter 5 and Appendix M presented an evaluation of the distribution of the loads of the primary water chemistry constituents affecting dissolved oxygen within the Lower Savannah River Estuary. The distribution was between the local point source loads, the upstream boundary at Cloy, the marshes above Fort Jackson, the non-point source loads, and the effects of sediments on dissolved oxygen either through uptake (SOD) or ammonia flux.

Figures 7-1 through 7-4 presents the longitudinal distribution of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile instream CBOD<sub>u</sub>, ammonia, nitrate/nitrite, and organic nitrogen concentrations plotted against the measured data. The percentiles are calculated for the full calibration period (August-September 1999). Additionally, the time series of the data are plotted in Appendix U for all of the constituents at all stations for the full simulation period. Given the discrete nature of the water chemistry data, it is not practical to perform statistical error analyses as is done for the dissolved oxygen. Therefore, the determination of whether or not the model is properly simulating the instream response of these parameters will be the capturing of the overall values and longitudinal patterns.

### 7.2.1 CBOD<sub>u</sub>

Figures 7-1a and 7-1b present the longitudinal comparisons of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile CBOD<sub>u</sub> concentrations from the model versus the measured LT<sub>BOD</sub> data and the BOD-5 data converted based upon the average f-ratio. As many of the BOD-5 data were at or near the method detection limit, and it was determined that the 5-day BOD tests did not produce the equivalent of the 5-day BOD from the LT<sub>BOD</sub> tests, it was determined that the LT<sub>BOD</sub> data are more reliable for model comparison purposes. The 5-day BOD results are presented on this plot to provide additional longitudinal trend information.

In Section 2.0 plots showing the longitudinal distribution of CBOD<sub>u</sub> were presented and the results showed a pattern of rising CBOD<sub>u</sub> in the harbor area between RM 13 and RM 20. This results is seen in the data and the concentration levels match that found in the LT<sub>BOD</sub> test results. The model simulations do not reflect the wide distribution from the converted BOD-5 data but this is not unexpected based upon the comparisons of the directly measured BOD-5 values and the 5-day BOD taken from the LT<sub>BOD</sub> tests. The model simulated concentrations and the distribution of concentrations match that found in the LT<sub>BOD</sub> tests.

### 7.2.2 Ammonia (NH<sub>3</sub>)

Figures 7-2a and 7-2b present the longitudinal comparisons of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile ammonia concentrations from the model versus the measured data. Looking at the data along the Front River (7-2a), a pattern of higher ammonia concentrations in the area between RM 10 and 20 can be seen and this is simulated with the model. The rise in ammonia is more dramatic in the bottom than in the surface and this also is seen from the model results. The data support the notion of ammonia flux from the sediments in the areas of high SOD given the bottom data versus the surface data and this is simulated.

The data show higher maximum ammonia values as well as a greater range in the minimum and maximum values. Examination of the time series comparisons presented in Appendix U provides further insights into this. Looking at the time series plots the data show high values throughout the harbor at the beginning of the simulation period (prior to 8/12). This is a phenomena that was noted early on in the data review process. It was surmised that a spill occurred prior to the monitoring and this accounted for the increased ammonia concentrations. Examination of the data following this event showed that the model is

simulating the instream ammonia concentrations within the range of the data and remains relatively constant through the end of the simulations.

Looking at the data along the Middle and Little Back Rivers (7-2b) the data show relatively low concentrations of ammonia and this is also shown with the model. The high values shown in the Little Back River, like the Front River come primarily during the beginning of the simulations, this can be seen in the time series plots and the model simulates within the range for the remaining time period.

### **7.2.3 Nitrate-Nitrite (NO<sub>3</sub>-NO<sub>2</sub>)**

Figures 7-3a and 7-3b present the longitudinal comparisons of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile nitrate-nitrite concentrations from the model versus the measured data. The data for the Front River show a pattern of decreasing nitrate-nitrite moving through the harbor from upstream to downstream. The data show ranges at the upstream point between 0.15 and 0.3 mg/L falling steadily through the harbor down to offshore values less than 0.1 mg/L. The model shows similar trends and ranges with slightly lower values through the harbor. The time series data from the Front River show a lot of scatter in the data with the model simulating around the range but potentially lower than the data show.

Along the Middle and Back Rivers the model simulates well the range of concentrations measured with relatively constant values between 0.1 and 0.2 mg/L.

### **7.2.4 Organic Nitrogen (ON)**

Figures 7-4a and 7-4b present the longitudinal comparisons of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile organic nitrogen concentrations from the model versus the measured data. While the data for organic nitrogen is highly variable throughout the system, the model simulations are nearly constant at around 0.4 mg/L which is not a bad approximation of the mean values but does not reflect the variations measured. This is primarily a function of the fact that the upstream and downstream boundaries are near constant, and no temporally varying organic nitrogen inputs come into the model moving through the harbor. With the introduction of a time varying offshore boundary condition, and additional examination of the time varying nature of the upstream boundary a greater variation could be simulated. As Organic Nitrogen is not a primary constituent controlling dissolved oxygen through the harbor,

the representation of the mean throughout the simulation with the model will not create significant errors in the overall model results.

### **7.2.5 Phosphorus**

While phosphorus is not a key parameter controlling dissolved oxygen concentrations within the harbor and adjacent waters, the time series of simulated versus measured PO<sub>4</sub> values are presented in Appendix U along with the longitudinal 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentiles. The data show reasonable comparison with the pattern, trends and concentrations.

### **7.2.6 Chlorophyll a**

As stated earlier, the primary productivity was implemented in the model to provide a check on the models simulation of processes. If working correctly the model should respond with little to no primary productivity in the harbor due to light limitation. Figures 7-5a and 7-5b present the longitudinal 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile chlorophyll a as projected by the model in comparison to the available data. The chlorophyll a data were corrected to provide results for only live chlorophyll a and not detrital material.

The results show the surface and bottom Chlorophyll a concentrations drop off rapidly entering the harbor and reflect the boundary conditions prescribed at the open boundary. The instream values are below 5 ug/L by RM 10 to 15 with the bottom values higher reflecting the intrusion of the offshore waters where higher chlorophyll a exists. The primary productivity simulations confirm that the model is simulating the processes correctly.

## **7.3 DISSOLVED OXYGEN SATURATION**

Appendix U presents time series plots of the simulated and measured dissolved oxygen saturation values. These provide a baseline upon which the evaluation of the dissolved oxygen simulations can be made, and an additional evaluation of the models simulation of the salinity and temperature. Overall the results show good agreement between the model and the data. Maximum errors are nearly all less than 0.5 mg/L, with the model at times not capturing the degree of fluctuation, but doing well at capturing the patterns and trends over time.

## 7.4 DISSOLVED OXYGEN

The following presents comparisons of the simulated and measured dissolved oxygen in the system. The comparisons are presented using four methods as prescribed by the Technical Review Group. The methods are;

- longitudinal comparisons of the simulated and measured 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentiles of dissolved oxygen;
- comparisons of the Mean Error (ME), Absolute Mean Error (AME), and Root Mean Squared (RMS) error;
- direct time series comparisons between the simulated and measured dissolved oxygen;
- Comparison of snapshot vertical profiles from the EPD measurements.

### 7.4.1 Longitudinal Percentiles

The first comparison method examines the accuracy of the model in simulating the median and extreme dissolved oxygen concentrations in the system (10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentiles). This is a static look at the processes and does not identify how the model responds temporally. Figures 7-14a and 7-14b present the measured and simulated longitudinal percentiles for the Front River and the Middle\Little Back River respectively. Table 7-1 presents the percentiles in tabular format. The results are presented for the full calibration period. Sub-period tables are presented in Appendix U. It should be noted that where no measured data are available the simulated values are not incorporated into the percentile calculations assuring that the model to data comparisons are compatible.

#### **Front River**

Examination of Figure 7-14a shows that for the bottom and surface conditions, the model is simulating the median levels and ranges of dissolved oxygen. The model captures the longitudinal variations and gradients and is now doing a better job of simulating the range of

dissolved oxygen at GPA-08 and GPA-09. This was one aspect of the measured data that the model was previously not simulating well. The model is generally capturing the critical low dissolved oxygen levels within the bottom waters of the Harbor, but still slightly high in the 10<sup>th</sup> percentile dissolved oxygen concentrations. From Table 7-1, errors in the median values range from 0.0 mg/L to 0.5 mg/L, with an overall trend of the model being low in the 50<sup>th</sup> percentiles. The errors in the bottom 10<sup>th</sup> percentiles range from 0.0 mg/L to 0.5 mg/L with the model on average higher than the measured data.

In Appendix U the percentiles are tabulated for five two-week sub-periods to see how the model performs under various conditions. The periods represent two extreme spring-neap cycles and three more normal spring neap cycles. Where there are blanks insufficient data were available to perform the percentile calculations.

In general during the normal spring-neap periods the model percentile differences in the 50<sup>th</sup> and 90<sup>th</sup> percentiles are similar to that seen for the full simulation period. For the August extreme spring-neap period the model percentile differences for the 10<sup>th</sup> and 50<sup>th</sup> percentiles are slightly higher ranging from 0.0 mg/L to 0.8 mg/L overall with the model percentiles higher than the data. For the September spring-neap period, the differences are back to the 0.0 to 0.3 mg/L range overall with the model showing lower values. It should be noted that for some of the sub-periods the data records were not very long due to instrument fouling and this may create lower statistical significance to the results.

### **Middle River and Little Back River**

Examination of Figure 7-14b shows that for the dissolved oxygen simulations in the Middle River and Little Back River the errors in the 10<sup>th</sup> and 50<sup>th</sup> percentiles range from 0.0 mg/L to 0.7 mg/L with the model percentiles generally lower. This is also seen in the sub-period comparisons in the Middle and Little Back Rivers. One note is that the measurement of the marsh LT<sub>BOD</sub> showed relatively low decay rates relative to the remaining areas. The higher decay rate of 0.09 1/day, which was utilized to capture the dissolved oxygen conditions along the Front River, may be too high for the Little Back River area. This may contribute to the lower values simulated.

## **7.4.2 Error Statistics**

The second comparison method quantifies the Mean Error (ME), the Absolute Mean Error (AME), and the Root Mean Squared error (RMSE). These statistics provide information on various comparisons between the simulated and measured signals. The ME evaluates the average difference between the two models (and is similar to the comparison of the 50<sup>th</sup> percentiles for a normally distributed signal) and balances positive and negative differences. The AME and the RMS on the other hand, provide quantification of the overall difference between the two signals. Figures 7-13a and 7-13b present the error statistics longitudinally by River Mile (RM). Table 7-1 presents the error statistics in tabular form. The results are presented for the full calibration period. Sub-period tables are presented in Appendix U.

### **Front River**

The Mean Error magnitudes range from 0.1 mg/L up to 0.6 mg/L, with an average mean error of -0.1 mg/L. The ME are both positive and negative with the greatest errors seen in the area of GPA-08 where the Middle and Front Rivers meet, a highly complex and dynamic area. The RMS and AME errors range from 0.2 mg/L to 0.9 mg/L with average errors of 0.6 mg/L and 0.5 mg/L respectively.

In Appendix U the errors are tabulated for five two-week sub-periods to see how the model performs under various conditions. The ME, the AME, and the RMSE remain relatively consistent throughout all of the sub-periods with the AME and RMSE values identical for four of the sub-periods and the other sub-period only off by 0.1 mg/L from the others.

### **Middle River and Little Back River**

The ME on the Middle and Little Back Rivers generally show the simulated dissolved oxygen levels lower than the measured data with magnitudes ranging from 0.1 mg/L to 0.8 mg/L. The averages are -0.2 mg/L and -0.4 mg/L for the Middle and Little Back Rivers respectively. The RMSE and AME errors range from 0.5 mg/L to 1.1 mg/L, with averages between 0.7 and 0.9 mg/L for the Middle and Little Back Rivers respectively.

### **7.4.3 Time Series Comparisons**

Figures 7-8 through 7-12 present time series comparisons of the measured versus simulated dissolved oxygen at key stations throughout the system. The time series are presented for the full calibration. The full time series from all of the stations are presented in Appendix U.

#### **Front River**

Figures 7-8, 7-9, and 7-10 present key stations along the Front River above Fort Jackson in the areas where the lowest dissolved oxygen measurements were found. In the Lower Reaches of the Front River above Fort Jackson (GPA-04, GPA-21) shown on Figure 7-8 the model simulates the overall trends and magnitudes of the data as well as the degree of variation over a tidal cycle. The model is simulating the lower values in the bottom layer and the surface bottom differences. The data show a limited degree of vertical stratification/destratification over the simulation period and the model captures these small variations.

Moving upstream to stations GPA-06 and GPA-22 (Figure 7-9), the data begin to show a higher degree of vertical stratification and more pronounced stratification/destratification. The model captures these patterns. The model is simulating the low values of dissolved oxygen measured at GPA-06 and GPA-22, but appears to miss the phasing of the event in August while capturing the overall recovery trend through the remaining simulation. The changes in the surface dissolved oxygen, through the stratification/destratification process, are also well represented. Examination of GPA-22 highlights that the model appears to move the area of sharp gradient of dissolved oxygen slightly too far upstream based upon the tidal variation seen in the measured bottom data versus the modeled. The surface layer results seem to indicate that the location of the gradient in the surface waters is simulated well.

A past problem with the model was that the tidal variations seen in the data at GPA-08 and GPA-09 (Figure 7-10) were not simulated well. This indicated that the model was not capturing the gradient of dissolved oxygen at the end of the channel and was potentially too dispersive. The results presented show that while the model may be smoothing the gradient somewhat (the variations are still not as large) the model is capturing the gradient and the resultant transport of that gradient past the measurement points. Once again based upon the results from GPA-22 versus GPA-08, it appears that the gradient in the model may be slightly too far upstream.

## **Middle and Little Back River**

Figure 7-11 presents the results of the simulations for the Middle River. The results at GPA-10 show very good agreement between the model and the data. GPA-12 which is upstream of GPA-10 shows reasonable simulation of the mean, but other than the first part of the record, does not show good agreement relative to tidal variation. This indicates a source of low dissolved oxygen water reaching GPA-12 that the data does not measure.

On the Little Back River (Figure 7-12 and Appendix U) the results show the model simulates the trends but misses some events such as the low dissolved oxygen event at GPA-15 around the period of the extreme neap when higher saline waters reach GPA-15, most likely through Rifle Cut; the model misses this event. The remaining periods are simulated well.

### **7.4.4 Comparisons of Vertical Profiles**

Figure 7-15 presents comparisons of the measured versus simulated vertical profiles of dissolved oxygen from the EPD stations along the Front River from RM 13 to RM 18. The profiles are shown at four locations for two separate times, low tide on September 13<sup>th</sup>, and high tide on September 27<sup>th</sup>. While September 13<sup>th</sup> represents a period entering into a neap tide, September 27<sup>th</sup> represents a period coming out of a neap tide to a spring tide. The results show that the model is simulating the vertical structure of dissolved oxygen, i.e. capturing the overall shape and degree of vertical variation as well as the point of highest gradient. One point to note with the vertical profile comparisons is that when examining the vertical profiles at different times in the system, the results indicate that the simulated dissolved oxygen is lower than that measured during profiling events. This is in contrast to the comparisons with the continuous data which show for the bottom layers that the model is slightly over predicting the dissolved oxygen. As the continuous measurements record dissolved oxygen very near the bottom, the simulations may reflect a conservative evaluation of the bottom dissolved oxygen conditions.

## **7.5 DISSOLVED OXYGEN DEFICIT**

The following presents comparisons of the simulated and measured dissolved oxygen deficit in the system. The dissolved oxygen deficit comparisons provide a direct evaluation of the

models simulation of oxygen uptake. Because the saturation values for dissolved oxygen vary based upon the salinity and temperature, errors in the model projected temperature and salinity passed to the water quality model, can introduce errors into the dissolved oxygen predictions. By comparing dissolved oxygen deficits, these errors are eliminated and a direct evaluation of the water quality kinetics can be made. The comparisons are presented using four methods prescribed by the SMART along with an additional comparison that looks at filtered dissolved oxygen deficit as done in Section 2.0. The methods are;

- longitudinal comparisons of the simulated and measured 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentiles of dissolved oxygen;
- comparisons of the Mean Error (ME), Absolute Mean Error (AME), and Root Mean Squared (RMS) error;
- direct time series comparisons between the simulated and measured dissolved oxygen;
- Comparison of snapshot vertical profiles from the EPD measurements.
- Comparison of the 24-hour average measured and simulated dissolved oxygen deficit.

### **7.5.1 Longitudinal Percentiles**

Figures 7-22a and 7-22b present the measured and simulated longitudinal dissolved oxygen deficit percentiles for the Front River and the Middle\Little Back River respectively. Table 7-2 presents the percentiles in tabular format. The results are presented for the full calibration period. Sub-period tables are presented in Appendix U.

#### **Front River**

In general Figure 7-22a shows similar results to that shown from the dissolved oxygen percentiles. Based upon the similar results, it appears that a significant portion of the differences do not seem attributable to errors in temperature or salinity projections. This was shown and discussed in Section 7.3. At one station, the 90<sup>th</sup> percentile dissolved oxygen

deficit agreement is better than was seen for the 10<sup>th</sup> percentile dissolved oxygen (GPA-06). Whereas in the dissolved oxygen percentile comparisons, the results showed a 10<sup>th</sup> percentile difference of 0.5 mg/L, the 90<sup>th</sup> percentile difference for dissolved oxygen deficit (which is equivalent to the 10<sup>th</sup> percentile in dissolved oxygen) is only 0.2 mg/L.

Examination of the tabular differences in Table 7-2 shows a range of error magnitudes on the Front River above Fort Jackson from 0.0 mg/L to 0.7 mg/L. In the 90<sup>th</sup> percentiles (the critical dissolved oxygen deficit) the average error is 0.0 mg/L indicating a balance between positive and negative errors. The general condition is one of under prediction of the deficit in the bottom waters and over prediction at the surface.

In Appendix U the dissolved oxygen percentiles are tabulated for five two-week sub-periods. Examination of the tables does not reveal a significant difference in any one period relative to statistics. The ranges are comparable and the average errors in the same range.

### **Middle River and Little Back River**

Examination of Figure 7-22b shows that for the dissolved oxygen deficit simulations in the Middle River and Little Back River the errors in the 10<sup>th</sup> and 90<sup>th</sup> percentiles range from 0.0 mg/L to 1.0 mg/L with the model percentiles generally higher.

### **7.5.2 Error Statistics**

Figures 7-21a and 7-21b present the error statistics longitudinally by River Mile (RM). Table 7-2 presents the error statistics in tabular form. The results are presented for the full calibration period. Sub-period tables are presented in Appendix U.

### **Front River**

The Mean Error magnitudes range from 0.0 mg/L up to 0.6 mg/L, with an average mean error of 0.1 mg/L, this is nearly identical to that found for the dissolved oxygen. The ME are both positive and negative with the greatest errors seen in the area of GPA-08. The RMS and AME errors range from 0.2 mg/L to 1.0 mg/L with average errors of 0.6 mg/L and 0.5 mg/L respectively, once again nearly identical to that found for the dissolved oxygen.

In Appendix U the errors are tabulated for five two-week sub-periods to see how the model performs under various conditions. The ME, the AME, and the RMSE remain relatively consistent throughout all of the sub-periods.

### **Middle River and Little Back River**

The ME on the Middle and Little Back Rivers generally show the simulated dissolved oxygen deficit levels higher than the measured data with magnitudes ranging from 0.1 mg/L to 1.0 mg/L. The averages are 0.1 mg/L and 0.6 mg/L for the Middle and Little Back Rivers respectively. The RMSE and AME errors range from 0.3 mg/L to 1.1 mg/L, with averages between 0.6 and 0.8 mg/L for the Middle and Little Back Rivers respectively.

### **7.5.3 Time Series Comparisons**

Figures 7-16 through 7-20 present time series comparisons of the measured versus simulated dissolved oxygen deficit at key stations throughout the system. The time series are presented for the full calibration. The full time series from all of the stations is presented in Appendix U.

### **Front River**

Figures 7-16, 7-17, and 7-18 present key stations along the Front River above Fort Jackson in the areas where the lowest dissolved oxygen measurements were found. The results from the dissolved oxygen deficit simulations show nearly identical results to the dissolved oxygen comparisons at the Front River Stations. This indicates that the errors found in the dissolved oxygen measurements do not seem to be significantly attributable to the accurate simulation of the saturation levels.

### **Middle and Little Back River**

Figure 7-19 and 7-20 presents the results of the simulations for the Middle River and Little Back River respectively. The simulations at all stations are presented in Appendix U. Once again the results are similar to that shown for the dissolved oxygen.

#### **7.5.4 Comparisons of Vertical Profiles**

Figure 7-23 presents comparisons of the measured versus simulated vertical profiles of dissolved oxygen deficit from the EPD stations along the Front River from RM 13 to RM 18. The profiles are shown at four locations for two separate times, low tide on September 13<sup>th</sup>, and high tide on September 27<sup>th</sup>. While September 13<sup>th</sup> represents a period entering into a neap tide, September 27<sup>th</sup> represents a period coming out of a neap tide to a spring tide. The results show that the model is simulating the vertical structure of dissolved oxygen deficit, i.e. capturing the overall shape and degree of vertical variation as well as the point of highest gradient.

#### **7.5.5 Comparisons of 24-Hour Averaged Dissolved Oxygen Deficit**

In Section 2.0 the response of the system to a significant variation in the point source discharges in the main harbor was presented and discussed. This variation represents a significant process affecting the dissolved oxygen deficit in both the surface and bottom waters of the harbor. In order to examine if the model is simulating this process, which reflects changes in dissolved oxygen deficit as a result of significant changes in the total load entering a small area in the model (between GPA-06 and GPA-22), the simulated dissolved oxygen at four key stations within the harbor (GPA-21, GPA-06, GPA-22, and GPA-08) was compared with the measured data after both have been put through a 24-hour averaging process. This eliminates the tidal signal and allows direct examination of the model response to the load variations.

Figures 7-6 and 7-7 present the simulated and measured 24-hour average dissolved oxygen deficit at the surface and bottom stations over the full simulation period. As was presented and discussed in Section 2.0, the point source loads to the system rise and peak (approx 100,000 lb/day) around the middle of August and then drop off steadily to a low point around mid September (approx 10,000 lb/day) and then rise back up following the low. The data show a swing in dissolved oxygen deficit at the two stations downstream and upstream of the primary discharge (GPA-06 and GPA-22) during this period that roughly mirrors the load changes. The magnitude is approximately 1.0 to 1.5 mg/L. The magnitude of this swing can be influenced by many factors in the system, i.e. temperature variations, stratification/destratification, residual transport. Looking at the results at GPA-06 and GPA-22, the model appears to respond to the variations in the load. While not perfectly simulating the various fluctuations, the model follows the trends and shows similar magnitude of

variation and response over the simulation period. Additionally, examination of the relative surface differences and absolute levels on an average basis the model is capturing the increase in the degree of stratification moving upstream from GPA-06 to GPA-22.

## **7.6 COMPARISON WITH FEDERAL EXPECTATIONS CRITERIA**

Tables 7-3a and 7-3b present the tabularized percentile results discussed earlier in comparison with the Federal Expectations Criteria. Table 7-3a presents the results for the dissolved oxygen, while 7-3b presents the results for the dissolved oxygen deficit. In each of the tables columns have been created for the 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentiles with a 1 or a 0. A 1 indicates passing and a 0 indicates not passing. At the bottom of each section (Front River, Middle River, and Back River) the average number passing is presented. For the dissolved oxygen it is the 50<sup>th</sup> and 10<sup>th</sup> percentiles which are defined under the Federal Expectations Criteria, while for the dissolved oxygen deficit it is the 50<sup>th</sup> and 90<sup>th</sup> percentiles.

For dissolved oxygen the 10<sup>th</sup> percentiles show 70 percent of the stations within the Front River passing the criteria while the 50<sup>th</sup> percentiles show 50 percent of the stations passing. On the Middle River 50 percent of the stations pass both the 50<sup>th</sup> and 10<sup>th</sup> percentiles, and on the Little Back River 33 percent of the stations pass.

For dissolved oxygen deficit the 90<sup>th</sup> percentiles show 55 percent of the stations within the Front River passing the criteria while the 50<sup>th</sup> percentiles show 45 percent of the stations passing. On the Middle River 100 percent of the stations pass the 50<sup>th</sup> percentile criteria and 50 percent pass the 90<sup>th</sup> percentile criteria. On the Little Back River 33 percent of the stations pass.

## 8.0 WATER QUALITY MODEL VALIDATION TO 1997 DATASET

This Chapter presents the results of the validation of the water quality model to the data set collected in 1997. The following presents comparison to the measured instream water chemistry, the dissolved oxygen, the dissolved oxygen deficit, and an evaluation of the results of the model calibration against the federal expectations criteria.

As stated earlier in the report, the 1997 data set was not as comprehensive as the data set collected in 1999. Numerous studies were performed in 1999 to quantify input conditions and instream conditions. Of specific note is that in 1999 meteorological stations were established to provide local forcing data. In 1997, the only available meteorological data would have been the Airport. Unfortunately during the period of data collection, the airport weather station was not in operation and no local meteorological data were available. For the water quality simulations presented herein, the reaeration is calculated from the currents only without a wind component, and temperature were input directly from the data and not from simulations from the hydrodynamic model. Additionally, the point source discharge data were based upon DMR data and not the detailed water chemistry characterization performed for 1999.

### 8.1 **IN-STREAM WATER CHEMISTRY**

Figures 8-1 through 8-4 presents the longitudinal distribution of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile instream CBOD<sub>u</sub>, ammonia, nitrate/nitrite, and organic nitrogen concentrations plotted against the measured data. The percentiles are calculated for the full calibration period (August-September 1997). Appendix S present measured and simulated time series for each parameter over the full calibration period.

#### 8.1.1 **CBOD<sub>u</sub>**

Figures 8-1a and 8-1b present the longitudinal comparisons of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile CBOD<sub>u</sub> concentrations from the model versus the measured LT<sub>BOD</sub> data. For the 1997 BOD-5 data, nearly all of the values reported were listed as less than detection limits, therefore the conversions to CBOD<sub>u</sub> using the f-ratio did not produce data reasonable

for comparison with the model projections. The available CBODu data were therefore utilized for comparison with the simulations.

Looking at Figures 8-1a and 8-1b the model is showing similar trends to that seen for the 1999 simulations with an area of increased CBODu in the main harbor which the data support. Time variant upstream and offshore boundaries were not available for the 1997 simulations; therefore, constants are prescribed at the boundaries. This reduces the upstream and downstream variability and therefore the variability of the model simulations. Looking at the data variability at GPA-14 it appears that if the model upstream temporal variations were represented (with ranges from 2-4 mg/L) the degree of variability and the net increase (around 2 mg/L) in the harbor area would agree with the measured data variability.

### **8.1.2 Ammonia (NH<sub>3</sub>)**

Figures 8-2a and 8-2b present the longitudinal comparisons of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile ammonia concentrations from the model versus the measured data. The simulated ammonia concentrations reflect the upstream boundary conditions as well as the inputs to the model moving downstream. The data show a high degree of variability with ammonia concentrations in the Harbor as high as 0.23 mg/L.

For the 1999 simulations it was shown that the higher concentrations of ammonia were seen at the very beginning of the calibration period. The concentrations then dropped off in the data and the simulated concentrations were on target for the remainder of the simulation period. The concentrations were at, or around, 0.05 mg/L and this was seen in the Front River, Middle River and Little Back River.

As many of the assumptions utilized in the 1999 simulations were carried over to the 1997 simulations, and given that time dependant upstream boundary concentrations were not produced for the 1997 simulations, the results from the model would be expected to reflect that seen in 1999. This is the case with less variability due to the constant upstream boundary. The longitudinal variations show some increase in the harbor, but overall the simulated concentrations represent the lower end of the measured concentrations while still representing the overall trend of higher concentrations in the harbor. The ammonia concentrations in the Back River and Middle River are also low relative to the measured data. Presently no explanation exists for the much higher concentrations seen in the 1997 data versus the 1999 data.

### **8.1.3 Nitrate-Nitrite (NO3-NO2-)**

Figures 8-3a and 8-3b present the longitudinal comparisons of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile nitrate-nitrite concentrations from the model versus the measured data. In contrast to the ammonia, the nitrate-nitrite data show similar concentration ranges between 1997 and 1999 (0.1 to 0.3 mg/L). Accordingly the model is capturing the trends and distribution of the organic nitrogen data as it did in the 1999 simulations. The data and model show a decreasing trend moving longitudinally through the estuary. The model simulates the lower concentrations but misses the higher concentrations.

### **8.1.4 Organic Nitrogen (ON)**

Figures 8-4a and 8-4b present the longitudinal comparisons of the simulated 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile Organic Nitrogen concentrations from the model versus the measured data. Once again as was seen in the 1999 simulations, the Organic Nitrogen data in 1997 is highly variable and the model represents near constant concentrations of 0.4 mg/L through the harbor with no discernable longitudinal trend other than a slight increase. In general the coefficients in the model do not promote significant kinetic reaction with the Organic Nitrogen and it remains a relatively stable parameter with little influence on the system dissolved oxygen.

### **8.1.5 Phosphorus**

While phosphorus is not a key parameter controlling dissolved oxygen concentrations within the harbor and adjacent waters, the time series of simulated versus measured values are presented in Appendix U along with the longitudinal 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentiles. The data show reasonable comparison with the pattern, trends and concentrations.

### **8.1.6 Chlorophyll a**

As stated earlier, the primary productivity was implemented in the model to provide a check on the models simulation of processes. If working correctly the model should respond with little to no primary productivity in the harbor due to light limitation. Figures in Appendix S present the longitudinal 10<sup>th</sup>, 50<sup>th</sup>, and 90<sup>th</sup> percentile chlorophyll a simulated by the model.

The data showed Chlorophyll a concentrations all less than 0.5 ug/L and appears somewhat suspect as even the more downstream values are not measurable. The test is then to see that the model is simulating the longitudinal distribution of chlorophyll a in a similar manner to that projected in 1999. This is the case and would be expected as the light penetration data, the offshore boundaries and the initial concentrations are as input to the 1999 simulations.

## **8.2 DISSOLVED OXYGEN SATURATION**

Appendix S presents time series plots of the simulated and measured dissolved oxygen saturation values. These provide a baseline upon which the evaluation of the dissolved oxygen simulations can be made and an additional evaluation of the models simulation of the salinity and temperature. Overall the results show good agreement between the model and the data. Maximum errors are nearly all less than 0.5 mg/L with the model at times not capturing the degree of fluctuation, but doing well at capturing the patterns and trends over time.

## **8.3 DISSOLVED OXYGEN AND DISSOLVED OXYGEN DEFICIT**

The following presents comparisons of the simulated and measured dissolved oxygen and dissolved oxygen deficit in the system.

### **8.3.1 Longitudinal Percentiles**

Figures 8-10a and 8-10b present the measured and simulated dissolved oxygen longitudinal percentiles for the Front River and the Middle/Little Back River respectively. Figures 8-16a and 8-16b present the measured and simulated dissolved oxygen deficit longitudinal percentiles for the Front River and the Middle/Little Back River respectively. Table 7-1 presents the dissolved oxygen percentiles in tabular format. Table 7-2 presents the dissolved oxygen deficit in tabular form. The results are presented for the full calibration period. Sub-period tables are presented in Appendix S.

## **Front River**

Examination of Figures 8-10a and 8-16a show that the model is simulating the overall distribution and longitudinal trends in the data but the simulated levels in the 10<sup>th</sup> and 50<sup>th</sup> percentile dissolved oxygen concentrations are too low, and the 50<sup>th</sup> and 90<sup>th</sup> percentile dissolved oxygen deficits are too high. Therefore while the model is capturing the overall longitudinal variation, the absolutes are low, on the order of 0.5 mg/L.

The net error may be the result of two causes. The first is that examination of the simulated dissolved oxygen conditions at the upstream station (GPA-14) show the dissolved oxygen concentrations entering the system are low, on the order of 0.5 mg/L. This is also the case for the downstream offshore boundary. For both of the boundaries, the percent saturation assumptions utilized in the 1999 simulations were carried over to the 1997 simulations. Pulling these two boundary conditions upward to reflect the less critical period of 1997 in comparison to 1999 would improve the results. The boundary specifications came from the levels utilized in the 1999 simulations and may not be fully reflective of 1997 conditions.

Another possibility is that SOD conditions during the 1997 period may be lower overall than that utilized for the 1999 simulations. This also would have the effect of bringing the dissolved oxygen levels up universally.

In Appendix S the percentiles are tabulated for five two-week sub-periods to see how the model performs under various conditions. All of the sub-periods show similar statistical differences as seen for the full calibration period.

## **Middle River and Little Back River**

Examination of Figures 8-10b and 8-16b show similar conditions in the Middle River and Little Back River simulations. The comparisons show the model is low on dissolved oxygen and high on dissolved oxygen deficit. The levels are similar to that found on the Front River on the order of 0.5 mg/L. The one exception is GPA-12 where the model is projecting concentrations too high.

### **8.3.2 Error Statistics**

Figures 8-9a and 8-9b present the dissolved oxygen error statistics longitudinally by River Mile (RM). Figures 8-15a and 8-15b present the dissolved oxygen deficit error statistics.

Table 7-1 presents the dissolved oxygen error statistics in tabular form, Table 7-2 presents the dissolved oxygen deficit error statistics. The results are presented for the full calibration period. Sub-period tables are presented in Appendix S.

### **Front River**

The Mean Error magnitudes for both the dissolved oxygen and the dissolved oxygen deficit range from -0.2 mg/L up to -1.1 mg/L, with similar ranges in the dissolved oxygen deficit positive. The ME are generally in one direction supporting the conclusions made in Section 8.4.1 of a net offset created by the boundary conditions or SOD. The RMS and AME errors average 0.7 mg/L to 0.9 mg/L with much of this error attributable to the shift in the means.

In Appendix S the errors are tabulated for five two-week sub-periods. The ME, the AME, and the RMSE remain relatively consistent throughout all of the sub-periods with the AME and RMSE values identical for four of the sub-periods and the other sub-period only off by 0.1 mg/L from the others.

### **Middle River and Little Back River**

The ME on the Middle and Little Back Rivers are similar to the Front River also showing low simulated dissolved oxygen and high dissolved oxygen deficit. The RMSE and AME errors average on the order of 0.9 mg/L.

### **8.3.3 Time Series Comparisons**

Figures 8-5 through 8-8 present time series comparisons of the measured versus simulated dissolved oxygen at key stations throughout the system and Figures 8-11 through 8-14 present the comparisons of the dissolved oxygen deficit. The time series are presented for the full calibration. The full time series from all of the stations are presented in Appendix S.

### **Front River**

The time series along the Front River for the 1997 simulations show higher levels of dissolved oxygen in the system than was measured in 1999. 1997 is clearly a less critical year and the model (other than the net error associated with the boundary assumptions in 1999) captures this less critical nature of the data. One unique aspect of the 1997 data set

are the apparent periods where surface dissolved oxygen values go up distinctly, and in two cases (GPA-06 and GPA-12) goes above saturation levels (Figures 8-11 and 8-13). This may be errors in the data set or there may be primary productivity processes occurring that did not exist in 1999. As no light or good Chlorophyll-a studies were available for 1997 a supersaturation event would not be simulated by the model under the imported 1999 conditions. The results show reasonable agreement with trends and variations as was seen in the 1999 simulations.

### **Middle and Little Back River**

Similar findings for the Middle and Little Back River were found for the 1997 simulations as found in the 1999 simulations. The degree of tidal variation at GPA-12 on the Middle River is too high while GPA-10 is reasonably simulated. On the Little Back River a station that was not available for the 1999 simulations (GPA-13) had dissolved oxygen data. The results show reasonable agreement with the measured data although the tidal fluctuations are slightly over predicted.

## **8.4 COMPARISON WITH FEDERAL EXPECTATIONS CRITERIA**

Tables 8-3a and 8-3b present the tabularized percentile results discussed earlier in comparison with the Federal Expectations Criteria. Table 8-3a presents the results for the dissolved oxygen, while 8-3b presents the results for the dissolved oxygen deficit. For the Front River the percent passing the Federal Expectations Criteria is 45 percent for the 10<sup>th</sup> percentile dissolved oxygen and the 90<sup>th</sup> percentile dissolved oxygen deficit. For the 50<sup>th</sup> percentiles the percent passing is 27 percent. It would be expected that if the net mean error associated with the definition of the upstream and downstream boundaries were fixed the percent passing would be much greater and on the order of the results from the 1999 simulations.

## 9.0 WATER QUALITY MODEL SENSITIVITY

This chapter presents the results of the sensitivity tests performed on the water quality model. Table 9-1 presents the suite of sensitivity runs performed. This list was based upon input from the SMART. The parameters tested included:

- Sediment Oxygen Demand
- Carbonaceous Decay Rate
- Marsh Loadings
- Point Source Loads
- Nitrification Rate
- Vertical Mixing
- Reaeration
- Upstream Loads
- Use of 2-Decay Rate

The sensitivity tests were run on a baseline model simulation for August of 1999. The sensitivity of the 50<sup>th</sup> and 10<sup>th</sup> percentile dissolved oxygen and the 50<sup>th</sup> and 90<sup>th</sup> dissolved oxygen deficit were compared with the baseline. The results are presented as mg/L change in dissolved oxygen or dissolved oxygen deficit based upon the parameters varied. Tables 9-2 and 9-3 present the results for the dissolved oxygen and Tables 9-4 and 9-5 present the results for the dissolved oxygen deficit. The changes are also presented graphically in Appendix W. The tables presented herein for salinity provide actual value changes in salinity concentration. The following sections discuss the results from each of the parameters tested.

### 9.1 **SEDIMENT OXYGEN DEMAND**

A spatially variant Sediment Oxygen Demand (SOD) was defined for the model that varied between 0.5 and 2.9 gm/m<sup>2</sup>/day (at 20°C) with the highest values in the Front River above Fort Jackson to the Turning Basin. For the sensitivity analysis, the baseline SOD was increased 30 percent and decreased 30 percent. As expected the results show the highest level of sensitivity in the bottom waters of the Front River between Fort Jackson and the Kings Island Turning Basin. The SOD variations result in changes of the dissolved oxygen and the dissolved oxygen deficit on the order of 0.2 mg/L. A slightly higher variation can be

seen in the dissolved oxygen deficit over the dissolved oxygen but the levels are negligible. Based upon the baseline concentrations this change represents a 5 to 8 percent change in dissolved oxygen.

## **9.2 CARBONACEOUS DECAY RATE**

The baseline decay rate from the model was 0.09 1/day. For the sensitivity analysis the decay rate was varied +/- 33 percent to 0.06 1/day and 0.12 1/day. This parameter is the most sensitive based upon the tests. The 33 percent change resulted in maximum dissolved oxygen differences in the Front River bottom stations of 0.3 to 0.4 mg/L. The increases associated with the lower rate were greater than the decreases associated with the higher rate. The change represents a 10 percent maximum variation in the bottom water dissolved oxygen concentrations.

## **9.3 MARSH BOUNDARIES**

For the marsh boundary tests, the baseline loads were varied +/- 25 percent. This level of variation did not create a significant variation in the dissolved oxygen and the dissolved oxygen deficit. Overall the changes associated with the marsh load variations were less than 0.1 mg/L with most less than 0.05 mg/L. This represents a less than 2-3 percent change.

## **9.4 POINT SOURCE LOADS**

For the point source tests, the loads were varied +/- 50 percent. The resultant instream changes are greatest in the area of the primary discharge and show levels of sensitivity equivalent to that found for the 30 percent SOD variations. The surface and bottom results along the Front River show similar levels of response with maximum variations of 0.3 mg/L which represents a 10 percent change. The sensitivity of the point sources drops off moving away from the locations of the primary discharges, with levels in the Middle River and Little Back River on the order of 0.05 mg/L.

## **9.5 NITRIFICATION RATE**

Within the model a significant variation in the nitrification rate from 0.01 to 0.07 1/day did not create any significant variation in the dissolved oxygen within the system. The dissolved oxygen and dissolved oxygen deficit are not sensitive to this parameter with variations at or less than 0.03 mg/L.

## **9.6 VERTICAL MIXING**

The model is relatively insensitive to the +/- 10 percent change in vertical mixing with variations generally less than 0.1 mg/L. The greatest sensitivity is found within the surface waters along the Front River where an increase in the vertical mixing creates a decrease in the dissolved oxygen and a decrease in the vertical mixing creates an increase in the surface dissolved oxygen as the degree of stratification increases.

## **9.7 REAERATION**

The model is also relatively insensitive to the +/- 10 percent change in reaeration, with variations generally less than 0.05 mg/L. As expected increasing reaeration increases dissolved oxygen, while decreasing drops dissolved oxygen levels.

## **9.8 UPSTREAM LOADS**

The model is relatively insensitive to the +/- 10 percent change in upstream loads with variations generally less than 0.05 mg/L. The variations are relatively constant throughout the model domain.

## **9.9 2-DECAY RATE**

Based upon recommendations by the SMART, an evaluation of the effects of using a 2-decay rate model was assessed. For this simulation all of the loads, other than the IP load, were oxidized at the calibration rate of 0.09 1/day. The IP load was put into the system and allowed to decay at a rate of 0.03 1/day. As expected the main area affected was upstream and downstream of the load (between GPA-06 and GPA-22) for both the surface and bottom stations. The reduced decay rate for the primary discharger resulted in an increase in

dissolved oxygen of around 0.3 mg/L in the surface and bottom readings. This increase trailed off moving away from the discharge point as expected.

## 10.0 SUMMARY AND CONCLUSIONS

The water quality model calibration effort presented herein was made possible by the existence of a comprehensive data set collected in 1999 and numerous coincident studies completed for the modeling effort. These studies were performed by EPA, GAEPD, USGS, Law Engineering for the Harbor Committee, and the USACE. The extensive studies provided an excellent understanding of the physical and chemical processes that affect water chemistry and specifically dissolved oxygen within the Lower Savannah River estuary.

The model development process has been completed with guidance and review by a team of experts representing federal, state and local agencies (SMART). These agency groups requested that a comprehensive evaluation of the model performance be done, and the results of that evaluation were presented in this report.

The BFWASP water quality model transport was tested by simulating a conservative tracer representing salinity. The results of the BFWASP simulations of salinity were compared with the BFHYDRO simulations as well as to the measured data to assure that the transport in WASP was reasonable. This is based upon the interpolation required of the hydrodynamic file transmitted to the BFWASP model. The tests showed that the difference in the transport within the BFWASP model and the BFHYDRO model were insignificant and the transport in BFWASP was fully adequate for water quality simulations.

The independent variables assessed in the calibration and verification included:

- Carbonaceous Biochemical Oxygen Demand
- Ammonia
- Nitrate-Nitrite
- Organic Nitrogen
- Ortho-Phosphate
- Dissolved Oxygen
- Dissolved Oxygen Deficit
- Chlorophyll-a

The statistical measures employed to quantitatively assess the model performance were:

- Mean error
- Absolute mean error
- Root mean square error

- Percentiles comparisons

These statistical measures were compared against site specific criteria designed to measure the performance of the model in the context of its ultimate use in evaluating the effects of the proposed deepening project on the dissolved oxygen. The Federal Criteria guidance provided a baseline from which a weight of evidence approach is to be utilized to evaluate the performance of the model to determine its applicability for use in impact evaluation. The weight of evidence must include not only an evaluation of the absolute performance, but also consider the uncertainty in available data and the present state of the art for models to simulate water quality processes.

In addition to the quantitative error analysis, wide-ranging qualitative analyses were performed through the use of many and varied graphs and plots with model-predicted and observed data overlain. This allowed the direct comparison of model predictions to the observations in an attempt to understand and evaluate trends and magnitudes of the water quality parameters.

The results of the 1999 model calibration and 1997 verification can be summarized for each of the parameters evaluated as follows:

- The water chemistry comparisons showed that the model is capturing the average longitudinal distribution of CBODu and nutrients. The measured high point of CBODu and ammonia in the center of the harbor area between RM 13 and RM 20 was simulated in 1999 and 1997. This was done within the context of a good representation of the distribution of the loads to the system based upon analysis of available data.
- The water chemistry simulations at times did not capture the range of measured variation in the CBODu and nutrients. The simulated ranges are limited by the variation in the available upstream boundary conditions, and the assumption of constant offshore concentrations.
- The simulation of the chlorophyll-a distribution in the system identified that the model is properly handling the light limited primary productivity.
- The longitudinal distributions of the dissolved oxygen and the dissolved oxygen deficit in the Front River, Middle River and Little Back River, were captured by the model

both in magnitude, longitudinal position, relative change, and tidal variability for the 1999 simulations.

- The 1997 simulations showed good agreement in relative change, longitudinal position, and tidal variability but the overall mean was too low. This was a function of utilizing the 1999 assumptions for percent saturation in the dissolved oxygen boundaries.
- The longitudinal simulation of the dissolved oxygen and dissolved oxygen deficit distributions for 1999 show very good agreement with the measured data based upon percentile comparisons. Under the stringent criteria defined by the Federal Agencies (0.2 mg/L for the percentile differences) the model showed 70 percent passing for the 10<sup>th</sup> percentile dissolved oxygen and 50 percent passing for the 50<sup>th</sup> percentiles.
- The longitudinal simulation of the dissolved oxygen and dissolved oxygen deficit for 1997 also showed good agreement but suffered from an overall mean error associated with boundary definitions.
- 24-hour running averages of the measured dissolved oxygen deficit at key stations in the harbor between RM 13 and RM 20 from the 1999 data, showed strong correlations with variations in the total point source discharge data (ranging from 120,000 lb/day down to 10,000 lb/day). The model captured the response to this load change indicating that the model is handling the loads and the instream kinetics properly.
- The model captures the general stratification/destratification processes in the harbor and the highly variable nature of the dissolved oxygen. The relative differences in the surface and bottom dissolved oxygen are simulated well with the spread in the degree of stratification moving upstream through the main harbor area simulated in the model.
- The vertical structure of the dissolved oxygen is captured well using the 11-layers. The position and gradient of dissolved oxygen near the pycnocline is captured.
- Based upon the range of the tidal variation simulated in the model, it appears that the simulated location of the area of sharp increase (high gradient area) is slightly upstream of where it was measured above GPA-22.

- Based upon the simulation of the tidal variations at GPA-08 and GPA-09 the model is reasonably simulating the longitudinal gradient of dissolved oxygen in this transition region and while somewhat dispersive

By definition, numerical modeling can only approximate reality and although no model calibration effort can be flawless, the present study has shown that the water quality model application to the Savannah River represents the key processes. The Lower Savannah River Estuary is a highly complex and dynamic area with a great deal of variation in the temporal and spatial distribution of the dissolved oxygen and dissolved oxygen deficit. The model calibration/validation presented herein, represents the best overall calibration on a system wide basis, with specific focus on the key areas within the harbor. The calibration/validation presentation has shown that the model is fully capable and suitable for use in the evaluation of deepening related changes in the river.

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