

Prepared for:



Georgia Ports Authority

Calibration of a Hydrodynamic and Water Quality Model for the Savannah Harbor

Volume 1: Hydrodynamic Modeling Report



98-991 H&WQ Title.cdr 11/12/03

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January 2004

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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 Expansion 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 simulating the existing water surface elevation, currents, temperature, salinity, and dissolved oxygen (DO) in the estuary, as well as tools capable of 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 conducted 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).

This report (Volume I) provides a detailed presentation of the calibration and validation of the Hydrodynamic Model, along with all assumptions, inputs, formulations and analyses conducted throughout this study. The Hydrodynamic Model is calibrated to the more comprehensive data set collected in 1999 and then validated against the original data collected in 1997.

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 which 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 upstream of where the river crosses I-95 to its confluence with the Atlantic Ocean. Through this region, the river transitions from fresh water 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 mile system within the study area, and the location of the City of Savannah in relation to the river. While the primary area of concern is from upstream of I-95 to the mouth, 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 (2 meters) and a maximum range on the order of 9-10 feet (3 meters). 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 28) and reversing flow conditions are measured as far upstream as Ebenezer Creek. Tidal fluctuations within the river extend upstream of Hardeeville.

The Clyo 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 which, prior to 1950, exceeded 60,000 cfs (1700 m³/s) at times. 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 m³/s) 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 value measured during the study period of August to September of 1999 was 5,600 cfs (159 m³/s) while it was 10,600 (300 m³/s) in 1997.

1.3 STUDY GOALS

The general goal of this study was to develop a three-dimensional hydrodynamic model that is capable of accurately simulating the temporal and spatial distribution of the water surface elevation, currents, salinity and temperature within the Lower Savannah River Estuary under existing conditions as well as under a proposed deepened condition.

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 water surface elevation, currents, salinity and temperature. The draft write up of the performance criteria is presented within Appendix GG (the document was not finalized through this process). The criteria provide guidelines for model performance and acceptability, but based upon extensive 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 follow section outlines the report components that are to provide the basis for a weight of evidence review of the Hydrodynamic Model for the Lower Savannah River Estuary.

1.4 REPORT OUTLINE

This report presents the calibration and validation of the Hydrodynamic Model to the data sets from 1999 and 1997 respectively. In addition, it summarizes results and studies presented within other reports that are relevant to the development and calibration of the hydrodynamic model. The following outlines the specific chapters of this report:

- ✚ **2.0: Characterization of the Hydrodynamics of the Lower Savannah River Estuary** – Outlines key aspects of the system hydrodynamics (determined from analysis of the measured data in 1999 and 1997), and provides the groundwork for evaluation of the models ability to capture key processes.
- ✚ **3.0: Hydrodynamic Model Formulation** – Presents the formulation of the BFHYDRO Hydrodynamic Model.
- ✚ **4.0: Convergence, Sigma Transport and Mass Balance Tests** – Presents the results of a series of test conducted on the BFHYDRO model to assure proper formulation and solution of the equations as well as sufficient grid resolution to resolve the system.

- ✚ **5.0: Application of the BFHYDRO Model to the Lower Savannah River Estuary** - Presents the development of the baseline hydrodynamic model for the Lower Savannah River Estuary using the BFHYDRO model including; the simulation periods, model geometry, boundary condition inputs, and model coefficients for both the calibration period in 1999 and the validation period in 1997.
- ✚ **6.0: Hydrodynamic Model Calibration Methodology** – Presents the graphical and statistical methods used in the calibration and validation of the hydrodynamic model.
- ✚ **7.0: Hydrodynamic Model Calibration to 1999 Dataset** – Presents, the results of the calibration of the hydrodynamic model to the 1999 data set, including the graphical and statistical comparisons.
- ✚ **8.0: Hydrodynamic Model Validation to 1997 Dataset** – Presents, the results of the validation of the Hydrodynamic Model to the 1997 data set, including the graphical and statistical comparisons.
- ✚ **9.0: Hydrodynamic Model Sensitivity Analyses** – Presents results from sensitivity analysis of the Hydrodynamic Model.
- ✚ **10.0: Summary and Conclusions**

2.0 HYDRODYNAMIC CHARACTERIZATION OF THE LOWER SAVANNAH RIVER ESTUARY

This section describes the physical environment of the Lower Savannah River Estuary and the resulting hydrodynamic 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 are along the south side of 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 of the City 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 Clio, Georgia, (RM 61) average 11,600 cfs (329 m³/s) with maximum and minimum annual mean discharges of 20,900 cfs (592 m³/s) and 9,820 cfs (278 m³/s), respectively, since 1962. The U. S. Geological Survey (USGS) station at Clio, 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 fps (1.2 m/s) on the flood tide and 5 fps (1.5 m/s) on ebb tide. Ebb velocities are usually somewhat higher than flood velocities.

2.3 ANTHROPOGENIC IMPACTS TO THE SYSTEM

Granger (1968) summarized the early work on the Savannah River:

Work on the harbor, and on the river above and below the town, falls into two general periods: First, operations that were designed to increase depths in

front of the town by diverting water from the Back River to the Front River and to reduce shoaling by removing obstruction; and second, overall plans for improvements that were based on comprehensive studies for obtaining a desired depth in the entire channel from the Bar to the upper harbor limits.

The first period, covering the years from 1733-1850, consisted of work done when necessary by the town, the Commissioners of the Port and Pilotage, by the U.S. Treasury, by the Corps of Engineers and by the Topographical Bureau; the second period covers the jurisdiction of the Corps of Engineers from the 1850's to the present time with the exception of the confused interruptions during the Civil War years.

The 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.

It is clear from the history presented above that the Lower Savannah River Estuary has undergone significant physical alteration over the past century. These alterations, especially the continued deepening, the construction of the tide gate, and excavation and filling of connecting channels (i.e., New Cut) have permanently altered the hydrodynamic conditions in the system. The most dramatic result of these alterations has been the increased intrusion of salinity up the main channel of the river. Presently, saline conditions extend to the I-95 Bridge crossing nearly 27 miles upriver of the mouth at Fort Pulaski.

The simulation of the present hydrodynamic conditions within the system, including the salinity intrusion is the primary goal for the development of the hydrodynamic model. The following describes the measured hydrodynamic data sets utilized in the development of the hydrodynamic model and some key hydrodynamic characteristics to be simulated by the model.

2.4 JULY TO SEPTEMBER 1997 MONITORING

For the purpose of model calibration, ATM conducted an intensive field-monitoring program in 1997 to quantify the hydrodynamic conditions within the Lower Savannah River Estuary. Under this monitoring effort a total of 14 continuous monitoring stations measured water

surface elevation, specific conductivity (converted to salinity), and temperature between July 1997 and September 1997. The continuous monitoring stations consisted of permanently mounted instruments that 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 to provide the worst-case condition of salinity intrusion. Additionally, continuous current measurements were taken at locations within and outside of the navigation channel. Detailed descriptions of the methodologies utilized, the locations of stations, the data collected, and findings from the intensive 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 different hydrodynamic data collected.

2.4.1 Continuous Salinity and Temperature

Figure 2-2 shows the locations of the continuous salinity and temperature 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 salinity (in the channel areas along the Front River); or bottom salinity (outside of the channel). A single station that measured the offshore salinity (GPA-01) was positioned in the middle of the water column. In addition to the GPA stations, USGS maintained specific conductance sensors on their stations at the Houlihan Bridge, Lucknow Canal, and the USF&W station. Figure 2-4 presents the locations of the USGS stations. Plots of the measured continuous salinity and temperature data, collected in 1997, are presented in Appendix A.

2.4.2 Continuous Currents

To quantify the vertical variation in the density-driven flow, as well as the tidal flow passing through the system, two bottom-mounted Acoustic Doppler Current Profilers (ADCP) and two electro-magnetic current meters (S-4) were deployed. Figure 2-3 shows the locations of the current meters. The ADCPs recorded continuous currents at 1-meter intervals over the water

column, and the S-4 collected mid-depth current velocities, at 15-minute intervals, over a 30-day period. The two S-4 current meters experienced significant problems during deployment. Plots of the measured current data, collected in 1997, are presented in Appendix A.

2.4.3 Water Surface Elevation Fluctuations

Each of the GPA stations where continuous salinity and temperature data were collected had a pressure sensor that recorded the water surface elevation fluctuations. In addition, USGS maintained various stage gages throughout the system as shown in Figure 2-4. While the USGS stations were surveyed relative to the National Geodetic Vertical Datum of 1929 (NGVD 1929), the GPA stations were not. Corrections to the pressure sensor data were performed to bring each station as close as possible to the datum used for the USGS gages. This correction is described in detail in the report entitled, "Hydrodynamic and Water Quality Monitoring of the Lower Savannah River Estuary, July-September 1997" (Applied Technology and Management, 1998b). Plots of the 1997 measured water surface elevation data are presented in Appendix A.

2.4.4 Freshwater Flow

USGS maintains a flow measurement station at Clyo. This flow measurement station provided the upstream freshwater inflow data for the model. The Clyo gage is located approximately 60 miles upstream of the mouth of Savannah Harbor.

2.4.5 Cross-Section Flow Measurements

Boat-mounted ADCP transects measured cross-sectional discharges across the width and depth of the river at critical locations. Figures 2-5a and 2-5b show the location of the cross-section transects. These data were used to quantify flux at these areas throughout the tidal cycle. The sections were chosen to try and capture the distribution of flows where the Front River splits at Fort Jackson, the distribution of flows in the Front River, Middle River, and Little Back River where the Houlihan Bridge crosses the system just above the channel, and finally in the upper reaches where the three branches rejoin just below the I-95 bridge.

2.4.6 Meteorological

For the 1997 monitoring effort it was anticipated to use the meteorological station located at the Savannah Airport. Unfortunately, this gage was not operating at the time of the 1997 data collection effort and no local data were available. Searches for other meteorological stations from which accurate local data could be extracted did not provide a station near enough for reliable data to use in the model. This limited the ability of the 1997 simulations to accurately predict temperature.

2.5 AUGUST TO OCTOBER 1999 MONITORING

Based upon review of the modeling performed under the Tier I EIS, it was determined that a more comprehensive data collection effort was required to calibrate the water quality component of the model. The monitoring study consisted of a series of data collection efforts conducted in parallel from August 2, 1999 through October 9, 1999. The data utilized in the development of the hydrodynamic model are summarized in the following list:

- Deployment of YSI water quality instruments at 29 instrument locations in the river. There were 21 stations with 8 in the navigational channel consisting of top and bottom instruments. The water quality instruments measured temperature and salinity at 5-minute intervals.
- Deployment of YSI pressure transducers at 21 instrument locations in the river. Water surface elevation was measured at 5-minute intervals.
- Deployment of 2 bottom-mounted Acoustic Doppler Current Profilers in the harbor that measured vertical profiles of velocity at 10-minute intervals.
- Deployment of 6 Nortek Aquadopp Current Meters at and upstream of I-95 Bridge that measured a point velocity at 10-minute intervals.
- ADCP transects performed at 29 locations throughout the estuary to monitor flow during a tide cycle.
- Longitudinal profiling of 10 stations established by EPD in the 1980s.

- Deployment of 3 meteorological stations that measured rainfall, air temperature, barometric pressure, wind speed and direction, solar radiation, and relative humidity at 5-minute intervals.

Detailed descriptions of the methodologies utilized, the locations of stations, and the data collected from the intensive field monitoring program are presented in a report entitled "*Hydrodynamic and Water Quality Monitoring of the Lower Savannah River Estuary, August 2 through October 9, 1999*" (Applied Technology and Management, 2000). These data are used for the calibration and verification of the hydrodynamic and salinity model. The following summarizes the types of data collected relative to the hydrodynamic model.

2.5.1 Continuous Salinity and Temperature

Figures 2-6a and 2-6b show the locations of the continuous salinity and temperature measurements throughout the system. The stations are distributed up the Front River, Back River, Middle River, and Little Back River from the mouth near Fort Pulaski up to Ebenezer Creek. As the legend shows, the stations measured bottom and surface salinity and temperature in the channel areas along the Front River, surface temperature and salinity in the Middle and Little Back Rivers, and bottom or mid-depth temperature and salinity in other areas outside of the channel. In contrast to the bottom measurements collected during 1997, surface measurements were performed in the Middle River and Little Back River for the 1999 monitoring in order to record the salinity that enters the marshes during high tide periods. The surface sensors were mounted on buoys and therefore provided an accurate measurement of the true surface values even as the water surface fluctuated.

In addition to the GPA stations, USGS maintained specific conductance sensors on their stations at the Houlihan Bridge, Limehouse, and the USF&W dock. Figure 2-4 presents the locations of the USGS stations. Plots of the measured continuous salinity and temperature data, collected in 1999, are presented in Appendix B.

2.5.2 Continuous Currents

To quantify the vertical current structure, two bottom-mounted Acoustic Doppler Current Profilers (ADCPs) were deployed along with side viewing Aquadopp Current Meters. Figures

2-7a and 2-7b show the locations of the current meters. The ADCPs recorded continuous currents at 1-meter intervals over the water column, and the Aquadopps collected single mid-depth current readings. The Aquadopps, which were located at and above I-95, were installed primarily for the Chloride Study (a separate study associated with the SHEP), but provided some additional verification of the flows in the upper river. Plots of the measured current data collected in 1999 are presented in Appendix B.

2.5.3 Continuous Water Level

Each of the GPA stations where continuous salinity and temperature data were collected had a depth sensor that recorded the water surface elevation fluctuations. In addition, USGS maintained various stage gages throughout the system as shown in Figure 2-4. While the USGS stations were surveyed relative to the NGVD 1929 datum, the GPA stations were not. Corrections to the pressure sensor data were performed to bring each station as close as possible to the datum used for the USGS gages. This correction is described in detail in the report entitled, "Hydrodynamic and Water Quality Monitoring of the Lower Savannah River Estuary, August 2 through October 9, 1999" (Applied Technology and Management, 2000). Plots of the measured water surface elevation data collected in 1999 are presented in Appendix B.

2.5.4 Freshwater Flow

As in the 1997 period, the USGS maintained flow measurement station at Clyo was used to provide freshwater inflow data. The Clyo gage is located approximately 60 miles upstream of the mouth of Savannah Harbor.

2.5.5 Cross-Section Flow Measurements

Boat-mounted ADCP transects measured cross sectional discharge across the width and depth of the river at critical locations. Figure 2-8 shows the transect locations. These data were used to quantify flux at these areas throughout the tidal cycle.

2.5.6 EPD Sampling Station Synoptics

Studies conducted in the 1980s by GAEPD performed synoptic profile measurements of salinity and temperature at 10 stations traveling upriver on the Front River (Figure 2-9). The EPD stations were sampled as crews followed the slack high and low tide conditions traveling upriver. Lag between the observed low and high slack conditions between Fort Pulaski (entrance to Savannah River from Atlantic Ocean) and Port Wentworth (Approximately Front River Mile 21.2) is 1.3 hours. For the 1999 monitoring period these stations were again sampled synoptically three times. The dates for the synoptic measurements were September 13, September 20 and September 27 1999. During the September 13th sampling, efforts were made to provide cross-sectional representations of the system as well as synoptic measurements. Sampling in four locations along the river cross section at each EPD monitoring location slowed the sampling such that synoptic high and low tide measurements could not be completed given the number of crews available. The number of boats and crew were modified for the subsequent samplings, and synoptic high and low tide measurements were taken.

2.5.7 Meteorological

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

2.6 SUMMARY OF KEY HYDRODYNAMIC PROCESSES

In any successful modeling study of a complex system, it is critical to identify how the model is to be used, and focusing the model development on the simulation of the associated key processes. For the Savannah Harbor Hydrodynamic Model these key processes were determined through extensive analysis of the data and documented in three reports: "Analysis of the Historical Data for the Lower Savannah River Estuary" (Applied Technology and Management, 1998a), "Hydrodynamic and Water Quality Monitoring within the Lower Savannah River Estuary, July-September 1997" (Applied Technology and Management,

1998b), and “Hydrodynamic and Water Quality Monitoring within the Lower Savannah River Estuary, August-October 1999” (Applied Technology and Management, 2000). Additionally, the goals of the study determine the key processes. For the Hydrodynamic Model the goals are:

- Simulation of the salinity intrusion into the system, and the temporal and spatial distribution of the salinity above Fort Jackson (primarily within the marshes of the Savannah National Wildlife Refuge).
- Simulation of the water levels throughout the system and the resulting high tide inundation of the marshes.
- Evaluation of the effects of the proposed navigation channel deepening on the hydrodynamics and primarily the salinity intrusion and distribution above Fort Jackson (primarily within the marshes of the Savannah National Wildlife Refuge).
- Development of transport processes sufficient for simulation of dissolved oxygen conditions within the main harbor area.

One of the major findings of the monitoring program was to confirm the importance of the stratification/destratification process on the temporal and spatial distribution of salinity throughout the harbor, the Middle River, and the Little Back River. The analysis of the historic data showed that following the decommissioning of the Tide Gate, the maximum salinity intrusion along the Front River occurred primarily during neap tide conditions, whereas maximums occurred during spring tide conditions when the Tide Gate was in operation. One potential cause for this alteration is the reduction in the ebb tide velocities along the Front River above Fort Jackson following the Tide Gate decommissioning. Since vertical turbulence is directly proportional to tidal velocities, a reduction in the velocities causes an associated reduction in turbulent mixing. Therefore, during neap tide conditions, there is not enough energy to break down the salinity gradient, and water masses with higher salinity are able to intrude further into the system.

Furthermore, the analyses of the continuous and synoptic data identified mechanisms of salinity transport in the system not reported in previous studies. The higher levels of salinity within the Middle River, in comparison to the Little Back River, appear to be transported directly from the Front River through the connection at RM 20. Since the closure of New Cut, the only downstream connection remaining between the Middle River and the Little Back River is Rifle Cut. Salinity measured in the Little Back River at Station GPA-15 identified the

impacts on salinity concentrations due to flows from the Middle River through Rifle Cut. Based upon the data from the USGS gage at the U. S. Fish and Wildlife Service (USF&W) Dock, these impacts appear to be localized to the vicinity of the entrance to Rifle Cut.

The timing of the salinity distribution also shows some interesting characteristics. Along the Front River, as the tidal forcing goes from a neap tide condition to a spring tide condition the stratification begins to breakdown. At this point the peak salinity concentrations are beginning to reduce along the Front River but begin to peak up in the Middle and Little Back River. Overall, the data showed around a three to four day lag in the timing of the salinity high tide peaks in the Front River as compared to the Little Back River. This characteristic is somewhat unique and defines the timing of salinity spikes in the areas of the freshwater marshes.

Evaluation of the water surface elevation data showed that the tidal amplitudes in the system increase moving upstream to a point above the Houlihan Bridge after which the tidal amplitudes are gradually dampened. At the Houlihan Bridge the tidal amplitudes are on the order of 20 percent greater than at the mouth of the system. The dampening continues upstream past I-95 where there is a net mean water level set up that continues as the tidal amplitudes are reduced. This balance within the Front River carries over to the Middle and Little Back River where the tidal amplitudes are dampened relative to the main stem and a net mean water level setup exists.

In summary, the analyses of the data identified some important characteristics relative to the temporal and spatial distribution of the salinity and the water levels within the Lower Savannah River Estuary, including:

- The stratification/destratification along the maintained portion of the Front River and the resulting upstream salinity intrusion under more stratified conditions;
- The increased surface salinity concentrations up the Middle River in relation to the Little Back River due to the direct connection with the Front River above Hutchinson Island;
- The transport of higher salinity waters from the Middle River to the Little Back River through Rifle Cut and the associated localized impacts to salinities;
- The lag of salinity peaks on the Middle and Little Back River relative to the Front River;

- The amplification and dampening of the water surface elevations throughout the system; and
- The net set up/set down of the mean water level.

The model development and calibration focused upon these characteristics. Additionally, the stratification/destratification and longitudinal transport is the primary mechanism of transport to be transferred over to the water quality modeling study.

3.0 HYDRODYNAMIC MODEL FORMULATION

The complexity of the physical environment must be considered when selecting a hydrodynamic model. It is clear from the characterization of the Lower Savannah River Estuary that there are a number of complex processes occurring within the system. In general, the water body is long, thin, and full of turns and branches. For the level of prediction required for the hydrodynamic simulations, a full 3-dimensional, coupled, prognostic hydrodynamic, salinity, and temperature model was utilized.

For a standard rectangular grid finite difference model, if the grid spacing is made small enough to resolve the smallest spatial scales of interest, the computational costs often become excessive. On the other hand, if the number of mesh points is not large enough, the numerical predictions may be in error throughout the solution domain. Ideally, a model grid would be able to incorporate variable cell sizes, enabling the modeler to resolve the areas of interest without being penalized by over-resolving the entire grid. In addition, the ideal grid would accurately follow the geometry of the coastline without the “stair step” problem or over-resolution required from a rectangular grid.

For the Lower Savannah River Estuary application, a boundary-fitted hydrodynamic model (BFHYDRO) was used to simulate water surface elevation, velocity, salinity and temperature. The boundary-fitted model matches the model coordinates with the shoreline boundaries of the water body accurately representing the study area. This system also allows the user to adjust the model grid resolution as desired. This approach is consistent with the variable geometry and coastal features of the Lower Savannah River Estuary. The model may be applied in either two or three dimensions depending upon on the nature of the problem and the complexity of the study. A copy of the BFHYDRO FORTRAN code, as used in this study, is included in Appendix HH.

The boundary-fitted method uses a set of coupled quasi-linear elliptic transformation equations to map an arbitrary horizontal multi-connected region from physical space to a rectangular mesh structure in the transformed horizontal plane (Spaulding, 1984). The three-dimensional conservation of mass and momentum equations, with approximations suitable for lakes, rivers, and estuaries that form the basis of the model, are then solved in this transformed space. In addition, an algebraic transformation is used in the vertical dimension to map the free surface and bottom on to coordinate surfaces. The resulting equations are solved using an efficient semi-implicit finite difference algorithm for the exterior mode (two-

dimensional vertically averaged) and by an explicit finite difference leveled algorithm for the vertical structure of the interior mode (three-dimensional).

A detailed description of the original model with associated test cases is included as Appendix BB (Muin and Spaulding, 1997). The manuscript was originally part of a Ph.D. dissertation that extended the boundary-fitted model capabilities by applying a contravariant velocity formulation to the transformed momentum equations. A brief description of the model is given in the following sections.

3.1 CONSERVATION EQUATIONS

The basic equations are written in spherical coordinates to allow for accurate representation of large model areas. The conservation equations for water mass, momentum (in three dimensions), constituent mass (salinity), and temperature form the basis of the model. It is assumed that the flow is incompressible, that the fluid is in hydrostatic balance, the horizontal friction is not significant, and the Boussinesq approximation applies.

The boundary conditions are as follows:

- At land the normal component of velocity is zero;
- At open boundaries the free surface elevation must be specified and salinity and temperature must be specified on inflow. On outflow, salinity and temperature are advected out of the model domain;
- A bottom stress or a no-slip condition is applied at the bottom;
- No water or salt or temperature is assumed to transfer to or from the bottom;
- A wind stress is applied at the surface; and
- Surface waters exchange heat with the atmosphere.

3.2 SOLUTION METHODOLOGY

The set of governing equations with dependent and independent variables transformed from spherical to curvilinear coordinates, in concert with the boundary conditions, is solved by a semi-implicit, split-mode finite difference procedure (Swanson, 1986). The equations of motion are vertically integrated and, through simple algebraic manipulation, are recast in

terms of a single Helmholtz equation in surface elevation. This equation is solved using a sparse matrix solution technique to predict the spatial distribution of surface elevation for each grid. The finite difference solutions utilize a staggered grid structure where velocity flux (vector) terms are defined on the outer boundaries of the grid cell, while scalar quantities such as water surface elevation, salinity and temperature are solved at the cell center. Figure 3-1 presents a schematic of the grid cell structure.

The vertically averaged velocity is then determined explicitly using the momentum equation. This step constitutes the external or vertically averaged mode. Deviations of the velocity field from this vertically averaged value are then calculated, using a tri-diagonal matrix technique. The deviations are added to the vertically averaged values to obtain the vertical profile of velocity at each grid cell, thereby generating the complete current patterns. This constitutes the internal mode. The methodology allows time steps based on the advective, rather than the gravity, wave speed as in conventional explicit finite difference methods and, therefore, results in a computationally efficient solution procedure (Swanson, 1986).

3.3 TRANSPORT EQUATIONS

The salinity and temperature transport models are solved by a simple explicit technique except for the vertical diffusion term which is solved by a three time level, implicit scheme to ease the time step restriction due to the small vertical length scale. The advection terms are solved using a first order upwind-differencing scheme that is first order accurate. The QUICKEST formulation for the advective terms was implemented and tested in the model to try and achieve sharper gradients in salinity structure. This formulation did not provide significant improvement in the model simulations but did introduce additional instability. For this reason the final simulations presented within this report utilize the first-order upwind solution scheme for the advective terms. Horizontal gradients in temperature, (as well as in salinity, density and pressure) are evaluated along lines of constant depth to reduce the artificial numerical dispersion in the vertical associated with the sigma transformed system.

The horizontal diffusion terms are solved by a centered-in-space, explicit technique. The diffusive and advective stability criteria for the numerical techniques are, $\Delta t < \Delta s^2 / (2D_h)$, and $\Delta t < \Delta s / U_s$, where Δs and U_s are horizontal grid size and velocity, respectively.

3.4 THERMAL MODEL

At the water surface the temperature is influenced by a number of factors in the environment above. The most important terms in the heat transfer with the environment can be summarized as follows:

- shortwave solar radiation, surface re-radiation and reflection;
- longwave atmospheric radiation;
- longwave radiation emitted from the water surface;
- convection, (sensible) heat transfer between water and air; and
- evaporation, (latent) heat transfer between water and air.

The heat exchange with the atmosphere is determined with the surface layer, thermal boundary condition, by calculating the net rate of heat transfer, (in or out) for each of the terms above on a grid cell by grid cell basis. The net exchange is based on the water temperature in each cell and the present atmospheric conditions.

3.5 CHANGES MADE TO THE MODEL FOR THE SAVANNAH APPLICATION

Sections 3.1 through 3.4 presented the basic model formulation for the BFHYDRO model within the WQMAP system. For the Savannah River application updates and changes were made to the model. The following sections describe the changes made to the model and their potential influence on the solution accuracy.

3.5.1 Marsh Boundaries

The Lower Savannah Estuary has extensive freshwater and saltwater marshes throughout its length. Of critical importance under this project are the extensive freshwater tidal marshes that have grown within the historic rice fields surrounding the upper Front River, the Middle River, and the Little Back River. These freshwater marshes provide for extensive flooding and drying (and therefore water storage) through each tidal cycle. These marsh areas flood and dry through narrow tidal creeks spaced along the main stems of the Front River, Middle River, Back River and Little Back River, and draw a significant volume of flow up the system and influencing the overall tidal prism.

In order to represent these storage areas in the model, a method was formulated to incorporate the marsh inundation effects on the circulation and transport within the estuary using special marsh boundary conditions. The marsh boundaries have two basic features: determination of the flow in and the flow out of the marshes, and storage of water, salinity, and heat. For salinity the marshes are fully conservative and the mass of salt that fluxes into the marsh during flooding is passed out during outflow. Similarly, the temperature of the inflowing waters are maintained and transferred out, no heat exchange occurs during the storage of the water within the marshes.

A particular marsh is specified by a set of physical parameters that include the surface area, front elevation, back elevation, flow length, and porosity. A detailed description of the general marsh boundary formulation was presented in a paper to the Estuarine and Coastal Modeling Conference (Mendelsohn, Yassuda, and Peene, 2000). A copy of this paper is included in Appendix Z. The paper provides the detailed description of this model change.

3.5.2 River Set Up

Results from the initial 1997 calibration and the initial application to the 1999 dataset indicated that the mean water level in the river upstream of GPA-11 was low. In addition, the tide range was too large, which was particularly noticeable at GPA-14. This error between GPA-11 and I-95 translated to unacceptable results at the Lucknow Canal station within the Little Back River for both tide range and mean water level. Although the salinity predictions for the calibration simulation were reasonable, the MTRG was unsatisfied with the results due to the water level and tide range discrepancies.

To address the water surface elevation (WSE) issues, several steps were undertaken. The first step was to develop an upstream river setup capability in the model. The upstream setup is a result of river topography that shows that the mean surface elevation at Clio is approximately 13 ft higher than at GPA-14. Including the setup would have the combined effect of increasing the mean water level in the upper estuary, and dampen the tidal signal above GPA-11, which the measured data show to be significantly damped at GPA-17 and completely damped at Clio.

The river setup routine was implemented in the model through a backwater calculation method where the upstream flow is ramped in slowly while maintaining high friction, thereby allowing the water level to increase. As the water level increases the sparse matrix solution

routine coefficients are re-calculated to adjust to the new, total mean water level depth. This routine is followed until the river attains a steady state flow and water level. The tidal simulation then proceeds at that point.

3.5.3 Vertical Mixing

Through the development process of the hydrodynamic model, difficulties in getting the turbulence formulations within the BFHYDRO model to simulate the complex stratification/destratification in the system and the resulting salinity intrusion lead to the development of a modified vertical turbulence formulation. This unique turbulence parameterization is based on a log law fit of the vertical mixing coefficients to the tidal energy in the system, (Mendelssohn et al., 1999) and was developed and first applied during the Savannah Harbor Deepening, Tier I EIS, (ATM 1997b). The formulation provides the vertical eddy viscosity for the solution of the momentum equation, and the vertical diffusivity for the solution of the advection-diffusion equations. Appendix Q presents a detailed description of this change to the hydrodynamic model along with a hindcast study that tested the formulation on the prediction of the salinity changes under the 1994 deepening effort using continuous salinity data from that period.

4.0 CONVERGENCE, SIGMA TRANSPORT AND MASS BALANCE TESTS

4.1 CONVERGENCE TEST

Based upon comments received from the Waterways Experiment Station (WES) of the USACOE in review of the Tier I model calibration effort, a convergence test of the WQMAP hydrodynamic model application to the Savannah River was performed. This test consisted of preparation of two series of grids, of increasing resolution, to represent the Savannah Harbor System along the Front River (FR) from Fort Pulaski to the I-95 Bridge and along the Little Back River (LBR) from Fort Jackson to the confluence of the Middle and Little Back Rivers at the North end of Argyle Island, respectively. The model predictions for each grid were compared with subsequent runs where the identical grid structure is systematically refined by reducing the horizontal and vertical grid spacing while maintaining identical geometry and bathymetry. The goal was to identify the differences in the model solution under the varying grid resolution and to determine the optimum grid resolution for model simulations.

Numerical models such as WQMAP are designed to solve processes described by partial difference equations (PDE). The solution approach uses a set of finite difference equations (FDE) that are expected to converge to the PDE solution as $\Delta x, \Delta t \rightarrow 0$. Since grid refinement is directly related to the computational cost of a simulation, the question posed is: "how coarse can a grid be designed before it starts to compromise the accuracy of the numerical solution?" Or conversely: "how fine does a grid need to be before additional refinement, and ensuing computational cost, does not provide an additional level of accuracy to the model results?" One way to evaluate the convergence of a model grid system is to compare a model solution with grid dimension Δ_1 and another solution with, say, $\Delta_2 = \frac{1}{2} \cdot \Delta_1$, where Δ can be any or all of Δ_x, Δ_y , or Δ_t .

Testing the convergence in non-orthogonal, boundary-fitted curvilinear grids is not a trivial task, and in a system with a complex geometry, such as the Lower Savannah River, it is impractical. Therefore, based upon input from the MTRG, a set of idealized grids, with bathymetry and dimensions comparable to the actual Lower Savannah River grid were designed to test the convergence properties of this application of the BFHYDRO model.

The resolution of the grid system designed for this model application is a critical factor in establishing the suitability of BFHYDRO to properly simulate the dynamics of the Lower

Savannah River Estuary. Since the main goal of this model application is to capture the water surface elevation dynamics and range, the current speeds, salinity dynamics, and the transport of pollutants in the system, the convergence test is presented in terms of time series of simulated WSE, current speeds, salinity, water volume flux and salt flux along the cross-section at selected stations (i.e., Fort Jackson, Port Wentworth, I-95 Bridge, GPA-07, and USF&W Dock in the Little Back River).

4.1.1 Model Grids

The convergence tests were performed on a series of grids designed to incrementally simulate the actual conditions in the Lower Savannah River. The setup consisted of preparation of two sets of grids, of increasing resolution for the Front River from Fort Pulaski to the I-95 Bridge, and the Little Back River from Fort Jackson to the confluence of the Middle and Little Back Rivers at the North end of Argyle Island, respectively. Both sets of grids extended an additional distance upstream to reduce the occurrence of reflected waves off the upstream boundary: to Clyo in the Front River case, and past I-95 in the Little Back River case. The base case Front River grid was specified with 5 cells across and 200 meter longitudinal. Variations in longitudinal resolution are 1/2X and 2X, at 100 and 400 meter grid lengths, respectively. For the latitudinal convergence tests two additional 200 m grids with 3 and 7 cells across were developed.

For the Little Back River convergence tests, the question was asked whether two cells across in certain areas along the grid were sufficient, or whether more latitudinal (across stream) resolution was necessary. Two LBR grids were again designed with 200m longitudinal resolution but with 2 and 4 cells across, respectively. Each of the test grids is given a shorthand designation for the plots and tables as shown in Table 4-1.

4.1.2 Convergence Test Results

The first test was designed to evaluate the longitudinal resolution, and how model results would be affected by the aspect ratio (the ratio between the grid cell longitudinal and transverse dimensions). For the Front River convergence tests, as in the calibration simulation, the measured tides were specified at the offshore boundary, and the flow as measured by the USGS at Clyo was specified at the upper boundary. For the Little Back River tests, the “open boundary” is assumed to be at Fort Jackson, so the measured tides

were scaled to represent the tidal signal at the entrance to the Back River. Similarly, the Clyo river flow was scaled to match the mean flow split between the Little Back and the Front and Middle Rivers, for the upstream boundary condition for the LBR tests.

A total of 3 simulations were conducted using a coarse grid (400 meter cell length), a medium grid (200 meter cell length), and a fine grid (100 meter cell length). The bathymetry of the grids was specified to simulate the decrease in channel depth between Fort Pulaski and I-95 for the Front River grids, and the bathymetry gradient between the sedimentation basin and the Little Back River confluence for the LBR grids.

A series of figures presented in Appendix P present the results of the convergence test runs in terms of time series plots of the dependent variables elevation, current speed, bottom salinity and the produced variables of volume flux and salt flux. The grid convergence was then evaluated by computing the difference between each step of refinement (i.e., medium minus coarse, and fine minus medium for each of the variables). The time series are shown at two stations for each of the variables and each of the tests. In addition, for each station there are two data plots: the first showing the model predictions (the whole range of the signal) and the differences between grids; and the second just showing the differences. For all of the difference plots, the scale has been decreased by an order of magnitude (at least) so that the variability of the differences can be seen. Tables 4-2 and 4-3 summarize the results of the convergence tests.

The tests demonstrated that the delta produced between medium and coarse grids is not highly significant, while the delta between fine and medium grids is almost negligible. The conclusion of this test is that there is little gain in resolution by refining the model between 200 m to 100 m cells in the longitudinal direction. In addition, in order to capture the particulars of the complex geometry along the Lower Savannah River, the actual grid used in the model calibration has an average cell dimension of less than 200 m in the longitudinal direction between Fort Pulaski and the I-95 Bridge for both the Front and Back Rivers. The results indicate that for all of the variables except salinity and salt flux the mean percent variation is near zero and the maximum is 1% or less. For salinity, the difference between the coarse and medium grids has a maximum of 5% and a mean of 3% at Fort Jackson decreasing to 3% and 1% for the difference between the fine and medium grids. Similarly, for the salt flux the maximum difference is 4% with a mean of 1% at Port Wentworth for the coarse to medium grid comparison; the differences decreases to 2% and 1% for the fine to medium grid comparison.

The horizontal resolution tests were even more conclusive, showing that the variation in results between the coarse and medium grids, for all of the parameters, was less than 2%, decreasing to less than 1% for the difference between the fine and medium grids.

The Little Back River grid resolution tests similarly showed that the horizontal resolution was adequate and varied very little by adding more cells. The greatest difference was again found in the salinity predictions with a maximum difference of about 1% between grids in the lower portion of the river. The remaining statistics indicate that the differences between the grids are less than 1% for all of the variables.

4.2 SIGMA COORDINATE TRANSPORT TEST

The sigma coordinate test was designed to determine whether the sigma stretched grid system creates any artificial transport within the system. The evaluation of the baroclinic pressure gradient terms in a sigma-stretched vertical grid system is a well-known problem in the geo-physical numerical modeling community. The problem arises due to the fact that in the sigma system the model uses an equal number of layers in the vertical dimension, no matter how deep the water column is.

In the simplest form of the numerical solution, the discretized, horizontal pressure gradient at a point is evaluated along a particular vertical layer sigma-layer, whether the adjacent cell is at a similar depth or not. This process works well in flat bottom cases, for example along the bottom of channel or in the flats, but it becomes troublesome in the region of steep bathymetric gradients such as the slope between a deep channel and adjacent shallow flats. In the pressure term of the momentum equation, the density induced pressure gradient is balanced by a bathymetry gradient term. This balance should, theoretically, account for and balance any artificially large gradient between a deep channel and the shallows that tend to unrealistically force salinity up and out of the channel into the shallows. Practically, what occurs is that the balance is a small difference between two large terms in the discretized numerical world and is subject to truncation errors.

The resolution that has been adopted for many models using the sigma coordinate system, as well as BFHYDRO, is to evaluate the pressure gradient term along lines of constant depth (z-level). The z-level evaluation is performed by interpolating the density in adjacent cells to the proper z-level depth from the known sigma-layer depth and calculating the horizontal pressure gradient using the interpolated values. Evaluating the pressure gradient in this

manner, the deep channel cells don't "see" the cells in the shallows and the cells in the shallows only "see" the surface layers of the channel (at similar depths).

The numerical tests described herein are designed to test whether the system developed for evaluation of the horizontal pressure gradient terms numerically generates any artificial pressures and therefore currents in the Savannah River grid.

4.2.1 Model Setup

The sigma test was run using the 1997 and 1999 calibration grid. The test consisted of setting up a stably stratified, "dead sea" situation in the system assigning salinity as a constant function of depth. At initialization then, the salinity at any given depth (1 meter below the surface for example) was constant throughout the system. Therefore, there were no horizontal pressure gradients anywhere in the system at the start of the simulation.

The model was then run with all of the external forcing turned off, including tides, river flow and wind. In addition, the vertical mixing term was also set to zero so that vertical movement of salt from mixing was not confused with the false numerical mixing for which we were testing. If the model has been developed and coded properly then under the given circumstances, everything should remain unmoving. No currents should be generated, and the salinity should not move. The goal was to show that under this condition the model does not produce any artificial flows or transport of salinity.

4.2.2 Sigma Coordinate Transport Test Results

The model was initialized as described above and then run for a simulation period of one week. The one-week period is many times longer than the 12-hour, M2 tidal, major forcing period in the system, over which salinities in many parts of the estuary vary up to 10 ppt. One week is also approximately half of the spring-neap tidal cycle over which the largest variation in the salinity regime occurs. If no significant flows or transport is developed over that period then one could safely conclude that the sigma-layer system does not cause any significant problems.

The results of the sigma test are summarized in Table 4-4. The percent change in salinity at each station in the estuary for which salinity data was compared during the calibration effort

(both surface and bottom where appropriate) is presented for two times during the simulation, after 24 hours and after 1 week.

Reviewing the results it can be seen that a maximum variation in salinity of less than 0.3% occurs after a 24-hour period (two tidal cycles). The maximum occurs at the GPA-04 bottom station. It can also be seen that all of the variations in the 24 hour period occur in the bottom stations (as might be expected) and that no variation in surface salinity is present.

After a period of one week somewhat larger variations in the salinity are observed in some of the bottom stations. Very small currents have developed in a few places that serve to mix the salinity in few cases. A maximum variation of 2.6% is achieved at the Rifle Cut bottom station, but again no variation is observed at any of the surface stations. The results clearly indicate that the model application to the Savannah River is not generating substantial false currents from the sigma-stretched grid. Numerical representation of the pressure gradients is also not generating spurious salinity transport.

4.3 MASS BALANCE TESTS

A mass balance test of the hydrodynamic model was completed which looked at the total conservation of mass over time within the system. The results and methodology of the mass balance test are presented in Appendix O.

5.0 APPLICATION OF THE BFHYDRO MODEL TO THE LOWER SAVANNAH RIVER ESTUARY

This section presents the model boundary conditions, the model coefficients, and the simulation periods for the 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 **SIMULATION PERIODS**

The model simulations included two periods: the summer and fall of 1999 for the model calibration, and the summer and fall of 1997 for the model validation

5.1.1 **Model Calibration**

The calibration of the hydrodynamic model was performed using the data from the 1999 monitoring effort. The data collection began on July 26, 1999 and was completed on October 9, 1999. During this period not all instruments were operating simultaneously but data were collected through this entire period. For the 1999 hydrodynamic simulations, the model was spun up over a two week period from July 7 to July 23, 1999. This spin up period allowed the circulation, salinity, and temperature to come to equilibrium with the external forcing functions of tides, wind, river flow, offshore salinity, and atmospheric inputs. The model was then run for a full 3-month period from July 24, 1999 to October 31, 1999.

While the model was run over 3 months, the primary period of model calibration was from August 4th through September 8th. This is based upon the availability of data that provided the time series offshore boundary condition for salinity. While presented in more detail in Chapter 7 (Model Calibration), it was determined that the most accurate representation of the system occurs where the best time dependent boundary conditions are available, and this period provided the most comprehensive data set. Model comparisons are presented for the full simulation period in Appendix T, but it is important to note the limitations of model predictions outside of the periods where the best boundary forcing data are available.

5.1.2 Model Validation

The validation of the hydrodynamic 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 hydrodynamic simulations, the model was spun up over a two-week period from July 1 to July 14, 1997. The model was then run for a full 3.5-month period from July 15 to October 31, 1997.

5.2 MODEL GRID AND BATHYMETRY

The following presents the geometric inputs to the model including the model grid and the model bathymetry. The origins and baseline data for each component are discussed.

5.2.1 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 Clio (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.

The WQGRID component of WQMAP consists of a set of tools to generate a boundary fitted grid. The grid is specified by locating points along shorelines and bathymetric features such as channels and depth contours. Each point has assigned grid indices to keep track of how each point relates to its neighbors. The grid spacing in the domain is roughly determined by spacing at land boundaries. Finer grid resolution is specified for increased flow resolution. Once the boundary points along the shoreline have been specified, and any bathymetric

feature located, the gridding model generates all the remaining interior points. These points are constrained to obey a Poisson equation and their locations solved iteratively by a Poisson solver.

In general, the grid aspect ratio reflects *a priori* estimates of expected flows. This means that the longer grid dimension, if any, is oriented along the major axis of the flow. This approach is necessary because the hydrodynamic model has inherent time step restrictions based on the ratio of grid size to flow speed. Faster model runs are possible when the grid is optimized in this manner.

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 mostly the case along the Back River above the former location of the tide gate. The model has a total of 2825 horizontal active 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.

5.2.2 Model Bathymetry

A depth value must be assigned to each grid. Two methods are generally combined to create the array of grid depths. First, a database of bathymetric soundings with associated latitude and longitude for the area is accessed. Each grid is automatically assigned a depth value by interpolation from the database based on a distance-weighting algorithm for soundings close to the grid location. Once all grids have depths assigned, the results are shown graphically and may be edited in WQGRID.

The second method is based on the experience of the modeler to more accurately specify depths. Tools are available to the user in WQGRID to select individual grids or groups of grids and specify depth values. This procedure becomes necessary when representing post-

project scenarios (e.g., channel deepening, borrow site excavation, or nearshore berm placement).

Since the model calibration and verification runs will include simulations of both 1997 and 1999 conditions, separate bathymetric data sets were obtained for both 1997 and 1999. Four types of hydrographic survey data were used to create the bathymetric data sets: USACE annual surveys, USACE exam surveys, a USACE contracted survey, and National Ocean Service (NOS) hydrographic surveys. The USACE, Savannah District, Hydrographic Survey Section was the primary source for the bathymetry data in the Savannah River. Annual surveys are published by the USACE in June for that calendar year. The Annual Survey publication is a patchwork of the most current bathymetry data available. Exam surveys are performed per contract by the USACE to determine navigation channel depth and possible dredging requirements. Exam surveys are performed on an as needed basis and as many as three exam surveys can be performed in a year. USACE contracted surveys are performed by requests for areas that are not normally covered in annual surveys. The NOS surveys provide hydrographic survey data along much of the United States coastline and include historic surveys performed by the former U.S. Coast and Geodetic Survey (USC&GS).

Tables 5-1 and 5-2 summarize the hydrographic survey data sets used to synthesize the 1997 and 1999 bathymetric data, respectively. In creating the model grids for 1997 and 1999, it was determined through evaluation of bathymetric differences and system wide contouring of those differences, that the changes in bathymetry did not warrant the use of two different bathymetries in the model. The differences were found within the maintained areas and were generally less than 1 foot. 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. The following sections will describe the source data in detail and the corrections used to convert the soundings to a common horizontal and vertical datum.

Datum Corrections

Bathymetry data obtained from the USACE, Savannah District, Hydrographic Survey Section was generally reported relative to the Mean Low Water (MLW) vertical datum. This is a local datum that varies spatially (e.g., the MLW datum rises as one travels up the Savannah River) and over time (e.g., change due to sea level rise). This presents a problem for models that

cover a large geographic area, or for comparisons of data sets that span a long period of time. Therefore, all hydrographic data were converted to the National Geodetic Vertical Datum of 1929 (NGVD). This datum is based on long-term tide gage measurements and precise leveling surveys. NGVD is a fixed geodetic datum that does not vary over time. The use of this datum allows direct comparison of survey data measured at different locations and times in the study area.

Conversion to NGVD from local MLW for bathymetry data for the Savannah River was accomplished by applying corrections for NGVD relative to River Mile. Tidal benchmarks along the Savannah River Federal Navigation Project have local MLW elevations. Bathymetry survey points were corrected to NGVD by determining the closest tidal benchmark and applying the correction from the local MLW elevation to NGVD. The offshore survey data sets were corrected from the MLW and Mean Lower Low Water (MLLW) datums to NGVD using the values published by NOS for the tidal benchmark at Ft. Pulaski.

All survey data were also converted to a common horizontal geodetic datum of NAD 83 (the North American Datum of 1983). USACE, Savannah District, Hydrographic Survey Section uses the Georgia State Plane horizontal coordinate system in the presentation of bathymetric survey data. The CORPSCON software (developed by the USACE) was used to convert the Georgia State Plane coordinates to latitude, longitude NAD 83 coordinates. The NOS surveys were obtained in NAD 83 coordinates in a digital format from the National Geophysical Data Center (NGDC); therefore, no horizontal datum correction was necessary for the NOS survey data.

July 1999 USACE Exam Survey

The July 1999 USACE exam survey was used for the 1999 bathymetric data set because the survey dates coincided with the summer 1999 data collection effort. The July exam survey was conducted July 17 and 21 of 1999, one week after the initial deployment of water quality instruments for the summer 1999 data collection effort. The annual survey data for the 1999 publication predated the summer 1999 data collection effort. Therefore, the July 1999 exam survey was the best representative data available for the 1999 bathymetric data set.

The coverage provided by the July 1999 USACE exam survey is similar to that of the annual survey. The annual survey is a publication of the MLW depths in the Federal Navigation Project. However, the July 1999 exam survey does not include the sedimentation basin,

whereas the 1999 annual survey does include the sedimentation basin. Therefore, a January 1999 sedimentation basin exam survey was included in the 1999 bathymetric data set. The January 1999 sedimentation basin exam survey is discussed in the next section.

January 1999 Sedimentation Basin Exam Survey

The January 1999 sedimentation basin exam survey is the best representative bathymetric data available for the time period of the summer 1999 data collection. Personal communication with David Hodges of the USACE, Savannah District, Hydrographic Survey Section confirmed the survey was the best data available for the sedimentation basin at the given time period. Mr. Hodges stated that small fragments of the sedimentation basin surveys are available closer to the time period of the summer 1999 data collection. However together these fragmented surveys do not cover the entire sedimentation basin.

1999 USACE Contracted Survey: I-95 Bridge to Ebenezer Creek

Recent bathymetry data for the Savannah River and tributaries upriver of I-95 was unavailable before May 1999. To obtain representative bathymetry of the Savannah River between I-95 Bridge and Ebenezer Creek, ATM commissioned a hydrographic survey with the USACE Savannah District Hydrographic Survey Section. The survey was completed over two days on May 14 and 15, 1999.

The survey between I-95 and Ebenezer Creek was performed using the 1950 Plane of Reference. The 1950 Plane of Reference is a plot of the local MLW relative to NGVD along the Savannah River from Savannah to Augusta. The USACE uses the Plane of Reference to determine the local MLW elevations at monuments along the Savannah River upriver of I-95. ATM used the same 1950 Plane of Reference to convert the survey data from local MLW to the NGVD datum.

1997 USACE Annual Survey

The annual survey is published each June for that calendar year. It is a collection of the most recent survey data available for the Federal Navigation Project. Areas not covered by the 1997 annual survey include the Back River above the tide gate and the South Channel. A 1997 USACE contracted survey provided bathymetry data for these areas.

1997 USACE Contracted Survey - South Channel, Middle River, Back River, Little Back River and Front River between Houlihan Bridge and I-95 Bridge

Prior to July 1997, no recent data were available for areas upriver of the Navigation Project on the Front River or above the tide gate on the Back River. Bathymetric data for the Middle and Little Back Rivers was not current. ATM commissioned the USACE, Savannah District, Hydrographic Survey Section to perform hydrographic surveys in areas without recent bathymetry data.

The 1997 survey is included in the 1999 bathymetric data set because it is still the most current bathymetry data for the coverage area. The survey was completed over four days. The Front, Middle, Little Back and Back River hydrographic surveys were performed on July 7 and 8, 1997. The hydrographic survey of the South Channel was performed on July 23 and 24, 1997.

Offshore Data Set

The offshore data was obtained from the NGDC Coastal Relief Model version 1.0, which incorporates the most recent NOS and USC&GS hydrographic surveys into a digital elevation model. The data was extracted from the Coastal Relief Model on a 3 arc second grid that covered the offshore model grid area. Also, the original offshore hydrographic surveys were obtained from the NGDC GEODAS (GEOphysical Data System) CD. Inspection of the data coverage revealed that surveys from several years were required to create the desired offshore coverage. Survey data from 1934, 1950's, 1970's and 1980's were combined to create the offshore bathymetric data set. However, the 1934 data was restricted to the area behind Hilton Head Island and is not used by the WQMAP model for this project. The hydrographic data used near the Savannah River entrance does not date earlier than 1971. Additionally, the offshore data was removed inside the Navigation Project boundaries and the USACE annual survey and exam survey data were used for the Bar Channel bathymetry.

5.3 MODEL COEFFICIENTS

Within the BFHYDRO Model there are limited coefficients that can be varied during the model calibration process. For the Savannah application, the coefficients used are the bottom

friction, the horizontal diffusivity, and the formulation of the vertical eddy viscosity/diffusivity. The following provides detailed descriptions of the model inputs for each coefficient.

5.3.1 Bottom Friction

The bottom friction varies spatially in the model with values ranging from 0.003 to 0.05. In general the spatial variation of bottom friction goes from lower values at the mouth to the highest values in the upper reaches of the model near Clyo. Within the main focus area of the study (i.e., below the I-95 bridge) the coefficient is constant at 0.003. Figure 5-4 presents the longitudinal variation in the bottom friction by River Mile. The values in the Middle River, Back River and Little Back River mirror the values in the main harbor area.

5.3.2 Horizontal Diffusivity

The horizontal eddy viscosity/diffusivity does not vary either in time or in space. The value input to the model is constant throughout the spatial and temporal domain at 1.0 m²/sec.

5.3.3 Vertical Eddy Viscosity/Diffusivity

Through the development process of the hydrodynamic model, difficulties in getting the turbulence formulations within the BFHYDRO model to simulate the complex stratification/destratification in the system (and the resulting salinity intrusion) led to the development of a modified vertical turbulence formulation. This unique turbulence parameterization is based on a log law fit of the vertical mixing coefficients to the tidal energy in the system, (Mendelsohn et al., 1999) and it was developed and first applied during the Savannah Harbor Deepening Tier I EIS (ATM 1997b). Appendix Q presents a detailed description of this formulation and its application to the Lower Savannah River Estuary. In addition, Appendix Q presents the results of a hindcast study that evaluates the models predictive capability under a past deepening effort in 1994 using continuous data available at that time. This hindcast verifies that the modified formulation is capable of capturing the effects of a deepening.

5.4 BOUNDARY CONDITIONS FOR 1999 SIMULATIONS

The boundary forcing functions used in the 1999 hydrodynamic simulation are: the offshore water level, salinity and temperature; the upstream freshwater inflow and temperature; the atmospheric forcings that influence hydrodynamics (wind, pressure, solar radiation, air temperature, and relative humidity); and the flooding and drying of the marshes above Fort Jackson. The forcing functions are applied at the open boundaries (i.e., the Atlantic Ocean, the headwaters of the Savannah River, and the marsh boundaries), except for atmospheric effects, which are applied over the entire model domain. The following presents the values used for each of these boundary conditions.

5.4.1 Offshore Boundary

Three time dependent forcing functions are applied at the offshore boundary: water surface elevation, salinity, and temperature. These time series are applied equally across the offshore boundary cells. The offshore forcing cells are “ghost cells” just outside of the first grid cell in the model in the offshore area (see figure 5-1).

The NOS maintains a series of tide gauges along the coast including a station at Fort Pulaski. A time series of surface elevation recorded at this station was used to simulate the offshore water surface elevation variations. The original time series was phase shifted slightly to allow for the lag between the model offshore boundary and the actual location of the tide gage. The shift was performed incrementally until a match was obtained between the model elevation predictions at Fort Pulaski and the gage data. The time series of the offshore boundary condition for the 1999 simulations is plotted in Figure 5-5.

Other factors that cause variation in the free surface are the winds and atmospheric pressure. The frictional effects of winds tend to cause setup as water piles up along a coast, and it also causes setdown as winds push water offshore. Atmospheric pressure acts to depress the water level (i.e., due to high atmospheric pressure) or raise the water level (i.e., due to low atmospheric pressure). Both wind and pressure effects cause storm surges that can be large enough to overwhelm the tidal signal. Therefore, the best open boundary tide condition is to use an actual time series measurement that includes all of these effects. With this approach, the model uses real data for the offshore forcing.

The second offshore forcing function is the time dependent salinity. Initial model simulations and comparison to data indicated that the use of a constant 35ppt offshore boundary did not represent the conditions in the system accurately. The influence of the freshwater outflow from the Savannah River, combined with the influence of the large tidal prism of Calibogue Sound to the north created conditions where a constant offshore boundary condition did not reflect the significant observed offshore variations.

Figure 5-7 presents the time series of salinity used in the model. This time series file was developed using a 2-ppt offset from the measured bottom salinity at GPA-26 and GPA-02. As the data show, there is a large gap in the data after September 13, 2003. During this period, the downstream bottom salinity data was bad (GPA-26b and GPA-02b), and therefore, a constant 35-ppt offshore condition was applied for this period. The offshore forcings were treated as well mixed with no variation over the vertical dimension.

The final offshore forcing function is the time dependent temperature. Figure 5-8 presents the time dependent temperature used for the offshore boundary. As with the salinity forcing, the temperature is constant over the vertical and was developed from the GPA-26 and GPA-02 bottom meters. No gaps existed in the temperature data at GPA-26.

5.4.2 Upstream Boundary

For the upstream boundary, two time dependent forcing functions were applied: freshwater flow and temperature.

The primary source of freshwater to the Lower Savannah River Estuary is from the Savannah River watershed (described in Section 1). The upstream model boundary was placed at Clyo where the USGS maintains a stage height monitor. Detailed records, both past and present, are available for river flow past this site. Daily volume flow records were obtained from the USGS for the August to October 1999 period and used as model input. Figure 5-6 presents the upstream freshwater inflow.

Based upon USGS published reports the gage at Clyo measures approximately 90 percent of the drainage basin of the Savannah River. The remaining 10 percent of the basin resides below Clyo. Given the very flat, undefined nature of the remaining drainage basin, it is difficult to quantify the contribution of freshwater inflow below Clyo. For the model simulations presented herein, a 10 percent additional contribution below Clyo was assumed. This 10

percent was applied to the flow measured at Clio. The uncertainty in the freshwater inflows to the system, especially the contribution below Clio, adds some level of uncertainty to the simulations of the salinity within the Harbor; this needs to be recognized in evaluating the model to data comparisons. This uncertainty is evaluated in Chapter 9 through sensitivity analysis.

For the temperature, time series measurements were available from the gage at GPA-17 over the entire simulation period. The GPA-17 measured data was input at Clio with a time shift, and the input temperature was iteratively time shifted until the simulated temperature passing GPA-17 matched the measured data. Figure 5-9 presents the upstream temperature boundary condition.

5.4.3 Marsh Boundaries

The formulation of the marsh boundary conditions was described in detail within Chapter 3 and Appendix Z. Figure 5-10 presents the extents of the marshes represented in the model by these storage areas. Table 5-3 outlines the physical characteristics of the marsh storage areas within the model. These characteristics drive the tidal prism that passes into each of these marsh storage areas through each tidal cycle. The marsh area delineations were obtained from GIS coverages of the marshes that were presented in Figure 5-10. The elevations used in the marshes (i.e., where the marsh begins to flood) represent an average condition as prescribed by ATM personnel working on the Marsh Succession Modeling effort. This value was around 0.58 meters NGVD.

5.4.4 Point Source Inflow

For the hydrodynamic model, the freshwater inflow associated with the point source discharges was not considered due to its insignificant nature in relation to the overall tidal prism and the freshwater inflow from the watershed.

5.4.5 Meteorological

For the hydrodynamic model the meteorological inputs drive the temperature simulations. The key parameters measured by the meteorological stations are the wind speed,

atmospheric pressure, air temperature, and solar radiation. For the 1999 monitoring program these parameters were measured at three stations spaced longitudinally along the river from the mouth up to above I-95. The measured time series from these stations were used directly in the model. Figures 5-11 and 5-12 present the time series for these parameters.

5.5 BOUNDARY CONDITIONS FOR 1997 SIMULATIONS

The boundary forcing functions used in the 1997 hydrodynamic simulation are: offshore water level and salinity; and upstream freshwater inflow. Under the 1997 monitoring program no meteorological stations were established. In addition, the only nearby meteorological station, at the Savannah Airport, was not functioning during the data collection effort. The simulation of the temperature in 1999 indicated that local wind measurements are critical for the proper simulation of the surface heat flux (i.e., the proper convective cooling). Without accurate wind data the thermal model predictions were unacceptable. Therefore, based upon a lack of adequate inputs to force the thermal model, the 1997 hydrodynamic simulations are performed with salinity only. The following presents the boundary conditions used in the 1997 hydrodynamic simulation.

5.5.1 Offshore Boundary

Two time dependent forcing functions are applied at the offshore boundary: water surface elevation and salinity. These time series are applied equally across the offshore boundary cells. In the 1997 monitoring program, a station was established offshore of the entrance to the Front River at Bloody Point Range. As the gage was mounted to a navigation range tower, it recorded water surface elevation fluctuations as well as time series of salinity and temperature. The time series of the offshore boundary condition for the 1997 simulation is plotted in Figure 5-13.

The time dependent offshore salinity was taken directly from the Bloody Point Range sensor. This offshore measured salinity was used as the offshore boundary conditions with no adjustments in the salinity values. Figure 5-15 presents the time series of salinity used in the model. As the data show, the offshore salinity conditions during the 1997 simulation period were on the order of 2-3 ppt lower than that used to force the 1999 simulations. This is

consistent with discussions with personnel from the Skidaway Institute who measured a high saline condition during 1999 at distant offshore stations in comparison to other years.

5.5.2 Upstream Boundary

For the upstream boundary the only forcing function is the time dependent freshwater inflow. As with 1999, this was obtained from the Clyo measurements with a 10 percent add on to account for the watershed area downstream of Clyo. Figure 5-14 presents the upstream freshwater inflow. Although temperature was not simulated in the 1997 model because of lack of meteorological information, the measured temperature data that would have been used for the offshore boundary and upriver boundary are presented in Figure 5-16.

5.5.3 Point Source Inflow

For the hydrodynamic model, the freshwater inflow associated within the point source discharges was not considered due to its insignificant nature in relation to the overall tidal prism and the freshwater inflow from the watershed.

6.0 HYDRODYNAMIC 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 and 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 are in the best possible agreement with measured data.

Throughout the development of the hydrodynamic 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 federal 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. The Draft document is presented in Appendix GG.

While the criteria outlined in Table 6-1 and the comparison methods discussed within the Federal Agency Expectations Document 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:

- Time series graphical comparisons of simulated versus measured water surface elevation, currents, salinity, and temperature at all stations where measured data were available;
- Tabular and graphical presentation of the mean error, absolute mean error, and Root Mean Square (RMS) error for water surface elevation, currents, salinity, and temperature at all stations where sufficient measured data were available for statistically significant results;

- Tabular presentation of the comparison of the measured versus simulated 5th, 50th, and 95th percentiles for water surface elevation and currents;
- Tabular and graphical presentation of the comparison of the measured versus simulated 10th, 50th, and 90th percentiles at all data collection stations for salinity and temperature;
- Graphical and statistical comparison of the measured versus simulated flows at key cross-sections; and
- Graphical comparison of measured versus simulated vertical profiles of salinity and temperature (snapshots in time using EPD stations).

One type of model to data comparison that is standard practice in tidal environments that was not specifically requested is harmonic analysis. Where sufficient signal exists between the model and the data, harmonic analysis provides a more robust evaluation of the phase and amplitude errors within a tidal environment, and therefore, it is also presented herein. Other comparison methods that are presented include:

- Graphical comparison of the measured versus simulated currents contoured over time and over the vertical dimension; and
- Graphical comparison of time series longitudinal profiles of salinity over time for the measured and simulated bottom salinity (i.e., to visualize the intrusion).

In comparing the simulated versus measured hydrodynamics in a tidally dominant system such as the Lower Savannah River Estuary, it is important to 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 were determined based upon the harmonic analysis and then the signals are shifted prior to calculation of the magnitude error statistics (i.e., RMS error, absolute mean error, mean error). This procedure is typical of model calibrations within estuarine environments. While harmonic analysis by its nature provides this separation, the other error statistics do not, and therefore, the adjustments are made to those calculations based upon the phase errors determined from the harmonic analysis.

These comparisons will support the weight of evidence evaluation of the hydrodynamic model that 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. The mean error is as it sounds, a comparison of how the simulated averages of a parameter (e.g., salinity) compares with the measured average over the period chosen for comparison.

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. It represents the average difference in the two signals as compared to the differences in the average.

6.3 ROOT MEAN SQUARE ERROR

The *root mean square error* is defined as

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

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^{th} percentile of a sample is a number P_n such that at least $n\%$ of the sample values is 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 the 50th percentile is a representative of the average conditions (for a normal distribution), while the 90th percentile is representative of the more extreme or maximum conditions. In the data analyses it was determined that the salinity is not normally distributed; therefore, a mean or average does not represent that value for which half the time the parameter concentration is above or below. A better representation is the median or 50th percentile.

In Sections 7 and 8 percentiles are used as a means of evaluating the signal changes. They provide a snapshot or static representation of a highly variable system. As percentiles are used with the model projections, it is prudent to examine how the model performs in terms of the percentiles.

7.0 HYDRODYNAMIC MODEL CALIBRATION TO 1999 DATASET

This Chapter presents the results of the calibration of the hydrodynamic model to the comprehensive data set collected in 1999. This calibration has developed over a nearly five-year period, with extensive review and input from various federal, state and local agency experts. As such it is necessary, prior to discussion of the calibration results, to present a history of the model development and the input that has driven it. This history is an important component of the model development process and why certain assumptions and changes were made to the model.

7.1 **BACKGROUND**

The three-dimensional boundary-fitted hydrodynamic model was originally developed and calibrated to the 1997 monitoring data where comparisons were made to observations for surface elevations, currents, volume flows and salinity. During the development of the model using the 1997 data, a unique vertical diffusivity and viscosity relationship (for mixing of salt and momentum, respectively) was developed. This relationship was utilized based upon the inability of the standard turbulence formulation within BFHYDRO to capture the temporal and spatial variations of salinity throughout the system at a sufficient accuracy to satisfy the needs of the Technical Advisory Group (TAG). This model was utilized in the evaluation of the impacts under the Tier I EIS.

Based upon review of the Tier 1 EIS, a recommendation was made to develop an independent verification data set for the hydrodynamic model. The independent data set was primarily for development of the water quality model, but it was also seen as an opportunity to test the vertical diffusivity formulation (i.e., as a verification that the methodology applied outside of the initial development period). In addition, a more comprehensive data set was desired to better understand questions raised by the model application using the 1997 data and to develop a well verified, model predicted, hydrodynamic simulation data set for use in the water quality model. In light of the fact that the 1999 water quality (WQ) data set was far more comprehensive and detailed than the 1997 data set, and that the 1999 WQ data set would be used for the WQ model calibration, it was decided that the hydrodynamic model calibration would be performed using the 1999 data set, and the independent verification would be performed using the original 1997 data.

Results from the initial 1997 calibration and the initial application to the 1999 dataset indicated that the mean water level in the river upstream of GPA-11 was low. In addition, the tide range was too large, which was particularly noticeable at GPA-14. This error between GPA-11 and I-95 translated to unacceptable results at the Lucknow Canal station within the Little Back River for both tide range and mean water level. Although the salinity predictions for the calibration simulation were reasonable, the MTRG was unsatisfied with the results due to the water level and tide range discrepancies.

To address the WSE issues several steps were undertaken. The first step was to develop an upstream river setup capability in the model. The upstream setup is a result of river topography that shows the mean surface elevation at Clio is approximately 13 ft higher than at GPA-14. Including the setup would have the combined effect of increasing the mean water level in the upper estuary, and dampen the tidal signal above GPA-11, which the measured data show to be significantly damped at GPA-17 and completely damped at Clio.

The river setup routine was implemented in the model through a backwater calculation method where the upstream flow is ramped in slowly, maintaining high friction, allowing the water level to increase. As the water level increases the sparse matrix solution routine coefficients are re-calculated to adjust to the new, total mean water level depth. This routine is followed until the river attains a steady state flow and water level. The tidal simulation proceeds at that point.

A series of barotropic simulations were performed to tune the WSE mean, range and phase primarily using bottom friction and river setup to balance the progression of the tidal wave upstream (i.e., the phase), the increase of the mean water level and the damping of the range in the upstream direction. The results were excellent in terms of surface elevation calibration and comparison with the observations. When the baroclinic terms were again turned on, and the resulting salinity predictions compared to observations, the results were less than satisfactory. The salinity results for the baroclinic simulation appeared to be generally too low. The baroclinic response also appeared to increase the mean water level along the Front River in the areas of the highest salinity gradients. In order to bring the salinity response back to the observed levels, a compromise was developed with the WSE calibration to best balance the

overall calibration. The resulting calibration balance (based upon modification of the friction terms) is discussed in detail in the following sections.

For the model calibration, a series of time periods were identified by the Federal Agencies for model to data comparison based upon the tide conditions, i.e., the spring/neap variations. Additionally, based upon availability of offshore forcing data, an additional period was defined. This additional period is called the Primary Calibration Period. This period reflects the time where continuous downstream bottom salinity was available to use as a forcing function in the model. A gap in the model forcing (when a constant value was used) follows this time period, possibly creating errors in the simulation. The time periods identified and over which model to data comparisons are done are as follows:

- August 4 to September 8, 1999: Primary Calibration Period
- August 1 to October 12: Full model simulation following model spin up.
- August 1 to August 14, 1999
- August 15 to August 29, 1999
- August 30 to September 12, 1999
- September 13 to September 27, 1999
- September 28 to October 12, 1999

The graphics and tables within the following sections present results for the Primary Calibration period in order to maintain consistency with the salinity presentation; the best boundary offshore boundary forcing is available for this time period. For each of the other time periods, the full sets of statistical evaluations were performed and are presented within Appendix T. The full time series model to data comparisons at all stations are also presented in Appendix T. The text discusses the full set of results.

Sections 7.2, 7.3, 7.4, and 7.5 present the graphical and statistical comparisons for the water surface elevation, currents, salinity, and temperature, respectively. Section 7.6 presents an evaluation of all parameters versus the Federal Expectations Criteria.

7.2 WATER SURFACE ELEVATION

The model was run using 11 layers in the vertical dimension. The barotropic time step was 10 minutes, although the model was still stable and accurate for a 30-minute time step. The advective time step was 0.2 minutes due to the extremely large currents in many locations along the river. For the initial simulations, the only physical parameter tuned was the bottom friction. After several simulations it was found that the quadratic law bottom friction coefficient, C_b , equal to 0.003 within the harbor produced a best fit to water surface elevation and current measurements. The surface elevation predictions were relatively insensitive to bottom friction in the lower river and harbor area but proved to be quite sensitive upstream. The tidal signal is increasingly damped as one moves up river starting just north of GPA-11. The damping is clearly observed in the tidal response at GPA-14 and stations upriver as a reduction in the overall range, from the bottom up, and an increasing mean elevation. This trend continues until the tidal signal is completely damped and is absent at Clyo. Initial simulations proved that although it was possible to reproduce this response by greatly increasing the friction in the grid cells north of I-95, this approach was somewhat unstable. To remove this instability, a river bottom slope solution was added to the model initialization process such that the river between I-95 and Clyo (with a change in elevation of 13 ft) was allowed to set up before the tidal forcing began. Instabilities were reduced, and the solution was greatly improved for both surface elevation and currents.

7.2.1 Graphical Comparison

Figures 7-1 and 7-2 present graphical comparisons of the simulated versus measured water surface elevation at selected stations: GPA-04, GPA-06, GPA-08, GPA-14, Hardeeville, and Limehouse. These stations represent conditions in the lower parts of the estuary (GPA-04), at the upper end of the primary area of concern for the hydrodynamic model (GPA-14), and within the Little Back River (Limehouse) for the Primary Calibration Period (August 4th through September 8th). The full set of model to data comparison plots over the entire simulation period is presented in Appendix T.

Examination of the plots here, and within Appendix T, indicates that the model is doing well simulating the phasing and amplitude for the water surface elevation throughout the system. A critical area for the water surface elevation predictions is in the Little Back River. The comparisons at Limehouse, where the USGS gage measured water surface elevations are

corrected to NGVD, show that the model is capturing the high tide surface elevation, with around a 0.1 m overshoot which represents a 5 percent error relative to the tidal signal. The signal at Hardeeville shows how well the model is simulating the damping of the tidal wave moving up the system.

It needs to be recognized that only the USGS stations were directly corrected to NGVD. The GPA stations were pressure sensors that were mounted on the bottom or on structures. These were un-vented sensors, and therefore not corrected for atmospheric pressure, and their corrections to NGVD were done as a best effort using the existing USGS gages. The mean water level projections for the GPA stations, therefore, are not considered fully reliable.

7.2.2 Statistical Comparisons and Harmonic Analysis

Table 7-1 presents the statistical evaluation of the measured versus simulated water surface elevation. The table presents the percentile comparisons as well as the Mean Error, Absolute Mean Error, RMS error, and the differences. Figure 7-3 presents longitudinal plots of the Mean Error, Absolute Mean Error, and the RMS error. These results are for the Primary Calibration Period from August 4th to September 8th. Tables within Appendix T present statistical comparisons for the full simulation period and the spring/neap sub-periods.

While not specifically identified in the Federal Agencies Expectations Criteria, harmonic analysis is a more rigorous methodology for evaluation of the amplitude and phase errors in a tidally dominant system such as the Lower Savannah River Estuary. This methodology is standard practice in hydrodynamic calibration and therefore included as part of the evaluation. Table 7-2 presents the results of the harmonic analysis at all of the stations for the primary calibration period.

Examination of all of the tabularized statistics and analyses paints a holistic picture of the accuracy of the water surface elevation predictions. The tidal amplitude errors (see Table 7-2) are between 0 and 3 cm along the Front River up to the Houlihan Bridge with percent errors less than 3 percent. Through this region the data and model show a 20 percent increase in the tidal range (M2 constituent goes from 1.0 meters to 1.2 meters) moving upstream, and this amplification is captured by the model. Above the Houlihan Bridge up to I-95, the tidal amplitude is reduced, and the model captures this with slightly less reduction in the simulated amplitude as compared to the data. Errors in the model above the Houlihan Bridge are on the order of 10 percent. Above I-95 up to Hardeeville the tidal amplitude is significantly reduced in both the model and the data. At Hardeeville the measured tidal wave

is almost completely damped, while the simulations show around an 80 percent reduction. The additional reduction of the tidal wave seen in the data is most likely a function of the river meandering that is not completely represented by the model. It should be noted that the area above I-95 was not a primary focus for this modeling effort; the grid was extended to Clio simply to provide direct freshwater inflow from the gaging station. Within the Little Back River, the only water surface elevation comparison station was at Limehouse. This station showed a 10 percent error in the magnitude of the tidal amplitudes.

Phase errors in the model are less than 30 minutes for all stations at or below the line where the Houlihan Bridge crosses the Front, Middle and Little Back River. Above this line the phase errors increase to up to 60 minutes at I-95 and Limehouse.

Table 7-1 presents statistics that allow the examination of the error in the mean tide range and the high tide level by looking at the Mean Error and the percentiles. The mean error indicates that the simulated mean water level is on the order of 15 cm high along the Front River. This error drops off above GPA-11 down to near zero at I-95. The simulated mean water level along the Little Back River is approximately 2 cm low with the extreme high tides on the order of 9 cm high (see 95th percentile). The RMS and absolute mean errors reflect the error in the mean water level as can be seen in the longitudinal error plot shown in Figure 7-3. Figure 7-3 provides a clear understanding of the nature of the errors in the system. Below where the Houlihan Bridge crosses the Front, Middle and Back Rivers the error in the model is primarily associated with overprediction of the mean water level with very accurate (within 2-3 cm) representation of the water level fluctuations. Above this line, the errors in mean water level are reduced and the errors are primarily associated with slight (on the order of 10 percent) overprediction of the tidal amplitude. As stated earlier in the report, the mean water level errors along the Front River result from trying to achieve a balance between the water level errors and the salinity intrusion errors, the results reflect the best overall statistical fit achieved.

Tables of the statistics for the entire calibration period as well as the sub-periods defined by the federal review group are presented in Appendix T. Examination of the statistics and graphics for these periods does not indicate a significant difference in the overall comparisons between the primary calibration period and the others. It also does not indicate that the model is performing better during some periods versus others.

7.3 CURRENTS AND FLOWS

There were six stations along the river where current measurements were made, including two ADCP sites in the harbor area (at GPA-04 and GPA-06) and four ADCM sites upstream of GPA-14 and the I-95 Bridge. While the stations at and above the I-95 bridge were established primarily for another study, the comparison of the model with their measurements does provide some evaluation of the current predictions in this area.

Cross-sectional flow measurements were made at numerous cross-sections throughout the system and the locations and methodology were presented in Chapter 2 (Figure 2-8). The flows provide an evaluation of the simulated flux of water past a specific location. In a system such as the Lower Savannah River Estuary, where the flow is relatively bi-directional and restricted, the accurate simulation of the flux is important for properly simulating the overall mass transport.

7.3.1 Graphical Comparison

Figures 7-4, 7-5, and 7-6 present the measured versus simulated currents at GPA-04, GPA-06 and upstream of I-95 bridge, respectively. The results show that the currents at GPA-04 are under predicted by the model with the surface measurements showing stronger flood flows while the ebb seems reasonably simulated. The bottom currents show an overall underprediction by the model. One possible reason for the discrepancy lies in the fact that the area around GPA-04 is complex and involves the confluence of the Front and Back Rivers to the north and the meeting of the North and South Channels to seaward of the station. The behavior of the currents in this area is extremely complex and multi-layered, with a good deal of bathymetric steering. Although the placement of the time series cell on the model grid reflected the correct geographical location (i.e., longitude and latitude), the model results may not accurately reflect all of the detailed bathymetric influence.

A key aspect to determine the flow and transport in the region of GPA-04 is the simulated versus measured volume flux. Figures 7-8 and 7-9 present the measured versus simulated flows at Fort Jackson (FJ), in the Front River at the Houlihan Bridge (FR2), at the I-95 bridge (I95), in the Middle River at the Houlihan Bridge (MR2), in the Back River at the sediment basin (BR) and in the Little Back River at the Houlihan Bridge (LBR2). The results show that the model accurately simulates the overall volume flux at Fort Jackson (near GPA-04) with

errors on the order of 10 percent. Also, the model accurately simulates the split of the flow between the three branches, as shown by the Houlihan Bridge transects in the Front River (FR2), Middle River (MR2) and Little Back River (LBR2). Overall, plots of the measured versus simulated flows along the Front River show that the volume flux is accurately represented by the model with errors on the order of 10 percent. Flows at other locations are presented in Appendix T.

The current projections at GPA-06 are presented in Figure 7-5. The model very accurately simulates both the surface and bottom currents at this location. The currents that are presented at the surface are at 10 meters above the bottom. This is nearly 2 meters below the water surface and this reflects the resolution of the ADCP current measurements where surface reflection creates inaccuracies in the data near the surface. Figure 7-7 presents a color contour of the vertical profile of currents over a 3 day period in August. The region of instability from the ADCP measurements can be clearly seen in this plot along with how well the model is doing representing the current distribution over the vertical over time.

Figure 7-6 presents simulated versus measured currents above I-95. The results show that the model is accurately simulating the net flow as well as the tidal fluctuations.

7.3.2 Statistical Comparison

Table 7-3 presents the statistical and percentile comparisons for the measured and simulated currents. The results show that along the Front River above GPA-04 the current magnitudes are very accurately simulated with errors in the percentiles on the order of 0.01 m/s to 0.2 m/s, mean errors overall less than 0.1 m/s, and errors in the signals on the order of 0.1 to 0.3 m/s, due mostly to phase differences. The errors seen at GPA-04 are within reasonable levels, but the accuracy of the volume flux at this cross-section indicates that local bathymetric steering and the momentum distribution across the channel may be the primary reason for the differences in the currents. The model may not be capturing these localized current effects.

Table 7-4 presents the results of the volume flux comparisons. The results show that the model is accurately simulating the distribution of flows throughout the system with the differences generally on the order of 10 percent.

Tables of the statistics for the entire calibration period as well as the sub-periods defined by the federal review group are presented in Appendix T. Examination of the statistics and graphics for these periods does not indicate a significant difference in the overall comparisons between the primary calibration period and the others. It also does not indicate that the model is performing better during some periods as versus others.

7.4 SALINITY

As discussed earlier, the accurate simulation of salinity requires good time series boundary conditions for the offshore forcing. The Primary Calibration Period provided the best continuous boundary forcing data extrapolated from GPA-26b to the offshore boundary. The following presents statistical and graphical comparisons during this period. The graphical and statistical comparisons over the full simulation period, and the federal agency defined sub-periods, are presented in Appendix T and discussed herein.

7.4.1 Graphical Comparison

Figures 7-10 through 7-13 present graphical comparisons of the measured versus simulated salinity at key stations throughout the system. Figures 7-10 and 7-11 present stations along the Front River channel from Ft. Jackson up to the end of the channel at GPA-09. The surface and bottom salinities at these stations are presented in order to allow the reader to see the dynamic nature of the stratification/destratification process and how the model simulations are capturing this process. The full set of graphical comparison plots with all stations for the entire simulation period is presented in Appendix T. For the salinity plots, in order to provide accurate scale representation of the significance of the signals and their differences, the vertical scales were kept constant for all stations; this was requested in past MTRG meetings.

Figure 7-16 provides an excellent representation of the models projection of the salinity intrusion its nature and extent. The plot presents the time along the x-axis and the longitudinal distribution of bottom salinity for the Front River from RM 0 to RM 28. The black symbols in the measured data plot give an indication of where measured data were available (the areas in between the measured data points were interpolated). The color contours show the movement of the salinity intrusion along the bottom as a function of time with the time

dependent water surface elevation presented in the upper plot (to show the spring/neap tide cycle). The simulated and measured salinities show similar levels of intrusion with fluctuations on the order of 10 miles.

Examination of the model predictions on the Middle River and Little Back River show that the model is doing very well simulating the low values of salinity in this region. The model also performs well simulating the variations and phasing of the peak periods of the salinity intrusion. As discussed in Chapter 2, one of the key processes affecting the timing of salinity in the Middle River and Little Back River is the breakdown of the stratification in the Front River as the system moves from a spring tide condition to a neap tide condition. The data showed lags from 2 to 4 days in the arrival of the peaks in the Middle and Little Back Rivers. Looking at the event around August 20th, the Front River peaks in salinity around August 20th, while the Middle River peaks around the 23rd (GPA-10), and the Little Back River peaks around the 24th (GPA-15). The model performs well in capturing this phenomenon.

Figure 7-17 presents snapshot plots of the measured vertical profiles from the EPD stations along the Front River above Fort Jackson. As this is a critical area where the vertical structure of the salinity (and therefore the density) will affect the model's ability to transport down the dissolved oxygen in the model, the accurate simulation of the vertical structure in this area is important. The results show the low tide slack profiles on September 20th and the high tide slack profiles on the 27th. The September 20th profiles represent a neap tide condition, while the September 27th profiles represent a spring tide condition. Examination of the plots shows that the model captures the vertical structure for both the spring and neap tide conditions very well with the model showing good representation of the vertical location and gradient of the salinity during the most stratified, neap tide conditions.

In order to evaluate the mass transport in the system, the measured versus simulated salt flux was calculated. The salt flux is defined as the mass of salt passing a cross-section within the system. Using the cross-sectional measured flows, and the measured data from the continuous gages, an estimate of the salt flux over the periods of the cross-sectional measurements was made. Figures 7-18a through 7-18c present the calculated salt flux versus the simulated flux. It should be noted that the measured salt fluxes were calculated using only surface and bottom salinities linearly interpolated over the depth. Based upon measured vertical profiles, there are inherent errors in this assumption. For this reason, the measured versus simulated salt flux is used as an order of magnitude evaluation. Examination of the plots shows that overall the salt flux is reasonably simulated.

7.4.2 Statistical Comparisons

Table 7-5 presents the statistical analyses for the salinity comparisons. The table presents the 10th, 50th, and 90th percentile comparisons along with the Mean Error, the Absolute Mean Error, and the RMS Error. Figures 7-14 and 7-15 present the longitudinal plots of the error statistics and the percentiles for the Front River, and the error statistics for the Middle River and the Little Back River.

Along the Front River bottom, the errors are on the order of 1-3 ppt for the 50th and 90th percentiles which equates to between 10 and 20 percent, while the overall RMS errors are on the order of 2-4 ppt. In general, it appears that much of the error is associated with the mean salinity conditions. Given the dynamic nature of the salinity conditions in Front River and the range of the salinity intrusion, these model projections are excellent. In general, the model overpredicts the mean salinities as well as the high tide salinity values in the main harbor.

For the Front River surface salinities, the errors are on the order of 0-2 ppt for the 50th and 90th percentiles, while the RMS errors are between 1 and 2 ppt. In general, the model underpredicts the salinities in the surface waters. The average errors in the Front River salinities are between 0 and 1 ppt for the percentiles, around 0.5 ppt for the mean errors and around 2 ppt for the RMS errors.

In the Middle River and Little Back Rivers the 50th percentile measured salinities are all less than 1.5 ppt, while the 90th percentile salinities are all less than 4.0 ppt, other than at station GPA-05. The average 50th percentile errors in the Middle River and Little Back River are 0.2 ppt and 0.5 ppt, respectively, with the model generally over predicting. For the 90th percentiles the model also tends to overpredict the salinity conditions.

Tables of the statistics for the entire calibration period as well as the sub-periods defined by the federal review group are presented in Appendix T. Examination of the statistics and graphics for these periods does not indicate a significant difference in the overall comparisons between the primary calibration period and the others. It also does not indicate that the model is performing better during some periods as versus others.

7.5 TEMPERATURE

The measured temperature within the system is far less dynamic than the measured salinities. In general, the spatial distribution is relatively constant with a general trend of decreasing salinity moving upstream. Temperatures range from 25 to 32 degrees C.

7.5.1 Graphical Comparison

Figures 7-19 through 7-22 present graphical comparisons of the measured versus simulated temperature at key stations throughout the system. Figures 7-19 and 7-20 present stations along the critical reach of the Front River from Ft. Jackson up to the end of the channel at GPA-09. Over the time period both the model and the data show steady reduction in the temperature from 31 deg C down to 27 deg C. The magnitudes of the surface fluctuations are similar to the measured with daily ranges on the order of 1-2 deg C. Both the simulated and measured bottom temperature shows little daily variation with fluctuations less than 0.5 deg C.

Figure 7-25 presents the vertical profiles of temperature for the Front River stations from the EPD sampling. The results show that the model is capturing the structure of the vertical temperature distribution well although there is not a great deal of stratification during either the spring or neap tide slack conditions. Very minor vertical variation in temperature can be seen in these profiles with the bottom temperatures showing slightly higher values indicating a period of surface cooling. The model captures this condition with slight over prediction of the bottom temperatures.

7.5.2 Statistical Comparisons

Table 7-6 presents the statistical analyses for the temperature comparisons. The table presents the 10th, 50th, and 90th percentile comparisons along with the Mean Error, the Absolute Mean Error, and the RMS Error. Figures 7-23 and 7-24 present the longitudinal plots of the error statistics and the percentiles for the Front River, and the error statistics for the Middle River and the Little Back River.

Throughout the system the errors are generally constant with the model showing errors on the order of 0.5 deg C. Along the Front River the model generally under predicts the surface

and bottom temperature, along the Middle River and Little Back River the model generally over predicts the temperature.

Tables of the statistics for the entire calibration period as well as the sub-periods defined by the federal review group are presented in Appendix T. Examination of the statistics and graphics for these periods indicates that the model errors over the entire calibration period are better than the primary calibration period. The model appears to be doing a better job of predicting the temperatures during September than August or during periods of lower temperature.

7.6 COMPARISON WITH FEDERAL CRITERIA

Tables 7-7a through 7-7e present summary tables of the performance of the model relative to the federal criteria defined in Appendix GG. The tables list the percentiles presented earlier along with columns that define whether or not the stations meet the Federal Criteria. The columns are for the percentiles identified or the criteria (i.e., the 50th and 90th percentiles for salinity). A “1” in the column means the station passed while a “0” means the station did not pass.

Tables 7-7a and 7-7b present the comparison of the Federal Criteria for the water surface elevation. The results are presented for the 5th, 50th and 95th percentiles and the phasing, as requested, as well as for the harmonic constituents. The harmonic constituents were presented because they provide the only test of the accuracy of the tidal amplitude simulations. The results show that for the 5th, 50th and 95th percentiles 6%, 18% and 12% of the stations pass, respectively, while for the harmonics 35% of the stations pass. This indicates that errors within the model are more associated with mean water level than tidal amplitude projections. For the phasing, 53% of the stations pass. Table 7-7b presents the other primary harmonic constituents other than the M2. The results show that the model passes at more stations for these constituents, with percent passing ranging from 71% to 94%.

It should be noted that the 2 cm error prescribed under the Federal Criteria document reflects a less than 1 percent allowable error relative to the mean tidal range in the system.

Table 7-7c presents the current statistics. The percent of stations passing ranges from 38% for the 95th percentile current speed to 63% for the 5th percentile current speed. The current

speed M2 harmonic amplitude passes 88% of the time, and 50% passes relative to the phasing of the current M2 harmonic.

Table 7-7d presents the flow statistics. For the flows 69 percent of the measured peak flows pass the federal criteria. This is important as the volume flux is a critical component of the transport in the system.

Table 7-7e presents the salinity statistics. Along the Front River 56% and 61% of the stations pass the 50th and 90th percentile criteria, respectively, and 61% pass the phasing criteria. Along the Middle River, GPA-10 passes the criteria all of the time, while GPA-12 passes for the 50th percentiles. Along the Little Back River, the Limehouse station passes for the 50th and 90th percentiles while the other stations do not pass. It should be noted that the USF&W and GPA-15 stations are both within 0.1 ppt of passing the criteria for the 50th percentiles. Also, while the percentiles show the model over predicting the salinities in these areas, the plots showed that for the peaks the model is doing reasonably well and while the data goes to zero the model has some salinity near 0.1 ppt that drives up the mean concentrations.

Table 7-7f presents the temperature statistics. For the temperature 95% of the stations pass criteria for the Front River, 100% pass for the Middle and Little Back Rivers and 67% of the stations pass above I-95.

8.0 HYDRODYNAMIC MODEL VALIDATION TO 1997 DATASET

This chapter presents the results of the validation of the hydrodynamic model to the data set collected in 1997. The validation runs were performed from July 15, 1997 to October 1, 1997 utilizing the same model coefficients and model formulation as the 1999 calibration runs.

For the model validation, a series of time periods were identified by the Federal Agencies for model to data comparison based upon the tide conditions (i.e., the spring/neap variations). The time periods identified are as follows:

- July 15 to September 30, 1997: Full Validation Period;
- July 15 to July 22, 1997;
- July 23 to August 6, 1997;
- August 7 to August 21, 1997;
- August 22 to September 5, 1997;
- September 6 to September 19, 1997; and
- September 20 to September 30, 1997.

The graphics and tables within the following sections present results for the whole validation period from July 15 to October 1. For each of the other time periods, the full set of statistical evaluations and graphics were made and are presented within Appendix R. The text discusses the full set of results.

Sections 8.2, 8.3, and 8.4 present the graphical and statistical comparisons for the water surface elevation, currents, and salinity. Section 8.5 presents an evaluation of all parameters versus the Federal Expectations Criteria. Based upon the lack of meteorological forcing available for the 1997 validation period, the model does not simulate temperature, and therefore, temperature comparisons are not presented for this period.

8.1 WATER SURFACE ELEVATION

As with the calibration to the 1999 data set, the river bottom slope solution was implemented for the upstream flow from Clyo down to the harbor. This allowed for the proper set-up of the upstream river inflows. In contrast to the 1999 monitoring, an offshore station GPA-01 was installed for the 1997 monitoring effort; this station collected offshore water surface elevation fluctuations. Where in 1999 boundary matching was utilized to move the tidal forcing function offshore with the goal of matching the measured tides at Fort Pulaski, the tidal forcing was taken directly from the GPA-01 station to the offshore boundary for the 1997 simulations.

8.1.1 Graphical Comparison

Figures 8-1 and 8-2 present graphical comparisons of the simulated versus measured water surface elevation at selected stations, GPA-04, GPA-06, GPA-08, GPA-14 (I-95) and Lucknow Canal. These stations represent conditions in the lower parts of the estuary (GPA-04), at the upper end of the primary area of concern for the hydrodynamic model (GPA-14), and within the Little Back River (Lucknow) from August 4 to September 8, 1997. The full set of model to data comparison plots over the entire simulation period is presented in Appendix R.

Examination of the plots here, and within Appendix R, indicates that the model is doing well simulating the phasing and amplitude for the water surface elevation throughout the system. It is important to note that by utilizing the offshore forcing from GPA-01, rather than boundary matching to Fort Pulaski as was done in 1999, some difference at Fort Pulaski is found between the simulation and the measured data. The validation plots do not show a significant difference in the response of the tidal wave propagating up the river in comparison to the 1999 simulations.

8.1.2 Statistical Comparisons and Harmonic Analysis

Table 8-1 presents the statistical evaluation of the measured versus simulated water surface elevation. The table presents the percentile comparisons as well as the Mean Error, Absolute Mean Error, RMS error, and the differences. Figure 8-3 presents longitudinal plots of the Mean Error, Absolute Mean Error, and the RMS error. These results are for the full

simulation period from July 15th to October 1st. Tables within Appendix R present statistical comparisons for the spring/heap cycle sub-periods.

Table 8-2 presents the results of the harmonic analysis at all of the stations for the full simulation period. Examination of all of the tabularized statistics and analyses provides validation of the calibration simulations. The harmonic analyses show that the amplification of the tidal wave moving upstream is consistent between the model and the data. The M2 amplitude shows an increase of 0.18 cm from Fort Pulaski to the Houlihan Bridge from the data, this same amplitude increase is also seen in the simulations. At Lucknow the validation runs show a 2 cm error in the M2 amplitude using the measured forcing from GPA-01 for the offshore. The relative error between the Fort Pulaski station and Lucknow shows an error of 8 percent at the Lucknow station. This is similar to that found in the 1999 calibration runs.

The longitudinal error statistics show errors along the Front River being less than 10 cm (less than 5 percent) as compared to the calibration runs where the results showed on the order of 10 percent errors due to the over prediction of the mean water level. The 95th percentile errors are also much lower with values ranging from 0.04 to 0.06 meters. These lower errors in the statistics and the percentiles may be a function of using direct offshore measurements as versus boundary matching to force the model.

Phase errors in the validation run are also lower than the calibration run. The phase differences below where the Houlihan Bridge crosses the Front River, Middle River and Little Back River are all less than 25 minutes. The Middle River stations show phase errors all less than 40 minutes, while phase errors along the Little Back River and at I-95 are all less than 55 minutes.

8.2 CURRENTS AND FLOWS

There were two stations along the river where current measurements were made in 1997 using ADCPs: GPA-04 and GPA-08. In addition, point current measurements were made at GPA-10 and GPA-15.

Cross-sectional flow measurements were made at 10 locations from I-95 to Fort Jackson. Three cross-sections in the area where the River splits into the Front River and the Back River measured the distribution of volume flux (FJ, BR, FR3). Three other stations where the Houlihan Bridge crosses the Front River, Middle River, and Little Back River, measured the

distribution of flow in the upper estuary (FR2, MR2, LBR2). Finally, a series of cross-sections measured the flows where the three rivers rejoin near I-95 (FR1, MR1, LRB1, and I-95).

8.2.1 Graphical Comparison

Figures 8-4 and 8-5 present the measured versus simulated currents at GPA-04 and GPA-08. As was seen in the 1999 model calibration, the currents at GPA-04 are under predicted by the model with the surface measurements showing stronger flood flows while the ebb seems reasonably simulated. The bottom currents show an overall under prediction by the model. This is consistent with the results from the calibration.

Once again, more important than the simulation of the velocity magnitudes is the simulation of the volume flux. Figures 8-6 and 8-7 present the measured versus simulated flows at various cross-sections. The results show that the model accurately simulates the overall volume flux with errors on the order of 10 percent. The split of the flows between the Front and Back River show that the model is accurately simulating the distribution of flows here and upriver. The simulated versus measured currents at GPA-10 (Middle River) and GPA-15 (Little Back River) show the model is reasonably simulating the currents in these areas, although the data from these current meters was suspect.

The current projections at GPA-08 are presented in Figure 8-5. The model accurately simulates both the surface and bottom current magnitudes at this location though the model seems to have a greater net downstream velocity.

8.2.2 Statistical Comparison

Table 8-3 presents the statistical and percentile comparisons for the measured and simulated currents. The results show that along the Front River above GPA-04 the current magnitudes are very accurately simulated with errors in the percentiles on the order of 0.06 m/s to 0.2 m/s, mean errors overall less than 0.1 m/s, and errors in the signals on the order of 0.1 to 0.3 m/s, due mostly to phase differences.

Appendix R presents the results of the volume flux comparisons. The results show that the model is accurately simulating the distribution of flows throughout the system with the differences generally on the order of 10 percent.

8.3 SALINITY

The following presents statistical and graphical comparisons for the full simulation period. The federal agency defined sub-periods, are presented in Appendix R.

8.3.1 Graphical Comparison

Figures 8-8 through 8-11 present graphical comparisons of the measured versus simulated salinity at key stations throughout the system from August 4 to September 8, 1997. Figures 8-8 through 8-9 present the stations along the critical reach of the Front River from Ft. Pulaski up to the end of the channel at GPA-09. Once again the results show that the model is able to capture the stratification/destratification processes in the system, and provides verification of the modified vertical turbulence scheme utilized in the model.

In order to evaluate the mass transport in the system, the measured versus simulated salt flux was calculated. The salt flux is defined as the mass of salt passing a cross-section within the system. Using the cross-sectional measured flows, and the measured data from the continuous gages, an estimate of the salt flux over the periods of the cross-sectional measurements was made. The salt flux comparisons are presented in Appendix R. Examination of the plots shows that overall the salt flux is reasonably simulated.

8.3.2 Statistical Comparisons

Table 8-5 presents the statistical analyses for the salinity comparisons. The table presents the 10th, 50th, and 90th percentile comparisons along with the Mean Error, the Absolute Mean Error, and the RMS Error. Figures 8-12 and 8-13 present the longitudinal plots of the error statistics and the percentiles for the Front River, and the error statistics for the Middle River and the Little Back River.

Along the Front River bottom, the errors are in general all less than 2 ppt for the 50th and 90th percentiles which equates to between 10 and 15 percent while the overall RMS errors are on the order of 1-3 ppt. For the validation the errors are generally not due to the mean differences and the overall statistical results are better than the calibration period. This may also be a function of the offshore salinity boundary condition being used.

For the Front River surface salinities the errors are on the order of 0-2 ppt for the 50th and 90th percentiles, while the RMS errors are between 1 and 2 ppt. In general, the model is low in the surface waters. The average errors in the Front River salinities are less than 1 ppt for the percentiles, around 0.1 ppt for the mean errors and around 2 ppt for the RMS.

In the Middle River the percentile errors are all less than 0.5 ppt for the 50th percentiles and between 0.5 ppt and 1.5 ppt for the 90 percentiles. The 50th percentiles along the Little Back River above the Houlihan Bridge are all less than 0.5 ppt, with some near zero. The 90th percentiles are also less than 0.5 ppt in the Little Back River.

Tables of the statistics for the entire calibration period as well as the sub-periods defined by the federal review group are presented in Appendix R. Examination of the statistics and graphics for these periods does not indicate a significant difference in the overall comparisons between the full validation period and the others. It also does not indicate that the model is performing better during some periods as versus others.

8.4 COMPARISON WITH FEDERAL CRITERIA

Tables 8-6a through 8-6e present summary tables of the performance of the 1997 model verification simulation relative to the federal criteria defined in Appendix GG. The tables list the percentiles presented earlier along with columns that define whether or not the stations meet the Federal Criteria. The columns are for the percentiles identified or the criteria (i.e., the 50th and 90th percentiles for salinity). A “1” in the column means the station passed while a “0” means the station did not pass.

Tables 8-6a and 8-6b present the comparison to the Federal Criteria for the water surface elevation. The results are presented for the 5th, 50th and 95th percentiles and the phasing, as requested, as well as for the harmonic constituents. In Table 8-6a, the results show that for the 5th, 50th and 95th percentiles 6%, 25% and 38% of the stations pass, respectively, while for the M2 harmonic amplitude 13% of the stations pass. This indicates that errors within the model are more associated tidal amplitude projections than with mean water level (the opposite of the 1999 simulation results). For the phasing, 56% of the stations pass. Table 8-6b presents the other primary harmonic constituents other than the M2. The results show that the model passes at more stations for these constituents, 62% to 100% for all the constituents except the higher order M4 harmonic which passes at 38%.

It should be noted that the 2 cm error prescribed under the Federal Criteria document reflects a less than 1 percent allowable error relative to the mean tidal range in the system.

Table 8-6c presents the current statistics. The percent of stations passing the current magnitude criteria ranges from 33% to 67%, and 17% pass relative to the phasing of the currents.

Table 8-6d presents the flow statistics. For the flows 75 percent of the measured peak flows pass the federal criteria. This is important as the volume flux is a critical component of the transport in the system.

Table 8-6e presents the salinity statistics. Along the Front River 50% of the stations pass the 50th and 90th percentile criteria and 73% pass the phasing criteria. Along the Middle River, all of the stations pass for the 50th percentile criterion, while none of the stations pass for the 90th percentile criterion. Along the Little Back River, 83% and 67% of the stations pass for the 50th percentile and 90th percentile criteria, respectively, which is a significant improvement over the 1999 simulation.

9.0 HYDRODYNAMIC MODEL SENSITIVITY

This Chapter presents the results of the sensitivity tests performed on the hydrodynamic model. Table 9-1 presents the suite of sensitivity runs performed on the model. This list was based upon input from the model technical review group. The parameters tested included:

- Vertical Diffusivity
- Boundary Salinity
- Horizontal Diffusivity
- Upstream Inflow
- Bottom Friction

The sensitivity tests were run on a baseline model simulation that covered the Primary Calibration Period for 1999 (August 4 to September 8). For this period, the baseline 50th and 90th percentile salinities, the 50th and 90th percentile water surface elevations, and the M2 tidal constituent were utilized for comparison purposes with each sensitivity run determining the percent change from the baseline value under the proposed scenario. The percent changes by station, for each sensitivity run, are presented in Appendix V in tabular as well as graphical form (as longitudinal plots of percent change). For the salinities the percent changes are based upon the baseline value at the station; therefore, moving upstream the percent changes result in smaller absolute changes in salinity. For example, at GPA-04, where the baseline 50th percentile salinity is 23.6 ppt, a 10 percent change is equivalent to a change in 50th percentile salinity of 2.4 ppt; while at GPA-10, where the baseline 50th percentile salinity is 1.5 ppt, a 10 percent change is equivalent to a salinity change of 0.15 ppt. This needs to be considered when examining the percent changes presented within the appendix tables. Tables 9-2 and 9-3 present the net change in salinity under each of the sensitivity scenarios for the 50th and 90th percentiles, respectively, while Tables 9-4 and 9-5 present the net change in water surface elevation as a percent of the base condition. 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 VERTICAL DIFFUSIVITY

The modified vertical mixing formulation defines a spatially and temporally varying vertical mixing coefficient. The formulation of this coefficient is presented in detail in Appendix Q. The sensitivity analysis included simulations with +/- 10% variation applied universally to the vertical mixing coefficient. Examination of the tables shows that the model is relatively sensitive to the variation in vertical diffusivity. A 10 percent change in the value can result in up to a 1.0 ppt change in the salinity along the bottom of the Front River in the middle of the harbor. An increase in vertical mixing results in a reduction in salinity and a decrease increase in vertical mixing results in an increase in salinity. This is expected intuitively because the reduced mixing should cause greater stratification, and therefore, greater baroclinic induced salinity intrusion to the estuary. The results show that the increases or decreases for both the 90th and 50th percentiles are similar; in essence, the vertical diffusivity affects the overall intrusion but not the relative transport.

Within the Middle River and Little Back River the variations in vertical diffusivity have relatively small effects on the salinities with the greatest effect felt at GPA-10 where the change is near 0.2 ppt. In all other stations the changes are near 0.1 ppt.

The results indicate that, overall, the water surface elevation is relatively insensitive to the vertical mixing coefficient. However, given the criteria for acceptance at 2 cm, the 2 to 3 percent variations are on the order of the acceptability of the model to predict water surface elevation. It was seen that the model mean water levels do respond to the gradients of salinity in the system (i.e., the upstream pressure created by the salinity gradients are balanced by a rise in mean water level). Therefore, it is not surprising that the model water levels show some sensitivity to this parameter.

Appendix V presents a table of tidal amplitude sensitivity and the results show that the variation of the vertical mixing has negligible effect on the tidal amplitudes.

9.2 BOUNDARY SALINITY

The sensitivity analysis included simulations with +/- 1 ppt variation at the offshore boundary. This variation had similar levels of effect as the vertical diffusivity with changes in the Front River bottom salinities on the order of 1.0 ppt maximum (comparable to the change in the boundary) and in the upstream Middle River and Little Back River the increases/decreases

are on the order of 0.1 to 0.2 ppt. It should be noted that for the Front River, Middle River and Little Back River the changes seen under the boundary salinity variation are on the order of the allowable error in the system. In the 1997 validation, when measured salinities were available for the offshore (at station GPA-01), the results showed better agreement than the 1999 simulations where measured downstream salinities were carried offshore (from GPA-26 to the offshore boundary).

The variation of the boundary salinity had little to no effect on the water surface elevations or tidal amplitude.

9.3 HORIZONTAL DIFFUSIVITY

The hydrodynamic model uses a constant horizontal diffusivity for the simulations. For the runs presented herein, that value was 1.0 m²/sec. For the sensitivity analysis, this value was varied +/- 25%. The model is overall insensitive to the variation in the horizontal diffusivity with variations in salinity around 0.2 ppt in the Front River and near zero in the upriver stations.

9.4 UPSTREAM INFLOW

Presently the model utilizes the measured freshwater inflow at Clio with a 10 percent increase to account for the watershed below Clio and its contribution to the estuary. As the watershed below Clio is relatively flat, and may not exhibit the same drainage characteristics as the watershed upstream, and given that much of the upstream watershed is dammed, there is inherent error in the freshwater inflows. For this reason a +/- 10% variation on the freshwater inflow was applied to the time dependent upstream boundary in order to assess the potential uncertainty in the model results based upon the downstream watershed assumptions.

Examination of Tables 9-2 and 9-3 show that the upstream salinities in the Middle River and Little Back River are the most sensitive to the variation in the upstream freshwater inflow. Changes in the 50th percentiles of 0.1 ppt to 0.2 ppt can be seen in the upstream stations while changes of 0.2 ppt to 0.3 ppt can be seen in the 90th percentiles. Given that the accuracy of the model in these areas needs to be on the order of 0.5 ppt, the level of

uncertainty introduced by the upstream inflow needs to be considered when evaluating model performance.

The upstream 50th percentile water levels at Hardeeville and GPA-17 are the most sensitive to changes in the upstream freshwater inflow, with variations of 0.13 m and 0.17 m, respectively. The downstream stations are much less sensitive (on the order of 0.01 m). Given that the Federal expectation criterion is 2 cm for water level, the uncertainty in upstream freshwater inflow causes much greater variation in the GPA-17 and Hardeeville water levels than the uncertainty allowed by the expectation criterion. However, this upstream area is outside of the area of interest within the model.

The tidal amplitudes presented in Appendix V do not show significant sensitivity to the freshwater inflow at all stations below I-95. Above I-95, as expected, the tidal projections are very sensitive to the freshwater inflow, but these areas are generally outside of the area of interest within the model.

9.5 BOTTOM FRICTION

The simulation of salinity is relatively insensitive to the bottom friction. A 10 percent variation in the overall bottom friction within the model did not result in significant variations in the simulated salinities.

The water level is sensitive to bottom friction in the upriver areas above I-95. A variation of the bottom friction of plus or minus 10 percent results in 50th and 95th percentile variations up to 0.1 m at GPA-17. The river below I-95 is relatively insensitive to bottom friction, with variations up to 0.01 m.

The tidal amplitude below I-95 is also insensitive to the bottom friction term. Above I-95, where the river slopes upward, the model is very sensitive to the bottom friction term with variations on the order of 10 percent in the most upstream stations.

10.0 SUMMARY AND CONCLUSIONS

The hydrodynamic model calibration effort presented herein was made possible by the existence of two comprehensive data sets developed from field programs run during the summer months of 1997 and 1999 in the Savannah River. Additional, less comprehensive but longer term data sets for salinity, river flow and surface elevations from the USGS, combined with the 1997 and 1999 field programs provided an excellent understanding of the physical processes that drive circulation and transport within the Lower Savannah River estuary, and the resulting temporal and spatial distribution of salinity.

The model development process has been completed with guidance and review by a team of experts representing federal, state and local agencies. 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 independent variables assessed in the calibration and verification included:

- Surface elevation
- Currents
- Volume flow
- Salinity
- Salt flux
- Temperature

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. 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 it's 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 hydrodynamic process.

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 hydrographic parameters.

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

- The tidal predictions show very good agreement in relation to the amplitude and phase, passing the federal expectations criteria of +/- 2 cm at a number of stations where the +/- 2 cm criteria represent an error on the order of 1 percent of the tidal signal, well below typical expectations for error (typically from 5 to 10 percent).
- The tidal amplitude and phase errors are achieved within a system where the tidal wave propagates a significant distance along multiple interconnecting channels with flooding and drying of marsh areas.
- The mean water surface elevation predictions overall are reasonable with areas where the model over predicts the mean water surface elevation on the order of 10 cm (upper Front River). This is balanced with mean water level predictions in the Little Back River that are approximately 2 cm low.
- Current magnitude and phase predictions are very good along the Front and Back Rivers with amplitude error magnitudes generally less than 10 cm/sec representing less than 10 percent error.
- Simulation of flows shows the model is doing well in the partitioning and phasing of flows and the tidal prisms between the multiple interconnecting channels.
- Simulation of the distribution of mean and high tide salinities throughout the system is good with greater than 50 percent of the stations passing the federal expectations criteria. The model also passes the federal expectations criteria at key stations in the upper Little Back River and the Middle River.
- Simulation of temperature throughout the system is excellent with greater than 93 percent of the stations passing the Federal Criteria.

By definition, numerical modeling can only approximate reality and although no model calibration effort can be flawless, the present study has shown that the 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 hydrodynamic processes. The model calibration/validation presented herein, represents the best overall calibration on a system wide basis accounting for the multiple needs of the model for evaluation of the impacts of the proposed deepening. The calibration 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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