Simulation of Water Levels and Salinity in the Rivers and Tidal Marshes in the Vicinity of the Savannah National Wildlife Refuge, Coastal South Carolina and Georgia

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Abstract

The Savannah Harbor is one of the busiest ports on the East Coast of the United States and is located downstream from the Savannah National Wildlife Refuge, which is one of the Nation's largest freshwater tidal marshes. The Georgia Ports Authority and the U.S. Army Corps of Engineers funded hydrodynamic and ecological studies to evaluate the potential effects of a proposed deepening of Savannah Harbor as part of the Environmental Impact Statement. These studies included a three-dimensional (3D) model of the Savannah River estuary system, which was developed to simulate changes in water levels and salinity in the system in response to geometry changes as a result of the deepening of Savannah Harbor, and a marsh-succession model that predicts plant distribution in the tidal marshes in response to changes in the water-level and salinity conditions in the marsh. Beginning in May 2001, the U.S. Geological Survey entered into cooperative agreements with the Georgia Ports Authority to develop empirical models to simulate the water level and salinity of the rivers and tidal marshes in the vicinity of the Savannah National Wildlife Refuge and to link the 3D hydrodynamic river-estuary model and the marsh-succession model.

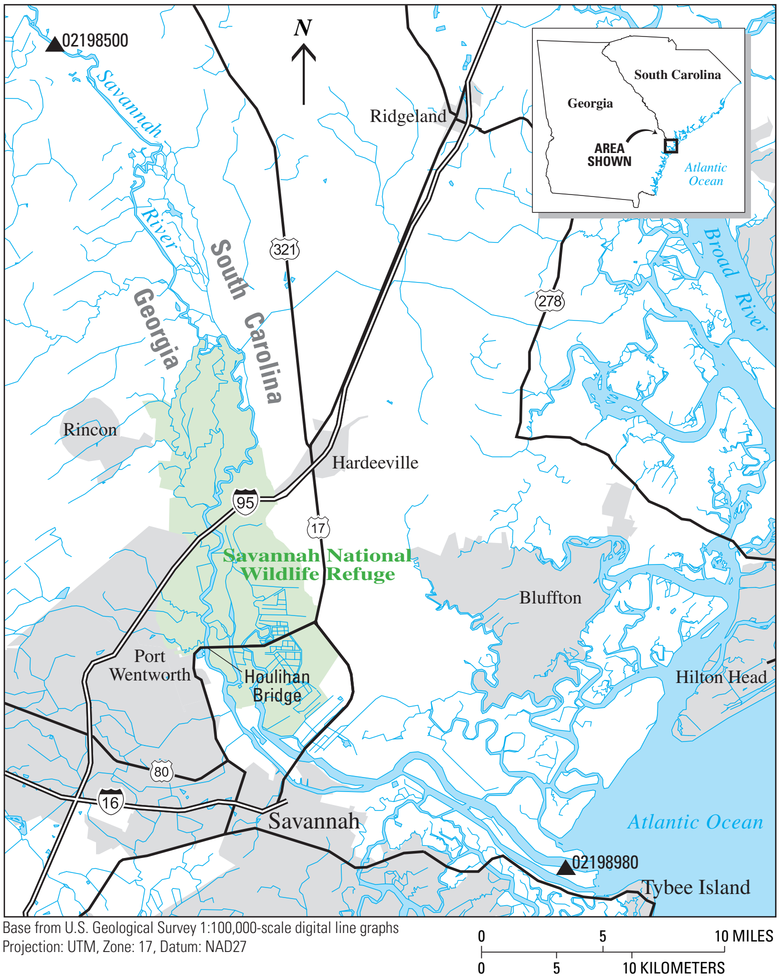
For the development of these models, many different databases were created that describe the complexity and behaviors of the estuary. The U.S. Geological Survey has maintained a network of continuous streamflow, water-level, and specific-conductance (field measurement to compute salinity) river gages in the study area since the 1980s and a network of water-level and salinity marsh gages in the study area since 1999. The Georgia Ports Authority collected water-level and salinity data during summer 1997 and 1999 and collected continuous water-level and salinity data in the marsh and connecting tidal creeks from 1999 to 2002. Most of the databases comprise time series that differ by variable type, periods of record, measurement frequency, location, and reliability.

Understanding freshwater inflows, tidal water levels, and specific conductance in the rivers and marshes is critical to enhancing the predictive capabilities of a successful marsh succession model. Data-mining techniques, including artificial neural network (ANN) models, were applied to address various needs of the ecology study and to integrate the riverine predictions from the 3D model to the marsh-succession model. ANN models were developed to simulate riverine water levels and specific conductance in the vicinity of the tidal marshes for the full range of historical conditions using data from the river gaging networks. ANN models were also developed to simulate the marsh water levels and pore-water salinities using data from the marsh gaging networks. Using the marsh ANN models, the continuous marsh network was hindcasted to be concurrent with the long-term riverine network. The hindcasted data allow ecologists to compute hydrologic parameters—such as hydroperiods and exposure frequency—to help analyze historical vegetation data.

To integrate the 3D hydrodynamic model, the marsh-succession model, and various time-series databases, a decision support system (DSS) was developed to support the various needs of regulatory and scientific stakeholders. The DSS required the development of a spreadsheet application that integrates the database, 3D hydrodynamic model output, and ANN riverine and marsh models into a single package that is easy to use and can be readily disseminated. The DSS allows users to evaluate water-level and salinity response for different hydrologic conditions. Savannah River streamflows can be controlled by the user as constant flow, a percentage of historical flows, a percentile daily flow hydrograph, or as a user-specified hydrograph. The DSS can also use output from the 3D model at stream gages near the Savannah National Wildlife Refuge to simulate the effects in the tidal marshes. The DSS is distributed with a two-dimensional (plan view), color-gradient visualization routine that interpolates and extrapolates model output to fill and color a grid of the study area. Grid cell size is either 10 or 100 meters (100.76 or 1,076 square feet). Interpolation is performed using a simple ratio of linear distance between nearest marsh gages and actual distance from each cell between nearest marsh gages. The salinity values and grid parameter, and corner coordinates, can be exported as an ASCII file for input into a mapping package such as ArcView™.

Introduction

The Savannah Harbor, as with many major estuarine systems, meets many local and regional water-resource needs. The tidal parts of the Savannah River provide water supply for coastal South Carolina and Georgia, provide habitat for the extensive freshwater marsh, provide assimilative capacity for municipal and industrial dischargers, and provide navigation for a major shipping terminal on the East Coast (fig. 1). With increases in industrial and residential development in Georgia and South Carolina, there are competing, and often conflicting, interests in the water resources of the Savannah River. As part of a proposed deepening of Savannah Harbor and modification of the navigation channel geometry, the environmental effect on many of the ecological and economic resources in Savannah, including the freshwater tidal marshes, are being evaluated.



Base from U.S. Geological Survey 1:100,000-scale digital line graphs
Projection: UTM, Zone: 17, Datum: NAD27

EXPLANATION

▲02198980 USGS gaging station and number

Figure 1. Study area in the vicinity of the Savannah National Wildlife Refuge, coastal South Carolina and Georgia. Savannah Harbor is located in the lower 21 miles of the Savannah River. The U.S. Geological Survey gaging stations at Savannah River near Clyo, Ga. (02198500) and Savannah River at Fort Pulaski (02198980) also are shown.

The freshwater-dominated parts of the tidal marsh may be the most sensitive of the tidal marshes to alterations of environmental gradients. Freshwater tidal marshes generally have a greater diversity of plant communities compared to saltwater tidal marshes. As numerous studies have shown (Odum and others, 1984; Latham, 1990; Gough and Grace, 1998; Howard and Mendelsson, 1999), the salinity gradient is a driving force in shaping the vegetative communities of a tidal marsh. A study by Odum and others (1984) estimated that there were 405,000 acres of tidal freshwater marshes along the Atlantic Coast, of which 28 percent were in coastal South Carolina and Georgia. In the late 1960s, the tidal freshwater wetlands of the lower Savannah River were estimated at 24,000 acres (Tiner, 1977), with approximately one-fifth of the tidal freshwater marsh in South Carolina and Georgia. Since that time, the amount of tidal freshwater marsh in the Savannah Estuary has been greatly reduced due to salinity intrusion. The remaining tidal freshwater marsh is an essential part of the 28,000-acre Savannah National Wildlife Refuge (SNWR), which was established in 1927 (*http://www.fws.gov/savannah/*).

As part of the Environmental Impact Statement (EIS) for a potential deepening of the harbor, two studies were undertaken (independent from the study described in this report) by plant ecologists from the U.S. Geological Survey (USGS) and Applied Technology and Management (ATM) to study the tidal marshes of the SNWR to understand how the plant communities respond to changing hydrologic and pore-water salinity conditions in the marsh. Using data and analysis from the marsh studies, plant succession models were developed that predict plant communities based on water-level and pore-water salinity conditions. Concurrently with the marsh studies, a three-dimensional (3D) hydrodynamic and water-quality model (also independent of the study described in this report) was applied to the Savannah Harbor to simulate changing flow and water-quality conditions in the rivers surrounding the tidal marshes. The plant succession models and the 3D hydrodynamic model will be used in conjunction to evaluate the effect of the harbor deepening on the tidal marshes. The 3D model simulates only changing flow and salinity in the rivers and not in the marshes. Defining the linkage between the water level and salinity of the Savannah River and tidal marshes and simulating marsh water-level and salinity conditions was critical to developing a successful plant succession model.

The U.S. Geological Survey (USGS), in cooperation with the Georgia Ports Authority (GPA), initiated a study to (1) develop empirical models to simulate water level and pore-water salinity at river gaging stations; (2) develop empirical models to simulate water level and salinity at marsh gaging stations; (3) develop a spreadsheet application that integrates historical databases, empirical river and marsh models, output from the 3D model of Savannah Harbor, and marsh predictions that is easy to use and can be readily disseminated; and (4) develop a visualization routine that will spatially extrapolate the model results across the marsh. The USGS collaborated with Advanced Data Mining on the study.

The USGS entered into a Cooperative Research and Development Agreement with Advanced Data Mining in 2002 to collaborate on applying data-mining techniques and artificial neural network (ANN) models to water-resources investigations. The emerging field of data mining addresses the issue of extracting information from large databases (Weiss and Indurkhya, 1998). Data mining is a powerful tool for converting large databases into knowledge to solve problems that are otherwise imponderable because of the large numbers of explanatory variables or poorly understood process physics. Data-mining methods come from different technical fields such as signal processing, statistics, artificial intelligence, and advanced visualization. Data mining uses methods for maximizing the information content of data, determining which variables have the strongest correlations to the problems of interest, and developing models that predict future outcomes. This knowledge encompasses both understanding of cause-effect relations and predicting the consequences of alternative actions. Data mining is used extensively in financial services, banking, advertising, manufacturing, and e-commerce to classify the behaviors of organizations and individuals, and to predict future outcomes.

Purpose and Scope

This report presents the results of a study that links water-level and salinity conditions of the Back River, Little Back River, Middle River, and Front River to tidal marshes in the vicinity of the SNWR (fig. 2). This report documents the development of the Model-to-Marsh application (also referred to as the M2M application) including the results of applying data mining and ANN models to the Savannah, Back, Little Back, Middle, and Front Rivers. The modeling scope of effort consisted of four phases: (1) simulating the long-term USGS water-level and salinity river data from the period 1994–2005; (2) simulating the short-term water-level and salinity river data collected by the GPA during summer 1997 and 1999 and the marsh water-level and pore-water salinity data collected by the USGS and the GPA during 1999 to 2005; (3) integrating the 3D model input into the application and spatially extrapolating the simulated salinity response across the marsh; and (4) integrating the developed models of the riverine and marsh gaging sites and historical databases into a spreadsheet application.

An important part of the USGS mission is to provide scientific information for the effective water-resources management of the Nation. To assess the quantity and quality of the Nation's surface-water, the USGS collects hydrologic and water-quality data from rivers, lakes, and estuaries using standardized methods, and maintains the data from these stations in a national database. Often these databases are under utilized and under interpreted for addressing contemporary hydrologic issues. The techniques presented in this report demonstrate how valuable information can be extracted from existing databases to assist local, State, and Federal agencies. The application of data-mining techniques, including ANN models, to the Savannah River Estuary demonstrates how empirical models of complex hydrologic systems can be developed, disparate databases and models can be integrated to support multidisciplinary research, and study results can be easily disseminated to meet the needs of a broad range of end users.

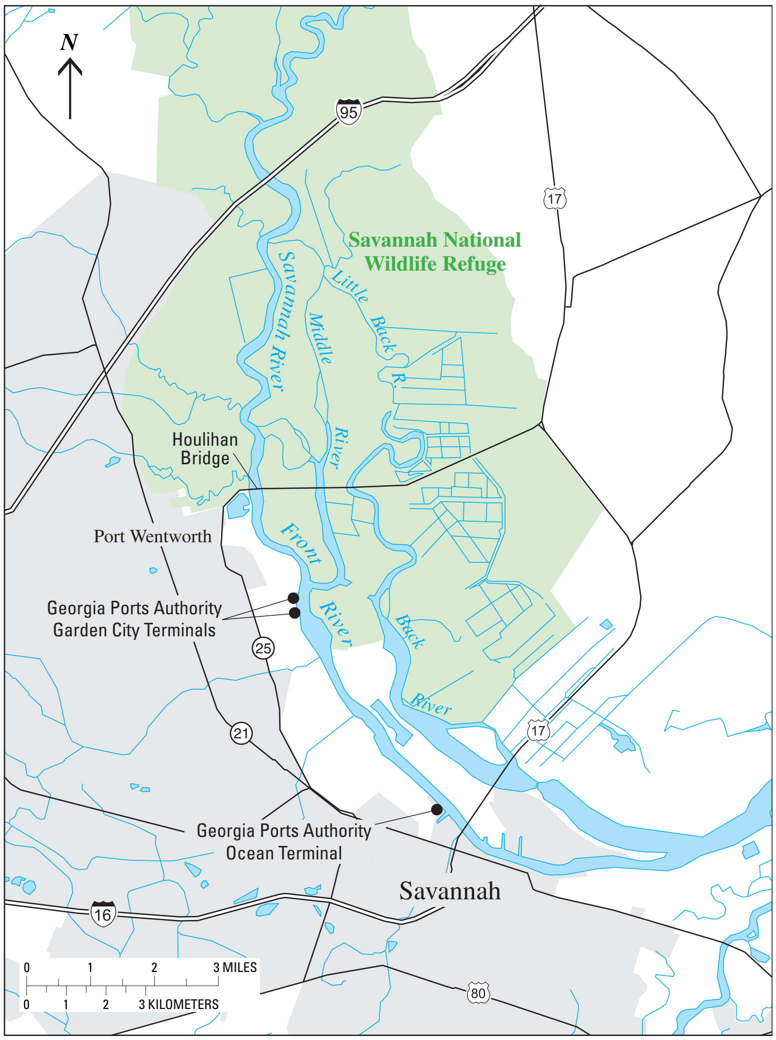


Figure 2. The Savannah, Front, Middle, Back, and Little Back Rivers in the vicinity of the Savannah National Wildlife Refuge.

Description of Study Area

The Savannah River originates at the confluence of the Seneca and Tugaloo Rivers, near Hartwell, Ga., and forms the State boundary between South Carolina and Georgia to the divergence of the Little Back River near the coast (figs. 2, 3). From Lake Hartwell, the Savannah River flows through two physiographic provinces, the Piedmont and the Coastal Plain (fig. 3). The city of Augusta, Ga., is on the Fall Line, which separates these two provinces. The slope of the river ranges from an average of about 3 feet per mile in the Piedmont to less that 1 foot per mile in the Coastal Plain. Upstream from the Fall Line, three large Federal multipurpose dams (Lake Hartwell, Richard B. Russell Lake, and J. Strom Thurmond Lake) provide hydropower, water supply, recreational facilities and a limited degree of flood control. Thurmond Dam is responsible for most of the flow regulation that affects the Savannah River at Augusta (Sanders and others, 1990).

From Augusta, Ga., the Savannah River flows 187 miles to the coast (fig. 3). The lower Savannah River is a deltaic system that branches into a series of interconnected distributary channels including the Little Back, Middle, Back, and Front Rivers (fig. 2). The hydrology of the system is dependent upon precipitation, runoff, channel configuration, streamflow, and seasonal and daily tidal fluctuations (Latham, 1990; Pearlstine and others, 1990). Savannah Harbor experiences semidiurnal tides of two high and two low tides in a 24.8-hour period with pronounced differences in tidal range between neap and spring tides occurring on a 14-day and 28-day lunar cycle. Periods of greatest tidal ranges are known as “spring” tides and the period of lowest tidal amplitude are known as “neap” tides. The tidal amplitude in the lower parts of the estuary is approximately 5 to 6 feet (ft) during neap tides and greater than 8 ft during spring tides. The resultant interaction of stream flow and tidal range allows the salinity intrusion to be detected more than 25 miles upstream and the tidal water-level signal to reach approximately 40 miles upstream, near Hardeeville (fig. 1, Bossart and others, 2001).

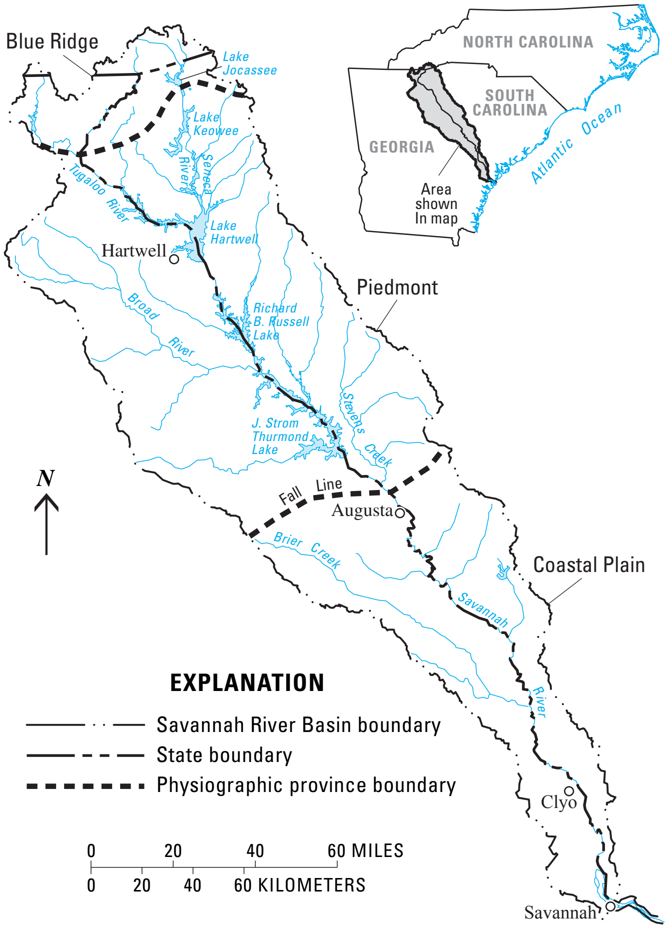


Figure 3. The physiographic provinces of the Savannah River Basin in South Carolina, Georgia, and North Carolina.

Rice plantations, with large diked fields along the banks of the Little Back, Back, Middle, and Savannah Rivers flourished in the 18th and 19th centuries. Many of the marshes and swamps were cleared, diked, impounded, and converted to rice fields during this period. With the advent of mechanized rice harvesting, rice production diminished because the heavy machinery was unsuitable for the clayey soil of the area. The rice fields were abandoned, and subsequently, many of the dikes were broken and the impoundments have reverted to tidal marshes.

Typical of coastal rivers in Georgia and South Carolina, the shallow, deltaic branches of the Savannah River did not provide natural features for a harbor, such as deep embayments or natural scouring of deep channels. Historically, the Back River had the largest channel geometry and the largest proportion of streamflow compared with the Front River (Barber and Gann, 1989). The Savannah Harbor was developed along the lower 21 miles of the Savannah River from the mid-1800s to the present (2006). The Savannah Harbor has a history of channel deepening, widening, creation of turning and sedimentation basins, and maintenance dredging and disposal as the harbor changed from a natural river system with a controlling depth of 10 ft at low tide to its currently maintained depth of 42 ft at low tide (Barber and Gann, 1989).

Two important resources are located in the Savannah River Estuary—the SNWR and the GPA (fig. 2). The tidal freshwater marsh is an essential part of the 28,000-acre SNWR. Located between river mile 18 and river mile 40, the SNWR is home to a diverse variety of wildlife and plant communities. Neighboring the SNWR, the GPA maintains two deepwater terminal facilities—Garden City Terminal and Ocean Terminal (fig. 2). To support navigation and the terminal activities of the GPA, the river channel and turning basins are maintained by dredging below U.S. Highway 17 Bridge (Houlihan Bridge) to approximately 20 miles offshore from the harbor entrance.

Substantial modifications made to the system during the past 30 years include the installation and operation of a tide gate on the Back River in 1977, deepening of the shipping channel to 38 ft (from 34 ft) in 1978, decommissioning of the tide gate in 1991, and deepening the shipping channel to 42 ft (from 38 ft) in 1994. The tide gate was operated to facilitate the maintenance dredging of the harbor by increasing scour in the Front River and creating a sedimentation basin in the Back River that was near the dredge disposal area. The tide gate opened on flood tides (incoming) and closed on ebb tides (outgoing). The increased flows on the Front River increased scouring of the channel and minimized maintenance dredging (Latham, 1990). The operation of the tide gate had the unintended consequence of moving the saltwater wedge (salinity value of 0.5 practical salinity units, [psu]) 2 to 6 miles upstream in the Back, Little Back, and Middle Rivers (Pearlstine and others, 1990, 1993). The approximate location of the freshwater-saltwater interface for four historical periods (1875, 1940, 1965, and 1997) and their associated channel depths are shown in figure 4 (E. EuDaly, U.S. Fish and Wildlife Service, written commun., 2005). Data used in figure 4 were obtained from available historical sources, and provide a qualitative comparison of the position of the freshwater/saltwater interface and the spatial extent of the freshwater marsh.

Previous Studies

Numerous ecological and hydrodynamic studies have been conducted to support the modification and management of the harbor and the resulting changes of the flow and salinity dynamics of the Savannah River Estuary. Many of the plant ecology studies have focused on the characterization of the plant communities in freshwater tidal marshes of the SNWR and how these communities respond to changing pore-water salinity conditions. Many of the hydrodynamic and water-quality studies have focused on how modifications to the harbor (deepening, connecting rivers, creating sedimentation basin) affect flow, sedimentation, salinity, and water quality. The following sections highlight some of these studies.

Plant Ecology Studies

The operation of the tide gate had substantial effect on the saltwater intrusion into the Little Back River and ultimately on the interstitial salinity concentration in the soils of the freshwater tidal marsh of the SNWR. In 1985, a study was initiated to characterize the plant communities and environmental conditions of the tidal marsh of the lower Savannah River (Latham, 1990). That study reported that plant species are closely linked to interstitial and riverine salinity levels. The changing salinity conditions also affect the ability of freshwater species to compete with brackish species. The increased salinity corresponded to changes in the plant communities from fresh-marsh to brackish-marsh conditions.

Pearlstine and others (1990, 1993) studied vegetation responses to salinity changes in the marshes and developed a plant succession model to predict plant communities for selected environmental conditions. The study reported that if the elevated salinity levels caused by the tide gate were maintained, salt marsh cordgrass (*Spartina alterniflora*) and salt marsh bulrush (*Scirpus robustus*) would become established in the freshwater tidal marshes in the SNWR. After the removal of the tide gate and the 4-ft deepening of the harbor, Latham and Kitchens (1995) revisited transects used by Latham (1990) and Pearlstine and others (1990, 1993), and concluded that the interstitial salinities had been reduced, especially in the areas with salinities ranging between 0.5 and 3.0 psu. Loftin and others (2003) reported that although the marsh was more characteristic of a freshwater marsh than prior to removal of the tide gate, the extent of recovery was not as great as predicted by Pearlstine and others (1993). The benefits of removing the tide gate and lowering the interstitial salinity may have been limited by salinity changes caused by the 4-ft deepening of the harbor. As part of the EIS concerning the proposed deepening of the harbor to 48 ft, two studies were initiated to evaluate changes in the tidal marsh plant community in response to changing salinity conditions (Bossart and others, 2001; Dusek, 2003; Applied Technology and Management, 2003).

Hydrodynamic and Water-Quality Studies

There is a long history of scientific and engineering studies of the tides and currents of Savannah Harbor and their effects on navigation and channel maintenance (Barber and Gann, 1989). In 1940, a physical model was built at the U.S. Army Corps of Engineers, Waterway Experiment Station (WES) in Vicksburg, Miss., to analyze shoaling dynamics. This early model had a horizontal scale of 1:1,000 and a vertical scale of 1:150 and could simulate a complete tidal cycle every 18 minutes (Rhodes, 1949). In 1956, an improved physical model was built at the WES to study reducing shoaling or to control shoaling in areas where it was easy to remove the dredged material. The new model reduced the horizontal and vertical scales to 1:800 and 1:80, respectively, and covered an area of 25,000 square feet (ft^2) (U.S. Army Corps of Engineers, 1961a, 1961b, 1963). One of the solutions presented in the study was to construct a tide gate and sedimentation basin on the Back River to allow for the maximum possible rate of shoaling near the dredge disposal areas. The tide gate and sedimentation basin construction was authorized in 1965, and the project was completed in 1977 (Barber and Gann, 1989).

The application of digital computer models to the Savannah River and Savannah Harbor replaced the use of physical models in the 1970s. Huvel and others (1979) at WES developed a one-dimensional model to re-evaluate the results of the freshwater control plan, including the tide gate and increased salinities in Little Back River; the plan was based on results from physical models of the 1950s and 60s. The model was based on the long-wave equations and the convective-dispersion equation, and was calibrated to field data collected in July 1950 and September 1972 (Huvel and others, 1979).

To evaluate proposals to deepen the harbor from 38 to 42 ft, the WES initiated a study to apply a two-dimensional, laterally averaged model called LAEMSED to the estuary. The objectives of the study were to simulate how channel deepening and widening would effect salinity intrusion and shoaling

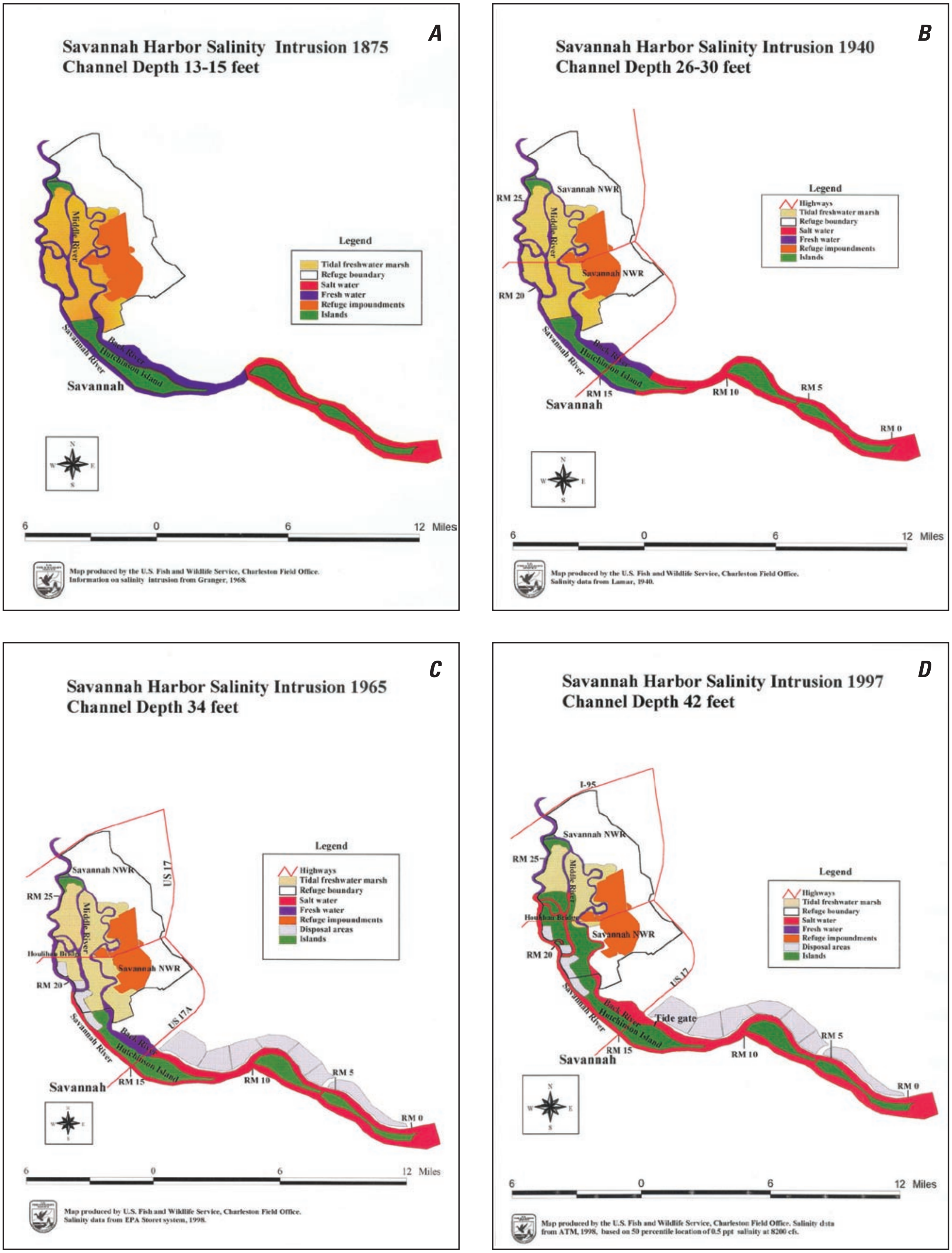


Figure 4. Location of the saltwater and freshwater interface for four channel depths: (*A*) 13–15 feet in 1875; (*B*) 26–30 feet in 1940; (*C*) 34 feet in 1965; and (*D*) 42 feet in 1997. Maps produced by the U.S. Fish and Wildlife Service, Charleston Field Office. Data references include: (*A*) Granger (1968); (*B*) Lamar (1942); (*C*) U.S. Environmental Protection Agency, STORET Database, 1998 (*http://www.epa.gov/STORET/*); and (*D*) Applied Technology and Management, 1998.

(U.S. Army Corps of Engineers, 1991). The model was verified using field data collected in 1986, 1988, and 1990. River flows ranged from 5,000 to 43,000 cubic feet per second (ft^3/s) over the sampling periods.

To evaluate a potential deepening of the harbor from 42 to 48 ft, the 3D model, Boundary Fitted Hydrodynamics (BFHYDRO) (Spaulding, 1984; Swanson, 1986; and Muin and Spaulding, 1997), was used by Applied Science Associates (ASA) and Applied Technology and Management (ATM) (Applied Science Associates and Applied Technology and Management, 1998). In addition to simulating tides, currents, and salinity, the model simulated dissolved oxygen using the Streeter-Phelps equation (Streeter and Phelps, 1925). The model was calibrated to field data collected in summer 1997 (Applied Technology and Management, 1998).

Results from the model were incorporated in the EIS regarding the potential deepening of the harbor from 42 to 48 ft (Georgia Ports Authority, 1998). After review of the EIS by State and Federal agencies, it was agreed that additional data collection was necessary to improve the water-quality model and to further refine the hydrodynamic model. To meet these goals, the 3D model, Environmental Fluid Dynamics Code (EFDC) (Hamrick, 1992) and U.S. Environmental Protection Agency (USEPA) Water Quality Assessment and Simulation Program version 7 (WASP7) (Ambrose and others, 1993; Wool and others, 2001) was applied to Savannah Harbor (Tetra Tech, 2005).

A number of mechanistic water-quality models of the river and estuary have been developed to investigate various regulatory issues of water-quality classification and assimilative capacity. A good summary of the technical history of mathematical water-quality models applied to the system from 1970 to 1988 can be found in the Georgia Environmental Protection Division (GaEPD) report, “Savannah River Classification Study” (Georgia Environmental Protection Division, 1988). Early models were either simplified steady-state calculations to estimate the assimilative capacity of the Savannah River (Olinger, 1970) or steady-state, one- and two-dimensional models to evaluate the effects of major discharges on the Savannah River (Hydroscience, Inc., 1970). The first dynamic water-quality model applied to the system was the Massachusetts Institute of Technology Transient Water Quality Network Model (Harleman, 1977). Additional field data for the model were collected in 1979 and 1980 (Pennington and Bond, 1981; Shingler, 1981). Lawler, Matusky, and Skelly Engineers (LMS) made modifications to the code and recalibrated the model in 1982 (Lawler, Matusky, and Skelly Engineers, 1983). The model was further refined by GaEPD and LMS to include more complex nutrient and algal dynamics and to validate the model with new data collected in October 1985 (Lawler, Mutusky, and Skelly Engineers, 1986; Georgia Environmental Protection Division, 1988). The USEPA has used the application of the EFDC and WASP7 codes for evaluating water-quality standards classification and Total Maximum Daily Loads for the harbor (U.S. Environmental Protection Agency, 2004).

Approach

The variability of salinity in the Savannah River is a result of many factors, including streamflow in the Savannah River and tidal conditions in the Savannah Harbor. The variability of pore-water salinity in the tidal marshes is a result of the adjacent river salinity concentration, the tidal creek connections to the river, elevation of the marsh and surrounding berms, soil type and the conditions of old abandoned rice fields and berms, and volume of water within the marsh. Although many of the plant succession models use hydrology and salinity inputs, these inputs have been derived from either field measurements or assumptions that long-term averaging from riverine-estuarine model simulations are adequate estimates of pore-water salinity in the marshes.

In order to simulate the dynamic response of the water level and salinity in the tidal marshes, empirical models were developed to simulate water levels and salinities in the river and marshes for changing hydrologic conditions (streamflow) and changing channel geometries simulated by a 3D mechanistic model (Tetra Tech, 2005). The empirical models were developed using data-mining techniques and ANN models. This is the first study in the Savannah River Estuary to integrate the dynamic water-level and salinity response of the estuary with the dynamic water-level and salinity response of the tidal marshes.

For the Savannah River and the tidal marsh, there are extensive continuous data sets of streamflow, tidal water level, and salinity in the river, harbor, and tidal marshes. Time-series data of the streamflow, salinity, and water levels in the rivers and marshes near the SNWR have been collected by various agencies during the past 20 years. The USGS has collected streamflow, water-level, and salinity data in the rivers near SNWR, and tidal conditions of the Savannah Harbor since the 1980s. The USGS Florida Cooperative Fish and Wildlife Research Unit (FCFWRU) has collected continuous water-level and pore-water salinity data in the tidal marshes since 2000. The GPA collected riverine data at more than 20 sites during summer 1997 and 1999 and marsh data for a 2-year period beginning in June 1999.

The application of data-mining techniques to simulate the water-level and pore-water response in the tidal marshes was undertaken in four phases. The first phase was to develop ANN models to simulate the riverine water-level and salinity response caused by changing streamflow condition. The second phase was to develop ANN models to simulate the marsh water-level and pore-water salinity response attributed to changing river conditions. The third phase was to incorporate the results from a 3D model of changing river conditions and a visualization module that spatially extrapolates the marsh response at selected marsh gages to the entire marsh. The final phase was the development of a Decision Support System (DSS) that integrates historical databases, model simulations, and streaming graphics with a graphical user interface (GUI) that allows a user to simulate scenarios of interest.

Acknowledgments

The complexity of this study required interagency cooperation, in addition to individual contributions. The authors thank David Schaller and Hope Moorer of the Georgia Ports Authority for their support and patience throughout the project; Larry Keegan of Lockwood Greene for his coordination of project activities with the Georgia Ports Authority; Bill Bailey, Alan Garrett, Joe Hoke, and Doug Plachy of the U.S. Army Corp of Engineers, Savannah District, for their project inputs; Ed EuDaly and John Robinette of the U.S. Fish and Wildlife Service for their support; and Steven Davie and Yuri Plis of Tetra Tech for their cooperation in integrating the 3D model output into the DSS.

Data Collection Networks

Many resource entities have been collecting data in the Savannah River Estuary, including the USGS, National Oceanic Atmospheric Administration, USEPA, GaEPD, South Carolina Department of Health and Environmental Control, the City of Savannah, the GPA, and local colleges and universities. Four existing continuous water-level and specific-conductance data sets for the harbor, river, and tidal marshes were used to build, train, and test the ANN water-level and salinity models. A description of each data set follows.

River Networks

The USGS streamflow gage near Clyo, Ga. (station 02198500; fig. 1) was established in 1929 and records streamflow on an hourly interval. The USGS has maintained a data-collection network in the Little Back River near the SNWR and in the lower Savannah River since the late 1980s. These stations collect water level and(or) specific-conductance data on a 15-minute interval (fig. 5*A*). Specific conductance is a measure of the ability of water to conduct an electrical current and is expressed in microsiemens per centimeter at 25° C. Specific conductance is related to the type and concentration of ions in solution and is a field measurement often used to compute salinity. The USGS stations are part of the USGS National Water Information System (NWIS) and are available in near real-time on the Web (*http://waterdata.usgs.gov/sc/nwis*). The USGS maintains NWIS, a distributed network of computers and fileservers for the storage and retrieval of water data collected through its activities at approximately 1.5 million sites around the country, as part of the USGS program of disseminating water data to the public. Locations of specific-conductance, water-level, and streamflow gages used in the study are listed in table 1 and shown in figures 1 and 5.

The GPA established a network of stations to support the application of the 3D hydrodynamic and water-quality model of the system (fig. 5*B*; table 1). The GPA network was maintained for the summer and fall of 1997 and 1999 by Applied Technology and Management (Applied Technology and Management, 2000). Fourteen stations were located in the vicinity of the SNWR during the two deployments. Six of the stations recorded specific-conductance values for the top and bottom of the water column.

Tidal Marsh Networks

Two continuous gaging networks were established in the tidal marshes as part of the ecological studies to evaluate potential effects to the plant communities as a result of harbor deepening (Bossart and others, 2001). The FCFWRU of the USGS has been collecting water-level and pore-water specific-conductance time-series data from a tidal-marsh gaging network since June 1999 (fig. 5*C*). The USGS network comprises four sites on the Little Back and Back Rivers, two on the Middle River, and one on the Front River. The monitoring sites consist of a pressure transducer and a specific-conductance probe just below the surface of the marsh. The locations of the USGS continuous monitors correspond to locations where the FCFWRU has been conducting plant studies since the 1980s. The GPA collected water-level and specific-conductance time-series data from June 1999 to October 2002 in tidal feeder creeks and marsh surface water, and marsh pore-water salinity at 10 locations (fig. 5*D*; table 1).

Characterization of Streamflow, Water Level, and Specific Conductance

> "The main drawback in studying estuaries is that river flow, tidal range, and sediment distribution are continually changing and this is exacerbated by the continually changing weather influences. Consequently, some estuaries may never really be steady-state systems; they may be trying to reach a balance they never achieve."
>
> *Keith Dyer*, from "Estuaries—
> A Physical Introduction" (1997)

Estuarine systems are complex systems that are constantly responding to changing hydrologic, tidal, and meteorological conditions. The Savannah River Estuary is constantly integrating the changing streamflow of the Savannah River, changing tidal condition of the Atlantic Ocean, and changing meteorological conditions including wind direction and speed, rainfall, low and high pressure systems, and hurricanes. The following sections characterize the streamflow and tidal water levels and how these affect the salinity intrusion in the rivers and the interstitial salinity concentrations in the marshes.

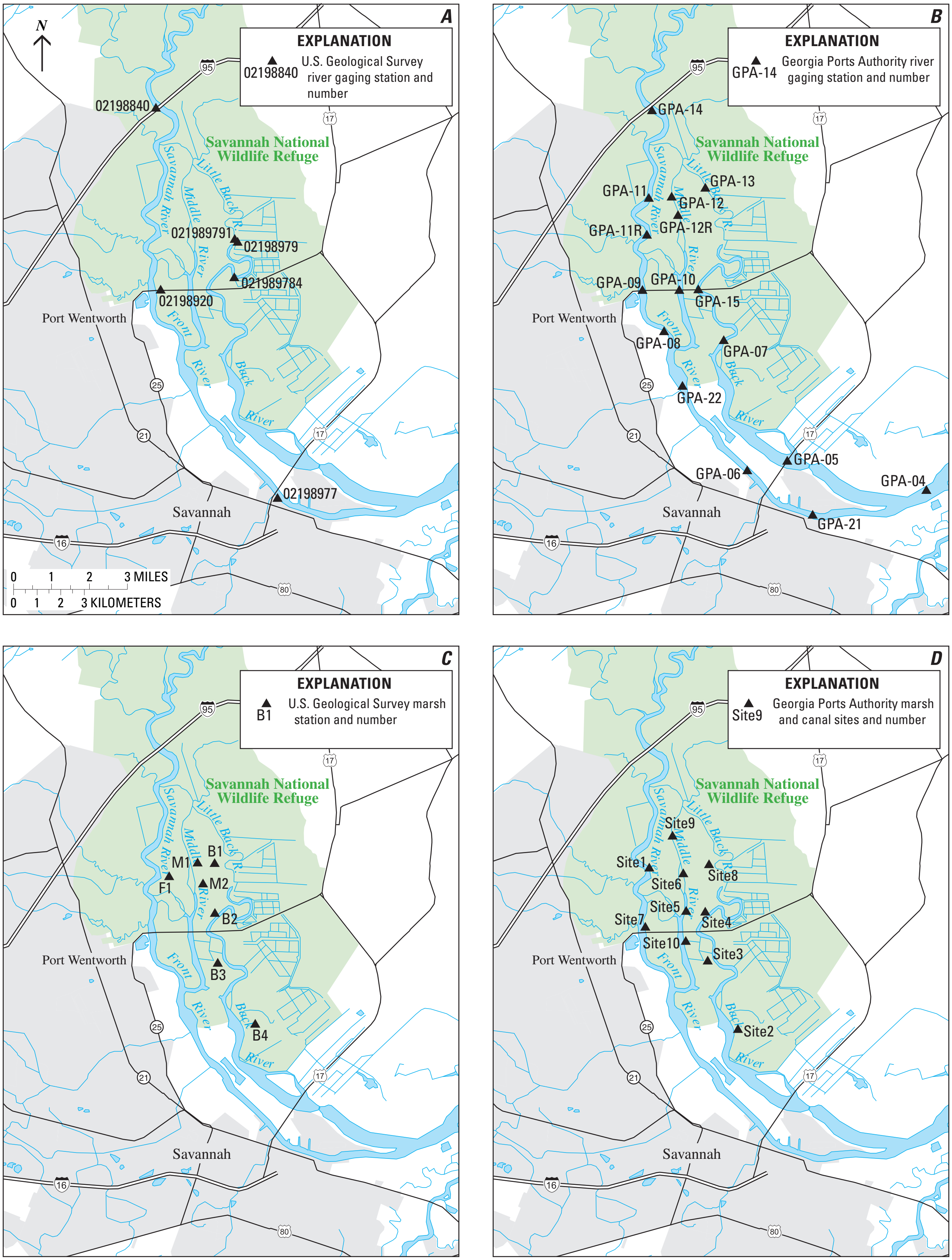


Figure 5. River and marsh continuous monitoring stations in the vicinity of the Savannah National Wildlife Refuge: (*A*) U.S. Geological Survey river stations; (*B*) Georgia Ports Authority river stations; (*C*) U.S. Geological Survey marsh stations; and (*D*) Georgia Ports Authority marsh and canal sites.

Table 1. U.S. Geological Survey and Georgia Ports Authority continuous river and marsh gaging network data used in the study.

[NAD 83, North American Datum of 1983; Q, flow; wl, water level; sc, specific conductance; scb, specific conductance-bottom probe; sbt, specific conductance-top probe]

Site identification	Station location and name used in this report	Parameters	Period of record	Longitude (decimal degrees, NAD 83)	Latitude (decimal degrees, NAD 83)
U.S. Geological Survey River Gaging Network					
02198500	Savannah River near Clyo	Q	October 1929–May 2005	81.26871649	32.52823709
02198840	Savannah River at I-95 Bridge	wl, sc	June 1987–May 2005	81.15122387	32.23575482
02198920	Front River at Houlihan Bridge	wl, sc	October 1987–May 2005	81.15122363	32.16603583
02198977	Front River at Broad Street	wl	October 1987–May 2005	81.09566748	32.18409111
021989784	Little Back River at Lucknow Canal	sc	May 1990–May 2005	81.11816773	32.17075822
02198979	Little Back River near Limehouse	wl	June 1987–May 2005	81.11705662	32.18492418
021989791	Little Back River at USFW Dock	sc	October 1989–May 2005	81.11788997	32.18575747
02198980	Savannah River at Fort Pulaski	wl	October 1987–May 2005	80.90316645	32.0341019
Georgia Ports Authority River Gaging Network					
GPA04	Savannah River near Fort Jackson	wl, scb, sct	July–September 1997 July–October 1999	81.026817	32.089001
GPA05	Back River upstream of Tide Gate	wl, scb	July–September 1997 July–October 1999	81.089816	32.100018
GPA06	Front River upstream of Broad Street	wl, scb, sct	July–September 1997 July–October 1999	81.107403	32.096371
GPA07	Back River downstream of Houlihan Bridge	wl, scb, sct	July–September 1997 July–October 1999	81.118187	32.146400
GPA08	Front River downstream of Houlihan Bridge	wl, scb, sct	July–September 1997 July–October 1999	81.144326	32.149994
GPA09	Front River at Houlihan Bridge	wl, scb, sct	July–September 1997 July–October 1999	81.155296	32.165272
GPA10	Middle River at Houlihan Bridge	wl, scb, sct	July–September 1997 July–October 1999	81.138367	32.165272
GPA11	Front River upstream of Houlihan Bridge	wl, scb	July–September 1997 July–October 1999	81.152778	32.201389
GPA11R	Front River upstream of Houlihan Bridge	wl, scb	July–September 1997 July–October 1999	81.152505	32.186568
GPA12	Middle River upstream of Houlihan Bridge	wl, sct	July–September 1997	81.141167	32.201229
GPA12R	Middle River upstream of Houlihan Bridge		July–October 1999	81.138367	32.194567
GPA13	Little Back River downstream of Union Creek	wl, scb	July–September 1997 July–October 1999	81.126183	32.204788
GPA14	Savannah River at I-95 Bridge	wl, scb	July–September 1997 July–October 1999	81.150048	32.234661
GPA15	Little Back River at Houlihan Bridge	sct	July–September 1997 July–October 1999	81.129593	32.165379
GPA21	Front River downstream of U.S. Highway 17 Bridge	wl, scb, sct	July–September 1997 July–October 1999	81.078194	32.079369
GPA22	Front River downstream of confluence with Middle River	wl, scb, sct	July–September 1997 July–October 1999	81.136643	32.128628

Table 1. U.S. Geological Survey and Georgia Ports Authority continuous river and marsh gaging network data used in the study.—Continued

[NAD 83, North American Datum of 1983; Q, flow; wl, water level; sc, specific conductance; scb, specific conductance-bottom probe; sbt, specific conductance-top probe]

Site identification	Station location and name used in this report	Parameters	Period of record	Longitude (decimal degrees, NAD 83)	Latitude (decimal degrees, NAD 83)
U.S. Geological Survey Marsh Network					
B1	Little Back River marsh	wl, sc	June 1999–May 2005	81.12750163	32.19237988
B2	Little Back River marsh	wl, sc	June 1999–May 2005	81.12707183	32.17320051
B3	Back River marsh	wl, sc	June 1999–May 2005	81.12595301	32.15408492
B4	Back River marsh	wl, sc	June 1999–May 2005	81.10885151	32.13068071
F1	Front River marsh	wl, sc	June 1999–May 2005	81.14764018	32.18721571
M1	Middle River marsh	wl, sc	June 1999–May 2005	81.13492806	32.19237218
M2	Middle River marsh	wl, sc	June 1999–May 2005	81.13266729	32.18436345
Georgia Ports Authority Marsh and Canal Network					
Site 1 marsh	Front River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.15105474	32.19017614
Site 1 canal	Front River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.15124878	32.19074944
Site 2 marsh	Back River	wl, sc	June 1999–October 2002	81.11120968	32.12842341
Site 2 canal	Back River	wl, sc	June 1999–October 2002	81.111181	32.12895093
Site 3 marsh	Back River	wl, sc	June 1999–October 2002	81.12476284	32.15492387
Site 3 canal	Back River	wl, sc	June 1999–October 2002	81.12479598	32.1545668
Site 4 marsh	Back River	wl, sc	June 1999–October 2002	81.12582291	32.1730909
Site 4 canal	Back River	wl, sc	June 1999–October 2002	81.12586215	32.17361898
Site 5 marsh	Middle River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.13409274	32.17312569
Site 5 canal	Middle River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.13404276	32.17383171
Site 6 marsh	Middle River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.13577841	32.18815865
Site 6 canal	Middle River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.13600421	32.1879131
Site 7 marsh	Front River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.15330879	32.16761313
Site 7 canal	Front River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.15307175	32.16800705
Site 8 marsh	Little Back River	wl, sc	June 1999–October 2002	81.12381219	32.19099895
Site 8 canal	Little Back River	wl, sc	June 1999–October 2002	81.12426637	32.19170637
Site 9 marsh	Middle River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.14075216	32.20263829
Site 9 canal	Middle River upstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.1408484	32.20241642
Site 10 marsh	Middle River downstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.13462583	32.16196182
Site 10 canal	Middle River downstream of Houlihan Bridge	wl, sc	June 1999–October 2002	81.13461947	32.16223939

Calculated Variables, Data Preparation, and Signal Processing

Tidal systems are highly dynamic and exhibit complex behaviors that evolve over multiple time scales. The complex behaviors of the variables in a natural system result from interactions between multiple physical forces. The semidiurnal tide is dominated by the lunar cycle, which is more influential than the 24-hour solar cycle; thus, a 24-hour average is inappropriate to use to reduce tidal data to daily values. For analysis and model development, the USGS data were digitally filtered to remove semidiurnal and diurnal variability. The filtering method of choice is frequency domain filtering, which is applied to a signal, or time series of data, after it has been converted into a frequency distribution by Fourier transform. This allows a signal component that lies within a window of frequencies (for example, the 12.4-hour tidal cycle lies between periods of 12.0 to 13.0 hours) to be excised, analyzed, and modeled independently of other components (Press and others, 1993). The filter for removing the high frequency tidal cycle often is referred to as a “low-pass” filter. Time series of the daily response of tidally affected signals were generated using a low-pass filter. The resulting time series represents the daily change in the tidal signal for a 30-minute time increment. Digital filtering also can diminish the effect of noise in a signal to improve the amount of useful information that a signal contains. Working from filtered signals makes the modeling process more efficient, precise, and accurate.

One variable was computed from the field measurements of the physical parameters—tidal range. Tidal dynamics are a dominant force for estuarine systems, and the tidal range is an important variable for determining the lunar phase of the tide. Tidal range is calculated from water level and is defined as the water level at high tide minus the water level at low tide for each semidiurnal tidal cycle.

Characterization of Streamflow

Streamflows at Savannah River near Clyo, Ga. (station 02198500) are regulated by releases from Lake Thurmond Dam near Augusta, Ga., and range from a minimum of 4,000 ft^3/s during periods of low flow to 50,000 ft^3/s or more during periods of high flows (fig. 6). Seasonally, the highest flows occur in late winter and early spring (February through March), and the lowest flows occur in late summer and early fall (August through October). Figure 6 shows daily duration hydrographs based on 75 years of data. Daily duration graphs characterize the state of a stream with respect to time. The plotted percentiles are best explained by an example. Suppose 75 years of daily value flow data exist for a station and the 10-percentile flow is 7,000 ft^3/s for a particular day of the year, say January 3. This means that 10 percent of all flows that occurred on January 3 of each of the 75 years of data were equal to or less than 7,000 ft^3/s. It is assumed that flows between the 0- and 10-percentiles occur during very dry hydrologic conditions and, likewise, it is assumed that flows between the 90- and 100-percentile occur during very wet hydrologic conditions. It is assumed that flows between the 25- and 75-percentiles occur during normal hydrologic conditions.

During the 11-year period from 1994 to 2004, inclusive, the Savannah River experienced extreme streamflow conditions. During the winter-spring of 1998, floods resulting from above-normal rainfall during El Niño conditions resulted in streamflows of greater than 50,000 ft^3/s (fig. 7) that were often between the 95th percentile and historical maximum daily streamflow for the period of record. After the El Niño of 1998, the southeastern United States experienced drought from 1998 to 2002, inclusive, with minimum flows of 4,500 ft^3/s. Streamflows during the drought generally ranged from the 5th percentile to the historical minimums for the period of record.

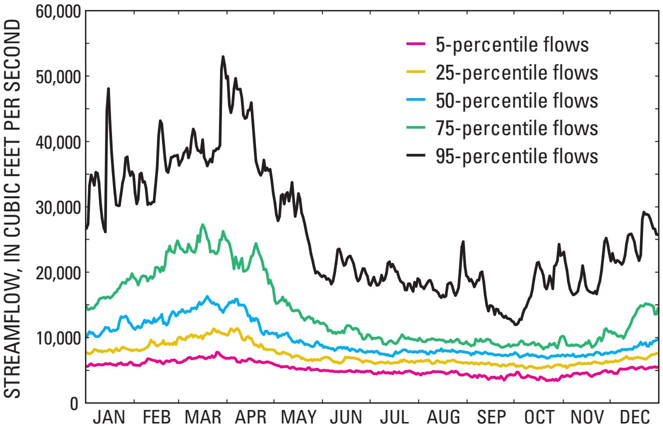


Figure 6. Duration hydrographs for Savannah River near Clyo, Ga. Percentile flows are based on streamflow data from 1929 to 2003.

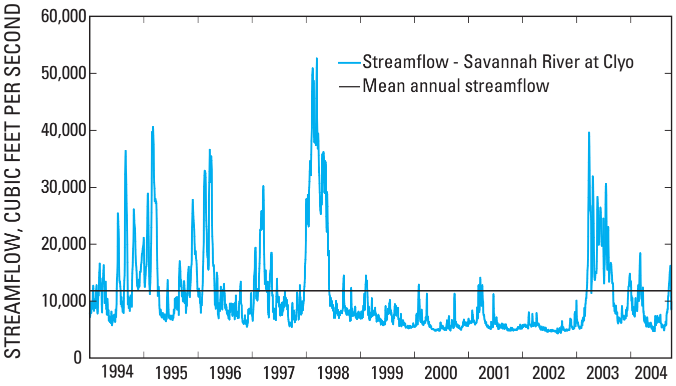


Figure 7. Daily streamflow and mean annual streamflow for Savannah River near Clyo, Ga., for the period October 1, 1994, to September 30, 2004.

Characterization of River and Marsh Water Levels

Savannah Harbor experiences semidiurnal tides of two high tides and two low tides in a 24.8-hour period. The semidiurnal tides exhibit periodic cycles of high- and low-tidal ranges (water-level difference between high and low tide) on a 14-day cycle. The mean tidal range is 6.92 ft at Fort Pulaski (*http://Co-ops.nos.noaa.gov/tides05/tab2ec3b.html#79*). As the tidal wave propagates upstream, the tidal ranges can be larger than those in the harbor. For example, the mean tidal ranges at Fort Jackson (near the confluence of the Back and Front Rivers), Port Wentworth, and the Back River U.S. Highway 17 are 8.1, 7.0, and 7.64 ft, respectively (fig. 2). Upstream from the U.S. Highway 17 Bridge, the tidal range decreases with the increased effects of the freshwater flow of the Savannah River and decrease in channel geometry. There is approximately a 1-hour lag of the tide from Fort Pulaski to the Little Back and Back Rivers at the U.S. Highway 17 Bridge.

Figure 8 shows the water levels at three USGS stations on the Savannah River for the period during October 2002. The neap tidal period, characterized by a relatively smaller amplitude in tidal range, occurred around October 14 and 28, and the spring tidal period, characterized by a larger amplitude in tidal range, occurred around October 7 and 21. During the spring tide early in the month, the highest water levels occurred at the Broad Street water-level gage (station 02198920, fig. 5)—greater than the downstream water-level gage at Fort Pulaski (station 02198980, fig. 1). As the tidal range diminished during October, the highest water levels were experienced at the most upstream gaging station at I-95 where the high water is often affected by the streamflow of the Savannah River.

A plot of the daily tidal range clearly shows the 14-day spring-neap tidal cycles along with seasonal and semiannual cycles. The tidal range for the Fort Pulaski water-level gage (station 02198980) is shown in figure 9 for the 2002 calendar year. The 14-day spring-neap cycles are clearly shown. For example, a high spring tide (tidal range greater than 8 ft) is followed by a low spring tide (tidal range less than 8 ft). A similar pattern is apparent in the neap tides where a low neap tide (tidal range less than 5.5 ft) is followed by a high neap tide (tidal range greater than 5.5 ft).

Seasonal and semiannual cycles of minimum and maximum tidal ranges can also be seen in figure 9. The highest difference in spring and neap tides occur in the spring (March and April) and the fall (October and November) of the year. Minimum differences between the spring and neap tides occur in the summer (June and July) and in the winter (December and January) of the year.

Water-level dynamics in the tidal marshes are dependent on the height of the water levels, the surface elevation of the tidal marsh, and inertial affects. Tidal fluctuations in marsh water levels are greatest during the high spring tides and are minimal during neap tides. Marsh water-level time series for USGS gaging stations on the Back, Middle, and Front River marshes are shown in figures 10 and 11. In figure 10, hourly water levels in the Little Back River near Limehouse

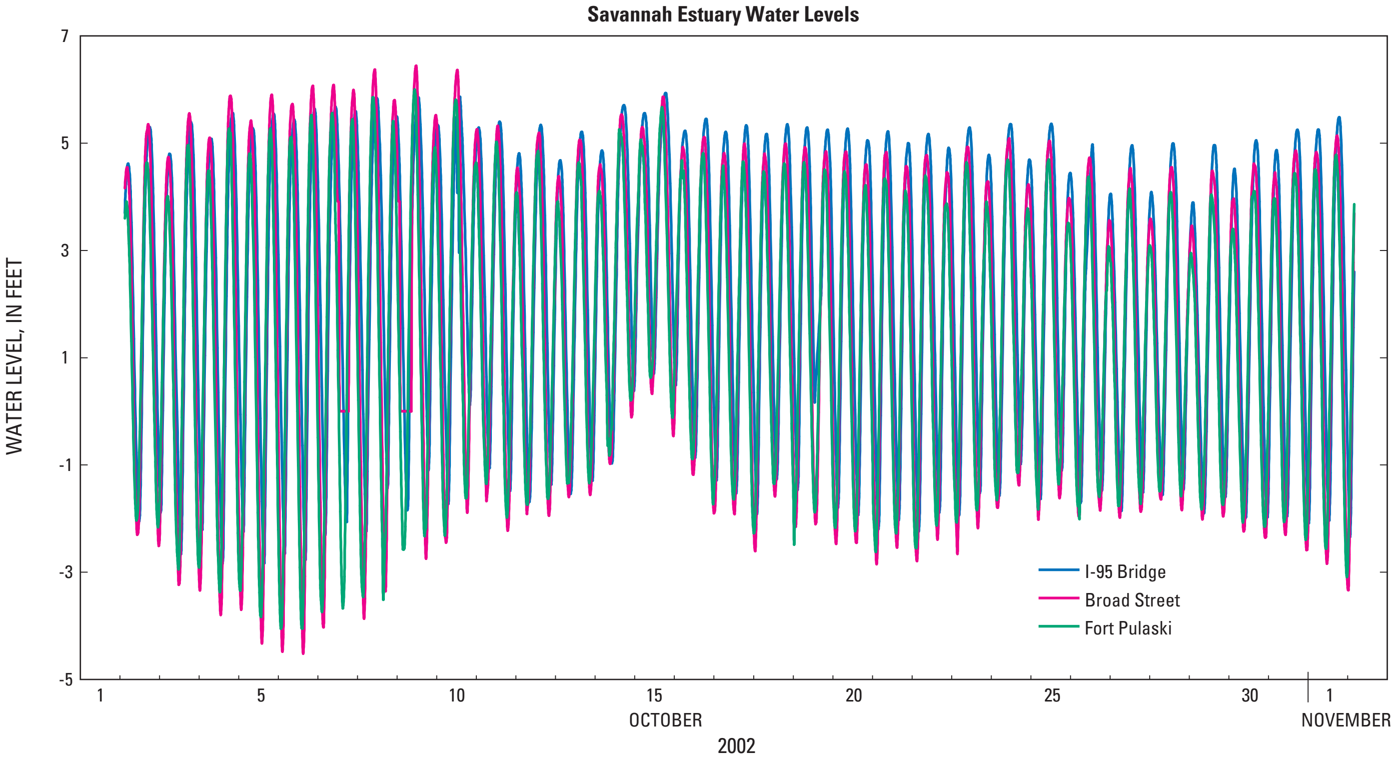


Figure 8. Hourly water levels at three gaging stations on the Savannah River for the period October 1 to October 31, 2002.

(station 02188979, left y-axis) are shown with marsh water levels (right y-axis). The Little Back River water-level time series show the periods of spring tides. Multiday periods of substantial tidal fluctuations for the four marsh sites along the Little Back and Back Rivers occur during spring tides beginning around December 15 and 29, and January 28, 2002. In figure 11, similar water-level responses are seen for the two marsh sites along the Middle River and the marsh site along the Front River. Multiday periods of substantial tidal fluctuations for the three marsh sites occur on spring tides beginning around November 10, November 29, December 10, and December 29, 2001.

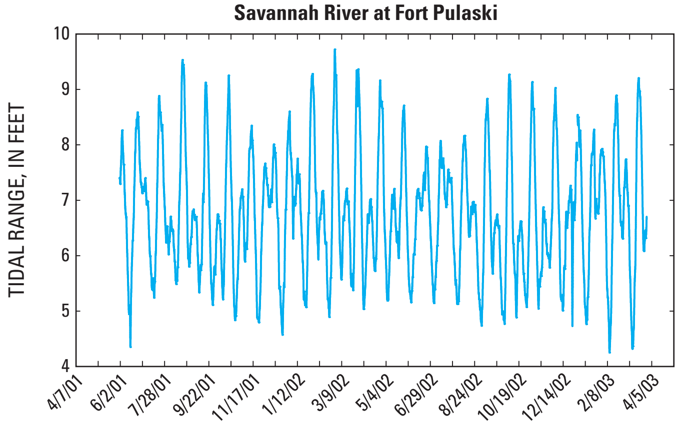


Figure 9. Daily tidal range at Savannah River at Fort Pulaski for the period June 2001 to May 2003.

Characterization of River and Marsh Specific Conductance

The location of the saltwater-freshwater interface is a balance between upstream river flows and downstream tidal forcing. During periods of high streamflow, it is difficult for salinity to intrude upstream, and thus, the saltwater-freshwater interface is moved downstream towards the ocean. During periods of low streamflow, salinity is able to intrude upstream; subsequently, the saltwater-freshwater interface is moved upstream. Historically, streamflows on the Savannah River range from 5,000 to 50,000 ft^3/s. Salinity in the Savannah River Estuary constantly responds to changing streamflow and tidal conditions. The daily mean specific conductance for the Little Back River near Limehouse (station 02198979) and daily mean streamflow for Savannah River near Clyo (station 02198500) for the 1994 to 2004 period are shown in figure 12. The period includes the full range of flows for the system from the high flows of the El Niño in 1998 to the low flows of the extended drought in the southeast from

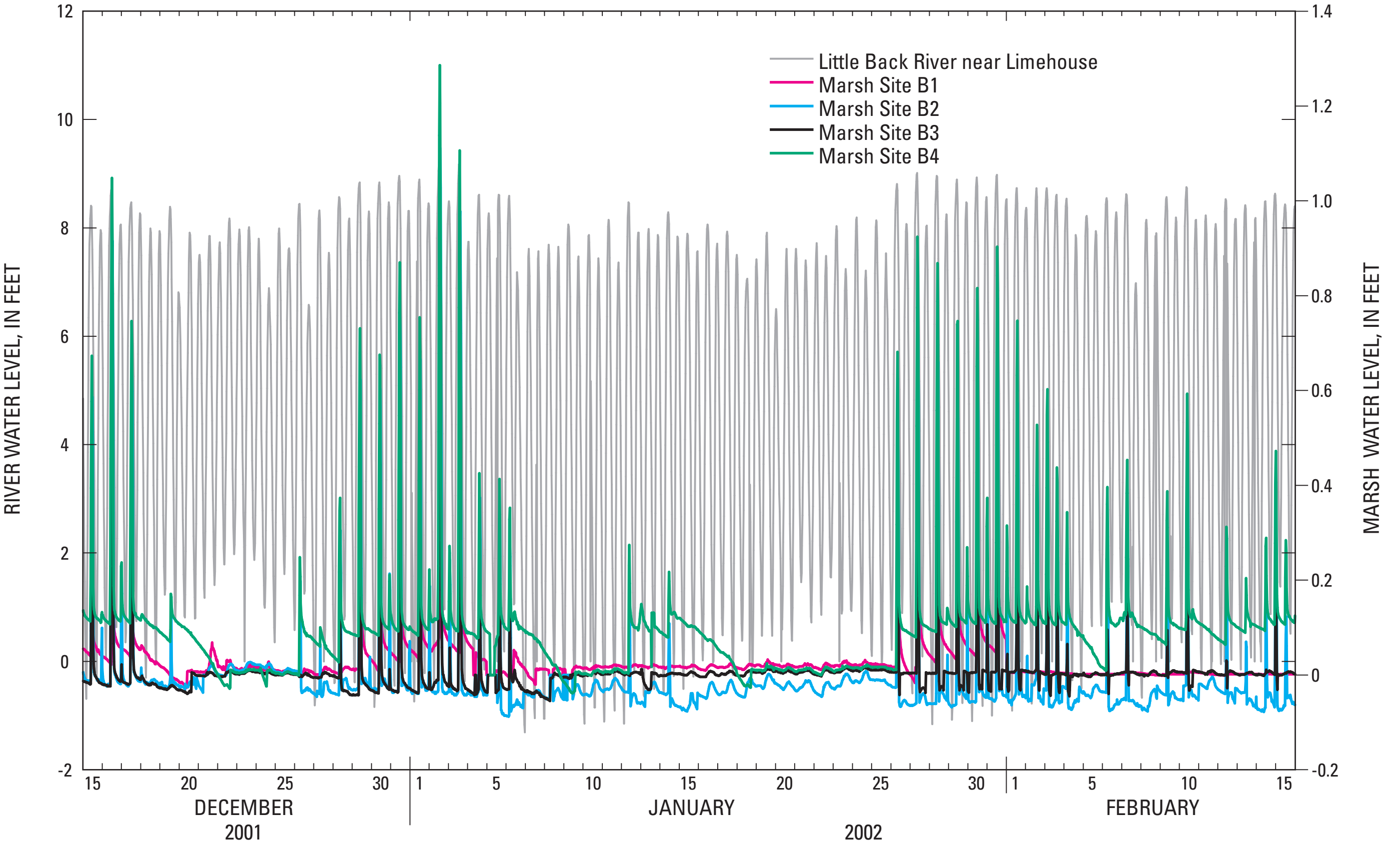


Figure 10. Hourly water-level data for the four Back River marsh gaging stations and Little Back River gaging stations for the period December 15, 2001, to February 15, 2002.

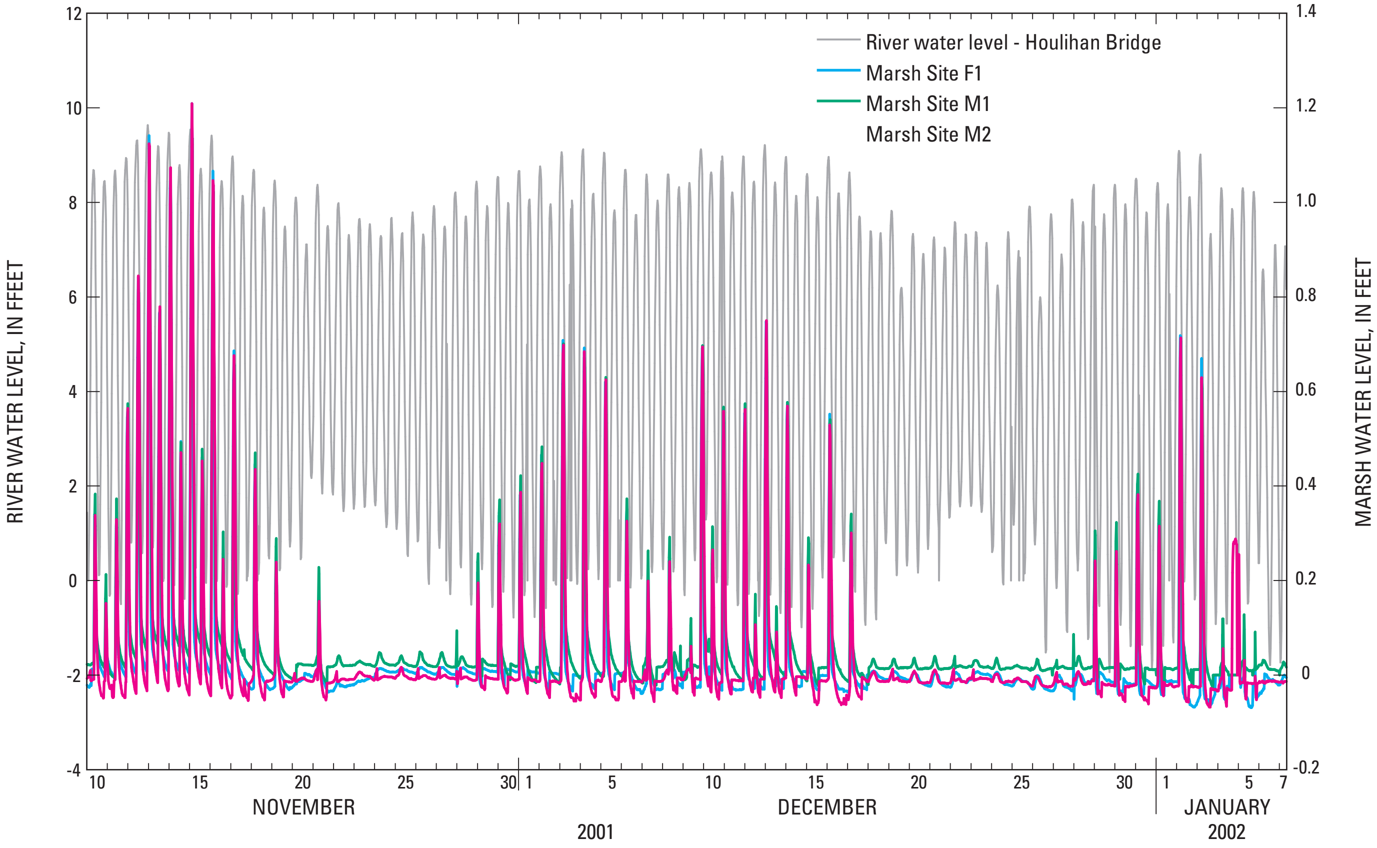


Figure 11. Hourly water-level data for three marsh gaging stations along the Middle and Front Rivers and Savannah River water level at Houlihan Bridge for the period November 10, 2001, to January 7, 2002.

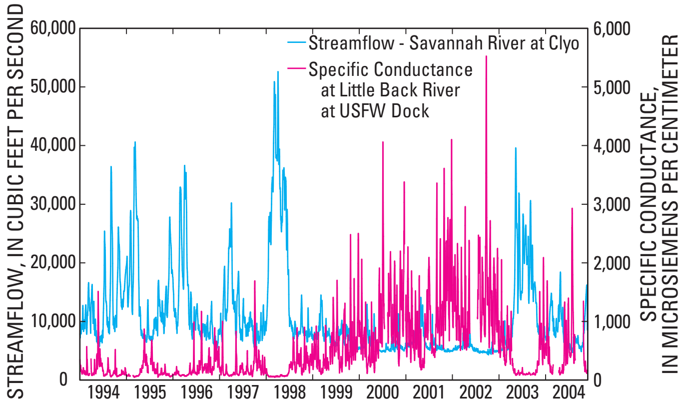


Figure 12. Daily specific conductance at Little Back River at U.S. Fish and Wildlife Service Dock gaging station and streamflow at Savannah River near Clyo, Ga., gaging station for the period January 1, 1994, to September 30, 2004.

1998 to 2002. During periods of medium streamflow and greater (streamflow greater than 10,000 ft^3/s), the specific-conductance values are low. During periods of low flow (streamflow less than 10,000 ft^3/s), specific-conductance values increase during periods of salinity intrusion. During the period prior to the high flows of El Niño in 1998, salinity intrusion with specific-conductance values of 500 to 1,000 microsiemens per centimeter (µS/cm) were not uncommon during low-flow periods. After the high flow of 1998 and the extended drought, flows were even lower and remained lower for extended periods. This resulted in greater salinity intrusions in the Little Back River with daily mean specific-conductance values as high as 4,000 µS/cm.

The Savannah River Estuary is considered a partially stratified system with large differences in surface and bottom salinities occurring during neap and spring tides over the 14- and 28-day cycles. A schematic of the largest factors that affect salinity transport along the Savannah River is shown in figure 13. During spring tides (tides with the largest tidal range), there is increased energy in the system and mixing of less dense freshwater of the river and denser saltwater of the harbor. The mixing results in smaller variation in vertical salinity concentrations. During neap tides (tides with the smallest tidal range), there is decreased energy in the system and less mixing between the freshwater and saltwater. The decreased mixing allows the freshwater to flow downstream over the saltwater intruding upstream. The decrease in mixing results in an increased salinity gradient from the surface to the bottom of the water column and increased salinity

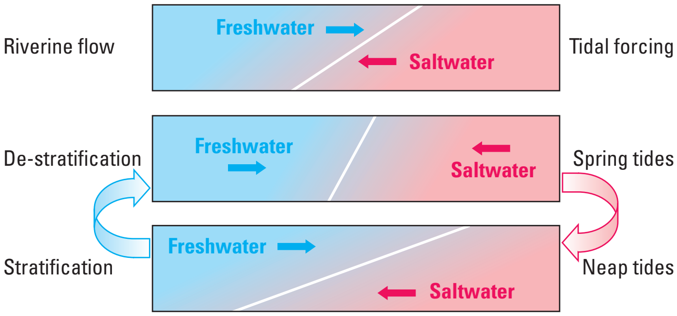


Figure 13. Conceptual model of the location of the freshwater-saltwater interface and salinity stratification-destratification cycle in estuarine rivers.

intrusion upstream. The stratification and de-stratification of salinity at station GPA04 for 2 months during summer 1997 is shown in figure 14. During the neap tides around Julian day 225, there is an approximate 15-psu difference between the bottom and surface salinities. During the spring tides around Julian day 205 and 235, the system de-stratifies and the differences between the bottom and surface salinities are only 3 to 5 psu.

The marsh salinities do not exhibit the semidiurnal salinity variability like the river and are dependent on the frequency and magnitude of the flooding of river water on the marsh. Tidal marshes are constantly integrating the changing river conditions in their water levels (frequency and duration of inundations) and the salinity concentration in the interstitial pore-water of the root zone. Plant distributions in the marshes are the result of the interstitial salinities. The interstitial salinities of the marshes with the surface salinities of the river, and the four marsh types and their corresponding estuarine salinity concentrations, are shown in figure 15.

Because the marshes do not flood every tide, the interstitial salinities are not the same as the river salinity. During low-flow periods and high tides, salinity intrudes farther upstream, and the surface salinities inundate the marshes. The highest salinity intrusions into the marshes occur when riverine salinity intrusions are concurrent with the spring-tide water levels. The specific-conductance time series of the four marsh gaging stations along the Little Back and Back Rivers with the specific conductance for the Front River at Houlihan Bridge (station 02198920) is shown in figure 16. The four marsh sites show a distinct gradient of increased specific-conductance values from upstream (Site B1) to downstream (Site B4). Increased specific conductance in the marsh generally occurs after increased specific conductance in the river. The specific-conductance time series of three marsh gaging stations along the Middle and Front Rivers and specific conductance for the Front River at the Houlihan Bridge water-level gage (station 02198920) are shown in figure 17.

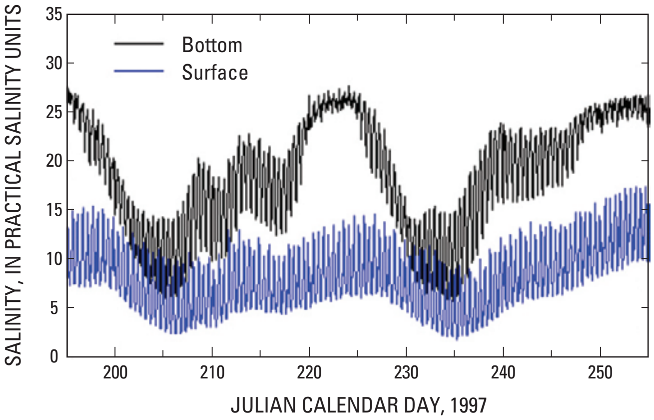


Figure 14. Surface and bottom salinities for station GPA04 for the period July 15 to September 13, 1997 (Tetra Tech, 2005). The plot shows the de-stratification of the Savannah River on about Julian days 205 and 235 and the stratification on about Julian day 225.

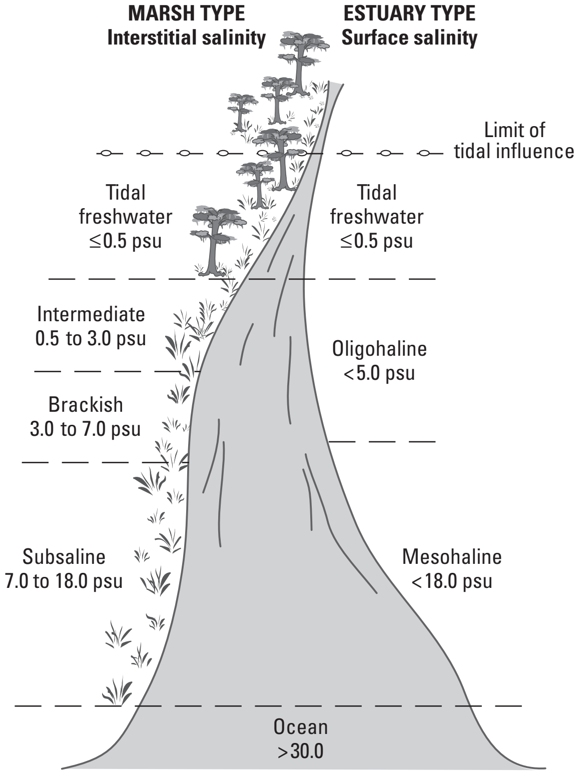


Figure 15. Tidal marsh types classified by interstitial salinity (Pearlstine and others, 1990) and average surface salinities (Cowardin and others, 1979) (modified from Odum and others, 1984).

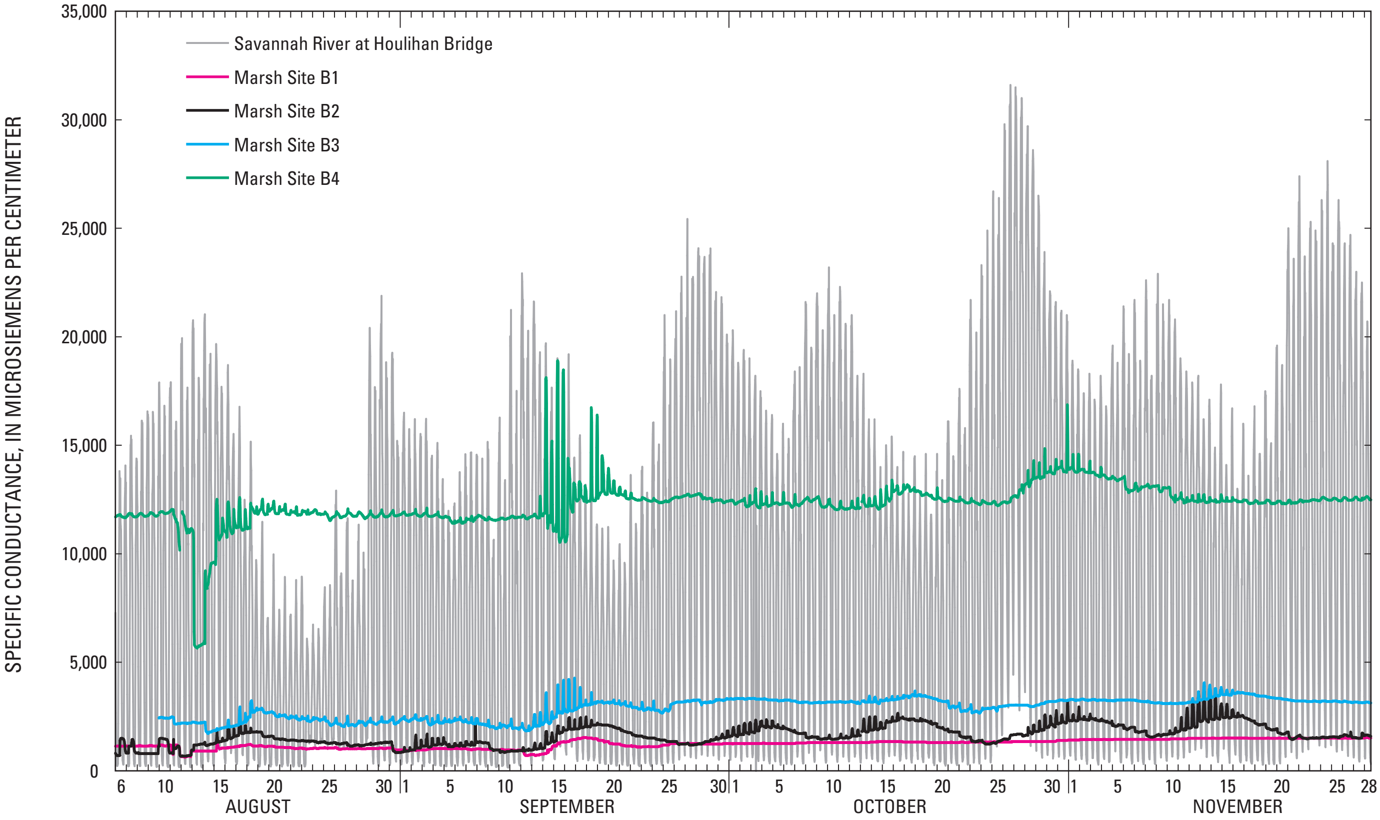


Figure 16. Hourly specific conductance at four marsh gaging stations along the Little Back and Back Rivers and specific-conductance values at the Houlihan Bridge on the Savannah River for the period August 6 to November 30, 2001.

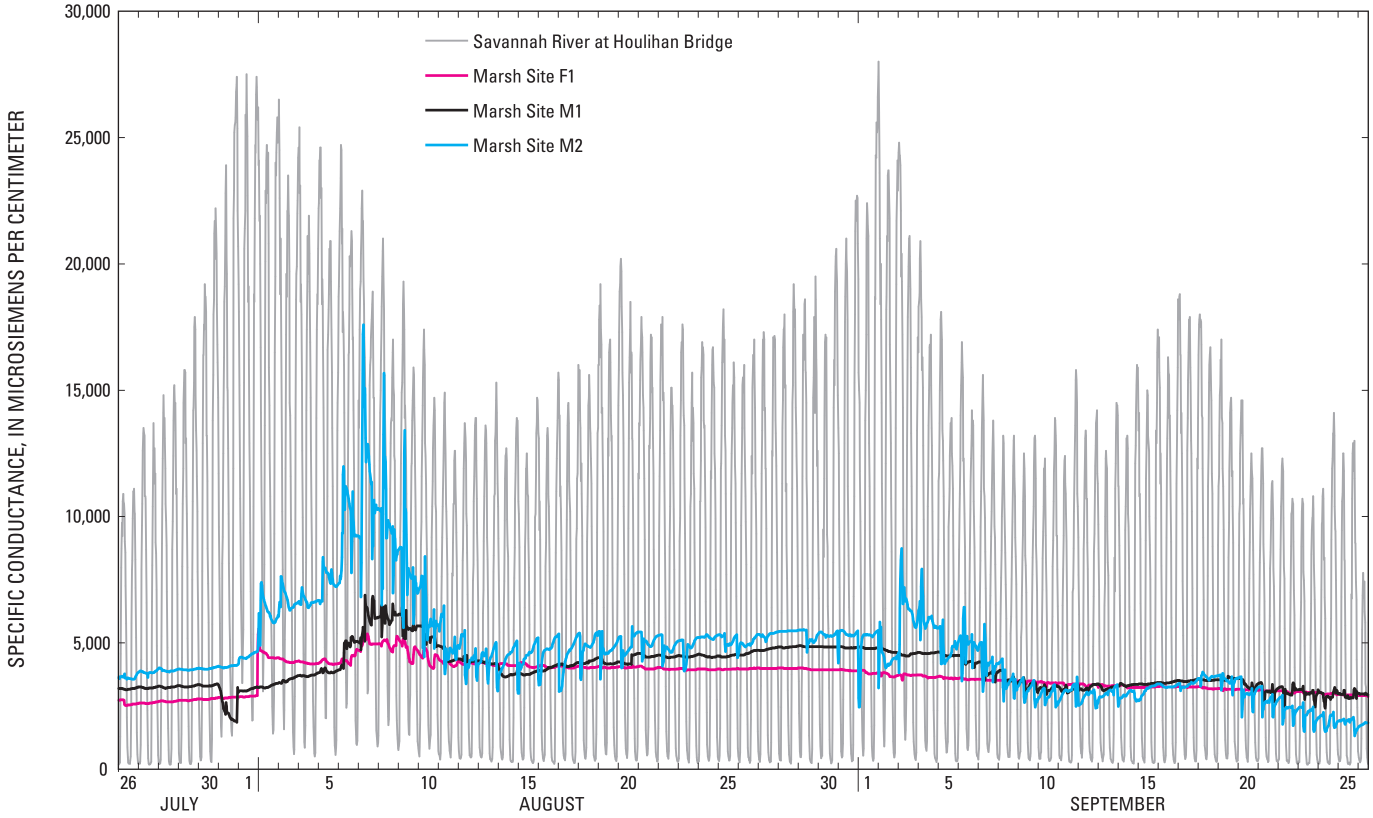


Figure 17. Hourly specific conductance for two marsh gaging stations on the Middle River, one marsh gaging station on the Front River, and at Houlihan Bridge on the Savannah River for the period July 26 to September 27, 2002.