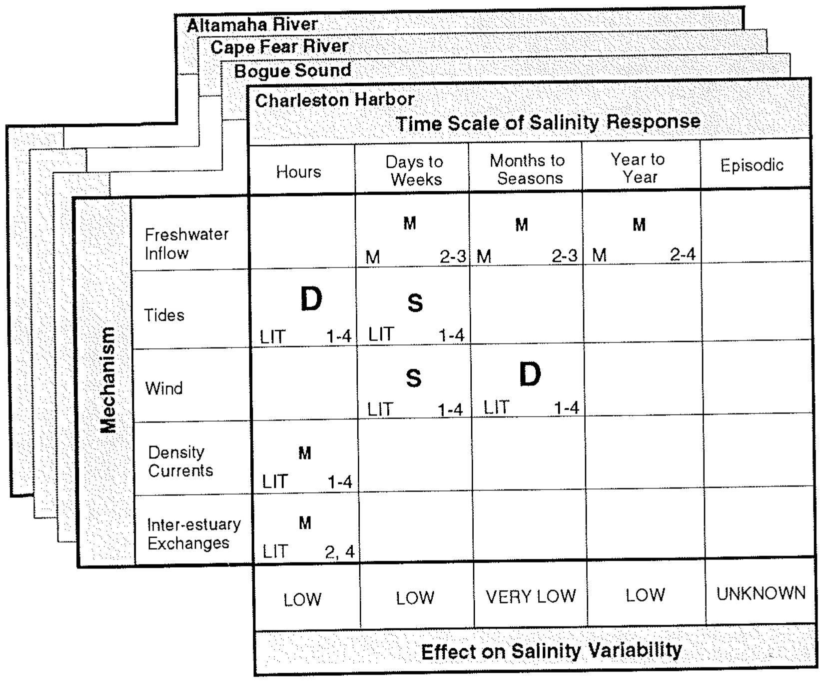
Salinity Characteristics of South Atlantic Estuaries

NOAA's National Estuarine Inventory Series



Matrix showing time scales and forcing mechanisms important to the salinity structure and variability for Charleston Harbor. A similar matrix has been developed for fourteen other South Atlantic estuaries.

U.S. Department of Commerce
National Oceanic and Atmospheric Administration

NOAA's National Estuarine Inventory

The National Estuarine Inventory (NEI) is a series of activities, within the Office of Ocean Resources Conservation and Assessment (ORCA) of the National Oceanic and Atmospheric Administration (NOAA), that defines and characterizes the Nation's estuarine resource base and develops a national estuarine assessment capability. NOAA began the NEI in 1983 because no comprehensive inventory of the Nation's estuaries or their resources existed, despite increased conflicting demands for the goods and services they provide: habitat for fish and wildlife; food; areas for recreation; water disposal; energy; and transportation. Four major NEI atlases, six national data bases, and numerous technical reports (including a Supplement Series) containing thematic information about the Nation's estuaries have been produced.

The first volume of the National Estuarine Inventory data atlas series was completed in November 1985. This atlas identified 92 of the most important estuaries of the contiguous U.S., specified their fundamental physical and hydrologic characteristics, and defined consistently derived spatial boundaries for each estuary. It also established the NOAA framework for data collection and analysis of the Nation's resource base. Other volumes in the atlas series have since been produced on land use, population, wetlands, and outdoor public recreation facilities. Other strategic assessment projects have been adapted to the NEI framework to characterize important resource themes and are published as supplements to the NEI or NOAA's *Coastal Trends series.* Projects on classified shellfishing waters, distribution of fish and invertebrates, and pollutant susceptibility are a few examples.

Development of the NEI data bases and assessment capabilities is a dynamic and evolving process. NOAA continues to evaluate the scale and scope of information in the NEI and make the necessary additions and refinements to improve its capability to assess the Nation's estuaries. The information now assembled in the NEI can be used for comparisons, rankings, and other analyses related to the resources, environmental quality, and economic values among the Nation's estuaries.

Additional information on these or other projects can be obtained from:

Physical Environments Characterization Branch (N/ORCA13)
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Salinity Characteristics of South Atlantic Estuaries

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Office of Ocean Resources Conservation and Assessment
National Ocean Service
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Executive Summary

The dynamics of the physical environment have important consequences for estuarine resources and water-quality management. The variability of estuarine salinity inherently integrates the relative influence of system morphology, freshwater inflow, and ocean exchange and, therefore, is an indicator of the important temporal and spatial dynamics of the estuary's physical environment. Thus, it can be used to distinguish functional differences between estuaries and, ultimately, to develop a framework for evaluating the probable response of management alternatives in similar estuaries. This report provides a comprehensive synthesis of salinity information for 15 principal South Atlantic estuaries. This study is an important component of NOAA's Strategic Assessment Program which provides scientific information needed to evaluate national or regional policies that balance development in coastal and ocean areas with conservation of their resources.

Area

Fifteen major estuaries in North Carolina, South Carolina, and Georgia were studied in this report. Three major estuaries located along Florida's Atlantic coast (i.e., St. John's River, Indian River, and Biscayne Bay) are being addressed in a separate study, as freshwater delivery in these systems is associated with the complex hydrology of Lake Okeechobee and the South Florida peninsula.

Objectives

The principal objectives were: 1) to characterize both the structure and variability of salinity; and 2) to identify the dominant physical processes affecting salinity behavior at time scales ranging from hours to years. Consequently, this report provides additional information on both the spatial and temporal aspects of salinity for which anthropogenic influences (e.g., freshwater diversions, dredged navigation channels, and inlet modifications) may be assessed. This is particularly important in the South Atlantic region where the coastal population is projected to increase by 15 percent to approximately 2.26 million people by 2010 (Culliton et al., 1990).

Approach

Time series records of freshwater inflow and salinity, in conjunction with available background information on tides, wind, and other factors, were used to define the seasonal salinity structure and quantify salinity variability at other time scales. For most U.S. estuaries, including those in the South Atlantic region, seasonal variation in freshwater inflow produces important changes in baywide salinity patterns. Representative three-month averaging periods depicted in this report reflect the normal range of high- and low-salinity regimes under typical and present-day hydrologic conditions. For both periods, the salinity structure was defined by isohalines at 5 parts-per-thousand (ppt) intervals from the head of tide to the ocean boundary for both the surface and bottom layers of the water column. To quantify estuary salinity response and relate it to various forcing mechanisms, an analysis of temporal variability ranging from hours to years was also provided. In addition, the dominant, secondary, and modifying influences of the physical processes affecting salinity variability were also identified.

Participants

This study required direct involvement of experts throughout the South Atlantic region. In particular, experts from the South Carolina Department of Natural Resources worked with NOAA's Strategic Environmental Assessments Division, the National Marine Fisheries Service (Galveston, TX), and the University of Texas at Austin to assimilate and interpret existing data and information in a manner consistent with a similar study prepared for 26 Gulf of Mexico estuaries (Orlando et al., 1993). Scientists and resource managers from Federal and state government agencies, academic institutions, and private organizations contributed data and information to this report. Technical review was provided by Georgia Department of Natural Resources; the Skidaway Institute of Oceanography; the North Carolina Department of Health, Environment, and Natural Resources; and Carolina Power and Light Company. The time and effort dedicated by all participants are acknowledged and greatly appreciated.

Summary of Results

Salinity Variability. To the extent that data allowed, salinity structure and variability was defined for normal and present-day hydrologic conditions. Nearly all South Atlantic estuaries experience significant salinity variability at many temporal scales. Data suggest that salinity in the

Altamaha River, St. Andrew/St Simons Sounds, and Ossabaw Sound is among the most variable. In contrast, Albemarle Sound, Charleston Harbor, and Broad River are among the most stable systems. This variability reflects the relative influence of the principal forcing mechanisms which differs both between estuaries and within any given estuary. Ultimately, temporal variability will be used to differentiate functional differences between estuary types that have direct influence on both resource distribution and water quality (Orlando et al., 1993). This approach suggests that management, monitoring, and research strategies for salinity-dependent estuarine attributes may be different in some estuary types than in others.

Limited Salinity Data. An important conclusion of this study contradicts a common belief that an abundance of salinity data is available for the South Atlantic estuaries. Data availability varies widely from estuary-to-estuary; large data sets exist for only a few estuaries, while others go nearly unsampled for extended periods. Available data sets are often spatially restricted to either (or both) a specific area of the estuary or depth within its water column. Similarly, sampling frequency is commonly limited to monthly or quarterly surveys. Therefore, characterization of salinity variability at some time scales is limited or impossible.

Salinity data is particularly sparse for most Georgia estuaries. For these systems, much of the information depicted in this report was manually keyboarded from a synthesis report entitled, *Georgia Estuarine Data, 1961-1977* (Winker et al., 1985).

With few exceptions (i.e., Santee River and Charleston Harbor), information describing salinity variability due to astronomical tides is extremely limited. Because of the potential for significant salinity variability at this time scale especially in South Carolina and Georgia, it is important to assess these changes. This is not, however, a trivial task. The effects of astronomical tides on salinity may differ by areas within an estuary and under varying freshwater inflow and wind conditions.

Considering the range of variability in these estuaries, this inadequate data resource fundamentally circumscribes the ability of scientists to quantitatively analyze these systems and limits the possibility of definitive environmental assessment. In view of the importance of these estuaries, the limited data resource is a disturbing and potentially dangerous problem.

What Remains?

The time-space relationship of salinity among the South Atlantic estuaries is delineated in this report through the characterization of salinity structure and variability. Orlando et al. (1993) used salinity variability in 26 Gulf of Mexico estuaries to distinguish functional differences among five estuary types and suggested that estuaries within each type may exhibit a similar response to resource management alternatives. A similar effort is currently underway for the 15 South Atlantic estuaries, but cannot be included in this report until additional information (particularly as it relates to salinity variability forced by astronomical tides) is available to further differentiate estuarine types. In addition, information is required to assess the effects of typical or episodic events associated with extremes in freshwater inflow that may be a dominant factor controlling salinity.

Introduction

This report presents information on the spatial and temporal characteristics of salinity for 15 of the Nation's estuarine systems. It is one component of NOAA's National Estuarine Inventory (NEI), a series of activities that defines and characterizes the Nation's estuarine resource base and develops a national estuarine assessment capability. The NEI is being conducted in cooperation with numerous government agencies, academic institutions, and nonprofit organizations. This report will provide managers and analysts with a synthesis and interpretation of existing information, thereby enabling them to make informed decisions about resources affected by the behavior of salinity in our Nation's estuaries.

This report emphasizes two aspects of salinity: its spatial structure and variability. Structure refers to the spatial distribution of salinity (i.e., the horizontal and vertical gradients) within the estuary at a defined point in time. Variability refers to the spatial and temporal changes in the salinity structure dictated by the principal forcing mechanisms (i.e., freshwater inflow, tides, wind, etc.). While the approach is descriptive, the philosophy is process-based (i.e., the basic physical controls affecting salinity are given explicit study). The basic postulate of the analytical methodology is that estuarine hydrology primarily controls salinity; therefore, salinity regimes can be defined by examining the temporal and spatial variation of hydrology. Additional salinity characteristics may be governed by other physical processes quantified on an estuary-specific basis. Even in systems where the postulate proves to be false (e.g., south Texas) (Orlando et al., 1993), it provides the motivation for an objective and consistent procedural framework.

Background

In 1985, NOAA published the *National Estuarine Inventory Data Atlas, Volume 1: Physical and Hydrologic Characteristics* (NOAA, 1985). This atlas identifies 92 of the Nation's estuaries and provides base-line estimates of certain physical and hydrologic data, including salinity. In addition, it identifies the spatial framework for the consistent synthesis and depiction of physical, chemical, and biological attributes defining these estuaries. The framework contains both a land- and water-based component, with the latter based on salinity. The NEI and its related data bases have been the foundation for *strategic* regional- and national-level assessments of the use and health of the Nation's estuarine resource base (NOAA, 1985).

Why Study Salinity?

Salinity has traditionally been a central parameter for estuarine analysis, particularly as an indicator of estuarine hydrography and habitat potential. The reasons to study salinity include:

1) Salinity is a direct measure of the relative influence of the sea and freshwater sources in an estuary;

2) Salinity is an excellent hydrographic tracer. It is virtually conservative and indicates the movement and exchange of water masses;

3) Salinity, as a hydrodynamic variable, dominates the density structure of an estuary and therefore exerts important controls on currents and turbulence;

4) Salinity is an essential element in determining estuarine habitat. It directly affects the distribution, abundance, and composition of biological resources; and

5) Salinity is easily measured using various techniques, and historical information is generally available.

Need for Improved Salinity Data. The revision of the original salinity framework was initiated in 1989 to improve the spatial and temporal resolutions necessary for more rigorous analysis of estuarine resources, pollutant transport behavior, and modeling activities. At its completion, this project will define the spatial structure of salinity and characterize its variability in both time and space for more than 120 estuaries in our Nation. The scale of these refinements is generally at the subsystem level. The intent is to incorporate a *dynamic* dimension to the previously *static* portrayal of salinity.

NEI Salinity Characterization. Salinity was included in the NEI because of its recognized value as an indicator of estuarine circulation and pollutant transport (Officer, 1983) and its significance in determining the distribution of biological resources (Smayda, 1983). The salinity structure consisted of three generic zones, represented by a tidal fresh zone (0-0.5 ppt), mixing zone (>0.5-25 ppt), and seawater zone (>25 ppt). Although a relatively simple depiction of salinity, this zonation was sufficient for the development and analysis of other important salinity-dependent data bases. For example, NOAA's *Distribution and Abundance of Fishes and Invertebrates in Texas Estuaries* characterized the distribution and relative abundance of estuarine-dependent living marine resources and keyed these profiles to the original salinity zones (Monaco et al., 1989). Additionally, an estuary's flushing/retention characteristics were determined as an indicator of pollution susceptibility based on salinity and freshwater statistics from Volume 1 (Klein and Orlando, 1989).

Salinity Structure. This study improves the original framework by depicting 5-ppt increments for both surface and bottom salinities (Figure 1). This structure is defined for two 3-month periods that reflect *typical* high- and low-salinity periods (see *Representative Salinity Averaging Periods*, page 6). These refined distributions significantly upgrade the ability to understand the system. The profiles: 1) provide further characterization of the horizontal and vertical gradients previously defined by extensive mixing zones (>0.5-25 ppt); and 2) suggest the relative influence of freshwater and seawater sources on salinity.

Salinity Variability. Variability refers to the spatial and temporal changes associated with the defined salinity structure. Restated, the structure represents a static *average* about which the variability is occurring. The frequency and magnitude of salinity variability differ within any given estuary, depending on the relative influence of the operable forcing mechanisms. For most estuaries, the primary forcing mechanisms include, but are not limited to, freshwater inflow; astronomical tides; wind; and coastal shelf processes. In some estuaries, salinity variability may also depend on other mechanisms such as evaporation, density currents, or inter-estuary exchanges.

Figure 2 identifies the principal forcing mechanisms affecting estuarine salinity and the dominant time scales of salinity variability. Time scales spanning from *hours* to *year-to-year* represent variability that is somewhat predictable under a *normal* range of conditions. In contrast, *episodic* forcing includes events having a statistically low probability of occurrence. For many estuaries under *normal* conditions, the dominant time scale of variability (i.e., the time scale at which the magnitude of salinity variability is greatest) is months-to-seasons and is attributable to freshwater-inflow patterns. However, this seasonal dominance does not necessarily preclude important changes to the salinity structure at other time scales. This report uses a summary matrix (Figure 3) to consistently characterize salinity variability at each time scale, identifies the dominant forcing mechanism(s) responsible for the variability at each time scale, and indicates the subsystems within each estuary most likely to experience variability at each time scale.

Although the magnitude of salinity variability experienced under normal conditions is often exceeded by low-frequency episodic events (e.g., a 100-year flood or 20-year drought), a characterization of variability at the episodic time scale is beyond the scope of this report. First, information for these events is generally not available. In addition, management strategies designed to regulate resources that are salinity-dependent can not reasonably accommodate this extreme and unpredictable variation range.

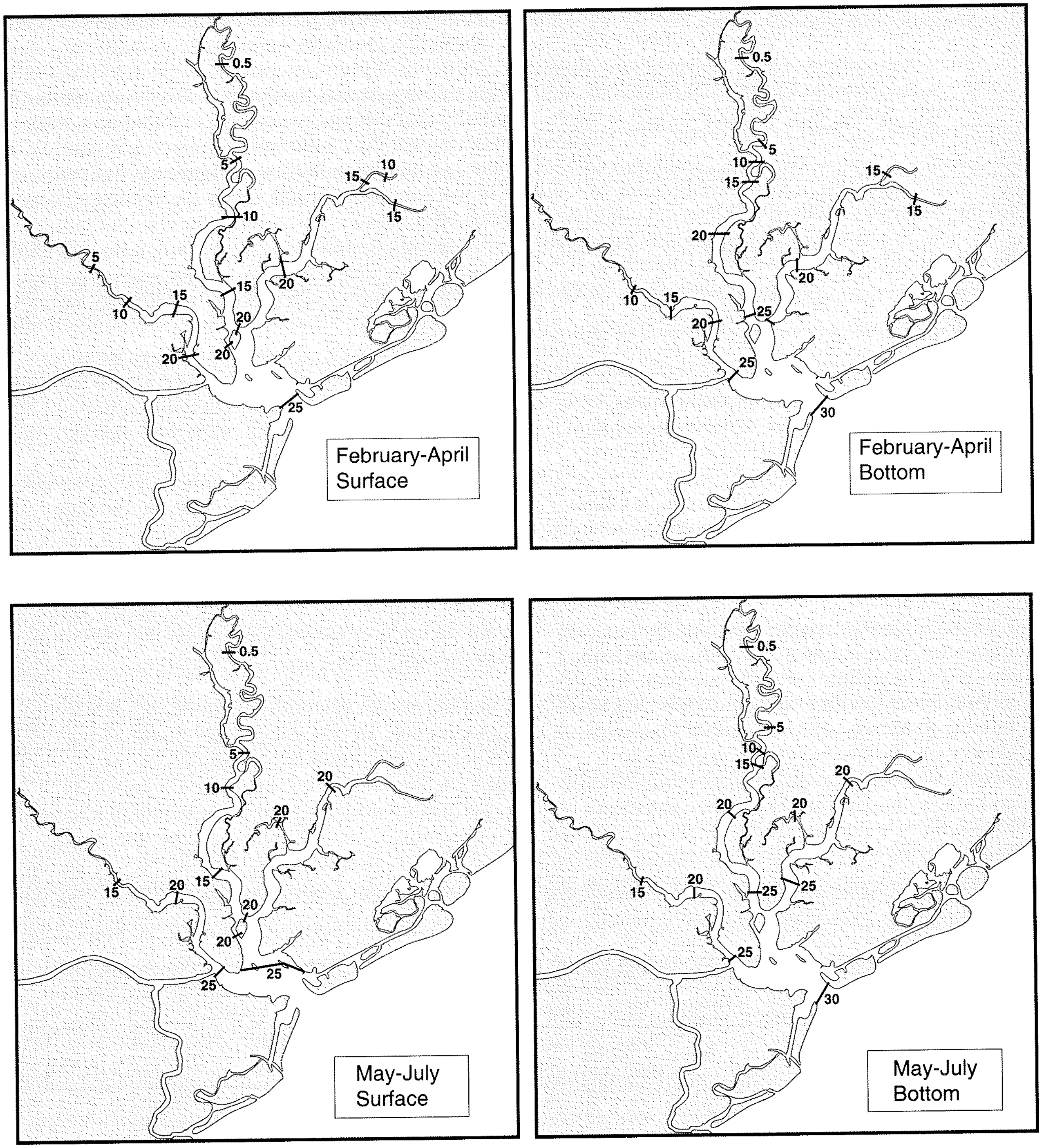
To quantify salinity variability, this report uses all available information and attempts to characterize variability, as data permits, at five unique time scales. The primary forcing mechanisms and their range of influence on salinity vary at each time scale.

- *Hours.* Variability of the salinity structure at this time scale is most often attributable to the diurnal tide cycle. This mechanism is associated with intruding high-salinity ocean waters and commonly encourages water-column mixing. In the Gulf estuaries, this mechanism is usually not important except near inlets; its influence is generally more extensive for Atlantic and Pacific coast estuaries where tidal ranges are greater.

- *Days-to-Weeks.* Variability of the salinity structure at this time scale is most often attributable to short-duration freshwater pulses, the biweekly (spring-neap or tropic-equatorial) tidal cycle, and frontal passages. Freshwater pulses are particularly influential in areas immediately near their source, but may exert significant short-term control over a large area of an estuary. These pulses generally displace vertically stratified waters seaward within an estuary, decreasing vertical stratification in areas immediately near the source, but intensifying stratification in areas downstream of the immediate inflow source. Biweekly tides enhance saltwater intrusion and intensify water-column mixing. Frontal passages are generally high-energy events that may be responsible for intense short-term variation in water levels, horizontal salinity gradients, and water-column mixing. These effects are most noticeable in microtidal environments (e.g., Gulf coast) where they overwhelm the influence of astronomical tides.

- *Months-to-Seasons.* For most estuaries in the U.S., the dominant time scale of variability occurs at the seasonal level. On average, the net change in

Figure 1. *Refined spatial structure for Charleston Harbor, SC* *



* Data Sources: See data sources listed for Charleston Harbor in the Appendix.

Figure 2. *Primary forcing mechanisms and time scales important to estuarine salinity variability (Cloern and Nichols, 1985)*

Mechanism	Time Scale: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		Freshets	Seasonal discharge	Wet vs. dry years	Tropical storms & diversions
Tides	Semi-diurnal & diurnal	Spring-neap & tropic-equitorial	Seasonal		
Wind	Diurnal	Frontal passages	Prevailing seasonal winds		
Coastal Shelf Processes		River plumes & upwelling	River plumes & upwelling	El Nino	

salinity for an entire estuary is greater at this time scale, primarily due to changes in seasonal freshwater discharges and, to a lesser extent, prevailing seasonal wind speed and direction.

- *Year-to-Year.* Annual variations are most often less pronounced than typical seasonal differences, excluding the anomalous events described below (see *Episodic*).

- *Episodic.* Episodic variation refers to the low-frequency, high-intensity, short-duration floods that not only include naturally occurring tropical storms, but may also result from infrequent high-volume water releases from control structures. In either case, the effect is generally dramatic: salinities throughout the estuary become *brackish* and may even approach *tidal-fresh* conditions as high-salinity waters are flushed and then replaced by the intense freshwater discharge. Under these conditions, vertical stratification may be nearly eliminated and tidal influence is suppressed until the freshwater pulse is reduced.

Figure 4 summarizes the major project components. Salinity characterizations were completed on a state-by-state basis, and cooperative agreements were often established with local academic institutions, whose expertise is considered absolutely essential to the project.

The Data

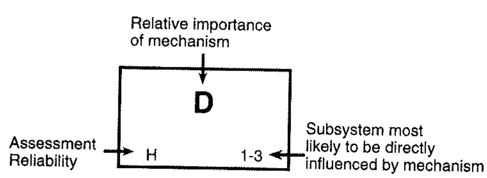
Data Availability. A common misperception is that an abundance of salinity data is available for the Nation's estuaries. In fact, a respectable volume of data exists only for a handful of the *most studied* estuaries (e.g., Galveston Bay and Chesapeake Bay), where hundreds of salinity measurements have been made annually over several years. Even for these systems, salinity information is not centralized and must be gathered from numerous sources. In contrast, some estuaries go completely unsampled for extended periods. The amount of salinity data available for most estuaries lies somewhere between these two extremes.

Given the disparate volume of information available, data sets cover an enormous range of spatial and temporal scales within any given estuary. Most often, the largest salinity data sets have been collected in support of long-term water-quality monitoring programs, usually administered by state regula-

Figure 3. *Matrix summarizing time scales and forcing mechanisms important to salinity structure and variability for Charleston Harbor, SC*

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		M M 2-3	M M 2-3	D M 2-4	D L 1-4
Tides	D LIT 1-4	S LIT 1-4			
Wind		S LIT 1-4	D LIT 1-4		
Density Currents	M LIT 1-4				
Inter-estuary Exchanges	M LIT 2, 4				
Effect on Salinity Variability	LOW	LOW	VERY LOW	LOW	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 40 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

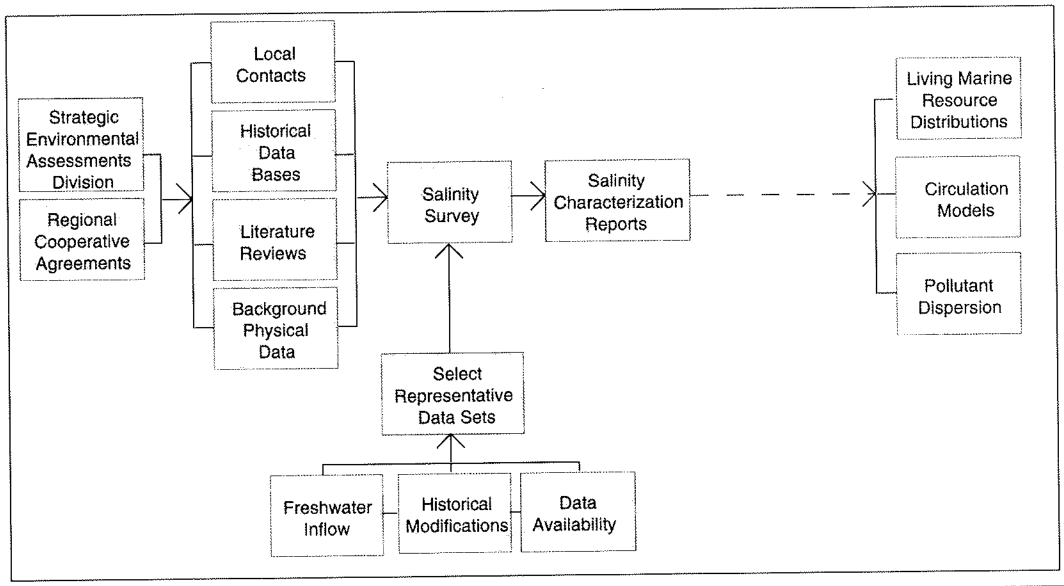
tory agencies. Under this scenario, salinity is scheduled to be routinely measured throughout the water column at numerous times and locations within an estuary. These comprehensive monitoring strategies, however, have frequently been curtailed (usually for financial reasons). Other salinity data sets have been collected as part of short-term special studies. Most of these, however, were limited both spatially and temporally (i.e., sampling stations were few, their sampling distribution was limited to a specific area of an estuary, and salinity was often measured for only the surface or bottom layer of the water column). The Appendix provides the primary data sources used in this report.

Data Relevance. To characterize *present-day* and *typical* salinity conditions, data should be considered from other perspectives beyond the volume of available data. First, most of the Nation's estuaries (and their watersheds) have been subject to significant modifications. The most important modifications have included: 1) flow diversions and reservoir construction which may significantly alter the volume or timing of freshwater discharge to the estuary; 2) creation or deepening of navigation channels which promote high-salinity bottom-water intrusion; and 3) large-scale dredge material disposal site construction (including diked disposal islands) which modifies circulation patterns. As a result, salinities throughout an estuary may undergo important historical alterations completely unrelated to its natural variability. Thus, if major alterations have recently occurred, only the most current salinity data will reflect present-day conditions within an estuary. This does not mean that historical records are not *good* data, but that they pre-date existing conditions within the system.

Historical Modifications. To determine the degree to which representative periods reflect present-day conditions, major modifications made to the estuary and its watershed were documented. The objective was to choose representative periods post-dating the modifications, since they may have resulted in a substantial alteration of estuarine salinities or freshwater input to the system. Major modifications include, but are not limited to:

- Major navigation channels (e.g., Wilmington Ship Channel in Cape Fear River, NC)
- Dredged material disposal islands (e.g., in Bogue Sound, NC)
- Inlet modification (e.g., Oregon Inlet in Albemarle/Pamlico Sound, NC)
- Shoreline modification (e.g., the "Rocks" in Cape Fear River, NC)
- Reservoir construction (e.g., Lakes Moultrie and Marion in North/South Santee Rivers and Charleston Harbor, SC)
- Saltwater control structures (e.g., the tide gate in Savannah River, SC)
- Freshwater diversions (e.g., North/South Santee Rivers and Charleston Harbor, SC)

Figure 4. *Project components*



Advantages of this Report. Because of the complexities associated with trying to capture the time and space variations of salinity, this report consistently characterizes disparate long-term, short-term, synoptic, and spatially-biased data sets providing a better understanding of salinity and its variability than any of the studies when considered independently. For most estuaries, more information is assimilated in this report than within any other government, academic, or private repository. In addition, the data are supported by extensive documentation of the major physical processes, morphology, natural features, and anthropogenic modifications that determine estuarine circulation and salinity. Furthermore, this study directly incorporates the knowledge base of experts who were solicited to provide guidance and interpretation. This information is consistently synthesized for each estuary and its interpretation includes expert guidance and review. The finished products (e.g., the salinity characterization summaries) are identically formatted and provide a brief, but information-rich summary emphasizing the most essential aspects of this information.

Representative Salinity Averaging Periods

This salinity analysis focused on two 3-month periods extracted from a subset of the historical data records. These periods were thought to represent the typical range of high- and low-salinity conditions experienced under average and present-day seasonal freshwater inflow conditions. Three months was selected to be the appropriate averaging period because seasonal variation in freshwater inflow produces an important change in estuary-wide salinity patterns in most of the Nation's estuaries. In addition, three months was considered to be the minimum period necessary to observe the response of salinity to freshwater and other physical forces operating at and within the seasonal time scale. Because a consistent time scale is necessary for comparisons among the Nation's estuaries, three-month seasonal distributions were delineated for each estuary.

Selection of Three-Month Averaging Periods. High- and low-salinity averaging periods were based on average monthly salinity concentrations during the available historical salinity record for each estuary (generally 1970-1992). High- and low-salinity periods reflect the three consecutive monthly averages having the highest and lowest salinity values, respectively. For many South Atlantic estuaries, salinity is typically highest during September-November or October-December and lowest during February-April (Figure 5). These periods generally coincide with seasonal freshwater inflow patterns.

As this study also attempted to characterize present-day conditions, the selection process also identified major modifications to the estuary and its watershed that significantly altered historical salinity conditions. In the South Atlantic region, the North/South Santee Rivers, Charleston Harbor, and Savannah River were subject to extensive structural modifications. Since 1985, freshwater was diverted from the Cooper River (in Charleston Harbor) to the Santee River system. In the Savannah River, a tide gate operated during 1977-1989. For the other 12 South Atlantic estuaries without major modifications, the entire available historical salinity record was used to determine long-term average monthly salinities for each estuary. For the Santee, Charleston, and Savannah systems, only the salinity record subsequent to the modification was used to derive average monthly salinity values.

Salinity Structure: Developing Isohalines for the Three Month High- and Low-Salinity Periods. For the two 3-month averaging periods defined above, isohalines were developed to represent the typical range of high- and low-salinity conditions experienced under *average* and *present-day* seasonal freshwater inflow conditions. Average freshwater inflow conditions were determined through analysis of the gaged freshwater inflow volume during each three-month averaging period when compared to the long-term mean for each period. *Average* conditions were defined by the volume of freshwater inflow within ±1 standard deviation of the long-term mean (Figure 6). This approach assumed that the subset of the historical salinity record measured under average high and low seasonal freshwater inflow conditions (i.e., ±1 standard deviation) reflects the typical range of seasonal salinity conditions. Thus, this subset of salinity data was used to construct isohalines. In contrast, the subset of the historical salinity record *not* measured under average high- and low-seasonal freshwater inflow conditions reflects salinities measured during low-frequency drought and flood conditions. This procedure was applied to 12 of 15 South Atlantic estuaries, excluding the Santee, Charleston, and Savannah systems.

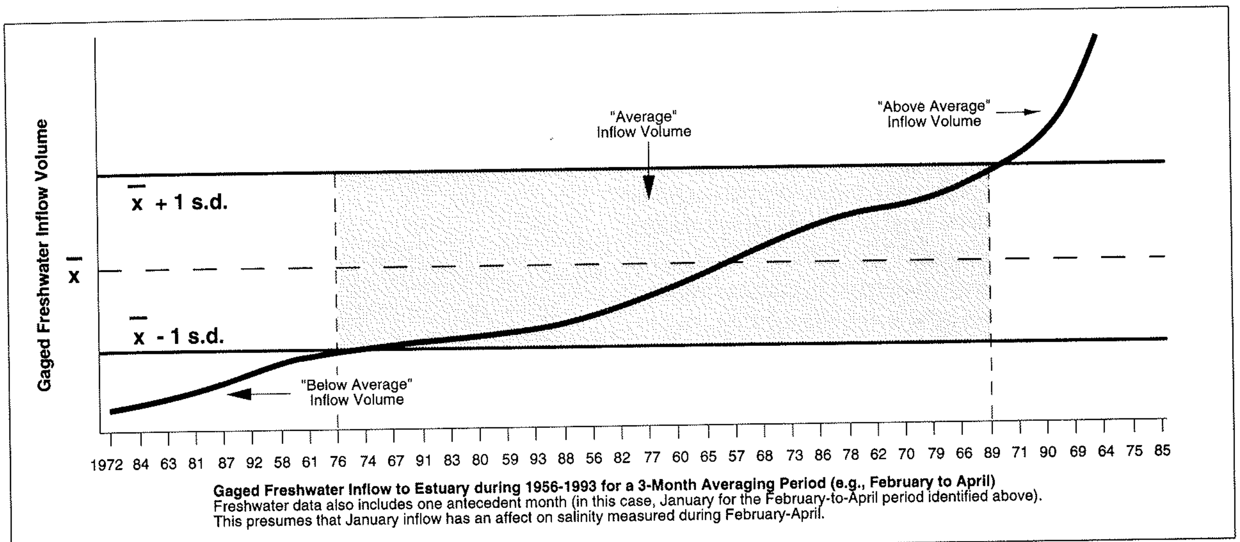
For the North/South Santee Rivers and Charleston Harbor estuaries, the 1985 freshwater diversion significantly altered and regulated inflow volumes

Figure 5. *Typical low- and high-salinity periods for South Atlantic estuaries*

	January	February	March	April	May	June	July	August	September	October	November	December
Albemarle/Pamlico Sounds		○	○	○					●	●	●	
Bogue Sound	○	○	○			●	●	●				
New River		○	○	○					●	●	●	
Cape Fear River		○	○	○					●	●	●	
Winyah Bay		○	○	○					●	●	●	
North/South Santee Rivers		○	○	○		●	●	●				
Charleston Harbor		○	○	○	●	●	●					
St. Helena Sound		○	○	○					●	●	●	
Broad River		○	○	○					●	●	●	
Savannah River		○	○	○					●	●	●	
Ossabaw Sound		○	○	○						●	●	●
St. Catherines/Sapelo Sounds		○	○	○						●	●	●
Altamaha River		○	○	○					●	●	●	
St. Andrew/St. Simons Sounds		○	○	○						●	●	●
St. Marys River/Cumberland Sound		○	○	○		●	●	●				

○ Low-salinity period ● High-salinity period

Figure 6. *Defining average freshwater inflow conditions**



* Example of freshwater inflow volume analysis used to determine "average" conditions for a hypothetical February-April period identified as the "3-month low-salinity period." Average conditions are defined by the volume of freshwater inflow within ±1 standard deviation of the long-term mean (i.e., the shaded portion of the freshwater curve). A similar process is applied to the "3-month high-salinity period." Salinity structure and variability described in this report is based on salinity data sampled under "average" inflow conditions.

delivered to each system. Because the post-diversion freshwater inflow record is arguably too short to determine a meaningful statistical mean and standard deviation, the salinity structure for these estuaries includes all salinity data available after 1985 during each three-month averaging period. In the Savannah River system, the salinity structure includes all salinity data available after 1989 for each three-month averaging period.

Salinity Variability. The temporal and spatial variability of salinity is described for average and present-day salinity and freshwater conditions, using the subset of the historical salinity record (i.e., ±1 standard deviation of average freshwater volume) to define the salinity structure. The magnitude of salinity variability quantified at time scales of days-weeks, months-seasons, and year-year was derived from further analysis of the same subset of historical salinity and freshwater data used to characterize the salinity structure. The magnitude of salinity variability at the hourly time scale was based on available literature or analysis of salinity at limited continuous monitoring stations. The magnitude of variability at the *episodic* time scale is generally unknown, but is undoubtedly significant in many South Atlantic estuaries. The relative importance of each forcing mechanism on salinity variability was based on available literature and guidance from locally recognized experts. Subsystems defined for each estuary suggest areas where either the magnitude of salinity variability and/or the dominant forcing mechanism responsible for salinity variability differs within an estuary.

Regional Overview

The South Atlantic coast extends from North Carolina to southern Florida (NOAA, 1990). Because south Florida systems are a coupled, highly controlled network of estuaries, wetlands, and bights, this complex region is studied in a separate report; therefore, excluded from this report are St. Johns River, Indian River, and Biscayne Bay.

An estuary's salinity structure is determined primarily by hydrodynamic mechanisms governed by the interaction of marine and terrestrial influences. The present approach used to characterize the salinity structure is to identify each estuary's controlling factors and its associated response to salinity. To provide a setting for this characterization, the general physical attributes and controlling environments (i.e., South Atlantic circulation and hydroclimatology of nearby states) of these estuaries are summarized below.

Geomorphology and Bathymetry

The coastal zone of North Carolina, South Carolina, and Georgia includes 15 major estuarine systems that encompass more than 9,400 km^2 (NOAA, 1990). It includes two geomorphologically and hydrologically distinct areas. Cape Hatteras, North Carolina, marks the transition between the Middle Atlantic Bight to the north and the South Atlantic Bight (SAB) to the south. The SAB may be further subdivided into a northern region (i.e., the Carolina Capes) extending from Cape Hatteras to Cape Romain, South Carolina, and a southern region extending from Cape Romain to Cape Canaveral, Florida. The South Carolina and Georgia component of the southern region is known as the Sea Island Coast.

Carolina Capes. The Carolina Capes is defined by: 1) a chain of low-lying barrier islands (i.e., the Outer Banks) bordering Onslow and Raleigh Bays; and 2) a marshy coastal plain bordering Long Bay (Pietrafesa et al., 1985). The Outer Banks separate the bar-built Albemarle/Pamlico and Bogue sounds from the coastal ocean. The estuarine area lies principally within Pamlico Terrace, an extensive low, flat, plain separated from the higher, inland plain (Talbot Terrace) by a relict shoreline known as Suffolk Scarp (Copeland et al., 1983). The estuarine systems are characterized by five shoreline types: marsh, low bank, high bank, bluff, and swamp forest (Copeland et al., 1983). The shelf is characterized by complex topography and prominent shoals.

Sea Island Coast. The Sea Island Coast is part of an arcuate coastline featuring extensive coastal islands that separate the estuarine environment from the coastal ocean. The entire area is part of the Atlantic Coastal Plain physiographic province in which the topography consists of broad depositional terraces aligned in belts parallel to the present shoreline (Mathews et al., 1980). Coastal island types include: 1) *sea islands* with an ocean fringe of marsh and/or beach dune ridges; 2) *sandy barrier islands* with extensive dune ridges; and 3) *marsh islands* with widely spaced dune ridges surrounded by marsh. The nearshore bathymetry is relatively uncomplicated. Isobaths tend to parallel the coastline, diverging north of Cape Canaveral as the shelf broadens and converging again south of Cape Romain as the shelf narrows (Lee et al., 1985).

The Sea Island Coast includes numerous estuaries; some receive substantial freshwater inflow from major rivers, while others receive very little inflow from minor rivers. The former are drowned river valleys, while the latter are bar-built systems located behind barrier islands. Charleston Harbor and Port Royal Sound are classic examples of drowned river valleys, while Calibogue and Cumberland sounds are examples of bar-built estuaries. Winyah Bay, Sapelo Sound, and St. Andrews Sound exhibit features of both types. Major rivers, which drain the Appalachian Mountains and Piedmont Plateau, occupy broad valleys with meandering channels, oxbow lakes, distributaries, and extensive sand dunes. The drainages of minor rivers originate within the coastal plain.

Anthropogenic Alterations. Besides natural bathymetry modifications due to such forces as waves, tides, currents, and wind, anthropogenic changes have occurred from channel dredging and dredged material disposal. Jetties, seawalls, breakwaters, and groins have also accelerated local deposition and erosion rates. Upstream dams, constructed for hydroelectric power and to alleviate shoaling problems in shipping channels, have dramatically altered freshwater discharges and sediment loads to some estuarine systems, with the Cooper and Santee rivers as being the most extreme examples (Kjerfve et al., 1990).

Tides

Tidal currents dominate inner and mid-shelf dynamics in the SAB, with lunar semi-diurnal tides accounting for almost 80% of the total kinetic energy (Pietrafesa et al., 1985). Although nine semi-diurnal and six diurnal tides exist among the principal tidal harmonic constituents in the SAB, the M2 partial tide with a period of 12.42 solar hours dominates SAB tides. In general, high M2 kinetic energy values occupy an alongshore mid-shelf region, extending from Charleston, South Carolina, south almost to Cape Canaveral, North Carolina, with energy decreasing both toward the sea and shore. Maximum energy and tidal ranges (2.2 m) occur off the coast of Savannah, Georgia where the shelf is widest, while minimum energy and tidal ranges (1.3 m at Cape Fear, North Carolina and 1.1 m at Cape Canaveral, Florida) occur at both the northern and southern boundaries of the SAB.

Quantitative differences in tidal currents exist over relatively short distances on the inner shelf of the SAB due to irregular bottom topography and the proximity of coastal inlets. Tidal currents are directed in an onshore-offshore direction and are strongest near the mouths of inlets (Blanton and Atkinson, 1978). The apparent south-to-north flow in the SAB is caused by the difference in tides occurring at the southern and northern boundaries of the region, with tides at Cape Canaveral preceding those at Cape Hatteras by approximately one hour. While some seasonal differences exist in the character of tidal currents, these differences are relatively subtle possibly due to a modification of the frictional environment caused by changes in stratification (Pietrafesa et al., 1985).

Shelf Circulation, Temperature, and Salinity

Gulf Stream. The Gulf Stream is the primary force controlling circulation in the SAB (SIO, 1981). The Gulf Stream, forming the eastern boundary of the SAB, is a fast moving (i.e., 1-2 m/s), deep boundary current flowing northerly along the edge of the continental shelf (i.e., the shelf break). Maximum salinities in the Gulf Stream between Florida and North Carolina are typically less than 36.7 ppt, while surface temperatures range from 21°C in winter to 29°C in summer (Atkinson, 1985). Throughout most of the SAB, shelf and Gulf Stream waters are adjacent, with the transition zone characterized by steep gradients of temperature and salinity over short distances.

Periodically, *meanders* or eddies break away from the Gulf Stream, having profound effects on surface and bottom currents, temperatures, salinities, and shelf water nutrient concentrations (Blanton, 1971; Tenore et al., 1978). Meanders frequently form at the Gulf Stream front and flow north along the shelf break. Lateral displacements of the front grow rapidly, and the waves onshore may elongate and form an eddy flowing south, opposite the main Gulf Stream flow. In addition, upwelling of deep Gulf Stream water may occur between the eddy and the Gulf Stream's boundary.

Bottom topography can also cause upwelling of water. The "Charleston Bump" (prominent ridge at the shelf break located off Charleston, South Carolina) deflects the Gulf Stream offshore, forming a semipermanent 10-to-150 km meander and causing water to be upwelled into shallow depths (Pietrafesa et al., 1985), with the Gulf Stream returning to the shelf break. The Carolina Capes shelf break also experiences topographically enhanced upwelling since a sharp increase exists in the bottom slope at a depth of about 50 m. Closer inshore, the Carolina Capes and their shoals form barriers to the north along the coast and direct the upwelled water onshore into embayments. Such onshore-offshore flow cycles, independent of winds, drive a well-defined circulation pattern in some embayments.

Shelf Water Temperatures. Gulf Stream meanders and topographical induced upwelling of Gulf Stream waters cause mixing of deep ocean and shelf waters at and below the surface. The colder, more dense shelf water during winter sinks beneath the warmer, less dense Gulf Stream water. Intrusions of high salinity surface water exhibiting Gulf Stream characteristics have been detected within 15 miles of Charleston, South Carolina during winter (Mathews and Pashuk, 1977; 1982). During summer, the density of shallower shelf water decreases as it warms, and the denser, more saline Gulf Stream water intrudes toward the shore along the bottom. Nearshore water, exhibiting properties intermediate to those of the Gulf Stream and shelf waters, has been observed during fall (Mathews and Pashuk, 1977; 1982).

Average surface water temperatures on the inner shelf of the SAB closely follow air temperatures, while those on the outer shelf are moderated by the Gulf Stream. Similarly, bottom temperatures near the coast are affected primarily by air temperatures and wind mixing. Bottom temperatures near the shelf break are affected more by intrusions of Gulf Stream waters, causing outer shelf water to be warmer in winter and colder in summer relative to the middle and inner shelf. Nearshore surface water temperatures vary seasonally from 10°C to 25°C (USEPA, 1983).

In the Carolina Capes, surface isotherms tend to parallel the coastline throughout the year (Pietrafesa et al., 1985). The along-shelf thermal gradients are generally an order of magnitude smaller than their cross-shelf counterparts, with temperatures increasing toward the south. During winter, shelf waters are much cooler than Gulf Stream waters, producing a cross-shelf temperature gradient of approximately 8°C. In spring, the cross-shelf temperature gradient weakens and a vertical temperature gradient begins to develop. By summer, a strong thermocline develops, and the temperature difference between the inner shelf and the Gulf Stream lessens to approximately 1°C. As autumn approaches, winds increase and air temperatures drop, causing surface cooling and strong vertical mixing. Thus, maximum vertical differences occur in summer and maximum cross-shelf differences in summer and winter.

Shelf Salinity. Average surface salinities in the SAB are influenced by variations in freshwater runoff and by the effect of shelf circulation. Surface salinities typically vary from about 32 to 34 ppt, with seasonally fluctuating river discharge volumes (USEPA, 1983). High runoff in spring causes lower inner shelf salinities and increased cross-shelf salinity gradients. Conversely, low runoff in summer results in diminished cross-shelf gradients as salinities increase. Although runoff remains low during fall, inner shelf salinities are often reduced, especially off north Florida and Georgia (Atkinson, 1985). Blanton and Atkinson (1983) hypothesize that the cause of this lowered salinity is high southward winds that restrict cross-shelf flow and advect coastal water southward.

Due to the proximity of the Gulf Stream and the relatively low river runoff along the Carolina Capes, the shelf water is more saline than in the Middle Atlantic Bight to the north or the Georgia Bight to the south (Bumpus, 1955; Stefansson et al., 1971). The salinity distribution along the Carolina Shelf is highly variable, ranging from 30 to 36 ppt (Stefansson et al., 1971). In general, surface isohalines parallel the coast, increasing seaward to the Gulf Stream front. Minimum salinities occur in spring when river runoff is at a maximum, evaporation at a minimum, and wind-driven intrusions of less saline Virginia coastal waters frequent. Conversely, maximum salinities occur during late summer and fall when freshwater inflow is at a minimum and the Gulf Stream is closest to shore (Giese et al., 1985; Kruczynski, 1974).

Salinity gradients off the Carolina Capes follow a seasonal pattern similar to that of temperature. Maximum vertical gradients and minimum horizontal gradients occur in summer, while the reverse occurs in winter (Pietrafesa et al., 1985). Cross-shelf salinity gradients do not vary seasonally at Cape Hatteras, but are greatest off Charleston during spring, in Onslow Bay during summer, and in Raleigh Bay during winter (Pietrafesa et al., 1985). Along-shelf salinity gradients are strongest in Cape Hatteras at the boundary between Virginia coastal water and Carolina Capes shelf water. Less saline Virginia coastal water can move around Cape Hatteras after periods of prolonged northeasterly winds and can lower salinities as far south as Cape Fear (Bumpus, 1955; Stefansson et al., 1971).

Climatology

The temperate to subtropical climate of the southeastern United States is strongly influenced by the ocean. Seasons are not as well defined as in areas to the north. In fact, two seasons (rainy and dry) exist, differentiated largely by precipitation which is highest during summer. Winters tend to be short and mild, while summers are long, hot, and humid. Winds are generally low, flowing from the north or northwest during winter and from the southern quadrants during summer (USDOI, 1983).

The moderating effect of the ocean on the southeastern coastal climate is evident through a comparison of inland and coastal areas with respect to temperature minima and maxima and the duration of freeze-free or growing periods. In general, temperature maxima are lower and minima are higher along the coast than inland, as illustrated by 30-year average temperatures (Mathews et al., 1980). In South Carolina, the freeze-free period ranges from 225 days inland to 294 days along the coast. A similar pattern is evident in Georgia, where the freeze-free period varies from 170 days in the mountains to about 300 days along the coast (Mathews et al., 1980). An average annual freeze-free period of 239 days has been reported for the North Carolina coast (Kruczynski, 1974).

Average winter air temperatures range from 7°C at Cape Hatteras to 16°C at Cape Canaveral. Summer air temperatures at these locations range from 26°C to 28°C, respectively. The relatively moderate temperatures at Cape Hatteras are caused by the cool Virginia coastal waters, which periodically intrude around the cape and into Raleigh Bay. Excessively high temperatures are rare. However, beginning in May, high temperatures are recorded with increasing frequency until July when the afternoon maximum averages 32°C (VIMS, 1974).

Precipitation along the SAB coast ranges from 121 to 142 cm/year (USEPA, 1983). Average annual rainfall is highest at the northern and southern extremes of Cape Hatteras and Cape Canaveral, respectively, and lowest near Charleston, South Carolina. Most precipitation is associated with cyclonic activity. Maximum rainfall generally occurs from July through September and minimum seasonal rainfall from November to February (USEPA, 1983). Although maximum rainfall occurs along the coast in summer, maximum freshwater discharge to estuaries usually occurs in March or April because most drainage areas of the southeastern United States are in the mountain and piedmont areas which receive most of their rainfall in early spring.

Meteorological Forcing

Coastal winds comprise three basic time scales: seasonal (>1 month); synoptic (3-20 days) due to the passage of weather systems; and diurnal (<1 day) due to changes in sea breezes (Blanton et al., 1985). Surface waters of the SAB respond relatively quickly to wind changes, due to their broad expanse and shallow depth. Fluctuations in the Icelandic Low, the Bermuda-Azores High, and the Ohio Valley High largely govern the mean wind patterns in the SAB (Blanton et al., 1985). Fluctuations in this mean wind pattern, in turn, provide the dominant forcing to shelf circulation in areas removed from direct Gulf Stream influence.

High Pressure Cells. Winds blowing over the SAB originate either from the Bermuda-Azores High in the North Atlantic or from a smaller scale anticyclone centered over the Ohio Valley (the Ohio Valley High). These winds cover the southern United States, east of 110°W, and result in mean eastward winds across the SAB (Blanton et al., 1985). During spring (March-May), the prominent influence of the Ohio Valley High is replaced by the Azores High. The northward flow of warm humid air over the western North Atlantic and Gulf of Mexico originates as westward flow on the southern flank of the Azores High. In summer (June-August), the northward flow of air strengthens as the Azores High strengthens and shifts west. The airstreams which pass into the Gulf of Mexico turn north, flowing northeast over land into the SAB and joining the airstreams flowing north over the ocean. This pattern produces a confluence zone where frequent rain occurs over land. During the autumn (September-November), the penetration of tropical air in the SAB rapidly collapses and is replaced by air originating from the Ohio Valley High. The airstreams flow out of the eastern flank of the Ohio Valley High and produce strong southwest winds over the SAB.

Seasonal Wind Patterns. Blanton et al. (1985) describes five seasonal winds for the SAB. During winter (November-February), southeast winds over the northern SAB gradually shift south toward more southerly latitudes. Winds are stronger in northern SAB during this season. In spring (March-May), winds gradually shift east and northeast, yielding offshore Ekman Transport in central SAB near shore. The removal of low-salinity water near the Georgia coast occurs most rapidly in spring just after maximum river discharge (Blanton and Atkinson, 1983). Low-salinity water in surface waters adjacent to the Georgia and South Carolina coasts is advected toward the outer shelf between 32°N and 33°N (Bush et al., 1985). During early summer (June-July), wind is west and southwest along southern Florida. Wind stress is more north and northeast in the northern Bight and over the Blake Plateau. In August, the organized field of northward stress continues over the Blake Plateau, but breaks down in the SAB as opposing airstreams from the Ohio Valley High and the Azores High result in weak and erratic mean winds over the SAB. The autumn winds (September-October) exert strong southwest winds and onshore Ekman Transport in the SAB. This regime is the most dynamic one of the year and assists in driving coastal currents south during September-November (Weber and Blanton, 1980; Blanton, 1981; Atkinson et al., 1983; Blanton et al., 1985). As mentioned earlier, the restriction of cross-shelf flow and advection of coastal water south during fall may account for the reduced inner shelf salinities, despite seasonally low runoff (Atkinson, 1985).

Tropical and Extra Tropical Storm Events. Storm surges resulting from such meteorological events as hurricanes or extra tropical cyclones can also affect estuarine salinity. Several factors affect the severity of storm surges, including atmospheric pressure; wave direction; bathymetry; and shoreline configuration. Along the South Atlantic coast, water levels over 16 feet (5 m) have been recorded (VIMS, 1974). Hurricanes (tropical storms with wind speeds >63 knots) cause the highest rise in seawater levels. Tropical cyclones may occur in the region at any time between late May and early December. Hurricanes occurring in the SAB in late summer and early fall travel east-to-west in a curved path, with an 8% probability of striking the southeastern U.S. coast (USEPA, 1983). Extra tropical cyclones form offshore between 30°N and 40°N from November to April and are associated with strong northeasterly winds. Tornadoes associated with tropical and extra tropical cyclones generally travel in a southwest-to-northeast direction through the SAB and strike the coast approximately 12 times per year (USEPA, 1983).

Freshwater Inflow

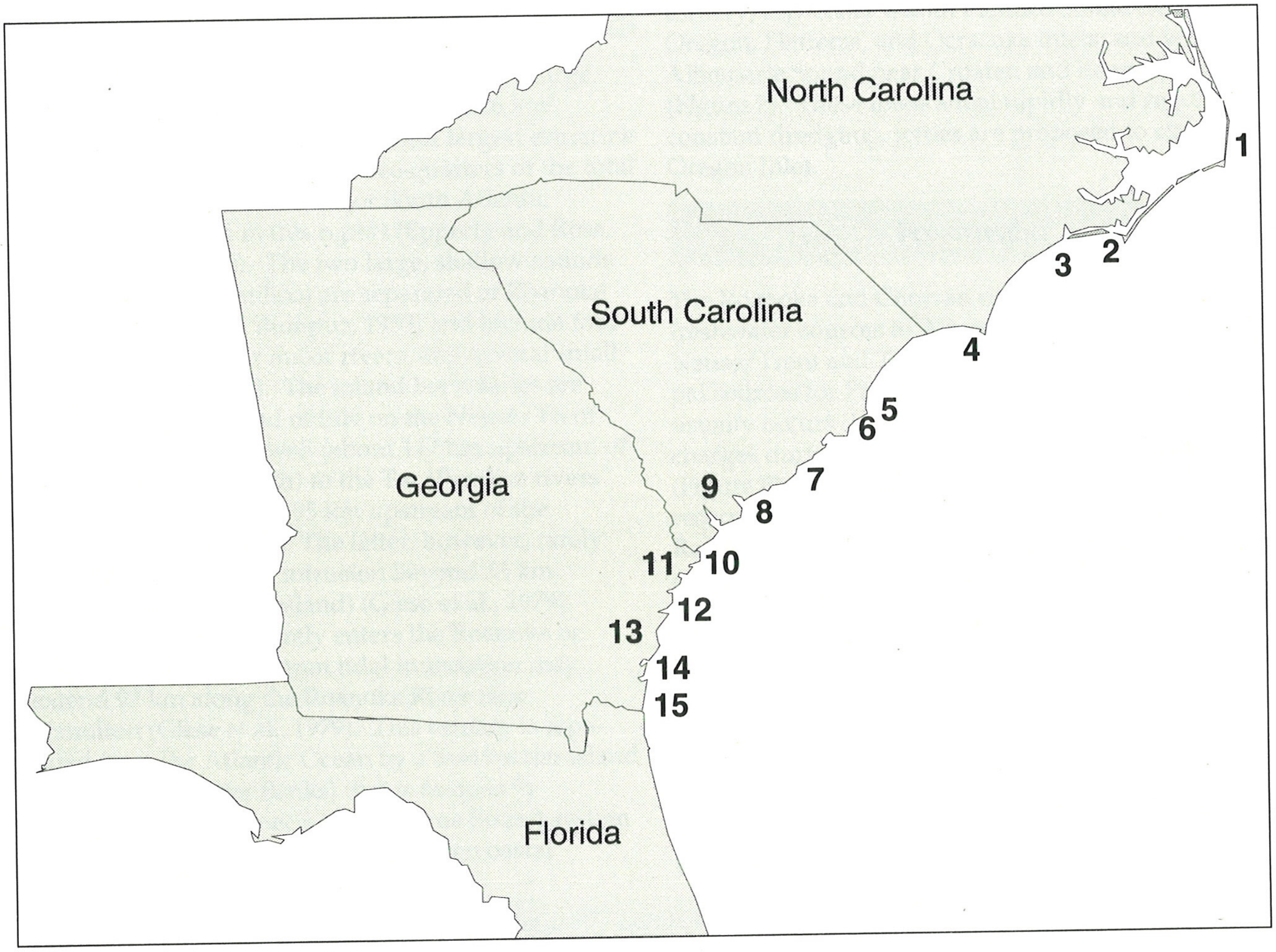
Carolina Capes. Freshwater inflow to this region is dominated by discharge to the Albemarle/Pamlico Sound estuary. The Roanoke and Chowan rivers are the principal sources to Albemarle Sound, while the Neuse-Trent and Tar-Pamlico rivers are the major inputs to Pamlico Sound.

Sea Island Coast. Four major river systems (i.e., Altamaha, Savannah, Pee Dee, and Cooper/Santee Rivers) provide over 80% of the total freshwater discharge between Cape Romain, South Carolina and Jacksonville, Florida. All four major rivers originate in the Appalachian Mountains and Piedmont Plateau. Several smaller rivers and creeks, originating within the coastal plain, account for the remaining freshwater in this area.

Relationship to Estuarine Circulation and Salinity. In the Cape Fear River estuary, circulation is dominated by tidal exchanges and, to a lesser extent, by freshwater inflow and winds (Giese et al., 1985). In all other major North Carolina estuaries (with the probable exception of the Roanoke River subsystem of Albemarle Sound), winds are usually the dominant short-term current-producing force, followed by ocean tides and freshwater inflow (Giese et al., 1985). These estuaries are partially enclosed by the Outer Banks and subject to the tide-dampening effects of Pamlico and Albemarle sounds. Saltwater intrusion occurs periodically in all major North Carolina estuaries, except in the Roanoke River where releases from freshwater reservoirs during low-flow periods effectively block saltwater intrusion. Salinity stratification is common in Cape Fear and Northeast Cape Fear rivers, but is less common in other estuaries lacking direct oceanic connection and where wind is usually effective in vertical mixing.

Circulation patterns in estuaries of the Sea Island Coast primarily depend on the freshwater discharge volume (Mathews et al., 1980). Where discharge is significant, the resulting pattern is a two-layer flow with vertical mixing (e.g., Charleston Harbor, Winyah Bay, Savannah River, and Altamaha River). Where freshwater discharge is minimal (e.g., Port Royal, Wassaw, and Sapelo sounds), a vertically homogeneous salinity pattern results, with tidal currents predominating.

Salinity Characterization Summaries



South Atlantic Estuaries

1	Albemarle/Pamlico Sounds
2	Bogue Sound
3	New River
4	Cape Fear River
5	Winyah Bay
6	North/South Santee Rivers
7	Charleston Harbor
8	St. Helena Sound
9	Broad River
10	Savannah River
11	Ossabaw Sound
12	St. Catherines/Sapelo Sounds
13	Altamaha River
14	St. Andrew/St. Simons Sounds
15	St. Marys River/ Cumberland Sound

Description

The Albemarle/Pamlico Sounds estuary is a large, bar-built lagoonal system occupying 8,516 km^2 (NOAA, 1990). The Nation's second largest estuarine system, it represents nearly three-quarters of the total water surface area of the major South Atlantic estuaries included in this report (Epperly and Ross, 1986; NOAA, 1990). The two large, shallow sounds (Albemarle and Pamlico) are separated at Roanoke Island (Roelofs and Bumpus, 1953) and include four smaller sounds, four major rivers, and several small tributaries (Figure 7). The inland boundaries are defined from the head of tide on the Neuse/Trent rivers near Fort Barnwell (about 117 km upstream of the Neuse River mouth) to the Tar/Pamlico rivers near Greenville (about 95 km upstream of the Pamlico River mouth). The latter, however, rarely experiences saltwater intrusion beyond 55 km upstream (near Grimesland) (Giese et al., 1979). Although saltwater rarely enters the Roanoke or Chowan rivers, maximum tidal inundation may extend 97 km along the Roanoke River near Hamilton (Giese et al., 1979). This estuary is separated from the Atlantic Ocean by a thin barrier island complex (the Outer Banks) that is frequently overwashed. It connects to the Bogue Sound system through Core Sound, the Atlantic Intercoastal Waterway (AIWW), and Harlowe Canal. This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 7).

Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level (NOAA, 1990). Naturally deep areas exist in western Albemarle Sound and in two open basins of Pamlico Sound to the northeast and southwest of Bluff Shoal. This shoal effectively separates the Pamlico Sound basins both physically and biologically (Epperly and Ross, 1986). Currituck, Croatan, Roanoke, and Core sounds are comparatively shallow. The AIWW (3.7 m at mean low water [MLW]) crosses the estuary on a northeast to southwest axis, essentially providing a nominal connection between this estuary and both the Chesapeake Bay and Bogue Sound system. Smaller channels exist throughout the estuary, especially within Pamlico Sound near Oregon, Hatteras, and Ocracoke inlets; and within Albemarle Sound near Croatan and Roanoke sounds (Figure 7). These inlets shoal rapidly and require constant dredging. Jetties are proposed to stabilize Oregon Inlet.

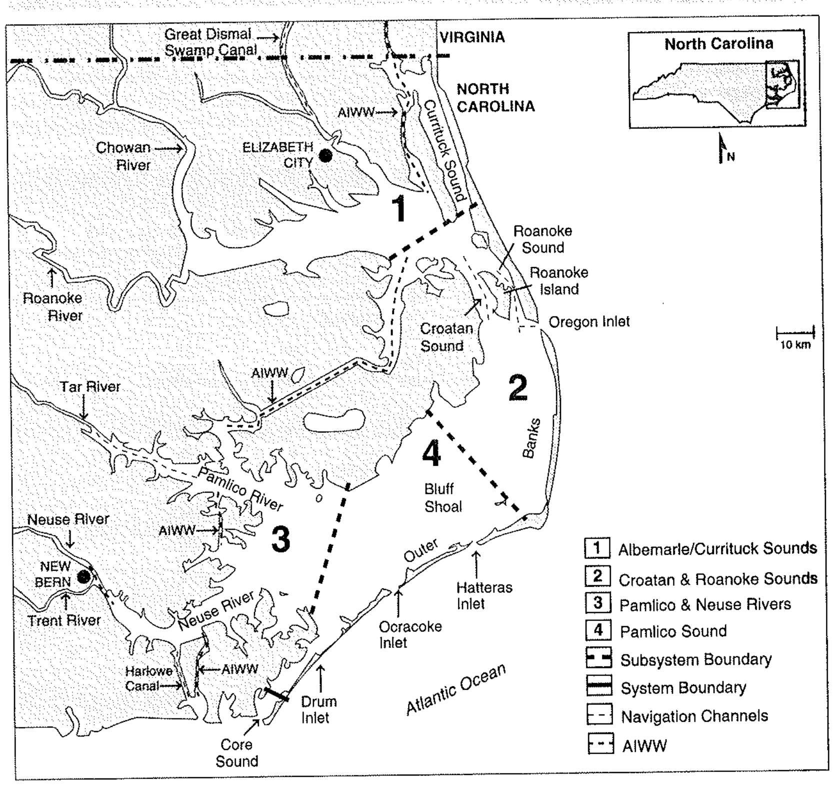
Freshwater

The Roanoke and Chowan rivers are the two major freshwater sources to Albemarle Sound, while the Neuse/Trent and Tar/Pamlico rivers are the principal sources for Pamlico Sound. Highest streamflow usually occurs during February-April; lowest discharges during September-November (NOAA, 1985) (Figure 8). The Roanoke River is regulated by several reservoirs, most notably at Kerr Lake and Roanoke Rapids Lake. The influence of regulation is probably most apparent in August through November under low-flow augmentation schedules (Giese et al., 1979). Figure 9 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

Tides

Tidal exchange occurs across the shifting bars of Oregon, Hatteras, Ocracoke, and Drum inlets.

Figure 7. *Location map and subsystem identification*



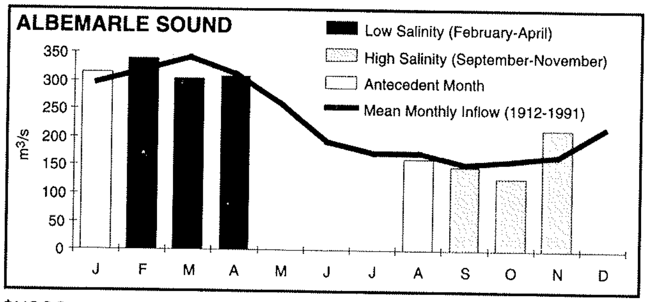
Astronomical tides range 0.6 m at Oregon, Hatteras, and Ocracoke inlets, but rapidly reduce to 0.2 m in Pamlico Sound (NOAA, 1991). Tides often increase to 0.3 m in the major tributaries due to bathymetric funneling (Giese et al., 1979). Water level, current speeds, and circulation patterns depend more on wind conditions (Giese et al., 1979; NOAA, 1991).

Salinity

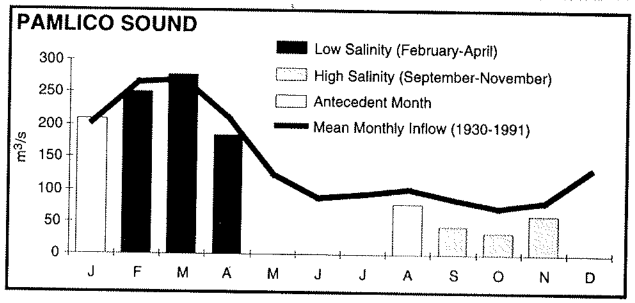
Although Albemarle and Pamlico sounds differ significantly in their physiography and hydrography (Epperly and Ross, 1986; Giese et al., 1979), their salinity structure is primarily determined by seasonal freshwater discharge. However, Pamlico Sound experiences greater seasonal salinity variation than Albemarle Sound due to the controlling influence of freshwater in Albemarle Sound. Salinities in Albemarle Sound are typically no more than 5 ppt and vertically homogeneous, but may exhibit higher salinities and greater variability near Croatan Sound (Figure 10).

In Pamlico Sound, a steep horizontal salinity gradient exists between Croatan Sound and Bluff Shoal. Salinities in this area of Pamlico Sound are highly variable and commonly experience weak-to-moderate vertical stratification. Comparatively the most saline within this estuary, Pamlico Sound is generally vertically homogeneous, except for weak-to-moderate stratification in the western sound near Neuse and Pamlico river mouths. Salinity variability in Pamlico Sound is dominated by wind-driven circulation and currents (Giese et al., 1979), although freshwater is also important. Salinities in the Neuse and Pamlico rivers are variable and often moderately stratified. Core Sound receives little freshwater inflow; its hydrography is dominated by astronomical tides and wind (Epperly and Ross, 1986) that often maintain high salinities and vertically homogeneous conditions. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 11.

Figure 8. *Comparison of gaged freshwater volume for Roanoke River (Albemarle Sound) and Neuse and Tar rivers (Pamlico Sound) during periods of salinity depiction shown in Figure 9**



*USGS gage on the Roanoke River reflects 28% of the Albemarle/Pamlico watershed (76,661 km²) (USGS, 1993)



*USGS gage on Neuse/Tar Rivers reflects 16% of the Albemarle/Pamlico watershed (76,661 km²) (USGS, 1993)

Figure 9. *Salinity sampling information and average salinity during low- and high-salinity periods**

Albemarle Sound

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1978	4	0	0	100	4	0	0	100
1982	26	0	0	100	6	0	0	100
1983	54	0	0	100	29	0	0	100
1985	45	0	0	100	32	0	0	100
1989	57	0	0	100	53	0	0	100
1990	34	0	0	100	28	0	0	100
1991	17	0	0	100	13	0	0	100
Total Observations	237	0	0	100	165	0	0	100
Average Salinity (ppt)	2.3				2.3			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 9. *Salinity sampling information and average salinity during low- and high-salinity periods (continued)**

Pamlico Sound

February-April
Low-Salinity Period

Years Available	Surface Total Observations	Surface % Flood Observations	Surface % Ebb Observations	Surface % Unknown Observations	Bottom Total Observations	Bottom % Flood Observations	Bottom % Ebb Observations	Bottom % Unknown Observations
1971	95	0	0	100	3	0	0	100
1972	36	0	0	100	4	0	0	100
1974	212	0	0	100	100	0	0	100
1976	104	0	0	100	37	0	0	100
1977	103	0	0	100	65	0	0	100
1978	137	0	0	100	135	0	0	100
1979	344	0	0	100	340	0	0	100
1980	282	0	0	100	279	0	0	100
1982	345	0	0	100	304	0	0	100
1985	325	0	0	100	294	0	0	100
1989	254	0	0	100	221	0	0	100
1990	97	0	0	100	84	0	0	100
1991	43	0	0	100	32	0	0	100
Total Observations	2,377	0	0	100	1,898	0	0	100
Average Salinity (ppt)	10.1				9.8			

Albemarle Sound

September-November
High-Salinity Period

Years Available	Surface Total Observations	Surface % Flood Observations	Surface % Ebb Observations	Surface % Unknown Observations	Bottom Total Observations	Bottom % Flood Observations	Bottom % Ebb Observations	Bottom % Unknown Observations
1978	8	0	0	100	8	0	0	100
1982	57	0	0	100	34	0	0	100
1984	64	0	0	100	39	0	0	100
1985	79	0	0	100	57	0	0	100
1987	153	0	0	100	137	0	0	100
1988	182	0	0	100	182	0	0	100
1990	51	0	0	100	48	0	0	100
1991	66	0	0	100	67	0	0	100
Total Observations	660	0	0	100	572	0	0	100
Average Salinity (ppt)	4.5				5.1			

Pamlico Sound

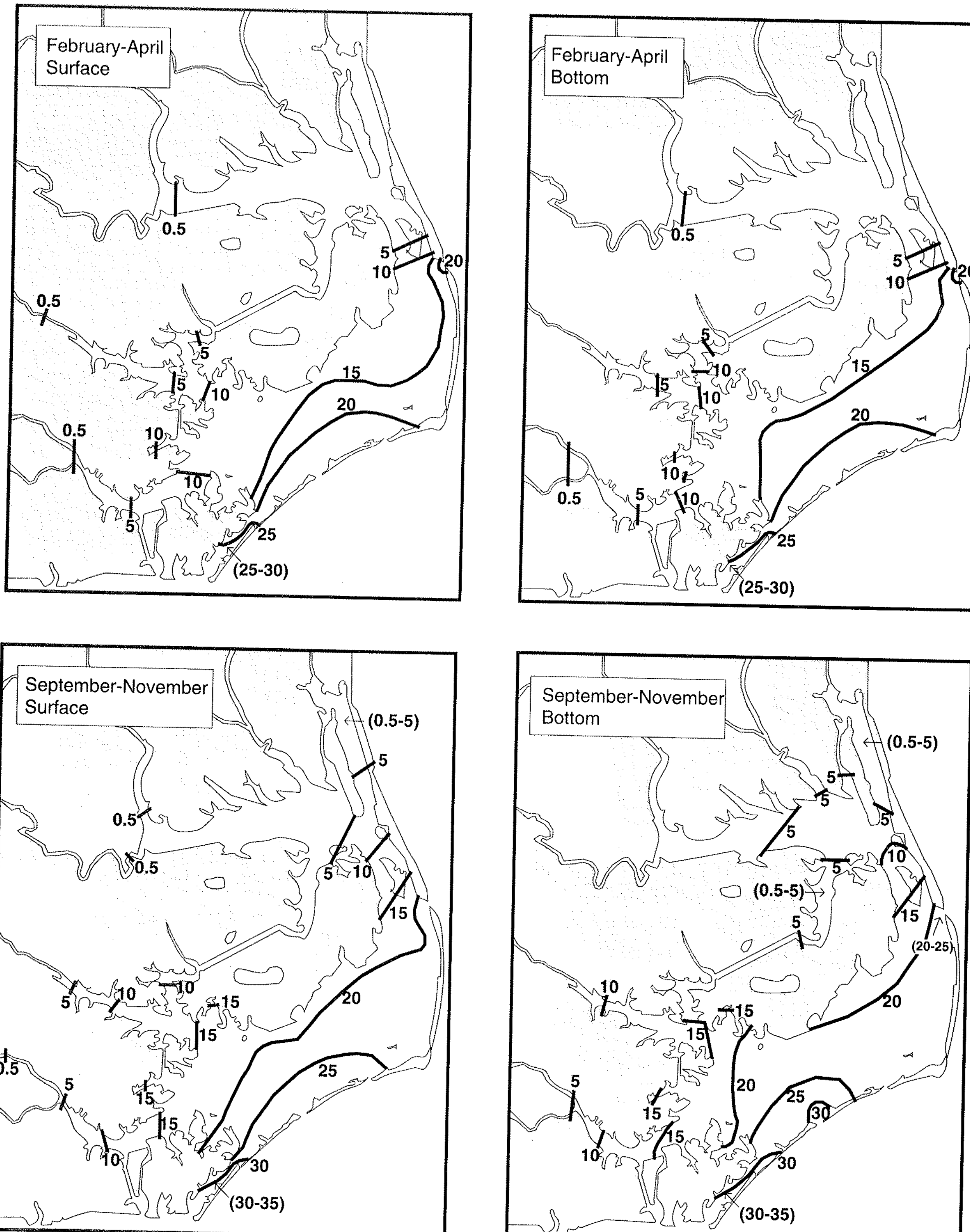
September-November
High-Salinity Period

Years Available	Surface Total Observations	Surface % Flood Observations	Surface % Ebb Observations	Surface % Unknown Observations	Bottom Total Observations	Bottom % Flood Observations	Bottom % Ebb Observations	Bottom % Unknown Observations
1973	226	0	0	100	180	0	0	100
1975	141	0	0	100	69	0	0	100
1976	98	0	0	100	82	0	0	100
1977	58	0	0	100	57	0	0	100
1978	415	0	0	100	380	0	0	100
1981	369	0	0	100	339	0	0	100
1982	331	0	0	100	305	0	0	100
1984	316	0	0	100	294	0	0	100
1985	297	0	0	100	265	0	0	100
1986	279	0	0	100	248	0	0	100
1988	364	0	0	100	336	0	0	100
1990	138	0	0	100	124	0	0	100
1991	127	0	0	100	114	0	0	100
Total Observations	3,159	0	0	100	2,793	0	0	100
Average Salinity (ppt)	15.5				16.4			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 10. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 9* *



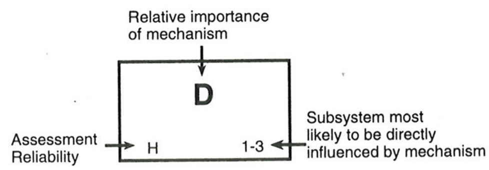
* Data Sources: See data sources listed for Albemarle/Pamlico Sounds in the Appendix.

Figure 11. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 9**

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		**S** M 2-4	**D** M 1-4	**D** M 1-4	
Tides	**D** LIT 2-4				
Wind		**D** LIT 1-4			
Effect on Salinity Variability	UNKNOWN	LOW[a] MEDIUM[b]	LOW[a] MEDIUM[b]	LOW[a] MEDIUM[b]	UNKNOWN

[a] Albemarle Sound (Subsystem 1)
[b] Pamlico Sound (Subsystems 2-4)

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 10 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability and stratification, especially within western Pamlico Sound and its tributaries. Freshets temporarily displace saline waters toward the inlets, resulting in a steep horizontal salinity gradient and weak-to-moderate vertical stratification in these areas.

Months-Seasons. Dominant estuary-wide influence on the salinity structure, although seasonal salinity changes are greater in Pamlico Sound and its tributaries than in Albemarle Sound. Releases from Roanoke Rapids Lake and other reservoirs during otherwise low-flow periods effectively block saline water from the Albemarle system (Giese et al., 1979).

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant influence on salinity variability and water-column mixing, primarily near the inlets. Tides are semi-diurnal and range 0.6 m near the inlets, but only 0.2 m within Pamlico Sound (NOAA, 1991). Tidal currents are negligible in Pamlico Sound except near the inlets (NOAA, 1991). Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Dominant estuary-wide influence on salinity variability, water-column mixing, circulation, and water elevation (Giese et al., 1979; NOAA, 1991). These effects are intensified by the onset of "northeasters." Easterly winds tend to increase salinity in Pamlico Sound, while westerly winds have the opposite effect. Salinities in northern Pamlico Sound increase during southerly winds and decrease during northerly winds (Giese et al., 1979). Short-term, wind-driven water level changes generally override tidal influences. Current speeds through Oregon inlet approach 4 m/s during southwesterly winds (NOAA, 1991).

* Data Sources: See data sources listed for Albemarle/Pamlico Sounds in the Appendix.

Description

The Bogue Sound estuary is a narrow, shallow lagoonal system located behind a thin chain of sandy barrier islands. Occupying 264 km², this system includes Bogue and Back sounds, as well as White Oak, Newport, and North rivers which are tidally influenced throughout their length. It is connected to the Atlantic Ocean through the Bogue, Beaufort, and Barden inlets which are shallow and subject to continuous shoaling (Figure 12). It is also connected to Pamlico Sound through Core Sound and to the Neuse River through the AIWW and Harlowe Canal. This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 12).

Bathymetry

The average depth of this estuary is approximately 1.5 m at mid-tide level (NOAA, 1990). This estuary contains numerous marshy isles, particularly within the mouths of the White Oak, Newport, and North rivers. Extensive shoals and dredged material disposal areas are also located throughout this system. The principal navigation channels include the Beaufort Inlet-Morehead City Channel (13 m at MLW), the Beaufort Channel (4 m at MLW), the Gallants Channel (3.7 m at MLW), and the AIWW (3.7 m at MLW).

Freshwater

Freshwater to the estuary is limited by its small watershed (1,760 km²) (NOAA, 1990), but is sufficient to produce strong salinity gradients in the White Oak, Newport, and North rivers during the late winter and spring (Figure 13). Figure 14 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

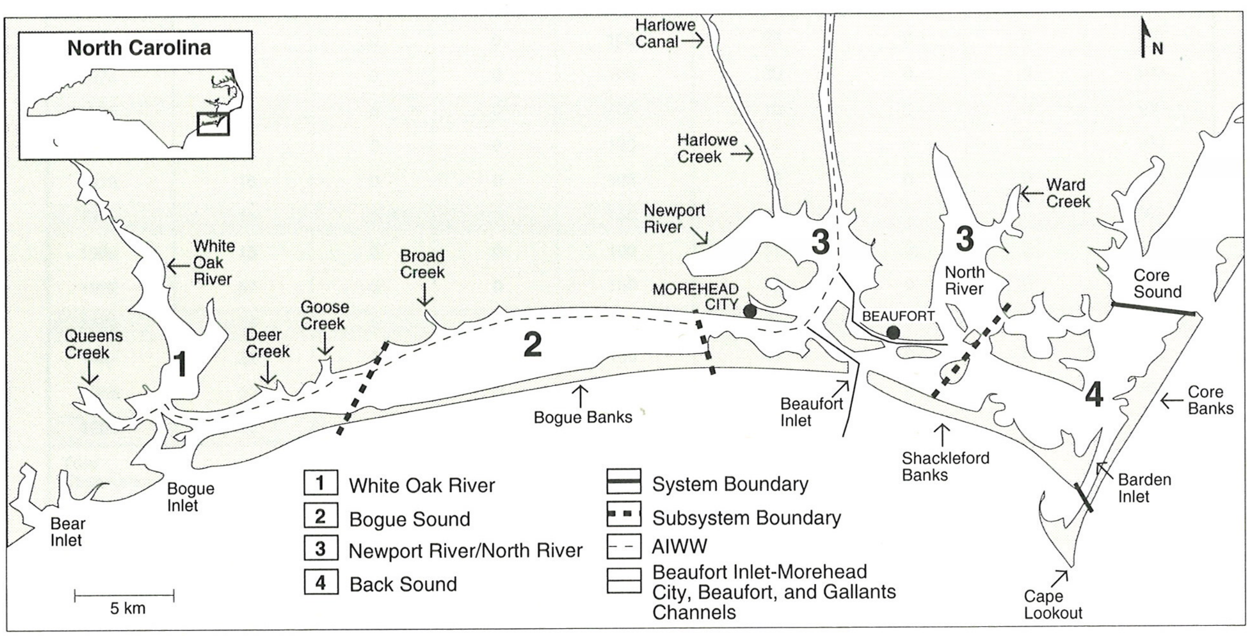
Tides

Most tidal exchange occurs through Bogue, Beaufort, and Barden inlets with limited exchanges through Bear Inlet and Core Sound. Mean tide range is approximately 0.7 m at Bogue and Beaufort inlets, but decreases to 0.3 m in central Bogue Sound and 0.15 m near Core Sound. Strong south or southwest winds may raise the tide level more than 0.3 m, while north or northwest winds may lower the tide level by the same amount (NOAA, 1991).

Salinity

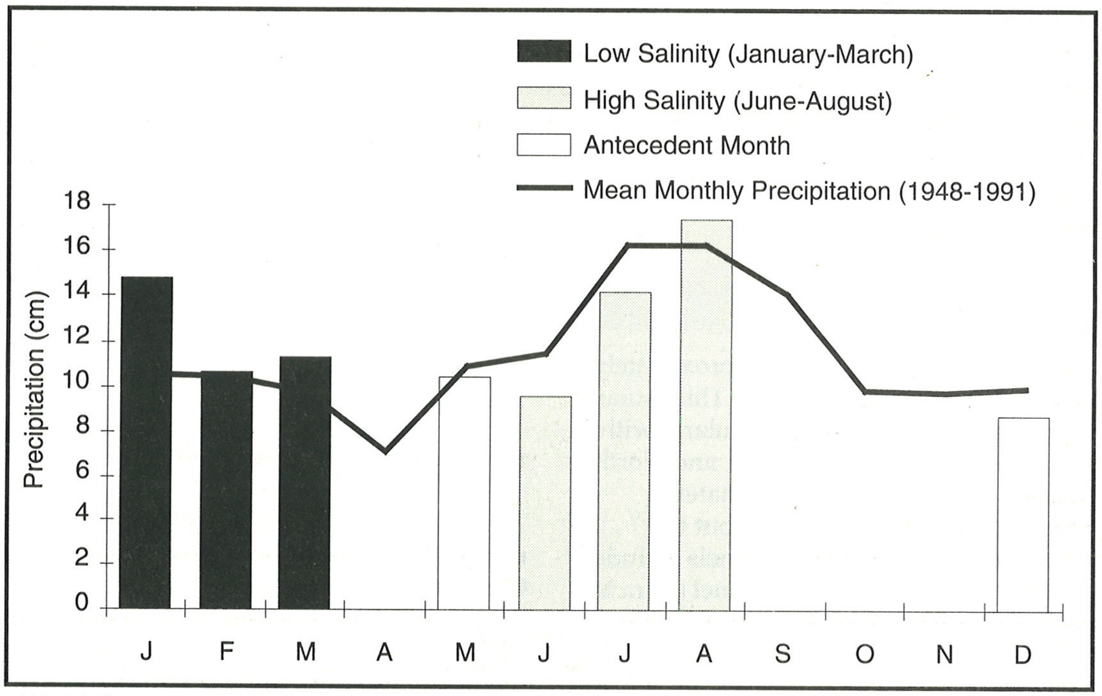
The salinity structure is most likely controlled by rainfall and evaporation patterns (Kirby-Smith and Costlow, 1989). Seasonal salinities differ by 5 ppt throughout the estuary, with the greatest changes apparent in White Oak, Newport, and North rivers (Figure 15). During the low-salinity period, salinities

Figure 12. *Location map and subsystem identification*



in these major river systems are generally moderately stratified and experience greater variability than the vertically homogeneous and more stable conditions in Bogue and Back sounds. During the high-salinity period, salinities become more stable and less stratified in the major river systems, while stable and vertically homogeneous conditions remain in Bogue and Back sounds. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 16.

Figure 13. *Comparison of total precipitation (cm) at Morehead City, NC during periods of salinity depiction shown in Figure 14*



Abbreviation: cm - cubic meters

Figure 14. *Salinity sampling information and average salinity during low- and high-salinity periods**

January-March
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1970	4	0	0	100	0	0	0	100
1971	113	0	0	100	0	0	0	100
1972	136	0	0	100	49	0	0	100
1974	41	0	0	100	38	0	0	100
1975	18	0	0	100	16	0	0	100
1978	7	0	0	100	7	0	0	100
1979	16	0	0	100	11	0	0	100
1985	37	0	0	100	9	0	0	100
1987	8	0	0	100	3	0	0	100
1988	20	0	0	100	15	0	0	100
1989	15	0	0	100	11	0	0	100
1991	5	0	0	100	0	0	0	100
1992	5	0	0	100	0	0	0	100
Total Observations	425	0	0	100	159	0	0	100
Average Salinity (ppt)	18.9				21.4			

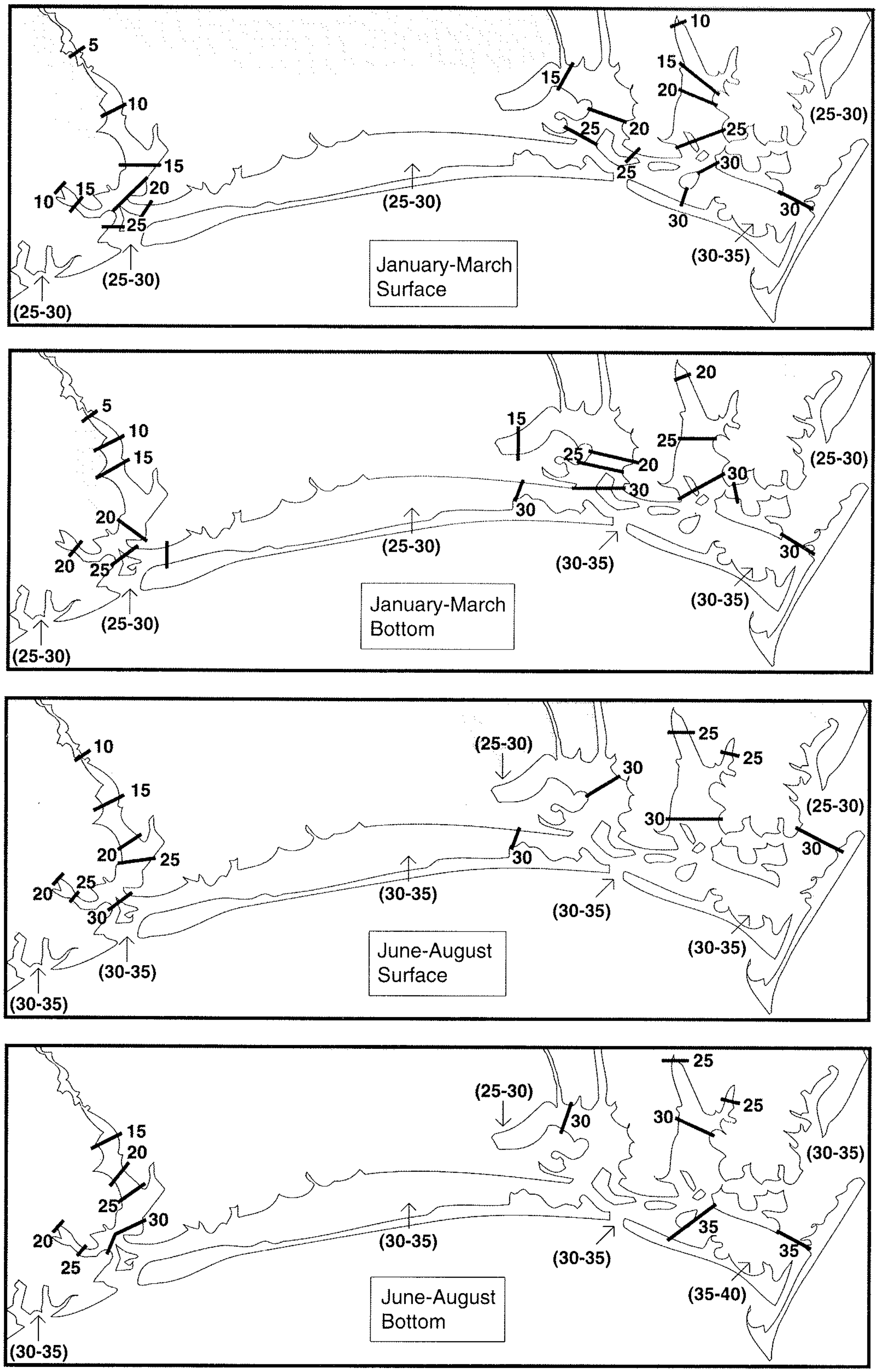
June-August
High-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1971	170	0	0	100	0	0	0	100
1973	27	0	0	100	23	0	0	100
1974	28	0	0	100	20	0	0	100
1975	13	0	0	100	10	0	0	100
1977	7	0	0	100	7	0	0	100
1978	15	0	0	100	15	0	0	100
1979	15	0	0	100	15	0	0	100
1980	15	0	0	100	15	0	0	100
1982	57	0	0	100	45	0	0	100
1985	56	0	0	100	27	0	0	100
1987	22	0	0	100	17	0	0	100
1988	53	0	0	100	48	0	0	100
1989	23	0	0	100	18	0	0	100
Total Observations	501	0	0	100	260	0	0	100
Average Salinity (ppt)	26.3				27.2			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 15. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 14* *

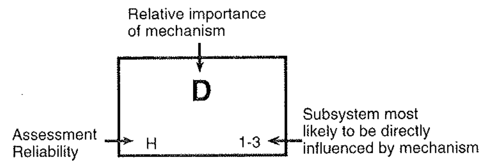


* Data Sources: See data sources listed for Bogue Sound in the Appendix.

Figure 16. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 14**

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		**S** L 1, 3	**D** L 1-3	**D** L 1-4	
Tides	**D** LIT 1-4				
Wind		**S** LIT 1-4			
Density Currents		**S** LIT 1-4			
Effect on Salinity Variability	UNKNOWN	HIGH	MEDIUM	HIGH	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 15 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability and stratification, primarily in the White Oak, Newport, and North rivers.

Months-Seasons. Dominant influence on the salinity structure, primarily in the White Oak, Newport, and North rivers.

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant influence on salinity variability and water-column mixing, especially in the White Oak, Newport, and North rivers. Tides are semi-diurnal and range 0.7 m at Bogue and Beaufort inlets, but decrease to 0.3 m in central Bogue Sound and 0.15 m near Core Sound (NOAA, 1991). Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability.

Density Currents

Days-Weeks. Secondary influence on salinity variability related to increased salinity concentrations and vertical stratification within major navigation channels.

* Data Sources: See data sources listed for Bogue Sound in the Appendix.

Description

The New River estuary is a small, coastal plain system occupying 83 km² (NOAA, 1990). Its boundaries are defined from the head of tide on the New River, approximately 3 km upstream of Jacksonville (NOAA, 1985; Payonk, Pers. Comm.), to its terminus with the Atlantic Ocean at New River Inlet. This estuary includes three major bays (Morgan, Farnell, and Stones) and several smaller bays and coves (Dennis, 1988) (Figure 17). Its northwest-southeast axis is highly convoluted and contains several constricting points along its length. This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 17).

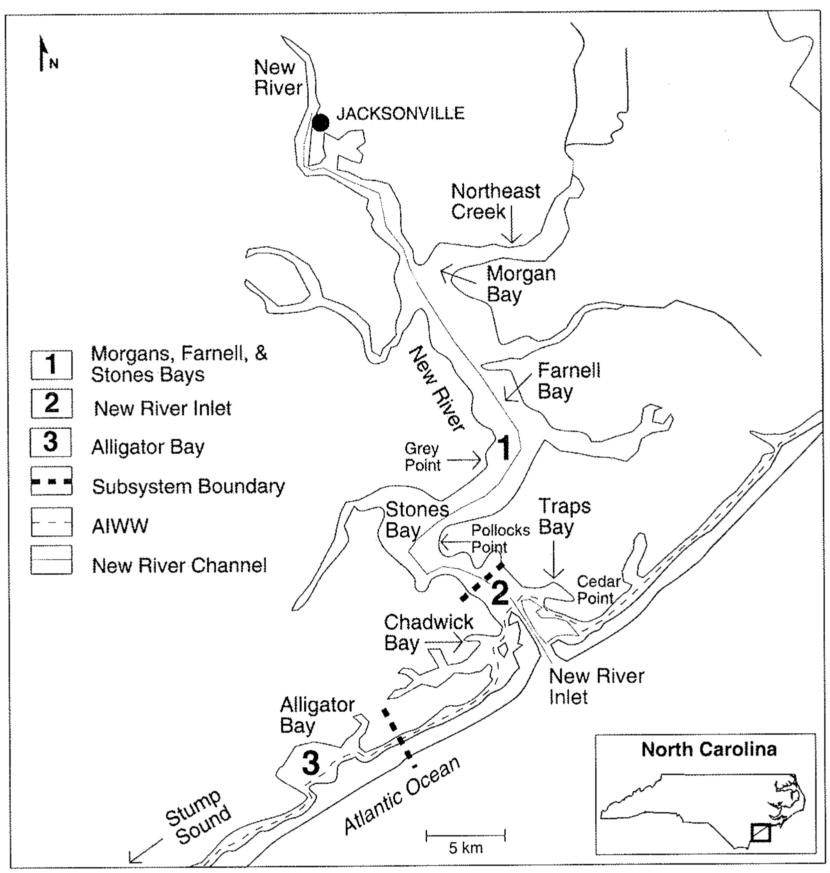
Bathymetry

The average depth of this estuary is approximately 2 m at mid-tide level (NOAA, 1990). Broad, relatively deep (ca. 3 m) natural channels exist throughout Morgan, Farnell, and Stones bays, while the estuary below Pollocks Point is generally less than 1 m at MLW. The AIWW (4 m at MLW) crosses the lower estuary from Salliers Bay (not shown) to Alligator Bay. The New River Channel is shallow (2 m at MLW) and segmented, extending from the AIWW near New River Inlet to Jacksonville. Numerous dredged material disposal areas exist along the New River Channel.

Freshwater

This estuary receives most of its freshwater from New River, although the total inflow volume is limited by its small watershed (1,295 km²). This watershed, the smallest of all major South Atlantic systems, lies almost entirely within Onslow County (NOAA, 1990). Highest river discharge usually occurs during the winter and early spring; lowest discharge occurs during the late summer and fall (Dennis, 1988) (Figure 18). Direct precipitation to the estuary increases during the summer due to thunderstorm activity, although concurrent evaporative losses are also high (Clay et al., 1975; NOAA, 1980; Schoenbaum,1982) (Figure 18). Figure 19 provides

Figure 17. *Location map and subsystem identification*



salinity sampling and average salinity during low- and high-salinity periods.

Tides

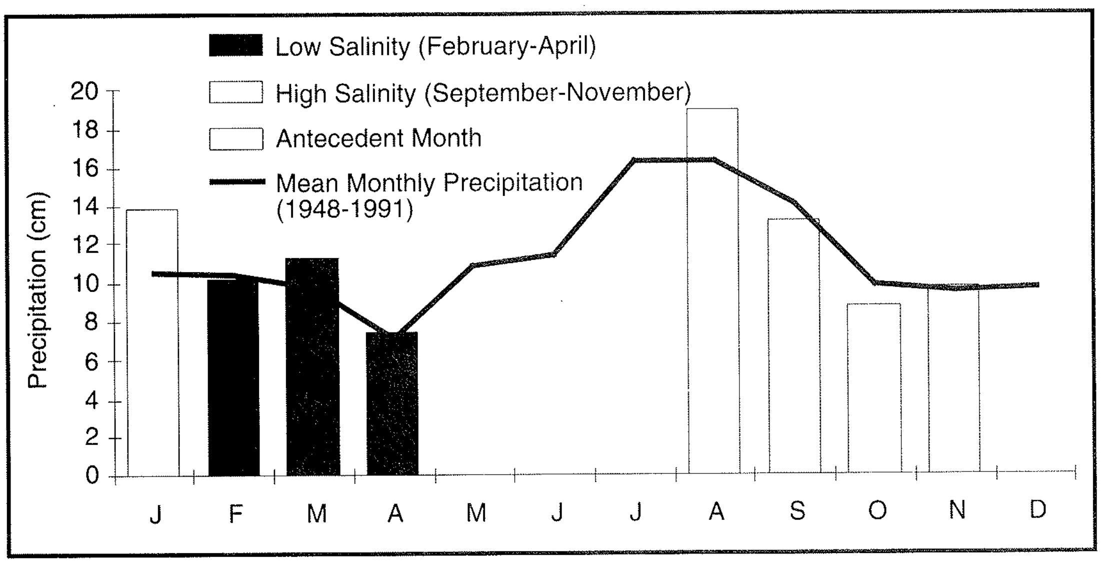
Tidal exchange occurs through New River Inlet. This pass, constricted by extensive tidal marshes and flats, is subject to frequent shoaling. The astronomical tidal range is 0.9 m at New River Inlet, but is reduced to 0.15 m above Cedar Point (Dennis, 1988).

Salinity

The salinity structure is primarily determined by the seasonal freshwater discharge from the New River, although areas above Pollocks Point experience the greatest change (Figure 20). Vertical stratification occurs infrequently in the lower estuary, but moderately stratified conditions persist throughout Morgan, Farnell, and Stones bays.

Under low-inflow conditions, salinities are most variable in Morgan Bay and near Pollocks Point. Under high-inflow conditions, variability in Stones and Farnell bays increases while Morgan Bay becomes more stable. Tidal influence is generally restricted to the lower estuary, increasing vertical mixing and maintaining relatively stable salinities in the estuary. However, high-salinity waters can extend into the upper estuary under low-inflow conditions, but appear to readily recede into Farnell and Stones bays during freshets. Salinities in Alligator Bay may be independent of conditions in the remaining estuary. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 21.

Figure 18. *Comparison of total precipitation (cm) at Morehead City, NC during periods of salinity depiction shown in Figure 19*



Abbreviation: cm - cubic meters

Figure 19. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1972	98	0	0	100	84	0	0	100
1973	36	0	0	100	36	0	0	100
1974	36	0	0	100	36	0	0	100
1975	36	0	0	100	36	0	0	100
1978	1	0	0	100	1	0	0	100
1979	30	0	0	100	30	0	0	100
1980	30	0	0	100	30	0	0	100
1984	37	0	0	100	28	0	0	100
1985	31	0	0	100	21	0	0	100
1987	36	0	0	100	22	0	0	100
1988	35	0	0	100	20	0	0	100
1989	26	0	0	100	20	0	0	100
1990	14	0	0	100	0	0	0	100
1991	14	0	0	100	0	0	0	100
1992	5	0	0	100	0	0	0	100
Total Observations	465	0	0	100	364	0	0	100
Average Salinity (ppt)	12.9				15.4			

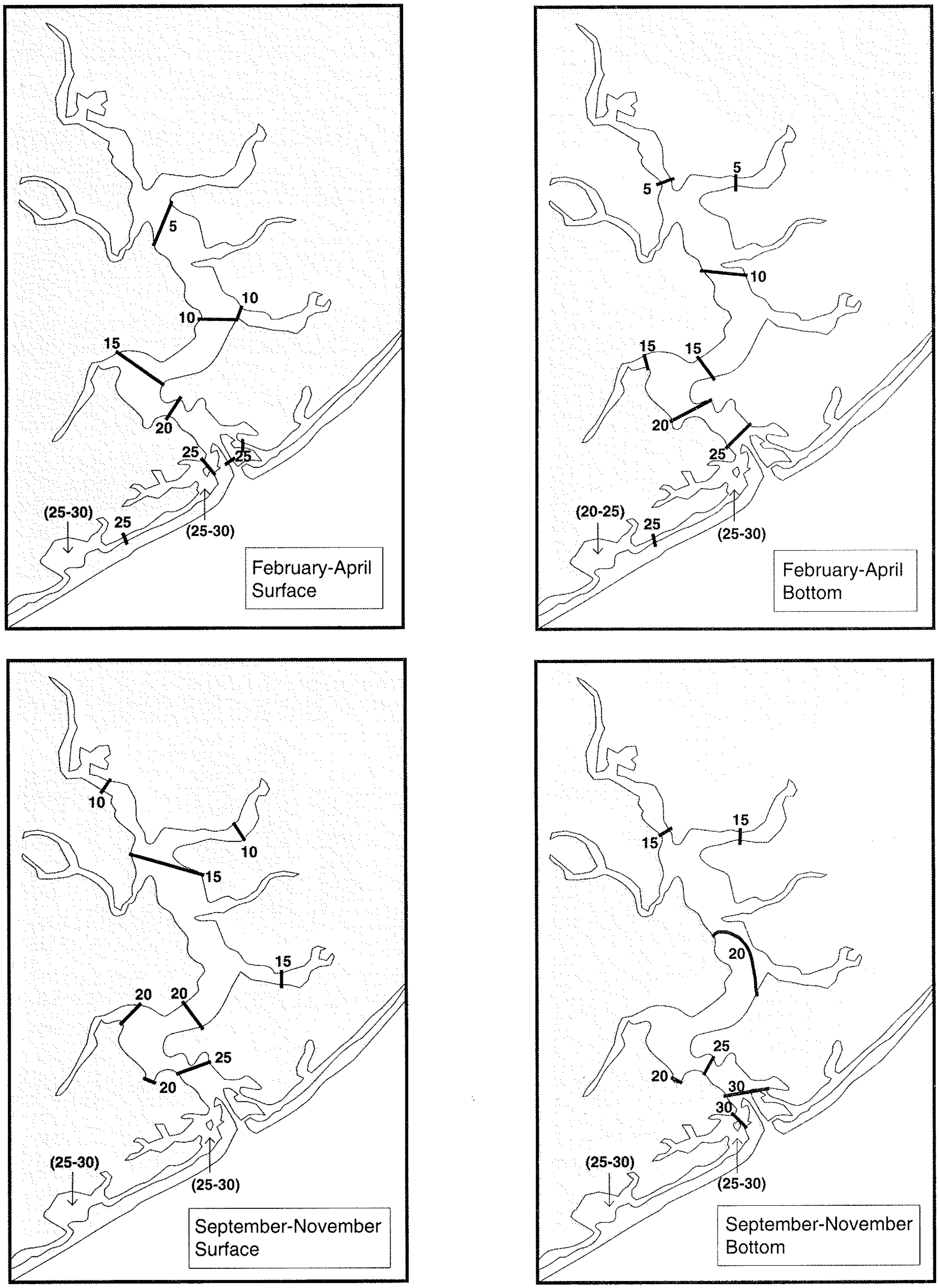
September-November
High-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1972	104	0	0	100	103	0	0	100
1973	36	0	0	100	36	0	0	100
1974	36	0	0	100	36	0	0	100
1975	13	0	0	100	13	0	0	100
1976	49	0	0	100	49	0	0	100
1979	45	0	0	100	45	0	0	100
1980	45	0	0	100	45	0	0	100
1981	54	0	0	100	45	0	0	100
1982	46	0	0	100	37	0	0	100
1983	44	0	0	100	35	0	0	100
1984	50	0	0	100	42	0	0	100
1986	64	0	0	100	45	0	0	100
1987	57	0	0	100	42	0	0	100
1988	55	0	0	100	39	0	0	100
1991	15	0	0	100	0	0	0	100
Total Observations	713	0	0	100	612	0	0	100
Average Salinity (ppt)	19.4				21.8			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 20. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 19* *

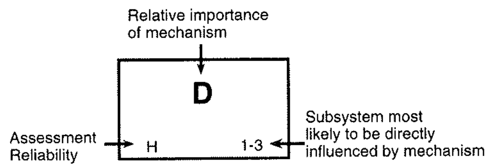


* Data Sources: See data sources listed for New River in the Appendix.

Figure 21. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 19**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		D (L, 1)	D (L, 1-3)	D (L, 1-3)	
Tides	D (LIT, 2-3)				
Wind		S (LIT, 1-3)			
Density Currents			M (LIT, 1-3)		
Effect on Salinity Variability	UNKNOWN	HIGH	MEDIUM	MEDIUM	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt	**D** - dominant	**H** - high
High = 11-20 ppt	**S** - secondary	**M** - moderate
Medium = 6-10 ppt	**M** - minor	**L** - low
Low = 3-5 ppt		**LIT** - Literature Only
Very Low = < 2 ppt		



NOTE: Isohalines illustrated in Figure 20 represent the "mean" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Dominant influence on salinity variability and stratification, primarily in the upper estuary and major tributaries. Freshets temporarily displace saline bottom waters towards Farnell and Stones bays and may increase vertical stratification in these areas.

Months-Seasons. Dominant estuary-wide influence on the salinity structure, primarily above Pollocks Point.

Year-Year. Dominant estuary-wide influence on the salinity structure, primarily above Pollocks Point.

Tides

Hours. Dominant influence on salinity variability and water-column mixing, primarily in the lower estuary. Tides are semi-diurnal and range 0.9 m at New River Inlet, but only 0.15 m above Cedar Point (Dennis, 1988). Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability, particularly when associated with fronts. These winds increase water-column mixing and estuary-ocean exchanges. The effects are intensified by the onset of "northeasters."

Density Currents

Months-Seasons. Minor influence on the salinity structure, primarily in Stones, Farnell, and Morgan bays.

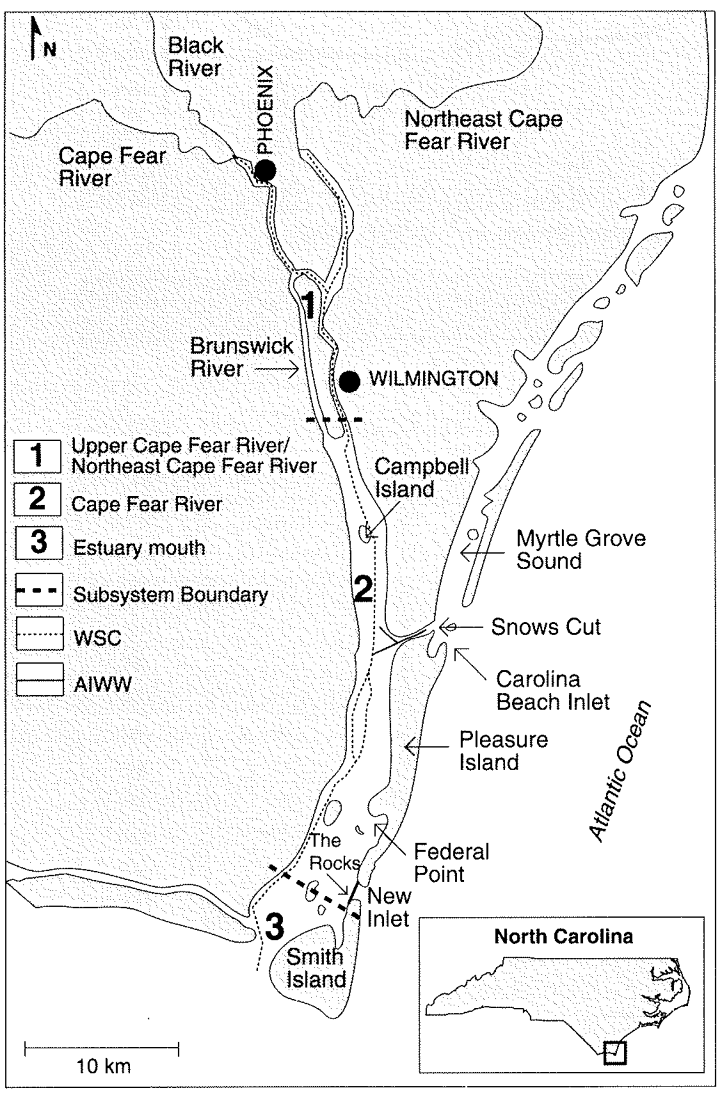
* Data Sources: See data sources listed for New River in the Appendix.

Cape Fear River, NC

Description

The Cape Fear River estuary is a coastal plain, drowned river valley system (Pietrafesa and Janowitz, 1988), encompassing 98 km^2 (NOAA, 1990). It includes Cape Fear and Northeast Cape Fear rivers which combine near Wilmington, North Carolina to form a narrow, elongated tidal basin (Figure 22) containing numerous islands, tidal flats, and marshes (Pietrafesa and Janowitz, 1988). This estuary is defined from the head of tide on the Cape Fear River at Lock and Dam No. 1 (61 km upstream of Wilmington, NC) and on the Northeast Cape Fear River near Holly Shelter Creek (Giese, Wilder, and Parker, 1979). It has been divided into three sub-systems based on the response of salinity to forcing mechanisms and time scales (Figure 22).

Figure 22. *Location map and subsystem identification*



Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level (NOAA, 1990), although most of it is less than 2 m deep. The Wilmington Ship Channel (WSC) (12 m at MLW) extends from the Atlantic Ocean to beyond Wilmington and facilitates the saltwater intrusion into this estuary (Giese, Wilder, and Parker, 1979; Hackney and Yelverton, 1990).

Freshwater

This estuary receives most of its freshwater from the Cape Fear River, although the South (not shown), Black, and Northeast Cape Fear rivers collectively drain an additional 40% of the estuary's watershed (NOAA, 1990; USGS, 1993). Highest river discharge usually occurs in the spring due to snowmelt and rainfall from mountains and piedmont areas; lowest discharge occurs during late summer and fall (Blanton et al., 1985; Crawford, 1983) (Figure 23). A minimum flow rate (17 m^3/s at Lillington, NC) is maintained on the Haw River, a tributary of the Cape Fear River, through releases from the B. Everett Jordan Dam (USACE, 1992). This structure has little influence on estuarine salinities (Giese, Wilder, and Parker, 1979). Figure 24 provides the salinity sampling and average salinity during low- and high-salinity periods.

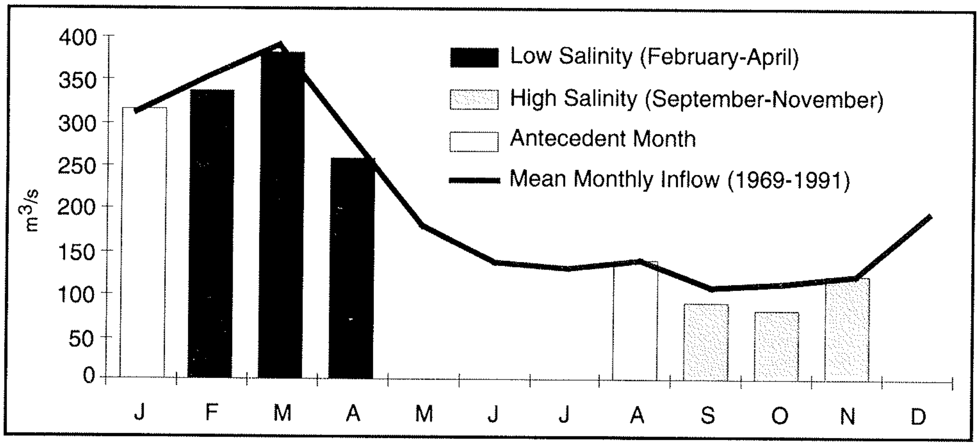
Tides

Most tidal exchange occurs through the river mouth at Smith (Bald Head) Island. Additional exchange is limited through Snows Cut, a narrow and shallow (2.5 m at MLW) connection between the WSC (12 m at MLW) and the AIWW (4 m at MLW). New Inlet, a shallow (<1 m) breach between Smith and Pleasure islands, was once a navigable pass. Since the construction of a breakwater called *The Rocks* (1889), New Inlet has continued to shoal and is, at present, nearly closed (USACE, 1984).

Salinity

The salinity structure is primarily determined by the seasonal freshwater discharge of the Cape Fear River and its tributaries. Under typical high-flow conditions, the plume may generate tidal-fresh to brackish salinities below Wilmington, although this condition is restricted to upper Cape Fear River and its tributaries under low-flow conditions. Salinities in the WSC are rarely unstratified, often becoming moderately-to-highly stratified under seasonally high-flow conditions (Giese, Wilder, and Parker, 1979; USACE, 1989). In contrast, the shallow periphery of this estuary is typically vertically homogeneous. This estuary experiences significant intra-annual variability, particularly between Campbell Island and Federal Point (Figure 25). Relatively stable salinities are restricted to upper tributaries and estuary mouth. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 26.

Figure 23. *Comparison of gaged freshwater volume for Cape Fear, Northeast Cape Fear, and Black rivers during periods of salinity depiction shown in Figure 24**



* USGS gages reflect 72% of the estuary's watershed (23,568 km^2) (USGS, 1993)

Figure 24. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1971	10	0	0	100	8	0	0	100
1972	65	0	0	100	65	0	0	100
1974	20	0	0	100	12	0	0	100
1976	6	0	0	100	6	0	0	100
1977	8	0	0	100	8	0	0	100
1978	16	0	0	100	16	0	0	100
1979	28	0	0	100	28	0	0	100
1980	27	0	0	100	27	0	0	100
1982	150	27	47	26	139	29	50	20
1985	160	39	28	33	140	45	32	23
1987	152	23	54	23	142	25	58	18
1989	137	54	25	21	126	59	27	14
1990	133	39	49	12	117	44	56	0
1991	133	41	47	12	117	46	54	0
Total Observations	1045	31	34	35	951	34	38	29
Average Salinity (ppt)	8.1				12.9			

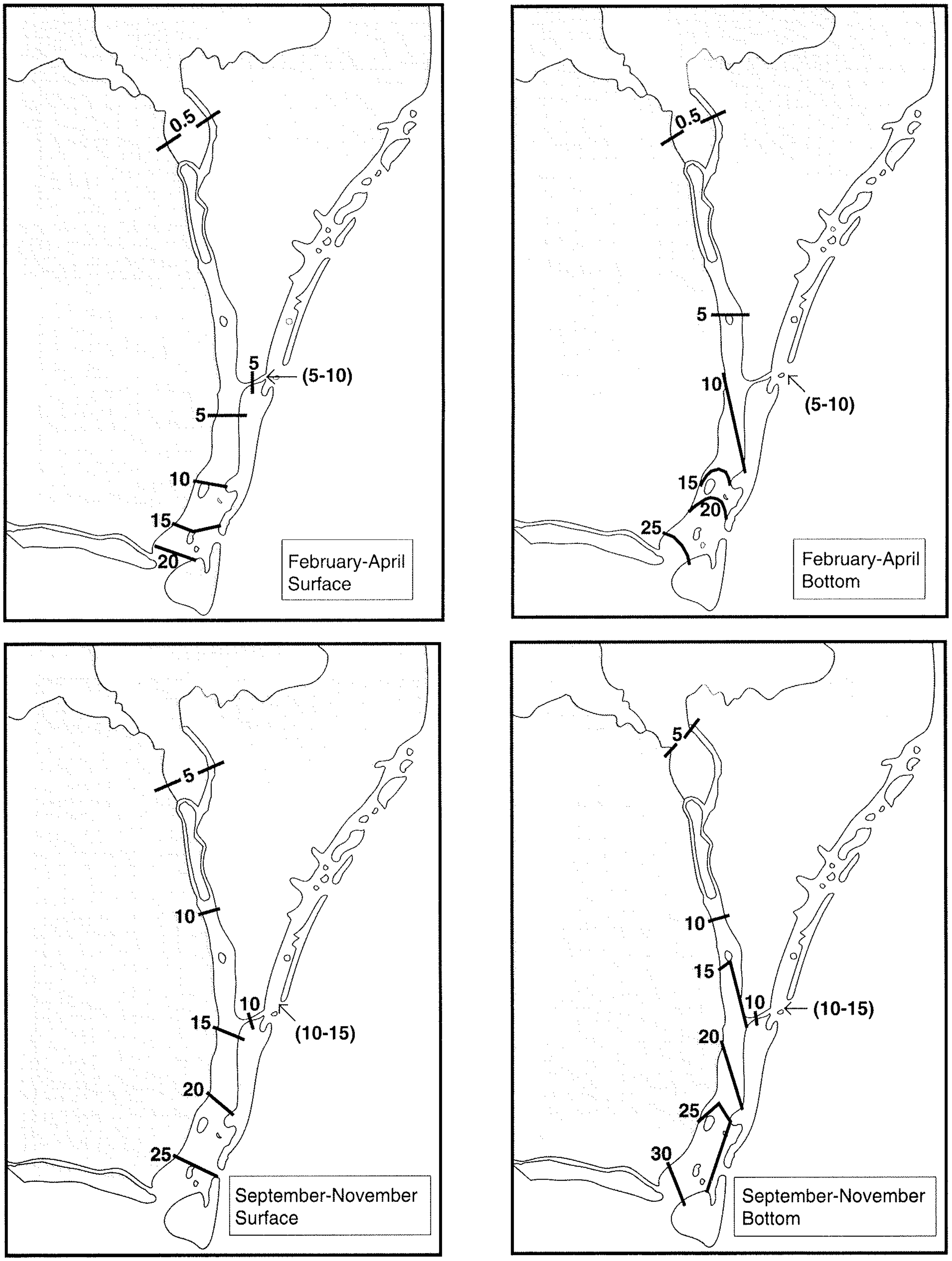
September-November
High-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1970	35	0	0	100	35	0	0	100
1972	61	0	0	100	61	0	0	100
1975	21	0	0	100	21	0	0	100
1977	14	0	0	100	14	0	0	100
1978	45	0	0	100	45	0	0	100
1981	51	0	0	100	41	0	0	100
1982	176	26	45	28	165	28	48	24
1984	180	34	31	35	165	38	33	29
1985	188	28	35	38	165	32	39	29
1986	186	47	16	37	166	53	17	30
1988	170	17	52	31	153	19	58	24
1990	132	31	58	11	117	35	65	0
1991	145	51	30	19	117	63	37	0
Total Observations	1404	28	31	41	1265	31	34	21
Average Salinity (ppt)	17.3				12.9			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 25. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 24* *

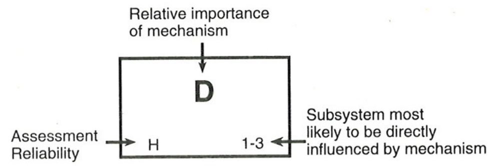


* Data Sources: See data sources listed for Cape Fear River in the Appendix.

Figure 26. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 24**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (M, 1-2)	D (M, 1-3)	D (M, 1-3)	
Tides	D (LIT, 2-3)	M (LIT, 2-3)			
Wind		S (LIT, 1-3)	S (LIT, 1-3)		
Density Currents			S (LIT, 2-3)		
Effect on Salinity Variability	UNKNOWN	MEDIUM	MEDIUM	MEDIUM	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 25 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability and stratification, primarily in the upper and mid-estuary. Freshets displace saline bottom waters, resulting in vertically homogeneous conditions in the upper bay and stratified conditions within the WSC (Giese, Wilder, and Parker, 1979). Freshwater discharges of 370 m^3/s and 650 m^3/s are required to prevent flood-tide flow reversals on the Cape Fear River near Phoenix and the Northeast Cape Fear River mouth, respectively (Giese, Wilder, and Parker, 1979).

Months-Seasons. Dominant estuary-wide influence on the salinity structure. Discharge from the principal rivers is three times greater during the high-flow period than during the low-flow period. Isohalines are displaced by approximately 5 ppt throughout most of the estuary (Giese, Wilder, and Parker, 1979).

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant influence on salinity variability and water-column mixing, primarily in lower and mid-estuary. Tides are semi-diurnal and range 1.3 m near the estuary mouth (Giese, Wilder, and Parker, 1979; Hackney and Yelverton, 1990). Data insufficient to determine salinity changes during a tidal cycle.

Days-Weeks. Minor influence on salinity variability, causing modest additional increases of salinity and water-column mixing. Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability, particularly when associated with fronts. These winds increase water-column mixing and may either flush estuarine waters or increase seawater intrusion to the estuary, depending on the location of the low pressure cell relative to the estuary. The effects are intensified by the onset of "northeasters."

Months-Seasons. Secondary estuary-wide influence on the salinity structure. Prevailing winds are generally from the north or northeast during October-February, south or southeast during January-June, and south or southwest during July-August. These winds influence ocean water levels and circulation patterns, affecting estuary-ocean exchanges (Giese, Wilder, and Parker, 1979; Hackney and Yelverton, 1990; Pietrafesa and Janowitz, 1988).

Density Currents

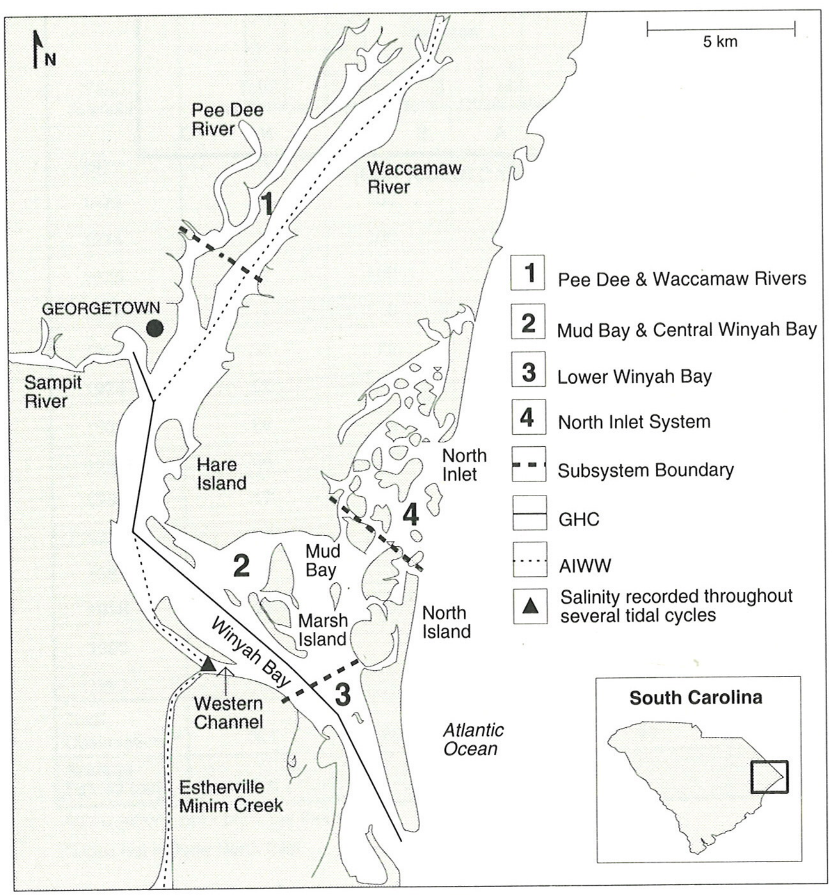
Months-Seasons. Secondary influence on the salinity structure. The WSC increases tidal amplitude and salinity intrusion (Hackney and Yelverton, 1990). The effect on seawater intrusion and vertical stratification is augmented by the dredged material disposal along the channel (Adams, Pers. Comm.), but also depends on river discharge and wind (Giese, Wilder, and Parker, 1979).

* Data Sources: See data sources listed for Cape Fear River in the Appendix.

Description

The Winyah Bay estuary is a small coastal plain system that occupies 78 km^2 (NOAA, 1990) and contains numerous marshes, shoals, and interior islands (Blood and Vernberg, 1992; DeVoe, 1992). It includes the Pee Dee, Waccamaw, Black (not shown), and Sampit rivers which combine at Georgetown where the estuary widens and changes orientation (Figure 27). The inland boundary is defined from the head of tide on Pee Dee River (approximately 60.8 km upstream of the entrance to Winyah Bay), Waccamaw River (131 km), and Black River (74 km) (Blood and Vernberg, 1992). The Sampit River is tidal along its entire length (Bloomer, 1973). Winyah Bay is connected to North Inlet by three creeks, although water exchange is limited (DeVoe, 1992) and to the North Santee River system through the AIWW. This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 27).

Figure 27. *Location map and subsystem identification*



Bathymetry

The average depth of this estuary is approximately 3.4 m at mid-tide level (NOAA, 1990). Naturally deep areas occur near the estuary entrance and in major river systems, although most of Winyah Bay (between Georgetown and Mud Bay) is less than 2 m. The Georgetown Harbor Channel (GHC) (8 m at MLW) extends from the entrance jetty to Georgetown and requires frequent dredging (DeVoe, 1992; Trawle and Boland, 1979). The AIWW (3.7 m at MLW) exists primarily within the natural channels of the Waccamaw River and Western Channel, but also joins with the GHC south of Georgetown.

Freshwater

The Pee Dee River and Little Pee Dee River (not shown) are the principal freshwater sources to the estuary. Highest river discharge usually occurs during spring due to runoff from the Blue Ridge Mountains, while lowest discharge occurs during fall (Figure 28). Figure 29 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

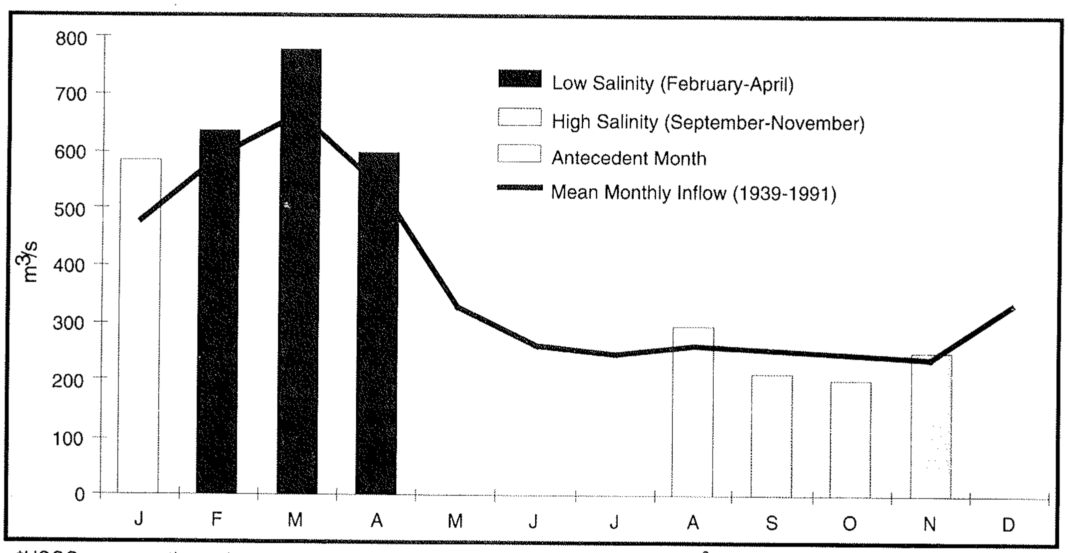
Tides

Astronomical tides range 1.2 m at the entrance to Winyah Bay, 1.0 m throughout Winyah Bay and the lower Waccamaw River, and 1.4 m at North Inlet. Tides may be a dominant factor influencing circulation (Blood and Vernberg, 1992; DeVoe, 1992) and salinity. Limited salinity data recorded for the Western Channel (Figure 27) during 1977-78 suggest that surface salinity concentrations most commonly changed 9-14 ppt throughout a tidal cycle, while bottom salinities commonly changed 10-19 ppt (SCWMRD, unpublished).

Salinity

The salinity structure is primarily determined by seasonal freshwater discharge from the Pee Dee and Little Pee Dee rivers. During the low-salinity period, freshwater maintains brackish and vertically homogeneous conditions in the upper and central estuary; variable and moderately stratified conditions exist in the Western Channel and seaward of Marsh Island. During the high-salinity period, salinities increase approximately 5-10 ppt throughout the estuary (Figure 30). Moderately stratified conditions are most common between Georgetown and Marsh Island, while other areas are generally vertically homogeneous. Surface salinities are most variable in the Western Channel and seaward of Marsh Island, while bottom salinities are most variable between Georgetown and the Western Channel. Salinities in North Inlet and its tidal tributaries are generally unstratified and remain near ocean concentrations, but may experience brief salinity reductions due to local precipitation, exchanges through Mud Bay, or plumes from adjacent estuaries. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 31.

Figure 28. *Comparison of gaged freshwater volume for Pee Dee and Little Pee Dee rivers during periods of salinity depiction shown in Figure 29**



*USGS gages on these rivers reflect 64% of the estuary's watershed (46,877 km^2) (USGS, 1993)

Figure 29. *Salinity sampling information and average salinity during low- and high-salinity periods***

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1970	18	44	56	0	0	0	0	0
1974	5	60	40	0	1	100	0	0
1977	55	73	27	0	52	77	23	0
1978	56	68	32	0	51	76	24	0
1980	10	0	0	100	0	0	0	0
1982	25	0	0	100	13	0	0	100
1987	28	4	43	54	15	0	0	100
1989	15	0	0	100	15	0	0	100
1990	15	0	0	100	15	0	0	100
1991	19	0	21	79	15	0	0	100
Total Observations*	246	37	25	39	177	45	14	41
Average Salinity (ppt)	4.2				3.8			

September-November
High-Salinity Period

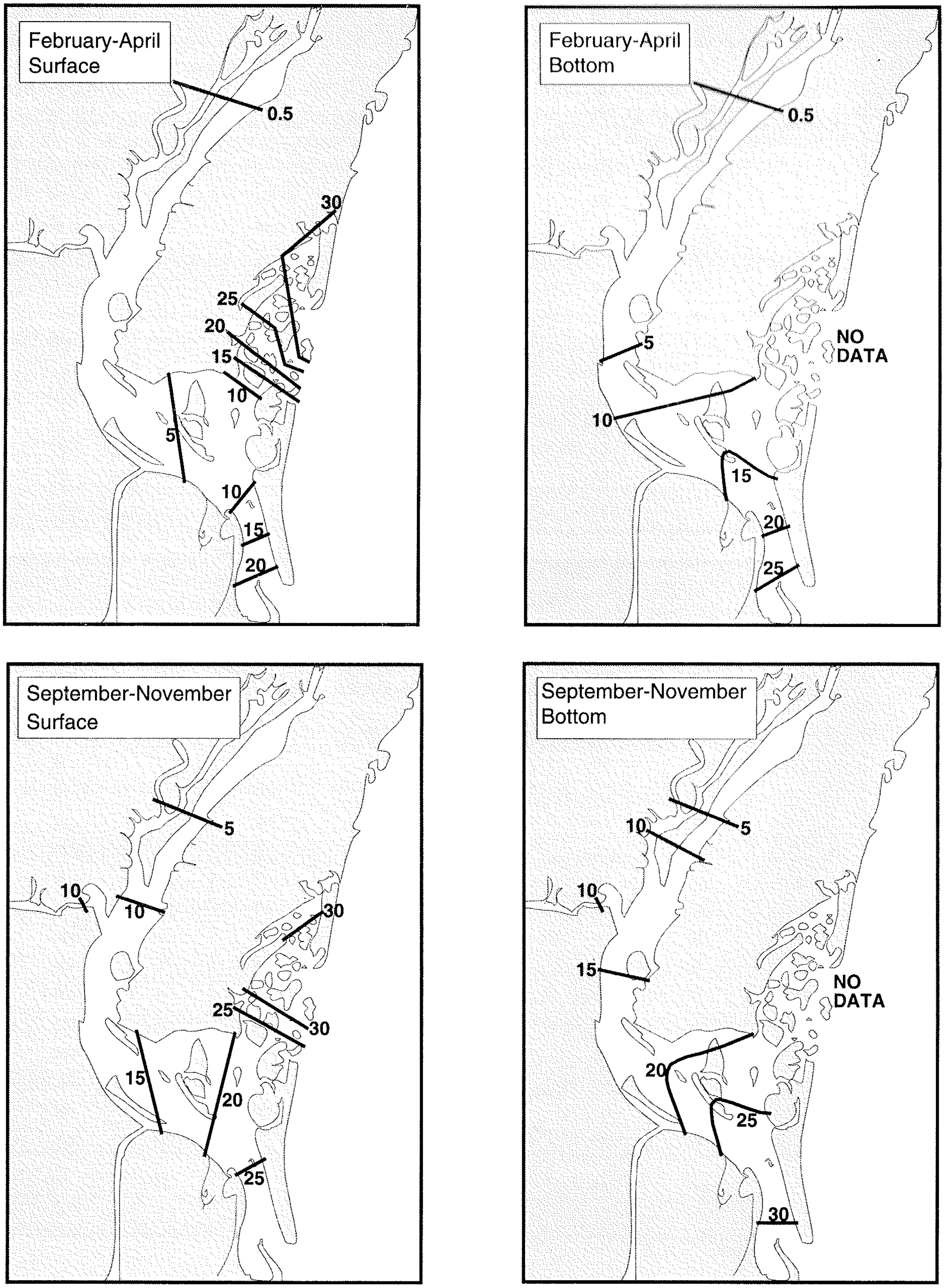
Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1972	10	40	60	0	0	0	0	0
1973	1	100	0	0	1	100	0	0
1974	1	100	0	0	1	100	0	0
1975	1	100	0	0	1	100	0	0
1976	1	0	100	0	1	0	100	0
1977	52	72	23	0	52	77	23	0
1978	52	79	21	0	54	78	22	0
1981	28	0	0	100	14	0	0	100
1982	24	0	0	100	13	0	0	100
1984	17	0	0	100	17	0	0	100
1985	27	11	26	63	17	0	0	100
1987	17	0	0	100	17	0	0	100
1988	27	7	7	85	16	0	0	100
1990	17	0	0	100	17	0	0	100
1991	46	0	39	61	11	0	0	100
Total Observations*	321	29	18	53	232	37	11	53
Average Salinity (ppt)	11.6				12.7			

Abbreviation: ppt - parts per thousand

*Does not include North Inlet

**Includes years when freshwater inflow volume was within +1 standard deviation of the long-term mean.

Figure 30. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 29* *

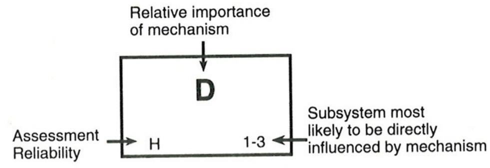


* Data Sources: See data sources listed for Winyah Bay in the Appendix.

Figure 31. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 29**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		**S** L 1-2	**D** L 1-3	**D** L 1-4	
Tides	**D** LIT 1-4				
Wind		**S** LIT 1-4			
Density Currents			**S** LIT 1-3		
Shelf Processes			**M** LIT 3-4		
Effect on Salinity Variability	UNKNOWN	MEDIUM	MEDIUM	MEDIUM	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 30 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability and stratification, primarily in the upper estuary and its major tributaries. Freshets temporarily displace saline bottom waters toward Marsh Island and may increase vertical stratification in these areas.

Months-Seasons. Dominant influence on the salinity structure, primarily in Winyah Bay and its tributaries (less influence within the North Inlet system). Typical seasonal inflows alter salinities approximately 10 ppt throughout most of the estuary. In addition, areas of stratification and variability migrate according to inflow volume. Typical high inflows may have some influence on salinities in North Inlet.

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant estuary-wide influence on salinity variability and water-column mixing. Limited data suggests that tide-induced salinity changes are significant in the Western Channel (SCWMRD, unpublished) although information is not available for other areas of this estuary. Tides are semi-diurnal, ranging about 1 m throughout most of the estuary and its tributaries.

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability, particularly when associated with fronts. These winds increase water-column mixing and may affect exchanges between Mud Bay and North Inlet. These effects may be intensified by the onset of "northeasters."

Density Currents

Months-Seasons. Secondary influence on the salinity structure, primarily in the lower and mid-estuary.

Shelf Processes

Months-Seasons. Minor influence on the salinity structure, primarily in lower Winyah Bay. Discharges from adjacent estuaries may lower salinities of shelf waters entrained into Winyah Bay.

* Data Sources: See data sources listed for Winyah Bay in the Appendix.

Description

The North/South Santee Rivers estuary is a coastal plain, drowned river valley system that occupies 23 km^2 (Mathews et al., 1980; NOAA, 1990). It includes the Santee River below Lake Marion (not shown), and its two principal distributaries, the North and South Santee rivers (Figure 32). It is defined from the head of tide, approximately 77 km upriver from the mouth (NOAA, 1985; USACE, 1991a). This estuary is separated from Winyah Bay to the north and from coastal plain creeks, sounds, and bays to the south by tidal nodes in the AIWW. This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 32).

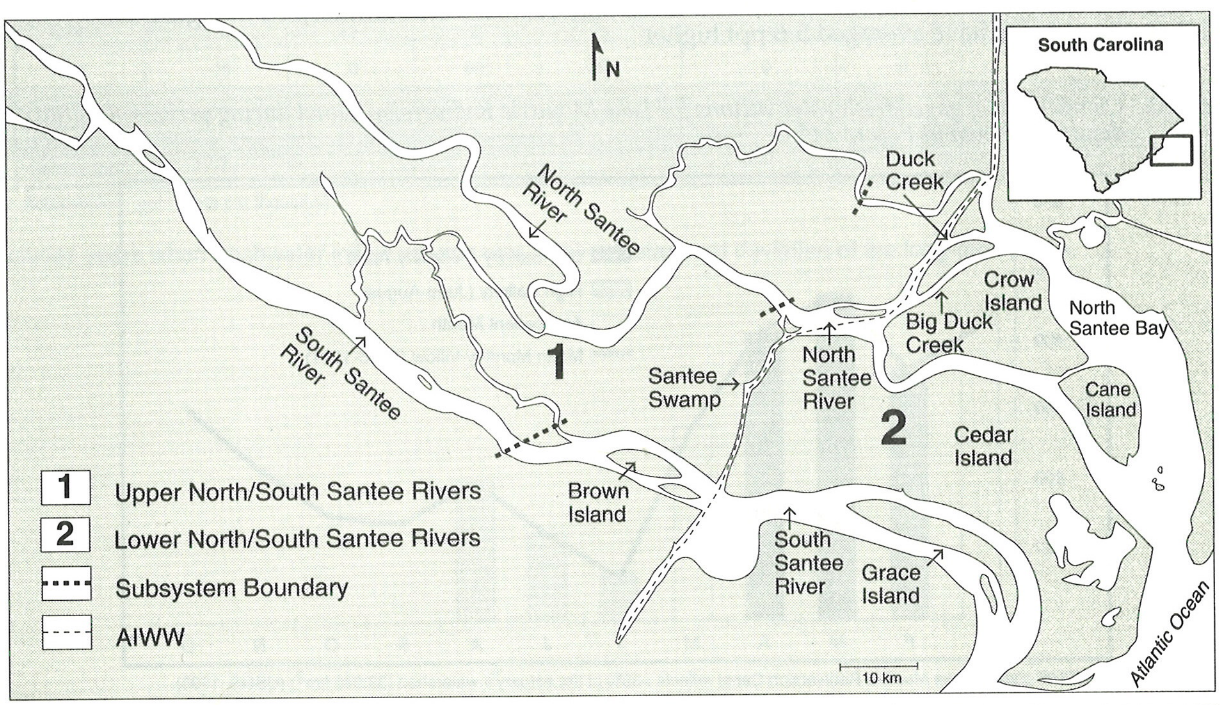
Bathymetry

The average depth of this estuary is approximately 2.4 m at mid-tide level (NOAA, 1990), with depths ranging from <1 m to >11 m throughout the system. The South Santee River becomes wider and shallower below Brown Island, and is split by Grace Island before converging again toward the mouth. The North Santee River is connected to the broad, shallow North Santee Bay (1.3 m deep) by Duck and Big Duck creeks and by the AIWW above Crow Island (Figure 32). The North Santee River and North Santee Bay converge again below Cane Island before flowing into the Atlantic Ocean. The AIWW (3.7 m at MLW) is the only actively maintained navigation channel in this estuary, and may serve as a conduit for high-salinity water between the North Santee River and Winyah Bay (Mathews and Shealy, 1982).

Freshwater

This estuary receives most of its freshwater from the Santee River which, together with its two distributaries, drains a total surface area of 40,000 km^2 (NOAA, 1990). Before 1941, the Santee River drainage basin was the fourth largest on the Atlantic coast south of the St. Lawrence River (Kjerfve, 1976). As part of a hydroelectric project, construction was completed in 1942 on the Wilson Dam, 163 km upriver from the mouth of Santee River, creating Lake Marion (Kjerfve and Greer, 1978; Mathews et al., 1981; Tiner, 1977). A canal from Lake Marion to Lake Moultrie diverted an average of 88% of the Santee River's freshwater flow to the Cooper River. Average annual freshwater flow in the Santee River dropped from 525 to 74 m^3/s, allowing saltwater intrusion into the system (Kjerfve and Greer, 1978). In 1985, approximately 70% of Cooper River's flow was rediverted from Lake Moultrie back into the Santee River, raising flow to approximately 367 cms and lowering salinity again throughout the system

Figure 32. *Location map and subsystem identification*



(USACE, 1991a). Since rediversion, most flow into the North/South Santee Rivers system has come through the Lake Moultrie Rediversion Canal, although occasional releases from the Wilson Dam on Lake Marion following a freshet can increase flow dramatically. Figure 33 provides a comparison of gaged freshwater volume from the Lake Moultrie Rediversion Canal during periods of salinity depiction. Figure 33 does not reflect additional discharge to Santee River from Lake Marion. The average daily flow from Lake Marion is approximately 18 m^3/s; however, on two occasions (March 1987 and October 1990), the average daily discharge increased to approximately 500 m^3/s. Figure 34 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

Tides

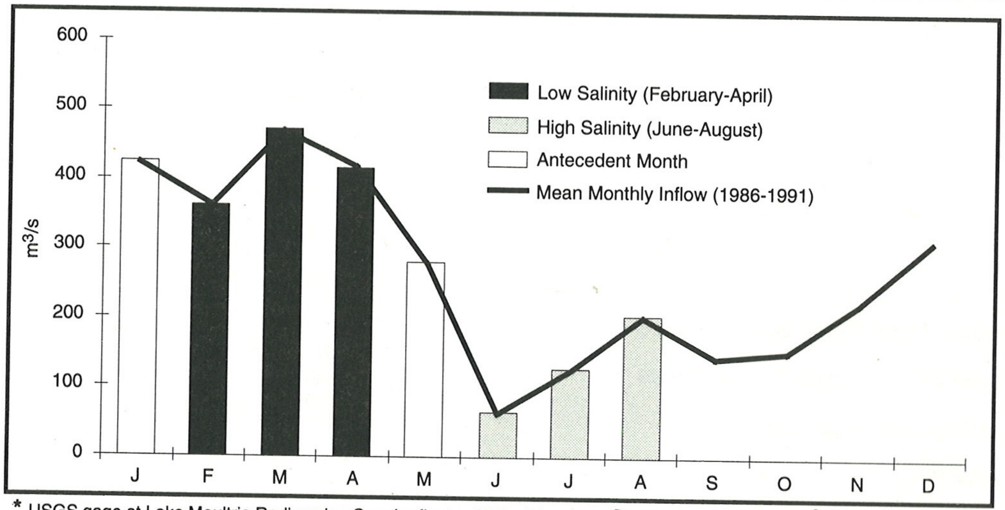
Most tidal exchange occurs through the mouths of North and South Santee rivers, although limited exchanges may also occur with Winyah Bay to the north and with tidal creeks, inlets, and bays to the south through the AIWW (Mathews and Shealy, 1982). Tidal range at the mouths of North and South Santee rivers is 1.3 m (USACE, 1991a).

Salinity

The salinity structure is primarily determined by controlled seasonal freshwater discharge from the Lake Moultrie Rediversion Canal and by tidal influence. Since rediversion, surface salinities throughout the estuary have averaged 5-6 ppt higher during the typical high-salinity period (June-August) than during the typical low-salinity period (February-April). However, greater seasonal variability is apparent in the lower estuary (below the AIWW). Vertical stratification is generally weak and slightly greater (<2 ppt on average) under high-flow conditions in spring than under low-flow conditions in fall. Stratification is more pronounced and salinities are more variable in the mid-estuary (i.e., near the AIWW within North and South Santee rivers) than in the upper estuary or near the mouth.

This estuary experiences significant intra-annual variability, particularly near the AIWW. Relatively stable salinities are restricted to the upper estuary where salinities are generally <5 ppt (Figure 35). Highest variability occurs in the lower estuary, seaward of the AIWW. Freshwater inflow and tides are the dominant mechanisms controlling salinity variability. Data available at numerous locations throughout the estuary during 1986-1991 (SCWMRD, unpublished) suggest that semi-diurnal tides can have a great effect on surface and bottom salinities in North and South Santee rivers, particularly during the high-inflow season. Salinity differences average almost 15 ppt between successive high and low tides in lower North and South Santee rivers (below river kilometer 6 and river kilometer 5, respectively). Above river kilometer 14 in South Santee River and river kilometer 16 in the North Santee River, salinity differences are commonly <2 ppt. These ranges, however, depend on prevailing freshwater and wind conditions, and may vary considerably. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 36.

Figure 33. *Comparison of gaged freshwater volume for Lake Moultrie Rediversion Canal during periods of salinity depiction shown in Figure 34**



* USGS gage at Lake Moultrie Rediversion Canal reflects >95% of the estuary's watershed (39,946 km^2) (USGS, 1993)

Figure 34. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1986	55	36	56	7	39	51	49	0
1987	43	37	63	0	19	0	100	0
1988	37	14	65	22	19	32	68	0
1989	12	0	100	0	0	0	0	0
1990	12	0	100	0	0	0	0	0
1991	12	0	100	0	0	0	0	0
1992	6	0	100	0	0	0	0	0
Total Observations	177	23	70	7	77	34	66	0
Average Salinity (ppt)	5.1				6.8			

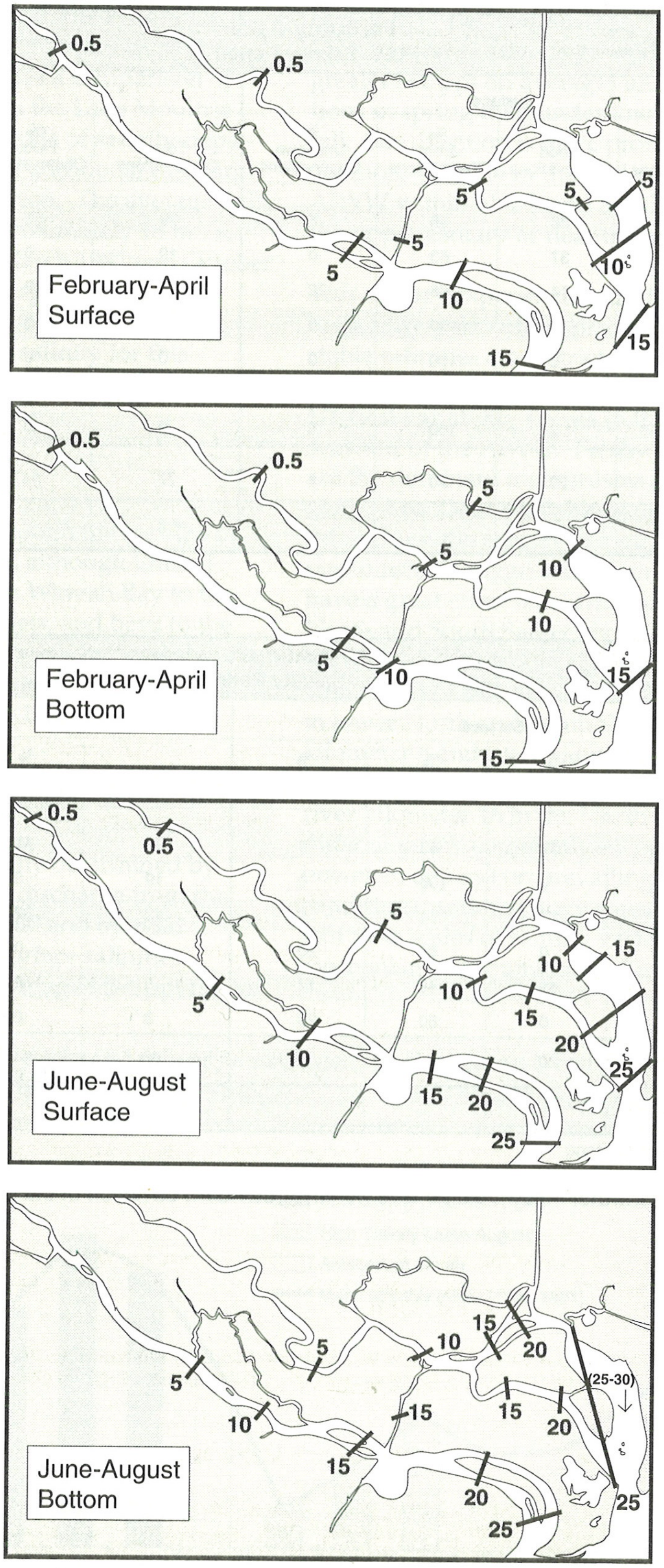
June-August
High-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1986	57	37	63	0	39	51	49	0
1987	25	0	100	0	19	0	100	0
1988	35	17	74	9	22	32	64	5
1989	15	0	80	20	0	0	0	0
1990	14	43	43	14	0	0	0	0
1991	15	0	80	20	0	0	0	0
Total Observations	161	20	73	7	80	34	65	1
Average Salinity (ppt)	10.6				10.0			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within +1 standard deviation of the long-term mean.

Figure 35. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 34* *

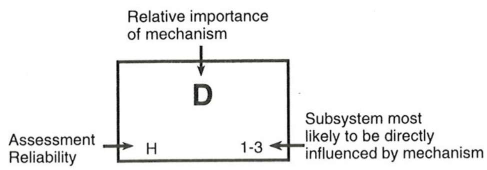


* Data Sources: See data sources listed for North/South Santee Rivers in the Appendix.

Figure 36. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 34**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S M 1-2	D M 1-2	D M 1-2	
Tides	D LIT 1-2	S LIT 1-2			
Wind		M LIT 1-2	S LIT 1-2		
Inter-estuary Exchanges	M LIT 2				
Effect on Salinity Variability	MEDIUM	MEDIUM	MEDIUM	MEDIUM	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 35 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Secondary estuary-wide influence on the salinity structure, particularly during low-flow periods. Periodic releases from the Wilson Dam spillway, following freshets, displace higher salinity waters seaward and temporarily increase vertical stratification (Mathews et al., 1980).

Months-Seasons. Dominant estuary-wide influence on the salinity structure. Freshwater inflow through the rediversion canal at St. Stephen is greatly increased during the winter and spring. Periodic releases from the Wilson Dam spillway also occur more frequently during these seasons.

Year-Year. Dominant estuary-wide influence on the salinity structure. During dry years, less water is rediverted to Santee River to maintain a minimum flow rate in Cooper River.

Tides

Hours. Dominant influence on the salinity structure, primarily in the lower and mid-estuary. Tides are semi-diurnal and range 1.3 m near the estuary mouth (USACE, 1991a). Data available at numerous locations throughout the estuary during 1986-1991 (SCWMRD, unpublished) suggest that semi-diurnal tides can have a great effect on surface and bottom salinities in North and South Santee rivers, particularly during the high-inflow season. Salinity differences average almost 15 ppt between successive high and low tides in lower North and South Santee rivers (below river mile 4 and river mile 3, respectively). Above river mile 9 in South Santee River and river mile 10 in North Santee River, salinity differences are commonly <2 ppt. These ranges, however, depend on prevailing freshwater and wind conditions, and may vary considerably.

Days-Weeks. Secondary influence on the salinity structure, primarily in the lower estuary due to the semi-lunar spring/neap tidal cycle.

Wind

Days-Weeks. Minor influence on the salinity structure, particularly in the lower estuary. Winds associated with fronts can increase water-column mixing and estuary-ocean exchanges. Alongshore winds can set up nearshore currents with a mass flux onshore or offshore, depending on wind direction (Schwing et al., 1983).

Months-Seasons. Secondary estuary-wide influence on the salinity structure. In spring, northeast winds generate an offshore flow of low-salinity water in the surface layer due to Ekman Transport (Blanton and Atkinson, 1983). Higher salinity water from the mid-shelf is advected onshore along the bottom.

Inter-estuary Exchanges

Hours. Minor influence on salinity variability in the lower estuary. Tidal exchanges with Winyah Bay to the north and coastal creeks and inlets to the south occur through the AIWW (Mathews and Shealy, 1982), contributing to high variability in the mid-estuary.

* Data Sources: See data sources listed for North/South Santee Rivers in the Appendix.

Description

The Charleston Harbor estuary is a coastal plain, drowned river valley system occupying 96 km^2 (Mathews et al., 1981; NOAA, 1990). Including Charleston Harbor and all or part of three river systems, it is defined from the headwaters of the Ashley and Wando rivers, and from the Jefferies Dam in Pinopolis at the lower end of Lake Moultrie on Cooper River (Davis and Van Dolah, 1992; Kjerfve and Magill, 1990). This estuary is separated from coastal plain creeks, sounds, and bays to the north by a tidal node in the AIWW, southwest of the Ben Sawyer Bridge (not shown) (Tucker, Pers. Comm.); and from the North Edisto River basin to the south (Tucker, Pers. Comm.) by a tidal node in the Stono River, west of the Limehouse Bridge (not shown). This estuary has been divided into four subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 37).

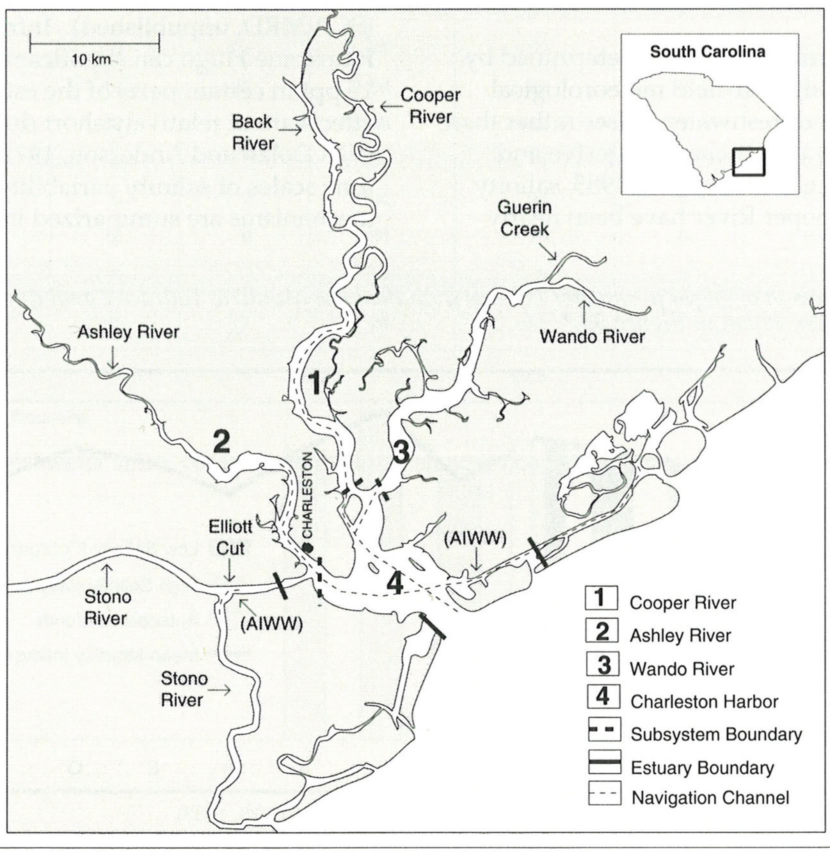
Bathymetry

The average depth of this estuary is approximately 5 m at mid-tide level (NOAA, 1990). Depths in the Charleston Harbor Channel are maintained at 12.2 m (MLW) from the estuary entrance to Charleston Harbor and at 10.7 m (MLW) in lower Cooper River (32 km upstream of Charleston Harbor) (Van Dolah and Davis, 1990; USACE, 1991a). In Wando River, a 10.7 m (MLW) channel is maintained but is scheduled to be deepened to 12.2 m (MLW) by 1994 (USACE, 1991a). Ashley River depths range from 3.4 m to 6.4 m (MLW) (Goodwin, 1989; USACE, 1991a), whereas the AIWW is 3.7 m (MLW) deep.

Freshwater

This estuary receives most of its freshwater from the Cooper River, while Ashley and Wando rivers contribute relatively little freshwater to the system (Kjerfve and Magill, 1990; Pinckney and Dustan, 1990). The three rivers, together with Charleston Harbor, drain a total surface area of 40,900 km^2 (NOAA, 1990). Originally, Cooper River was a tide-dominated stream with a flow rate of 2 cms (Kjerfve, 1976). In 1942, construction was completed on the Jefferies Dam, as part of a hydroelectric project, forming Lake Moultrie on Cooper River, as well as on a 12-km diversion canal connecting Lake Moultrie to Lake Marion on Santee River (Kjerfve, 1976; Kjerfve and Magill, 1990). The canal diverted an

Figure 37. *Location map and subsystem identification*



average of 88% of the Santee River flow, increasing the mean freshwater flow in Cooper River to 418 cms and lowering mean estuarine salinities (8 km from the open ocean) from 30 to 17 ppt. In 1985, an effort was made to alleviate excessive shoaling in the Harbor caused by the diversion from Lake Moultrie by diverting flow back into the lower Santee River through the 18.5 m St. Stephen's Rediversion Canal. Since rediversion, a weekly average flow rate of 122 cms has been maintained on Cooper River to protect industrial and municipal water supplies from saltwater intrusion (Kjerfve and Magill, 1990). Figure 38 provides a comparison of gaged freshwater volume from the Lake Moultrie Tailrace Canal during periods of salinity depiction. Figure 39 provides salinity sampling and average salinity for this estuary during low- and high-salinity periods.

Tides

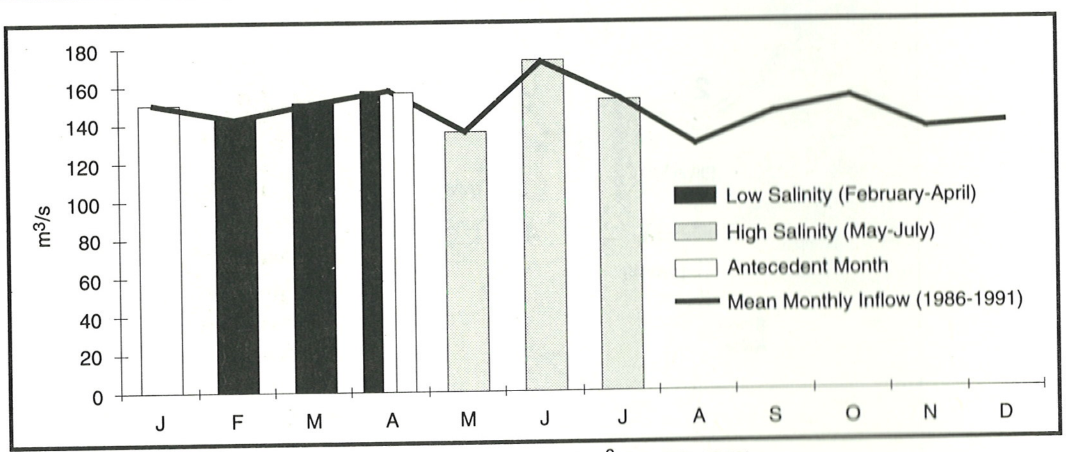
Most tidal exchange occurs through the entrance to Charleston Harbor, although limited exchange occurs with: 1) the Stono River (primarily through Elliott Cut); 2) Folly Creek (primarily through Schooner Creek); and 3) several smaller tidal creeks and inlets to the north and south.

Salinity

The salinity structure is primarily determined by the semi-diurnal tides, far-field meteorological forcing, and isolated freshwater pulses rather than by seasonal freshwater discharge (Kjerfve and Magill, 1990). Since rediversion in 1985, salinity distributions in Cooper River have been nearly identical during the typical high- and low-inflow periods because average monthly discharges from Jefferies Dam have been maintained within a fairly narrow range (92-147 cms). Some seasonal variation is apparent in Ashley and Wando rivers where isohalines are displaced down river during late winter and spring due to precipitation within the watershed. Vertical stratification is more pronounced in Cooper River (particularly in the lower and middle reaches) than in other parts of the estuary (Van Dolah and Anderson, 1991) (Figure 40).

In general, salinities in this estuary are relatively stable, particularly in Cooper River. Variability is considerably greater in Ashley River and, to a lesser extent, in Wando River. Since rediversion, the lower and more constant freshwater discharge rate has eliminated more distinct seasonal trends reported before rediversion (Davis et al., 1990). Limited post-rediversion data suggest that inter-annual salinity variability is also low (Davis et al., 1990). Due to the diminished freshwater flow, the effects of tidal forcing have increased (Kjerfve and Magill, 1990). Data available on numerous areas within the estuary during 1986-91 indicate that salinity differences between successive high and low tides averaged about 5 ppt in Charleston Harbor and lower Cooper, Wando, and Ashley rivers. Variability was higher (near 10 ppt) in the upper and middle areas of Ashley River and lower (<5 ppt) in upper Cooper River (SCWMRD, unpublished). Infrequent events such as Hurricane Hugo can significantly lower salinities by 15 ppt in certain parts of the estuary; however, these effects are of relatively short duration (<1 month) (Van Dolah and Anderson, 1991). The important time scales of salinity variability and responsible mechanisms are summarized in Figure 41.

Figure 38. *Comparison of gaged freshwater volume from the Lake Moultrie Tailrace Canal during periods of salinity depiction shown in Figure 39 **



* USGS gages reflect >92% of the estuary's watershed (41,233 km^2) (USGS, 1993)

Figure 39. *Salinity sampling information and average salinity during low- and high-salinity periods**

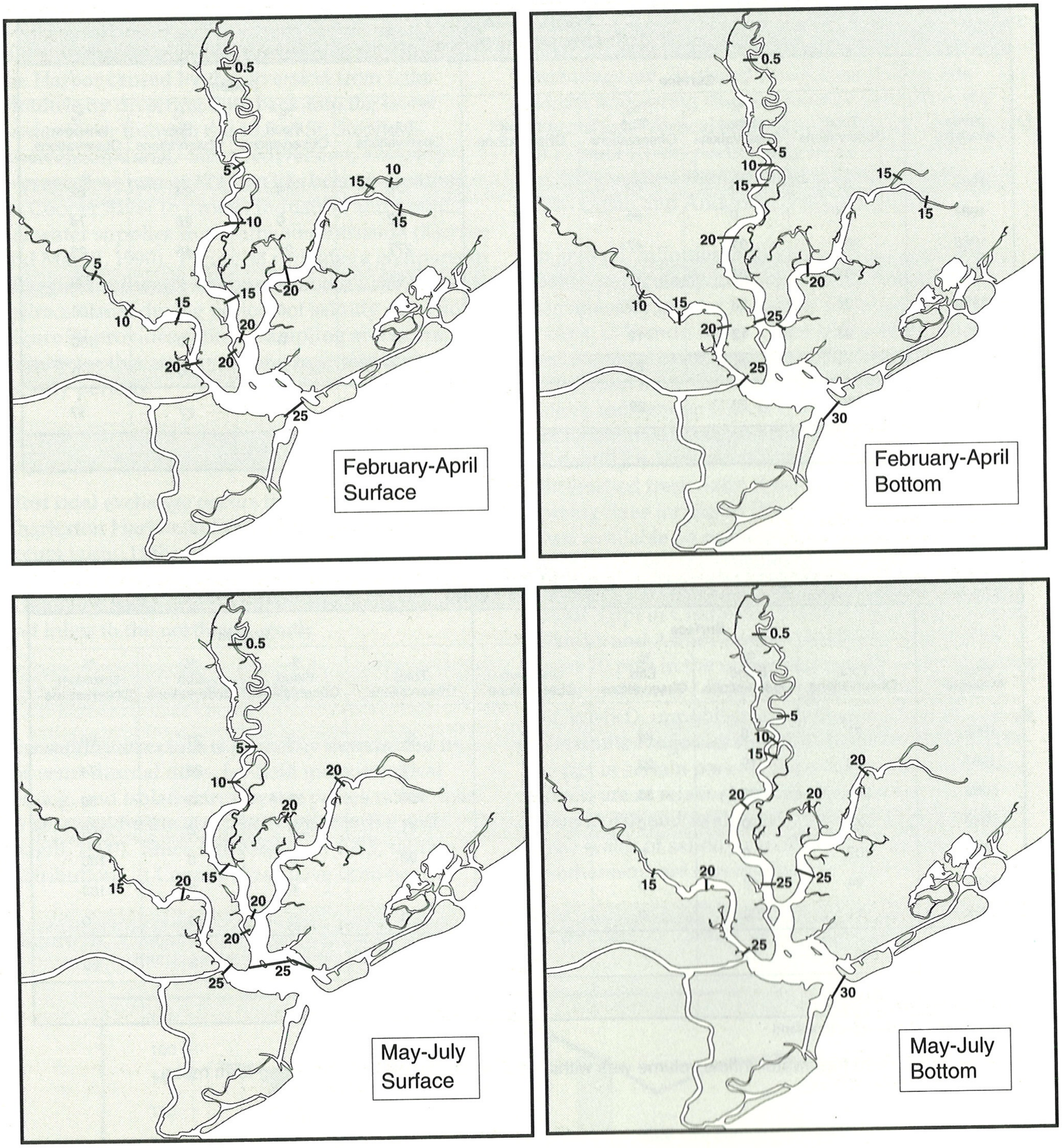
February-April Low-Salinity Period								
	Surface				Bottom			
Years Available	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1986	87	13	20	68	76	14	24	62
1987	65	0	25	75	62	0	26	74
1988	301	31	47	22	277	31	45	23
1989	97	23	10	67	61	0	0	100
1990	106	22	20	58	59	0	0	100
1991	93	12	12	76	67	0	0	100
1992	11	73	27	0	0	0	0	0
Total Observations	760	22	29	49	602	16	27	57
Average Salinity (ppt)	18.2				20.3			

May-July High-Salinity Period								
	Surface				Bottom			
Years Available	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1986	71	0	24	76	52	0	31	69
1987	90	19	23	58	62	0	26	74
1988	249	32	33	35	230	33	31	36
1989	77	0	0	100	71	0	0	100
1990	107	0	0	100	93	0	0	100
1991	94	12	0	88	79	0	0	100
1992	11	100	0	0	0	0	0	0
Total Observations	699	17	17	66	587	13	18	69
Average Salinity (ppt)	20.4				22.6			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 40. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 39* *

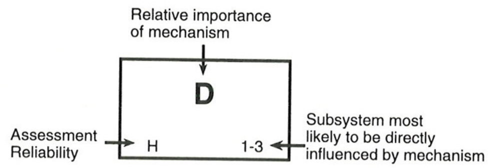


* Data Sources: See data sources listed for Charleston Harbor in the Appendix.

Figure 41. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 39**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		M (M, 2-3)	M (M, 2-3)	D (M, 2-4)	D (L, 1-4)
Tides	D (LIT, 1-4)	S (LIT, 1-4)			
Wind		S (LIT, 1-4)	D (LIT, 1-4)		
Density Currents	M (LIT, 1-4)				
Inter-estuary Exchanges	M (LIT, 2, 4)				
Effect on Salinity Variability	LOW	LOW	VERY LOW	LOW	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt	**D** - dominant	**H** - high
High = 11-20 ppt	**S** - secondary	**M** - moderate
Medium = 6-10 ppt	**M** - minor	**L** - low
Low = 3-5 ppt		**LIT** - Literature Only
Very Low = < 2 ppt		



NOTE: Isohalines illustrated in Figure 40 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Minor influence on salinity variability. Sporadically greater discharges from Jefferies Dam, following freshets, can temporarily lower salinities and increase vertical stratification.

Months-Seasons. Minor influence on the salinity structure. Freshwater inflow to Cooper River is maintained within a narrow range and seasonal variations are negligible (Davis et al., 1990). Small changes in salinity occur in Ashley and Wando rivers due to precipitation within the watershed.

Year-Year. Dominant influence on the salinity structure, although the highly regulated flow in Cooper River and the consistently low flow in Ashley and Wando rivers result in small inter-annual salinity variability.

Episodic. Dominant influence on the salinity structure throughout the estuary. Freshwater associated with Hurricane Hugo lowered salinity by 15 ppt in parts of the estuary; however, these effects persisted less than one month (Van Dolah and Anderson, 1991).

Tides

Hours. Dominant influence on the salinity structure, primarily in central and upper Ashley and Cooper rivers (Davis et al., 1990). Tides are semi-diurnal, ranging approximately 1.6 m near the harbor mouth (Davis et al., 1990; NOAA, 1993). Data available on numerous areas within the estuary during 1986-91 indicate that salinity differences between successive high and low tides averaged about 5 ppt in Charleston Harbor and lower Cooper, Wando, and Ashley rivers. Variability was higher (near 10 ppt) in upper and middle areas of Ashley River and lower (<5 ppt) in upper Cooper River (SCWMRD, unpublished).

Days-Weeks. Secondary influence on salinity variability, primarily in the lower to mid-estuary, due to the semi-lunar spring/neap tidal cycle. Vertical stratification is intensified during neap tides, while well-mixed conditions prevail during spring tides (Bradley et al., 1990).

Wind

Days-Weeks. Secondary estuary-wide influence on the salinity structure. Storms and other catastrophic weather events can significantly alter the local tidal range and cause a shift in the longitudinal salinity profile (Bradley et al., 1990).

Months-Seasons. Dominant estuary-wide influence on the salinity structure. In spring, northeast winds generate an offshore flow of low salinity surface water due to Ekman Transport, while higher salinity water from the middle shelf is advected onshore along the bottom (Blanton and Atkinson, 1983).

Density Currents

Hours. Minor estuary-wide influence on the salinity structure. Deep navigation channels enhance tidal amplitude and salinity intrusion (Kjerfve, 1989). The extent of saltwater intrusion and its effect on vertical stratification depends on tidal and wind forcing (Kjerfve, 1989; Kjerfve, Magill, and Sojisuporn, 1990).

Inter-estuary Exchanges

Hours. Minor influence on salinity variability. Tidal exchanges occur through the AIWW with Stono River to the south, and with coastal creeks and inlets to north and south.

* Data Sources: See data sources listed for Charleston Harbor in the Appendix.

Description

The St. Helena Sound estuary is a drowned river valley/bar-built system containing numerous marsh islands and tidal creeks (Bearden et al. 1985; Hopkins, 1956; Mathews et al., 1980; Stapor 1984). Occupying 220 km^2, it is among the largest of the South Atlantic estuaries (NOAA, 1990). This estuary includes St. Helena Sound, as well as South Edisto, Combahee, Coosaw, and Morgan rivers (Figure 42). Its upstream boundary is defined by the head of tide on South Edisto River at 61 km, Ashepoo River at 51 km, and on Combahee River at 58 km (Johnson, 1977; Mathews et al., 1980). A tidal node at the confluence of Coosaw and Beaufort rivers separates this system from St. Helena Sound (NOAA, 1985). This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 42).

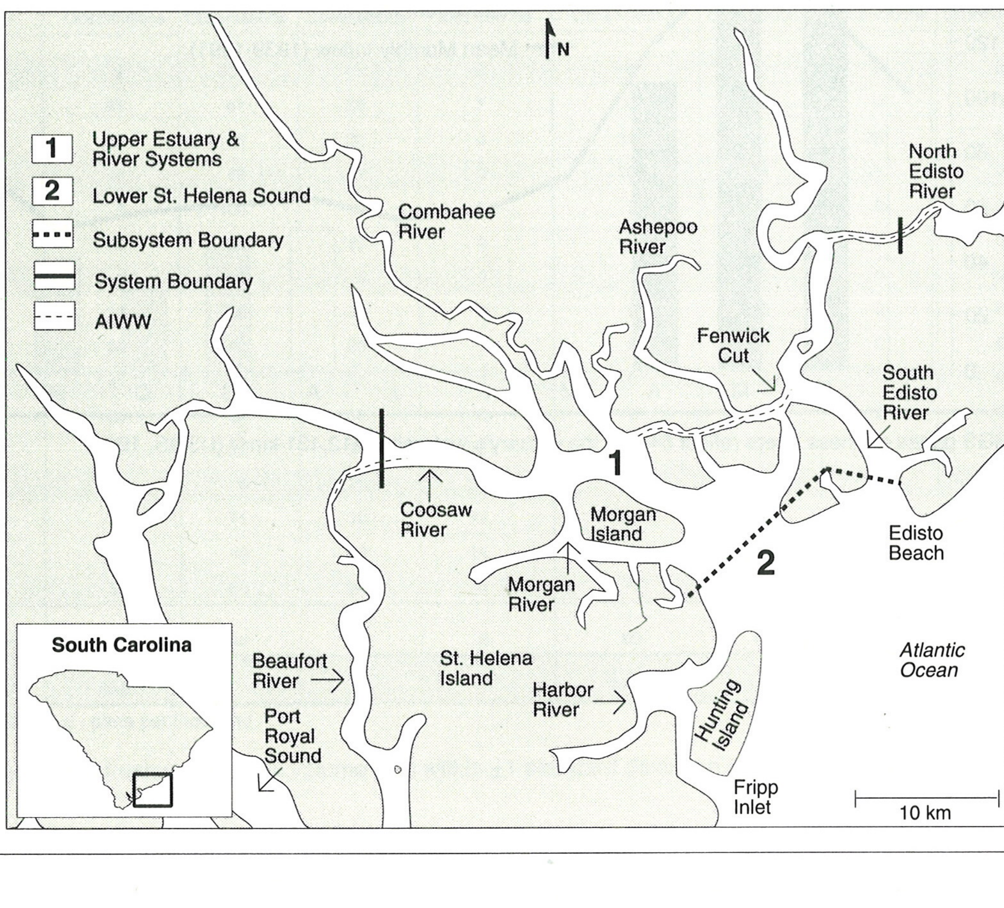
Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level (NOAA, 1990). A naturally deep channel extends through central St. Helena Sound and branches toward Coosaw and Morgan rivers. A natural channel also exists in lower South Edisto River. Extensive shallow areas and numerous tidal flats (e.g., Egg Bank) exist within the estuary, but are most predominant in St. Helena Sound. The AIWW (3.7 m at MLW) is the only maintained navigation channel, connecting the estuary with both North Edisto and Broad rivers.

Freshwater

The South Edisto River is the estuary's major freshwater source (Johnson, 1977; Wenner et al., 1991). It combines with Ashepoo River at Fenwick Cut and discharges near the estuary mouth in northeast St. Helena Sound. Ashepoo River carries enough freshwater to retain some riverine characteristics, but its flow is quite low compared to South Edisto River (Hopkins, 1956; Johnson, 1977). Although the Combahee/Salkehatchie River system (not shown) drains most of the estuary's watershed, its freshwater input is limited. Figure 43 provides a comparison of gaged freshwater volume for Edisto and Salkehatchie rivers during periods of salinity

Figure 42. *Location map and subsystem identification*



depiction. Figure 44 provides salinity sampling and average salinity for this estuary during low- and high-salinity periods.

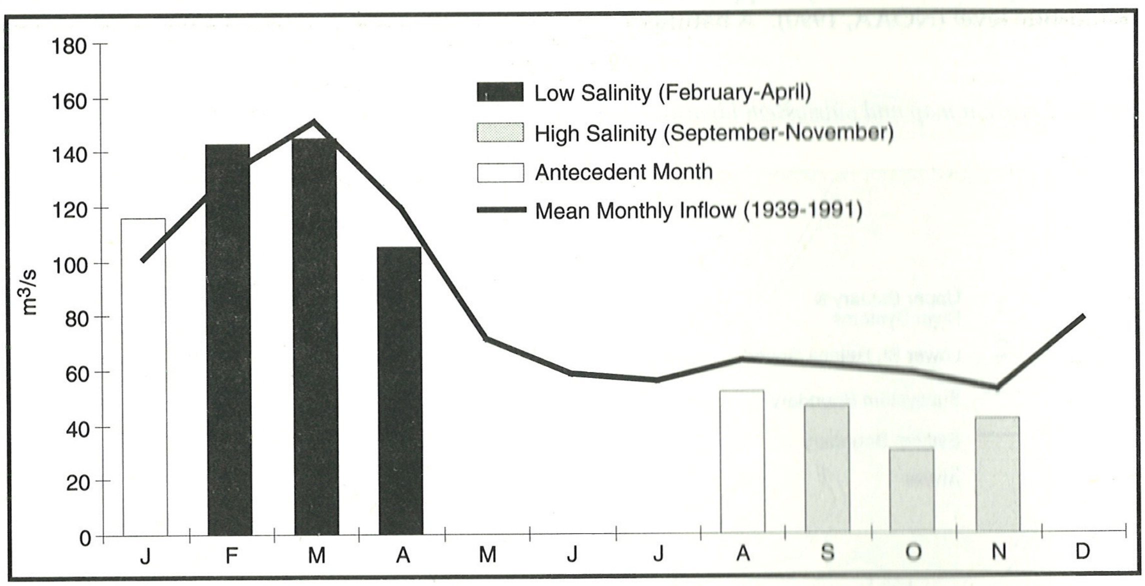
Tides

Most tidal exchange occurs through the opening to St. Helena Sound and produces strong tidal currents in the sound (Mathews and Shealy, 1978; Wenner et al., 1991). Additional exchange is limited through Fripps Inlet. Exchanges with Beaufort River (Broad River estuary) occur through Coosaw River and small tidal creeks transecting St. Helena Island (Mathews et al., 1980).

Salinity

The seasonal salinity structure, primarily determined by the freshwater discharge from South Edisto and Combahee/Salkehatchie rivers, typically fluctuates less than 5 ppt between typical high- and low-salinity periods (Figure 45). Seasonal variability is most pronounced in upper St. Helena Sound and lower Combahee and South Edisto rivers. These areas may experience weak vertical stratification, while vertically homogeneous conditions dominate other areas of the estuary (Johnson, 1977; Mathews and Shealy, 1982). Salinity variability is substantially greater at other time scales (Figure 46). In particular, freshets may temporarily compress isohalines and produce weak vertical stratification in Combahee River, South Edisto River, and upper St. Helena Sound. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 46.

Figure 43. *Comparison of gaged freshwater volume for Edisto and Salkehatchie rivers during periods of salinity depiction shown in Figure 44**



* USGS gages on these rivers reflect 64% of the estuary's watershed (12,431 km^2) (USGS, 1993)

Figure 44. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1974	55	49	51	0	31	68	32	0
1977	34	97	3	0	3	100	0	0
1978	53	60	40	0	0	0	0	0
1979	42	29	40	31	12	0	0	100
1980	37	54	0	46	16	0	0	100
1982	38	13	61	26	10	0	0	100
1987	77	26	56	18	11	0	0	100
1989	63	79	3	17	11	0	0	100
1990	33	15	45	39	13	0	0	100
1991	32	34	31	34	11	0	0	100
Total Observations	464	46	34	19	118	20	8	71
Average Salinity (ppt)	20.0				20.0			

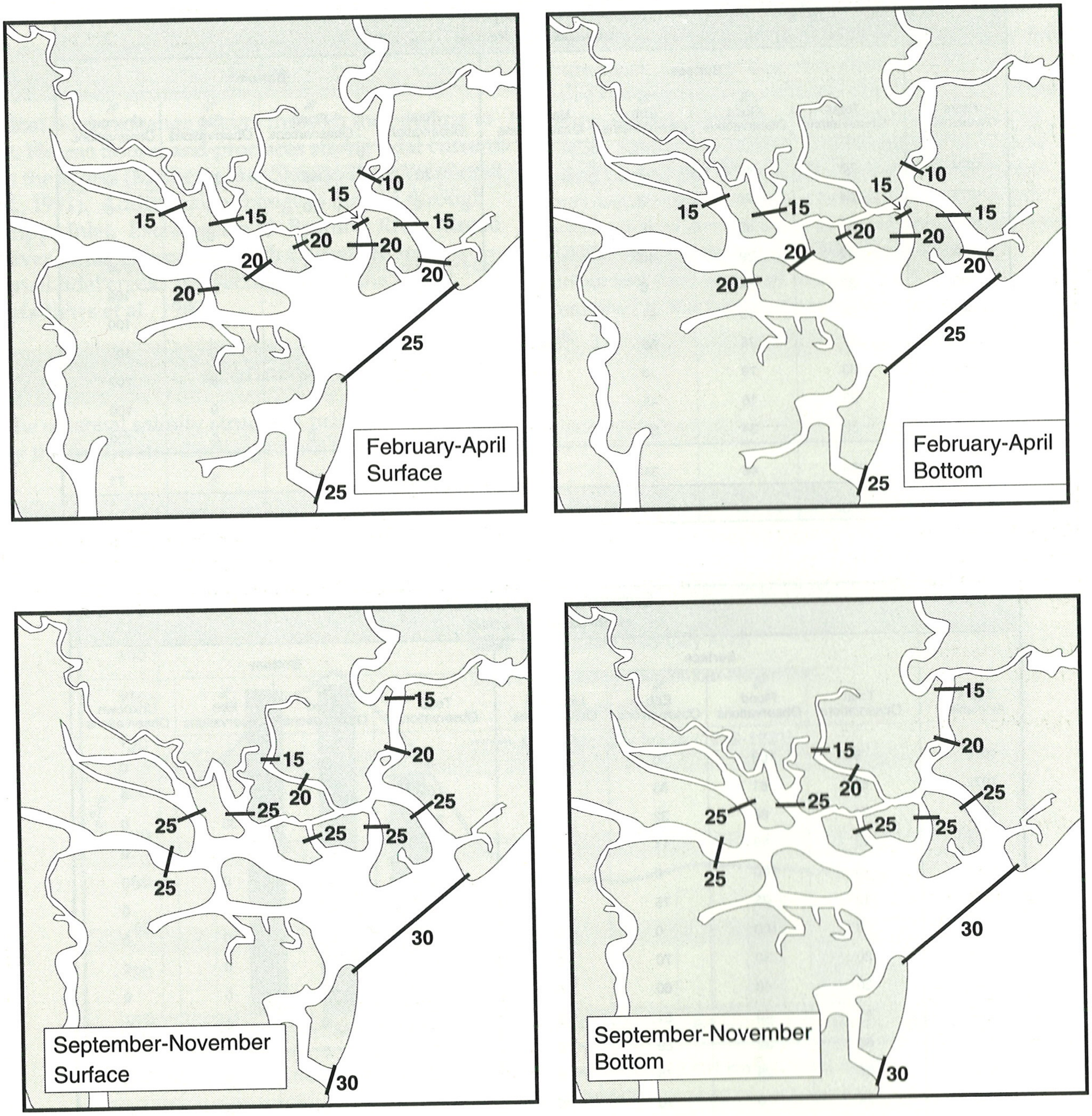
September-November
High-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1970	9	100	0	0	0	0	0	0
1972	61	61	33	7	0	0	0	0
1973	37	68	32	0	31	65	35	0
1974	18	89	11	0	18	89	11	0
1975	3	100	0	0	3	100	0	0
1976	12	25	75	0	3	100	0	0
1977	3	100	0	0	3	100	0	0
1978	30	30	70	0	0	0	0	0
1981	30	40	60	0	0	0	0	0
1982	41	46	51	2	0	0	0	0
1984	38	32	68	0	0	0	0	0
1985	67	25	75	0	0	0	0	0
1987	74	0	70	30	22	0	0	100
1988	76	71	12	17	12	0	0	100
1990	44	43	43	14	6	0	0	100
1991	32	66	34	0	0	0	0	0
Total Observations	575	45	47	8	98	46	13	41
Average Salinity (ppt)	25.6				23.5			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 45. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 44* *

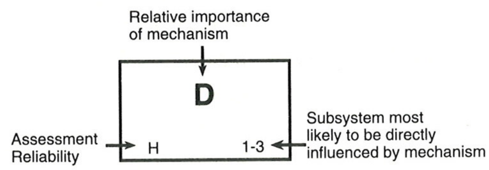


* Data Sources: See data sources listed for St. Helena Sound in the Appendix.

Figure 46. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 44**

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		**S** M 1	**D** M 1	**D** M 1-2	
Tides	**D** LIT 1-2				
Wind		**S** LIT 1-2			
Density Currents			**M** LIT 1		
Inter-estuary Exchanges			**M** LIT 1		
Effect on Salinity Variability	UNKNOWN	MEDIUM	LOW	MEDIUM	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 45 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability and stratification, primarily in Combahee River, South Edisto River, and upper St. Helena Sound. Freshets may temporarily displace and compress isohalines toward lower St. Helena Sound and may also increase vertical stratification in Combahee River, South Edisto River, and upper St. Helena Sound.

Months-Seasons. Dominant influence on the salinity structure throughout most of the estuary. Mean salinity varies 4-5 ppt between typical high- and low-salinity periods.

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant estuary-wide influence on salinity variability and water-column mixing. Tides are semi-diurnal, ranging 2.1 m near the estuary mouth and 2.5 m in the upper estuary (Baltzer, 1972; Hopkins, 1956). Under typical freshwater inflow conditions, saltwater penetrates to 31 km in South Edisto River and 39 km in Ashepoo River during high tide and recedes to 23 km and 32 km, respectively, during low tides (Johnson, 1977).

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability, particularly when associated with fronts. These winds increase water-column mixing and estuary-ocean exchanges. The effects are intensified by the onset of "north-easters."

Density Currents

Months-Seasons. Minor influence on the salinity structure, primarily in South Edisto and Combahee rivers and upper St. Helena Sound under sufficiently high freshwater inflow conditions.

Inter-estuary Exchanges

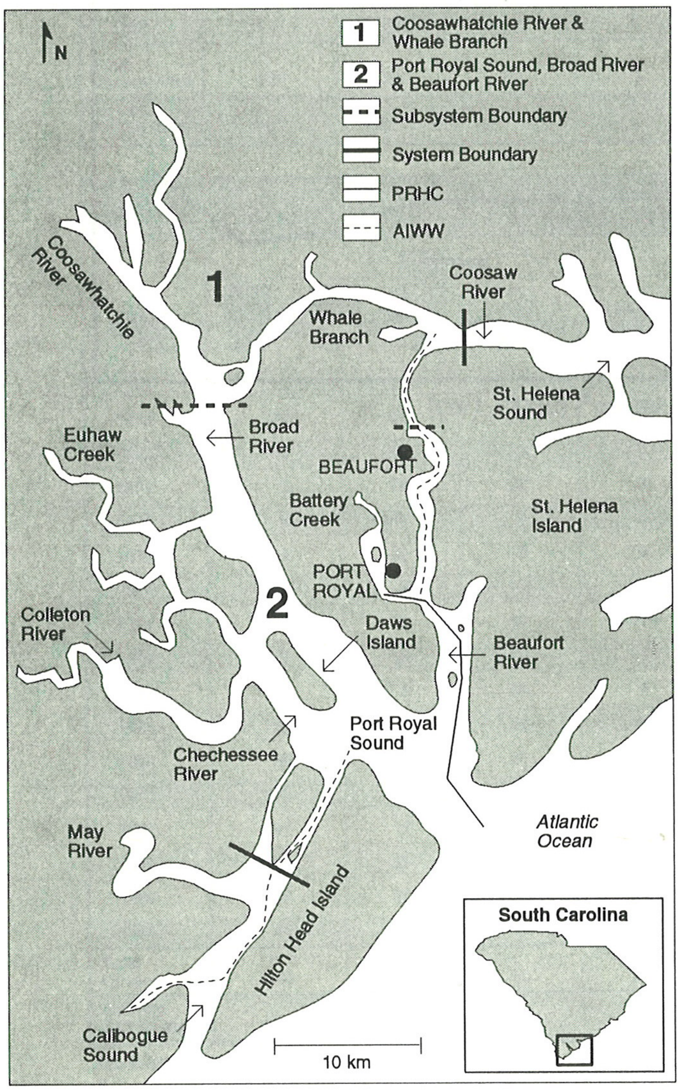
Months-Seasons. Minor influence on salinity variability, primarily in Morgan and Coosaw rivers due to conditions in Beaufort River.

* Data Sources: See data sources listed for St. Helena Sound in the Appendix.

Description

The Broad River estuary is a drowned river valley system located in the lower Atlantic Coastal Plain of South Carolina (Mathews et al., 1980). The largest of Sea Island Coastal Region estuaries (219 km^2), it includes an extensive system of marshes, tidal creeks, and sea islands (Figure 47). This estuary, which includes Broad River, Beaufort River, Port Royal Sound, and several tidal tributaries, is defined from the head of tide on Coosawhatchie River, approximately 50 km upstream of Port Royal Sound's entrance. It is separated from the Savannah River estuary by a tidal node in Calibogue Sound, just northeast of the May River (Van Dolah, Pers. Comm.). A tidal node at the confluence of Coosaw and Beaufort rivers separates this system from St. Helena Sound (NOAA, 1985). This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 47).

Figure 47. *Location map and subsystem identification*



Bathymetry

The average depth of the estuary is approximately 7 m at mid-tide level (NOAA, 1990). Broad, deep natural channels exist throughout Port Royal Sound, Broad River, and major tidal tributaries. Large shoal areas occur primarily in Beaufort River and Port Royal Sound near Daws Island. The Port Royal Harbor Channel (PRHC) (9 m at MLW) and AIWW (3.7 m at MLW) are the only maintained navigation channels.

Freshwater

This estuary receives most of its freshwater from Coosawhatchie River, although total inflow volume is limited by its small watershed (2,590 km^2) (Kilpatrick and Cummings, 1972; NOAA, 1990). Highest river discharges usually occur during winter and spring; lowest river discharge occurs during fall (Mathews and Pashuk, 1977) (Figure 48). Freshwater input from the other tributaries is not significant (Baltzer, 1972). Direct precipitation to the estuary due to thunderstorm activity increases during late June to early September (NOAA, 1980). Historical groundwater levels have been reduced due to increased withdrawals in Savannah, Georgia (Mathews et al., 1980). Figure 49 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

Tides

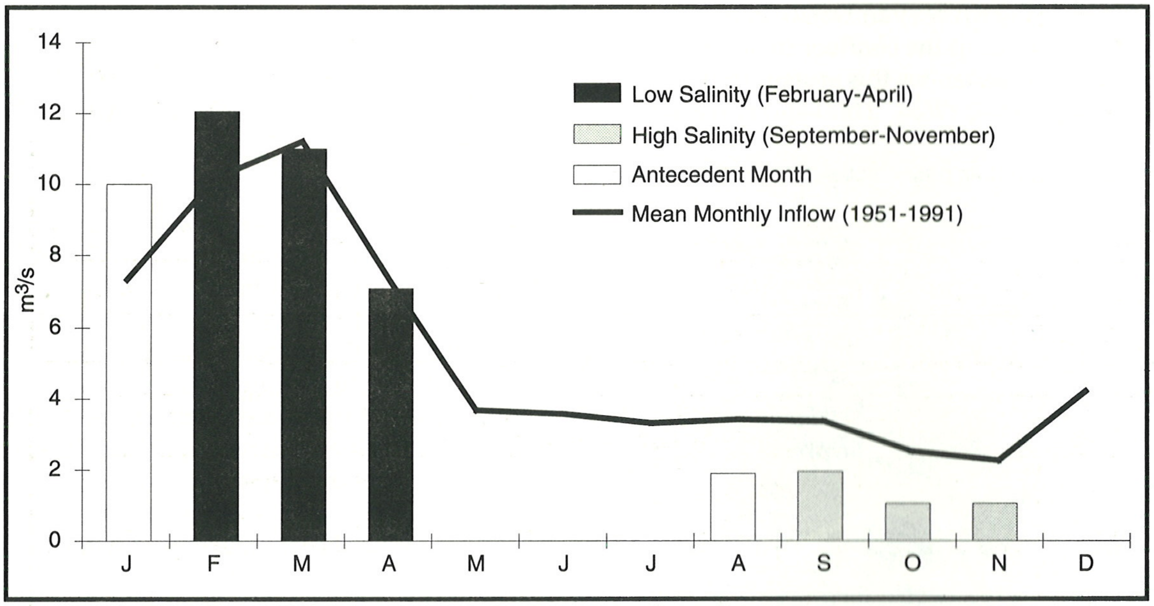
Most tidal exchange occurs through the opening at Port Royal Sound. Port Royal Sound experiences strong tidal currents (Baltzer, 1972; Hopkins, 1956; Kilpatrick and Cummings, 1972), while high tidal amplitudes extend into Broad River (Baltzer, 1972). Limited exchanges occur with St. Helena Sound and the Savannah River system (Mathews et al., 1980).

Salinity

The salinity structure is primarily determined by the seasonal freshwater discharge from the Coosawhatchie River, although mean salinities fluctuate less than 5 ppt between typical high- and low-salinity periods. Vertical stratification is uncommon, but may briefly occur near freshwater sources following significant inflow events.

This estuary is among the most stable in the South Atlantic region, experiencing little variability at any time scale. Most variability occurs in the upper reaches of major tidal tributaries during inflow events. Astronomical tides and winds increase exchanges between the estuary and ocean (Schwing et al., 1983) and maintain vertically homogeneous conditions, but have little influence on salinity variability throughout most of the estuary. The estuary may, however, entrain reduced-salinity shelf waters impacted by the Savannah River plume. In addition, exchanges with the St. Helena Sound estuary may influence salinity in upper Beaufort and Broad rivers. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 51.

Figure 48. *Comparison of gaged freshwater volume for Broad and Coosawhatchie rivers during periods of salinity depiction shown in Figure 49**



* USGS gage reflects 20% of the estuary's watershed (2,590 km^2) (USGS, 1993)

Figure 49. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface				Bottom			
	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1971	91	43	56	1	0	0	0	0
1972	29	48	52	0	0	0	0	0
1974	71	75	25	0	3	100	0	0
1975	12	75	25	0	3	100	0	0
1977	61	51	39	10	3	100	0	0
1978	46	91	9	0	0	0	0	0
1979	70	46	46	9	5	0	0	100
1982	47	68	13	19	6	0	0	100
1984	81	57	28	15	9	0	0	100
1986	131	1	89	11	10	0	0	100
1987	86	21	59	20	14	0	0	100
1990	87	13	69	18	15	0	0	100
1992	117	31	68	1	0	0	0	0
Total Observations	929	39	52	9	68	13	0	87
Average Salinity (ppt)	24.7				27.5			

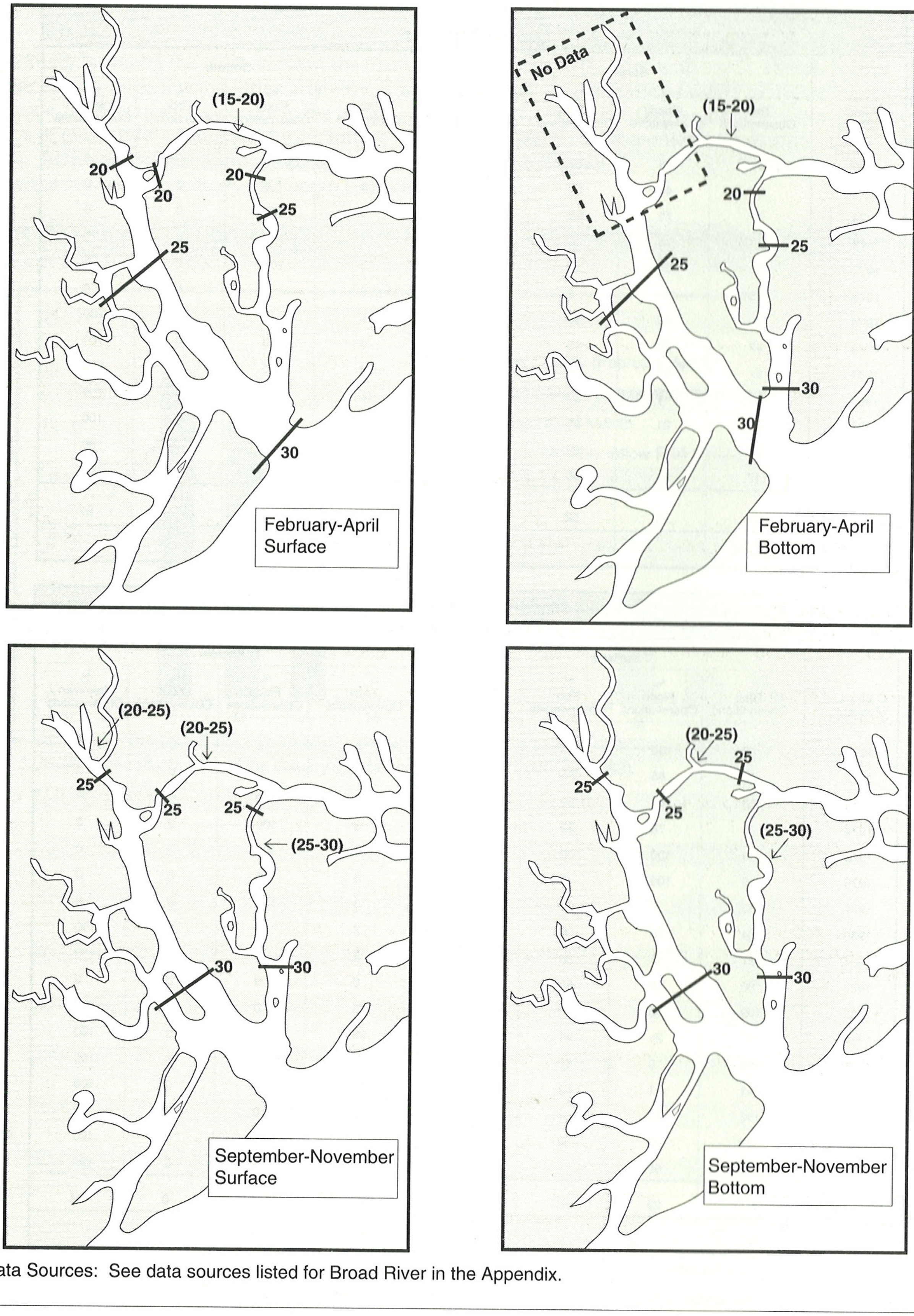
September-November
High-Salinity Period

Years Available	Surface				Bottom			
	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1970	3	100	0	0	0	0	0	0
1972	20	65	25	10	0	0	0	0
1973	163	41	59	0	3	100	0	0
1974	9	78	22	0	3	100	0	0
1975	3	100	0	0	3	100	0	0
1976	19	100	0	0	3	100	0	0
1977	33	9	91	0	3	100	0	0
1980	64	50	30	20	2	0	0	100
1981	27	11	70	19	2	0	0	100
1982	80	8	89	4	0	0	0	0
1983	109	50	22	28	25	0	0	100
1984	95	21	51	28	23	0	0	100
1986	100	0	62	38	32	0	0	100
1987	141	1	62	37	49	0	0	100
1988	116	29	34	36	38	0	0	100
1989	89	26	52	22	19	0	0	100
1990	48	65	17	19	7	0	0	100
Total Observations	1119	29	50	22	212	7	0	93
Average Salinity (ppt)	27.7				27.9			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 50. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 49* *

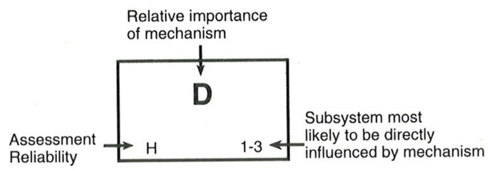


* Data Sources: See data sources listed for Broad River in the Appendix.

Figure 51. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 49**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		**D** L 1	**D** L 1	**D** L 1-2	
Tides	**D** LIT 2				
Wind		**M** LIT 1-2			
Density Currents			**M** LIT 2		
Inter-estuary Exchanges			**M** LIT 1		
Effect on Salinity Variability	UNKNOWN	LOW	LOW	LOW	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 50 represent a "steady state" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Dominant influence on salinity variability and stratification, primarily in the upper major tidal tributaries. Freshets temporarily displace saline bottom waters toward Port Royal Sound and may increase vertical stratification in the tidal tributaries.

Months-Seasons. Dominant influence on the salinity structure throughout most of the estuary. Salinity profiles indicate little difference between typical high- and low-salinity periods because the water volume entering the estuary, even during an average high-inflow period, is barely of sufficent magnitude to displace isohalines.

Year-Year. Dominant estuary-wide influence on the salinity structure, although mean salinity concentrations vary little from year-to-year.

Tides

Hours. Dominant influence on salinity variability and water-column mixing, primarily in the lower estuary. Tides are semi-diurnal, ranging 2.1 m near the estuary mouth and 2.5 m in the upper estuary (Baltzer, 1972; Hopkins, 1956). Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Minor estuary-wide influence on salinity variability, particularly when associated with fronts. These winds increase water-column mixing and estuary-ocean exchanges. The effects are intensified by the onset of "northeasters."

Density Currents

Months-Seasons. Minor influence on the salinity structure, primarily in Beaufort River.

Inter-estuary Exchanges

Months-Seasons. Minor influence on salinity variability, primarily in the upper Beaufort River due to conditions in St. Helena Sound.

* Data Sources: See data sources listed for Broad River in the Appendix.

Description

The Savannah River estuary is a coastal plain system occupying 126 km^2 (NOAA, 1990) and includes New, Wright, and Savannah rivers and several distributaries of Savannah River (e.g., Front, Back, and Middle rivers and the South Channel) (Figure 52). It is defined from the head of tide on the Savannah River, about 52 km upstream from the estuary's mouth (NOAA, 1985). It is separated from the Broad River estuary by a tidal node in Calibogue Sound, just northeast of May River (not shown) (Van Dolah, Pers. Comm.); and from Wassaw Sound to the south by tidal nodes in Wilmington River and St. Augustine, Richardson, Lazarette, and Tybee creeks (not shown) (Rogers, Pers. Comm.). This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 52).

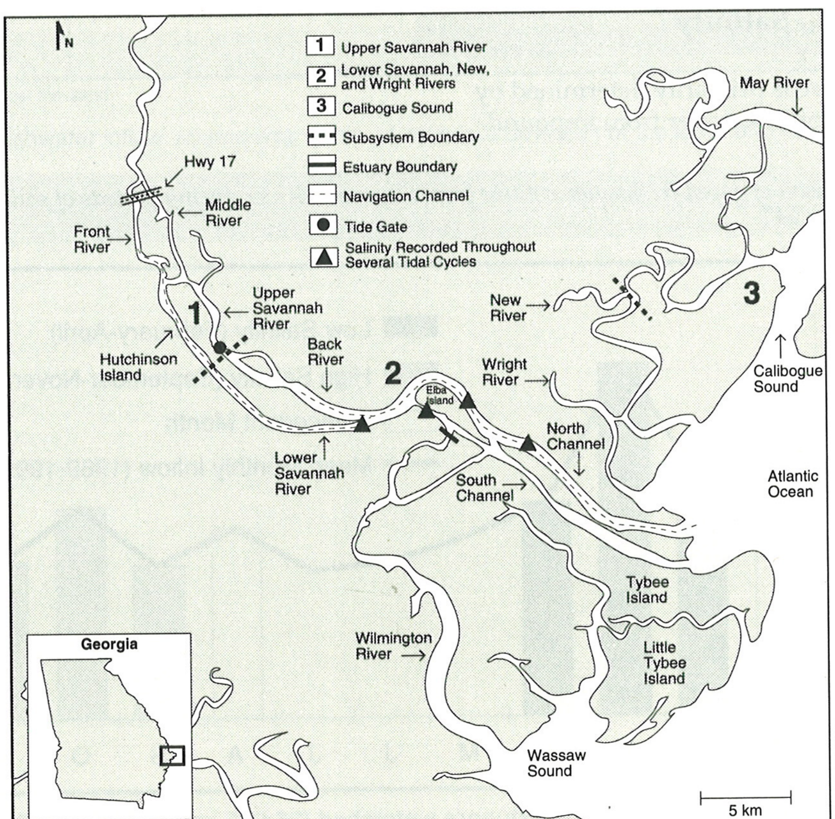
Bathymetry

The average depth of the estuary is approximately 5 m at mid-tide level (NOAA, 1990). Navigational channels downstream from Highway 17 in the lower Savannah and Front rivers (Figure 52) range from 9 m to 12 m MLW in depth, and facilitate the intrusion of saltwater into the estuary (GADNR, 1981). The conversion of thousands of acres of saltwater wetlands into diked disposal areas on the South Carolina side of the estuary could also have altered flow patterns and salinity regimes (SCCC, 1987). Small scale widening, deepening, and straightening of channels upstream from Highway 17 have had comparatively little effect on saltwater intrusion (SCCC, 1987).

Freshwater

The estuary receives most of its freshwater from Savannah River, which is formed by the confluence of Seneca and Tugaloo rivers (Brunswick Junior College, 1975; Mathews et al., 1980). Highest river discharge usually occurs in late winter and spring due to heavy precipitation in the Blue Ridge and piedmont areas; lowest discharge occurs during late summer and fall (Brunswick Junior College, 1975; Stokes et al., 1991) (Figure 53). A minimum flow rate of about 190 m^3/s is maintained on Savannah River by releases from Lake Hartwell and Lake Thurmond (formerly Clark Hill Reservoir) (GADNR, 1974 and

Figure 52. *Location map and subsystem identification*



1981). Smaller lakes and reservoirs further upstream (including Mathis Reservoir and Lake Burton) have only minor effects on streamflow and salinity (GADNR, 1974; Stokes et al., 1991). Figure 54 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

Tides

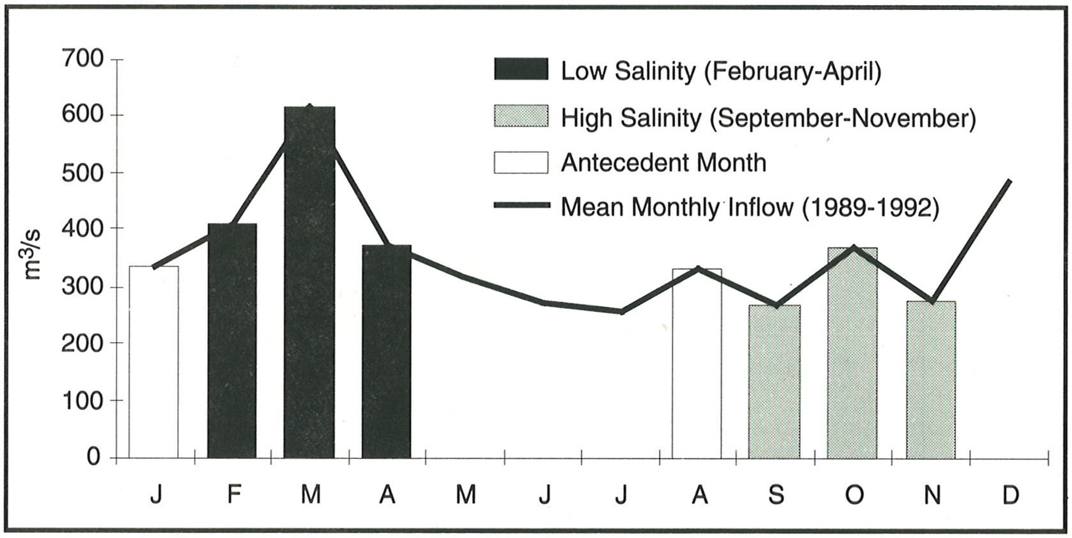
A tide gate and sediment basin were constructed in Back River during the 1970s to increase current velocities and decrease shoaling in Front River. This increased salinities upstream from the tide gate in Front, Middle, and Back rivers at both high and low tides (GADNR, 1981; Pearlstine et al., 1989). Freshwater canals and dikes were constructed to help maintain the freshwater of the Savannah National Wildlife Refuge during tide gate operations. The tide gate has not been operating since March 1989.

Most tidal exchange occurs through the entrance to Savannah River, primarily through the North Channel; however, limited exchange occurs with the Broad River estuary through Calibogue Sound. Additional exchanges occur with Wassaw Sound through Wilmington River and numerous tidal creeks (Rogers, Pers. Comm.).

Salinity

The salinity structure is primarily determined by controlled releases of freshwater from impoundments on Savannah River and its tributaries. Seasonal salinities differ by about 5 ppt throughout most of the estuary, with the least change in upper Savannah River above Hutchinson Island (Figure 55). While the tide gate was in operation (before March 1989), tidal influence on salinity variability in the upper estuary was reported to be most pronounced during low river flow and insignificant during high flow (GADNR, 1981). Also, a prominent salt wedge was in the lower estuary throughout the year (Stickney and Miller, 1973); however, recent information (1989-1992) does not necessarily support this finding. The information, where available, suggests vertically homogeneous conditions during both periods except moderate stratification in lower Savannah River. It also suggests that bottom salinities are most variable in Savannah River below Hutchinson Island. Insufficient data are available to determine salinity variability during a tidal cycle for the post-tide gate period (i.e., since March 1989). Limited data are available during 1972 (pre-tide gate conditions) at stations identified in Figure 52 (Winker et al., 1985). These data suggest that surface and bottom salinities change 3-11 ppt throughout a tide cycle. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 56.

Figure 53. *Comparison of gaged freshwater volume from Savannah River during periods of salinity depiction shown in Figure 54**



* USGS gage reflects 95% of the estuary's watershed (26,935 km^2) (USGS, 1993)

Figure 54. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1989	26	0	0	100	18	0	0	100
1990	415	0	9	91	32	0	0	100
1991	335	1	5	95	31	0	0	100
1992	205	3	24	72	124	0	0	100
Total Observations	981	1	10	80	205	0	0	100
Average Salinity (ppt)	4.3				10.4			

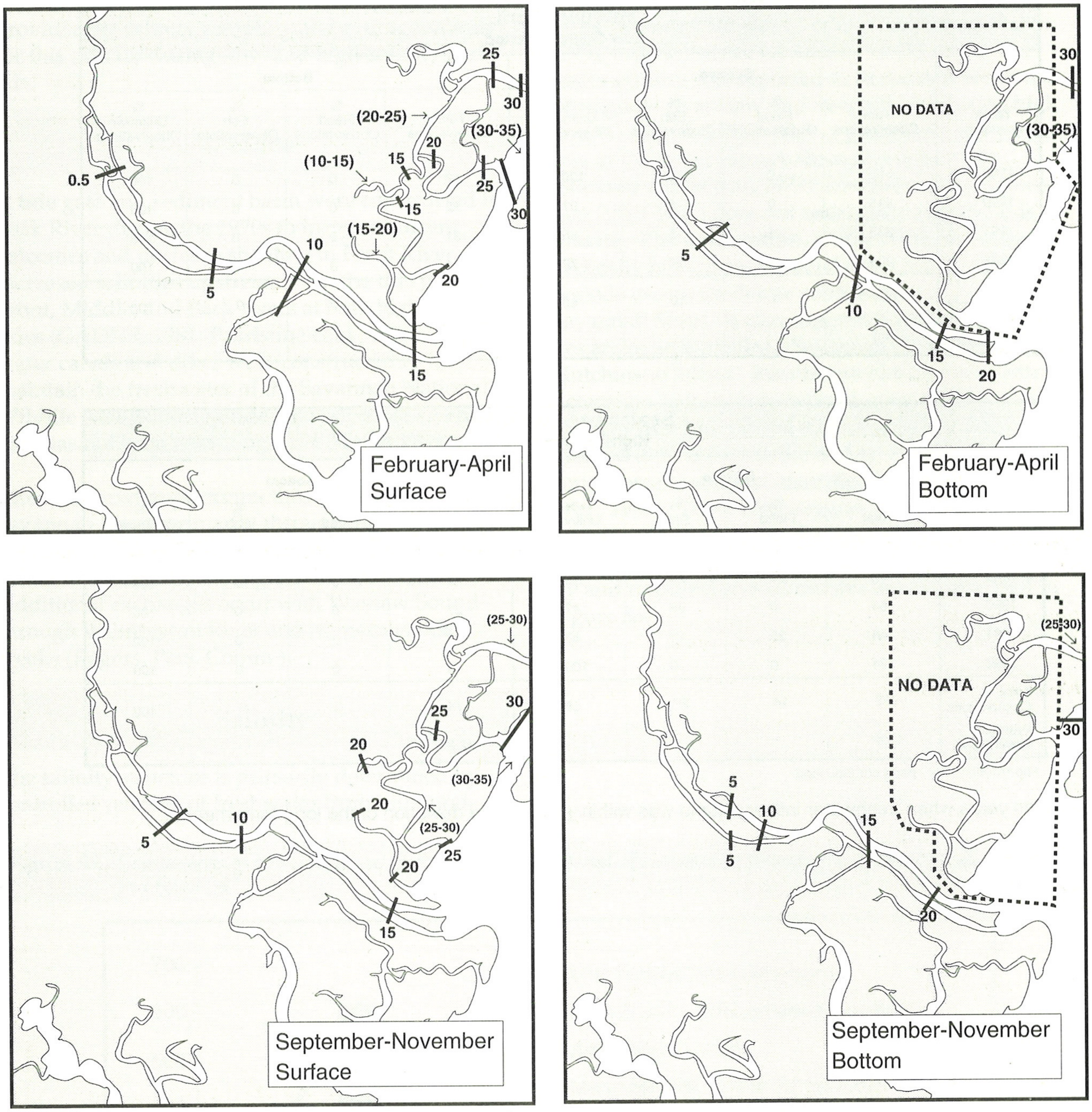
September-November
High-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1989	76	24	24	53	37	0	0	100
1990	64	0	53	47	27	0	0	100
1991	48	25	13	63	7	0	0	100
1992	24	0	0	100	3	0	0	100
Total Observations	212	14	27	58	74	0	0	100
Average Salinity (ppt)	16.4				12.9			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 55. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 54* *

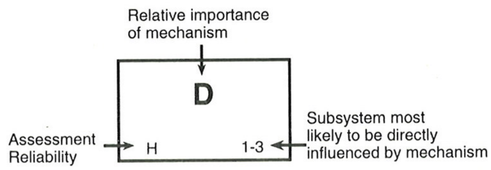


* Data Sources: See data sources listed for Savannah River in the Appendix.

Figure 56. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 54**

Mechanism	Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
	Time Scale of Salinity Response				
Freshwater Inflow		**D** L 1, 2	**D** L 1-3	**D** L 1-3	
Tides	**D** LIT 1-3				
Wind		**M** LIT 1-3			
Density Currents		**M** LIT 2			
Inter-estuary Exchanges	**M** LIT 3				
Effect on Salinity Variability	UNKNOWN	MEDIUM	MEDIUM	LOW	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 55 represent the "mean" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Dominant influence on salinity variability and stratification, primarily in Wright, New, and Upper Savannah rivers.

Months-Seasons. Dominant estuary-wide influence on the salinity structure. Seasonal salinities from 1989 to 1992 changed by 5 ppt throughout most of this estuary.

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant estuary-wide influence on salinity variability and water-column mixing. Tides are semi-diurnal, ranging from 2.0 m at the estuary's mouth to 2.5 m in Savannah River above Elba Island. Insufficient data are available to determine salinity variability during a tidal cycle for the post-tide gate period (i.e., since March 1989). Limited data are available during 1972 (pre-tide gate conditions) at stations identified in Figure 52 (Winker et al., 1985). These data suggest that surface and bottom salinities change 3-11 ppt throughout a tide cycle.

Wind

Days-Weeks. Minor estuary-wide influence on salinity variability.

Density Currents

Days-Weeks. Minor influence on the salinity structure, particularly along North Channel and Lower Savannah River.

Inter-estuary Exchanges

Hours. Minor influence on salinity variability from Broad River to the north due to limited exchanges through Calibogue Sound, and from Wassaw Sound to the south due to exchanges through Wilmington River and numerous tidal creeks (Rogers, Pers. Comm.).

* Data Sources: See data sources listed for Savannah River in the Appendix.

Description

The Ossabaw Sound estuary is a small coastal plain system occupying 85 km^2 (NOAA, 1990). Defined from the head of tide on the Ogeechee River (about 52 km upstream of the entrance to Ossabaw Sound), this estuary includes Ossabaw Sound and Ogeechee, Little Ogeechee, Burnside, and Vernon rivers (Mathews et al., 1980). It is separated from Wassaw Sound by tidal nodes in Wassaw, Rhodes, and Habersham creeks (not shown but located on Wassaw Island), and by a tidal node in Skidaway Narrows between Burnside and Skidaway rivers. This estuary is also separated from the St. Catherines/Sapelo Sound system by tidal nodes in the Skipper Narrows section of Kilkenny Creek on the AIWW near the confluence of Cane Patch and Bulkhead creeks, and in Big Tom Creek (Rogers, Pers. Comm.). This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 57).

Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level (NOAA, 1990), although both naturally deep areas and shoals are interspersed throughout the estuary. The AIWW (3.7 m at MLW) is the only actively maintained navigation channel (Figure 57).

Freshwater

This estuary receives most of its freshwater from Ogeechee River. Smaller inputs are supplied by Canoochee River, a tributary of the Ogeechee River, which drains an additional 23% of the estuary's watershed (NOAA, 1990; Stokes et al., 1991). Highest river discharge usually occurs during late winter and spring due to increased precipitation in the piedmont area; lowest discharge occurs during late summer and fall (Brunswick Junior College, 1975) (Figure 58).

Figure 57. *Location map and subsystem identification*

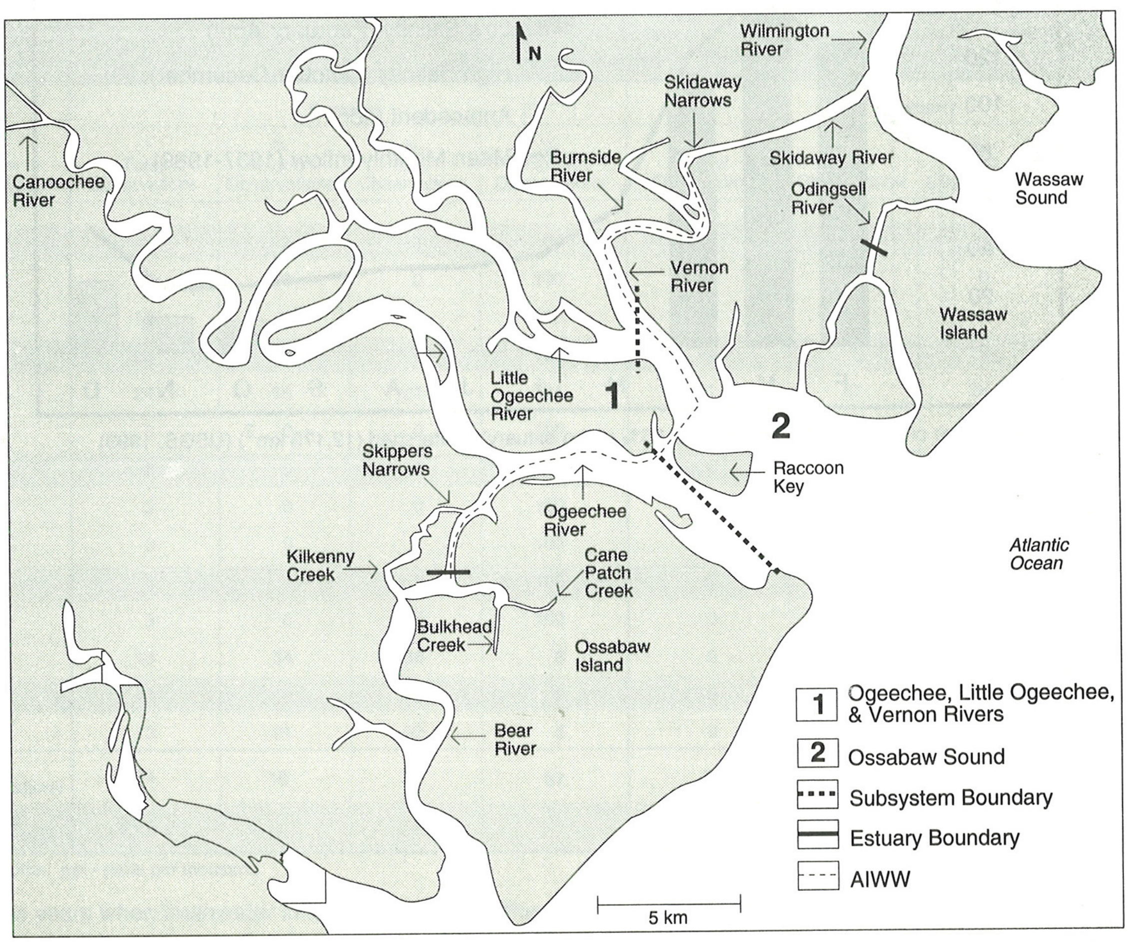


Figure 59 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

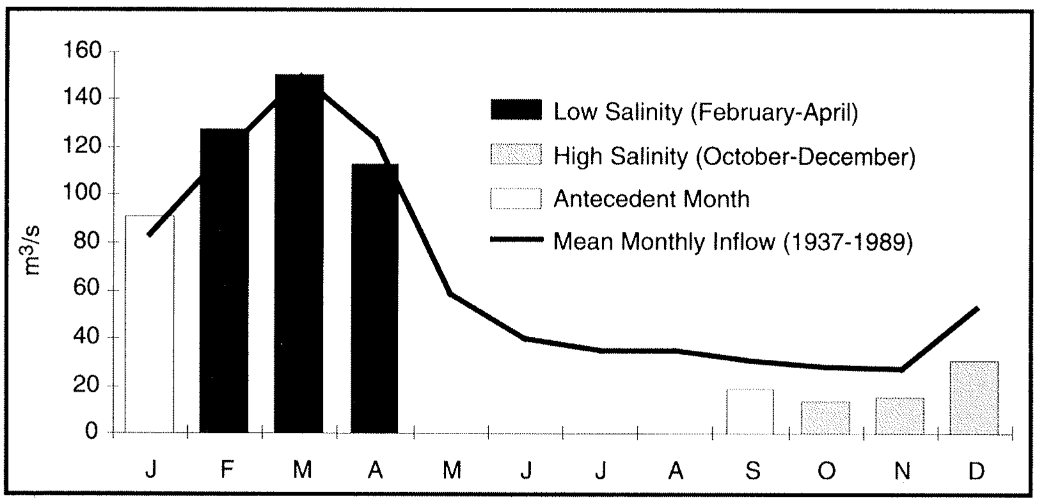
Tides

Most tidal exchange occurs through the entrance to Ossabaw Sound, although limited exchange occurs with Wassaw Sound through Burnside River and tidal creeks near the estuary's mouth. Additional exchanges with the St. Catherines/Sapelo Sound system occur primarily through the AIWW (Rogers, Pers. Comm).

Salinity

The salinity structure is primarily determined by seasonal freshwater discharge from Ogeechee River and its tributaries. Seasonal salinities differ by 5-10 ppt throughout most of the estuary, with the greatest changes apparent in lower Ogeechee River (below Shad Island) (Figure 60). During the low-salinity period, salinities are generally stable and unstratified in Little Ogeechee and Vernon rivers, but are variable and moderately stratified in lower Ogeechee River and Ossabaw Sound. During the high-salinity period, salinities throughout most of the estuary are relatively stable and unstratified, but are more variable in Ogeechee River above Shad Island. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 61.

Figure 58. *Comparison of gaged freshwater volume from Ogeechee River during periods of salinity depiction shown in Figure 59**



*USGS gage on Ogeechee River reflects 56% of the estuary's watershed (12,173 km^2) (USGS, 1993)

Figure 59. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1971	95	0	0	100	79	0	0	100
1972	3	0	0	100	0	0	0	0
1974	16	0	0	100	8	0	0	100
1976	33	73	3	24	1	82	4	14
1977	3	0	0	100	28	0	0	0
1978	3	0	0	100	0	0	0	0
1979	15	20	60	20	0	0	0	0
1980	3	0	0	100	0	0	0	0
1982	3	0	0	100	0	0	0	0
1986	13	77	15	8	0	0	0	0
Total Observations	187	20	6	74	115	20	1	79
Average Salinity (ppt)	9.8				11.2			

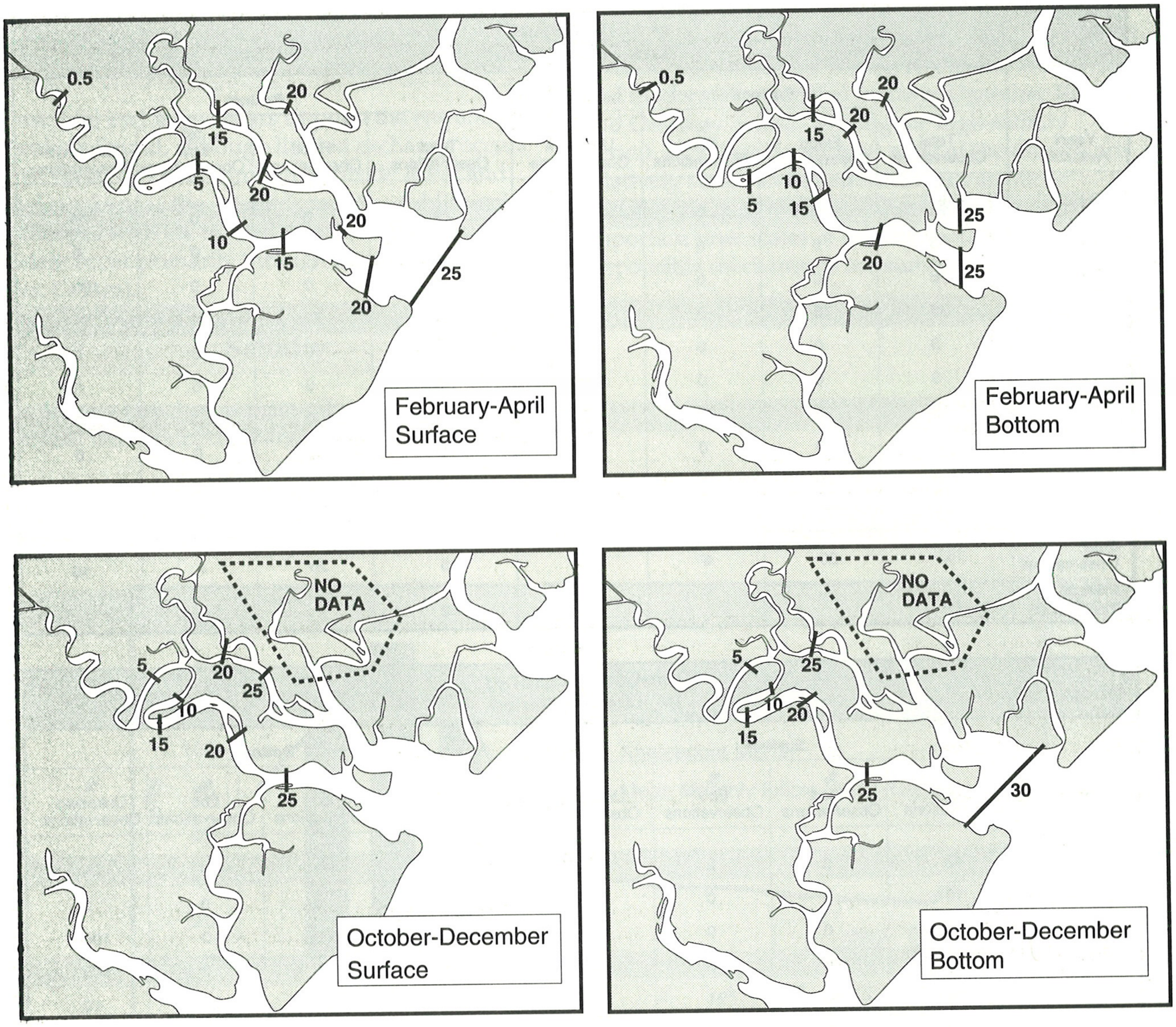
October-December
High-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1970	42	2	2	95	37	3	3	95
1972	19	0	0	100	0	0	0	0
1973	13	0	0	100	7	0	0	100
1974	20	0	0	100	14	0	0	100
1975	24	58	21	21	21	67	24	10
1977	3	0	0	100	0	0	0	0
1978	2	0	0	100	0	0	0	0
1979	3	0	0	100	0	0	0	0
1980	3	0	0	100	0	0	0	0
1981	3	0	0	100	0	0	0	0
1982	3	0	0	100	0	0	0	0
1986	13	54	38	8	0	0	0	0
1987	13	46	46	8	0	0	0	0
1988	13	31	62	8	0	0	0	0
Total Observations	174	18	14	67	79	19	8	73
Average Salinity (ppt)	21.9				24.6			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 60. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 59 **

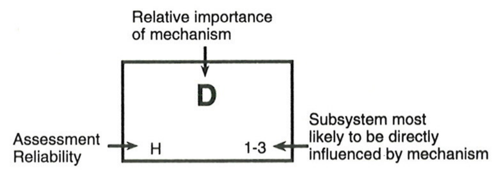


* Data Sources: See data sources listed for Ossabaw Sound in the Appendix.

Figure 61. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 59**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (L, 1)	D (L, 1-2)	D (L, 1-2)	
Tides	D (LIT, 1-2)				
Wind		S (LIT, 1-2)			
Inter-estuary Exchanges	M (LIT, 1)				
Effect on Salinity Variability	UNKNOWN	MEDIUM	HIGH	HIGH	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 60 represent the "mean" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability and stratification, primarily in Ogeechee River. Freshets temporarily displace saline bottom waters toward lower Ogeechee River and may increase vertical stratification in this estuary.

Months-Seasons. Dominant influence on the salinity structure, primarily in Ogeechee River and Ossabaw Sound. Typical seasonal inflows alter salinities by 10 ppt throughout most of this estuary.

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant influence on salinity variability and water-column mixing throughout most of this estuary. Tides are semi-diurnal and average 2.1 m throughout Ossabaw Sound and lower major tributaries. Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability, particularly when associated with fronts and "northeasters."

Inter-estuary Exchanges

Hours. Minor influence on salinity variability in Vernon River and lower Ogeechee River, primarily due to exchanges through the AIWW.

* Data Sources: See data sources listed for Ossabaw Sound in the Appendix.

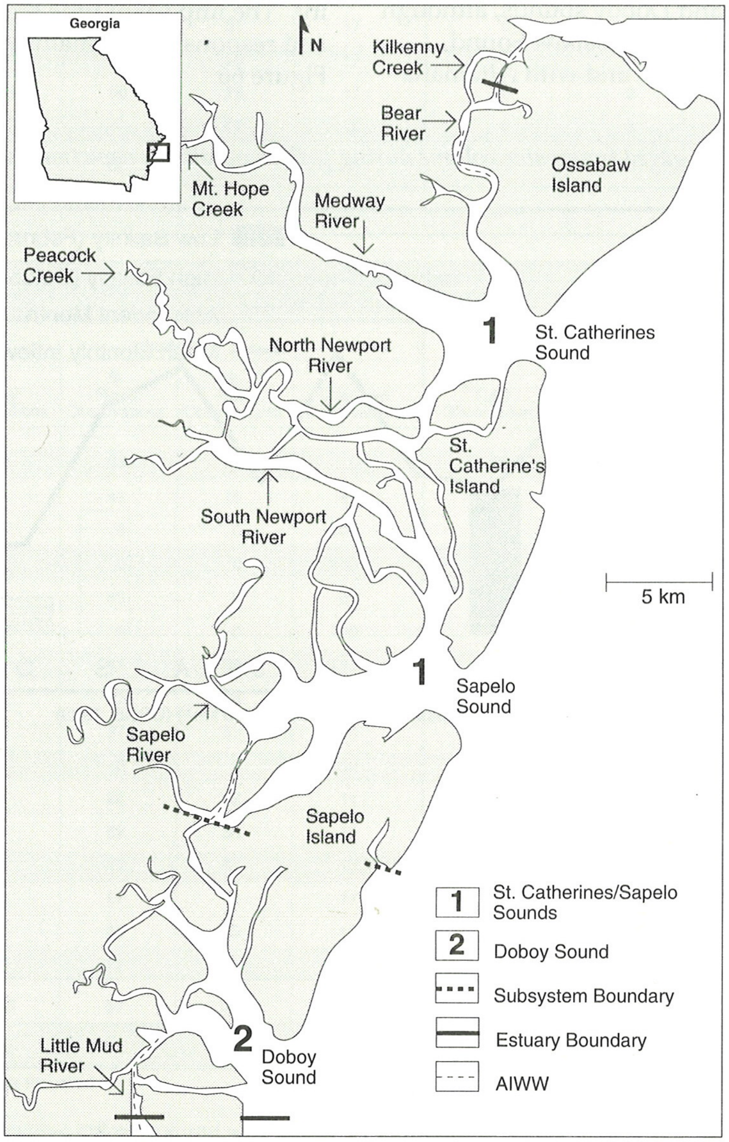
Description

The St. Catherines/Sapelo Sounds estuary is a drowned river valley-barrier island system (Mathews et al., 1980), encompassing 194 km^2 (NOAA, 1990). It includes three sounds (St. Catherines, Sapelo, and Doboy) and numerous coastal plain rivers, including Bear, Medway, North and South Newport, and Sapelo rivers (Figure 62). This estuary is defined from the heads of tide on Mt. Hope and Peacock Creeks, approximately 40 km upstream of the entrance to St. Catherines Sound (NOAA, 1985). It is separated from Ossabaw Sound to the north by tidal nodes located in the AIWW and in Kilkenny and Big Tom Creeks (Rogers, Pers. Comm.). Tidal nodes in Little Mud River and Threemile Cut separate the St. Catherines/Sapelo Sound estuary from the Altamaha River system to the south. This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 62).

Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level (NOAA, 1990), although greater depths are interspersed with shoals throughout the estuary. Deeper water is found in natural channels near the mouths of the three sounds and at sharp river bends (UGA, 1971). The AIWW (3.7 m at MLW) is the only actively maintained navigation channel (Figure 62).

Figure 62. *Location map and subsystem identification*



Freshwater

Due to the small size of its watershed, this estuary receives limited freshwater inflow, primarily from mainland freshwater runoff, groundwater, and lateral flow from the trans-piedmont, piedmont, and coastal plain rivers (Brunswick Junior College, 1975; Kjerfve, 1973; Mathews et al., 1980; NOAA, 1990). Lowest river discharge usually occurs in summer and early fall (Figure 63) due to precipitation within the watershed (Brunswick Junior College, 1975). Figure 64 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

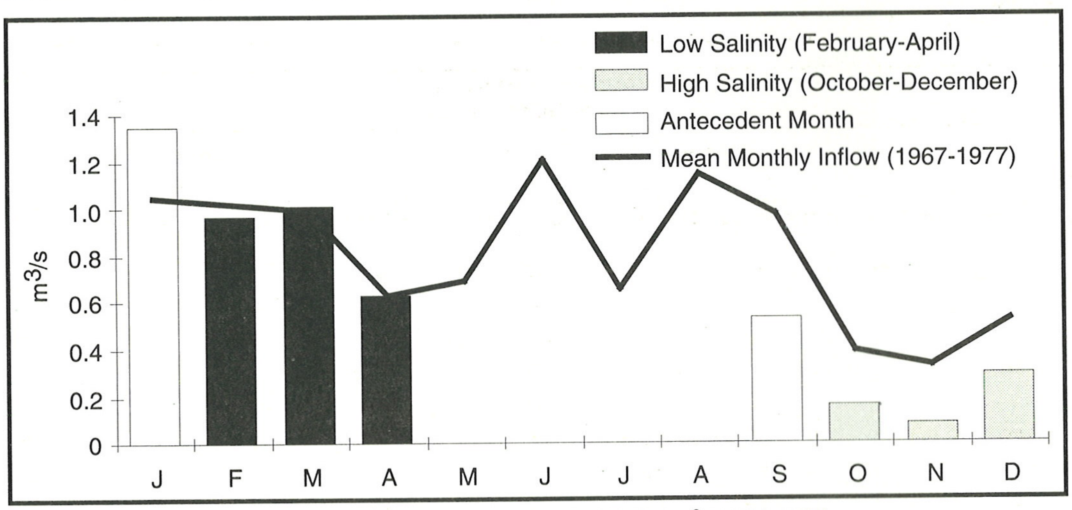
Tides

Most tidal exchange occurs through the entrances to St. Catherines, Sapelo, and Doboy sounds, although limited exchanges occur with Ossabaw Sound, primarily through the AIWW, and with Altamaha Sound through Threemile Cut and Little Mud River (Rogers, Pers. Comm.).

Salinity

The salinity structure is determined by seasonal freshwater discharge. An undetermined amount of inflow is possibly contributed by Altamaha and Ogeechee rivers through the AIWW and through an extensive network of small coastal rivers and creeks. Very limited data available for this estuary suggest weak vertical stratification in Doboy Sound and its tributaries (Figure 65). In the absence of any significant freshwater inflow, salinities tend to be vertically homogeneous. Spring tides and northeasterly winds are important mechanisms controlling salinity variability (Ragotzkie and Bryson, 1955). Seasonally higher precipitation along the coastal plain during late summer and fall can also affect salinity variability. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 66.

Figure 63. *Comparison of gaged freshwater volume during periods of salinity depiction shown in Figure 64**



*USGS gage on Peacock Creek reflects 3% of the estuary's watershed (2,590 km^2) (USGS, 1993)

Figure 64. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1963	17	12	88	0	17	12	88	0
1967	86	37	30	33	28	0	0	100
1972	67	46	36	18	56	55	45	0
1974	23	0	0	100	7	0	0	100
1975	12	0	0	100	0	0	0	0
1977	3	0	0	100	0	0	0	0
1978	2	0	0	100	0	0	0	0
1979	51	37	57	6	0	0	0	0
1981	13	38	38	23	0	0	0	0
1982	15	27	53	20	0	0	0	0
1984	14	36	43	21	0	0	0	0
1986	18	22	61	17	0	0	0	0
1988	18	6	78	17	0	0	0	0
1990	18	56	28	17	0	0	0	0
1992	17	41	47	12	0	0	0	0
Total Observations	374	32	40	28	108	31	37	32
Average Salinity (ppt)	19.5				20.5			

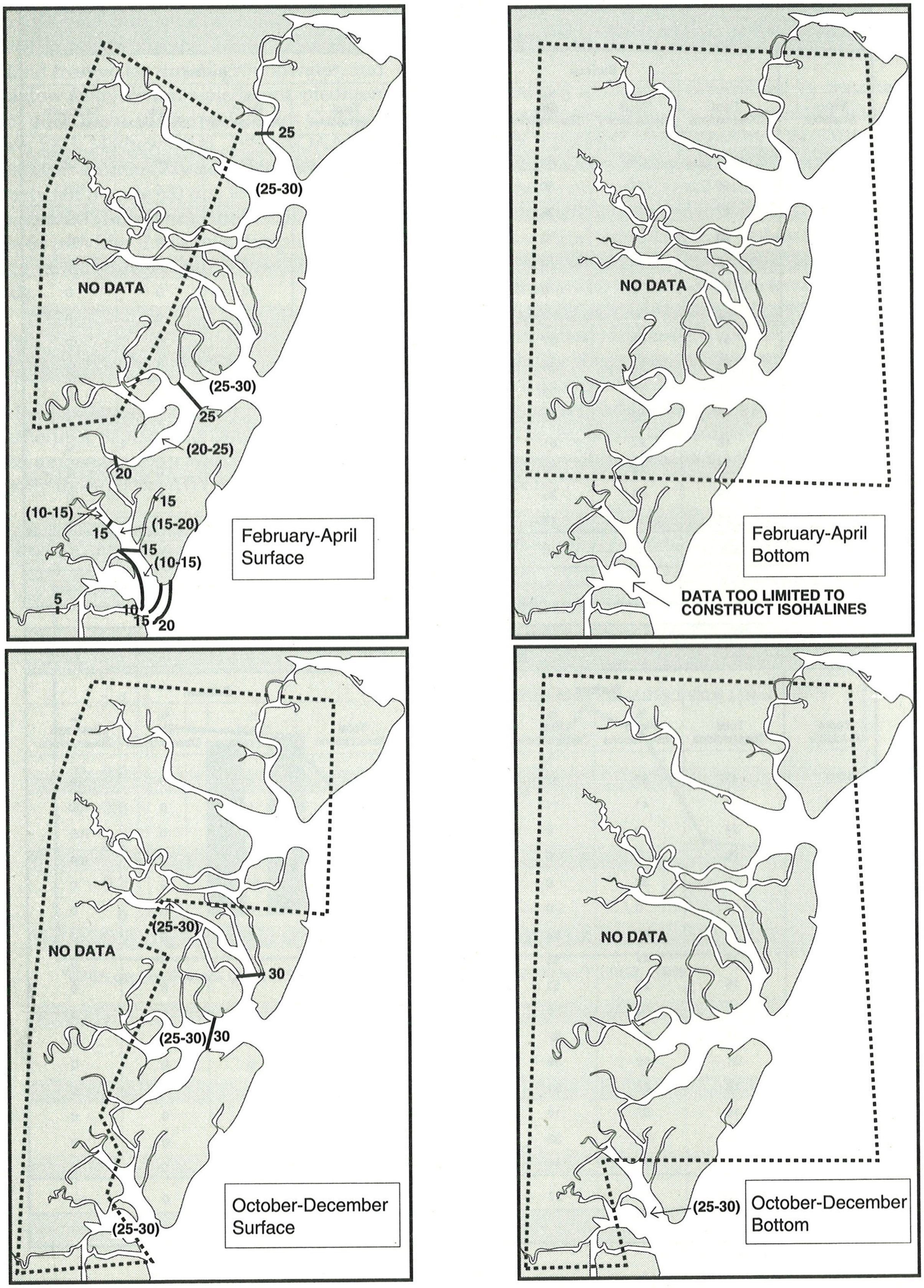
October-December
High-Salinity Period

Years Available	Surface: Total Observations	Surface: % Flood Observations	Surface: % Ebb Observations	Surface: % Unknown Observations	Bottom: Total Observations	Bottom: % Flood Observations	Bottom: % Ebb Observations	Bottom: % Unknown Observations
1966	49	53	47	0	0	0	0	0
1968	81	41	15	44	8	0	0	100
1973	24	0	0	100	7	0	0	100
1974	29	0	0	100	14	0	0	100
1975	9	33	0	67	3	100	0	0
1978	2	0	0	100	0	0	0	0
1979	9	11	56	33	0	0	0	0
1980	15	47	33	20	0	0	0	0
1982	15	27	53	20	0	0	0	0
1983	3	0	0	100	0	0	0	0
1984	21	24	62	14	0	0	0	0
1985	21	52	33	14	0	0	0	0
1987	18	22	61	17	0	0	0	0
1988	18	67	17	17	0	0	0	0
1990	18	50	33	17	0	0	0	0
1992	18	72	11	17	0	0	0	0
Total Observations	350	37	27	36	32	9	0	91
Average Salinity (ppt)	24.0				22.6			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 65. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 64* *

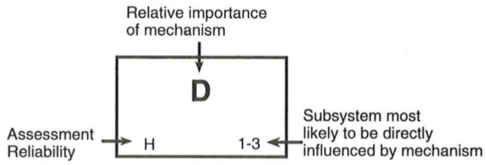


* Data Sources: See data sources listed for St. Catherines/Sapelo Sounds in the Appendix.

Figure 66. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 64**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		**S** L 1-2	**S** L 1-2	**D** L 1-2	
Tides	**D** LIT 1-2				
Wind		**S** LIT 1-2			
Inter-estuary Exchanges			**S** LIT 1-2		
Effect on Salinity Variability	UNKNOWN	MEDIUM	MEDIUM	MEDIUM	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 65 represent the "mean" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

NOTE: Matrix primarily reflects conditions in Doboy Sound due to data limitations.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability, possibly due to local precipitation.

Months-Seasons. Secondary influence on the salinity structure.

Year-Year. Dominant influence on the salinity structure.

Tides

Hours. Dominant influence on salinity variability and water-column mixing throughout most of this estuary. Effect is enhanced during spring tides. Tides are semi-diurnal and average about 2-3 m (Mathews et al., 1980; Ragotzkie and Bryson, 1955). Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability.

Inter-estuary Exchanges

Months-Seasons. Secondary influence on the salinity structure, possibly through the AIWW.

* Data Sources: See data sources listed for St. Catherines/Sapelo Sounds in the Appendix.

Description

The Altamaha River estuary is a coastal plain system, occupying 39 km² (NOAA, 1990). It includes Altamaha River, Altamaha Sound, and several tidal tributaries (Figure 67) and is defined from the head of tide on the Altamaha River, about 39 km upstream of the entrance to Altamaha Sound (Brooks and McConnell, 1983). It is separated from the St. Catherines/Sapelo Sounds system by tidal nodes located in Little Mud River and Threemile Cut (Rogers, Pers. Comm.). Tidal nodes near the head of Hampton River and at the heads of Mackay and Frederica rivers separate the Altamaha River system from the St. Andrew/St. Simons Sounds system (Rogers, Pers. Comm.). This estuary has been divided into three subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 67).

Bathymetry

The average depth of the estuary is approximately 3 m at mid-tide level (NOAA, 1990), although greater depths are interspersed with shoals throughout this estuary. The AIWW (3.7 m at MLW) is the only actively maintained navigation channel (Figure 67).

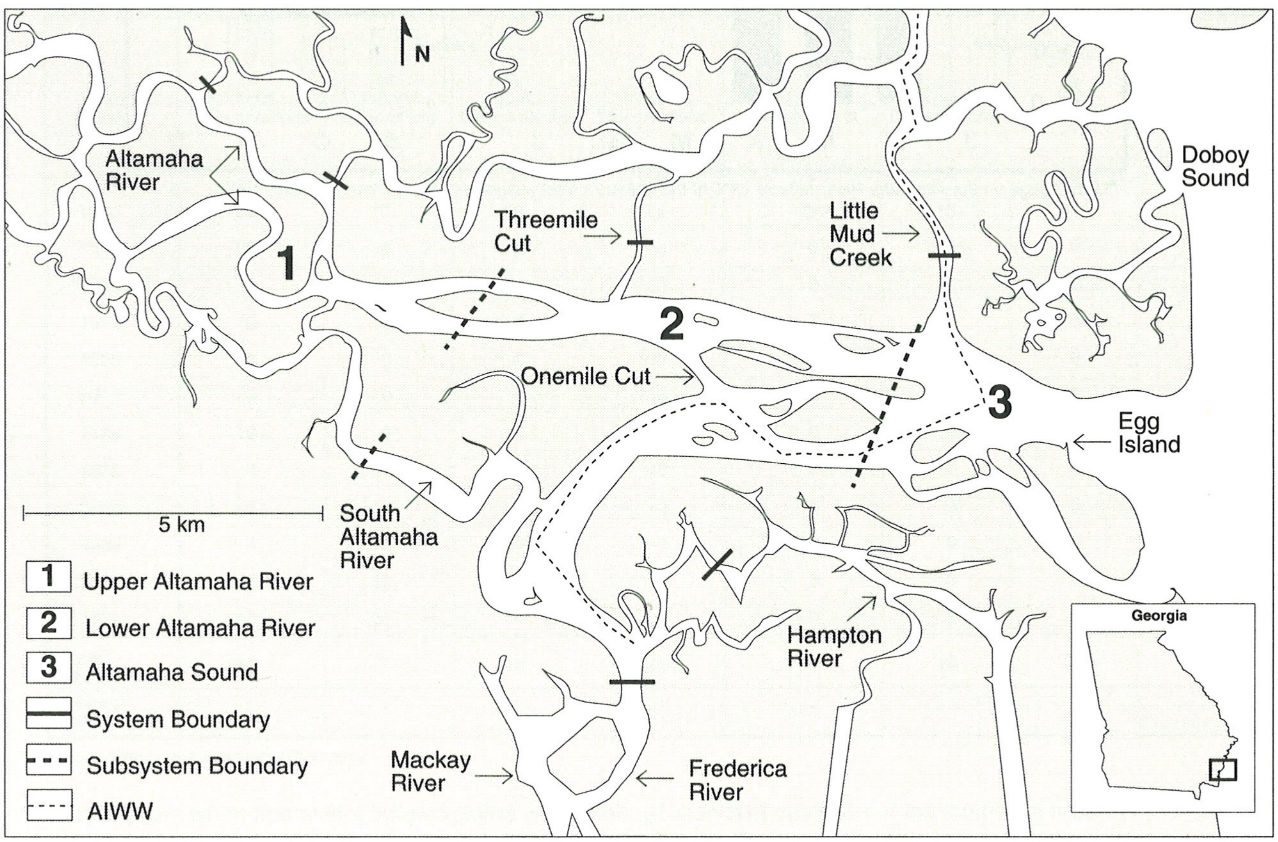
Freshwater

This estuary receives most of its freshwater from Altamaha River, which is formed by the confluence of Ocmulgee and Oconee rivers (not shown). Highest river discharge usually occurs in late winter and spring due to heavy precipitation in the piedmont area; lowest discharge occurs during late summer and fall (Brunswick Junior College, 1975; Stokes et al., 1991) (Figure 68). Dams forming Lake Oconee and Sinclair Reservoir on Oconee River, and Lloyd Shoals Reservoir on the Ocmulgee River (not shown) have little influence on estuarine salinities (Brunswick Junior College, 1975; Stokes et al., 1991). Figure 69 provides the salinity sampling and average salinity during low- and high-salinity periods.

Tides

Most tidal exchange occurs through the entrance to Altamaha Sound, although limited exchange occurs with Doboy Sound through Threemile Cut and Little

Figure 67. *Location map and subsystem identification*



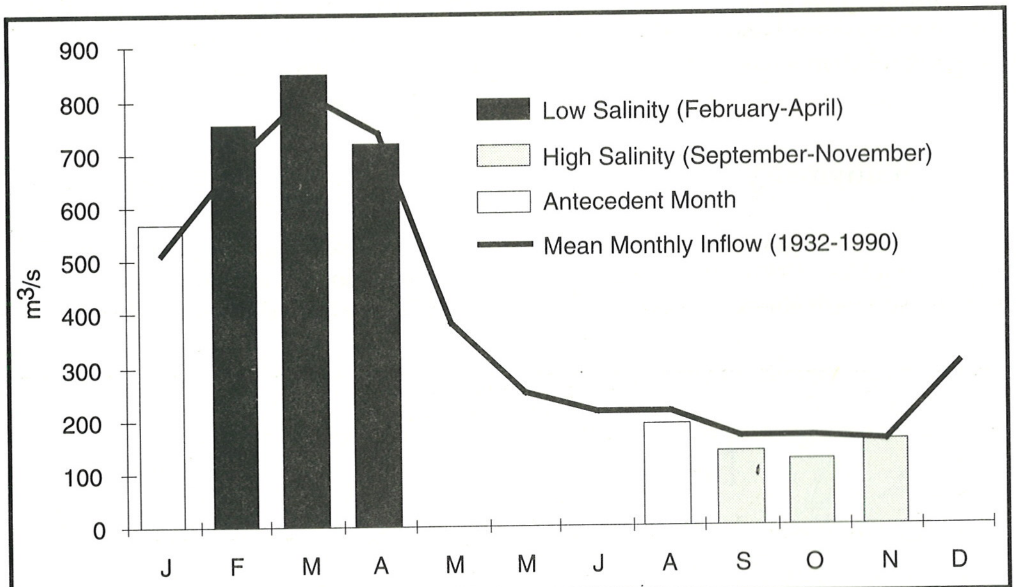
Mud River. Additional exchanges with St. Simons Sound occur through Hampton, Mackay, and Frederica rivers (Mathews et al., 1980 and Rogers, Pers. Comm.).

Salinity

The salinity structure is primarily determined by the seasonal freshwater discharge from Altamaha River. During the low-salinity period, freshwater maintained brackish and vertically homogeneous conditions in Altamaha River above Onemile Cut and throughout South Altamaha River.

Variable and moderate to highly stratified conditions existed in the central and lower estuary. During the high-salinity period, surface salinities increased 5-10 ppt throughout most of the estuary seaward of Onemile Cut (no bottom data were available) (Figure 70). Surface salinities were most variable seaward of Onemile Cut. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 71.

Figure 68. *Comparison of gaged freshwater volume for Altamaha River during periods of salinity depiction shown in Figure 69**



*USGS gage on the Altamaha River reflects 96% of the estuary's total watershed (36,777 km^2) (USGS, 1993)

Figure 69. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface				Bottom			
	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1970	9	22	0	78	0	0	0	0
1971	9	0	0	100	0	0	0	0
1972	9	0	0	100	0	0	0	0
1974	10	0	0	100	7	0	0	100
1976	38	50	16	34	35	54	17	29
1977	3	0	0	100	0	0	0	0
1978	3	0	0	100	0	0	0	0
1979	15	20	60	20	0	0	0	0
1980	6	50	0	50	0	0	0	0
1982	10	30	40	30	0	0	0	0
1984	8	63	38	0	0	0	0	0
Total Observations	120	29	18	53	42	45	14	40
Average Salinity (ppt)	3.7				10.7			

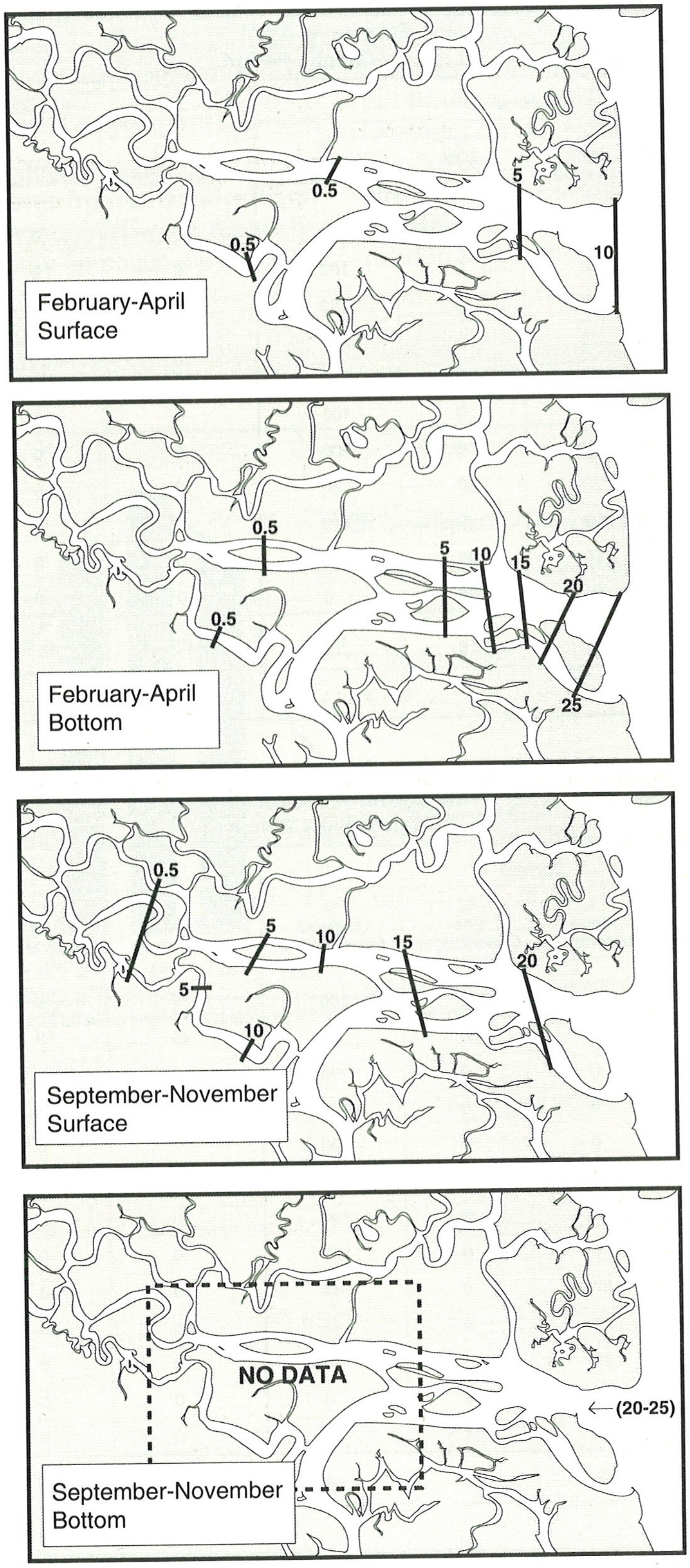
September-November
High-Salinity Period

Years Available	Surface				Bottom			
	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1968	2	0	0	100	2	0	0	100
1970	59	17	29	54	49	18	31	51
1972	29	0	0	100	0	0	0	0
1973	3	0	0	100	0	0	0	0
1974	10	0	0	100	7	0	0	100
1976	3	0	0	100	0	0	0	0
1977	3	0	0	100	0	0	0	0
1978	3	0	0	100	0	0	0	0
1979	7	57	0	43	0	0	0	0
1982	7	57	0	43	0	0	0	0
1983	4	75	25	0	0	0	0	0
1984	11	82	18	0	0	0	0	0
1985	13	38	54	8	0	0	0	0
Total Observations	154	23	18	60	58	16	26	59
Average Salinity (ppt)	13.4				20.0			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 70. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 69**

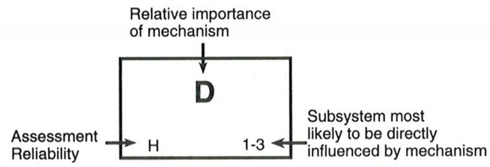


* Data Sources: See data sources listed for Altamaha River in the Appendix.

Figure 71. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 69**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		D (L, 2-3)	D (L, 2-3)	D (L, 1-3)	
Tides	D (LIT, 2-3)				
Wind		M (LIT, 2-3)			
Density Currents		M (LIT, 2-3)			
Effect on Salinity Variability	UNKNOWN	HIGH	MEDIUM	HIGH	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 70 represent the "mean" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Dominant influence on salinity variability and stratification, primarily in the lower and mid-estuary where freshets temporarily increase vertical stratification.

Months-Seasons. Dominant influence on the salinity structure throughout most of the estuary. During the low-salinity period, discharge from Altamaha River and its principle tributaries is five times greater and salinities approximately 15 ppt lower than during the high-salinity period.

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant influence on the salinity structure, primarily in the lower and mid-estuary. Tides are semi-diurnal, averaging 2.0 m near the estuary's mouth (USACE, 1991b). Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Minor influence on salinity variability, particularly when associated with fronts. These winds increase water-column mixing and estuary-ocean exchanges. The effects are intensified by the onset of "northeasters."

Density Currents

Days-Weeks. Minor influence on the salinity structure, primarily in the AIWW and lower estuary.

* Data Sources: See data sources listed for Altamaha River in the Appendix.

Description

The St. Andrew/St. Simons Sounds estuary is a drowned river valley-barrier island system (Mathews et al., 1980), encompassing 186 km^2 (NOAA, 1990). It includes St. Andrew and St. Simons Sounds, as well as the Satilla River; Little Satilla River; and several coastal plain rivers and creeks (Figure 72). This estuary is defined from the head of tide on Satilla River, approximately 80 km upstream of the entrance to St. Andrew Sound (NOAA, 1985). It is separated from the Altamaha River estuary to the north by tidal nodes located near the heads of Mackay and Frederica rivers (Rogers, Pers. Comm.). Tidal nodes in the Brickhill and Cumberland rivers separate this estuary from the Cumberland Sound system to the south. This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 72).

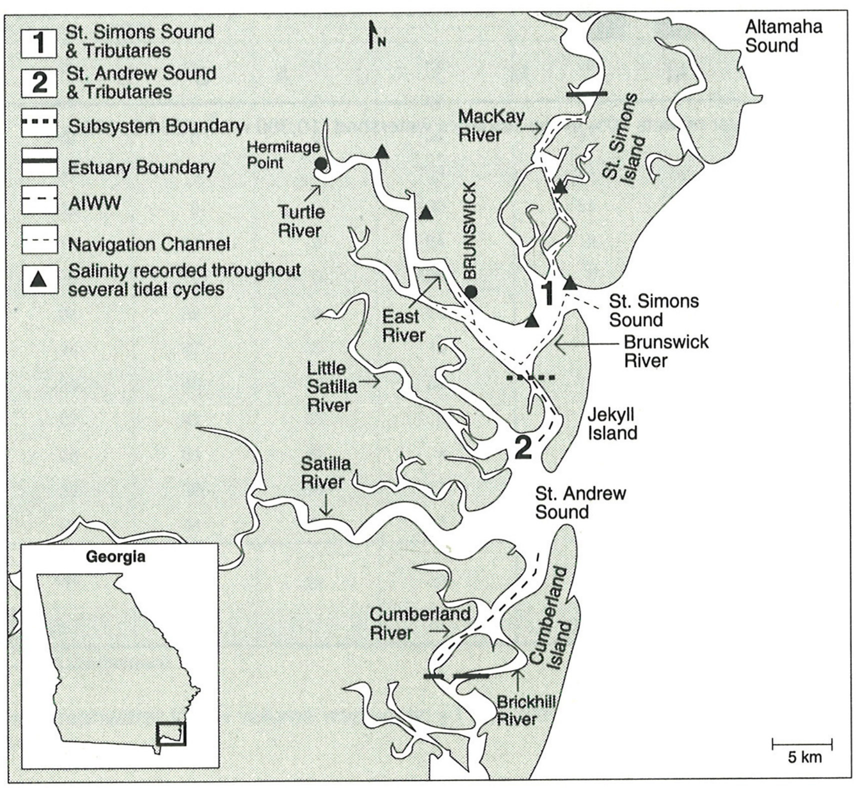
Bathymetry

The average depth of this estuary is approximately 4 m at mid-tide level (NOAA, 1990), although numerous shoals and naturally deep areas are interspersed throughout the estuary. The Brunswick Harbor Channel (BHC) (10 m at MLW) extends from the entrance of St. Simons Sound to Brunswick; a smaller channel extends toward the lower Turtle River. The East River Channel is susceptible to shoaling from sediments originating primarily in Altamaha River that are transported through Mackay River (Mathews et al., 1980). The AIWW (3.7 m at MLW) crosses the lower estuary (Figure 72).

Freshwater

This estuary receives most of its freshwater from Satilla River (Havens and Emerson, Ltd., 1974; Mathews et al., 1980; Stokes et al., 1991). Although precipitation within the watershed is greatest in summer, highest river discharge usually occurs during late winter and spring; lowest discharge occurs during fall (Brunswick Junior College, 1975; Mathews et al., 1980; Stokes et al., 1991) (Figure 73). Figure 74 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

Figure 72. *Location map and subsystem identification*



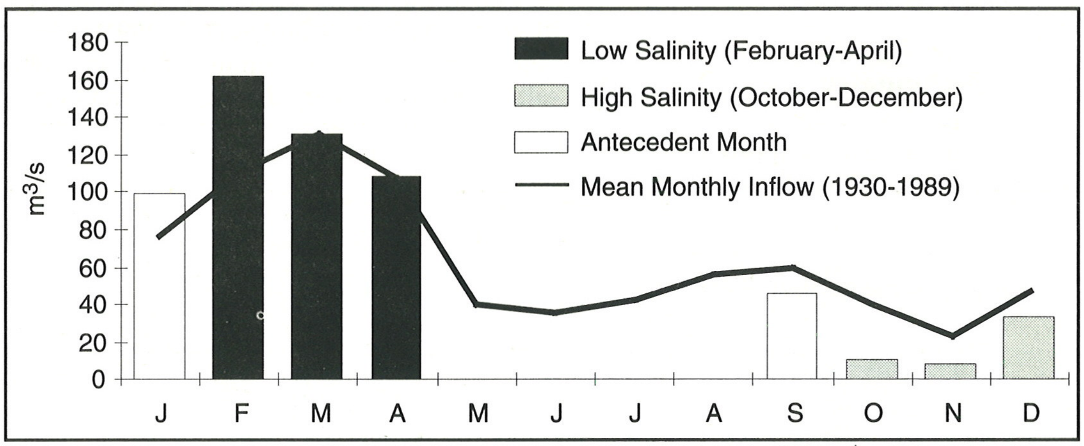
Tides

Most tidal exchange occurs across shifting bars at the entrances to St. Andrew and St. Simons sounds. Additional exchanges occur with Altamaha River (primarily through Mackay and Frederica rivers) and with the Cumberland Sound system through Cumberland River (Rogers, Pers. Comm.).

Salinity

The salinity structure of St. Andrew Sound is primarily determined by seasonal freshwater discharge from the Satilla River (Stokes et al., 1991). Although St. Simons Sound lacks any comparable direct freshwater inflow, exchanges with Altamaha River (through Mackay River) appear to have considerable influence on its seasonal salinity structure. Limited data available for Mackay River, St. Simons Sound, and Brunswick River suggest that salinities are highly variable and weakly stratified, particularly in the low-salinity period (Figure 75). Tides and freshwater inflow are probably the dominant mechanisms controlling salinity variability. Limited data are available during 1971-72 at stations identified in Figure 72 to describe salinity variability throughout several tide cycles (Winker et al., 1985). These data suggest that surface and bottom salinities vary 1-8 ppt at this time scale. The important time scales of salinity variability and responsible mechanisms are summarized in Figure 76.

Figure 73. *Comparison of gaged freshwater volume during periods of salinity depiction shown in Figure 74**



* USGS gage on Satilla River reflects 70% of the estuary's watershed (10,360 km^2) (USGS, 1993)

Figure 74. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface				Bottom			
	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1970	0	0	0	0	14	57	14	29
1971	39	28	51	21	45	40	49	11
1972	80	16	20	64	76	17	20	63
1974	33	0	0	100	21	0	0	100
1976	15	40	0	60	6	100	0	0
1977	6	0	0	100	0	0	0	0
1978	6	0	0	100	0	0	0	0
1979	33	73	9	18	0	0	0	0
1980	15	40	20	40	0	0	0	0
1982	24	25	50	25	0	0	0	0
1984	19	37	58	5	0	0	0	.0
Total Observations	270	27	24	49	162	28	24	48
Average Salinity (ppt)	13.8				13.1			

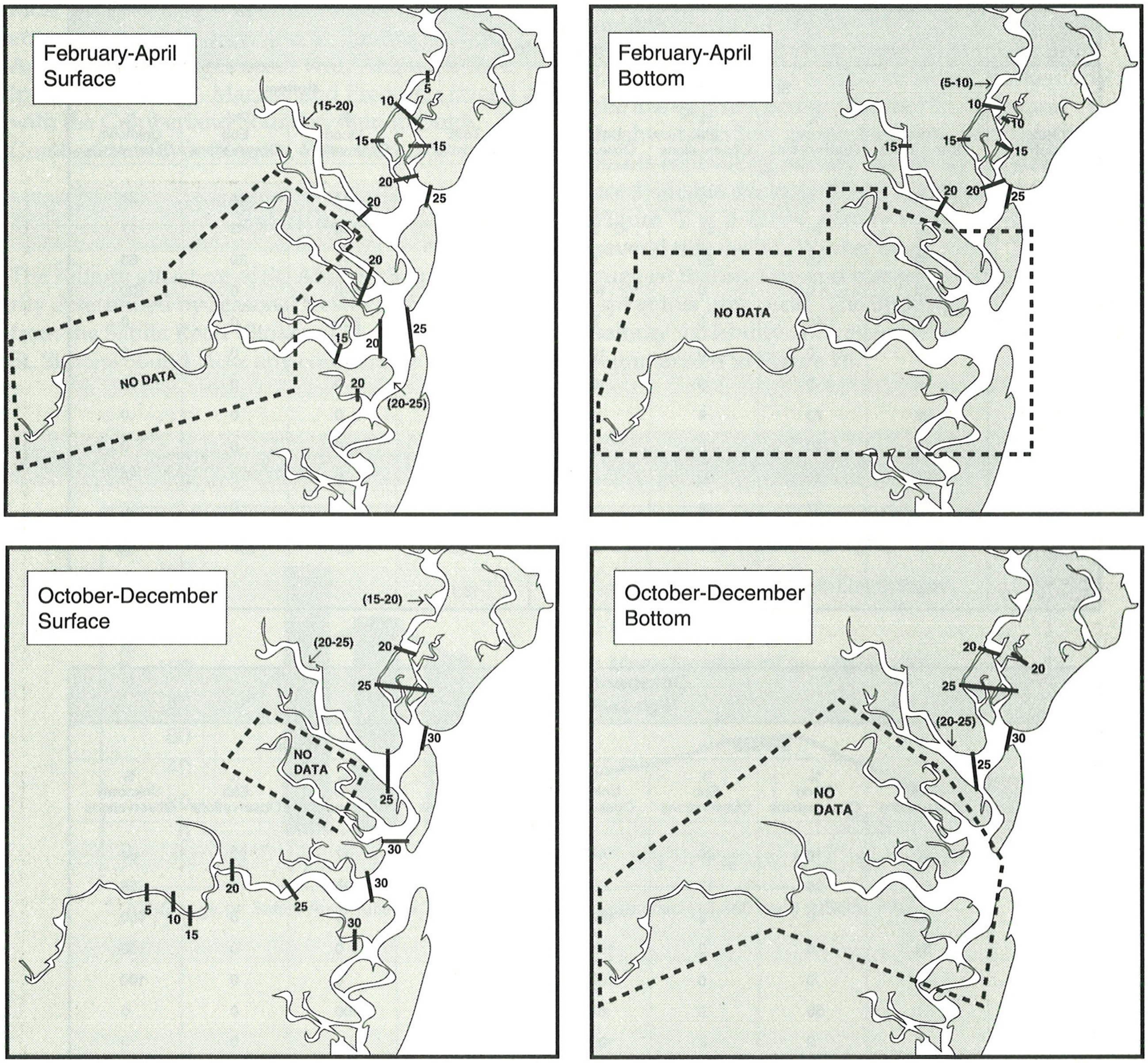
October-December
High-Salinity Period

Years Available	Surface				Bottom			
	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1970	96	16	20	65	96	17	20	64
1971	69	25	17	58	69	25	17	58
1972	43	0	0	100	34	0	0	100
1973	33	0	0	100	21	0	0	100
1974	33	0	0	100	21	0	0	100
1975	14	36	0	64	5	100	0	0
1977	6	0	0	100	0	0	0	0
1980	24	38	38	25	0	0	0	0
1981	34	47	35	18	0	0	0	0
1982	23	43	30	26	0	0	0	0
1984	27	67	33	0	0	0	0	0
1986	28	61	36	4	0	0	0	0
1987	29	28	66	7	0	0	0	0
1988	29	31	62	7	0	0	0	0
Total Observations	488	25	24	51	246	15	13	72
Average Salinity (ppt)	25.7				24.7			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 75. *Surface and bottom salinities during low- and high-salinity periods shown in Figure 74* *

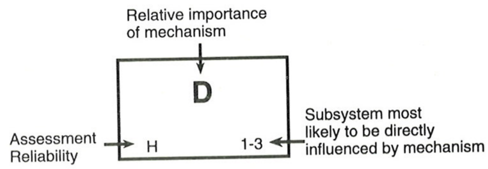


* Data Sources: See data sources listed for St. Andrew/St. Simons Sounds in the Appendix.

Figure 76. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 74**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		D L 1-2	S L 1-2	D L 1-2	
Tides	D LIT 1-2				
Wind		S LIT 1-2			
Density Currents			M LIT 1		
Inter-estuary Exchanges			S LIT 2		
Effect on Salinity Variability	UNKNOWN	HIGH	HIGH	HIGH	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 75 represent the "mean" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Dominant influence on salinity variability and stratification.

Months-Seasons. Secondary influence on the salinity structure.

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant influence on salinity variability and water-column mixing throughout most of the estuary. Tides are semi-diurnal, ranging 2.0 m at the entrances to the estuary and increasing to 2.2 m near Brunswick and 2.4 m at Hermitage Point (NOAA, 1991). Limited data are available during 1971-72 at stations identified in Figure 72 to describe salinity variability throughout several tide cycles (Winker et al., 1985). These data suggest that surface and bottom salinities vary 1-8 ppt at this time scale.

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability.

Density Currents

Months-Seasons. Minor influence on salinity stratification, primarily in St. Simons Sound and Brunswick River.

Inter-estuary Exchanges

Months-Seasons. Secondary influence on the salinity structure in Mackay River and St. Simons Sound.

* Data Sources: See data sources listed for St. Andrew/St. Simons Sounds in the Appendix.

15 St. Marys River/Cumberland Sound, GA/FL

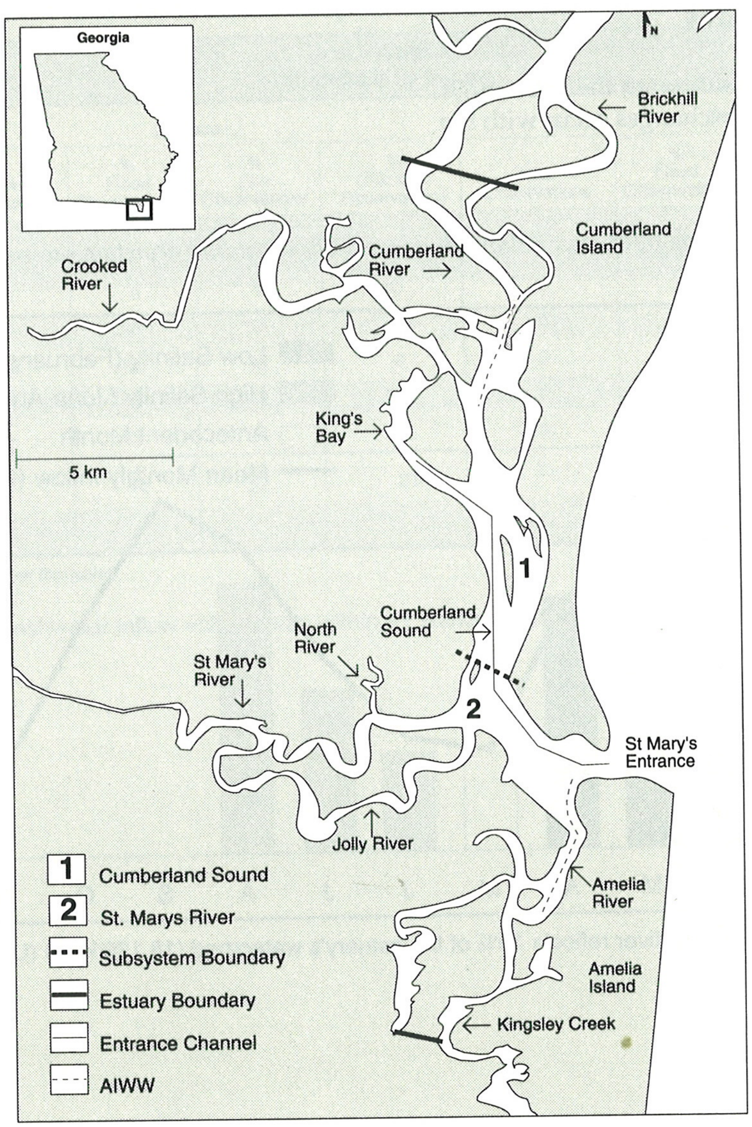
Description

The St. Marys River & Cumberland Sound is a bar-built estuary, encompassing 67 km^2 (Mathews et al., 1980; NOAA 1990). This estuary includes St. Marys, Crooked, and Amelia rivers; Kings Bay; Cumberland Sound; and a network of smaller coastal plain rivers and creeks. It is defined from the head of tide on St. Marys River, approximately 64 km from its mouth (Brooks and McConnell, 1983). It is separated from the St. Andrew/St. Simons Sounds estuary to the north by tidal nodes in Cumberland and Brickhill rivers (Rogers, Pers. Comm.). A tidal node in Kingsley Creek, south of Amelia River, separates this estuary from Nassau Sound to the south. This estuary has been divided into two subsystems based on the response of salinity to forcing mechanisms and time scales (Figure 77).

Bathymetry

The average depth of this estuary is approximately 6 m at mid-tide level (NOAA, 1990). Navigation channels (14 m at MLW) through St. Marys Entrance and Cumberland Sound to Kings Bay Naval Submarine Base probably enhance shoaling rates (Radtke, 1985) and may facilitate saltwater intrusion in this part of the estuary. Additional smaller channels exist in Cumberland Sound (9 m at MLW), North River (9 m at MLW), and through St. Marys River (5 m at

Figure 77. *Location map and subsystem identification*



MLW). The AIWW enters Cumberland Sound from Cumberland River and continues south through Amelia River (Figure 77).

Freshwater

This estuary receives most of its freshwater from St. Marys River, which originates in Okefenokee Swamp (Brunswick Junior College, 1975; Stokes et al., 1991) and is part of the boundary between Georgia and Florida. Although precipitation within the watershed is greatest in summer, highest river discharge usually occurs during late winter and spring, while lowest river discharge occurs in fall (Brunswick Junior College, 1975; GADNR, 1973; Havens and Emerson, Ltd., 1975; Stokes et al., 1991) (Figure 78). Figure 79 provides the salinity sampling and average salinity for this estuary during low- and high-salinity periods.

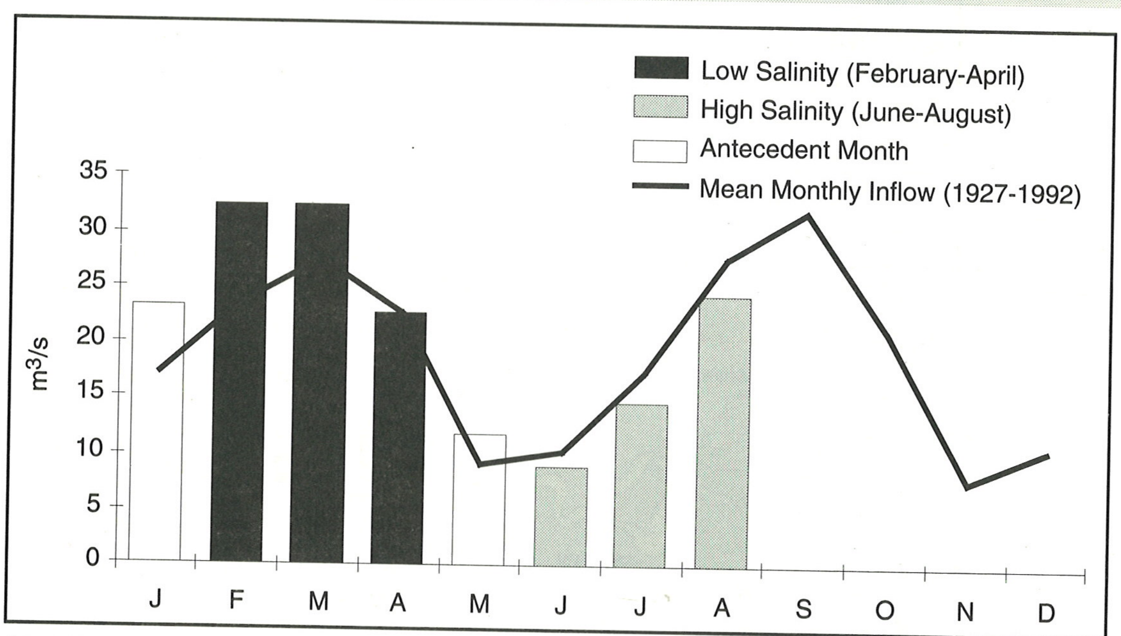
Tides

Most tidal exchange occurs through the jetties of St. Marys Entrance. Limited exchanges occur with the St. Andrew/St. Simons Sounds system through Cumberland River (Radtke, 1985; Rogers, Pers. Comm.) and with the St. Johns estuary through Amelia River (NOAA, 1985).

Salinity

The salinity structure is primarily determined by seasonal freshwater discharge from St. Marys River and its tributaries (Mathews et al., 1980; Radtke, 1985; Stokes et al., 1991). Radtke (1985) reports that salinities in the lower estuary are generally polyhaline to euhaline and tend to be vertically homogeneous due to mixing caused by strong ocean breezes and tidal currents. Changes in salinity over a tide cycle are typically small, except near the mouth of St. Marys River where bottom salinities have been shown to differ by more than 10 ppt between successive ebb and flood tides (Radtke, 1985) (Figure 80). The important time scales of salinity variability and responsible mechanisms are summarized in Figure 81.

Figure 78. *Comparison of gaged freshwater volume during periods of salinity depiction shown in Figure 79**



* USGS gage on St. Marys River reflects 10% of the estuary's watershed (18,129 km^2) (USGS, 1993)

Figure 79. *Salinity sampling information and average salinity during low- and high-salinity periods**

February-April
Low-Salinity Period

Years Available	Surface				Bottom			
	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1972	3	0	0	100	0	0	0	0
1979	12	83	17	0	0	0	0	0
1981	8	50	50	0	0	0	0	0
1982	8	63	38	0	0	0	0	0
1983	8	75	25	0	0	0	0	0
1986	8	50	50	0	0	0	0	0
1988	12	33	67	0	0	0	0	0
Total Observations	59	56	39	5	0	0	0	0
Average Salinity (ppt)	23.4				0			

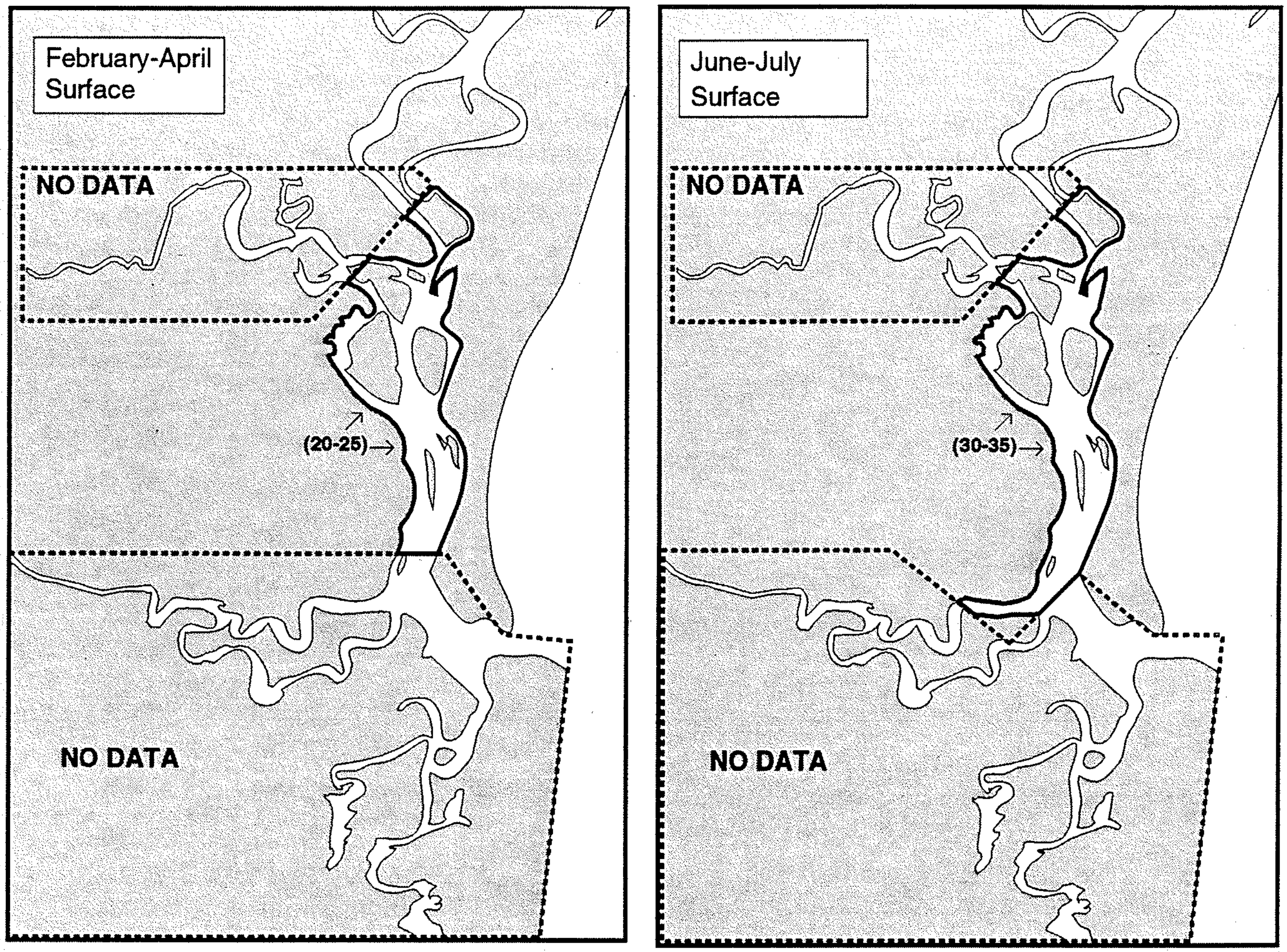
June-August
High-Salinity Period

Years Available	Surface				Bottom			
	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations	Total Observations	% Flood Observations	% Ebb Observations	% Unknown Observations
1972	2	0	0	100	0	0	0	0
1974	10	0	0	100	7	0	0	100
1982	8	50	50	0	0	0	0	0
1984	13	62	38	0	0	0	0	0
1986	12	58	42	0	0	0	0	0
1987	12	42	58	0	0	0	0	0
Total Observations	57	42	37	21	7	0	0	100
Average Salinity (ppt)	28.8				30.7			

Abbreviation: ppt - parts per thousand

*Includes years when freshwater inflow volume was within ±1 standard deviation of the long-term mean.

Figure 80. *Surface salinities during low- and high-salinity periods shown in Figure 79* *

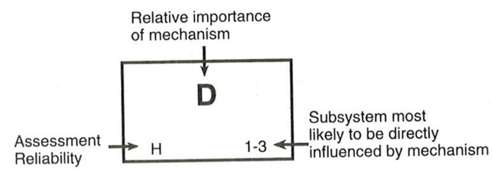


* Data Sources: See data sources listed for St. Marys River/Cumberland Sound in the Appendix.

Figure 81. *Time scales and forcing mechanisms important to salinity structure and variability as shown in Figure 79**

Mechanism	Time Scale of Salinity Response: Hours	Days to Weeks	Months to Seasons	Year to Year	Episodic
Freshwater Inflow		S (L 1)	D (L 1-2)	D (L 1-2)	
Tides	D (LIT 1-2)				
Wind		S (LIT 1-2)			
Density Currents			M (LIT 1-2)		
Inter-estuary Exchanges			M (LIT 2)		
Effect on Salinity Variability	UNKNOWN	MEDIUM	LOW	LOW	UNKNOWN

Salinity Variability	Importance of Mechanism	Assessment Reliability
Very High = > 21 ppt **High** = 11-20 ppt **Medium** = 6-10 ppt **Low** = 3-5 ppt **Very Low** = < 2 ppt	**D** - dominant **S** - secondary **M** - minor	**H** - high **M** - moderate **L** - low **LIT** - Literature Only



NOTE: Isohalines illustrated in Figure 80 represent the "mean" salinity structure that is subject to the temporal and spatial variability indicated by this matrix. The lower portion of the matrix presents the magnitude of salinity variability at a particular time scale. The information within each column indicates the mechanisms most responsible for that variability.

Freshwater Inflow

Days-Weeks. Secondary influence on salinity variability.

Months-Seasons. Dominant estuary-wide influence on the salinity structure. Typical seasonal inflows alter salinities by approximately 5 ppt throughout Cumberland Sound.

Year-Year. Dominant estuary-wide influence on the salinity structure.

Tides

Hours. Dominant influence on salinity variability in St. Marys River (Radtke, 1985) and water-column mixing throughout most of the estuary. Tides are semi-diurnal, averaging about 1.8 m at St. Marys Entrance. Maximum current velocities are reported to be 1.0-2.0 m/s in St. Marys River Entrance and 0.5-1.3 m/s in the Cumberland Sound Channel (NOAA, 1991). Data insufficient to determine salinity changes during a tidal cycle.

Wind

Days-Weeks. Secondary estuary-wide influence on salinity variability, particularly when associated with fronts.

Density Currents

Months-Seasons. Possible minor influence on salinity stratification near St. Marys River Entrance.

Inter-estuary Exchanges

Months-Seasons. Minor influence on salinity variability.

* Data Sources: See data sources listed for St. Marys River/Cumberland Sound in the Appendix.

Concluding Comments

This report has examined salinity structure and variability of 15 South Atlantic estuaries. To the extent that data allowed, salinity structure was represented by typical seasonal distributions existing under normal and present-day hydrologic conditions. This structure: 1) indicates the relative influence of seawater and freshwater sources in the estuary; 2) provides a common basis for comparisons between estuaries; and 3) becomes a reference point for salinity variability analysis.

Summary of Findings

Nearly all South Atlantic estuaries experience significant salinity variability at many temporal scales. Data suggest that salinity in the Altamaha River, St. Andrew/St. Simons Sounds, and Ossabaw Sound is among the most variable. In contrast, Albemarle Sound, Charleston Harbor, and Broad River are among the most stable systems. This variability reflects the relative influence of forcing mechanisms which differs both between estuaries and within any given estuary.

Freshwater inflow is a dominant forcing mechanism controlling salinity in this region. Many of the South Atlantic estuaries are drowned river valley systems that receive substantial freshwater inflow throughout the year (i.e., Albemarle/Pamlico Sounds, Cape Fear River, Winyah Bay, Santee River, Savannah River, and Altamaha River). Others are lagoonal systems or are supported by small watersheds that provide little freshwater (i.e., Bogue Sound, New River, Broad River, and St. Catherines/Sapelo/Doboy Sounds). The remaining estuaries receive intermediate inflow volumes.

The expression of freshwater on estuarine salinity is primarily determined by the relative influence of ocean salinity. Twice daily, the astronomical tides average is less than 1 meter in many of the North Carolina systems and the tides have restricted access to these estuaries through narrow inlets. In the South Carolina and Georgia estuaries, tides increase to 2-3 meters and have comparatively more influence. Information describing the role of wind, shelf processes, and inter-estuarine exchanges on salinity is limited, although these processes may have considerable influence in many of these estuaries.

Ultimately, temporal variability will be used to differentiate functional differences between estuary types that have direct influence on both resource distribution and water quality (Orlando et al., 1993). This approach suggests that management, monitoring, and research strategies for salinity-dependent estuarine attributes may be different in some estuary types than in others.

***

This report is one component of an effort to synthesize and interpret existing data on the Nation's estuarine resources and resource-use conflicts (see inside front cover). This research supplements an information base bridging the gap between identifying site-specific estuarine problems and formulating management strategies at the state, regional, or national level. Filling this gap is more important now than ever before, as it is becoming clear that the cumulative impact of small, incremental changes in an estuary may have a systemic effect on that estuary, adjacent estuaries, or nearshore coastal waters (Monaco et al., 1989). Compiling and organizing fragments of estuarine information are difficult tasks, but are necessary for effectively managing the Nation's estuaries. Because the information available to conserve and protect estuaries is limited, it can be maximized through the inter- and intra-estuarine comparisons afforded by this data synthesis effort. When combined with other National Estuarine Inventory (NEI) data sets, this information will be used to advance our knowledge of estuarine circulation, pollutant transport, and living marine resource distributions.

References

Cited Works

Atkinson, L.P. 1985. "Hydrography and Nutrients of the Southeastern U.S. Continental Shelf." In: *Oceanography of the Southeastern U.S. Continental Shelf*, edited by L.P. Atkinson, D.W. Menzel, and K.A. Bush, 77-92. Washington, DC: American Geophysical Union.

Atkinson, L.P., T.N. Lee, J.O. Blanton, and W.S. Chandler. 1983. *Climatology of the Southeastern United States Continental Shelf Water.* J. Geophys. Res. 88:4705-4718.

Baltzer, R.A. 1972. "Mathematical Simulation of the Flow Dynamics and Constituent Transport in Port Royal Sound, South Carolina: An Interim Report." In: *South Carolina Water Resources Commission Staff, Port Royal Sound Environmental Study*, 21-46. Columbia, SC: South Carolina Water Resources Commission.

Bearden, C., R. Low, R. Rhodes, R. Van Dolah, C. Wenner, E. Wenner, and D. Whitaker. 1985. *A Review and Analysis of Commercial Shrimp Trawling in the Sounds and Bays of South Carolina.* Charleston, SC: South Carolina Marine Resource Center, Tech. Rep. 62. 51 pp.

Blanton, J.O. 1981. *Ocean Currents along a Nearshore Frontal Zone on the Continental Shelf of the Southeastern United States.* J. Phys. Oceanogr. 11:1627-1637.

Blanton, J.O. 1971. *Exchange of Gulf Stream Water with North Carolina Shelf Water in Onslow Bay During Stratified Conditions.* Deep Sea Resources 18:167-178.

Blanton, J.O. and L.P. Atkinson. 1983. *Transport and Fate of River Discharge on the Continental Shelf of the Southeastern United States.* J. Geophys. Res. 88:4730-4738.

Blanton, J.O. and L.P. Atkinson. 1978. "Physical Transfer Processes between Georgia Tidal Inlets and Nearshore Waters." In: *Estuarine Interactions*, M. Wiley (Editor), pp. 514-532. New York, NY: Academic Press.

Blanton, J.O., F.B. Schwing, A.H. Weber, L.J. Pietrafesa, and D.W. Hayes. 1985. "Wind Stress Climatology in the South Atlantic Bight." In: *Oceanography of the Southeastern U.S. Continental Shelf*, L.P. Atkinson, D.W. Menzel, and K.A. Bush (Editors), pp. 10-22. Washington, DC: American Geophysical Union.

Blood, E.R. and F.J. Vernberg. 1992. "Characterization of the Physical, Chemical, and Biological Conditions and Trends in Winyah Bay and North Inlet Estuaries: 1970-1985." In: *Characterization of the Physical, Chemical, and Biological Conditions and Trends in Three South Carolina Estuaries: 1970-1985, Volume 2*, III-1 through III-117. Charleston, SC: South Carolina Sea Grant Consortium.

Bloomer, D.R. 1973. *A Hydrologic Investigation of Winyah Bay, South Carolina and the Adjacent Coastal Waters.* Atlanta, GA: M.S. Thesis, Georgia Institute of Technology. 57 pp.

Brooks, M.H., and J.B. McConnell. 1983. *Inland Travel of Tide-driven Saline Water in the Altamaha and Satilla Rivers, Georgia, and the St. Marys River, Georgia-Florida.* U.S. Geological Survey Water Resources Investigations Report 83-4086. 17 pp.

Brunswick Junior College. 1975. *Water Quality Investigation of Estuaries of Georgia.* Georgia Department of Natural Resources, Environmental Protection Division. 73 pp.

Bumpus, D.F. 1955. *The Circulation Over the Continental Shelf South of Cape Hatteras.* Eos. Trans. Amer. Geophys. Union 36:601-711.

Bush, K.A., J.O. Blanton, and L.P. Atkinson. 1985. "Summary and Future Plans for South Atlantic Bight Oceanography." In: *Oceanography of the Southeastern U.S. Continental Shelf*, L.P. Atkinson, D.W. Menzel, and K.A. Bush (Editors), pp. 153-156. Washington, DC: American Geophysical Union.

Clay, J.W., D.M. Orr, Jr., and A.W. Stuart (Eds). 1975. *North Carolina Atlas, Portrait of a Changing Southern State.* Chapel Hills, NC: University of North Carolina Press. 178 pp.

Cloern, J.E. and F.H. Nichols. 1985. *Time Scales and Mechanisms of Estuarine Variability, A Synthesis from Studies of San Francisco Bay.* Hydrobiologia 129:229-237.

Copeland, B.J., R.G. Hodson, S.R. Riggs, and J.E. Easley, Jr. 1983. *The Ecology of Albemarle, North Carolina: An Estuarine Profile.* Washington, DC:

U.S. Fish & Wildlife Service, Office of Biological Services, FWS/OBS-83/01. 68 pp.

Crawford, J.K. 1983. *Water-Quality Characteristics for Selected Sites on the Cape Fear River, North Carolina, 1955-80: Variability, Loads, and Trends of Selected Constituents.* Raleigh, NC: U.S. Geological Survey Open File Report 83-526. 66 pp.

Culliton, T.J., M.A. Warren, T.R. Goodspeed, D.G. Remer, C.M. Blackwell, and J.J. McDonough III. 1990. *A Special Earth Week Report: 50 Years of Population Change along the Nation's Coasts, 1960-2010.* Rockville, MD: National Oceanic and Atmospheric Administration, Office of Oceanography and Marine Assessments, Strategic Environmental Assessments Branch. 41 pp.

Davis, K.B., G.S. Anderson, and A.M. Durel. 1990. "Hydrography." In: *A Physical and Ecological Characterization of the Charleston Harbor Estuarine System*, edited by R.F. Van Dolah, P.H. Wendt, and E.L. Wenner, 11-47. Final Report. Charleston, SC: South Carolina Coastal Council.

Davis, K.B. and R.F. Van Dolah. 1992. "System Characterization." In: *Characterization of the Physical, Chemical, and Biological Conditions and Trends in the Charleston Harbor Estuary: 1970-1985, Vol I.* Draft. Charleston, SC: South Carolina Sea Grant Consortium.

Dennis, W.A. 1988. "New River Shore Protection Study." In: *Symposium on Coastal Water Resources*, edited by W.L. Lyke and T.J. Hoban, 1-16. Wilmington, NC.

DeVoe, M.R.. 1992. "Executive Summary." In: *Characterization of the Physical, Chemical, and Biological Conditions and Trends in Three South Carolina Estuaries: 1970-1985, Volume 2*, 1-20. Charleston, SC: South Carolina Sea Grant Consortium.

Epperly, S.P. and S.W. Ross. 1986. *Characterization of the North Carolina Pamlico-Albemarle Estuarine Complex.* NOAA Technical Memorandum NMFS-SEFC-175. 55 pp.

Georgia Department of Natural Resources (GADNR). 1981. *Salinity Study of the Upper Savannah River Estuary.* Atlanta, GA: Environmental Protection Division. 61 pp.

Georgia Department of Natural Resources (GADNR). 1974. *Savannah River Basin Plan.* Atlanta, GA: Environmental Protection Division.

Georgia Department of Natural Resources (GADNR). 1973. *Water Quality Investigation of St. Marys River Basin in Georgia.* Atlanta, GA: Environmental Protection Division. 36 pp.

Giese, G.L., H.B. Wilder, and G.G. Parker, Jr. 1985. *Hydrology of Major Estuaries and Sounds of North Carolina.* Raleigh, NC: U.S. Geological Survey, Water Supply Paper 2221. 108 pp.

Giese, G.L., H.B. Wilder, and G.G. Parker, Jr. 1979. *Hydrology of Major Estuaries and Sounds of North Carolina.* Raleigh, NC: U.S. Geological Survey, Water Resources Investigations 79-46. p. 2

Goodwin, M.H. 1989. "The Charleston Harbor Estuary: Historic, Geographic, and Socio-economic Setting." In: *Charleston Harbor: Issues, Resources, Status, and Management.* NOAA Estuary-of-the-Month Seminar Series No. 16. 62 pp.

Hackney, C.T. and G.F. Yelverton. 1990. "Effects of Human Activities and Sea Level Rise on Wetland Ecosystems in the Cape Fear River Estuary, North Carolina, USA." In: *Wetland Ecology and Management: Case Studies*, edited by D.F. Whigham, 55-61. Netherlands: Kluwer Academic Publishers.

Havens and Emerson, Ltd. 1975. *St. Marys River Basin Water Quality Management Analysis.* Georgia Department of Natural Resources, Environmental Protection Division.

Havens and Emerson, Ltd. 1974. *Satilla River Basin Water Quality Management Analysis.* Georgia Department of Natural Resources, Environmental Protection Division.

Hopkins, S.H. 1956. *The Boring Sponges which Attack South Carolina Oysters, with Notes on Some Associated Organisms.* Contrib. Bears Bluff Lab., No. 23. 30 pp.

Johnson, F.A. 1977. *A Reconnaissance of the Hydrology of the Edisto and Ashepoo Estuaries, South Carolina.* Columbia, SC: South Carolina Water Resource Committee, Report No. 6. 53 pp.

Johnson, B.H., M.J. Trawle, and P.G. Kee. 1987. *A Numerical Model Study of the Effect of Channel Deepening on Shoaling and Salinity Intrusion in the Savannah Estuary. Volume I: Main Text.* Draft Report. Savannah, GA: U.S. Army Engineer District.

Kilpatrick, F.A. and T.R. Cummings. 1972. "A Tracer Simulation Study of Potential Solute Movement in Port Royal Sound." In: *South Carolina Water Resources Commission Staff, Port Royal Sound Environmental Study,* 47-72. Columbia, SC: South Carolina Water Resources Commission.

Kirby-Smith, W.W. and J.D. Costlow. 1989. *The Newport River Estuarine System.* UNC SEA Grant Pub No. UNC-SG-89-04. Beaufort, NC.

Kjerfve, B. 1989. "Physical Processes in Charleston Harbor." In: *Charleston Harbor: Issues, Resources, Status, and Management.* NOAA Estuary-of-the-Month Seminar Series No. 16. 62 pp.

Kjerfve, B. 1976. "The Santee-Cooper: A Study of Estuarine Manipulations." In: *Estuarine Processes, Volume I,* edited by M. Wiley, 44-56. New York, NY: Academic Press Inc.

Kjerfve, B. 1973. *Volume Transport, Salinity Distribution and Net Circulation in the Duplin Estuary, Georgia.* USDI/OWRR Project No. B-035-Ga. Sapelo Island, GA: University of Georgia Marine Institute. 30 pp.

Kjerfve, B. and J.E. Greer. 1978. *Hydrography of the Santee River during Moderate Discharge Conditions.* Estuaries 1(2):111-119.

Kjerfve, B. and K.E. Magill. 1990. *Salinity Changes in Charleston Harbor, 1922-1987.* Jour. of Waterway, Port, Coastal, and Ocean Engineering, ASCE 116:153-168.

Kjerfve, B., K.E. Magill, and P. Sojisuporn 1990. "Physical Dynamics." In: *A Physical and Ecological Characterization of the Charleston Harbor Estuarine System,* edited by R.F. Van Dolah, P.H. Wendt, and E.L. Wenner, 99-120. Final Report. Charleston, SC: South Carolina Coastal Council.

Klein, C.J. and S.P. Orlando, Jr. 1989. *National Estuarine Inventory: Estuarine Pollution Susceptibility—An Approach to Estuarine Classification.* Rockville, MD: NOS/National Oceanic and Atmospheric Administration (NOAA), Strategic Environmental Assessments Division. Unpublished Report.

Kruczynski, W.L. 1974. *A Review of the Oceanography and Fishery of Onslow Bay, North Carolina.* Information Series Number 6. North Carolina Division of Commercial and Sport Fisheries. 47 pp.

Lee, T.N., V. Kourafalou, J.D. Wang, W.J. Ho, J.O. Blanton, L.P. Atkinson, and L.J. Pietrafesa. 1985. "Shelf Circulation from Cape Canaveral to Cape Fear During Winter." In: *Oceanography of the Southeastern U.S. Continental Shelf,* L.P. Atkinson, D.W. Menzel, and K.A. Bush (Editors), pp. 33-62. Washington, DC: American Geophysical Union.

Mathews, T.D. and O. Pashuk. 1982. *A Description of Oceanographic Conditions of the Southeastern United States during 1974.* Charleston, SC: South Carolina Marine Resource Center, Tech. Report No. 50.

Mathews, T.D. and M.H. Shealy, Jr. 1982. *A Description of the Salinity Regimes of Major South Carolina Estuaries.* Charleston, SC: South Carolina Marine Resource Center, Tech. Report No. 54. 14 pp.

Mathews, T.D., M.H. Shealy, Jr., and N. Cummings. 1981. *Hydrography of South Carolina Estuaries, with Emphasis on the North and South Santee and Charleston Harbor-Cooper River Estuaries.* Charleston, SC: South Carolina Marine Resource Center, Tech. Report No. 47. 24 pp.

Mathews, T.D., F.W. Stapor Jr., C.R. Richter, J.V. Miglarese, M.D. McKenzie, and L.A. Barclay (Eds). 1980. *Ecological Characterization of the Sea Island Coastal Region of South Carolina and Georgia, Volume I: Physical Features of the Characterization Area.* FWS/OBS-79/40. Washington, DC: U.S. Fish & Wildlife Service, Office of Biological Services, FWS/OBS-79/40. 211 pp.

Mathews, T.D. and M.H. Shealy, Jr. 1978. *Hydrography of South Carolina Estuaries, with Emphasis on the North and South Edisto and Cooper Rivers.* Charleston, SC: South Carolina Marine Resource Center, Tech. Report No. 30. 148 pp.

Mathews, T.D. and O. Pashuk. 1977. *A Description of Oceanographic Conditions of the Southeastern United States during 1973.* Charleston, SC: South Carolina Marine Resource Center, Tech. Report No. 19. 103 pp.

Monaco, M.E., T.E. Czapla, D.M. Nelson, and M.E. Pattilo. 1989. *Distribution and Abundance of Fishes and Invertebrates in Texas Estuaries.* Rockville, MD: Strategic Environmental Assessments Division, NOAA. 107 pp.

National Oceanic and Atmospheric Administration (NOAA). 1993. *Tides Tables 1993, High and Low Water Predictions—East Coast of North and South America, including Greenland.* Riverdale, MD: National Ocean Service. 300 pp.

National Oceanic and Atmospheric Administration (NOAA). 1991. *United States Coast Pilot #4: Cape Henry to Key West.* 22d Ed. Rockville, MD.

National Oceanic and Atmospheric Administration (NOAA). 1990. *Estuaries of the United States: Vital Statistics of a National Resource Base.* A Special NOAA 20th Anniversary Report. Silver Spring, MD: Strategic Environmental Assessments Division, ORCA. 79 pp.

National Oceanic and Atmospheric Administration (NOAA). 1985. *National Estuarine Inventory: Data Atlas, Volume 1: Physical and Hydrologic Characteristics.* Silver Spring, MD: Strategic Environmental Assessments Division, ORCA. 103 pp.

National Oceanic and Atmospheric Administration (NOAA). 1980. *Climates of the States, Volume I.* Detroit, MI: Gale Research Co. 588 pp.

Officer, C.B. 1983. "Physics of Estuarine Circulation." In: *Ecosystems of the World: Estuaries and Enclosed Seas,* B.H. Ketchum (Editor), Volume 26, 500 pp. Elsevier Publishing Company.

Orlando, S.P., Jr., L.P. Rozas, G.H. Ward, and C.J. Klein. 1993. *Salinity Characteristics of Gulf of Mexico Estuaries.* Silver Spring, MD: National Oceanic and Atmospheric Administration, Office of Ocean Resources Conservation and Assessments. 209 pp.

Pearlstine, L.G., R.D. Bartleson, W.M. Kitchens, and P.J. Latham. 1989. *Lower Savannah River Hydrological Characterization.* Florida Cooperative Fish and Wildlife Research Unit. 139 pp.

Pietrafesa, L.J. and G.S. Janowitz. 1988. "Physical Oceanographic Processes Affecting Larval Transport around and through North Carolina Inlets." In: *Larval Fish and Shellfish Transport through Inlets.* American Fish Society Symposium 3:34-50.

Pietrafesa, L.J., G.S. Janowitz, and P.A. Wittman. 1985. "Physical Oceanographic Processes in the Carolina Capes." In: *Oceanography of the Southeastern U.S. Continental Shelf,* L.P. Atkinson, D.W. Menzel, and K.A. Bush (Editors), pp. 23-32. Washington, DC: American Geophysical Union.

Pinckney, J. and P. Dustan. 1990. *Ebb-tidal Fronts in Charleston Harbor, South: Physical and Biological Characteristics.* Estuaries 13:1-7.

Radtke, D.B. 1985. *Sediment Sources and Transport in Kings Bay and Vicinity, Georgia and Florida.* U.S. Geological Survey Professional Paper 1347, presented July 8-16, 1982. 120 pp.

Ragotzkie, R.A. and R.A. Bryson. 1955. *Hydrography of the Duplin River, Sapelo Island, Georgia.* Bull. Marine Sci. Gulf Carib. 5(4):297-314.

Roelofs, E.W. and D.F. Bumpus. 1953. *The Hydrography of Pamlico Sound.* Bulletin of Marine Science, Gulf Caribbean 3:181-205.

Schoenbaum, T.J. 1982. *Islands, Capes, and Sounds: The North Carolina Coast.* Winston Salem, NC: J. F. Blair, Publisher. 331 pp.

Schwing, F.B., B. Kjerfve, and J.E. Sneed. 1983. *Nearshore Coastal Currents on the South Carolina Continental Shelf.* Jour. Geophys. Res. 88(C8):4719-4729.

Skidaway Institute of Oceanography (SIO). 1981. *Oceanography of the South Atlantic Bight.* Skidaway Island, GA. 16 pp.

Smayda, T.J. 1983. "The Phytoplankton of Estuaries." In: *Ecosystems of the World: Estuaries and Enclosed Seas,* B.H. Ketchum (Editor), Volume 26, 500 pp. Elsevier Publishing Company.

South Carolina Coastal Council (SCCC). 1987. *Lower Savannah River Special Area Management Plan.* Charleston, SC: South Carolina Coastal Council. 73 pp.

South Carolina Wildlife and Marine Resources Department (SCWMRD). *Salinity Data Base for South Carolina and Georgia Estuaries, 1973-1991.* Charleston, SC. Unpublished.

Stapor, F.W. Jr. 1984. *Sand Transport at Edisto Beach, Colleton County, South Carolina.* Charleston, SC: South Carolina Marine Resource Center, Tech. Report No. 60. 7 pp.

Stefansson, U., L.P. Atkinson, and D.F. Bumpus. 1971. *Hydrographic Properties and Circulation of the North Carolina Shelf and Slope Waters.* Deep Sea Res. 18:383-420.

Stickney, R.R. and D. Miller. 1973. *Chemical and Biological Survey of the Savannah River Adjacent to Elba Island.* Savannah, GA: Skidaway Institute of Oceanography. 68 pp.

Stokes, W.R., III, R.D. McFarlane, and G.R. Buell. 1991. *Water Resources Data for Georgia, Year 1991.* U.S. Geological Survey Water-Data Report GS-91-1. 527 pp.

Tiner, R.W., Jr. 1977. *An Inventory of South Carolina's Coastal Marshes.* South Carolina Marine Resources Center, Technical Report No. 23. 33 pp.

Tenore, K.R., C.F. Chamberlain, W.M. Dunstan, R.B. Hanson, B. Sherr, and J.H. Tietjen. 1978. "Possible Effects of Gulf Stream Intrusions and Coastal Runoff on the Benthos of the Continental Shelf of the Georgia Bight." In: *Estuarine Interactions*, edited by M.L. Wiley, 577-598. New York, NY: Academic Press

Trawle, M.J. and R.A. Boland, Jr. 1979. *Georgetown Harbor, South Carolina: Report 2, Effects of Various Channel Schemes On Tides, Currents, and Shoaling; Hydraulic Model.* U.S. Army Corps of Engineers, Misc. Paper H-78-6. 117 pp.

University of Georgia (UGA). 1971. *An Ecological Survey of the North and South Newport Rivers and Adjacent Waters with Respect to Possible Effects of Treated Kraft Mill Effluent.* Final Report to Georgia Water Quality Control Board, UGA #D2422-122. Sapelo Island, GA: University of Georgia Marine Institute. 280 pp.

U.S. Army Corps of Engineers (USACE). 1992. *Water Control Manual, Everett Jordan Dam and Lake, Cape Fear River Basin, North Carolina.* Wilmington, NC: Wilmington District. pp. 3-1 to 7-7.

U.S. Army Corps of Engineers (USACE). 1991a. *Project Maps, Charleston District.* Charleston, SC: Charleston District. 63 pp.

U.S. Army Corps of Engineers (USACE). 1991b. *Project Maps, River and Harbor, Flood Control, and Beach Erosion Control Projects.* Savannah, GA: Savannah Corps of Engineers, U.S. Army Engineer District.

U.S. Army Corps of Engineers (USACE). 1989. *Long-term Maintenance of Wilmington Harbor, North Carolina, Final Environmental Statement.* Wilmington, NC: Wilmington District. 100 pp. + Appendix.

U.S. Army Corps of Engineers (USACE). 1984. *To Great and Useful Purpose: A History of Wilmington District.* Wilmington, NC: Wilmington District. 172 pp.

U.S. Department of the Interior (USDOI). 1983. *Final Environmental Impact Statement, Proposed 1983 Outer Continental Shelf Oil and Gas Lease Sale Offshore the South Atlantic States,* OCS Sale No. 78. New York, NY: Atlantic OCS Region. 353 pp.

U.S. Environmental Protection Agency (USEPA). 1983. *Final Environmental Impact Statement (EIS) for Savannah, GA; Charleston, SC; and Wilmington, NC Ocean Dredged Material Disposal Sites Designation.* EPA 440/2-83-014.

U.S. Geological Survey (USGS). 1993. *Gaged Streamflow Data Base.* Reston, VA. Unpublished.

Van Dolah, R.F. and G.S. Anderson. 1991. *Effects of Hurricane Hugo on Salinity and Dissolved Oxygen Conditions in the Charleston Harbor Estuary.* Charleston, SC: South Carolina Wildlife and Marine Resources Department, Marine Resources Research Institute.

Van Dolah, R.F. and K.B. Davis. 1990. "Description of the Study Area." In: *A Physical and Ecological Characterization of the Charleston Harbor Estuarine System,* edited by R.F. Van Dolah, P.H. Wendt, and E.L. Wenner, 7-10. Final Report. Charleston, SC: South Carolina Coastal Council.

Virginia Institute of Marine Science (VIMS). 1974. *A Socio-economic Environmental Baseline Summary for the South Atlantic Region between Cape Hatteras, North Carolina and Cape Canaveral, Florida, Volume I.* Prepared for the Bureau of Land Management, Contract No. EQ4AC007. 247 pp.

Weber, A.H. and J.O. Blanton. 1980. *Monthly Mean Wind Fields for the South Atlantic Bight.* J. Phys. Oceanography 10:1256-1263.

Wenner, E.L., W.P. Coon, III, P.A. Sandifer, and M.H. Shealy, Jr. 1991. *A Comparison of Species Composition and Abundance of Decapod Crustaceans and Fishes from the North and South Edisto Rivers in South Carolina.* Charleston, SC: South Carolina Marine Resource Center, Tech. Report No. 78. 48 pp.

Winker, C.D., L.C. Jaffe, and J.D. Howard. 1985. *Georgia Estuarine Data, 1961-1977.* Skidaway, GA: Georgia Marine Science Center, University System of Georgia, Technical Report Series #85-7, Volumes I and 2.

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Appendix - Primary Data Sources

This appendix identifies the primary sources of salinity data used in this estuarine characterization report (Table 1). Most salinity data was provided by state water quality monitoring programs. Winker, Jaffe, and Howard (1985) supplemented salinity information available for Georgia estuaries. Information describing salinity variability during astronomical tide cycles is limited in nearly all South Atlantic estuaries.

Table 1. *Primary Sources of Salinity Data*

State/Estuary	Source[1]	Surface/ Bottom	Tides[2]	Years (19__)	Sampling Frequency (Approximate)	Number of Stations[3] Minimum	Number of Stations[3] Maximum	Total # of Samples
NORTH CAROLINA								
Albemarle Sound	DEM	Surface	No	81-92	Monthly	0	31	1437
		Bottom	No	81-92	Monthly	0	22	887
Pamlico Sound	DEM	Surface	No	81-92	Monthly	0	37	2303
		Bottom	No	84-92	Monthly	0	27	1121
	DMF	Surface	No	71-91	Monthly	0	139	14,255
		Bottom	No	71-91	Monthly	0	134	12,517
	ECU	Surface	No	75-92	Monthly-Weekly	0	20	7058
Bogue Sound	DEM	Surface	No	81-92	Monthly	0	11	517
	DMF	Surface	No	70, 73-91	Monthly	0	17	2434
				71-72	2/day per month	0	41	
		Bottom	No	70-71, 73-91	Monthly	0	17	1,532
				72	2xday per month	0	28	
New River	DEM	Surface	No	81-92	Monthly	0	5	447
	DMF	Surface	No	71, 73-91	Monthly	0	24	2507
				72	2xday per month	3	39	
		Bottom	No	71, 73-91	Monthly	0	23	2,458
				72	2xday per month	3	37	
Cape Fear River	DMF	Surface	No	70, 73-91	Monthly	0	19	2299
				71-72	2xday per month	0	19	
		Bottom	No	70, 73-91	Monthly	0	19	2260
				71-72	2xday per month	0	19	
	CP&L	Surface	Yes	82-92	Weekly	9	9	5160
		Bottom	Yes	82-92	Weekly	9	9	5160
	DEM	Surface	No	81-92	Monthly	0	11	649
SOUTH CAROLINA								
Winyah Bay (excluding North Inlet)	SCWMRD	Surface	Yes	73-76, 79, 88-91	3-4 times per year	0	4	474
				77-78	Monthly	10	10	
		Bottom	Yes	73-76,79	3-4 times per year	0	2	435
				77-78	Monthly	10	10	
	DHECWQ	Surface	No	80-91	Monthly	0	11	696
		Bottom	No	80-91	Monthly	0	11	536
	DHECSHELL	Surface	Yes	70,72-74,77-79, 84-92	Inconsistent	0	7	191
	USC	Surface	No	80-82	5-6 times per year	0	19	130
		Bottom	No	80-82	5-6 times per year	0	19	132
North Inlet	DHECWQ	Surface	No	March 85 +86	1X in March	1	1	2
	DHECSHELL	Surface	Yes	70,72-74,77-91	Inconsistent Jun-Aug	0	9	391

1 **DEM** - Division of Environmental Management; **DMF** - North Carolina Division of Marine Fisheries; **ECU** - East Carolina University, Institute for Coastal & Marine Resources; **CP&L** - Carolina Power and Light Company; **SCWMRD** - South Carolina Wildlife & Marine Resources Department; **DHECWQ** - South Carolina Department of Health & Environmental Control, Water Quality Monitoring Stations; **DHECSHELL** - South Carolina Department of Health & Environmental Control, Shellfish Monitoring Stations; and **USC** - Belle W. Baruch Institute for Marine Biology & Coastal Research, University of South Carolina.

2 Tidal information available to NOAA's SEA Division

3 Minimum or maximum number of stations sampled each month during the period of record

Table 1. *Primary Sources of Salinity Data (continued)*

State/Estuary	Source[1]	Surface/ Bottom	Tides[2]	Years (19__)	Sampling Frequency (Approximate)	Number of Stations[3] Minimum	Number of Stations[3] Maximum	Total # of Samples
SOUTH CAROLINA (Continued)								
North/South Santee Rivers	SCWMRD	Surface	Yes	73-74,77,79-80,82 85-91	Inconsistent	0	22	1007
				75-76	Monthly	9	9	
		Bottom	Yes	73-74,77,79-80,82, 85-88	Inconsistent	0	22	987
				75-76	Monthly	9	9	
	DHECSHELL	Surface	Yes	70-73,75,78-84	Inconsistent	0	5	498
				85-92	Monthly	0	6	
Charleston Harbor	SCWMRD	Surface	Yes	73-77,79-80,82-86	Monthly	0	20	2795
				87-91	2xday per month	3	42	
		Bottom	Yes	73-77,79-80,82-86	Monthly	0	20	2778
				87-91	2xday per month	3	42	
	DHECWQ	Surface	No	80-91	Monthly	0	22	1953
		Bottom	No	80-91	Monthly	0	19	1501
	DHECSHELL	Surface	Yes	86-92	Monthly	0	11	422
St. Helena Sound	SCWMRD	Surface	Yes	73-77,79-91	Inconsistent	0	8	580
		Bottom	Yes	73-77,79-91	Inconsistent	0	8	529
	DHECWQ	Surface	No	83 (February-June)	2 times per year	0	1	4
				85+86 (March)	1 time per year	0	1	
	DHECSHELL	Surface	Yes	70-93	Monthly	0	32	2340
Broad River	SCWMRD	Surface	Yes	73-77,79-80,82-91	Inconsistent	0	8	402
		Bottom	Yes	73-77,79-80,82-91	Inconsistent	0	8	395
	DHECWQ	Surface	No	80-82,84-91	Monthly	0	13	851
				83	Biweekly	0	26	
		Bottom	No	81,84-91	Inconsistent	0	12	645
				83	Biweekly	0	25	
	DHECSHELL	Surface	Yes	70-92	Monthly to Biweekly	0	45	3371
SOUTH CAROLINA/ GEORGIA								
Savannah River	SCWMRD	Surface	Yes	73-77,79-80,82-91	4xyear	0	4	240
		Bottom	Yes	73-77,79-80,82-91	4xyear	0	4	237
	DHECWQ	Surface	No	80-91	Monthly	0	3	229
		Bottom	No	83-91 (May-Nov)	Monthly	0	2	86
	DHECSHELL	Surface	Yes	70,72,74-75,77-92 (September-May)	Inconsistent	0	20	1358
	SKIDAWAY	Surface	Yes	68,69,72	Monthly	0	8	505
				70-71,73-75	Inconsistent	0	26	
		Bottom	Yes	68,69,72	Monthly	0	13	548
				70-71,73-75	Inconsistent	0	29	
	PHLANS	Surface	No	90 (Apr,Jun-Aug)	Weekly	6	6	134
	PEST	Surface	No	89 (Mar, Apr,Jun-Nov)	Monthly	2	2	23
		Bottom	No	89 (Mar, Apr,Jun-Nov)	Monthly	2	2	23
	GAFWRU	Surface	No	89-91 (March-May)	Daily	0	6	751
	GAEPD	Surface	No	70-92	Monthly	0	10	2174
		Bottom	No	70-92	Monthly	0	8	1594

1 **SCWMRD** - South Carolina Wildlife & Marine Resources Department; **DHECWQ** - South Carolina Department of Health & Environmental Control, Water Quality Monitoring Stations; **DHECSHELL** - South Carolina Department of Health & Environmental Control, Shellfish Monitoring Stations; **SKIDAWAY** - Georgia Estuarine Data 1961-77, Charles D. Winker, Louise C. Jaffe, James D. Howard; Georgia Marine Science Center, University System of Georgia, Skidaway Island, Georgia, Technical Report Series, Number 85-7, Vols. 1 and 2; **PHLANS** - Philadelphia Academy of Sciences; **PEST** - U.S. Environmental Protection Agency, Region IV; **GAFWRU** - University of Georgia, Athens/U.S. Fish & Wildlife Service Cooperative Unit; and **GAEPD** - Georgia Department of Natural Resources, Environmental Protection Division.

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3 Minimum or maximum number of stations sampled each month during the period of record

Table 1. *Primary Sources of Salinity Data (continued)*

State/Estuary	Source[1]	Surface/ Bottom	Tides[2]	Years (19__)	Sampling Frequency (Approximate)	Number of Stations[3]		Total # of Samples
						Minimum	Maximum	
GEORGIA								
Ossabaw Sound	SKIDAWAY	Surface	Yes	67, 70-76	Monthly	0	35	801
		Bottom	Yes	67, 70-76	Inconsistent	0	28	452
	GAEPD	Surface	No	73-92	Monthly	0	1	140
	GADNR	Surface	Yes	79,83,86-93	Monthly	0	4	385
St. Catherines/ Sapelo Sounds	SKIDAWAY	Surface	Yes	61,63,66-76	Inconsistent	0	12	2124
		Bottom	Yes	61,63,67-76	Inconsistent	0	11	830
	GAEPD	Surface	No	70-92	Monthly	0	1	292
	GADNR	Surface	Yes	79-93	Monthly	0	16	879
Altamaha River	SKIDAWAY	Surface	Yes	59,68-76	Monthly	0	12	434
		Bottom	Yes	59,68-70,73-76	Inconsistent	0	15	262
	GAEPD	Surface	No	73-92	Monthly	0	1	141
	GADNR	Surface	Yes	79-85	Monthly	0	4	229
St. Andrews/ St. Simons Sounds	SKIDAWAY	Surface	Yes	59,68-76	Inconsistent	0	19	854
		Bottom	Yes	59,68-76	Inconsistent	0	11	858
	GAEPD	Surface	No	73-92	Monthly	0	3	331
	GADNR	Surface	Yes	79-93	Monthly	0	9	1306
GEORGIA/FLORIDA								
St. Marys River/ Cumberland Sound	SKIDAWAY	Surface	Yes	72-74	Monthly	0	1	63
		Bottom	Yes	73 (Dec), 74 (Mar, Jun, Sep, Dec)	Every hour for 7 hrs per month	0	1	34
				74 (Feb)	Monthly	1	1	
	GADNR	Surface	Yes	79, 81-93	Monthly	0	4	551

1 **SKIDAWAY** - Georgia Estuarine Data 1961-77, Charles D. Winker, Louise C. Jaffe, James D. Howard; Georgia Marine Science Center, University System of Georgia, Skidaway Island, Georgia, Technical Report Series, Number 85-7, Vols. 1 and 2; **GAEPD** - Georgia Department of Natural Resources, Environmental Protection Division; and **GADNR** - Georgia Department of Natural Resources, Crustacean Monitoring Cruises.

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